DESIGN OF A PATCH ARRAY ANTENNA FOR 5G APLICATIONS

2023
MASTER THESIS
ELECTRIC-ELECTRONICS ENGINEERING

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Prepared as
Master Thesis

KARABUK
January 2024

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ABSTRACT

Master Thesis

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January 2024, 62 pages

Microstrip patch antennas play a major role and commonly used in modern communication systems because of their small size, low profile, and simplicity of integration.

This research presents optimized designs for a single element microstrip patch and patch array antenna for 5G applications operating at 3.6 GHz. The patch is constructed of copper and is built on a low-cost Rogers RT5880 substrate with a dielectric constant of 2.2 and a loss tangent of 0.009. The proposed design focuses on achieving a broad bandwidth, high gain, and efficient radiation patterns. The antenna's geometry is carefully selected to resonate at the desired frequency, and the design is optimized using electromagnetic simulation CST microwave studio. The impact of various parameters, including patch dimensions and substrate properties, on the antenna's performance is systematically analyzed. Special attention is given to achieving a low VSWR to guarantee efficient power transfer.

Simulated results demonstrate that the proposed microstrip patch antenna meets the design objectives, offering a wide bandwidth of 160 MHz with a return loss of about -39 dB, a peak gain of 10.14 dBi, an efficiency of 0.98, and excellent radiation characteristics for the patch array antenna (1×2) with a size of 99.454 × 48.84 × 2.424 mm3. Furthermore, the single-element patch provides 100 MHz bandwidth with a return loss of about -42 dB and a peak gain of 7.311 dBi with excellent radiation characteristics with an efficiency of 0.85 and a size of 64.4 × 81.25 × 2.572 mm3.

Keywords : Microstrip patch array, 5G antenna, design, CST, Gain, high efficiency, Microstrip inset feeding mechanism.

Science Code : 90516

ÖZET

Yüksek Lisans Tezi

5G UYGULAMASI İÇİN YAMA DİZİSİ ANTEN TASARIMI

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Tez Danışmanı:
Doç. Dr. Lokman KUZU
January 2024, 62 sayfa

Mikroşerit yama antenleri, küçük boyutları, düşük profilleri ve entegrasyon kolaylıkları nedeniyle modern iletişim sistemlerinde önemli bir rol oynar ve yaygın olarak kullanılır.

Bu araştırma, 3.6 GHz'de çalışan 5G uygulamaları için tek elemanlı bir mikroşerit yama ve yama dizisi anteni için optimize edilmiş tasarımlar sunmaktadır. Yama bakırdan yapılmıştır ve dielektrik sabiti 2.2 ve kayıp tanjantı 0.009 olan düşük maliyetli bir Rogers RT5880 alt tabakası üzerine inşa edilmiştir. Önerilen tasarım, geniş bir bant genişliği, yüksek kazanç ve verimli radyasyon modelleri elde etmeye odaklanmaktadır. Antenin geometrisi, istenen frekansta rezonansa girecek şekilde özenle seçilir ve tasarım, elektromanyetik simülasyon CST mikrodalga stüdyosu kullanılarak optimize edilir. Yama boyutları ve alt tabaka özellikleri dahil olmak üzere çeşitli parametrelerin antenin performansı üzerindeki etkisi sistematik olarak analiz edilir. Verimli güç aktarımını garanti etmek için düşük bir VSWR elde etmeye özellikle dikkat edilir. Simüle edilmiş sonuçlar, önerilen mikroşerit yama anteninin yaklaşık -39 dB'lik bir geri dönüş kaybı, 10.14 dBi'lik bir tepe kazancı, 0.98'lik bir verimlilik ve 99.454 × 48.84 × 2.424 mm3 boyutunda yama dizisi anteni (1×2) için mükemmel radyasyon özellikleri ile 160 MHz'lik geniş bir bant genişliği sunarak tasarım hedeflerini karşıladığını göstermektedir. Ayrıca, tek elemanlı yama -42 dB civarında bir geri dönüş kaybı, 7311 dBi'lık bir zirve kazancı ve 0.85 verimlilik ile mükemmel radyasyon özellikleri ile 64.4 × 81.25 × 2.572 mm3 boyutunda bir bant genişliği sağlar

Anahtar Kelimeler : Mikroşerit yama dizisi, 5G anten, tasarım, CST, Kazanç, yüksek verimlilik, Mikroşerit besleme mekanizması.

Bilim Kodu : 90516

ACKNOWLEDGMENT

First of all, I would like to give thanks to my advisor, Prof. Dr. Lokman KUZU, for his great interest and assistance in the preparation of this thesis. Special thanks to Assist. Prof. Dr. Cihat ŞEKER for his valuable assistance. All the teachers I met during my life really appreciate.

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SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

Q	: quality factor
εr	: dielectric constant of the substrate
φ	: azimuth angle
θ	: elevation angle
D	: directivity
Ae	: effective area
π	: pi
μ	: efficiency
λ	: wavelength of the operating frequency.
Lr	: loss due to radiation.
Lc	: conductor loss.
Ld	: dielectric loss
Lt	: losses factor
Pr	: power radiated.
Pc	: Dissipation of power as a result of conductors.
Pd	: the power dissipation caused by dielectric.
G	: gain
Γ	: reflection coefficient
RL	: return loss
W	: width
h	: height
L	: length
Zc	: transmission line impedance
εeff	: effective dielectric constant
ΔL	: change in length
fr	: resonant frequency

δeff : effective loss tangent

tan δ : Dielectric Loss Tangent

C : speed of light

Ls : substrate length

Ws : substrate width

hs : substrate thickness

Lp : patch length

Wp : patch width

ht : patch and substrate thickness

Zo : Characteristic Target Impedance

h : substrate thickness

t : trace thickness

ABBREVITIONS

XG : Generations, 0G – 5G

Log : logarithmic

MIMO : Multiple input multiple output

GHz : Giga hertz

CST : Computer Simulation Technology

MWS : microwave studio

LTE : Long term evolution

IoT : internet of things

MPAs : microstrip patch antennas

RF : radio frequency

RHCP : right hand circular polarization

LHCP : left hand circular polarization

PCB : printed circuit board

VSWR : voltage standing wave ratio

RFID : radio-frequency identification

Wi-Fi : wireless fidelity

Rr : radiation resistance

FR-4 : Flame Retardant fiber glass epoxy

CAD : Computer-Aided Design

HFSS : high-frequency structure simulator

PTFE : polytetrafluoroethene

FEM : finite element method

FIT : finite integration technique

MATLAB: Matrix laboratory

PART 1

INTRODUCTION

1.1. GENERAL VIEW

Wireless technology has revolutionized communications. Each generation from 0G to 4G is an older and Enhanced version. 4G technology is widely utilized in various applications, including video call data streaming, remote host monitoring, and device-type communications. Although 4G presents certain advantages, it fails to address issues related to inferior coverage., poor quality, communication loss, channel congestion, poor interconnection, and high-power consumption. Because of the fast growth of devices connected to the telecom system, present 4G technology will not match the present demand. As a result, the mobile communication infrastructure must be updated to the next generation (5G) to fulfill upcoming desires of high data rates. The antenna is an essential component of any wireless system and one of the most important keys. It is a gadget that sends and receives electromagnetic waves. Typically, antenna is resonant tools that work successfully across a clearly tiny frequency range. Antennas play an essential role in 5G wireless communications networks, as they are essential for transmitting and receiving signals between devices and base stations. In 5G networks, antennas have evolved to fulfill the need for increased data rates, lower latency, and increased connectivity. 5G technology relies heavily on MIMO technology, which utilizes several antennas at each transmitter and receiver to improve radiation efficiency and overall network performance.

1.2. PROBLEM STATEMENT

Main problem that faced in 5G antenna’s design is the high gain and bandwidth demand, considering the high installation and manufacturing cost.

1.3. AIMS AND OBJECTIVES

The primary purpose in this research endeavor is to design and build a 5G antenna for the operating frequency of 3.6 GHz with 150 MHz bandwidth that enhances the gain and other radiation characteristics of the antenna with an inexpensive cost, compact size, and simple design. Therefore, a patch antenna array is proposed to meet the demand for 5G feature and meet the high QoS requirement demanded by users.

1.4. METHODOLOGY

We make calculations and figure out the main design parameters values for patch antenna. Substrate selection is the first crucial stage in antenna design. An antenna's impedance matching and bandwidth are heavily impacted by substrate factors such as dielectric constant, thickness, and tangent loss (tan δ). Using a very thin substrate can result in high copper losses, whereas a larger substrate might reduce antenna performance owing to surface waves. In order to achieve a high gain, an array of Microstrip antenna will be designed. The most appropriate feeding strategies will be chosen based on the design specifications. Microstrip patch will be designed and simulated using CST software in the frequency 3.6 GHz.

1.5. THESIS OUTLINES

This thesis contains five chapters. The first chapter provides a brief introduction to the proposed project; Chapter two provides a theoretical overview and related research on microstrip patch antennas; and Chapter three displays the design and construction of an antenna simulation. The results and debates have been left for Chapter four. Finally, Chapter five contains the conclusion and recommendations.

PART 2

THEORITICAL OVERVIEW AND LITERATURE REVIEW

2.1. INTRODUCTION

The 5G of wireless technologies marks a considerable jump in the evolution of mobile and wireless communications. It builds upon the foundations of 4G (LTE) and earlier generations but introduces a range of new capabilities and technologies. This introduction provides an overview of 5G, highlighting its key features, significance, and potential impacts on various industries. 5G promises significantly faster data rates compared to 4G. Peak data rates can reach several gigabits per second, enabling ultra-high-definition video streaming, low-latency gaming, and other data-intensive applications. Additionally, 5G networks have exceptionally low latency, which reduces the time taken for data to transit between endpoints and the network. This is critical for applications like driverless vehicles, remote surgery, and real-time industrial automation. 5G is perfect for IoT applications since it would be able to connect a large number of devices at once. It is capable of supporting a significantly greater number of devices per unit area compared to 4G. In terms of reliability, fifth-generation network desires deliver elevated availability and dependability, offering crucial services and applications remain operational even in challenging conditions. From the other hand 5G introduces network slicing, which allows the construction of virtual network established for certain utilize cases. This authorizes the coexistence of various services on a single physical network infrastructure. In addition to sub-6 GHz frequencies, 5G utilizes mm-Wave bands, which offer extremely high bandwidth and capacity. These high-frequency bands enable faster speeds but have shorter propagation distances. Furthermore, 5G networks deploy Massive MIMO technology, utilizing huge numbers of antennas to improve spectral efficiency and network capacity. 5G has the potential to transform the method we communicate, work, and live. Its high speeds, low latency, and massive connectivity make it a key enabler for a wide range of applications, industries, and technologies. However, its successful deployment and realization of its full potential will require collaboration among industry stakeholders, policymakers, and regulators.

An antenna is one of the most crucial components of any wireless system. It is a gadget that sends and receives EM waves. It plays a fundamental role in 5G wireless communication networks, as they are essential for transmitting and receiving signals between devices and base stations. An antenna is a resonant device that operates efficiently across a restricted frequency band. In 5G, antennas have evolved to satisfy the necessities of high data rates, lower latency, and increased connectivity. 5G relies heavily on MIMO technology employs several antennas at the transmitter and receiver to improve both spectral proficiency and network performance as a whole. Large MIMO includes a significant number of antennas on base stations to serve multiple users simultaneously, increasing capacity and reducing interference. Beamforming is a critical feature in 5G antennas. It allows the antenna system to focus signal transmission on the direction of the intended receiver, enhancing signal strength and reducing interference. Beamforming is used in both mm-Wave and sub-6 GHz 5G deployments. 5G operates over a widespread range of frequency bands, incorporate mm Waves and sub-6 GHz frequencies. Antennas must be designed to operate in these different frequency bands, which can require different antenna configurations and technologies. 5G networks are expected to deploy a vast number of small cells and Massive MIMO antennas to improve coverage and capacity in urban and densely populated areas. Small cells are particularly important for mm-Wave 5G deployments due to their shorter range. Antenna diversity is crucial for maintaining a robust and reliable connection in challenging radio environments. Multiple antennas, including multiple spatially separated antennas on devices and base stations, provide diversity to combat fading and interference. In 5G smartphones and other mobile devices, antenna design is a critical consideration. Integrated antennas are engineered to be compact and efficient, often using advanced materials and multiple antenna elements to support various frequency bands and MIMO configurations. 5G antennas are designed to support massive connectivity, serving many IoT devices simultaneously. These antennas are optimized for low power consumption and efficient use of spectrum. Smart antennas in 5G networks can adapt their beamforming and direction based on network conditions, device location, and traffic demands, enhancing network efficiency. Antenna designs often incorporate advanced materials to optimize performance, reduce interference, and adapt to the high-frequency bands used in 5G, especially in mm-Wave deployments. As we mentioned above, in 5G networks, network slicing is employed to establish customized virtual networks for specific applications and scenarios. This involves segmenting resources, including antennas, to support different services and applications. [1].

Therefore, antennas are a critical component of 5G networks, enabling the high-speed, low-latency, and massive connectivity capabilities of this next-generation wireless technology. Their design and deployment are essential for realizing the full potential of 5G in various applications, from enhanced mobile broadband to IoT, smart cities, and beyond.

2.2. OVERVIEW OF MICROSTRIP PATCH ANTENNA

The MPAs present an enticing choice due to their compatibility, cost-effectiveness, and lightweight nature. It has an active device and a printed line feed network that combine smoothly. Wireless antenna engineering is a relatively young field. Since the mid-1950s, the radiative characteristic of beneficial ribbon architectures has been recognized. However, it wasn't until the early 1970s, when there arose a demand for compact, missile-compatible antennas, that this type of antenna found practical applications. Among the resonant patch configurations, rectangular and circular designs have gained prominence, often deployed in a variety of array setups [2].

One significant impetus behind the recent strides in MPAs is the ongoing growth in the miniaturization of electronic circuits, a consequence of advances in large-scale integration. Classic antennas, frequently cumbersome and expensive components of electronic systems, gave way to microstrip antennas, crafted using photolithography technology an engineering achievement.

The microstrip antenna configuration involves connecting the patch to a ground plane, with a dielectric substrate in between. This concept materialized alongside the surge throughout the 1970s in large-scale integration and electronic circuit compression. Subsequently, various authors explored ground-plane radiation facilitated by dielectric substrates with distinct configurations. Early work by Munson introduced small ribbon antennas, initially designed for employment as low-level antennas that mount on skyrockets and projectiles, establishing the practicality of this concept across a spectrum of antenna-related challenges.

Numerous mathematical models have been developed for this antenna, expanding its applications across diverse fields. The growing volume of research articles published in journals over the past decade underscores the pivotal role these antennas have assumed. Small ribbon antennas have become the preferred choice for contemporary antenna designers. Substrates characterized by Low dielectric constants are definitely favored to optimize the radiation. While patches could adopt various shapes, rectangular and circular configurations stand out as the most used due to their practicality. Alternative configurations, while possible, often entail complex numerical calculations and analysis.

Key attributes defining a small ribbon antenna include its input impedance, width length, radiation patterns and gain. Subsequent chapters delve into a comprehensive exploration of various parameters and layout considerations for microstrip antennas.
The antenna's length, approximately half the wavelength within the dielectric, emerges as a critical parameter that governs the antenna's resonant frequency. Determining the width of the patch, however, lacks standardized guidelines.

In its fundamental design, as seen in Figure 2.1 below, an MPA has a dielectric substrate with a ground plane on one side and a radiated patch on the other.

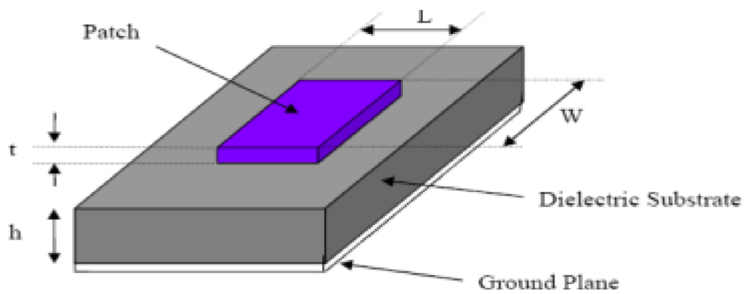


Figure 2.1. Microstrip patch antenna structure [3].

Typically, patches are fabricated from conductive materials such as gold or copper and can assume a wide range of shapes. Both the feed lines and radiating patch are commonly photo-etched onto the insulating substrates.

To facilitate analysis and performance prediction, the patch is commonly rendered in simple geometric shapes, including elliptical, triangular, square, rectangular, circular, or various other standard configurations, according to the illustration in Figure 2.2. For instance, in this case, the length of a rectangular patch typically falls within the range of $0.3333\lambda o < L < 0.5\lambda o$, where λo represents the wavelength of free space. Patches are designed to be exceptionally small, with their thickness (t) satisfying the condition $t << \lambda o$. Additionally, the height (h) of the dielectric substrate typically adheres to the range of $0.003\lambda o \leq h \leq 0.05\lambda o$. The substrate's dielectric constant (εr) usually falls within $2.2 \leq \varepsilon r \leq 12$.

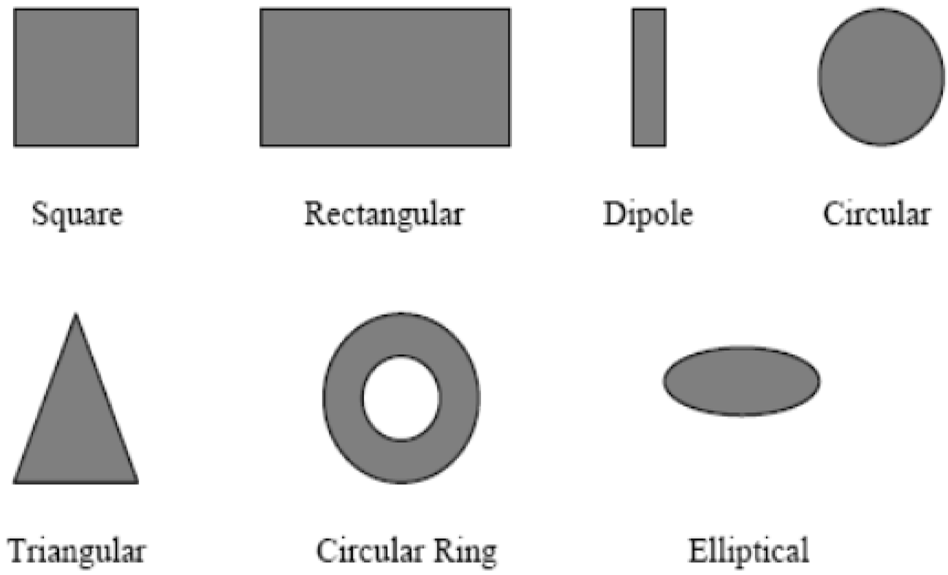


Figure 2.2. Microstrip patch element different shapes [4].

MPAs predominantly emit radiation through the fringing fields that occur among the ground plane's and the patch's boundaries. A thick dielectric substrate with lower dielectric constants is preferable for best antenna performance since it enhances efficiency, broadens bandwidth, and improves radiation characteristics. However, this design leads to a larger antenna. To create a compact MPA, substrates with a greater dielectric constant are employed, albeit at the cost of efficiency and narrower bandwidth. Consequently, there exists a trade-off between the antenna's dimension and performance. Although they have some disadvantages and advantages, MPAs have gained popularity in wireless applications, primarily owing to their low-profile construction. This makes them exceptionally well-suited for integration as incorporated antennas in portable wireless devices, like pagers and cell phones. They are also favored for use in missile telemetry and communication antennas, where a conformal, thin design is crucial. Another domain where they have found success is in satellite communication. A few of the main benefits include:

- Flat, low-profile design that can readily conform to host surfaces.
- Light-weight and compact
- Economical to manufacture in large quantities.
- Compatible with both circular and linear polarization.
- Reliable for operating across dual and triple frequencies.
- Seamless integration with microwave-integrated circuits (MICs).
- Demonstrates mechanical resilience when affixed to rigid surfacing.

MPAs exhibit many limitations when contrasted with regular antennas. Some of the primary drawbacks include:

- Unwanted radiation stemming from feeds and junctions.
- Limited bandwidth.
- Reduced efficiency.
- Modest gain.
- Susceptibility to surface wave excitation.
- Diminished power-handling capacity.
- Ineffectiveness as an end-fire radiator, except for tapered slot antennas.

MPAs exhibit a notably elevated antenna's quality factor (Q), reflecting the inherent distortions within the antenna system. A higher Q value is associated with a narrower bandwidth and reduced efficiency. One approach to mitigate this effect is by expanding the dielectric substrate's thickness, which can lower the Q value. However, as the substrate thickness grows, a greater fraction of the total power supplied by the source is directed toward a surface wave. This contribution of surface wave power is regarded undesirable, because it ultimately scatters at the bends of the dielectric, leading to a degradation of antenna characteristics. Issues like diminished power-handling capacity and gain could be achieved by adopting an array configuration for the antenna's elements.

2.3. MICROSTRIP PATCH ANTENNA CHARACTERISTICS

These are fundamental parameters and characteristics of microstrip patch antennas:

Radiation Pattern: It describes how an antenna radiates electromagnetic energy in three dimensions. It provides information about the antenna's directional characteristics and is represented in both elevation and azimuth planes. In Figures 2.3 (a and b), we observe two radiation patterns, one in the elevation ($\varphi = 90^\circ$) and the other in azimuth ($\varphi = 0$). Figure 2.3 (c) depicts another typical radiation pattern for a linearly polarized patched antenna. This diagram illustrates a horizontal (azimuth) plane cross section, with a comparable though not identical pattern in the vertical (elevation) plane. Utilizing a logarithmic scale, the diagram indicates that, for instance, the power radiated at 180◦ is around 15 dB less than the power at the beam center, situated at 90◦. The beam width covers around 65◦, and the gain achieves approximately 9 dBi. It's important to note that in the presence of an infinitely large ground plane, back radiation could be completely prevented. However, the actual antenna incorporates a relatively compact ground plane, resulting in back radiation being only approximately 20 dB weaker than the radiation in the primary beam direction.

Beam width: It is a measurement of the angular coverage that the antenna emits a sizable amount of power. It’s specified as the angular distance across two points where the radiation pattern's gain drops to half of the maximum gain. A narrower beam width indicates higher directivity. Figure 2.3 shows various radiation patterns for a Microstrip Patch Antenna (MSA). These visual representations clearly demonstrate that MSAs typically exhibit exceptionally broad beam widths in both the azimuth and elevation planes.

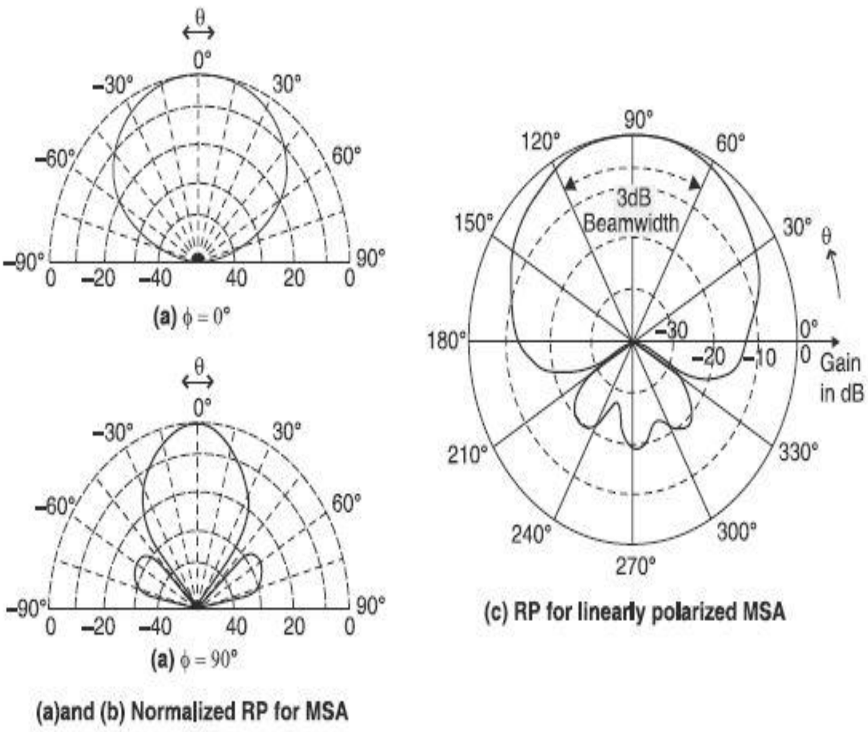


Figure 2.3. Radiation patterns of MSA [5].

Directivity: Directivity quantifies how perfectly the antennas focus their radiation in a specific orientation. It's the ratio of the average radiation intensity across all directions to the radiation intensity in the peak direction of the main lobe. A higher directivity implies better focusing. Directivity (D) of a MPA can be calculated by the following equation:

$$\boldsymbol{D = \frac{4\,\pi}{\lambda^2}\ .\, \mu .\, Ae} \qquad (2.1)$$

Where:

D directivity of the antenna.
λ operation frequency wavelength.
η efficiency of the antenna.
Ae effective aperture area of the antenna.

Directivity quantifies the capability of the antenna to concentrate its radiation in a particular direction and is expressed as a dimensionless quantity (often in decibels, dBi). To calculate the directivity, we would need to determine the efficiency and effective aperture area, which depends on the specific design and characteristics of the MPA.

Antenna Efficiency: Antenna efficiency measures how successfully the antenna transforms input power into radiated power. Higher efficiency is needed to minimize losses.

The total loss factor for a microstrip patch antenna can be defined as:

$$L_T = Lc + Ld + Lr \tag{2.2}$$

Where:

- Ld denotes to dielectric loss.
- Lc stands for the conductor loss.
- Lr represents the loss due to radiation.

These losses in both the conductor and the dielectric substrate(s) lead to a decrease in the radiation efficiency, which is quantified by the following equation:

$$\boldsymbol{\eta} = \frac{\mathcal{P}r}{\mathcal{P}c+\mathcal{P}d+\mathcal{P}r} \tag{2.3}$$

Here:

- Pc presents the power that was lost due to conductor loss.
- Pr represents radiated power.
- Pd is the power lost as a result of dielectric losses.

Gain: Gain evaluates the antenna's capacity to direct its radiation in a specific direction. It is usually stated in decibels (dBi) and is an important parameter for assessing the antenna's performance. The rectangular microstrip patch antenna with an air dielectric and an assumed gain falls within the range of approximately 7 to 9 dB, and this estimation is based on the following considerations:

The gain of the patch antenna, as derived from its directivity in relation to the vertical axis, is typically around 2 dBi This assumption holds true when the patch’s length corresponds to half of the wavelength.

When the patch's shape is square, the radiation's pattern in the horizontal plane becomes directed. In essence, this square patch can be seen as similar to the pair of dipoles that are separating by fifty percent of a wavelength. This arrangement adds 2 to 3 dB to the overall gain.

The presence of a ground plane effectively obstructs the majority of radiation directed behind the antenna, resulting in a power gain.

These factors collectively contribute to the estimated gain range of 7 to 9 dB for the rectangular MPA with an air dielectric.

Voltage Standing Wave Ratio (VSWR): It’s a measurement’s metric used to figure out the effectiveness of a strength switch between a transmission line and an antenna. It's a dimensionless ratio that shows how effectively the antenna’s system fits the transmission line.

VSWR may be computed using the formula below:

$$VSWR = (1-|\Gamma|)/(1+|\Gamma|) \quad (2.4)$$

Where:

- VSWR: Voltage Standing Wave Ratio.

- Γ (Gamma): is the reflection coefficient.

Gamma is derived from the ratio of reflected and incident voltages. A perfectly matched system would have $\Gamma=0$, resulting in a VSWR of 1:1. As the VSWR value increases, it indicates a less efficient correspondence between the antenna and the transmission line., leading to increased power reflection. A perfect match can be indicated by the value 1 of VSWR, while higher values (e.g., 2:1 or 3:1) suggest increased power reflections and a less optimal system match. Thus, may result in decreased efficiency and loss of power.[6]

Return loss: When the antenna and feeding line can't sync up in terms of impedance, some power gets lost in translation. This phenomenon is known as "return loss. We refer to this occurrence as "return loss." The powers reflected by the antenna and delivered into it from the feeding line are compared logarithmically and expressed in dB.

$$RL = -20 \log(\Gamma) \text{ dB} \quad (2.5)$$

Return loss serves as a crucial indicator of antenna efficiency and performance. If it goes beyond -10 dB, it's a sign that the antenna isn't working optimally, indicating a mismatch between the feeding line and the antenna.

Bandwidth: It defines the frequency ranges through which it can work effectively. A wider bandwidth is often preferred for practical applications. The distance between the patch and the ground plane has a big influence on a patch antenna's impedance bandwidth. Less energy is released and more energy is retained in the capacitance and inductance of the patch as it approaches the ground plane. In other words, the impedance bandwidth falls and the antenna's quality factor Q rises. An alternative approach is to print the patch on a dielectric board, which is frequently easier to manufacture and results in slightly thinner antennas. However, this reduces the antenna's overall volume, and the bandwidth falls correspondingly as the quality factor Q increases, which is related to the substrate's dielectric constant.

In practice, genuine patch antennas frequently employ ground planes that are just slightly bigger than the patch, which affects their performance. In addition, the antenna's feed structure influences bandwidth. The voltage standing ratio ('S') is an important metric to consider, especially at the input and in resonance situations. If Q0 indicates the quality factor of the unloaded radiation, it is linked to the bandwidth using the relationship:

$$Bandwidth = \frac{S-1}{Q0\sqrt{S}} \quad (2.6)$$

According to this relationship, we may deduce that as 'S' grows, so does the impedance bandwidth.

Polarization: It determines the orientation of the electromagnetic waves it can transmit or receive. Common polarizations include linear (horizontal or vertical) and circular. Patch antennas have the inherent benefit of being able to provide polarization diversity. These antennas can be readily constructed to exhibit various polarizations, such as left-hand circular (LHCP), right-hand circular (RHCP), horizontal, or vertical. This versatility is accomplished by using either a single feed point or various points in combination with an asymmetric patch structure. This unique characteristic allows patch antennas to cater to diverse communication links with varying requirements. To generate circularly polarized waves from patch antennas, one approach involves exciting a square patch with two feeds, each with a 90° phase shift. In this configuration, the vertical current reaches its maximum when the horizontal current is at a minimum (zero), resulting in a vertically radiated electric's field. Throughout a quarter-cycle, the condition reverses, yielding a horizontal radiated field. Over time, the radiated field of equal magnitude rotates, -creates a circularly polarized wave. Circular polarization can also be accomplished with a single feed point by providing asymmetric slots or various features in the patch that displace the current distributions. These techniques can be equally applied to a circular patch to achieve a circularly polarized wave. Nonetheless, it's important to note that the symmetric circular patches with only one feed point primarily produce linearly polarized radiation. To obtain circular polarization, a nearly square patch with dimensions slightly deviating from the resonant length and width and driven at the corner is utilized, producing a wave that is polarized in a circle.

Quality Factor: Microstrip patch antennas are characterized by their exceptionally high-quality factor, denoted as ‘Q’. The extent of losses related to the performance of the antenna is indicated by ‘Q’. A low 'Q' value might be enhanced by adding more thickness to the substrate's dielectric, but a high 'Q' value results in a limited bandwidth. On the other hand, a significant portion of the total power supplied by the source undergoes conversion into surface waves when the substrate thickness increases. Such modification represents an undesired power loss, as it eventually scatters at the bends of the dielectric, leading to a deterioration in the antenna's characteristics. To mitigate the presence of surface waves, the utilization of photonic band-gap structures can be employed. Additionally, challenges related to limited power-handling capacity and low gain can be effectively addressed through the implementation of array configurations.

Input Impedance: Input impedance characterizes the antenna's electrical impedance at its feed point. Matching the input impedance of the antenna to the transmission lines or source impedance is crucial for efficient power transfer.

Antenna Vector Effective Length: It’s a vector quantity that characterizes the relationship between the voltage at the antenna terminals and the electric field. It is useful for understanding the antenna's interaction with electromagnetic fields.

Equivalent Areas: it used to describe the antenna’s effective area in capturing or radiating electromagnetic energy. They help relate the antenna's physical characteristics to its performance.

Maximum Effective Area: Maximum effective area is the largest effective area of the antenna for receiving or transmitting electromagnetic waves. It is a theoretical value used for reference.

These parameters and characteristics are essential for designing, analyzing, and evaluating the performance of microstrip patch antennas in diverse applications, such as radar systems, satellite communication, and wireless communication. These parameters are used to customize antenna designs to satisfy particular needs and optimize performance.

2.4. FEEDING TECHNIQUES

The feeding techniques employed in microstrip antennas can be categorized into two significant classes: **Contacting Feed:** This approach involves directly supplying RF power to the patch using a linking component, for example, a coaxial line or microstrip line. Coaxial Feed and Microstrip Feed are frequently used contacting feeding methods. **Non-Contacting Feed**: This technique uses electromagnetic coupling to transfer energy from the feed line to the patch rather than directly powering it with radiofrequency radiation. The two most used non-contacting feed techniques are proximity-coupled feeding and aperture-coupled feeding. The function of feeding is paramount for making sure the green operation of the antenna, particularly in improving input impedance matching. The various kinds of feeding techniques that exist:

- Microstrip Line Feeding
- Inset Feeding
- Co-axial Feeding
- Aperture Coupled Feeding
- Proximity Coupled Feeding

2.4.1. Microstrip Line Feed

It's a common method used to supply radio frequency (RF) energy to microstrip patch antennas. This technique involves a transmission line, typically in the form of a microstrip line, which connects the antenna feed point to the external RF sources or receivers. Microstrip line feed is one type of transmission line that is made of a conductive strip on the surfaces of a dielectric substrates. This strip serves as the feed line, carrying RF signals to or from the patch antenna. The microstrip line feed consists of a transmission line structure that includes a conductive strip (often made of copper) throughout a dielectric substrate's surface. The transmission line may be a microstrip line, which is a simple and widely used structure for feeding microstrip patch antennas. The feed point, where the patch antenna connects to the transmission line, is strategically determined during the antenna's design. The antenna's performance can be strongly impacted by the feed point's location, including its impedance matching and radiation characteristics. Efficient power transfer requires proper impedance matching between the microstrip line and the patch antenna. This is typically accomplished by selecting the microstrip line’s width and length, as well as its position relative to the patch. Microstrip line feeds are versatile and can be designed for multiband, dual-band or single-band, operation, depending on the specific requirements of the antenna and its application.

Microstrip line feed offers several advantages, including ease of integration with the patch antenna on the same substrate. It is also well-suited for planar antenna designs and can be customized to operate over various frequency ranges. One of the challenges with microstrip line feeds is achieving a good impedance match over a wide frequency range, especially when designing multiband or broadband antennas. This may require additional design and matching techniques. The microstrip line's feed performance is impacted by the choice of dielectric substrate material, which affects the velocity of propagation and the characteristic impedance of the transmission lines.

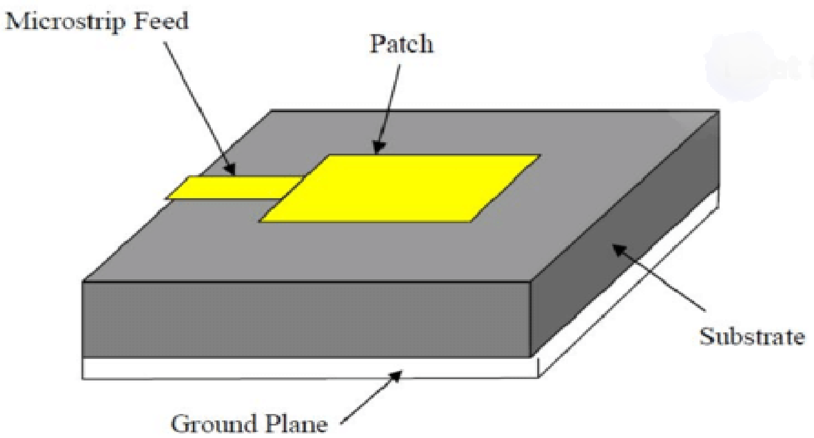


Figure 2.4. Microstrip line feed [7].

Microstrip line feeds may be manufactured with ordinary PCB technology, making them cost-effective and appropriate for mass manufacturing. Microstrip line feeds are commonly used in different applications, including satellite communication, radar, wireless communication systems, and aerospace technology. They are often employed in compact and lightweight antenna designs. The design of a microstrip line feed involves careful consideration of characteristics, including line length, width, and substrate materials. Simulations and testing are often employed to optimize the feed's performance. Therefore, microstrip line feed is a widely used technique to supply RF energy to microstrip patch antennas. It offers flexibility in design, impedance matching, and frequency coverage, making it appropriate for a wide scope of implementation where compact, planar antenna designs are required.

2.4.2. Inset Feed

It is a microstrip line feeding technology in which the conducting strip is narrower than the patch and has the advantage of providing a planar structure. The inset feeding technique is a method used in the design of microstrip or patch antennas to efficiently feed radio frequency (RF) signals into the antenna structure while achieving good impedance matching. This technique involves placing the feed point at a certain distance inward from the edge of the radiating patches. An inset feeding technique is one of several methods used for this purpose. The key feature of the inset feeding technique is that it involves positioning the feed point on the patch at a specific distance inward from the edge. This distance is known as the "inset distance." One of the primary goals of this technique is to achieve good impedance matching among the feeding transmission lines and antennas. Maximum power transfer and minimizes signal reflections granted by impedance matching the dimensions of the microstrip transmission line and the inset feed point connecting to it can be adjusted to fine-tune the antenna's impedance and radiation characteristics. This can be done through simulation and experimentation. Inset feeding can lead to improved antenna performance, including better impedance matching, wider bandwidth, and radiation pattern control. By regulating the inset distance and feed line dimensions, Designers can customize the antenna's features to match individual needs. The inset feeding technique is commonly used in a variety of applications, such as RFID (radiofrequency identification) tags, radar systems, satellite communication, and wireless communication systems (e.g., Wi-Fi, cellular). Therefore, the inset feeding technique is a valuable method for designing microstrip or patch antennas to ensure efficient RF signal transfer, good impedance matching, and control over the antenna's radiation characteristics. It is a fundamental aspect of antenna design in modern communication systems and other RF applications.

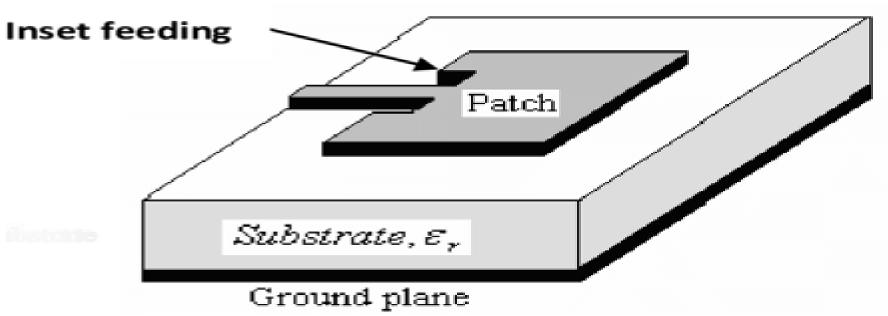


Figure 2.5. Inset feeding technique [8].

2.4.3. Co-axial Feed Technique

It is a popular method used to feed electromagnetic signals into several types of antennas, including parabolic dish antennas, patch antennas, and dipole antennas. It involves using a coaxial cable, which is a type of transmission line, to deliver RF (radio frequency) or microwave signals to the antenna elements. It is consisting of a central conductor, an insulating dielectric, a metallic shield (usually a braided or foil shield), and an outer insulating layer. This structure is designed to provide a balanced transmission line with good shielding properties. The coaxial feeding technique typically involves connecting one end of the coaxial cable to the transmitter or receiver equipment and the other end to the antenna's feeding point. This connection is often made at the antenna's feed point, which is where the electromagnetic signals are either transmitted from the antenna or received by the antenna. Coaxial cables provide a balanced feed, meaning that the inner conductor carries the signal, and the outer shield serves as the return path. This balanced feed helps minimize radiation from the transmission line and ensures efficient power transfer through the antenna. Coaxial feeding allows for easy impedance matching between the antenna and the transmission line. Coaxial feeding offers advantages such as good impedance control, low signal loss, and effective shielding against electromagnetic interference. Coaxial cables have frequency limitations, and signal losses can increase with higher frequencies. In cases where extremely low loss is critical, other transmission line types, such as waveguides, may be preferred. In summary, coaxial feeding is a versatile and widely used technique for connecting antennas to transmission equipment, providing efficient signal transfer, impedance matching, and electromagnetic shielding. It is a fundamental aspect of RF and microwave system design [9].

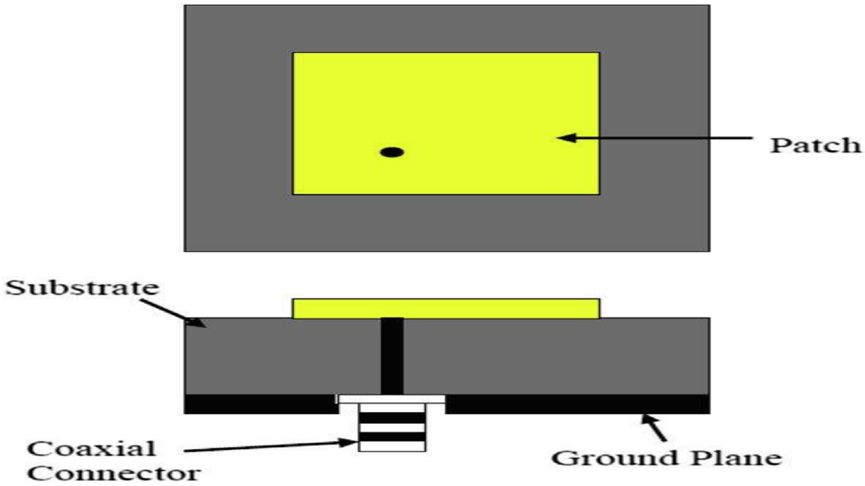


Figure 2.6. Coaxial feeding technique [7].

2.4.4. Aperture Coupled Feed

It is a feeding technique commonly deployed in the design of MPAs. This method involves coupling electromagnetic energy from one structure (Typically, a microstrip line connects to the radiating device (typically a patch antenna) via an aperture or opening in a grounded substrate. The aperture coupled feed technique creates an opening (slot) in the ground surface directly below the ignition patch. This opening serves as a means for coupling electromagnetic energy across the radiating element and the feed line. A microstrip line, which is a type of transmission line, is typically used to connect the feeding network (transmitter or receiver) to the aperture.

This microstrip line runs on the upper side of the substrate and extends to the aperture. Proper design of the microstrip line and the size of the aperture is critical for achieving impedance matching between the feeding network and the antenna. This guarantees efficient power transfer. Aperture coupled feed offers several advantages, including good isolation between the feeding network and the radiating patch, reduced electromagnetic interference, and control of the antenna's radiation pattern. This technique is commonly used in applications such as phased-array antennas, where precise regulate the radiation pattern of the antenna is crucial. It is also used in systems that require good isolation between the antenna and other components. The aperture coupled feed technique is a method used to efficiently feed electromagnetic signals into patch antennas, particularly when good isolation, radiation pattern control, and impedance matching are essential. It's a valuable approach to antenna design used in various microwave and radio frequency applications [10].

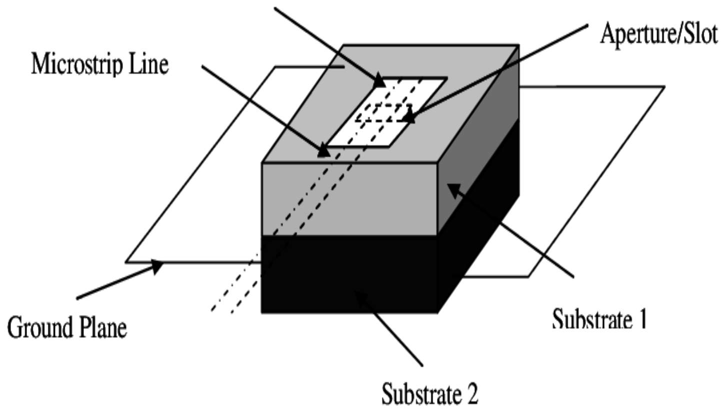


Figure 2.7. Aperture coupled feed [10].

2.4.5. Proximity Coupled Feed

Another name for this feeding technique is the electromagnetic coupling scheme. It involves the feed line is routed between two dielectric substrates, with the radiating patch mounted on the upper substrate. This feeding technique offers a significant advantage in that it effectively eliminates unintended feed radiation and yields a notably wide bandwidth, potentially reaching as high as 13%. This enhanced bandwidth results from the whole rise in the MPA's thickness.

Furthermore, two different dielectric materials can be chosen with this method: one for the feed line and one for the patch. This enables optimization of the individual performances of these elements. Importantly, this method proves advantageous in mitigating harmonic radiation associated with microstrip patch antennas implemented within a multilayer substrate [11].

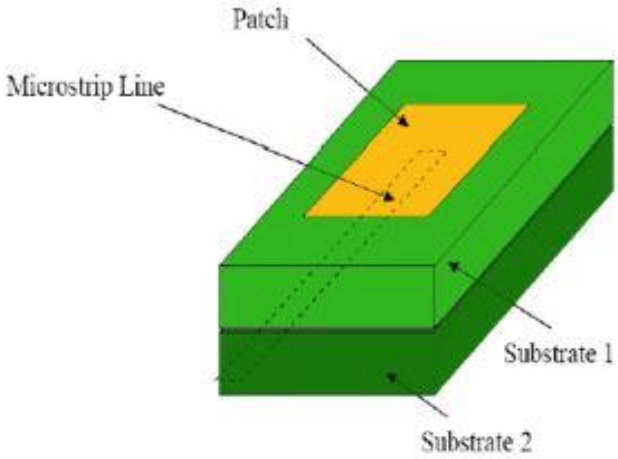


Figure 2.8. Proximity coupled Feeding technique.

2.5. METHODS OF ANALYSIS

The analysis of a MPA involves various procedures and techniques to understand and optimize its performance. each with its own advantages and trade-offs. The models that are most utilized are the full-wave model, which uses integral equations and the Moment Method, the cavity model, and the transmission-line model. The transmission-line model, while relatively straightforward, offers valuable physical insights into antenna behavior. However, it sacrifices some accuracy and may pose challenges in modeling coupling effects. In contrast, the cavity model provides improved accuracy, although it is more intricate. This model also offers valuable physical insights and can handle coupling, albeit with added complexity.

The full-wave models, when properly applied, stand out for their exceptional accuracy and versatility. They can analyze a wide range of scenarios, including finite and infinite arrays, stacked elements, single elements, and arbitrarily shaped elements. They do, nonetheless, tend to be the most complicated models and offer fewer perceptual physical insights.

For the purposes of this research, our focus will be primarily on the cavity and transmission-line models. Specifically, we will concentrate on rectangular patch configurations, while including representative radiation characteristics of other configurations for comprehensive coverage.

2.5.1. Transmission Line Model

As previously mentioned, it's the simplest approach, albeit with lower accuracy and versatility. However, it does offer some valuable physical insights. This section will demonstrate that an array made up of two radiating, narrow slots or apertures can be thought of as a rectangular microstrip antenna. Each of these slots is defined by its height (h), distance (L), and width (W). The transmission-line model depicts the microstrip antenna as two slots separated by a low-impedance transmission line (Zc) of length L. The patch's limited dimensions throughout its length and width result in fringing effects at its edges. Figures 2.8(a) and 2.8(b) exhibit the fringing effects over the length of the microstrip antenna's two radiating slots. Similar fringing effects occur along the patch's width. The size of the patches and the height of the substrates define the extent of fringing.

In the principal E-plane (xy-plane), fringing is influenced by the ratio of the patch length (L) to the substrate height (h) (L/h) and the dielectric constant of the substrate (εr). Since the aspect ratio L/h is approximately equal to or more than 1, which reduces fringing in microstrip antennas. Nevertheless, it must be considered as it has an influence on the antenna's resonant frequency. This principle also applies to the width dimension of the patch [12].

For a microstrip line, as depicted in Figure 2.9 (a), typical electric field lines are illustrated in Figure 2.9 (b). This microstrip line consists of two dielectrics, typically the air and substrate, creating a nonhomogeneous environment. The substrate contains the majority of the electric field lines, with only some parts extending into the air. When the aspect ratio W/h is approximately equal to or greater than 1, and the dielectric constant εr is also close to 1, the electric field lines primarily reside within substrates. With such cases, fringing effects make the microstrip line appear electrically larger than its actual dimensions.

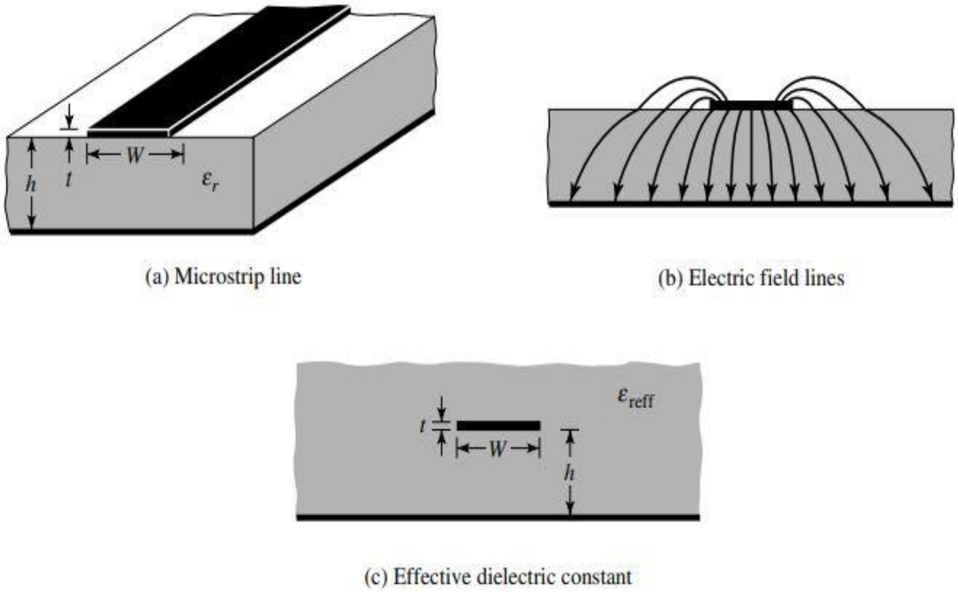


Figure 2.9. The geometry of the effective dielectric constant and the microstrip line's lines of electric field [4].

Given that certain electromagnetic wavelengths as some waves pass through the substrate and others through the air, the impact of fringing and wave propagation inside the line is taken into consideration by introducing an effective dielectric constant (εeff). To introduce the concept of the effective dielectric constant, let's investigate a scenario in which the central conductor of the microstrip line, maintaining the object is immersed in a uniform dielectric substance while preserving its original dimensions and distance above the ground plane. This configuration is illustrated in Figure 2.9 (c). Since the effective dielectric constant equals the dielectric constant of this homogeneous material, the line in Figure 2.9(c) has the same electrical properties as the real line in Figure 2.9(a), particularly with regard to the propagation constant.

For microstrip lines where air is located above the substrate, the effective dielectric constant typically falls within the range of $1 < \varepsilon eff < \varepsilon r$. In a significant number of applications where the dielectric constant substrate is significantly greater than 1 ($\varepsilon r \approx 1$), the amount of εeff tends to approach the real dielectric constant εr of the substrate. It's important to note that the operating frequency has an impact on the effective dielectric constant. As the operational frequency grows, A larger portion of the electric field lines are localized within the substrate. Consequently, the microstrip line begins to act more like a homogeneous line made of a single dielectric material (mainly the substrate), and the effective dielectric constant approaches the dielectric constant of the substrate. Figure 2.10 depicts typical changes in the effective dielectric constant for a microstrip line with three different substrate materials as a function of frequency [4].

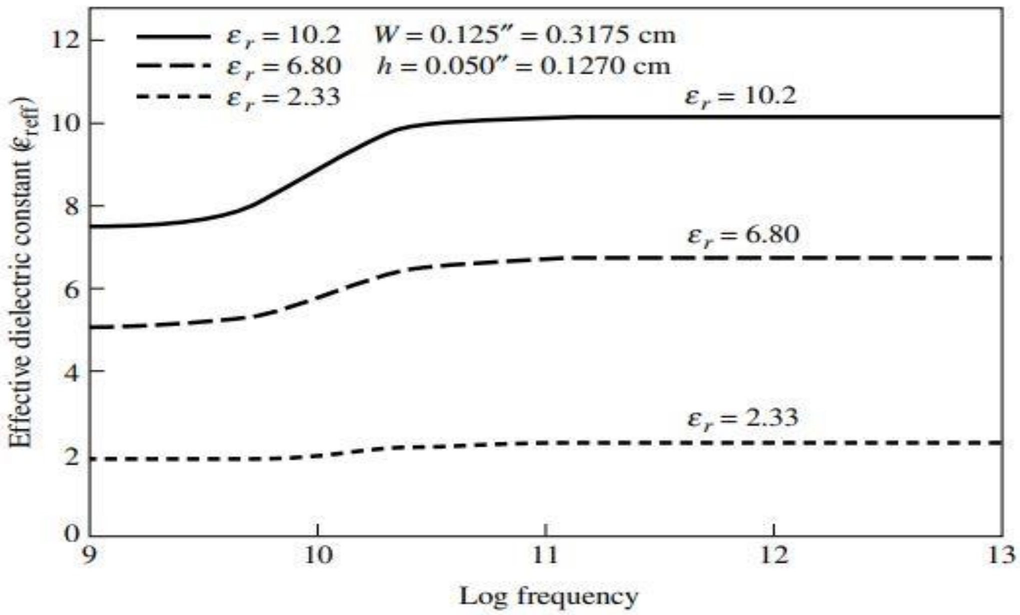


Figure 2.10. For typical substrates, the effective dielectric constant varies with frequency [4].

With lower frequencies, the effective dielectric constant remains relatively stable. As frequencies transition to intermediate levels, the effective dielectric constant exhibits a gradual, monotonic increase, eventually approaching values akin to the substrate's dielectric constant. Often referred to as the static values, the initial low-frequency values of the effective dielectric constant are found using the following particular equations:

$$\boldsymbol{\varepsilon}\mathbf{eff} = \frac{\varepsilon_r - 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\mathbf{1} + \mathbf{12}\,\frac{h}{W}\right]^{-1/2} \tag{2.7}$$

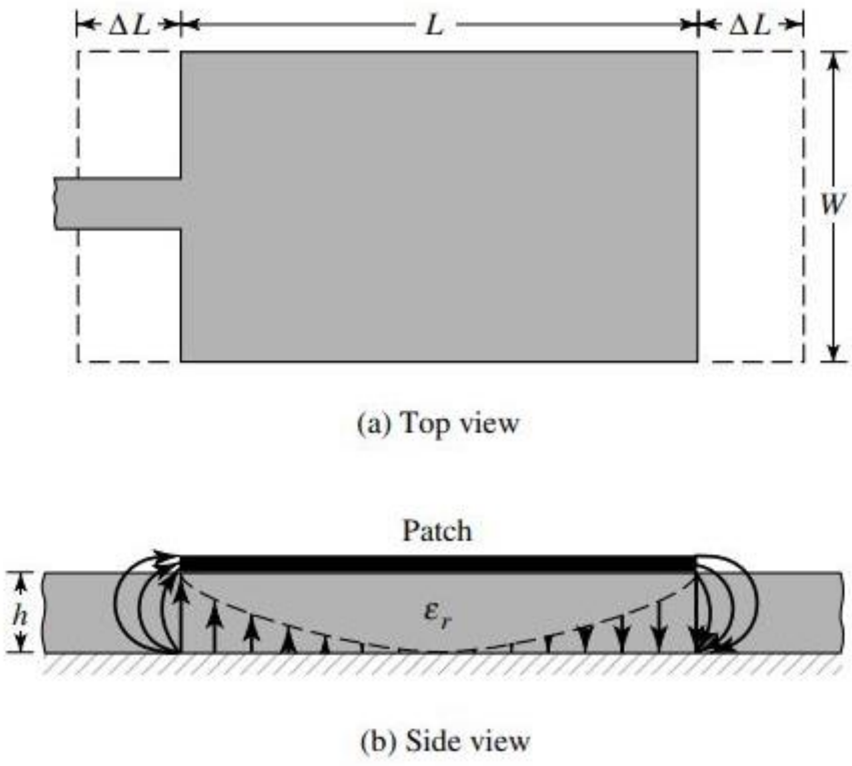


Figure 2.11. Rectangular microstrip patch physical and effective lengths.

Because of the fringing effects, the microstrip antenna's patch appears electrically wider than its actual dimensions. This phenomenon is exemplified in Figure 2.11, where the length of the patch is expanded at both ends by a distance represented by the letter 3L. This extension is dependent on the width-to-height ratio (W/h) and the effective dielectric constant ($\boldsymbol{\varepsilon}\mathbf{eff}$). Following equation describes a commonly used and useful approximation connection for the normalized extension of the length:

$$\frac{\Delta L}{h} = 0.412\ \frac{(\varepsilon\mathbf{eff}+\mathbf{0.3})(\frac{W}{h}+0.264)}{(\varepsilon\mathbf{eff}-\mathbf{0.258})(\frac{W}{h}+0.8)} \tag{2.8}$$

Extending the patch by ΔL on both sides results in an effective length of L (usually λ/2 for the dominant TM010 mode without fringing).

$$Leff\ =\ L\ +\ 2\Delta L \tag{2.9}$$

For the dominant TM_{010} mode, the microstrip antenna's resonant frequency primarily depends on its length. This resonant frequency is commonly expressed by equation 2. 10.

$$(f_r)_{010} = \frac{1}{2L\sqrt{\mu_0 \varepsilon_0}\sqrt{\varepsilon_r}} = \frac{v_0}{2L\sqrt{\varepsilon_r}} \tag{2.10}$$

in which υ0 represents the speed of light.

However, as equation 10 doesn’t take into account fringing effects, it should be adjusted to incorporate edge effects, as delineated in Eq. 11.

$$(f_{rc})_{010} = \frac{1}{2L_{eff}\sqrt{\mu_0 \varepsilon_0}\sqrt{\varepsilon_{eff}}} = \frac{1}{2(L + 2\Delta \mathrm{L})\sqrt{\mu_0 \varepsilon_0}\sqrt{\varepsilon_{eff}}}$$

$$= q\frac{1}{2L\sqrt{\mu_0 \varepsilon_0}\sqrt{\varepsilon_{eff}}} = q\frac{v_0}{2L\sqrt{\varepsilon_r}} \tag{2.11}$$

Were

$$q = \frac{(f_{rc})_{010}}{(f_r)_{010}} \tag{2.12}$$

The term "q factor" is often referred to as the fringe factor or length reduction factor. With an increase in substrate height, fringing effects also magnify, leading to greater separations between the radiating edges and consequent reductions in resonant frequencies.

Utilizing the straightforward formulation described, a systematic design approach is presented, facilitating the creation of functional designs for rectangular microstrip antennas. This approach presupposes that the provided data comprises the dielectric constant (Ɛr) substrate, the substrate's height (h), and the desired resonant frequency (fr). The steps involved in this procedure for an effective radiator, a practical width that results in high radiation efficiencies is:

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{vo}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (2.13)$$

Once W is found using equation (2.13), determine the extension of the length ΔL using equation 2.8. The actual patch length can be determined by solving

$$L = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}\sqrt{\varepsilon_{eff}}} = -2\Delta L \quad (2.14)$$

2.5.2. Cavity Model

Microstrip antennas, like dielectric-loaded cavities, exhibit higher-order resonances. A more accurate representation of the normalized fields within the dielectric substrate, located between the patch and the ground plane, can be obtained by treating this region as a cavity surrounded by electric conductors above and below it and magnetic walls around its perimeter, simulating an open circuit. This strategy, while approximate, results in a reactive input impedance (values of zero or infinite at resonance), and the antenna does not emit power. Nonetheless, assuming that the real fields substantially reflect those created by this model, the estimated pattern, input admittance, and resonant frequencies are consistent with observations. This method is widely accepted and shares similarities with perturbation methods successfully employed in the analysis of radiators, cavities, and waveguides.

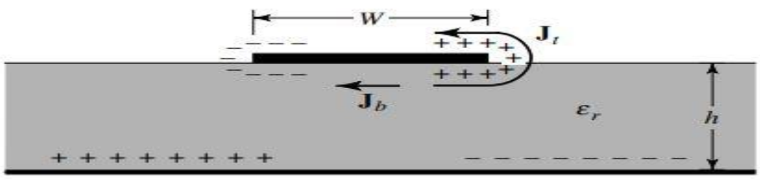


Figure 2.12. Charge distribution and current density creation on microstrip patch.

This charge distribution is controlled by two mechanisms: attracting and repulsive forces. The attractive force acts between opposing charges on the bottom side of the patch and the ground plane, thereby preserving the charge concentration on the patch's underside. In contrast, the repulsive force works between similar charges on the patch's bottom surface, causing some charges to migrate from the patch's underside across its borders to its top surface. This charge movement generates equivalent current densities on the patch's bottom and top surfaces, designated as Jb and Jt, respectively, as illustrated in Figure 2.12.

In practical microstrips with low height-to-width ratios, the attractive mechanism has the greatest impact on charge concentration and current flow underneath the patch. A small number of current flows from the patch's edges to its top surface, but this flow reduces as the height-to-width ratio falls. In an ideal case, with an infinitely tiny height-to-width ratio, the current flow to the top surface would be zero, preventing the formation of tangential magnetic field components at the patch's borders. This permits the four side walls to be approximated as completely magnetic conducting surfaces, which should not disrupt the magnetic and electric field distributions underneath the patch. Nonetheless, due to the limited height-to-width ratio in real instances, even if extremely tiny, the tangential magnetic fields at the margins are not absolutely zero. However, they are small enough to treat the side walls as completely magnetic conducting surfaces in a fair approximation to the cavity model. This model accurately captures the normalized electric and magnetic field distributions (modes) beneath the patch.

If the microstrip antenna was just considered a cavity, the absolute amplitudes of the electric and magnetic fields could not be determined. By treating the hollow walls and material within it as lossless, the cavity would not radiate, and its input impedance would be simply reactive. The impedance function would have only real poles. To accommodate radiation, a loss mechanism must be added. We have radiation resistance (Rr) and loss resistance. These two resistances cause the input impedance to become complex, integrating complex poles, where the imaginary poles represent radiation and conduction dielectric losses. To simulate an antenna using the cavity model, an effective loss tangent (δeff) is used to account for loss within the cavity. The adjusted loss tangent accurately represents the cavity's loss behavior as an antenna and is inversely linked to the antenna quality factor Q (δeff = 1/Q).

Considering the microstrip thickness is quite minuscule, waves that are created in the dielectric substrate between the patch and the ground plane experience substantial reflections when they reach the patch's edge. Consequently, only a tiny portion of the incident energy is radiated. As a result, the antenna is deemed highly ineffective. Cosine wave functions may be used to describe the standing waves that are formed by the fields underneath the patch. Due to the very small substrate height ($h \ll \lambda$, where λ is the wavelength within the dielectric), variations in the field along the height are regarded as constant. Additionally, the fringing of fields along the patch's edges is minimal due to the small substrate height. This results in the electric field being nearly normal to the patch's surface. Consequently, only TMx field configurations are considered within the cavity. While the top and bottom walls of the cavity are treated as perfectly electrically conducting, the four side walls are approximated as perfectly conducting magnetic walls, where tangential magnetic fields vanish along these four surfaces.

For this project transmission line model supposed to used according to its pros with the rectangular microstrip patch antenna design [4].

2.6. LITERATURE REVIEW

Sharma, Narinder (2017), analyzed and described different feeding techniques for microstrip patch antenna and its effect on various parameters of antenna i.e. bandwidth, return loss, VSWR, patch size… etc. These methods or techniques are divided into two categories i.e. contacting and non-contacting feeding. generally contacting methods consist of co-axial plane feed and microstrip line feed/ On the other hand, non-contacting techniques are proximity coupled feed and aperture coupled feed. Changing the feed point Coaxial feeding technique gives a perfect matching, and less return losses, reliability, easy to fabricate can be achieved by microstrip line feed. The aperture coupling feeding gives a maximum bandwidth, and the best impedance matching and radiation efficiency can be achieved by using proximity coupling feeding [13] Ms.Varsharani Mokal , Prof S.R.Gagare , Dr.R.P.Labade (2017), presents a performance analysis of a microstrip rectangular patch antenna for wireless applications, specifically for Bluetooth. Two feeding techniques, microstrip line feed and coaxial probe feed, are compared. The antenna is designed using an FR-4 dielectric substrate with dimensions of $46.70 \times 38.60 \times 1.6 mm^3$

and a dielectric constant of 4.4 and loss tangent of 0.02. The frequency of interest is 2.4GHz. The simulation results include return loss, impedance, VSWR, efficiency, gain, and radiation pattern for both the strip line and coaxial feeding techniques. The simulations were performed using CADFEKO Suite 7.0. The study concludes that the coaxial feeding technique has advantages over the microstrip line feeding technique in terms of return loss, bandwidth, efficiency, and input impedance within the specified frequency range. However, the microstrip line feeding technique has better gain compared to coaxial feeding [14]. Kajla, Ashok & Somwanshi, Devendra (2020), proposed three different array antennas: a 1 × 1, 1 × 2, and 1 × 4 configuration. Also, they have developed re-configurability for all three of these proposed structures, and to achieve a re-configurability PIN diodes have been utilized as switch. results show that as the number of elements in the array increases, antenna parameters such as gain and directivity improve [15].

A different shape was proposed by Jawad, Mustafa Mohammed & Hanoosh, H & Saare, Murtaja & Lashari, Saima & Ali, Sari & Ahmad, Sarosh & Khalill, Yaser & Hussain, Yaqdhan & Abdulateef, Ali & Ali, Murtaja & Hussein, Yaqdhan & Hanoosh, Hatem. (2021). they present a study on a T-shaped rectangular microstrip patch antenna operating at a resonating frequency range of 3.6 GHz for 5G applications (ranging from 2.9 to 4.4 GHz). The antenna has an overall size of 22x24x0.25 mm^3 and is fed using a 50 Ω feed line. It is printed on a compact Rogers RT 588 lZ substrate with a permittivity (εr) of 2.00, loss tangent (tan δ) of 0.0021, and thickness of 0.2 mm. The proposed antenna offers several advantages, including a small size, low profile, and simpler structure. The characteristics of the antenna, such as radiation pattern, reflection coefficient, gain, current distribution, and radiation efficiency, are simulated and analyzed using CST microwave studio. By introducing a slot with a rectangular T-shaped patch antenna, the proposed antenna achieves a lower frequency with a peak gain of 2, and a radiation efficiency of 98.474 dB at the resonant frequency of 3.6 GHz. The fractional bandwidth is 42.81% (ranging from 2.90 to 4.48 GHz) with a return loss of -28.76 dB [16] Asianuba, Ifeoma & Lucky, Nwanodim (2022) discusses the design and simulation of a microstrip patch antenna operating at a frequency of 3.6 GHz for 5G applications. The selection of frequency is guided by the expansive possibilities offered by 5G technology. The substrate material employed is flame-resistant four

(FR4) with a dielectric constant of 4.6 and a loss tangent of 0.023. The study outcomes encompass graphical representations of the voltage standing wave ratio, radiation pattern, return loss, and radiation efficiency. The parameters that influence the radiation characteristics of the patch antenna are the relative permittivity of the dielectric material, the position of the slot on the patch, the ground plane, substrate type, and the dimensions of the feed and patch [17]. A layout and simulation of a single-band microstrip-feed patch antenna for 5G applications proposed by Navneet Kaur, Surbhi Sharma & Jaswinder Kaur. in July 2019. The antenna features a concave shape with slots and a split ring resonator loaded in the partial ground plane to enhance its bandwidth. The patch is printed on an Epoxy Glass FR-4 substrate with specific dimensions and properties. The antenna resonates at a frequency band of 3.4-3.8 GHz with a bandwidth of 400 MHz and a return loss of -25dB. The design is simulated using CST MWS V14.0, and the radiation performance is analyzed in terms of gain and efficiency. The antenna achieves a peak gain of 3.2 dB and a radiation efficiency of 94% [18].

Yadav, M. K., and colleagues have introduced the design of a 2 × 1 microstrip patch array antenna tailored for 5G C-band access point applications. This array incorporates rectangular microstrip antenna elements with U-shaped slots on parasitic patches, specifically engineered for 5G C-Band operation within the frequency range of 3.4 to 3.8 GHz. Additionally, a microstrip feed network has been integrated into the antenna array design. This two-layered, low-profile antenna array exhibits strong potential for use in 5G C-band access point applications. The paper presents an in-depth analysis of various parameters, including return loss, efficiency, radiation pattern, among others, for both individual antenna elements and the entire array. The design and analysis of the antenna have been conducted using HFSS simulation software [19]. Research in antenna design and simulation is a growing field with significant relevance to wireless communication. Antennas serve as fundamental components in wireless technology, with a wide range of shapes and types tailored to various applications. In contemporary electronics, microstrip patch antennas have gained prominence due to their utility. This study focuses on exploring different types of microstrip antennas and assesses their performance based on key parameters such as return loss (ideally less than -10dB), VSWR (typically within the range of 1-2), bandwidth, resonant frequency, and gain.

various microstrip antenna geometries and techniques contribute to enhancing their efficiency in wireless communication. Despite the challenges posed by the complexity of different antenna shapes, the diverse wireless applications make this research area valuable. Tiwari, Rovin & Sharma, Raghavendra & Dubey, Rahul. (2020), offers a review of previous research and a comparative analysis, CST software is used in antenna design. The critical parameters for evaluating antenna design include bandwidth, return loss, resonant frequency, VSWR, gain, and efficiency [2]. Zoukalne and others introduced a microstrip patch antenna designed for 5G operation at 3.6GHz. They achieved an expanded bandwidth for the antenna by employing an array configuration technique and modifying the geometry of the radiating element. The proposed antenna exhibits impressive performance characteristics, including a return loss of 34.8dB, a gain of 9dBi, and a 200MHz bandwidth. The design process of this antenna consists of two main steps. Firstly, the team designed and optimized the basic microstrip antenna, which initially had a limited bandwidth. They enhanced this bandwidth by implementing a networked structure, increasing the substrate thickness, and incorporating two slots in each radiating element, along with one on the power line [20]. Ahmed Al-Gburi and a team of researchers developed hexagonal microstrip patch antennas, simulating their performance for wireless backhaul at 3.5 GHz. They employed Computer Simulation Technology (CST) software to simulate four different antenna types. Their design process ranged from creating a single element antenna to an array of 1×8 elements.

The resulting 1×8 array antenna utilizes a microstrip corporate feed line for its feed mechanism, generating directional radiation. This directional radiation is valuable for base stations seeking to deliver high-quality, high-capacity network connectivity, especially for long-distance point-to-point connections. The completed antenna achieved notable results, boasting a high gain of 6.938 dB at 3.5 GHz and a return loss of -10dB. Additionally, the researchers recommend a hexagonal-shaped slotted array antenna for 5G applications, highlighting that the slotted approach was instrumental in improving the gain for each design [21]. Also, Saurabh, Kumar & Meshram, Manoj. (2020), have a study introduces a compact two-element multiple-input-multiple-output (MIMO) antenna system tailored for sub-6 GHz 5G applications, featuring enhanced impedance matching and isolation. The system comprises two identical tapered microstrip line-fed radiating elements with a modified rhombus shape. These elements are positioned in the same orientation on a compact substrate area measuring $0.24\lambda 0 \times 0.42\lambda 0$ (where $\lambda 0$ corresponds to 3.6 GHz) and share a rectangular ground. To improve impedance bandwidth and isolation, a redesigned T-shaped ground stub is strategically placed between a pair of radiating elements. Additionally, a split U-shaped stub, connected to the center of each radiating element, is employed to achieve the desired resonant frequency of 3.6 GHz. The proposed antenna operates within a -10 dB bandwidth spanning 3.34 to 3.87 GHz (530 MHz), while maintaining over 20 dB of isolation between the two elements. The MIMO performance is both analyzed and experimentally validated, with the measured results closely matching the simulated outcomes. Furthermore, a simulation study investigates the impact of housing and an extended ground plane on the two-element MIMO antenna for practical applications. The research also explores the feasibility of realizing a 12-element MIMO system using the proposed two-element MIMO antenna [22].

In this work patch array antenna is proposed for 3.6 GHz frequency band of 5G applications. with a substrate Rogers RT 5880 with thickness of 2.2 mm. Moreover, the array design consists of identical rectangular-shaped elements implementable involving simple fabrication processes. The following chapters will describe design specification with detailed information.

PART 3

METHODOLOGY AND DESIGN SIMULATION

Microstrip patch array antennas are widely used for many applications in communication systems as 5G applications. Designing an effective microstrip patch array antenna requires a systematic approach to fulfill specific performance criteria. In this research, we followed a simplified and easy method to implement this design as it is illustrated in the following flowchart in figure 3.1, and these steps consist of: firstly, defining the main design parameters as shape of patch and substrate, secondly calculations of the suggested prototype design, thirdly, simulation and optimization process to have optimal results and finally fabrication for the simulated design from the previous step.

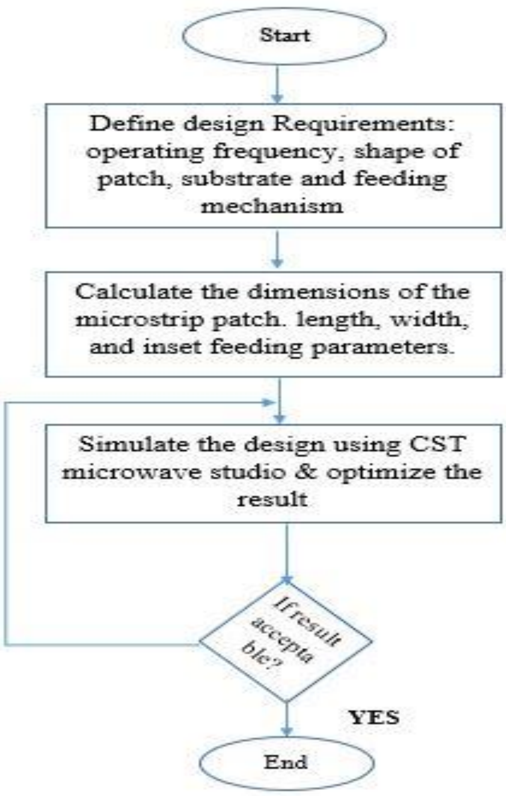


Figure 3.1. Design methodology flowchart.

3.1. DEFINE DESIGN REQUIREMENTS

Microstrip Patch array antennas represent a category of antennas comprising multiple patch elements organized in an array. The configuration of a patch array antenna is determined by several design parameters, including:

Shape and Size

As mentioned before Patch elements can adopt various shapes, such as square, rectangular, circular, or fractal. The selection of a specific shape depends on factors such as application requirements, aesthetics, and ease of fabrication. For this design rectangular patch has been selected due to many reasons will be discussed here. Mainly, the simplicity and ease of fabrication make rectangular patches a practical choice for manufacturing, it simplifies the production process, contributing to cost-effective manufacturing. From the other side it provides resonant frequency control, the dimensions of the rectangular patch directly affect the resonant frequency of the antenna. So, it can easily tune and control the resonant frequency by adjusting the width and the length values of the rectangular patch. Another benefit is the Compatibility with different feeding techniques and this will have discussed in the previous paragraphs. Also, its support radiation pattern control, through dimensions and aspect ratio of a rectangular patch, it can influence the radiation pattern of the antenna. For that, rectangular patch antenna is the best shape for this prototype.

The dimensions of the patch elements determine the achievable gain and operating frequency. They are directly influenced by the size of the patch. Also, efficiency, Impedance Matching, polarization and radiation pattern influenced by the patch antenna size. Larger patches are typically led to higher gain, making them suitable for applications that demanding increased signal strength. Usually, the size is chosen based on the wavelength of the desired beamwidth or the desired frequency. Furthermore, the type of antenna single patch or array patch will be effect on the design size.

Patch Material

Choosing the materials used in patch antenna greatly affect antenna performance in terms of conduction, loss and structural integrity. Here are the basic considerations regarding patch materials:

- Conductivity: The efficiency of the microstrip patch antenna directly affected by the conductivity of the material. Common materials such as gold, aluminum and copper have a high conductivity, are often preferred to improve overall performance and reduce signal loss.
- Dielectric constant: The speed of propagation of electromagnetic waves in the substrate affected by the dielectric constant of the material that used in the patch. It influences the dimensions of the patch and thus the resonant frequency of the antenna.
- Loss tangent: It manipulates the dielectric loss of the antenna. It is preferable to use low-loss materials in order to reduce the signal absorption and preserve higher antenna efficiency.
- Cost and Availability: Material patch cost and availability are practical considerations in the design process. Balance between the cost effectiveness and performance is needed.
- Frequency stability: Some applications need for consistent antenna performance through a wide range of frequencies. Material properties, especially temperature stability, can influence the frequency stability of a microstrip patch antenna.
- Substrate Compatibility: The patch is usually applied to the dielectric substrate. Compatibility between the patch material and the substrate is critical to achieve an optimal impedance matching, radiation characteristics, and overall antenna performance.

Common materials that used for microstrip patch antennas include:

- Gold: High conductivity and corrosion resistance, its suitable for high-performance and demanding applications.

- Aluminum: Good conductivity, often chosen for its cost effectiveness.
- Copper: Excellent conductivity and is used in high performance applications widely.

In this design copper patch is used due to its excellent conductivity and is widely used in high performance applications

Substrate

The substrate, which is the dielectric material on which the patch elements are positioned, affects impedance matching, radiation pattern, and bandwidth. Common substrates encompass FR-4 fiberglass, epoxy, and ceramic. The performance of a microstrip patch antenna is greatly influenced by the substrate selection, making it an essential component of antenna design. The following things to think about while choosing a substrate for a microstrip patch antenna:

- Dielectric Constant (εr): An important parameter is the substrate material's dielectric constant. It influences the rate at which electromagnetic waves travel through the substrate, which in turn impacts the patch's total size and, ultimately, the antenna's resonant frequency. Polytetrafluoroethylene, sometimes known as Teflon or PTFE, ceramic, and FR-4 fiberglass are common dielectric materials.
- Dielectric Loss Tangent (tan δ): This tangent represents the energy that the substrate material has absorbed. In order to reduce signal absorption and optimize antenna efficiency, low-loss substrates are recommended. Materials having low loss tangent values are frequently PTFE-based substrates.
- Substrate Thickness: The radiation properties and impedance matching of the antenna are affected by the thickness of the substrate. It is frequently selected in accordance with the needs of the application and the intended resonant frequency. Although thicker substrates may impact the antenna's bandwidth, they can also offer structural stability.
- Substrate Material Stability: In situations where temperature fluctuations may affect the antenna, the substrate material's stability with regard to temperature

changes is critical. The performance of the antenna is maintained under various climatic conditions with the use of stable materials.

- Cost and Availability: The substrate material's cost and availability are practical factors to take into account. Common materials, such as FR-4, are commonly available and reasonably priced, making them appropriate for a wide range of applications.

Microstrip patch antennas often use the following substrate materials:

- FR-4 Fiberglass: Due to its availability and low cost, this material is often used. But in comparison to some specialized substrates, it might have a higher loss.
- Ceramic: Can be a bit more expensive, but it offers stability and minimum loss. For high-performance applications, it is appropriate.
- Teflon: also known as PTFE, is a material that works well in high-frequency and high-performance applications due to its excellent stability and low dielectric loss. It can be more expensive.
- Rogers: A high-frequency laminate with consistent dielectric characteristics and minimal loss, Rogers is appropriate for high-performance applications. and that’s the main reason for suggested it for this design. It has been selected because a substrate with a high dielectric constant reduces the size of the antenna.

Feeding Mechanism

The feed mechanism supplies the radio frequency signal to the patch elements. The feeding mechanisms are playing a critical role in the microstrip patch antenna design and performance. Impedance Matching, Bandwidth, Radiation Pattern, Polarization, efficiency, Complexity of Design, Size and Dimensions, Resonant Frequency all of these parameters of microstrip patch antenna can influenced by the feeding mechanism. Different feed techniques, such as proximity-coupled feeding or microstrip-line feeding, can be utilized to optimize impedance matching and reduce losses. As mentioned previously, the microstrip inset feeding mechanism is a type of feeding mechanisms and will be used in this design.

Number of Elements

Number of Elements: Directivity, gain, and radiation pattern are all influenced by the number of patch elements in the array. More elements may result in increased directivity and gain, but they may also add to the expense and complexity of the system. The following factors can be taken into consideration in order to optimize these settings for the desired performance:

- Bandwidth: It can be affected by the feed mechanism's optimization and the selection of a substrate material with minimal dielectric loss.
- Gain can be improved by employing higher-conductivity materials, increasing the size of patch components, or adding more elements.
- Efficiency can be increased by minimizing losses in the substrate and feed mechanism, choosing low-loss dielectric materials, and fine-tuning the patch element design.
- Radiation Pattern: The right array elements can be chosen in terms of size, shape, and spacing to affect the radiation pattern. To direct radiation in particular directions, a variety of beamforming techniques can be utilized.

Numerical simulation methods, such as electromagnetic simulation techniques are used to analyze, model, and optimize antenna design parameters in order to achieve the desired performance. this part will be explained more the simulation section.

3.2. CALCULATING IMPORTANT PARAMETERS

The design of a microstrip patch antenna involves a series of calculations and considerations to guarantee optimal performance.

Important Parameters

Main parameters contain of operation frequency, patch dimensions (length and width) and the substrate (length and width) as well as ground.

- **Operation Frequency (fo):** This design works on 3.4 to 3.8 GHz so; operation frequency has been determined 3.6 GHz. The frequency that which the antenna is aimed to work.
- **Patch Dimensions (Length, Width):** Dimensions of the rectangular patch as appeared in figure 3.2, calculated based on the chosen frequency and substrate properties. Many elements need to be taken into account when calculating the length and width of a microstrip patch antenna. These include the intended operating frequency, the substrate material's dielectric constant, and other variables.

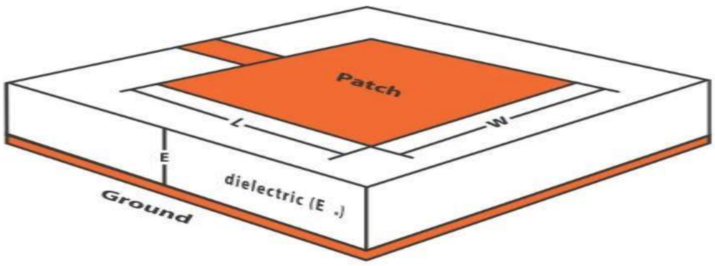


Figure 3.2. Microstrip patch structure [23].

To get the width (W) of a rectangular microstrip patch, following general formula is used:

$$W = \frac{C}{2\, f_0 \sqrt{\frac{2\varepsilon_r+1}{2}}} \tag{3.15}$$

Where:

C= The speed of light
fo= is the operating frequency
W= width of the microstrip patch antenna
εR= dielectric constant

Then, to calculate length we need firstly to get the value of effective dielectric constraint **εeff**, the equations 16 and 17 bellow were used:

$$\boldsymbol{\varepsilon eff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \quad (3.16)$$

$$L = \frac{1}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\,\frac{(\varepsilon eff+0.3)(\frac{W}{h}+0.264)}{(\varepsilon eff-0.258)(\frac{W}{h}+0.8)} \quad (3.17)$$

Where:

L= length of the microstrip patch antenna
fo= operating frequency
W= width of the microstrip patch antenna
h= height of the substrate

From the above equations the length of the patch is 26.612 mm; Effective Dielectric Constant is 2.034, Characteristic Impedance Cal. is 48.226 Ohms and Width of Patch is 32.940 mm.

- **Substrate (Length and Width):** Thickness of the substrate material, impacting the antenna's radiation characteristics.

$$\mathrm{Ls} = 6\mathrm{h} + \mathrm{Lp} \quad (3.18)$$

$$\mathrm{Ws} = 6\mathrm{h} + \mathrm{Wp} \quad (3.19)$$

Where:

h= height of substrate
Lp= patch length
Wp= patch width
Ls= Substrate length
Ws= Substrate Width

The ground plane dimensions have the same values of the substrate width and dimensions. Distance between the feedline and the patch, and the size of the ground plane, affecting antenna performance.

- **Microstrip Feedline:** Width and length of the microstrip feedline for impedance matching. The distance between the feedline and the patch affecting antenna performance. Figure 3.3 below showed the feed line from the side view.

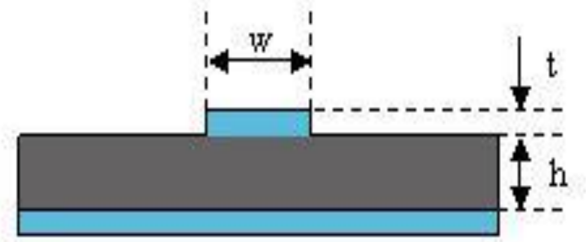


Figure 3.3. Microstrip feed Line structure [24].

$$w = \frac{7.46\ X\ h}{e^{\left(Z_0 \frac{\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25\ \times t \qquad (3.20)$$

Equation 3.20 determine the value of the microstrip feed line width Where:

Zo= Characteristic Target Impedance
h= substrate thickness
t= trace thickness

50 ohms of characteristic impedance was used for the single element patch, while 50 and 100 ohms of characteristic impedance were used for the array design. The feed line and patch thickness are both 0.035 mm. MATLAB was used for the calculations.

Table 3.1. Single patch design parameters.

Parameter	Value(mm)	Description
Wp	32.94	Patch width
Lp	26.79	Patch length
Wg	64.4	Ground & substrate width
Lg	81.25	Ground & substrate length
Hs	2.5	Substrate thickness
Ht	0.035	Copper thickness
InsetL	8.128	Inset feed length
InsetG	3.851	Inset feed width
Wf	7.703	Feed line width
Lf	25.383	Feed line length

3.3. SIMULATION AND MEASUREMENT TOOLS

One of the popular software suites for performing electromagnetic simulations is CST Microwave Studio. Its main goal is to assist researchers and engineers in the analysis, design, and optimization of electromagnetic systems and components. The main functions and uses for CST Microwave Studio are as follows:

- Electromagnetic Simulation: CST Microwave Studio, which specializes in overcoming electromagnetic field difficulties, can simulate a wide range of processes, including wave propagation, radiation, scattering, and coupling within various structures and devices.
- Applications: The program is widely used in the design and analysis of antennas, filters, connectors, and other microwave and radio frequency (RF) components. Its customers include the telecommunications, aerospace, defense, and electronics industries.
- User-Friendly Interface: User-Friendly Interface: CST Microwave Studio provides engineers with a user-friendly interface that makes it easier to create and analyze complex electromagnetic models. It includes a set of tools for designing as well as optimizing components.
- Solver Technology: The software accurately models electromagnetic behavior by utilizing powerful numerical algorithms and solver technologies. It is compatible with a variety of numerical approaches, including the finite element method (FEM) and the finite integration technique (FIT).

- Parametric Analysis: Designers can undertake parametric studies to investigate how changes in design parameters affect the performance of electromagnetic devices. This capacity is critical for optimizing designs to fulfill certain specifications.
- Integration with CAD Systems: CST Microwave Studio interacts with a variety of computer-aided design (CAD) systems, allowing for the smooth movement of geometry and design data between the simulation and CAD environments.
- Frequency and Time Domain Analysis: The software supports both frequency domain and time domain analysis, allowing engineers to investigate device performance under various scenarios.
- Visualization Tools: CST Microwave Studio has powerful visualization capabilities to assist users in evaluating simulation results. Electromagnetic fields, antenna patterns, and other relevant data can be visualized by engineers.
- Parameterization and Optimization: The program makes it possible to parameterize designs, which streamlines the process of exploring design areas and makes it easier to do optimization research in order to meet predetermined performance goals [25].

The result of the simulation design is shown in the following chapter.

PART 4

RESULTS AND DISCUSSIONS

In this chapter, the results of designing a rectangular microstrip patch antenna using CST microwave studio are demonstrated.

4.1. SIMULATION RESULTS

This chapter describes how to use CST software to create a rectangular microstrip patch antenna. Additionally, the outcomes of the simulations are shown.

When designing a rectangular microstrip patch antenna (MPA), the following three factors are crucial to consider:

- Frequency of operation (fo): The antenna's resonance frequency needs to be chosen carefully. between 3.4 and 3.8 GHz. As a result, this frequency range must be compatible with the antenna that is developed. 3.6 GHz is the chosen resonance frequency for this system.
- Dielectric constant of the substrate (εr): For this design, Rogers RT5880 has been utilized, which has a dielectric constant of 2.2.
- Dielectric substrate height (h): The microstrip patch antenna must be small in order to be utilized in applications. Thus, 1.8 mm is chosen as the dielectric substrate's height. 48 Therefore, the following are the design's crucial parameters:

  – Fo is equal to 3.6 GHz.
  – εr is equal to 2.2.
  – h is equal to 1.8 mm.

Firstly, a single patch was designed to obtain the required characteristics, and then a high-gain and high-efficiency rectangular patch array antenna (1 x 2) was implemented. An illustration of the established antenna is presented in Figure 4.1.

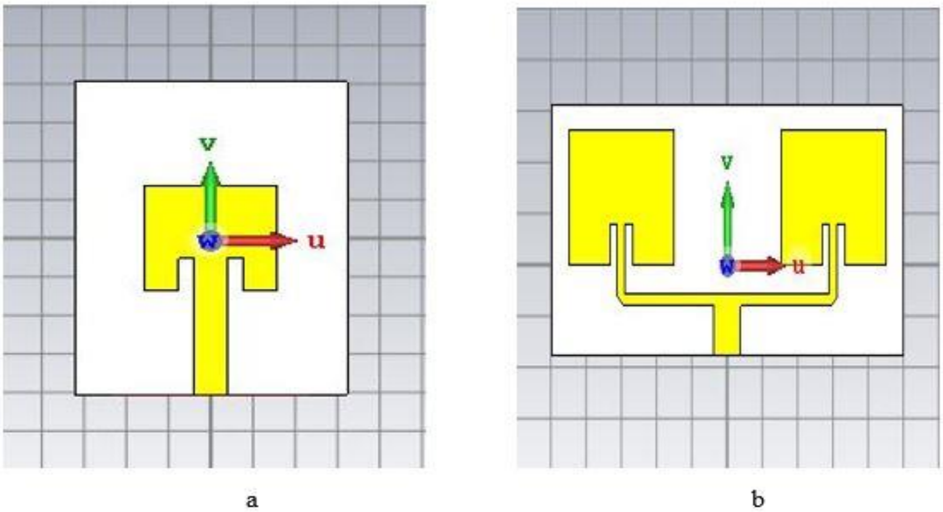


Figure 4.1. Patch Antenna (a) rectangular patch antenna (b) rectangular patch array antenna (1 × 2).

4.1.1. Design Specifications

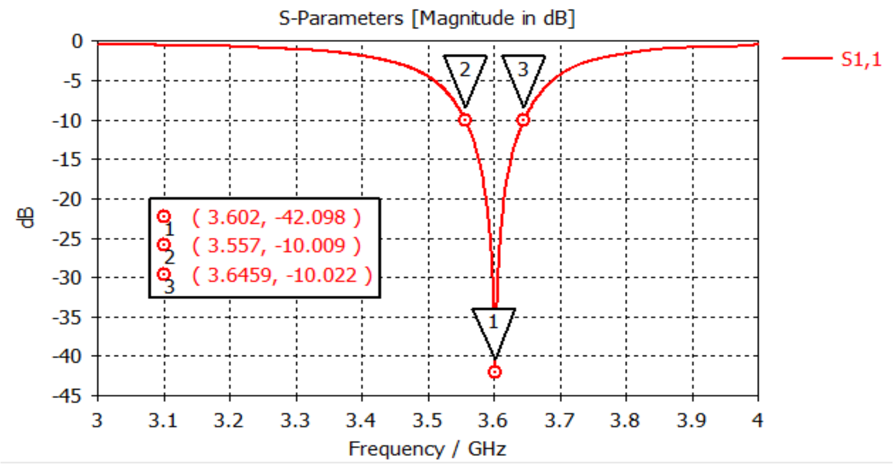
Table 4.1 illustrates a comparative analysis between three distinct microstrip patch antenna designs: one derived from previous work and the others representing current proposed designs.

Table 4.1. Designs specifications comparison.

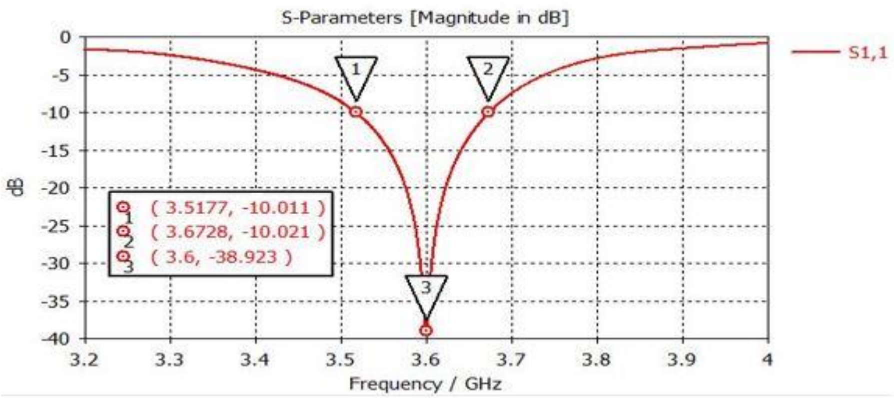
Parameter	Proposed Designs	
	Single patch(optimized)	Patch array antenna 1 × 2
Operating Frequency	3.6 GHz	3.6 GHz
Substrate	Rogers RT5880	Rogers RT5880
Feeding Mechanism	Inset Feed	Inset Feed
dielectric constant	2.2	2.2
Gain	7.311 dBi	10.14 dBi
Directivity	7.964 dBi	10.21 dBi
HPBW	74.2 deg.	38.7 deg.
S 1,1	- 42.09	-38.923 dB
Bandwidth	100 MHz	160 MHz
VSWR	1.03	1.02
Total efficiency	85.9 %	98.3%

4.1.2. Return Loss

In order to reduce power reflections, impedance matching is a crucial component of antenna design. Throughout the intended frequency range, the microstrip patch antenna's return loss properties were closely examined. The outcomes provide insight into how well the antenna can emit and absorb power, guaranteeing peak performance. The simulation results of return loss for a single patch are shown in Figure 4.2. (a) return loss is about -42 dB at 3.6 GHz, the -10 dB bandwidth is approximately 100 MHz Furthermore, the value of the return loss for a patch array is shown in Figure 4.2. (b) is about -38.93 dB at 3.6 GHz, and the -10 dB bandwidth is approximately 160 MHz



(a)

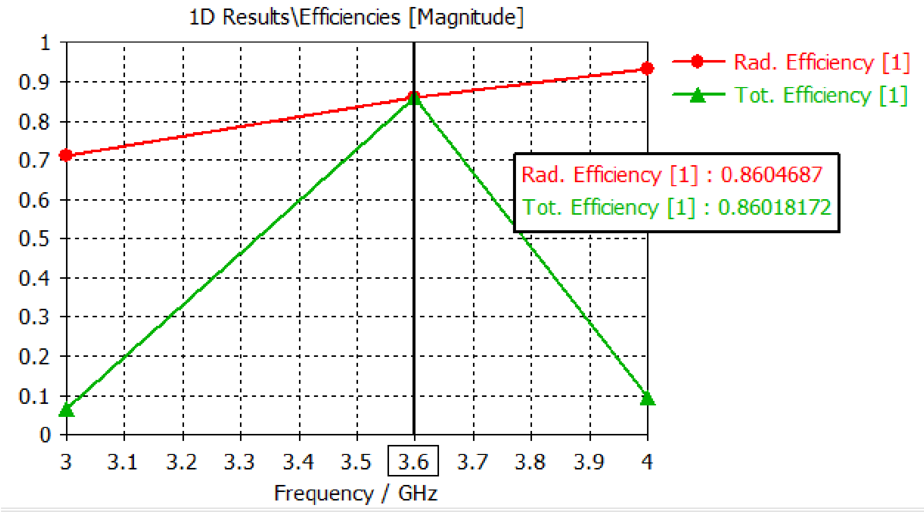


(b)

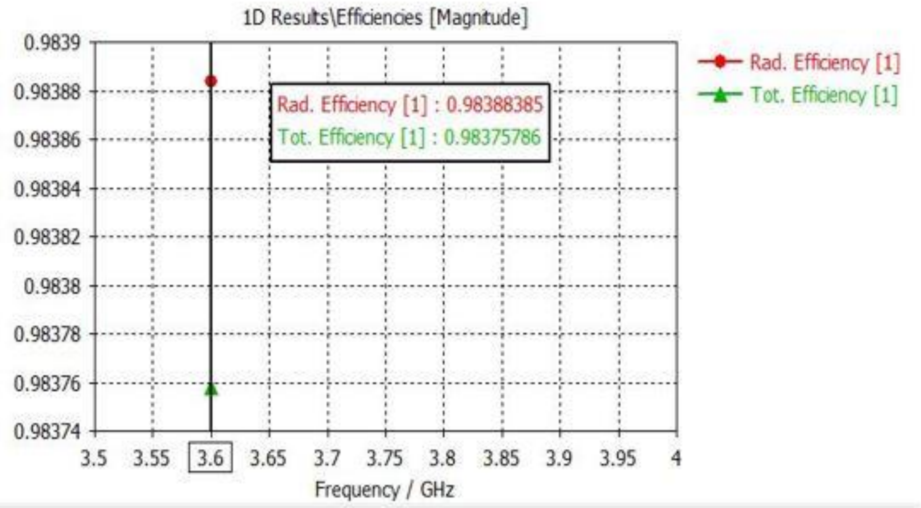
Figure 4.2. Return loss for proposed designs (a) single element patch antenna and Microstrip patch array 1 × 2.

4.1.3. Efficiency

An antenna's ability to convert input power into radiated power is measured to determine its efficiency. The radiation efficiency of the single patch and patch array antennas is 0.86 and 0.98, respectively. Both designs demonstrate optimal efficiency at 3.6 GHz, as shown in figure 4.3 below.



(a)

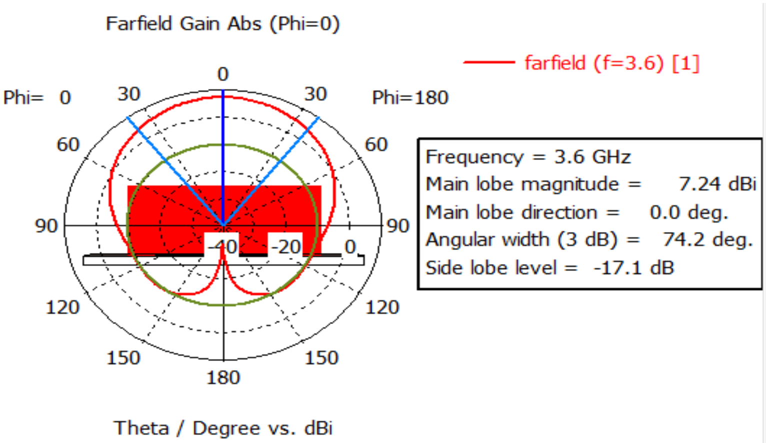


(b)

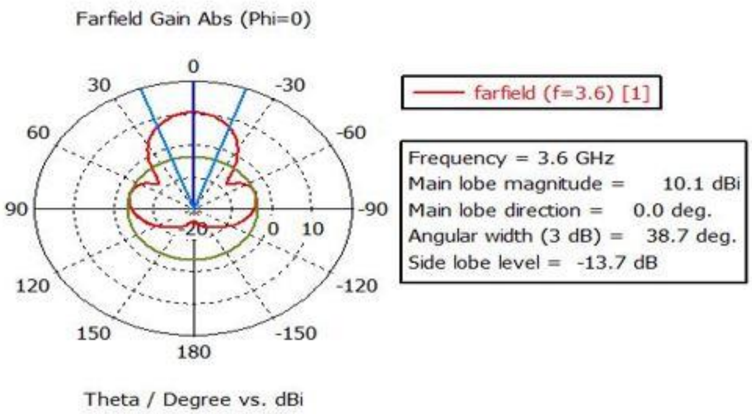
Figure 4.3. Efficiency for (a) one single element patch antenna (b) patch array antenna 1 × 2.

4.1.4. Radiation Pattern

The radiation patterns of the developed antenna were thoroughly investigated in order to figure out its directional properties. The coverage, beamwidth, and side lobe levels of the antenna were evaluated by closely examining simulated patterns in the E- and H-planes. The E and H plane far-zone radiation pattern for the gain of rectangular microstrip patch antenna at 3.6 GHz frequency is shown in Fig. 4.4. The main lobe magnitude of the E-plane is 7.24 dBi with direction 0°, where, as main lobe magnitude of the H-plane is about -10 dBi for the single patch antenna, Figure 4.4 (a) describes it. When the rectangular patch array used, the main lobe magnitude of the E-plane is 10.1 dBi. Where, the main lobe magnitude of the H-plane is around -3.5 dBi with direction 0°, as declared with the figure 4.4 (b) below.



a)

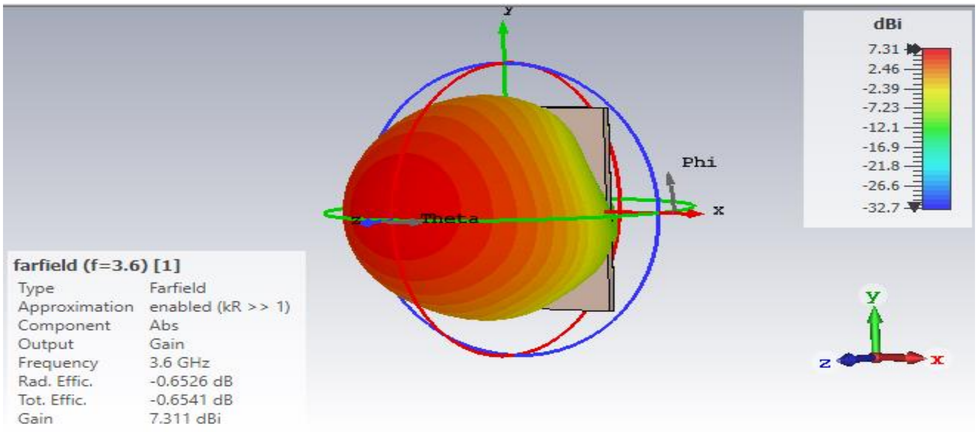


(b)

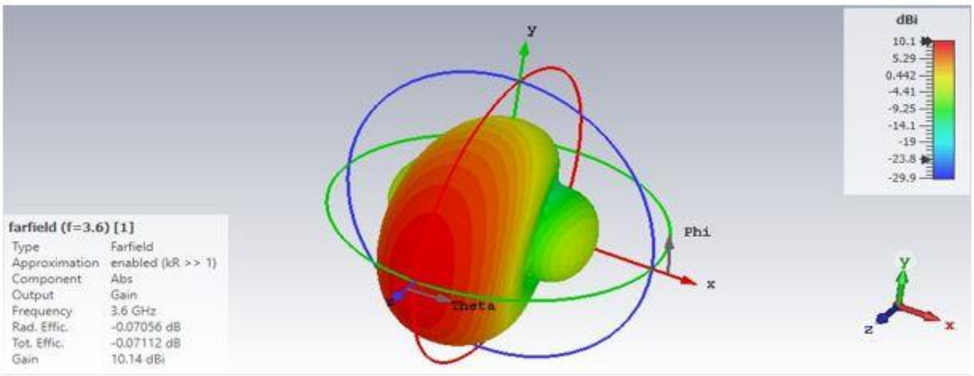
Figure 4.4. Radiation patterns for (a) one single element patch antenna (b) patch array antenna (1 × 2).

4.1.5. Gain and Directivity

A high-gain microstrip patch antenna has been proposed. The simulation results of a rectangular microstrip patch antenna at 3.6 GHz are presented. Figure 4.5 shows the gain of the proposed single and array rectangular microstrip patch antennas. The single patch has a gain of 7.311 dBi and a directivity of 7.964 dBi, which is a significant increase over the previous antenna. However, the antenna array showed a directivity of 10.21 dBi and a gain of 10.14 dBi. Much better than the previous two designs. Therefore, it can be seen that the values of rectangular patch array antenna were better.



(a)



(b)

Figure 4.5. Gain of the proposed designs (a) Gain of single element patch antenna (b) Gain of rectangular patch array antenna 1 × 2.

4.1.6. Voltage Standing Wave Ratio

Voltage standing wave ratio is one crucial metric that illustrates how effectively power is transferred between the transmission line and the antenna. A lower VSWR denotes improved power transfer, reduced signal reflections, and improved impedance matching. The VSWR value in ideal designs should be close to 1. The VSWR value in the first single element design was 1.03, while the value in the rectangular patch array 1 X 2 design is 1.02.

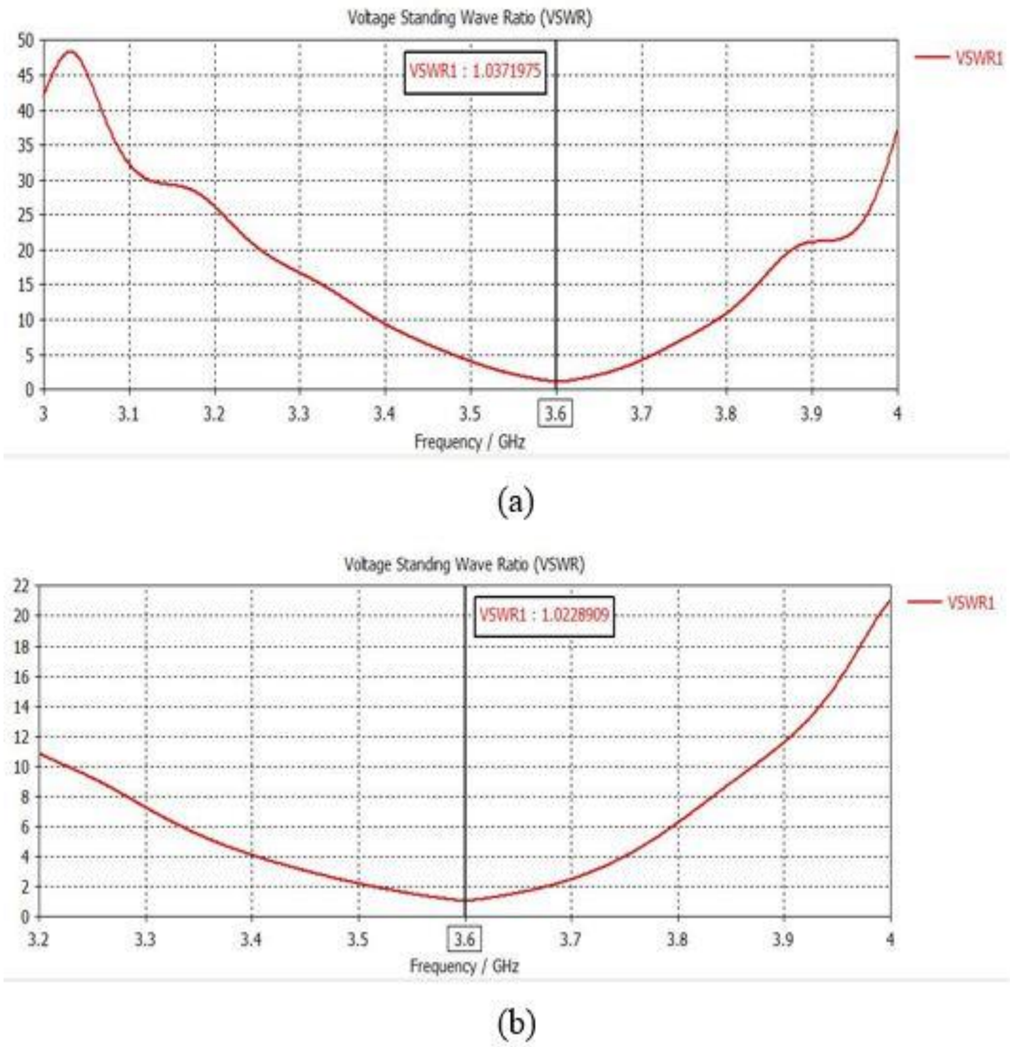
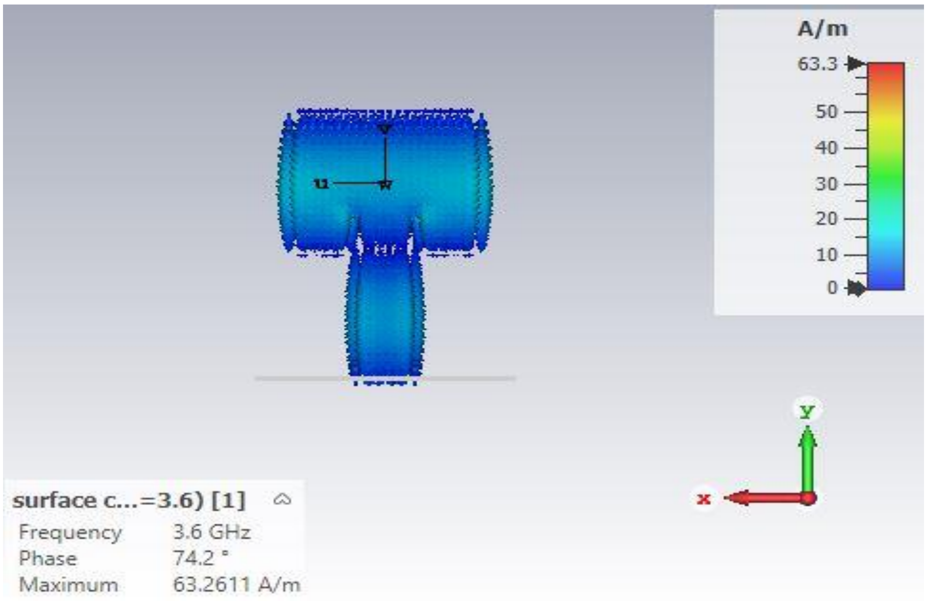


Figure 4.6. VSWR for the proposed designs (a) single patch antenna (b) 1 × 2 patch array antenna.

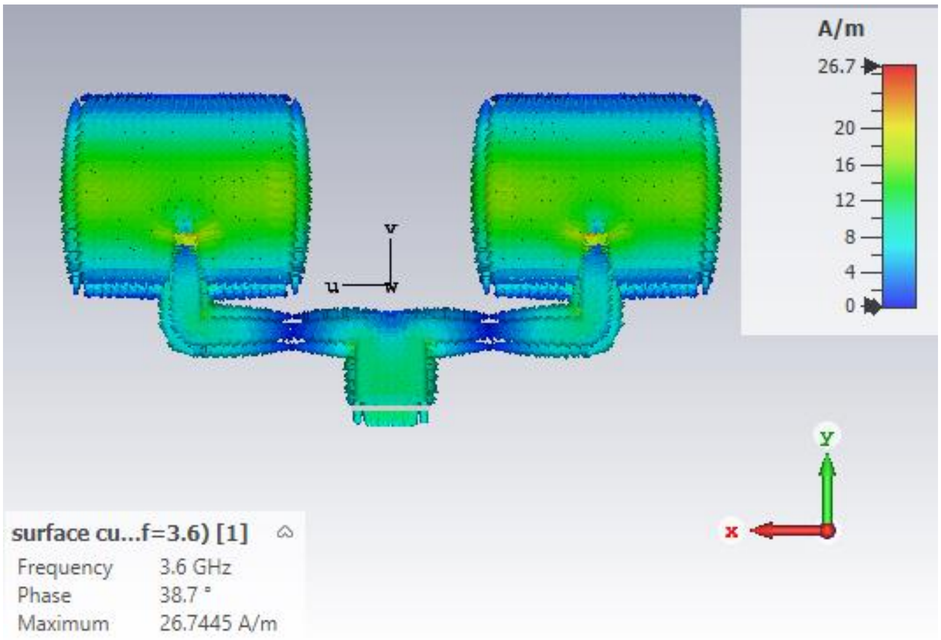
Therefore, it can be seen that the values of rectangular patch array antenna were more optimal with better values of return loss, VSWR, directivity, Gain and efficiency.

4.1.7. Surface Current Distribution

Surface current distribution affects radiation characteristics, efficiency, polarization, bandwidth, and overall performance of microstrip patch antennas. It also shows the antenna behavior. Figure 4.7 illustrates the current surface for both single and array patch antenna.



(a)



(b)

Figure 4.7. Surface current distribution (a) single patch antenna (b) antenna array patch

PART 5

CONCLUSION AND RECOMMENDATION

The rising need for high data rates and enhanced mobile broadband connectivity necessitates the exploration of efficient antenna solutions for 5th generation (5G) wireless networks. Patch array antennas, with their superior performance characteristics such as high gain, wide bandwidth, and ease of integration, emerge as promising candidates for 5G applications. This thesis delves into the design and optimization of patch array antennas specifically tailored for 5G operation.

The research focuses on the analysis and implementation of various patch element configurations and array architectures optimized for key 5G frequency bands. The thesis systematically explores the impact of patch geometry, element spacing, feed networks, and substrate materials on the overall antenna performance. Techniques for achieving desired radiation characteristics, including beamforming and impedance matching, are investigated and implemented. The proposed antenna is a good solution for 5G antenna design and other wireless applications. It offers excellent performance, high gain and wide bandwidth. This antenna is suitable for base stations that require high-speed, reliable, and efficient connectivity. It can also be used for smart cities as well as various services such as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC).

It is highly recommended to establish collaboration with industry stakeholders, such as telecommunication providers and equipment manufacturers, to align research efforts with real-world implementation challenges and industry standards. Additionally, evaluate how the patch array antenna affects Quality of Service (QoS) metrics and user experience, taking reliability, latency, and data rates into account.

REFERENCES

[1] A. K. Jain, R. Acharya, S. Jakhar and T. Mishra, "Fifth Generation (5G) Wireless Technology “Revolution in Telecommunication”," ***Second International Conference on Inventive Communication and Computational Technologies (ICICCT)***, Coimbatore, India, 2018, pp. 1867-1872, doi: 10.1109/ICICCT.2018.8473011.

[2] R. Tiwari, R. Sharma, and R. Dubey, “Microstrip Patch Antenna Array Design Anaylsis for 5G Communication Applications,” ***SMART MOVES JOURNAL IJOSCIENCE***, vol. 6, no. 5, pp. 1–5, May 2020, doi: 10.24113/ijoscience.v6i5.287.

[3] O. Bhunia and B. Maity, “Design of compact microstrip omnidirectional wideband monopole antenna,” in *2017* ***International Conference on Communication and Signal Processing (ICCSP)***, IEEE, Apr. 2017, pp. 0889–0893. doi: 10.1109/ICCSP.2017.8286497.

[4] C. A. Balanis, “*ANTENNA THEORY ANALYSIS AND DESIGN THIRD EDITION*.” ***John Wiley & Sons***, Inc., Hoboken, New Jersey. 0-471-66782-X

[5] Internet: V. L. Subrahmanya, “Pattern Analysis of ‘The Rectangular Microstrip Patch Antenna.’” https://api.semanticscholar.org/CorpusID:123698818

[6] B. Kamo, S. Cakaj, V. Koliçi, and E. Mulla, “Simulation and Measurements of VSWR for Microwave Communication Systems,” ***International Journal of Communications, Network and System Sciences,*** vol. 05, no. 11, pp. 767–773, doi: 10.4236/ijcns.2012.511080., (2012).

[7] Internet: A. Al Nahian, “DESIGN AND PERFORMANCE ANALYSIS OF U-SLOT, Y-SLOT AND U-Y SLOT MICROSTRIP PATCH ANTENNA FOR WIRELESS APPLICATIONS.”, https://www.researchgate.net/publication/312606602

[8] Internet: Y. K. Choukiker, “Analysis Of Dual Band Rectangular Microstrip Antenna Using IE3D/PSO.”, https://www.researchgate.net/publication/37394525

[9] G. Singh and J. Singh, “Comparative Analysis of Microstrip Patch Antenna With Different Feeding Techniques,” ***International Conference on Recent Advances and Future Trends in Information Technology*** (iRAFIT2012) Proceedings published in ***International Journal of Computer Applications IJCA***.

[10] Y. Rhazi, S. Bri #1, and R. Touahani, "Effect of Microstrip Antenna Feeding in the K-band." ***International Journal of Engineering and Technology (IJET),*** (2012- 2013).

[11] A. N. Rao, "Fractal Microstrip Antenna for enhancement of bandwidth to operate at multi-frequencies", https://www.researchgate.net/publication/338213512 doi: 10.13140/RG.2.2.24590.31048. (2019).

[12] A. F. Alsager, "Design and Analysis of Microstrip Patch Antenna Arrays."

[13] Internet: N. Kaur, M. Tech Scholar, N. Sharma, and N. Singh, "A Study Of Different Feeding Mechanisms In Microstrip Patch Antenna.", http://www.warse.org/IJMA/static/pdf/file/ijma02612017.pdf

[14] Ms. V. Mokal, P. S. R. Gagare, and Dr. R. P. Labade, "Analysis of Micro strip patch Antenna Using Coaxial feed and Micro strip line feed for Wireless Application," ***IOSR Journal of Electronics and Communication Engineering***, vol. 12, no. 03, pp. 36–41, doi: 10.9790/2834-1203033641, (2017).

[15] A. Kajla and D. Somwanshi, "Reconfigurable Microstrip Patch Array Antenna: Design and Performance Analysis," 2020, pp. 287–293. doi: 10.1007/978-981-15-1059-5_32, (2020).

[16] A. A. Abdulbari *et al.*, "Design compact microstrap patch antenna with t-shaped 5g application," ***Bulletin of Electrical Engineering and Informatics***, vol. 10, no. 4, pp. 2072–2078, doi: 10.11591/EEI.V10I4.2935, (2021).

[17] B. A. Ifeoma and N. Lucky, "Design Analysis of 5G Microstrip Antenna," *INTERNATIONAL JOURNAL OF ENGINEERING AND MODERN TECHNOLOGY*, vol. 8, no. 4, pp. 12–24, doi: 10.56201/ijemt.v8.no4.2022. pg12.24, Oct. (2022).

[18] N. Kaur, S. Sharma, and J. Kaur, "Concave shape microstrip patch antenna using SRR for 5G applications," ***International Journal of Innovative Technology and Exploring Engineering,*** vol. 8, no. 9 Special Issue, pp. 743–746, doi: 10.35940/ijitee.I1120.0789S19, Jul. (2019).

[19] W. S. Chen and Y. C. Lin, "Design of 2×2 microstrip patch array antenna for 5G C-band access point applications," ***IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition, iWEM 2018, Institute of Electrical and Electronics Engineers Inc***., doi: 10.1109/iWEM.2018.8536673, (2018).

[20] K. Zoukalne, A. Chaibo, and M. Y. Khayal, "Design of Microstrip Patch Antenna Array for 5G Resonate at 3.6GHz," ***Current Journal of Applied Science and Technology***, pp. 164–170, doi: 10.9734/cjast/2020/v39i3431046, (2020).

[21] H. Alwareth, I. M. Ibrahim, Z. Zakaria, A. J. A. Al-Gburi, S. Ahmed, and Z. A. Nasser, "A Wideband High-Gain Microstrip Array Antenna Integrated with Frequency-Selective Surface for Sub-6 GHz 5G Applications," ***Micromachines (Basel)***, vol. 13, no. 8, doi: 10.3390/mi13081215, (2022).

[22] A. K. Saurabh and M. K. Meshram, "Compact sub-6 GHz 5G- multiple-input-multiple-output antenna system with enhanced isolation," ***International Journal of RF and Microwave Computer-Aided Engineering***, vol. 30, no. 8, doi: 10.1002/mmce.22246, (2020).

[23] L. Zahid *et al.*, "Artificial Magnetic Conductor to Enhance Microstrip Patch Textile Antenna Performance for WiMAX Application," in ***IOP Conference Series: Materials Science and Engineering***, IOP Publishing Ltd. doi: 10.1088/1757-899X/932/1/012076, (2020).

[24] Internet: "Microstrip Width Calculator", https://cdn.everythingrf.com/live/new_microstrip_pcb_microstrip_calculator2.jpg

[25] Internet: "Electromagnetic Simulation Solvers, CST Studio Suite. Available" https://www.3ds.com/products-services/simulia/ products/cst-studio-suite/solvers (accessed on 28 February 2023)

APPENDIX A.

DESIGN PARAMETERS CALCULATION MATLAB CODE

```
%% Rectangular Microstrip patch Antenna Design


function Patchantenna(fr,epsilon_r,h,Zc)
%% Input Parameters
% fr = Operating Frequency in GHz
% epsilon_r = Dielectric Constant
% h  = Substrate Height in mm
% Zc = Characteristic Impedence
C = 3*10^8 ;         % Light speed at free space
% Considering the antenna's axis as the z axis and Antenna's Length (L) in
Y-axis
% and Antenna's Width (W) in X-axis. Microstrip Feedline is along the Y-
axis.
%% Width of the Antenna's Patch

W = (C/(2*fr*10^9))*sqrt(2/(epsilon_r + 1)) ; % in meters

%% Effective dielectric constant (epsilon_eff)

epsilon_eff = ((epsilon_r + 1)/2) + ((epsilon_r - 1)/2)*(1 + (12*h*10^-
3/W))^(-0.5) ;
%% Extension of length (delta_L) of the Antenna's Patch

delta_L = (0.412*h*10^(-3))*(((epsilon_eff + 0.3)*(W/(h*10^(-3)) +
0.264))/((epsilon_eff - 0.258)*(W/(h*10^(-3)) + 0.8))) ;
%% Actual Length of the Antenna's Patch
L = (C/(2*fr*10^9*sqrt(epsilon_eff))) - 2*delta_L ; % in meters
%% Width of the Feed Line (W0)
A = (Zc/60)*sqrt((epsilon_r + 1)/2) + ((epsilon_r - 1)/(epsilon_r +
1))*(0.23 + 0.11/epsilon_r);
B = ((377*pi)/(2*Zc*sqrt(epsilon_r)));
W_A = (8*exp(A))/(exp(2*A)-2);
W_B = (2/pi)*(B-1-log(2*B-1) + ((epsilon_r - 1)/(2*epsilon_r))*(log(B-1) +
0.39 - 0.61/epsilon_r) );
if W_A < 2
    W0 = W_A*h; % in mm
elseif W_B > 2
    W0 = W_B*h; % in mm
```

```
end
%% Characteristic Impedence of the feed line (Z0)
% In the calculation we have taken Z0 as 50 (Z0=Zc). BUt also we can
% calculate the real Z0 as given below.
if (W0/h) <= 1
    Z0 = (60/sqrt(epsilon_eff))*log((8*h*10^(-3)/W0) + (W0/(4*h*10^(-
3))));
elseif (W0/h) > 1
    Z0 = (120*pi/sqrt(epsilon_eff))/((W0/h) + 1.393 + 0.667*log((W0/h) +
1.444));
end
%% Antenna Input Impedence (Rin)
k0 = (2*pi*fr*10^9/C);
x = k0*W ;
Si_x = sinint(x) ; % Sine integral
I_1 = -2 + cos(x) + x*Si_x + sin(x)/x ;
G_1 = I_1/(120*pi.^2);
fun = @(theta)
(((sin(k0*W*cos(theta)/2))/(cos(theta)))^2).*((sin(theta)).^3).*besselj(1,
k0*L*sin(theta)) ;
G_12 = (1/(120*pi.^2))*integral(fun,0,pi);
Rin_odd = 1/(2*(G_1 + G_12)) ; % in Ohms (for odd modes)
Rin_even = 1/(2*(G_1 - G_12)) ; % in Ohms (for even modes)
%% Position of the inset-feed point (y0)
y0 = acos(abs(sqrt(Zc/Rin_odd)))*L/pi ; % in meters
%% Displaying Calculated Results
disp('-------------------------------------')
disp('Calculated Parameters and Dimensions')
disp('-------------------------------------')
fprintf('Operating Frequency           = %.3f GHz\n',fr)
fprintf('Dielectric Constant           = %.3f \n',epsilon_r)
fprintf('Substrait Height              = %.3f mm\n',h)
fprintf('Free space light speed        = %.1e m/s\n',C)
fprintf('Characteristic Impedence      = %.2f Ohms\n\n',Zc)
fprintf('Effective Dielectric Constant = %.3f \n',epsilon_eff)
fprintf('Characteristic Impedence Cal. = %.3f Ohms\n',Z0)
fprintf('Width of Patch                = %.3f mm\n',W*1000)
fprintf('Lenght of Patch               = %.3f mm\n',L*1000)
fprintf('Width of Feed line            = %.3f mm\n',W0)
```

```
fprintf('Inset-feed point position      = %.3f mm\n',y0*1000)
disp('                                                    ')
disp('          |--------------------------|  ^     ')
disp('          |                          |  | x   ')
disp('          |  y0                      |  |     ')
disp('          |------|                   |        ')
disp(' W0 |||||||||||||                    | Width  ')
disp('          |------|                   |        ')
disp('          |                          |        ')
disp('          |                          |        ')
disp('          |--------------------------|        ')
disp('                    Length   ---> y           ')
```

RESUME

The researcher graduated from the Sudan University of Science and Technology's (SUST) Department of Electronic Engineering. After that, she started working as a collaborating teaching assistant at the Sudan University of Science and Technology. Then, in 2014, she started working as a research assistant in the National Centre for Research (NCR)-Sudan department of electronic and communication engineering. To complete her M.Sc. education, she moved to Karabuk University, Department of Electric - Electronics Engineering.