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WIDEBAND MIMO 5G ANTENNAS IN HANDSETS

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ZAID ATIF ATTRAH

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Supervisor

Prof. Dr. Gölge ÖGÜCÜ YETKİN

by
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Zaid Atif ATTRAH

ABSTRACT

WIDEBAND MIMO 5G ANTENNAS IN HANDSETS

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M. Sc. In Electrical and Electronics Engineering
Supervisor: Prof. Dr. Gölge ÖGÜCÜ YETKİN
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In this work, a design of a MIMO antenna array is proposed for 5G communication systems. The proposed individual antenna element is constructed of H-geometry. The proposed antenna is oriented to suit the frequency bands of new radio (NR) n77, n78, and n79 with an excellent matching coefficient. When the proposed antenna located in an array configuration, an excellent isolation is achieved below -15dB over the entire frequency bands of interest. For that, four elements are oriented on a rectangular FR-4 substrate to obtain an excellent size reduction of 13.4mm×6mm×0.75mm. The MIMO array`s radiation efficiency is found to be in the range of 70% to 88% within the frequency band of interest. The antenna gain is found to be in maximum of 5dBi at 4.5GHz. The maximum correlation factor between the antenna elements in terms of ECC is found below 0.004 for the entire frequency band. The radiation patterns are found to be scattered to different direction at different frequencies to fit the portable communication 5G devices. The proposed work is optimized using HFSS and validated using CST MWS. From the obtained results in terms of S-parameters and radiation patterns, the antenna shows an excellent radiation properties and enhanced bandwidth. The obtained results from both CST and HFSS agreed well to each other.

Keywords: H-Shape, Antenna, NR-bands, 5G, MIMO, Array, CST MWS, HFSS.

EL CİHAZLARINDA GENİŞ BANT MIMO 5G ANTENLERİ

ATTRAH, Zaid Atif
Yüksek Lisans Elektrik ve Elektronik Mühendisliğinde
Danışman: Prof. Dr. Gölge ÖGÜCÜ YETKİN
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Bu çalışmada, 5G iletişim sistemleri için bir MIMO anten dizisi tasarımı önerilmiştir. Önerilen bireysel anten elemanı H-geometrisine inşa edilmiştir. Önerilen anten, mükemmel bir uyum katsayısı ile yeni radio (NR)n77, n78 ve n79 frekans bantlarına uyacak şekilde yönlendirilmiştir. Önerilen anten, bir dizi konfigürasyonuna yerleştirildiğinde, ilgilenilen tüm frekans bantlarında -15dB'nin altında mükemmel bir izolasyon elde edilir. Bunun için, dört eleman, 13.4mm×6mm×0.75mm'lik mükemmel bir boyut küçültme elde etmek için dikdörtgen bir FR-4 alt tabakasına yerleştirildi. MIMO dizisinin anten radyasyon veriminin ilgili frekans bandında %70 ila %88 aralığında olduğu bulunmuştur. Anten kazancının 4.5GHz'de maksimum 5dBi olduğu bulunmuştur. ECC cinsinden anten elemanları arasındaki maksimum korelasyon faktörü tüm frekans bandı için 0,004'ün altında bulunmuştur. Radyasyon paternlerinin, taşınabilir iletişim 5G cihazlarına uyması için farklı frekanslarda farklı yönlere dağıldığı bulunmuştur. Önerilen çalışma HFSS kullanılarak optimize edilmiş ve CST MWS kullanılarak doğrulanmıştır. S-parametreleri ve radyasyon paternleri açısından elde edilen sonuçlardan, anten mükemmel bir radyasyon özellikleri ve geliştirilmiş bant genişliği gösterir. Hem CST'den hem de HFSS'den elde edilen sonuçlar birbiriyle uyumluydu.

Anahtar Kelimeler: H Şekli, NR bantları, 5G, MIMO, Dizi, CST MWS, HFSS.

''Dedicated to my family''

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LIST OF ABBREVIATIONS

MIMO	Multiple-Input Multiple-Output
1G	First-Generation
2G	Second-Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
ECC	Envelope Correlation Coefficient
HFSS	High Frequency Structure Simulator
CST	Computer Systems Technology
GND	Ground Plane
IoT	Internet of Things
MM-Wave	Millimeter-Wave
NL	Neutralization-Line
Ofcom	Office of Communications
PCB	Printed Circuit Board
PEC	Perfect Electric Conductor
SISO	Single-Input Single-Output
T.E.	Total Efficiency
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

1.1 General

With the advancements in wireless communication technology, mobile phones have become an integral part of our daily lives. The development of 2G, 3G, and 4G networks enabled mobile phones to offer voice and text communication and internet access. However, as the demand for data-intensive applications grew, the need for faster and more efficient networks became apparent. This led to the fifth generation (5G) of wireless communication technology, which promises higher data rates, lower latency, and increased reliability.

The number of mobile subscriptions continues to rise while the data requirements of applications continue to increase [1]-[4]. The development of several wireless communication technologies and the ongoing evolution of mobile communications encourage the antenna community to create innovative, small antenna systems that may meet consumer needs. Particularly cellular systems, wireless communication technologies are rapidly expanding in the industrial sector. There are 4.68 billion mobile phone subscribers worldwide as of 2019.

The phrase "wireless communication" may be broken down into two words if we take it at face value: The first is communication, which is passing messages back and forth between two sites. The second word, wireless, denotes the absence of a physical cable and a link between the two contact sites. With the information presented above, we can define wireless communication as communicating between two separate sites without a physical connection. Using the tools at hand, early man communicated via radio. He employed various communication techniques, including smoke signals, light signals, reflecting lenses, voice signals, and others. All of these pre-industrial systems, however, suffered from a lack of distance between the various points of contact and required a clear line of sight between the transmitter and receiver; consequently, they continued to use control posts at high elevations to extend the communications' range (Andrea Goldsmith, 2005). When Marconi transmitted the first radio signal (an electromagnetic signal) in 1895 from approximately 18 kilometers, radio communication systems supplanted all previous wireless communication methods. The majority of wireless communication systems today employ digital signals, which are made up of binary bits, as opposed to the analog signals that were used in the early radio communication systems (Andrea Goldsmith, 2005).

1.2 . Background and Overview

1.2.1 Mobile Communications Evolution

Regarding mobile communications, they are described in terms of a particular system, speed, frequency, or overall technology (3G, 4G, or 5G, for example). Unique technologies of each age help to characterize it. Figure 1.1 depicts the progression of mobile technology Communication.

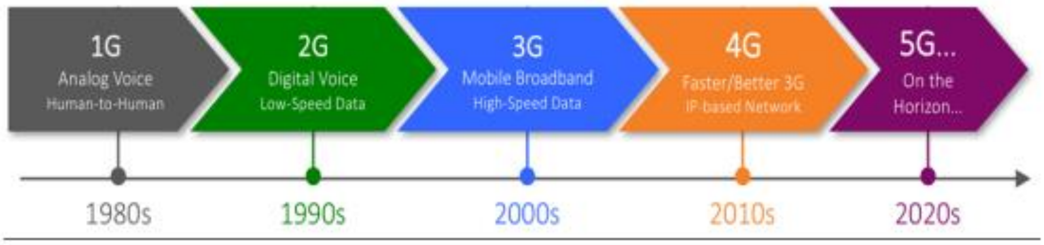

Figure 1.1 Mobile Communications evolution.

The very first generation of commercial cellular networks debuted in the late 1970s, with fully implemented standards developed in the 1980s [4]. Due to the analogue nature of 1G's radio transmissions, the audio of contact was modified to a higher frequency. Due to the degradation of analogue transmissions over time and distance, voice data within a conversation typically lacked fidelity. Digital communications, on the other hand, can effectively transmit more data.

In the early 1990s, GSM (Global System for Mobile Communication) technology was standardized, signaling the second generation. It enabled the transmission of digital voice and data over the network and the first-ever roaming for users. In addition, Signaling, Data Confidentiality, and Mobile Station Authentication were utilized further to enhance the security and privacy of telephone communications. Parallel to the transition from 1G to 2G technology, SMS, international roaming, conference calls, call hold, and service-based pricing were introduced, such as real-time invoicing and long-distance call prices.

Between 2000 and 2003, technological advancement led to the introduction of the packet network, or 2.5G, which facilitated high-speed Internet and data transit. EDGE (Enhanced Data GSM Environment) and GPRS (General Packet Radio Service) were among the standards (Enhanced Data Rates in GSM). GPRS facilitated variable data transmission speeds and maintained network connectivity. In addition, it allowed the service provider to charge customers based on the quantity of data transmitted rather than the length of their connection.

The 3G of mobile communications, which went on sale in 2001, was designed to accommodate a more extensive range of applications, provide more voice and data capacity, and boost data transfer at a reduced cost [5]. This generation enabled video calls, chat, conferencing, mobile TV, video-on-demand services, navigational maps, email, mobile gaming, music, and digital services such as movies in addition to fixed wireless Internet access and high-speed Internet access for the first time. 3G has significantly more security features, such as Network Access, Domain Security, and Application Security.

4G is a network architecture based only on IP implemented in 2010 [6]. Its purpose was to enhance security, reduce the cost of phone and data services, multimedia, and Internet over IP, and provide consumers with high speed, quality, and capacity. One of the primary benefits of an IP-based network was its ability to transition from an older infrastructure to voice seamlessly and data technologies based on GSM, UMTS, and CDMA2000. The succeeding LTE standard was introduced, which only supported packet switching and an IP-only network. To enable LTE, carriers had to restructure their voice call networks due to the circuit-switched nature of voice communications under GSM, UMTS, and CDMA. This necessitated significant infrastructure enhancements by service providers. LTE could not fulfil the standards, while LTE-Advanced did [7]. With carrier aggregation and MIMO, 4G networks could transfer data at a peak rate of 1 Gb/s [8] and used more than 40 frequency bands globally [5, 7].

1.2.2. Next generation 5G network in handsets

People's expectations for the speed of mobile communication have risen dramatically since the advent of the 4G mobile communication technology. Much research have been conducted on 5G mobile communication systems to fulfil these requirements, like vast machine-type communications, highly reliable networks, and wireless broadband connections [9]. 5G is currently in development and will simultaneously provide users with multiple wireless technologies via various pathways. Numerous areas, such as latency, mobility, data rate speed and resolution, etc., will experience substantial development [10, 11].

Illustrated are peak data rates up to 10 Gb/s with mobility up to 500 km/h, a minimum cell-edge data rate of 100 Mb/s, close to 10 bits/s/Hz spectral efficiencies, latency less than 1 millisecond, approximately 1 M simultaneous connections per km^2, and cost-effectiveness that is at least 10 times better than 4G. Multiple mobile technology companies participate in numerous 5G demonstration system trials [12]. As depicted in Figure 1.2, 5G will play a crucial role in enabling the Internet of Things (IoT) by connecting many objects to the Internet.

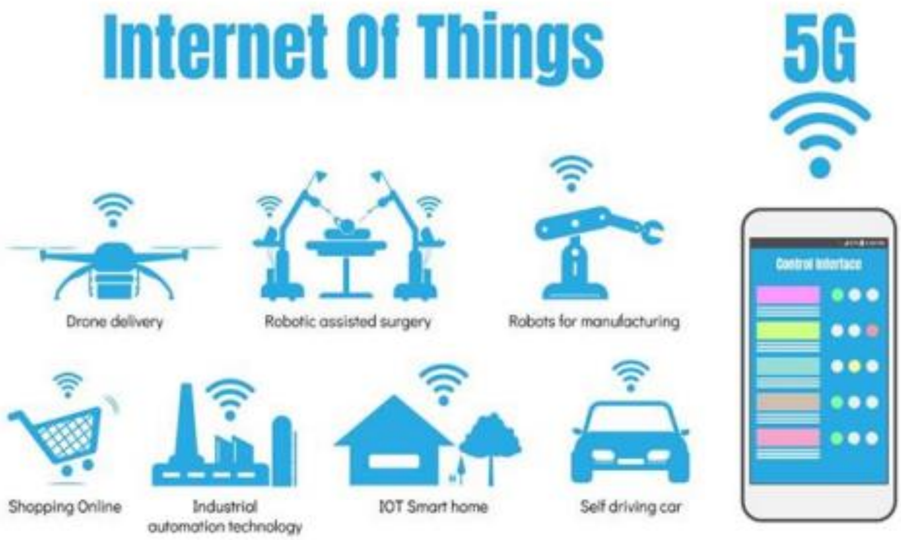

Figure 1.2 Internet of Things [13].

5G communications are classified by different frequency bands [14, 15].

The UK's communications regulator (Ofcom) classifies 5G new radios (NR) into low, middle, and high frequencies, as displayed in Figure 1.3.

- Low bands are less than 1 GHz to facilitate coverage over large areas.

- Mid bands are above 1 GHz and below 6 GHz: to support a large number of connected devices at high speeds.
- High bands can refer to anything greater than 12 GHz: Cells at these frequencies will offer ultra-high capacity and very low latency with very limited coverage and large bandwidths.

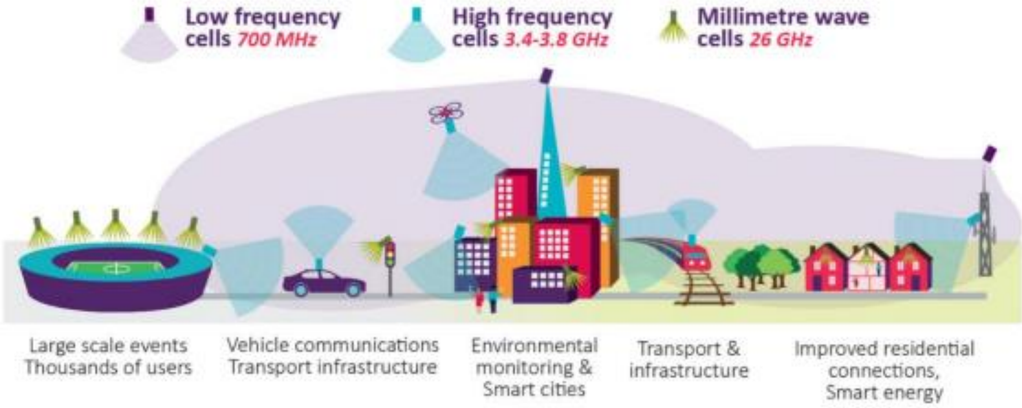

Figure 1.3 5G coverage [15]

1.2.3. Handsets Phone Antennas

In 1983, the first commercially available mobile phone was the DynaTAC 8000x. It was over one kilogram in weight and required 10 hrs. to charge. Since 1983, the number of mobile phone subscriptions has risen to more than 7 billion, more than enough to supply one for every person on the planet [16]. Figure 1.4 illustrates the evolution of mobile phones. It is difficult to predict the future's appearance and capabilities of 5G smartphones.

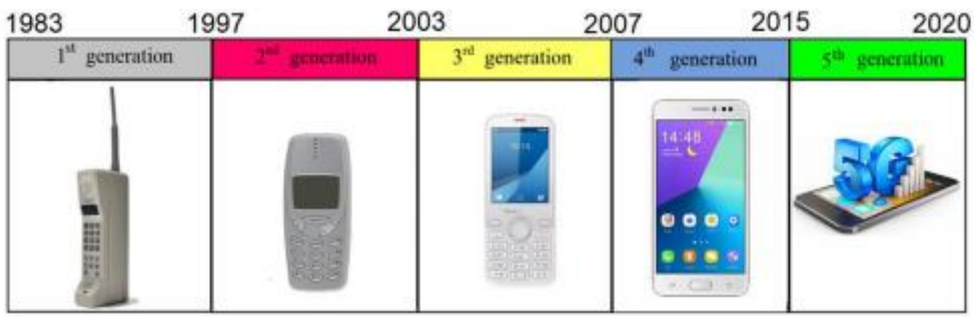

Figure 1.4 Mobile phones evaluation.

The antenna plays a crucial function in the transmission and reception of signals between terminals in mobile communications. In 1888, Heinrich Hertz introduced the antenna [17]. Physically made up of a number of conductors (occasionally including the dielectric) and capable of serving as both receiver and transmitter. The antenna terminal generates radio frequency (RF) current in transmit mode, causing the antenna to radiate and generate an electromagnetic field. For the receive mode, another source's electromagnetic field generates a voltage and current at the antenna's terminal [18, 19]. As shown in Figure 1.5, antennas function as converters between conducted waves and electromagnetic waves propagating through free space. Various varieties of antennas exist for various applications. Omnidirectional antennas, such as monopole antennas, are the simplest antennas. Directional antennas, such as the Log periodic antenna, are complex varieties.

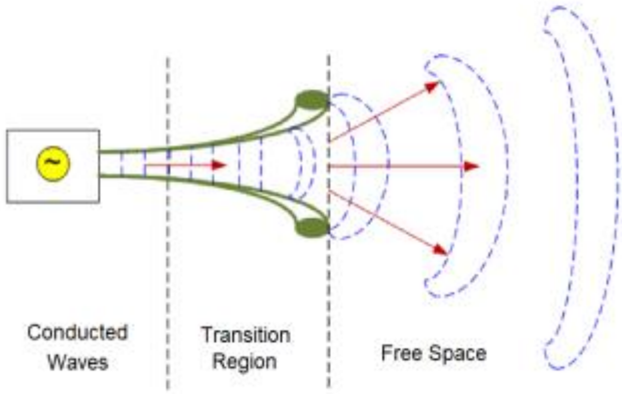

Figure 1.5 Antenna functionality.

The external antenna of the 1G mobile phone was typically a non-uniform helix that functions as a quarter-wave monopole at a non-uniform diameter and a lower frequency band for controlling the higher frequency band [20]. Mobile phones began to integrate an internal antenna at the end of the 1990s. In mobile antenna designs, monopole, planar inverted-F antenna (PIFA), and loop antennas are frequently utilized [21]. The metal bezel antenna is an additional mobile phone antenna that offers robust mechanical durability and is compatible with other antennas [22]. Figure 1.6 depicts the various varieties of antennas utilized by mobile phones.

Figure 1.6 The various varieties of antennas utilized by mobile phones.

1.2.4. Multiple-Input Multiple-Output (MIMO)

As commercial MIMO phased arrays for 5G become available on the market [23], communication architectures are undergoing rapid transformation.

At 5G application bands below 6 GHz, distributed MIMO array architectures will dominate [24, 25]. However, hybrid beamforming and phased array architectures are suggested for MM-Wave frequencies. Figure 1.8 demonstrates the MIMO system and phased array architectures.

With MIMO technology, multiple independent data streams (MIDS) can be transmitted simultaneously, resulting in a significantly higher data throughput than with single-input single-output (SISO). Multiple-Input Multiple-Output architecture has an expanded hardware footprint and permits us to trade off the channel's spatial diversity [26].

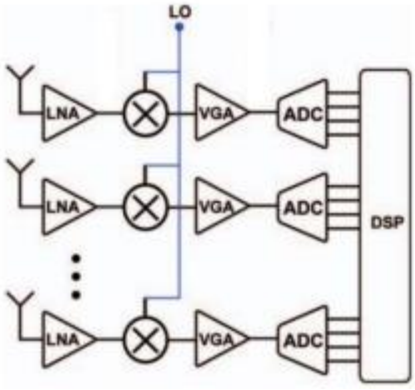

Figure 1.7 Architectures of MIMO system

1.3. Aims of the research

In this thesis, design a fifth generation (5G) multiple inputs multiple outputs(MIMO) antenna design is proposed for portable based handsets that covers all frequency bands for new radio (NR) applications at N77/N78/N79 to achieve the following aims:

- To obtain return losses below of -10dB,
- Reducing of a mutual coupling between antenna elements to be less than -15,
- Enhance the total radiation efficiency to be more than 60%.
- Reduce the effective ECC below 0.5 between antenna elements.

1.4. Thesis Outline

For ease, the contents of this thesis are arranged into the following sections:

Chapter 1: Introduction theoretical background Literature review containing a detailed overview.

Chapter 2: Detailed antenna design and parametric study.

Chapters 3: will discuss all the obtained results and discussion.

Chapter 4: A full conclusion of all observed data and future works.

1.5. Theoretical Background

Multiple antenna elements on the receiver and transmitter surfaces are utilized to generate numerous spatial channels, thereby increasing the data rate. Multi antenna systems are capable of establishing parallel data streams via distinct antenna elements

[27]. Multiple independent signal channels between the receiver and transmitter are capable of transmitting multiple independent data streams. Multi-antenna systems can also take up and constructively combine signals from multiple propagation paths. In general, there are two contradictory theories regarding multiantenna systems, namely phased array and MIMO. The following part examines the operation principles and essential parameters of phased array antennas and MIMO.

With the introduction of multiple-input multiple-output system technology, the design and implementation of multiple antennas at firstly; the base station and secondly; the user terminal have attracted considerable research focus and have become one of the most important developments for contemporary wireless communications, like 5G. Figure 1.8 depicts the operation principle of a 14-conventional MIMO antenna system. Multiple transmitting and multiple receiving antennas are utilized in a MIMO system. Notably, each spatial stream is transmitted on the same frequency channel from a distinct antenna chain. Each stream is received by the receiver on each of its identical chains. The receiver can reconstruct the original signals since it is aware of the phase offsets of its own antennas [28].

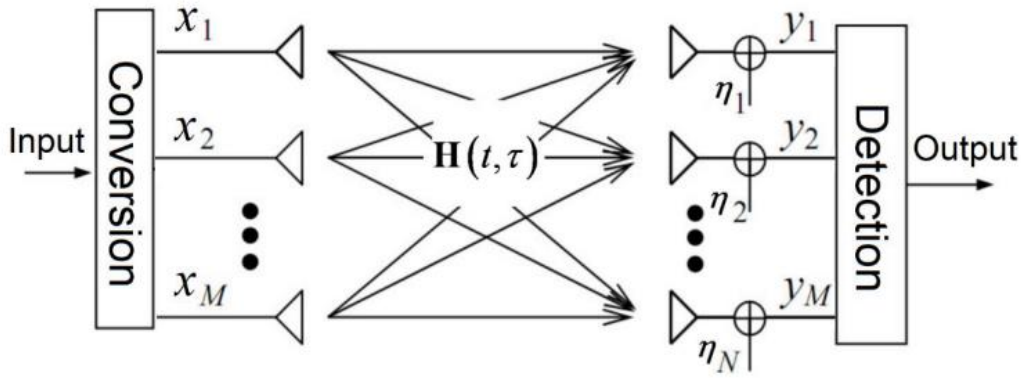

Figure 1.8 System MIMO conventional.

For a MIMO with a time-varying channel, the equivalent received signal with MT elements at the transmitter, and MR elements at the receiver can be calculated as follows:

$$y(t)=\int_{\tau} H\ (t,\tau)x(t-\tau)\ +\eta(t) \qquad (1.1)$$

x(t) is the transmitted and y(t) is the received signals [29].

$$x(t)=[x_1,\ x_2,\ldots,x_{Mt}] \qquad (1.2)$$

$$y(t)=[y_1,y_2,\ldots,y_{Mt}] \quad (1.3)$$

τ, H, and $\eta(t)$ are the delay, $MR \times MT$ channel matrix, and additive noise, respectively.

1.6. Key Parameters

1.6.1. S-Parameter

The S-parameters (or scattering parameters) are a matrix that measures the incident and reflected power of the signal at the antenna system's interface. S-parameters are represented by S_{ij}, which indicates the response at port i in response to a signal incident at port j.

$$S = \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ s_{N1} & \cdots & s_{NN} \end{bmatrix} \quad (1.4)$$

Sii is the ratio of the wave voltage reflected the wave voltage incident at the port of the i th element. S_{ji} represents the ratio of the voltage transferred from the jth element port to the i th element port to the voltage incident at the jth element port. S_{ji}, also known as the mutual coupling of the elements, is a crucial antenna parameter that must be carefully considered during the design of MIMO or phased array antennas.

1.6.2. Envelope Correlation Coefficient (ECC)

The ECC of antenna pairs is a standard measure of the multiple port efficacy of MIMO antennas. This parameter determines the relationship between the entanglement signals received by various antennas [30]. In general, the more diverse the patterns, the lower the ECC. ECC < 0.5 is a sufficient criterion for a desirable MIMO system. This independence can be measured and quantified for antennas without loss using the S-parameters.

$$ECC=\frac{\left|S_{ii}^{*}S_{ij}+s_{ji}^{*}S_{jj}\right|^{2}}{\left(1-\left|S_{jj}\right|^{2}-\left|S_{ij}\right|^{2}\right)\left(1-\left|S_{ji}\right|^{2}-\left|S_{jj}\right|^{2}\right)^{*}} \quad (1.5)$$

1.7. Literature review

Research into wideband MIMO in 5G has been ongoing for several years, with various approaches and techniques being explored. One common method is to use a compact antenna design that can support multiple frequency bands, such as dual-band, tri-band or even quad-band antennas. Another approach is to use a phased array antenna system, which allows for generating multiple beams that can be steered in different directions. This is particularly useful for 5G, which operates at higher frequencies and requires directional antennas to overcome higher path losses.

The research on wideband MIMO in handsets has made significant progress in recent years, with several promising approaches and techniques being developed. However, many challenges still need to be addressed, such as the design of compact, efficient and cost-effective antenna systems and the development of more advanced signal processing algorithms.

Ce Shi et al. [33] introduce a tiny wideband 6 port MIMO antenna for the 5G smartphone. Each antenna element has a coupling feed, and the unit has an I-shaped grounding structure attached to it to improve its impedance matching and increase its isolation level from other antenna units in the area. The frequency between 3.68 GHz and 5.27 GHz is covered by the F-type antenna built into the 5G MIMO antenna. The findings from the simulation indicate that it has favorable impedance matching, bandwidth, and isolation despite having a very low ground clearance. The addition of an I-type defect structure results in an improvement in the isolation between the antennas. Have also shown that the antenna satisfies the design criteria in the operating frequency range and that it is able to give acceptable impedance and radiation characteristics. A good ECC of less than 0.1 is produced, and it has been proved that the antenna satisfies these requirements.

Anping Zhao et al. [34] proposed for the purpose of implementing 5G in mobile terminals, a wideband 8-antenna MIMO system that is capable of covering the 3.3-5.0GHz spectrum is required. The essential result of the above-mentioned unusual arrangement is that it makes it possible to develop, for the first time, a new resonance mode that resides between the first (0.5) and second (1.0) resonance modes of the loop antenna. As a result, the bandwidth of the proposed coupled-loop antenna is enhanced when this new loop antenna mode is combined with the previous two-loop antenna modes. As a result, the coupled-loop antenna is able to cover all of the 5G new radio

(NR) bands. Both modelling and measurement were able to validate the performance of the 8-antenna multiple inputs multiple outputs system, leading to the successful achievement of excellent MIMO antenna performance. In particular, the wideband Eight-elements multiple inputs multiple outputs system that have been described demonstrates relatively strong isolation, a low envelope correlation coefficient, and high channel capacity. These characteristics are sufficient for implementing a viable 5G MIMO antenna in mobile terminals. As a result of the arguments that are presented in that research, the wideband 8-antenna MIMO system that has been developed might be one of the excellent options for the 5G multiple inputs multiple outputs applications in smartphones. So, the design presented in this research not only provides better wideband 5G MIMO antenna systems for mobile applications but also brings the loop antenna back to life and gives it a new lease on vitality.
Ziyan Zhou et al. [35] present a design for a four-element wideband multiple input-multiple output (MIMO) antenna with increased isolation that covers 1.9GHz-5.2GHz and is intended for use in 5G smartphones. The suggested MIMO antenna has a meandering monopole as its primary structural component; a dual-band is produced by involving a meandering L-shape strip and an inverted-F strip, and a wideband is produced by coupling a parasitic strip with a meandering monopole. Increasing the isolation between two neighboring input ports may be accomplished by etching at the ground two slots in the form of a H and two slots for a split-ring resonator. The MIMO array has overall dimensions of 54 by 120 by 13 mm3, and the antenna components are rotated symmetrically and vertically dispersed around the dielectric plate. Across the entire operation bandwidth, the antenna was able to achieve good impedance matching (return loss of less than -10dB), high isolation (less than -16dB), high total efficiency (greater than 65%), and a low envelope correlation coefficient (ECC of less than 0.05). Additionally, the antenna gained 6.1dB at 3.6GHz. Wide bandwidth and high isolation have both been effectively attained, and their practical use in 5G communication is now possible.

Ming-Yang et al. [36] suggested 8-port dual-polarized antenna array for probable future 5G operation in the 2.6 GHz band. This antenna array may be implemented in an 8 x 8 MIMO system. The 8-port antenna array presented is made up of four radiating strips with a square loop uniformity, and these radiating strips are stimulated by two feeding strips connected orthogonally. Consequently, orthogonal polarizations are achieved, and because of this property, increased isolations are also possible. It was decided to create a prototype of an eight-port antenna array, and the results of the measurements reveal that the array has an acceptable radiating efficiency of no less than 50% with an acceptable impedance bandwidth of 2558–2644 MHz throughout all bands of interest. It has also been determined that the suggested array has MIMO performances that are above average, with MEGs of 1 dB (differences) between any two ports and an ECC of 0.2. This suggests that the array has a high degree of MIMO capability. Over the frequencies of interest to the researchers, the predicted ergodic channel capacity of the eight-port antenna array in an 8 x 8 multiple-input multiple-output system was 39 bps/Hz. Consequently, the aforementioned performances have made it abundantly evident that the suggested 8-port antenna array is a desirable choice for any future 5G mobile applications that run below the 6 GHz band. This is the case since the proposed array has eight ports.

Hongwei Wang et al. [37] conducted research that successfully investigated a wideband 8-element antenna array for multiple-input multiple-output operation in the 5G -mobile terminals based on a co-coupled-fed IFA/loop antenna element. The suggested eight-antenna array is printed symmetrically along the two long side-edge frames of the mobile terminal's inner surface. This saves significant space on the system circuit board and eliminates the need for ground clearance. All of the advantageous operational characteristics of the proposed 8 x 8 MIMO antenna system are obtained. These operational characteristics include a good total radiation efficiency of 52% to 81%, a broad operating bandwidth in the range of 3300 to 6400 MHz, good isolations of all greater than 12 dB, small ECCs of all less than 0.08, and good channel capacities between 37.8 to 40 bps/ Hz. The proposed eight-element antenna array may be among the best candidates for wideband MIMO applications in future 5G handsets terminals because of its low profile and uncomplicated structure for integration and fabrication. It possesses a low profile and straightforward construction, in addition to many excellent qualities. Libin Sun et al. [38] offer an approach to constructing a highly integrated wideband MIMO antenna for use in 5G handsets that are space constrained. In the first step of this research project, the wideband decoupling of two closely spaced open-slot antennas in face-to-face and back-to-back configurations is explored. The face-to-face antenna pair has a broad bandwidth ranging from 3.3 to 7.2 GHz while having a tiny dimension of 24 by 2 by 5 mm3. An integrated quad-element

MIMO antenna with a tiny footprint of 60 x 2 x 6 mm3 is suggested here, and it is based on complementary antenna pairs. After that, an 8 x 8 MIMO system is realized by incorporating two sets of integrated quad-element MIMO antennas into the housing of a smartphone. The results of the simulations as well as the measurements, demonstrate that the 8 x 8 MIMO system has the potential to deliver a bandwidth of 3.3–5.0 GHz, with impedance matching that is better than 6 dB and isolations that are more than 10 dB. Also, with the 8 x 8 MIMO system, acceptable antenna efficiencies of between 52.8% and 70.8% and between 40.5% and 75.0% are attained. In addition to the integrated quad-antenna design, flexible expansion to the integrated multiantenna design is also being considered for potential higher-order MIMO applications. We believe that the suggested design scheme, which has the benefits of a high integration level, a broad bandwidth, and variable configurations, has the potential for the application of future 5G devices.

Jayshri Kulkarni et al. [39] presented an 8-port antenna array created for the future 5G 2.6 GHz band (2550–2650 MHz) to be used for MIMO in mobile applications. A square loop radiating strip that has orthogonal polarization is utilized so that the port isolation may be improved and the correlation between the antennas can be decreased. The suggested antenna array is made up of 4 pairs of uniform antenna elements arranged symmetrically at the 4 corners of the main board. Each of the four different antenna pairs consists of a communal square loop as well as two feeding strips that are coupled independently from one another. Two waves with polarizations that are orthogonal to one another are produced when a square loop is excited by two feeding strips in succession. These outcomes are in a total of eight antennas, four of which are polarized vertically and four of which are polarized horizontally. Because of this feature, the coupling between antenna pairs is lessened, which in turn helps improve MIMO performance. It was decided to construct a prototype of the suggested antenna array, and the results of the experiments indicate that the prototype has adequate impedance matching and appropriate isolation when tested across all of the bands of interest. Calculations are also done on the MIMO performances, including the mean effective gain, envelope correlation coefficient, channel capacity, and multiplexing efficiency. In addition to that, simulations of the antenna with the frequency moved to 3.5 GHz are also run. The constant performance indicates that the proposed structure has robust scalability and offers potential applications of 5G technology on smartphones.

Heng-You Liu et al. [40] presented an eight-port antenna array created for the future 5G 2.6 GHz band to be used for MIMO in smartphone applications. A square loop radiating strip that has orthogonal polarization is utilized so that the port isolation may be improved and the correlation between the antennas can be decreased. The proposed antenna array is made up of four different pairs of uniform antenna elements that are arranged symmetrically at the four corners of the main board. Each of the four different antenna pairs consists of a communal square loop and two feeding strips coupled independently from one another. Two waves with polarizations that are orthogonal to one another are produced when a square loop is excited by two feeding strips in succession. This results in eight antennas, four of which are polarized vertically and four of which are polarized horizontally. Because of this feature, the coupling between antenna pairs is lessened, which in turn helps improve MIMO performance. It was decided to construct a prototype of the suggested antenna array, and the results of the experiments indicate that the prototype has adequate impedance matching and appropriate isolation when tested across all of the bands of interest. Calculations are also done on the MIMO performances, including things like the mean effective gain, envelope correlation coefficient, channel capacity, and multiplexing efficiency. In addition to that, simulations of the antenna with the frequency moved to 3.5 GHz also are performed.

Anju Kumari Rai et al. [41] have demonstrated that an eight-element MIMO antenna may be verified satisfactorily. With an isolation of more than 12 decibels, the wideband MIMO antenna that has been proposed can span the entirety of the 5G NR n77/n78/n79/n96, LTE 46, and WLAN 5 GHz bands. It has attained a peak channel capacity of 42.7 bps/Hz and displayed an ECC of less than 0.069, which is the desired value. The SAR research on the proposed MIMO antenna was carried out to investigate the interaction that would take place between a human head and the specified MIMO array. According to the findings, the average SAR levels are far within the FCC's allowable range, making them acceptable. As a result, the suggested MIMO antenna array is a strong contender for a future small mobile terminal that supports 5G.

CHAPTER 2

DESIGN CONCEPTS AND METHODOLOGY

2.1. Introduction

MIMO-based planar inverted antennas (PIA) are an approach to antenna design that combines the benefits of MIMO technology with the compactness and performance of PIA antennas [40]. This design methodology is widely used in wireless communication systems to enhance data throughput, increase coverage, and improve overall system capacity [41]. MIMO is a technology that uses multiple antennas at the transmitting and receiving ends of a wireless communication system. MIMO uses multipath propagation by employing multiple antennas, where signals reflect off objects and arrive at the receiver through different paths. This enables MIMO systems to achieve higher data rates, improve signal quality, and enhance system performance [42]. The PIA antenna is a compact, planar design that operates in the microwave frequency range [40]. It consists of a metallic patch, typically placed on a ground plane, with a short parasitic element connected to the patch. PIA antennas are known for their small size, low profile, and ease of integration into portable devices, making them suitable for wireless communication applications [43]. However, it can provide a general overview of some key research areas and topics related to MIMO PIA antenna design [42]. These areas can serve as a starting point for conducting work to such research design:

1. MIMO Antenna Design: Explore research on MIMO antenna systems and their design methodologies. Understand the principles and techniques. Employed in designing multiple antennas for improved spatial diversity and capacity enhancement.
2. PIA Antenna Design: Investigate the fundamental concepts of PIA antenna design, including resonant frequency selection, impedance matching, radiation pattern control, and miniaturization techniques. Review research papers and

3. articles that discuss the performance optimization of PIA antennas, as will be summarized later in a comparison table.
4. MIMO PIA Antenna Integration: Focus on studies that specifically address the integration of multiple PIA antennas in MIMO systems. Examine the challenges associated with antenna placement, mutual coupling, and interference mitigation. Explore techniques for achieving high isolation and minimizing mutual coupling effects between closely spaced PIA antennas.
5. Performance Evaluation and Optimization: Look for research that evaluates the performance of MIMO PIA antennas through simulations, measurements, or both. Review studies that investigate the impact of various parameters, such as antenna spacing, ground plane effects, polarization diversity, and bandwidth requirements, on the performance of MIMO PIA systems. Additionally, explore optimization techniques to improve antenna efficiency, gain, and bandwidth.
6. Applications and Use Cases: Explore literature that discusses specific applications and use cases of MIMO PIA antennas, such as in wireless communication systems, mobile devices, Internet of Things (IoT) devices, and other wireless connectivity applications. Understand the challenges and opportunities of integrating MIMO PIA antennas in these systems.

2.2. Antenna Design Concepts

This section is based on two main parts that are discussed as follows:

2.2.1. Design concepts

When combining MIMO and PIA antenna technologies, several design concepts come into play:

1. Spatial Diversity: MIMO exploits the spatial diversity of multiple antennas to mitigate fading effects and improve signal quality [44]. In a MIMO PIA system, multiple PIA antennas are placed at different locations on the device to maximize the spatial separation between the antennas [23]. This spatial diversity helps in achieving better signal reception and transmission.
2. Mutual Coupling: Mutual coupling is the electromagnetic interaction between closely spaced antennas. In MIMO PIA design, it is essential to consider the mutual coupling between the antennas, as it can impact the system

performance. Mutual coupling can be minimized by proper antenna placement, isolation techniques, and decoupling elements [45].

3. Antenna Efficiency and Bandwidth: The efficiency and bandwidth of PIA antennas are crucial for achieving good system performance. Efficient radiation from the antennas ensures maximum power transfer and minimizes losses. Wideband characteristics are desired to support multiple frequency bands used in wireless communication systems [46].

2.2.2. Methodology for MIMO PIA antenna design

Designing a MIMO PIA antenna involves the following steps:

1. System Requirements: Determine the system requirements, such as frequency bands of operation, desired data rate, and spatial configuration (2x2, 4x4, etc.) of the MIMO system.
2. Antenna Selection: Choose a suitable PIA antenna design based on the desired characteristics, such as size, bandwidth, and efficiency. Consider antenna parameters like resonant frequency, radiation pattern, and impedance matching.
3. Antenna Placement: Determine the optimal locations for the PIA antennas on the device. This involves considering factors like antenna spacing, mutual coupling effects, and interference from other components [47].
4. Mutual Coupling Mitigation: Implement techniques to minimize the mutual coupling between the antennas. This may include adding isolation structures, decoupling elements, or using antenna designs with inherently low coupling.
5. Simulation and Optimization: Use electromagnetic simulation tools to analyze the antenna performance and optimize the design parameters. This step helps achieve desired antenna characteristics, such as impedance matching, radiation pattern, and efficiency [48].

2.3. Antenna Geometrical Details

The 5G is the upcoming commercial cellular network expected to speed up Internet connections considerably. The date of the commercial launch of 5G networks has received a variety of estimates, although they are typical. This study aimed to improve the performance of MIMO (Multiple Inputs, Multiple Outputs) antenna arrays for 5G terminals by converting the elements from an L-shape and F-shape to an H-shape.

The proposed antenna system used in mobile terminals is seen in Fig. 2.1. All the antenna elements are located along the two long sides of a 134mm×75mm ground plane, nearly the same size as many popular smartphones. Four antenna units are printed on two small substrates mounted perpendicular to the main system substrate. As shown in Figure 2.2, the dimensions of the small substrate are 134×6×0.75 mm, while the dimensions of the primary substrate are 150×75×0.75 mm. The small and main substrates are all double-sided FR4 with εr = 4.3 and tanδ = 0.02. Table 3.1 summarizes the main antenna parameters.

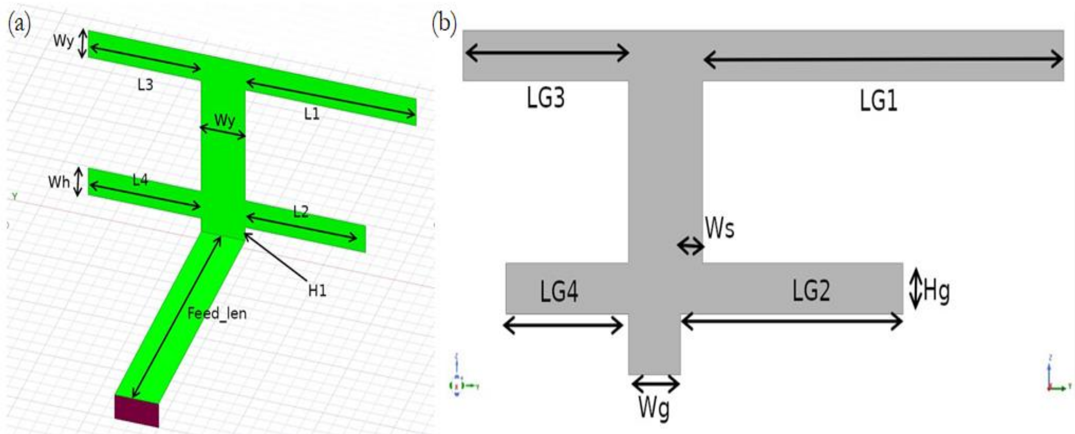

Figure 2.1 Antenna design (a) front piece (b) back piece.

Table 2.1 The main geometrical details of the proposed antenna.

Parameter	Value (mm)
L1	6.1
L2	4.25
L3	4
L4	4
Wy	1.6
Wh	0.9
H1	1.2
Lg1	11.1
Lg2	4.8
Lg3	6.45
Lg4	3.55
Wg	1.5
Ws	0.7
Hg	1.2

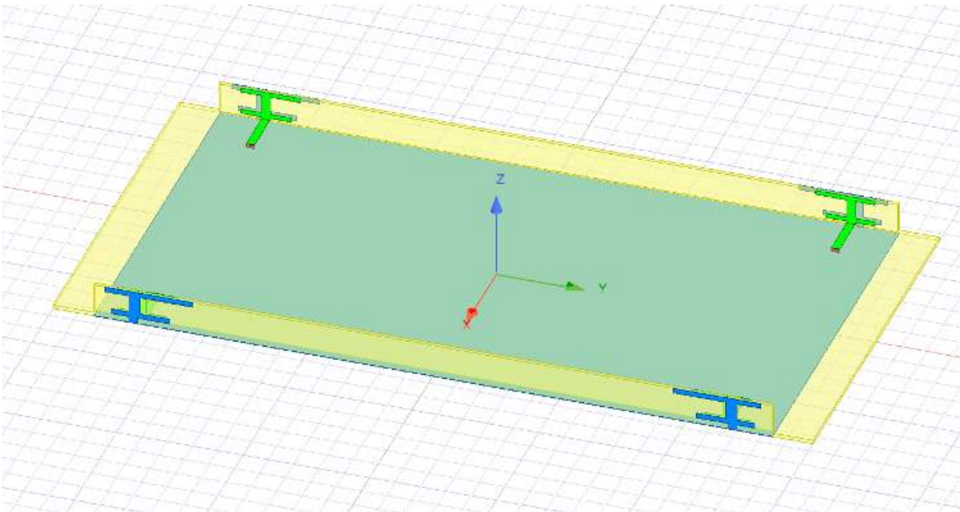

Figure 2.2 Antenna Array Geometry.

2.4. Preliminary Results of the Design Development Methodology

The proposed antenna array consisted of four triple-band antennas capable of supporting 5G New Radio (NR), including n77 (3.3-4.2GHz), n78 (3.3-3.8GHz), and n79 (4.4-5GHz), with a high bandwidth (>1.6 GHz) and high realized gain (>3 dBi). As shown in Fig. 2.3, the proposed design methodology is presented and discussed as shown below:

1. At the beginning of the design, a single element was employed for performing simulations, and the result was continuously improved until better results were achieved.
2. The next step is to simulate four items; if the findings are favorable, the analysis will proceed; otherwise, the simulation will be repeated with a single element.

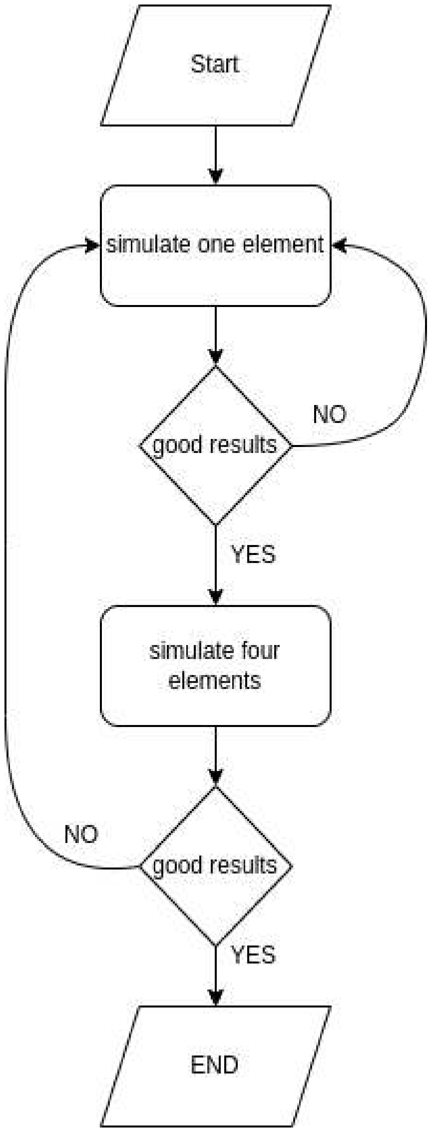

Figure 2.3 The proposed methodology flow chart.

In this work, we started from an initial design published previously in [42]. This reference presents a cutting-edge 4-antenna array for MIMO applications in 5G, featuring triple band antennas that cover 5G new radio (NR) and 5GHz-wireless vast area network (WLAN) operation. The proposed antenna array has been proposed to achieve high efficiency and isolation between each port.

For the proposed work, a design we introduced a modification based on L- and F-shapes to H- shaped structures. The introduced addition enhanced the antenna bandwidth to 3.3GHz-5GHz, as shown in Fig.2.4. The main advantages of increasing the antenna bandwidth due to the H- and L-shaped structures are attributed to the reduction in the surface wave and increasing the fringing effects at the edges of the kernel parts [43]. Nevertheless, the objective of increasing the antenna bandwidth leads to an increase the MIMO system channel capacity [46]. In other words, it is concluded that increasing the communication system channel capacity could be attributed to the antenna design structure parameters. Finally, such an antenna realizes good matching to the 5G handset devices that can be compacted within a limited size and small areas to suit wearable and portable devices [47].

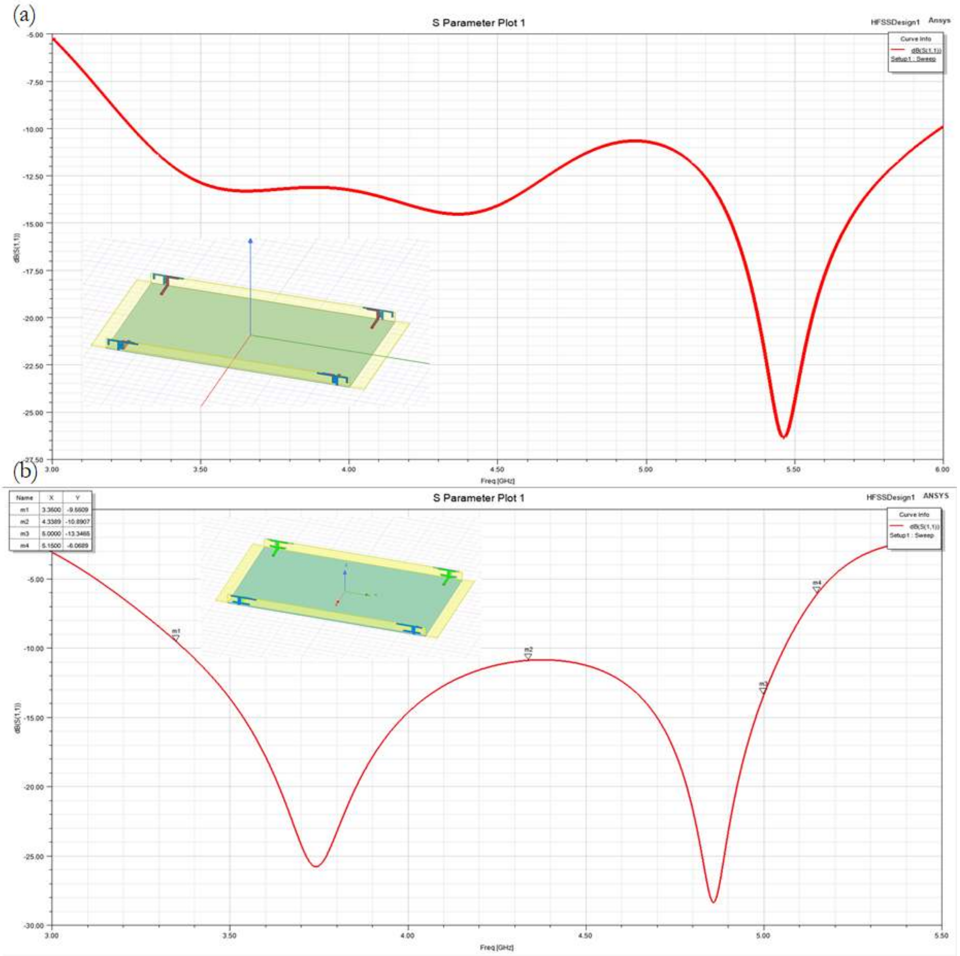

Figure 2.4: The obtained antenna results are based on two versions; (a) the Old version and (b) the new proposed version.

2.5. Parametric Study

Parametric studies in antenna design involve varying and analyzing different parameters to understand their impact on antenna performance. Regarding MIMO 5G printed antennas, parametric studies can provide valuable insights into the design process and help optimize antenna characteristics for specific requirements. Numerical simulations play a crucial role in conducting such studies. Here is a general approach to performing a parametric study for MIMO 5G printed antennas using numerical simulations:

1. Define System Requirements: Determine the specific requirements for the MIMO 5G antenna system, such as operating frequency bands, desired bandwidth, gain, efficiency, and radiation pattern characteristics. These requirements will guide the parametric study.
2. Identify Key Design Parameters: The critical design parameters may influence antenna performance. These parameters include antenna dimensions, substrate properties, feed structures, ground plane size, spacing between antennas, and other geometric features.
3. Select Simulation Software: Choose a suitable electromagnetic simulation software tool capable of accurately modelling the printed antenna structures and analyzing their performance. Commonly used software packages include CST Studio Suite, HFSS (High-Frequency Structure Simulator), FEKO, and ADS (Advanced Design System).
4. Set Up the Antenna Model: Construct the 3D or 2D model of the MIMO-printed antenna system within the simulation software. Define the material properties of the substrate, select appropriate numerical methods (such as finite element method or finite-difference time-domain), and specify boundary conditions.
5. Define Parametric Variables: Determine the range and step size of the parameters we want to study. For example, we might vary the antenna size, substrate thickness, feed location, or spacing between antennas. Define appropriate variables and their ranges within the simulation software.
6. Run Simulations: Perform the numerical simulations by systematically varying the selected parameters. Run simulations for different combinations of the parameter values to observe the effects on antenna performance metrics such as return loss, radiation pattern, gain, efficiency, and diversity performance.
7. Analyze Results: Analyze the simulation results to understand how the varied parameters impact the antenna performance. Evaluate metrics like impedance matching, isolation, diversity gain, envelope correlation, and capacity. Compare the results and observe trends to identify optimal parameter values.
8. Optimization and Validation: Based on the analysis, optimize the antenna design by selecting the parameter values that meet the desired performance criteria for the proposed design. Validate the optimized design through

additional simulations or experimental measurements to ensure accuracy, in our case, the bandwidth and gain.

9. Comparing: Discussing the obtained results from the parametric study, including the variations studied, simulation results, and conclusions drawn from the analysis.

Following this methodology, a comprehensive parametric study can be conducted for the proposed design to arrive at the optimal design structure. MIMO 5G printed antennas using numerical simulations. This approach will help us to understand the design specifications, optimize the antenna performance, and gain insights into the trade-offs involved in the design process. In Fig. 2.5 and Table 2.2, the most critical parameters are considered in this parametric study.

Table 2.2: Geometrical details of the proposed antenna.

parameter	Value(mm)	Parameter	Value(mm)
L1	6.1	LG1	11.1
L2	4.25	LG2	4.8
L3	4	LG3	6.45
L4	4	LG4	3.55
H1	1.2	Hg	1
Wz	1.55	Wg	1.5
Wh	0.9	D1	1.4
Wy	1.6	Thk	0.75
Feed_Len	9.2	Of	8.45
Ws	0.7	Copper_thk	0.035

Therefore, based on the previous discussion the author applied a strategy to arrive to the optimal design through the following:

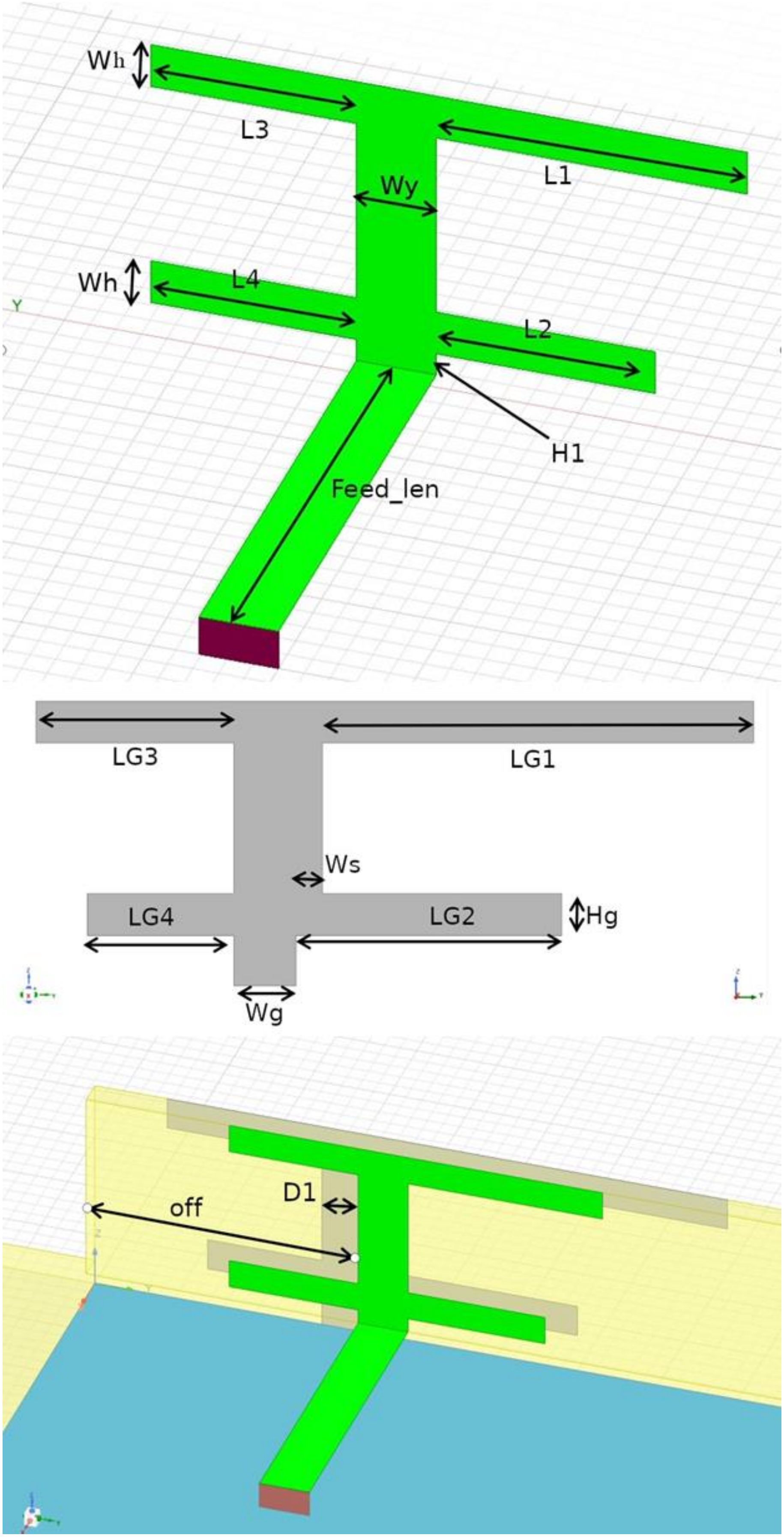

Figure 2.5 Antenna geometrical details for the proposed study.

2.5.1. L_1 influence on the antenna performance

The effects of changing the parameter L_1 with respect to the antenna performance is evaluated in terms of S_{11}. Thus, the variation in parameter L_1 is changed from 6mm to 6.2mm with a step of 0.1mm. It is found from the achieved results; insignificant enhancement is found in the matching impedance or frequency resonance. However, the proposed antenna shows much better performance when L_1=6.1mm. Therefore, we decided to keep this dimension to the next step of parametric study. The obtained results are presented in Fig. 2.6 for the three obtained cases.

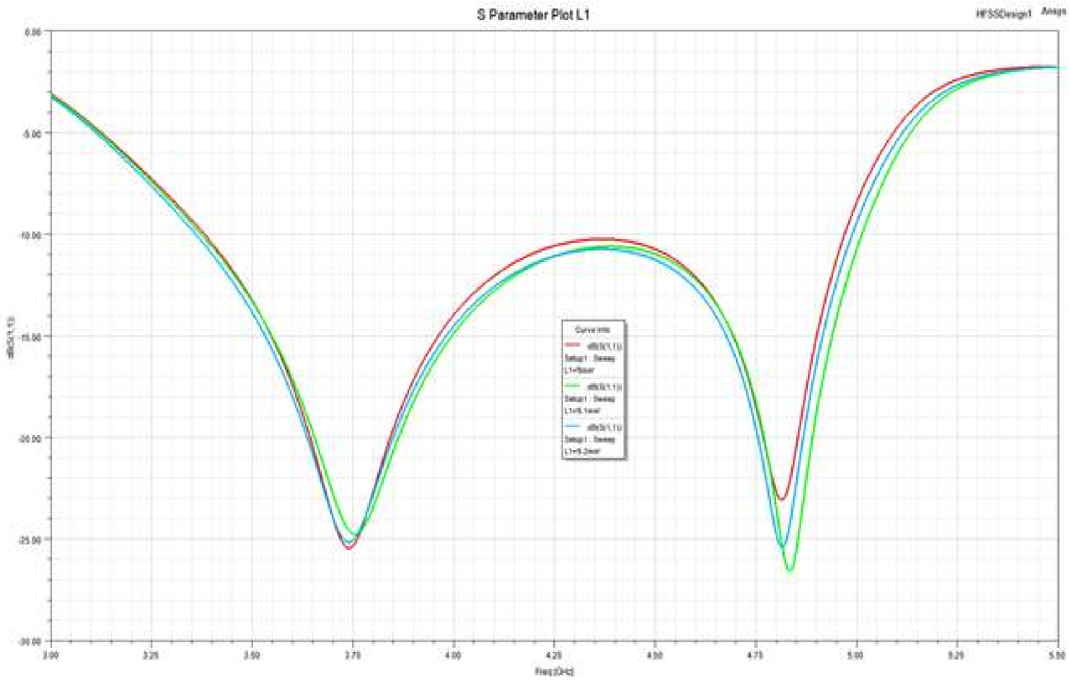

Figure 2.6: The obtained results for L_1 variation effects on S_{11} spectra.

2.5.2. L_2 influence on the antenna performance

Next, the obtained results in terms of S_{11} with respect to varying L_2 are recorded in Fig. 2.7. Therefore, parameter L_2 is changed from 4mm to 4.5mm with a step of 0.25mm. This study leads to an effective change in the second band of 4.8GHz. It is found that reaching L_2=4.25mm shows an excellent enhancement in antenna matching.

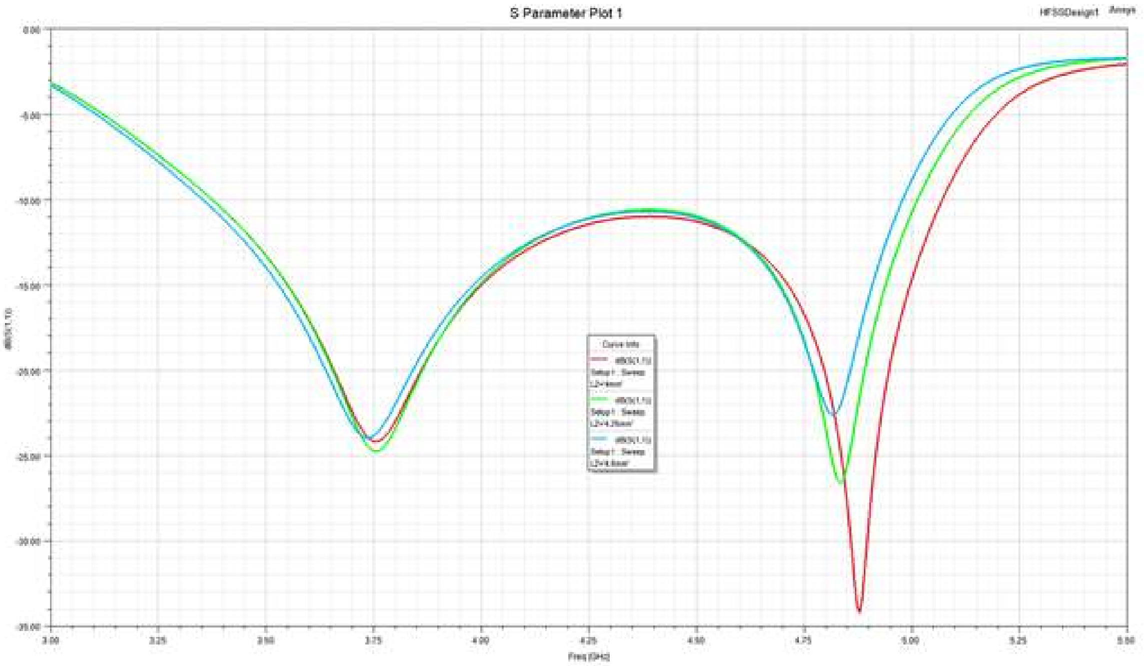

Figure. 2.7: The obtained S_{11} results with respect to varying L_2 parameter.

2.5.3. L_3 influence on the antenna performance

The proposed antenna variation in terms of S_{11} with respect to varying L_3 is proposed in this section. We changed the parameter L_3 from 3.9mm to 4.1mm with a step of 0.1mm. It is found that the proposed antenna shows an observable variation in two bands. The optimal variation is found to be achieved at L_3=4mm, as can be seen in Fig. 2.8.

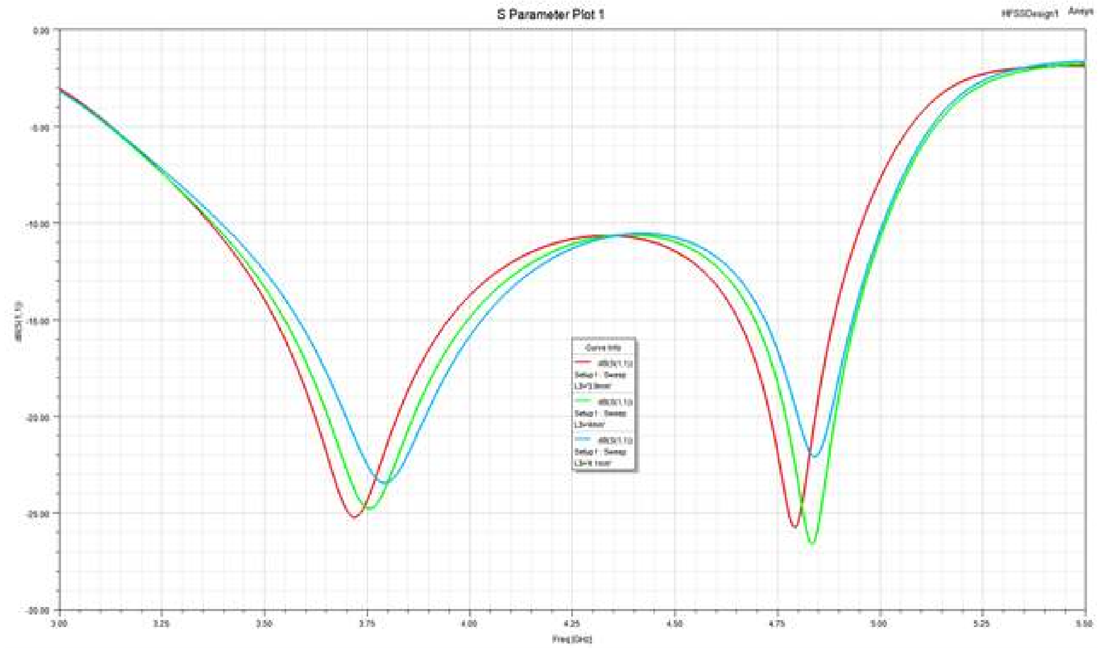

Figure 2.8: The obtained S_{11} results with respect to varying L_3 parameter.

2.5.4. W_y influence on the antenna performance

The proposed antenna in terms of W_y is changed from 1.5mm to 1.7mm with a step of 0.1mm. The achieved results from this study found that the proposed antenna S_{11} shows a significant change with respect to W_y variation. However, the best performance is achieved at W_y=1.6mm, as seen in Fig. 2.9.

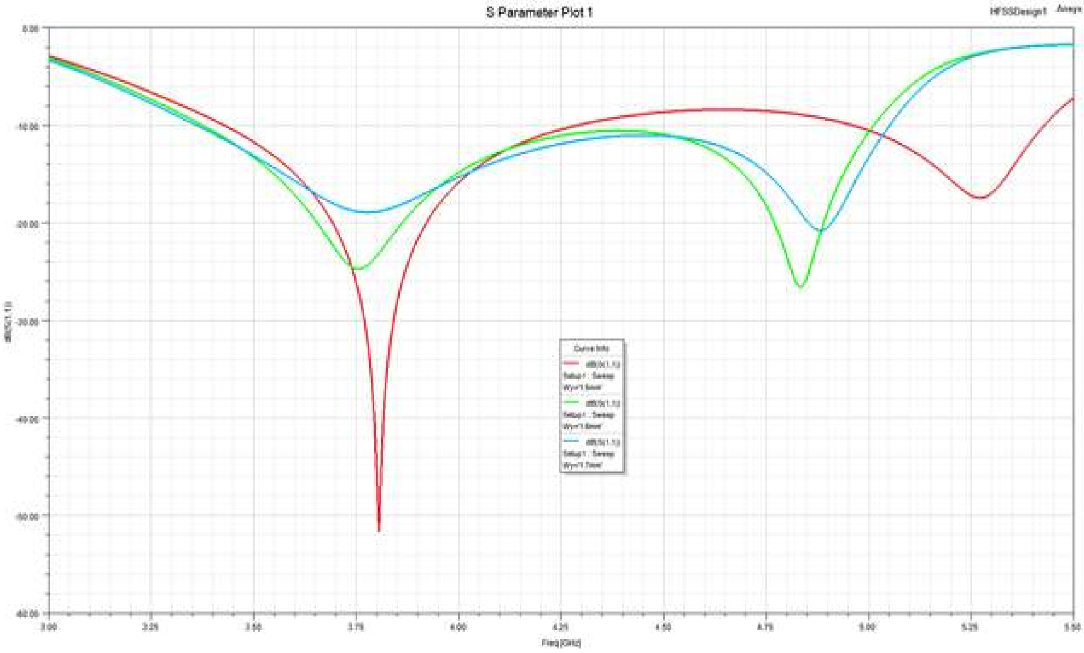

Figure 2.9: The obtained S_{11} results with respect to varying W_y parameter.

2.6. Radiation Pattern Properties

The proposed antenna radiation in the form of 3D electromagnetic radiation patterns is presented in this section. The proposed antenna within the frequency band of interest from 3GHz to 5GHz at: 3.3GHz, 3.7GHz, 4.2GHz, 4.4GHz, 4.8GHz, and 5GHz are shown in Fig. 2.10. It is found that the proposed antenna shows high scattering towered in different directions at higher frequencies. In contrast, the antenna at lower frequency bands shows fewer scattering effects. This observation is attributed to fringing that shows fewer effects at higher frequencies to realize an electrostatic surface current motion over the conductive parts of the antenna [33]. In both cases, the antenna is a desired property in modern communication systems.

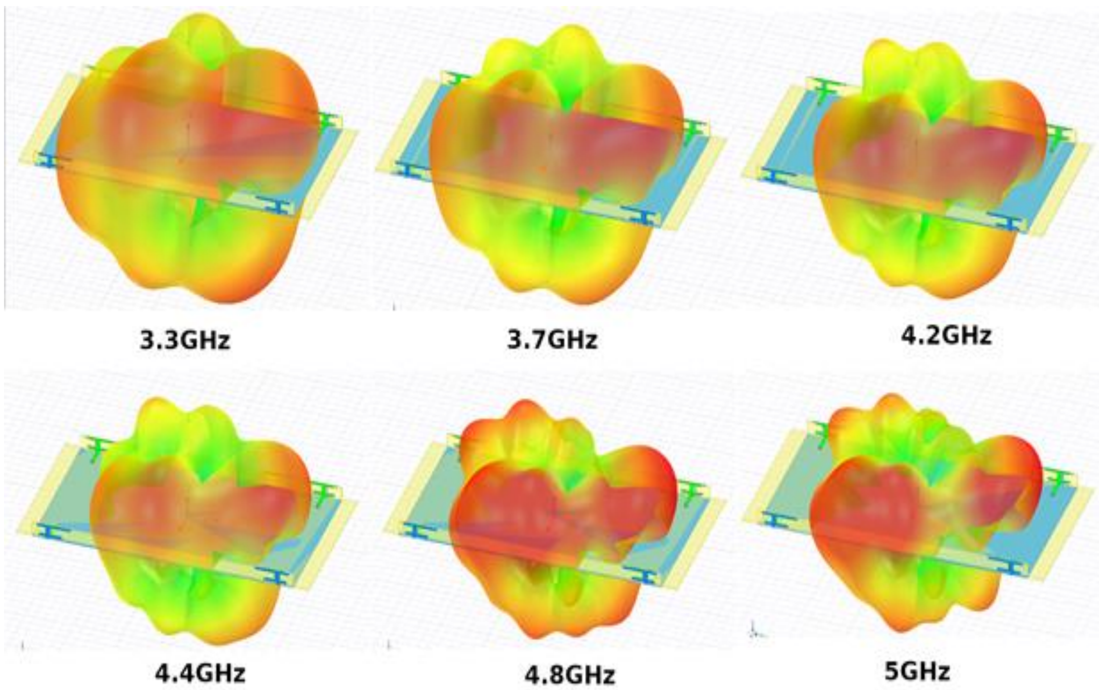

Figure 2.10: The proposed antenna 3D radiation patterns at several frequency bands.

CHAPTER 3

RESULTS VALIDATION AND DISCUSSION

3.1. HFSS and CST MWS Simulations Conditions

When performing a Finite Element Method (FEM) simulation using the HFSS (High-Frequency Structure Simulator) software, several important conditions and parameters must be considered. Here are some key aspects to keep in mind:

1. Geometry: Create or import the 3D geometry of our structure in HFSS. Ensure the geometry is accurate and adequately represents the physical system we want to simulate.
2. Material Properties: Assign appropriate material properties to the different parts of the proposed structure. These properties include electrical conductivity, dielectric constant, and magnetic permeability. Use the relevant material data for the substances involved in our simulation.
3. Excitation: Specify the excitation type to be applied to our structure. Depending on our application, this could be a voltage source, current source, or other types of excitations. Set the required excitation parameters such as frequency, amplitude, and phase.
4. Boundary Conditions: Define the appropriate boundary conditions for our simulation. Common boundary conditions include perfect electric conductor (PEC) or perfect magnetic conductor (PMC) boundaries [47]. These conditions determine how the electromagnetic fields interact with the boundaries of our structure.
5. Meshing: Create a mesh that divides the geometry of our structure into small elements. The meshing process determines the spatial resolution of our simulation. Choose an appropriate mesh size and type to balance accuracy and computational efficiency. HFSS offers various meshing algorithms, such as tetrahedral, hexahedral, and triangular meshing.
6. Simulation Setup: Configure the simulation setup according to our requirements. Specify the analysis type, such as electromagnetic (EM)

7. Simulation, modal analysis, or transient analysis. Set the simulation's frequency range, time duration, and other relevant parameters.
8. Solver Settings: Adjust the solver settings to control the accuracy and convergence of the simulation. HFSS provides different solver options, such as the frequency-domain solver (for steady-state solutions) and the time-domain solver (for transient responses). Configure the convergence criteria, adaptive meshing, and other solver-specific settings.
9. Post-Processing: After completing the simulation, analyze and visualize the results. HFSS offers various post-processing tools to examine fields, currents, voltages, S-parameters, radiation patterns, and other quantities of interest. Use these tools to gain insights into the behavior of our structure.

Remember that HFSS is a powerful tool for electromagnetic simulation, and the specific simulation conditions may vary depending on the complexity and requirements of a particular project. Next, when performing a Full-Wave Integral Equation Technique (FIT) simulation using CST Microwave Studio (CST MWS) software, several important conditions and parameters must be considered. Here are some key aspects to keep in mind:

1. Geometry: Create or import the 3D geometry of our structure in CST MWS. Ensure that the geometry accurately represents the physical system we want to simulate. Pay attention to the dimensions, shape, and positioning of the components.
2. Material Properties: Assign appropriate material properties to the different parts of our structure. These properties include electrical conductivity, dielectric constant, and magnetic permeability, among others. Use the relevant material data for the substances involved in our simulation.
3. Excitation: Specify the type of excitation we want to apply to our structure. This could be a voltage source, current source, or other types of excitations, depending on our application. Set the excitation parameters such as frequency, amplitude, and phase as required.
4. Boundary Conditions: Define the appropriate boundary conditions for our simulation. Common boundary conditions include perfect electric conductor (PEC) or perfect magnetic conductor (PMC) boundaries. These conditions determine how the electromagnetic fields interact with the boundaries of our structure.

5. Meshing: Create a mesh that divides the geometry of our structure into small elements. The meshing process determines the spatial resolution of our simulation. Choose an appropriate mesh size and type to balance accuracy and computational efficiency. CST MWS provides various meshing algorithms, such as tetrahedral, hexahedral, and triangular meshing.
6. Solver Settings: Configure the solver settings according to our requirements. CST MWS offers different solver options, such as the Method of Moments (MoM) solver for FIT simulations. Adjust the convergence criteria, accuracy settings, and other solver-specific parameters to ensure reliable results.
7. Simulation Setup: Set up the simulation according to our needs. Specify the analysis type, such as frequency-domain simulation, time-domain simulation, or eigenmode analysis. Set the simulation's frequency range, time duration, and other relevant parameters.
8. Post-Processing: After completing the simulation, analyze and visualize the results. CST MWS provides various post-processing tools to examine fields, currents, voltages, S-parameters, radiation patterns, and other quantities of interest. Utilize these tools to gain insights into the behavior of our structure.

It is important to note that CST MWS is a versatile electromagnetic simulation tool, and the specific simulation conditions may vary depending on the complexity and requirements of our project.

3.2. Results Discussions

The proposed antenna bandwidth is enhanced significantly from the previous chapter. It is found that the proposed antenna shows S_{11}≤-10dB at two frequencies of 3.75GHz and 4.85GHz. Therefore, the proposed antenna array in S_{11}, S_{22}, S_{33}, and S_{44} spectra are evaluated. It is found from the evaluated results that the proposed antenna shows similar performance as shown in Fig. 3.1(a). It is observed insignificant variation between S_{11}, S_{22}, S_{33}, and S_{44} spectra that reveals the validity of the proposed antenna for MIMO systems.

Next, the S-parameters in terms of S_{11}, S_{12}, S_{13}, and S_{14} spectra are presented in Fig. 3.1(b). The evaluated results show a low coupling between the antenna elements, where it is found the maximum coupling of about -18dB between the first and the second one. However, it is found to be reduced to -20dB between the first and the third element, with -30dB between the first and the fourth one. The monitored observations are recorded for the frequency band of interest, as seen in Fig. 3.1(b). Such reduction in the coupling between the antenna elements is attributed to the self-isolation property based on sequential feed orientation that minimizes the surface wave effects within a limited area [48]. Nevertheless, the observed reduction between the antenna coupling elements could be attributed to the variation in the antenna polarization with respect to each other, as discussed previously in [49]. Such property is usually intimated to the minimum reduction in the electrostatic charges that antennas without a traditional ground plane show [50].

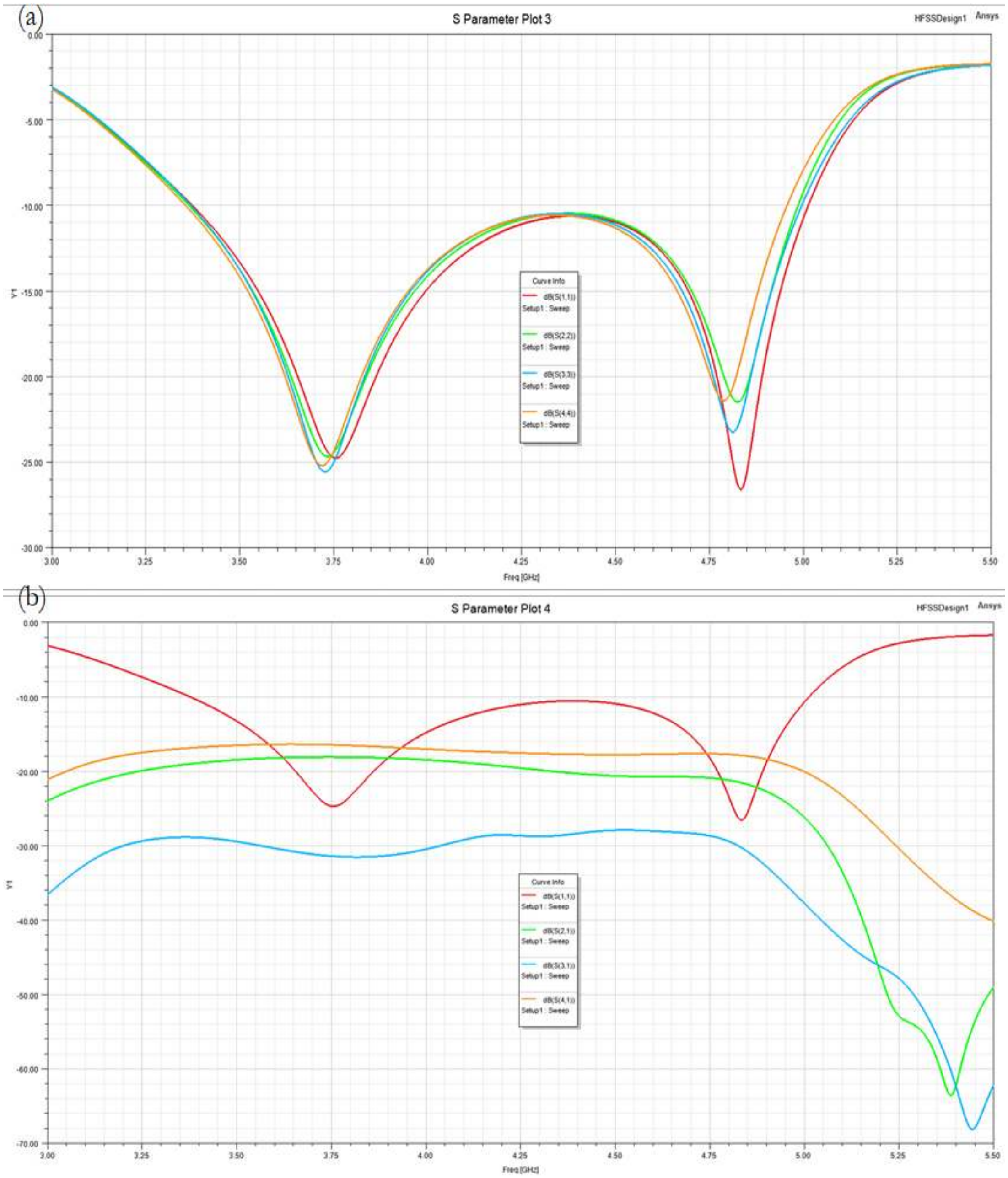

Figure 3.1: Antenna parametric study; (a) S_{11}, S_{22}, S_{33}, S_{44} spectra and (b) S-parameters: S_{11}, S_{12}, S_{13}, S_{14} spectra.

As seen in Fig. 3.2, the proposed antenna elements in their MIMO array configuration realize omni directional radiation patterns that fit many attractive applications, including mobile handset devices. The proposed antenna realizes a gain of about 5dBi that nominates such antennas for short and medium communication systems.

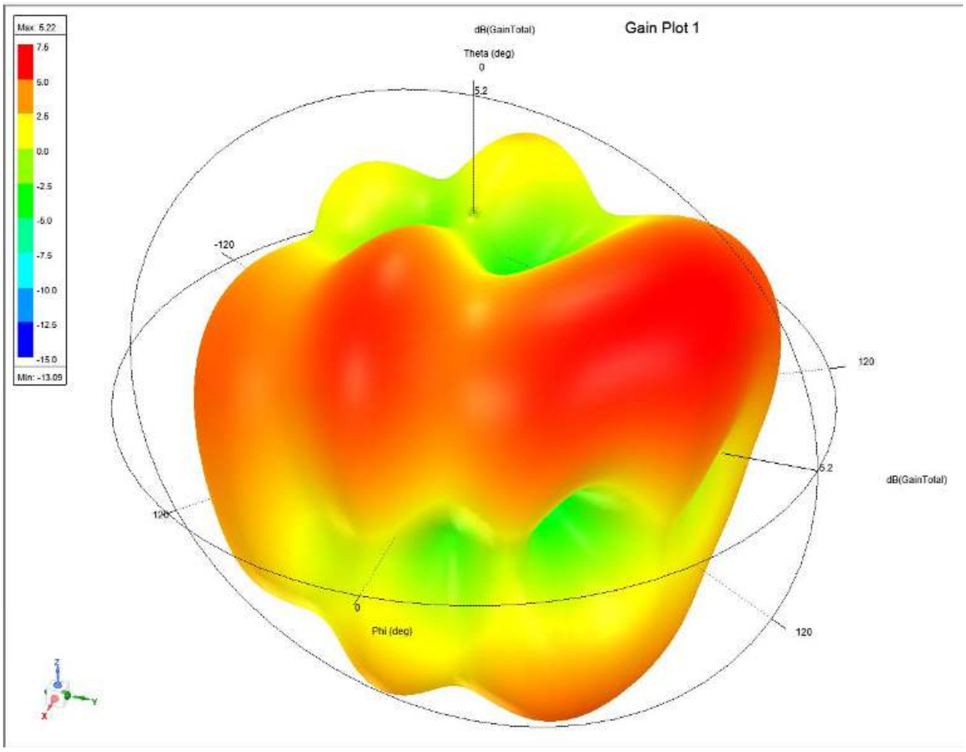

Figure 3.2: 3D antenna radiation pattern.

Next, the proposed antenna radiation efficiency is evaluated as shown in Fig. 3.3. Based on the obtained results; we found that the proposed antenna realizes significant efficiency enhancements at 3.75GHz and 4.85GHz within the band of interest. Such enhancements are attributed to minimizing the storing losses due to the inductive and capacitive equalization conjunctly addressed with charge accumulations at the substrate edges [51]. It is good to mention that the proposed antenna realizes a maximum efficiency of 88% at 3.8 GHz.

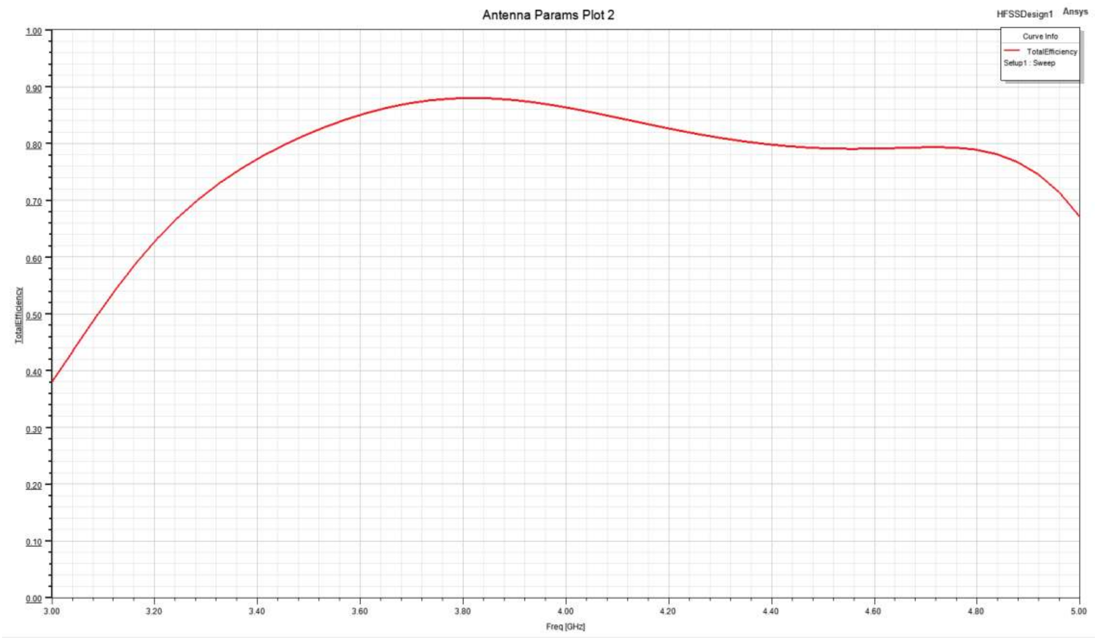

Figure 3.3: The evaluated radiation efficiency spectrum within the frequency band of interest.

Next, the Envelope Correlation Coefficient (ECC) spectrum is evaluated as shown in Fig. 3.4. ECC is commonly used in MIMO antenna systems, including those used in 5G networks. The ECC measures the correlation between the envelope of the signals received by different antennas in a MIMO system [52]. It quantifies the similarity or dissimilarity of the amplitude variations of the received signals. A low ECC indicates that the antennas are experiencing less correlation, which is generally desired in MIMO systems, as it allows for better spatial diversity and improved performance [53]. It is obvious from the obtained results that the maximum ECC value is less than 0.004, which is an acceptable level in MIMO systems [50].

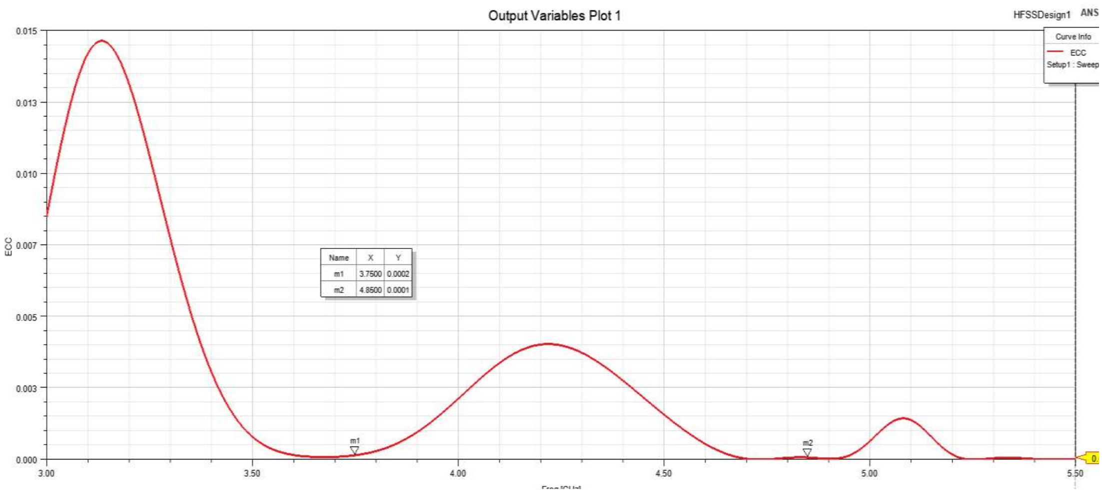

Figure 3.4: The evaluated ECC of the proposed antenna MIMO.

3.3.Results Validation

In this section, the proposed antenna is re-simulated, as shown in Fig. 3.5, using the CST software package. The proposed antenna array S11 spectra are tested numerically, as seen in Fig. 3.5(a). The proposed antenna array is tested at four elements to provide a frequency resonance matching similar to the obtained results from HFSS. Later, the antenna array radiation pattern is simulated, as seen in Fig. 3.5(b). The obtained results are compared with their relative simulation results from HFSS to reveal excellent agreement.

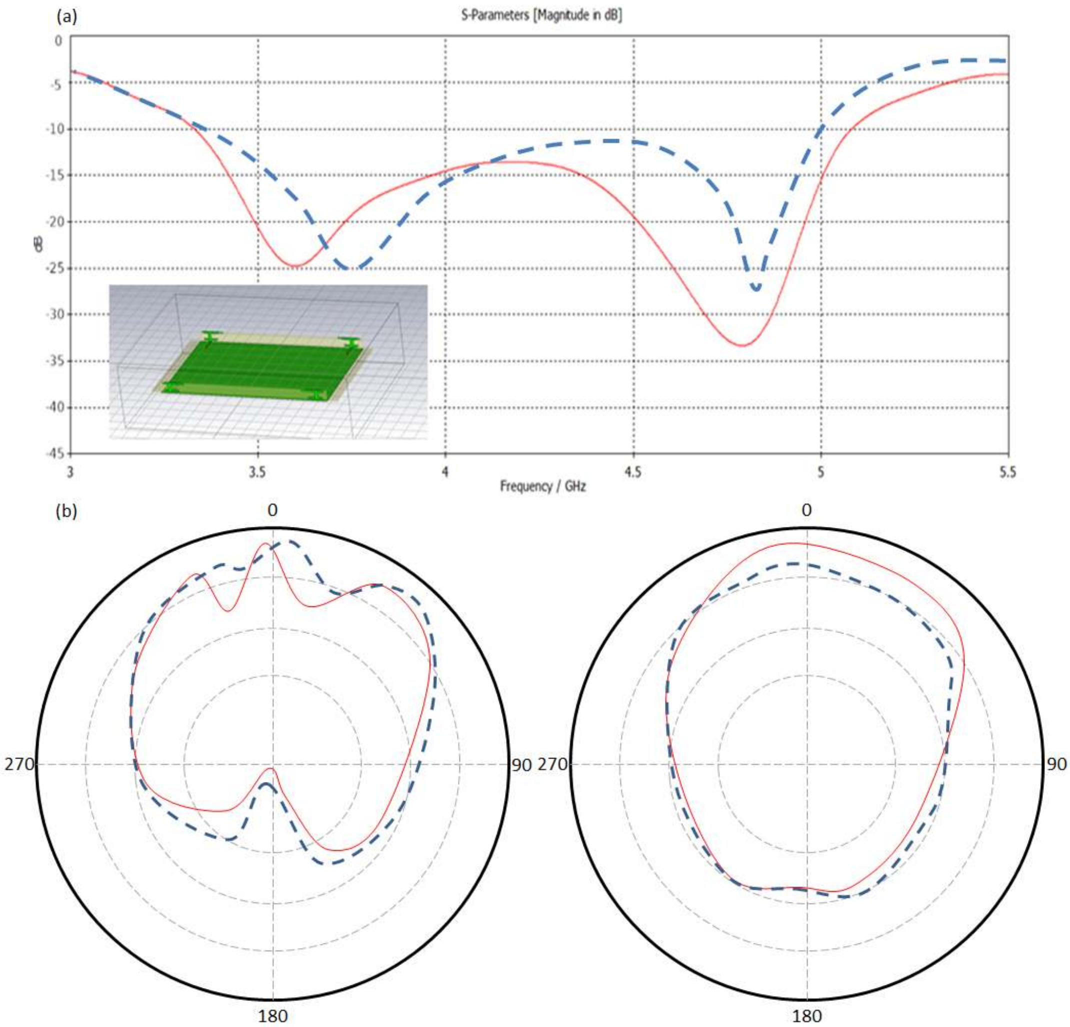

Figure 3.5: Antenna performance validation: (a) S_{11} and (b) radiation patterns. Note: the red line for CST MWS and blue line for HFSS

Finally, a comparison study in Table 3.1 is introduced to compare our proposed antenna performance with respect to other published results based on MIMO systems. From the comparison study, an attractive enhancement is achieved in the antenna performance in terms of gain, bandwidth, and size over other published results in the literature.

Table 3.1: Antenna performance with respect to the published results.

References	**Antenna array size**	**Frequency bandwidth/ GHz**	**Maximum Gain/ dBi**	**Coupling/ dB**	**Separation distance**
[41]	32.6×24 mm^2	2.8 (S_{11}≤-10)	2.1	-15	λ/3.2
[42]	62×62 mm^2	3.3-3.91 (S_{11}≤-10)	3.3	-16	λ/2.7
[43]	160×160 mm^2	3.38-3.95 (S_{11}≤-10)	4.9	-10	λ/4
[44]	66.7×48.6 mm^2	3.5 (S_{11}≤-10)	3.6	-18	λ/2.3
[45]	68.71×68.48 mm^2	3.5 (S_{11}≤-10)	4.2	-13	λ/4.3
[46]	133×133 mm^2	3.5 (S_{11}≤-10)	6.1	-19	λ/2.1
[47]	30×26 mm^2	2.8 (S_{11}≤-10)	4	-15	λ/3.4
[48]	50×110 mm^2	5.8 (S_{11}≤-10)	2.6	-10	λ/2.5
[49]	26×26 mm^2	5.8 (S_{11}≤-10)	5.5	-14	λ/2.3
[50]	50×50 mm^2	5.8 (S_{11}≤-10)	5.8	-15	λ/2.6
[51]	156×79 mm^2	3.4–3.6 (S_{11}≤-10)	5.1	-15	λ/8.6
[52]	150×80 mm^2	3.4-3.8, 5.15-5.925 (S_{11}≤-6)	6	-20	λ/10
[53]	150×80 mm^2	3.3-3.8	5.3	-20	λ/28
This work	13.4×6mm^2	3.3-5 (S_{11}≤-10)	5	-18	λ/11

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1. Conclusions

For the proposed antenna, four elements are placed on an FR4 substrate near each other as a single layer. The proposed study is devoted to simulating the return loss coefficients for each element and the isolation factor between them. The study examines the outcomes of modifying the element size and form geometrical parameters using HFSS simulation software and validated using CST software. Evaluating the antenna MIMO radiation patterns at different frequencies in the far field. The outcomes show that the suggested H-shaped MIMO antenna considerably enhanced the 5G terminal for MIMO antenna performance. At 3.75GHz, the S_{11} parameter plummeted to -25 dB, and at 4.85 GHz, it dropped to -26.5 dB, remaining less than -10 dB for the roughly 3.3GHz to 5 GHz frequency range to suit the entire NR bands. These findings show that the intended antenna is broad and suitable for 5G terminal usage. Overall, the study indicates that the performance of MIMO antenna arrays may be significantly enhanced by altering the geometry of the antenna components, which would enhance the performance of 5G terminals. Also, the antenna efficiency is found to be 88% at 3.8GHz with a maximum ECC of about 0.004 within the frequency range of interest. The maximum coupling between the antenna elements is found to be about -18dB over all the desired frequencies. Finally, the antenna performance is validated using two commercial HFSS and CSTMWS software packages.

4.2. Future Works

1. Multi-band Designs: Future works may focus on developing wideband MIMO antennas that can operate across multiple frequency bands, including both sub-6GHz and mmWave bands. Dual band designs capable of simultaneously supporting different frequency ranges will be of interest to

Accommodate diverse deployment scenarios and enable seamless connectivity.

2. Wideband Beamforming: Wideband MIMO antennas can benefit from advanced beamforming techniques that operate across a broader frequency range. Future research may explore adaptive algorithms and antenna architectures capable of efficient beamforming over wide bandwidths, thereby improving coverage, capacity, and link quality in 5G networks.
3. Compact and Low-profile Designs: Wideband MIMO antennas should be compact, low-profile, and easily integrated into various devices and infrastructure. Future works may focus on miniaturization techniques, innovative materials, and novel antenna structures to achieve wideband performance while maintaining small form factors, making them suitable for small cells, IoT devices, and other compact deployments.
4. Diversity Techniques: Wideband MIMO antennas can leverage diversity techniques to combat fading and improve signal reliability. Future research may explore advanced diversity schemes, such as polarization, spatial, and frequency diversity, to enhance performance in different propagation environments and combat the challenges associated with wideband transmission.
5. Efficiency and Energy Consumption: Future works will aim to enhance the efficiency of wideband MIMO antennas, considering radiation efficiency and power consumption. Efficient antenna designs can help reduce energy consumption and increase battery life in user devices, contributing to improved sustainability and user experience.
6. Massive Wideband MIMO: As 5G networks evolve towards massive MIMO deployments, future works may explore combining wideband and massive MIMO technologies. Research in this area will focus on developing large-scale antenna arrays capable of wideband operation to enhance network capacity and spectral efficiency further.
7. Channel Modeling and Performance Evaluation: Accurate channel modelling and performance evaluation are critical for the design and optimization of wideband MIMO antenna systems. Future research will likely involve developing advanced channel models that accurately capture wideband characteristics and performance evaluation methodologies to assess the impact of wideband MIMO on system-level performance metrics.

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