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Design of Slotted Patch MIMO Antenna and Investigation of Antenna Parameters for Sub-6 5G Network

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Abstract

A "Multiple-input-multiple-output (MIMO)" antenna with dual band features is presented herein research work and is taken into consideration for the unlicensed National Information Infrastructure radio band (n77, n78, and n46). Simple single-patch MIMO antennas give way to two-element MIMO antennas through a gradual development process. Using circular slots on the main patches, two Microstrip antennas are integrated. The development of numerous band features also makes use of reduced ground. In order to attain excellent isolation, Rectangular Metallic Strip (RMS) is used. Given that it covers two important frequency bands, the proposed MIMO antenna offers a considerable advantage. With a 2.18 GHz total bandwidth, the antenna system resonates at 3.26 GHz and 5.4 GHz. A 1.6 mm thick FR4 substrate was used in the antenna's design. A 8.2 mm feed line with an inset feed is employed, and a specifically designed SMA connector with perfect electrical conductor (PEC) and Teflon is used for simulation purposes in order to enhance impedance matching. Radiation properties such as mean effective gain, envelope correction coefficient, reflection coefficient, and others are investigated and researched. Less than -10 dB is the value of both the isolation and the reflection coefficient, with the former being less than -30 dB. Having this two-element, smaller MIMO antenna is very beneficial for 5G applications.

Keywords: MIMO, n46, n77, n78, RMS.

Introduction

The most recent advancement in wireless communication is the fifth-generation (5G) communication system, which promises to deliver high-speed data transfer, low latency, and boosted network efficiency (1). Because of its small size, low profile, and ease of integration with other circuit modules, the patch antenna is a great option. Antennas are essential to 5G systems, and one interesting option is the patch antenna (2). In 5G communication systems, multi-input multi-output (MIMO) technology is widely employed to advance the wireless channel's dependability, capability, and data transmission rate (3). The MIMO technique, widely used in 5G systems to boost channel capacity and throughput, suffers from performance issues due to mutual coupling between closely spaced antenna elements. Effective isolation techniques are crucial to mitigate this issue. A proposed hybrid decoupling technique, combining self-isolation and an orthogonal mode approach, significantly enhances isolation for high-order MIMO applications in 5G mobile systems (4). The rapid shrinking of Radio Frequency (RF) systems has led to an increasing number of studies devoted to the compactness of multi-antenna systems. The radiation properties are distorted as a result of the intense mutual contact caused by the small size of the antenna components. Numerous studies have been carried out to identify effective plans of action and methods that can reduce mutual coupling and improve the compactness of a MIMO antenna system's antenna elements. (5-7). These days, the fourth-generation (4G) technology that is now accessible provides enough bandwidth and data rate to meet the needs of the telecoms industry (8). However, the quantity of data traffic created by the many social apps, smart cities, video streaming, and internet of things (IOTs), cloud services, and other similar applications would surpass the capability of 4G infrastructure (9). Future communications will also be distinguished by better connections, lower latency, and lower energy use. These four features will be crucial as, in comparison to 4G, 5G and the next 6G technologies offer better capabilities. A greater data rate, wider bandwidth, higher output, enhanced capability, wide connectivity, reduced

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latency, more stable linking, and more frequency bands are a few of these attributes. Multiband multiple-input multiple-output, or MIMO, antennas are the most frequently selected way out for 5G mobile applications (10). The MIMO antenna system with slots on radiating, parasitic, and reduced ground elements is presented in this study. The return loss, radiation characteristics, reduced mutual coupling, mean effective gain, envelope correlation coefficient, and channel capacity loss of this system are assessed (11). MIMO antenna systems have the possibility of random phase excitations happening in any port. The antenna's impedance matching and mutual coupling are significantly impacted as a result of this (12). An evaluation of the reflection coefficient of MIMO systems exposed to random phase interactions is carried out using a computation called the total active reflection coefficient (TARC). To calculate the total reflected power ratio, take the square root of the total reflected power and divide it by the total generated power. Researchers (13) designed a substrate integrated waveguide rectangular ring slot (SIW RRS) antenna with a low profile, a broad bandwidth, and a half-TE 110 cavity mode and TM patch mode. The design process includes examining the bandwidth impacts of SIW cavities. An 8-element MIMO antenna is also constructed because the SIW RRS antenna is self-isolating. The antenna is appealing to MIMO due to its extensive bandwidth and good gain (14). The antenna has a modest profile and four FR-4 substrate-built components. In order to increase antenna gain, this antenna reduces the coupling between its frequency selective surface (FSS) and antenna elements by using a metasurface based on superstrate. A superstrate-based metasurface, positioned 15 mm below the antenna, is placed atop the proposed antenna. A concentric circular ring on a single-layered FR4 substrate makes up the FSS structure (15). A compact, efficient diamond-shaped MIMO antenna system is being designed for 5G wireless communications. Maximum diversity gain is 10 dB, envelope correlation coefficient is low, and elements are isolated (16). This novel system not only addresses the demand for enhanced performance but also exhibits remarkable attributes such as wide bandwidth, superior efficiency, and compact size, rendering it a promising candidate for the evolving landscape of millimeter-wave communication (17). The demand for high-speed, reliable, and ubiquitous wireless connectivity continues to surge with the advent of next-generation technologies such as 5G. In this context, the design and implementation of efficient antenna systems tailored for 5G-enabled devices, particularly smartphones, are paramount. Introduces a novel Dual-Polarized Wideband MIMO Antenna System designed to function in the N77 band, a crucial frequency range for 5G deployments (18). A novel technique for improving isolation in a Two-Element MIMO Antenna through the integration of electromagnetic metamaterial. By leveraging the unique properties of metamaterial, such as negative permeability and permittivity, the proposed method offers significant enhancements in isolation between antenna elements (19). By virtue of the fact that it is dependent on the radiation efficiency and impedance matching under the random phase excitation, higher mutual coupling has the potential to significantly reduce TARC. Antenna design is critical for enhancing the efficiency and reliability of 5G communication systems by optimizing signal propagation, enabling massive MIMO technology, and facilitating precise beamforming. It improves spectrum utilization and energy efficiency, supports the integration of millimeter-wave frequencies, and ensures robust service for diverse 5G applications. Moreover, advanced antenna designs prepare networks for future technological advancements, making them essential for achieving the high performance and dependability that 5G promises.

Policymakers have multiple levers at their disposal to promote the growth and use of sophisticated antenna technologies. Through strategic regulation, financial incentives, infrastructure support, and international collaboration, they can create an environment that fosters innovation, accelerates deployment, and ensures the widespread adoption of these critical technologies. The study is crucial for the development and implementation of 5G technology, which promises high speed, low latency, and extensive connectivity. It offers valuable insights and innovations to address technical challenges and optimize 5G deployment. Key impacts include: Improving network performance for applications like autonomous vehicles, smart cities, and IoT, introducing methods for efficient spectrum use to meet growing data demands, advancing signal propagation, network architecture, and energy consumption for robust and sustainable 5G networks, enabling faster and more cost-effective rollouts, benefiting industries, consumers, and governments with new services and business opportunities, strengthening a nation's or organization's edge in the global 5G race.

Methodology

High Frequency Structure Simulator, or HFSS for short, is used for both three-dimensional electromagnetic modeling and MIMO antenna design. The frequency range of the intended applications, the number of antenna components required for the design, the bandwidth requirements, and the isolation loss requirements must all be ascertained. Place the single element on the selected substrate material to start the antenna design process. Next, adjust the result to fulfill the bandwidth needs.

Single Antenna Design

To design this MIMO antenna, single antenna is considered using FR4 substrate is selected with thickness of 1.6 mm. To determine various geometrical parameters following expressions are used. Obtained values are optimized for the desired results. Single Microstrip patch antenna is designed of overall size 26 x 26 mm^2 with radiating element of 18 x 16 mm^2 as shown in Figure 1. In this design, antenna is fed using 50 ohm SMA connector keeping view of the realistic SMA connector using materials like Teflon and pec having relative permittivity of 2.1 and 1 respectively. It shown the good results compared to traditional wave port design using simulation software.

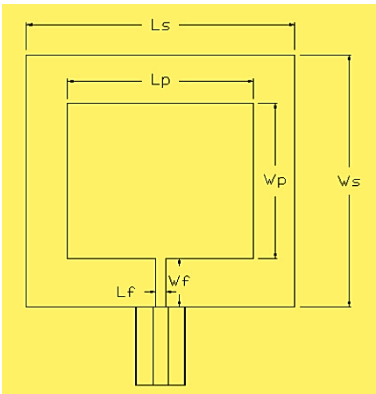


Figure 1: Geometrical Representation of Single Antenna (Antenna 1)

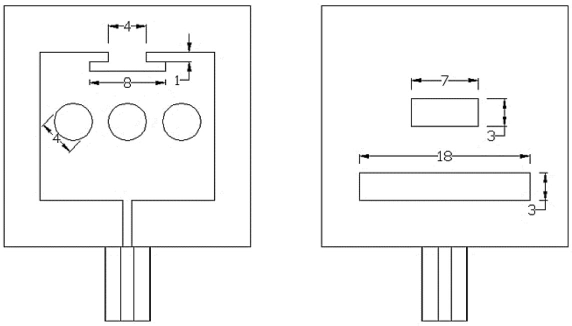


Figure 2: Modified Design of Single Antenna (Antenna 2)

This design is simulated using HFSS and its return loss is obtained -10.41 dB at 4.29 GHz, VSWR 1.86. Further modifications gave been implemented in this design using circular and rectangular slots on radiating element. Defected ground using slots on ground is also implemented to this design as shown in Figure 2.

This design has resonated at 3.63 GHz with bandwidth of 760 MHz, return loss of -29.86 dB and VSWR 1.06. Implementation of rectangular and circular slots, operating frequency is changed from 4.29 GHz to 3.6 GHz. Return loss and VSWR are compared and shown in Figure 3.

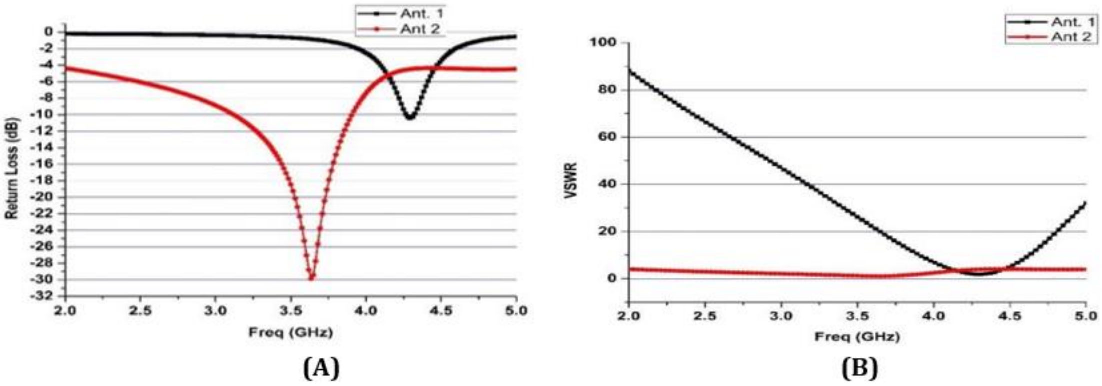


Figure 3: (A) Return Loss and (B) VSWR of Antenna 1 and 2

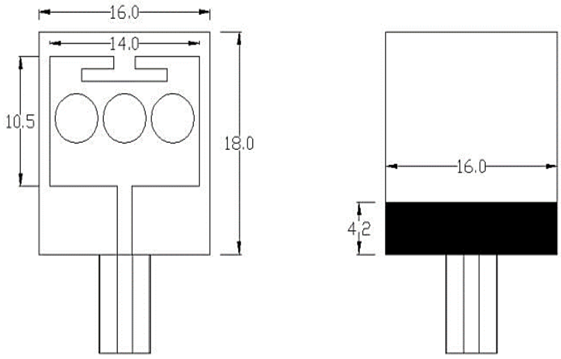


Figure 4: Antenna 3 with Reduced Ground

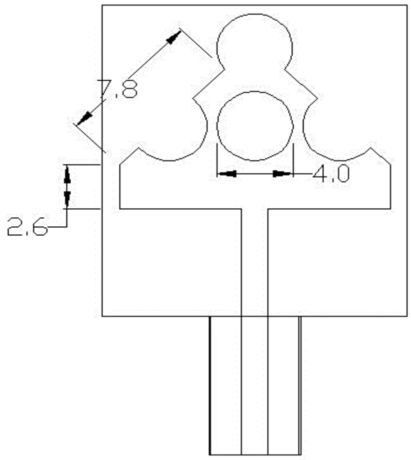
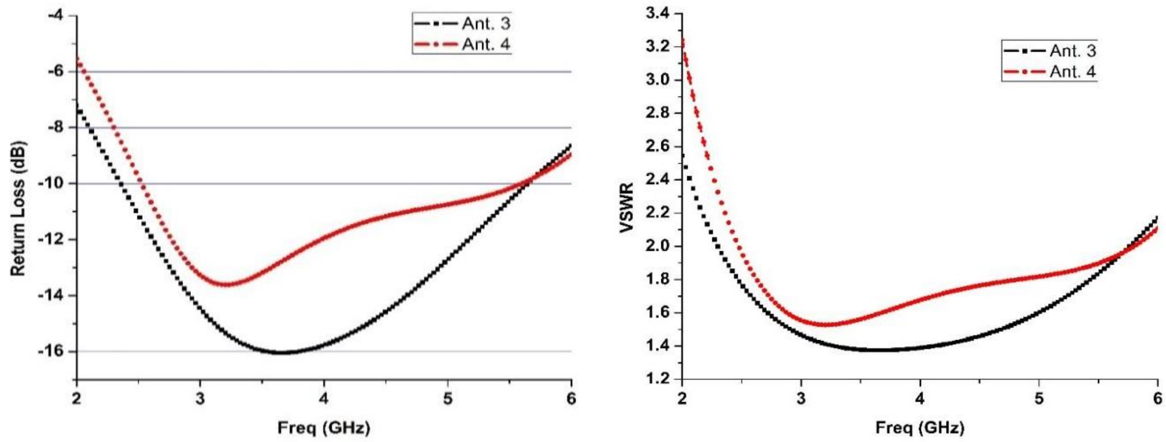


Figure 5: Antenna 4 with Triangular Antenna with Punch Holes

Further this design is modified and achieved size reduction up to 50% with partial ground as presented in Figure 4 which given the resonant frequency of 3.67 GHz and major improvement in bandwidth from 760 MHz to 3.320 GHz. Radiating element is reduced to triangular shape from rectangular shape. Also punch holes are introduced on the edges of radiating element presented in Figure 5. Hence, radiating area is reduced of antenna. This helps to broaden antenna's operating bandwidth. It can be observed plot Figure 6. But it is detected that it affects the radiation of the antenna. Return loss obtained is -15.24 dB at 3.65 GHz with enhanced bandwidth of 3.10 GHz, plots are demonstrated in Figure 6.

This work primarily aims to cover the C-Band through the construction of a MIMO antenna. Slotted MIMO patch antennas offer enhanced bandwidth, improved impedance matching, compact size, better isolation, design flexibility, multiband operation, and increased gain and directivity. These advantages make them ideal for modern communication systems. However, they also present challenges such as complex design processes, precision fabrication requirements, potential for increased mutual coupling, intricate simulation and testing, material limitations, performance trade-offs, and environmental sensitivity. To fully benefit from their advantages, careful design, advanced simulation, and thorough testing are essential. As a result, the first step in designing the suggested MIMO antenna is to align the individual antennas in overturn fashion. The basic mode, or first configuration, of the advised MIMO antenna is revealed in Figure 7. This clearly demonstrates that the MIMO antenna has two individual terminals. Microstrip feed lines and radiators in the shape of triangle having punch holes with reduced ground plane at the end of feed line and square shape with removed corners and slots below the radiator. Centrally placed Rectangular Strip Material (RSM) of dimensions 18 mm x 3.00 improved the isolation between elements. The critical separation between the radiating elements is achieved by positioning each antenna 43.00 mm center to center distance. This construction uses a FR4 substrate that is 1.6 mm. The slotted patch antenna design for a two-element MIMO system is chosen for its numerous advantages, including enhanced bandwidth and impedance matching, compact size, improved isolation, design flexibility, multiband operation, and better gain. These benefits stem from the altered current distribution and multiple resonances introduced by the slots, which allow for optimized performance in terms of signal quality, data rates, and directional radiation patterns. Additionally, slotted patch antennas are cost-effective and easy to fabricate, making them ideal for modern communication systems where space and efficiency are critical.



(A) (B)

Figure 6: Simulation Results of (A) Return Loss (B) VSWR of Antenna3 and 4

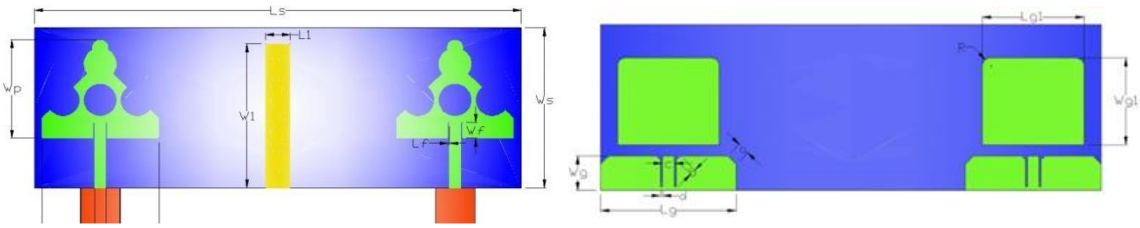

(A) (B)

Figure 7: 2 x 1 MIMO Antenna Configuration (A) Front, (B) Back Profile

Antenna Geometry

The depicted antenna system features a dual-antenna configuration aimed at improving MIMO performance for high-order 5G applications. The design incorporates two distinct antenna elements, each positioned symmetrically about a central axis, and these parameters are shown in Figure 7. Key geometric parameters include:

- Ls (Length of Substrate): The total length of the substrate housing both antenna elements.
- Lp (Length of Patch): The length of each antenna patch element.

- Ws (Width of Substrate): The width of the substrate.
- Wp (Width of Patch): The width of each antenna patch element.
- L1 (Length of Isolation Structure): The length of the central isolation structure, likely designed to reduce mutual coupling between the antenna elements.

The green sections represent the antenna patches, while the yellow section indicates an isolation structure aimed at reducing mutual coupling, thereby improving isolation and enhancing overall performance.

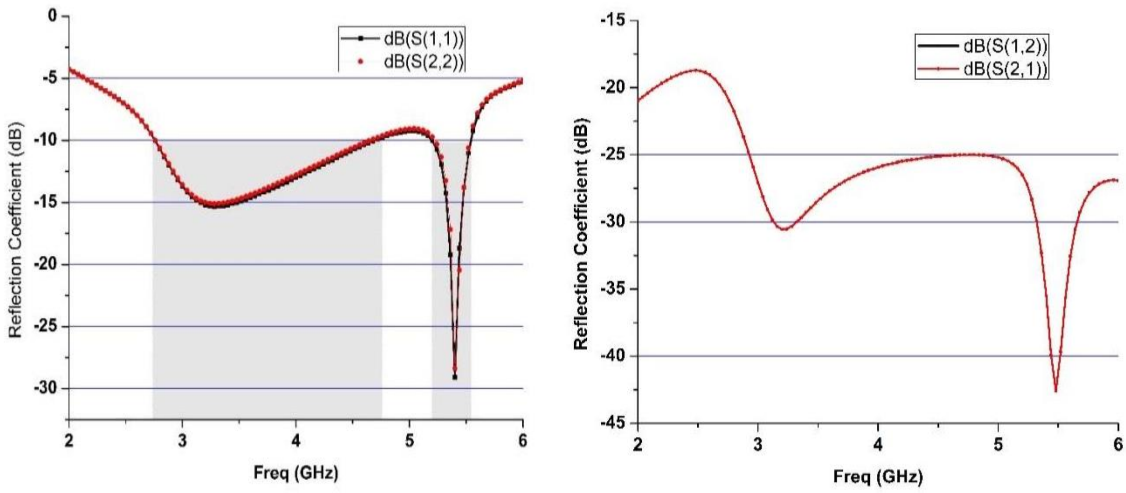
Table 1: Parameter Values of The Projected Two Elements MIMO Antenna

Parameter	Value (mm)	Parameter	Value (mm)
Ls	59.00	Ws	20.00
Lp	14.20	Wp	12.30
L1	3.00	W1	18.00
Lg	16.00	Wg	4.20
Lg1	12.00	Wg1	10.50
a	1.41	b	0.71
c	1.40	d	0.20
R	1.00		

The design is carefully crafted to balance the need for compactness (suitable for mobile devices) and high performance (necessary for effective MIMO operation). As per the table 1the substrate dimensions (Ls and Ws) provide a foundation for the antenna elements and isolation structures. The patch dimensions (Lp and Wp) are optimized for resonant frequency and bandwidth requirements, while the isolation structure dimensions (L1 and W1) are crucial for minimizing mutual coupling. The ground plane dimensions (Lg, Wg, Lg1, and Wg1) help stabilize the antenna's performance, ensuring good impedance matching and radiation efficiency. The additional geometrical parameters (a, b, c, d, and R) fine-tune the antenna's electromagnetic characteristics, potentially affecting factors like return loss, bandwidth, and radiation pattern.

Results

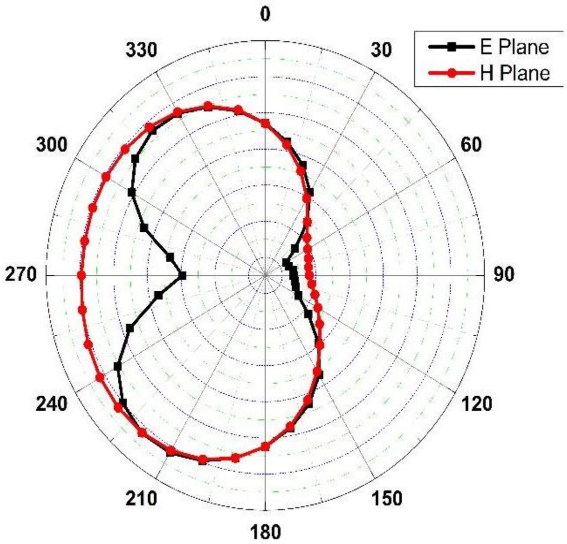
Designed MIMO antenna is resonating in two bands, i.e., 3.28 and 5.4 GHz. Moreover, the maximum reflection coefficient of antenna is −15.33 dB and – 29.11 dB which should minimum -10 dB and the isolation of antenna is −30.53 dB and −42.59 dB (< -15 dB) at operating frequencies 3.28 and 5.4 GHz respectively these plots are demonstrated in Figure. 8. This designed 2 element MIMO antenna is having dual band nature and operates from 2.75 GHz to 4.64 GHz and 5.24 GHz to 5.53 GHz. Thus covers n77, n78 (C-Band) and n46 (unlicensed National Information Infrastructure radio band) frequency bands. Overall bandwidth obtained through this system is 2.18 GHz.



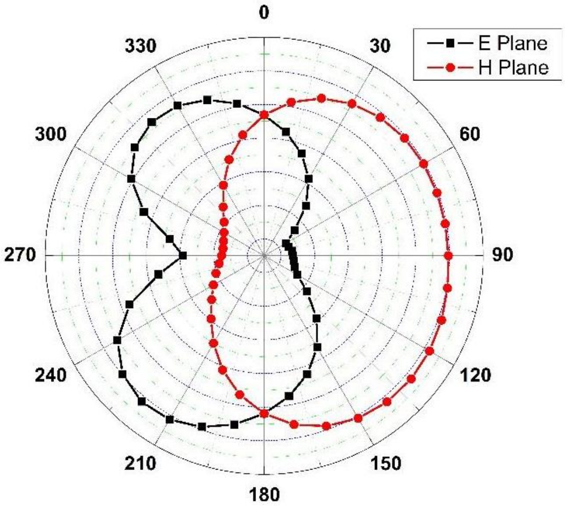
(A) (B)

Figure 8: Reflection Coefficients (A) S11and S22, (B) S12 and S21

HFSS software is used to design and analyzing the proposed antenna. The simulated reflection coefficients, radiation pattern for the E and H planes, or far-field radiation properties are exhibited using HFSS. Plots of the radiation patterns for both ports are shown. Since the pattern in the H-plane reflects the trace, the E-plane radiation gives similar results for both ports. These plots are demonstrated in Figure 9.



(A)



(B)

Figure 9: E-plane and H-plane Patterns for (A) Port 1 (B) Port 2

Diversity Performances

Diversity performance indicators are an extremely significant feature to take into consideration when analyzing the performance of a MIMO antenna. When doing an evaluation of the efficacy of MIMO antennas, it is extremely necessary that the DG and ECC properties be performed to the highest possible standard. Utilizing S-parameters and 3-D radiations, one may ascertain ECC values. Major parameters of MIMO antenna like "*Envelop Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), Mean Effective Gain (MEG) and Channel Capacity Loss (CCL)"* (20) are studied and presented here

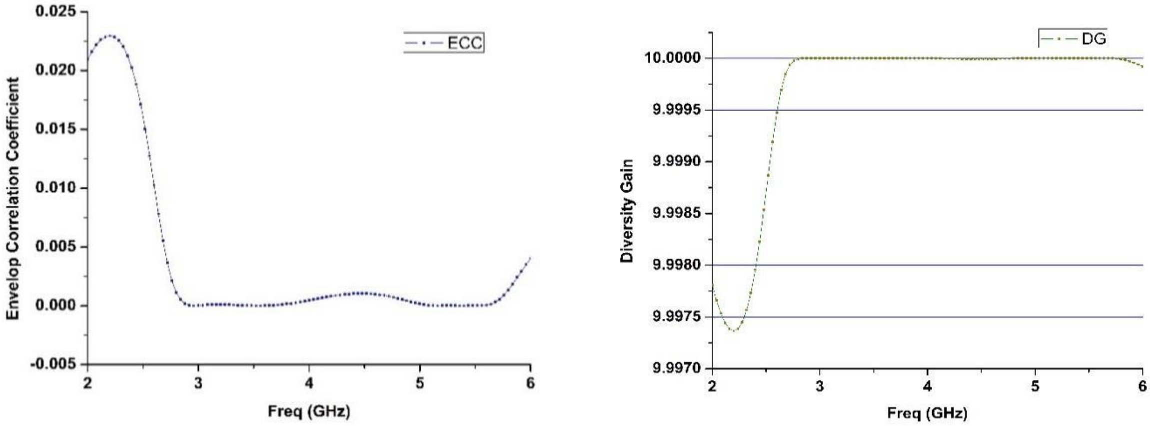
$$ECC = \frac{|S_{ii}*S_{ij}+S_{ji}*S_{jj}|^2}{(1-|S_{ii}|^2-|S_{ji}|^2)(1-|S_{jj}|^2-|S_{ij}|^2)} \quad ....[1]$$

In this equation, *Sii* and *Sjj* represent the coefficients of reflection, whereas *Sij* and *Sjj* represent the coefficients of transmission. It was discovered that the ECC is somewhere around 0.001, which is significantly lower than the maximum allowable value for a MIMO antenna. Plot of the ECC is displayed in Figure 10(a). In Figure 10(b), the plot of diversity gain is displayed. Diversity Gain is connected to ECC, which is greater than 9.99 dB.

$$DG = 10\sqrt{1-ECC^2} \quad ....[2]$$

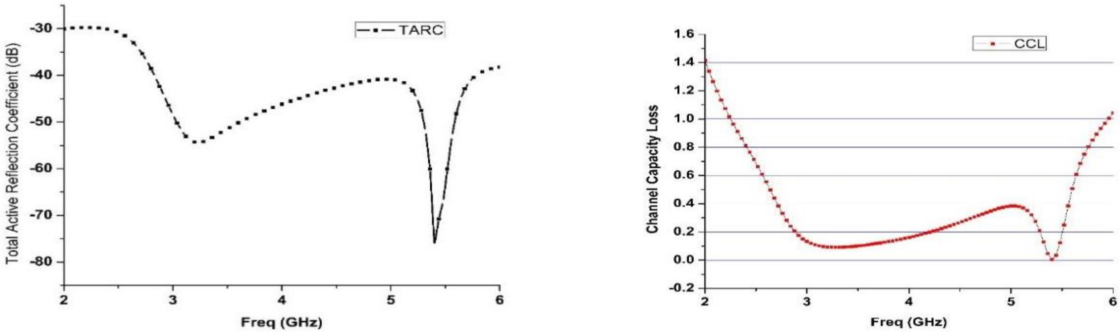
The total active reflection coefficient, also recognized as TARC, is a supplementary metric that is utilized in the process of defining the diversity efficacy of MIMO architectures. It is anticipated that a TARC value of less than 0 dB will be present in order for a MIMO to function appropriately

$$TARC = \sqrt{\frac{(S_{11}+S_{12})^2+(S_{22}+S_{21})^2}{2}} \quad .... [3]$$



(A) (B)

Figure 10: (A) Plot for ECC and (B) DG



(A) (B)

Figure 11: Plots for (A) TARC and (B) CCL

CCL is a measurement that determines whether or not the information or signal can be transmitted across the channel path without becoming disrupted in any way. Consequently, it is a very helpful aspect to test the quality of a MIMO antenna and the components that are associated with it. It is possible to compute CCL by utilizing the equation [4 – 6] (20).

$$CCL = -log_2 \, det(a) \quad .... [4]$$

where a is matrix of correlation.

$$a^R = (\rho_{11} \, \rho_{12} \, \rho_{21} \, \rho_{22}) \quad .... [5]$$

$$\rho_{ii} = 1 - (|S_{ii}|^2 + |S_{ij}|^2), and$$

$$\rho_{ij} = -(s_{ii} * s_{ij} + s_{ij} * s_{jj}),$$

$$for \;\; i \; and \; j = \; 1 \; and \; 2 \quad .... [6]$$

Discussion

The designed MIMO antenna resonates at two frequencies, 3.28 GHz and 5.4 GHz. It achieves maximum reflection coefficients of -15.33 dB and -29.11 dB, both well below the required minimum of -10 dB. The antenna's isolation is -30.53 dB and -42.59 dB at these operating frequencies, exceeding the required isolation threshold of -15 dB. These characteristics are illustrated in Figure 8. This dual-band, two-element MIMO antenna operates over the frequency ranges of 2.75 GHz to 4.64 GHz and 5.24 GHz to 5.53 GHz. It can be seen to determine that the CCL is lower than the practical specified limit of 0.6 bits/sec/Hz, and that the lowest possible amount of channel capacity loss (CCL) is accomplished within the operational bands of the projected MIMO antenna, which are depicted in Figure 11. The design of a small, dual-band planar MIMO antenna with a FR-4 substrate is presented in this study. The suggested antenna reduces surface waves and enhances inter-element isolation by using a 1 × 2 array with a Resonant Slot Mode (RSM). With a low profile and compact dimensions, the antenna is ideal for 5G n78/79 channel applications. S-parameters, VSWR, Diversity Gain (DG), Total Active Reflection Coefficient (TARC), Envelope Correlation Coefficient (ECC), and Channel Capacity Loss (CCL) are some of the metrics used to evaluate its performance. Interestingly, at 0.0002, the ECC value is remarkably low.

Table 2: Performance Comparison Between the Proposed Antenna Design and Existing Designs Documented in the Literature

Ref.No.	No. of Ports	Freq. (GHz)	BW (GHz)	S11 (dB)	Isolation (dB)	ECC	TARC (dB)	DG	CCL	Size (mm)	Technique used
(4)	10	3.5	-	-17	-19	<0.00001	<10	>9.97	<0.08	150 x 75	Antenna placed perpendicular to substrate
(5)	4	4.5-5.1	0.6	-32	-20	<0.01	-	9.99	-	56 x 56	Slots on patch and DGS
(6)	4	3.48 – 3.87	0.390	<-20	<-20	<0.01	-	-	-	150 x 75	Slots on patch and DGS
(8)	2	3.732 and 4.5993	0.284	<-40.83	-22.13	-	-	-	-	40 x 20	F-shaped antenna
(18)	4	3.25 – 4.49	1.24	-	-14.5	<0.025	-	>9.95	-	150 x 75	DGS and Slots on ground
Proposed design	2	2.75 – 4.64 and 5.24 – 5.53	2.18	-15.33 and -29.11	-30.53 and -42.59	<0.001	<-50	>9.99	<0.05	59 x 20	Slotted antenna and DGS

Conclusion

Efforts were made to enhance a MIMO antenna's performance and achieve the desired frequency by reducing the initial design's size by 50%. The goal was to create a compact dual-band planar MIMO antenna using an FR-4 substrate for C-Band frequencies. This design employs two elements with an additional resonant structure mechanism (RSM) at the center to prevent surface waves and improve isolation. The resultant antenna is appropriate for 5G n78/79 channels and has a low profile. Metrics including S-parameters, VSWR, diversity gain, TARC, ECC, and CCL were used to verify its performance. Excellent isolation is shown by the extraordinarily low ECC value of 0.0002. Because MIMO antennas increase data throughput and reliability, they are essential to 5G. Techniques like as substrate integrated waveguides, artificial magnetic conductors, or cavities between the patch and ground can all be further optimized for increased gain.

Abbreviations

MIMO: Multiple-Input-Multiple-Output
RMS: Rectangular Metallic Strip
PEC: Perfect Electrical Conductor
IOT: Internet of Things
ECC: Envelope Correlation Coefficient
DG: Diversity Gain
CCL: Channel Capacity Loss
TARC: Total Active Reflection Coefficient
HFSS: High-Frequency Structure Simulator
VSWR: Voltage Standing Wave Ratio

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Nil.

Author Contributions

All the authors have contributed to complete this work.

Conflict of Interest

The authors declare no conflict of interest.

Ethics Approval

Not applicable.

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