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Designing a Dual band 4X4 MIMO Antenna for Optimized Performance in 5G Mobile Devices

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ABSTRACT
The advent of 5G technology has ushered in a new era in wireless connectivity, giving rise to a need for advanced antennas that can fulfill the requirements of high-speed data transmission, low latency, and increased device connectivity. To address these demands, a specialized dual-band 4x4 Multi-Input Multi-Output antenna (MIMO) has been created for 5G connectivity in smartphones. Departing from traditional 5G antenna designs, this antenna features a distinct mounting approach through the base of the Printed Circuit Board (PCB), facilitating seamless integration into smartphones for 5G communications. Positioned perpendicularly to the circuit board's edge, it is tailored for use in popular full-screen cell phones. The design and development of this antenna, spanning frequencies from 3.3GHz to 3.6GHz and 4.8GHz to 5GHz, employed CST Studio software. Simulation results highlight promising performance metrics, with the module's reflection coefficient measuring below 6dB and isolation exceeding 12dB across the designated frequencies. The antenna showcases diverse test results, including a Directivity maximum of 4.65dB, Antenna gain maximum of 3.65dB, and Voltage Standing Wave Ratio (VSWR) ranging between 1.7-1.8 as a minimum. The Antenna Efficiency reaches a maximum of 86.6% over the designed frequencies. In addition, parameters such as the Envelope Correlation Coefficient (ECC) were simulated using MATLAB, yielding values of 0.41 at the frequency of 3.5GHz, dropping to 0.005 at 5GHz, respectively. These simulation outcomes affirm the antenna's capability to meet the demands of 5G applications, emphasizing its effectiveness in the ever-evolving landscape of wireless communication.

Keywords - 4X4 MIMO antenna, Directivity, Envelope Correlation Coefficient, Isolation, Printed circuit board

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I. INTRODUCTION

Multiple Input Multiple Output (MIMO) antennas stand out as a significant innovation in wireless communication, offering advancements in data transfer rates, system reliability, and spectral efficiency. MIMO [1] employs multiple antennas at both the transmitting and receiving ends of a communication system, enabling the simultaneous transmission and reception of multiple data streams. This technology optimizes spatial dimensions to enhance the overall performance of the system. At its core, MIMO exploits the diversity and spatial multiplexing features of multiple antennas to improve communication reliability and increase data throughput. Diversity uses multiple antennas to counteract fading and interference effects, while spatial multiplexing allows for the simultaneous transmission of independent data streams over the same frequency band.

MIMO antenna configurations vary, including 2X2, 4X4, and higher-order setups, indicating the number of antennas at both the transmitter and receiver. Design considerations for MIMO antennas, such as placement, spacing, and polarization, are critical for achieving optimal performance. MIMO technology is widely applied in modern wireless communication standards, encompassing 4G LTE and 5G [2] linkages, Wi-Fi, and other broadband communication systems. Through the capabilities of MIMO antennas, these systems attain higher data rates, improved signal quality, and overall enhanced network efficiency.

When a wireless communication system utilizes a single antenna for both transmitting (Tx) and receiving (Rx), it named as 1X1 MIMO antenna for which specific limitations should be considered [3]. These limitations are as follows:

- The system's inability to fully exploit spatial diversity, given the presence of only one antenna at both ends, hinders its capacity to mitigate signal fading and enhance reliability.
- Reduced data throughput arises from the absence of multiple antennas for simultaneous data transmission and reception, as observed in higher-order MIMO configurations.
- In comparison to MIMO systems equipped with multiple antennas, a single-antenna configuration may provide limited coverage and a constrained communication range.
- Higher-order MIMO configurations generally offer enhanced resistance to interference, whereas a single-antenna setup may compromise resistance to external disruptions.
- In environments characterized by reflection, scattering, or multipath propagation, a single-antenna system may face challenges in maintaining robust communication.

Recognizing and addressing these limitations is crucial when contemplating the deployment of a wireless communication system utilizing a single antenna for both transmission and reception.

Involving two antennas at both transmission and reception ends, a 2X2 MIMO [4] system, this enhances performance compared to a single-antenna system but presents certain limitations:

- Implementing a 2X2 MIMO system introduces added hardware and signal processing complexity, leading to increased costs compared to a single-antenna system. This heightened complexity may pose constraints in applications with budget considerations.
- The deployment of multiple antennas, even in a 2X2 configuration, may necessitate more physical space, creating challenges for integration into devices with restricted dimensions.
- Despite attempts to alleviate interference, the presence of multiple antennas in 2X2 MIMO may heighten susceptibility to co-channel interference, especially in densely populated wireless environments.
- While 2X2 MIMO facilitates the simultaneous transmission of two independent data streams, the potential spatial multiplexing gain is less compared to higher-order MIMO configurations. This limitation may impact achievable data rates.
- Achieving optimal performance in MIMO systems requires accurate knowledge of channel state information. Obtaining and maintaining this information can be challenging, particularly in dynamic and rapidly changing wireless settings.
- While 2X2 MIMO provides some diversity gain, its effectiveness in mitigating fading and improving reliability may be less pronounced than in higher-order MIMO configurations with more antennas.

These limitations are inherent to the 2X2 MIMO setup and should be considered during the design and deployment of wireless communication systems. The choice of MIMO configuration should align with the specific requirements and constraints of the given application or network.

To overcome the limitations of 1X1 and 2X2 MIMO antennas [5], a proposed solution involves introducing a 4X4 MIMO antenna designed to operate at dual-band frequencies, specifically spanning from 3.3GHz to 3.6GHz and 4.8GHz to 5GHz. The key objectives of this proposed antenna design are as follows:

1. *Achieving Isolation of 12dB:* Enhancing isolation between antenna elements is crucial for minimizing interference and crosstalk, ultimately contributing to improved system performance.
2. *Ensuring Envelope Correlation Coefficient Below 0.3*: Maintaining a low envelope correlation coefficient signifies reduced correlation between signals received by different antennas, promoting diversity and mitigating the effects of signal fading.
3. *Keeping Reflection Coefficient Below 6dB*: Maintaining a low reflection coefficient is essential for efficient power transfer between the antenna and the transmission line, optimizing signal transmission.
4. *Providing High Gain:* The antenna design aims to deliver high gain, contributing to increased signal strength and coverage. This is particularly important for ensuring reliable communication across various environments.

By incorporating these specifications into the design, the 4x4 MIMO antenna [6] aims to elevate the overall performance of wireless communication systems, addressing the limitations associated with smaller MIMO configurations. This approach aligns with the increasing demand for higher data rates, enhanced reliability, and greater capacity in wireless communication systems.

II. RESEARCH METHOD

MIMO technology stands as a crucial facilitator in contemporary wireless communication systems, revolutionizing performance by incorporating multiple antennas [7] at both the transmitting and receiving ends. Its core aim is to improve communication by simultaneously sending multiple data streams, thus increasing both data throughput and reliability. This objective is directed towards an overall enhancement in the effectiveness and reliability of wireless communications

In the context of MIMO, dual-band antennas [8] constitute a specific category engineered to operate seamlessly across two distinct frequency bands, enhancing flexibility, capacity and performance. This adaptability directly addresses current challenges in wireless communication, optimizing data throughput, reliability, and overall system performance. Additionally, this versatility enables their application across a broad spectrum of wireless communication standards, including Wi-Fi, cellular networks, and various other wireless communication systems.

2.1 Proposed antenna design using CST studio software

Designing dual-band MIMO antennas involves meticulous attention to physical characteristics to guarantee optimal performance across both frequency bands. The antenna design is created using CST Studio software, custom-tailored for the PCB layout to meet the demands of contemporary ultra-smartphones. This antenna configuration excels in operation within the frequency ranges of 3.3 - 3.6 GHz and 4.8 - 5 GHz. The system circuit board is meticulously designed, featuring dimensions of 130mm x 74mm. The board employs an FR-4lossy material for its substrate, characterized by a slender thickness of 0.8mm and a low loss tangent of 0.02. In Figure1(a), focusing on a single antenna among the four, the edge frame is consistently maintained at a height of 5mm, while the side frames cover an area measuring 3.9mm x 17mm. Simultaneously, Figure 1(b) showcases the strategic placement of an L-shaped stub at the back, serving as the radiating element for high-frequency impedance matching. The anticipated S-parameters are expected to register below -6dB.

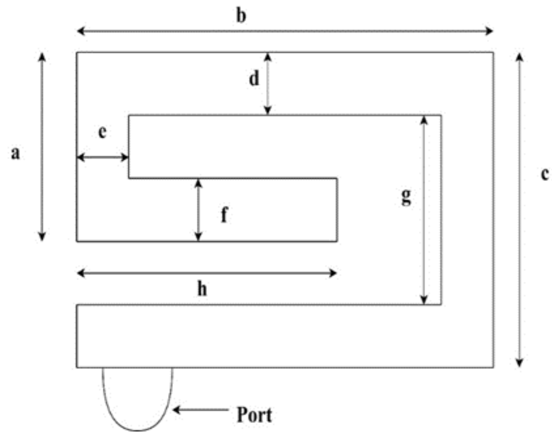

Fig. 1(a) Antenna element model Main view

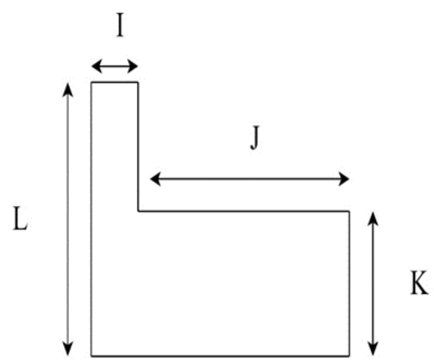

Fig. 1(b) Antenna element model Rear view

Table 1 presents the dimensions for both the main view and rear view of the individual antenna model, and these dimensions are consistent for all the remaining antennas in the set.

Table 1 Dimensions of Antenna Model Main view and Rear view

Dimensions of Main view of antenna element		Dimensions of Rear view of antenna element	
Parameters	Dimensions	Parameters	Dimensions
a	2.5 mm	L	4.2mm
b	17.7 mm		
c	3.9 mm	I	1mm
d	1 mm		
e	1.5 mm	J	4.4mm
f	0.9 mm		
g	1.9 mm	K	2mm
h	10 mm		

The suggested 4x4 MIMO antenna comprises four antenna elements, each crafted with specified dimensions using CST Studio software. Figure 2 visually illustrates the corresponding designs of the antennas. The arrangement of each of the four antenna elements, created using CST Studio software, is illustrated in Figure 3.

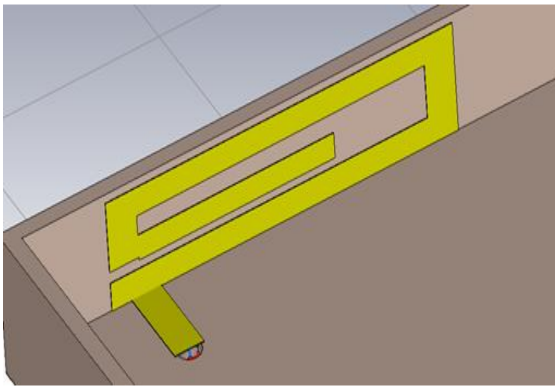

Fig. 2 4X4 Dual Band Antenna design using CST Studio Software

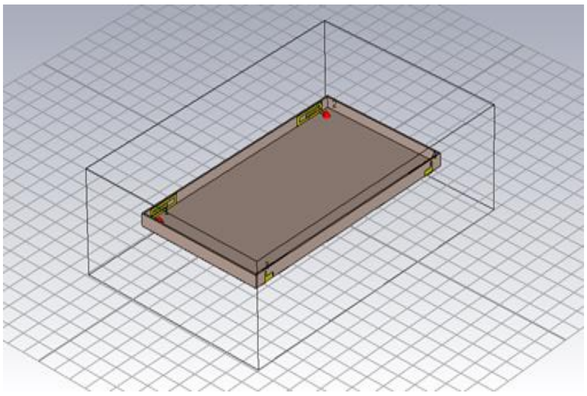

Fig. 3 Design of Single antenna

Following the design of the 4X4 MIMO antenna, featuring specific dimensions for both main view and rearview elements, each individual antenna within the 4x4 array is designated with a specific port- port 1, port 2, port 3, or port 4, as illustrated in Figure-4.

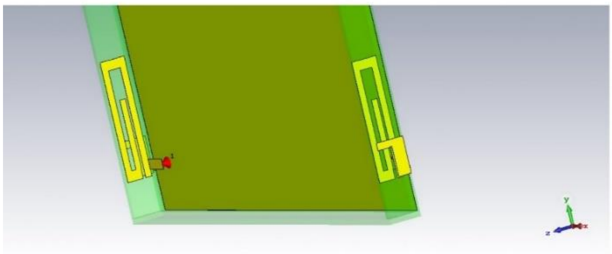

Fig. 4 Assigning Ports in Antenna design

2.2 Simulated Antenna Parameters

Simulated antenna parameters refer to the traits and performance measures of an antenna that are forecasted and scrutinized through computer simulations. Using dedicated software like CST Studio, these simulations predict values for various parameters including Antenna gain, S-parameters, Radiation efficiency, VSWR, Antenna efficiency and Envelope Correlation Coefficient (ECC). Essentially, these simulations provide a virtual evaluation of the antenna's characteristics and performance before any physical prototypes are created and tested.

VSWR: It stands for Voltage Standing Wave Ratio, is a metric utilized in RF (radio frequency) engineering to evaluate the effectiveness of power transmission within a transmission line or across an antenna system. This parameter plays a crucial role in determining the level of impedance matching between the source (such as a transmitter or signal generator) and the load (comprising the antenna or receiver). Lower VSWR values are preferred in RF systems to minimize reflections and optimize power transfer.

Directivity: Directivity is the measure of an antenna's ability to concentrate its radiation in a specific direction. It is often quantified as a ratio or in decibels, with higher values indicating better concentration of radiated power in a particular direction. Antennas with high directivity focus signals more precisely, while those with lower directivity have a broader coverage pattern. Antennas with high directivity are commonly employed in applications requiring directional beams, such as point-to-point communication, radar, or satellite communication.

Antenna Gain: The antenna gain is a metric indicating the antenna's capacity to concentrate or aim electromagnetic radiation toward a specific direction. It measures the extent to which the antenna amplifies the radiated power in the intended direction when compared to an isotropic radiator, which radiates uniformly in all directions. Gain plays a crucial role in the design of antennas and is commonly denoted in decibels (dB). Higher antenna gain is advantageous in applications such as communication and radar, providing stronger signals in desired directions. Importantly, antenna gain does not denote an increase in total radiated power; instead, it signifies the concentration of power in a specific direction.

Antenna Efficiency: Antenna efficiency (η) quantifies how well an antenna transforms the supplied power into radiated power. It is typically represented as a ratio or percentage and is directly related to the antenna's gain (G) and directivity (D). The connection between antenna efficiency, gain, and directivity can be expressed through the formula given by Eq. (1) as:

$$G = D \times \eta \qquad (1)$$

Where,

G is the antenna gain,
D is the antenna directivity, and
η is the antenna efficiency.

It illuminates the antenna's ability to concentrate radiated energy in a desired direction. A higher efficiency value signifies a more effective conversion of input power to radiated power, while lower efficiency suggests losses within the antenna system. In summary, antenna efficiency is determined by the ratio of gain to directivity, providing a measure of how efficiently the antenna utilizes input power for radiation.

Radiation Efficiency: Radiation efficiency is a metric that gauges how efficiently an antenna transforms electrical input power into radiated electromagnetic waves. It represents the antenna's effectiveness in minimizing losses and maximizing the power directed toward the desired direction. Radiation efficiency is expressed as a proportion or percentage, signifying the portion of input power utilized for effective radiation. Mathematically, it is characterized as the relationship between the power radiated by the antenna and the overall input power.

A higher radiation efficiency indicates that a greater percentage of the input power is efficiently converted into useful radiation, with fewer losses as heat or other non-radiative forms. This metric is crucial in antenna design, influencing the overall performance of the antenna system by ensuring that a significant portion of the input power contributes to effective radiation, leading to enhanced signal strength and communication reliability.

Total efficiency: In the realm of antenna design, total efficiency denotes the efficacy of the antenna system in converting input power into emitted electromagnetic waves, taking into consideration factors contributing to potential losses. It serves as a comprehensive metric encompassing both radiation efficiency and mismatch efficiency. Mismatch efficiency accounts for losses arising from impedance mismatches between the antenna and the transmission line or connected system, gauging the effectiveness of power transfer from the source to the antenna while minimizing reflections and substantial power losses. The formula for total efficiency in antenna design is often expressed as the product of radiation efficiency and mismatch efficiency, given by Eq. (2) as:

$$\text{Total efficiency} = \text{Radiation efficiency} * \text{Mismatch efficiency} \qquad (2)$$

Attaining a high total efficiency is a sought-after objective in antenna design, signaling that a significant proportion of input power is efficiently radiated as intended, with minimal losses attributable to impedance mismatches. Antenna designers actively work towards optimizing both radiation efficiency and mismatch efficiency to achieve the utmost total efficiency tailored to specific applications.

S-Parameters*:* S-parameters, or Scattering parameters, are essential coefficients used to describe the behavior of linear electrical networks, particularly in microwave and radio frequency (RF) applications. These coefficients offer valuable insights into how a device reacts to signals at its input and output ports, playing a crucial role in designing, analyzing, and optimizing RF components like amplifiers, filters, and antennas. Moreover, S-parameters measure the association between voltage and current waves at different ports of a network or device, arranged in a matrix known as the S-matrix.

The proposed antenna functions as a four-port device, and its performance is analyzed using scattering parameters (S-parameters). Utilizing these S-parameters, we can determine the reflection coefficients at each port of the antenna. The relationship between the reflection coefficients and the provided S-parameters is outlined as follows:

Reflection coefficient at Port 1 represented as Γ_1 given as $\Gamma_1 = s_{11}$

Reflection coefficient at Port 2 represented as Γ_2 given as $\Gamma_2 = s_{22}$

Reflection coefficient at Port 3 represented as Γ_3 given as $\Gamma_3 = s_{33}$

Reflection coefficient at Port 4 represented as Γ_4 given as $\Gamma_4 = s_{44}$

These relationships indicate that the reflection coefficient at each port is directly related to the corresponding diagonal element of the S-matrix.

Isolation: Isolation in the context of antennas pertains to the capacity of an antenna system to mitigate interference or crosstalk among its distinct ports or elements. It quantifies the extent to which signals at one part of the antenna system are shielded from signals at another part. The isolation [9] between ports in terms of the stimulated power and the power outgoing from all ports can be expressed as Eq. (3) as follows:

$$\text{Isolation} = 10 \log_{10}\left(\frac{P_{\text{stimulated}}}{P_{\text{outgoing from all ports}}}\right) \qquad (3)$$

Where,

$P_{\text{stimulated}}$ is the stimulated Power,

$P_{\text{outgoing from all ports}}$ is power outgoing from all ports

This formula quantifies the separation or isolation between different ports in an antenna system, considering the ratio of the power stimulated at one port to the total power outgoing from all ports. A higher isolation value indicates better separation and reduced interference between the ports.

Isolation, typically quantified in decibels (dB), reflects an increased level of separation. Higher isolation values are a sign of improved distancing, and this is especially beneficial in scenarios such as MIMO systems, where multiple antennas work together, and reducing interference enhances the overall efficiency of the system.

Envelope Correlation Coefficient: The envelope correlation coefficient (ECC) is a parameter in antenna engineering that measures the correlation between the envelopes of signals received or transmitted by two antenna elements. It quantifies how closely the amplitudes of these signals align with each other. The ECC ranges from 0 to 1, where 0 indicates no correlation, and 1 signifies perfect correlation. This coefficient is particularly relevant in multiple-input-multiple-output (MIMO) systems, where low ECC values are preferred to achieve diversity and enhance overall system performance by minimizing signal correlation between antennas.

III. RESULTS AND DISCUSSIONS

The 4X4 dual-band antenna has been created and simulated using CST Studio software. The associated simulated parameters are detailed below.

Figure 5 illustrates the VSWR measurements of the introduced antenna across various frequency ranges. Noteworthy observations include the VSWR nearing 2 within the 3.3GHz -3.6 GHz range, and consistently staying below 2 between 4.8GHz - 5 GHz, typically ranging from 1.7 to 1.8. This implies that the antenna performs well across a wide spectrum of frequencies.

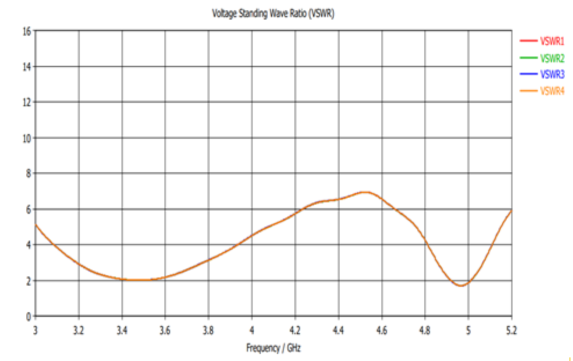

Fig. 5 Voltage Standing Wave Ratio of Dual band 4X4 MIMO antenna

Figure 6 depicts the Directivity measurements of the presented antenna across diverse frequency ranges. Notably, the peak directivity within the 3.3 GHz - 3.6 GHz range is 3.9 dB, specifically occurring at 3.6 GHz. Moreover, in the frequency span of 4.3 GHz - 4.6 GHz, the maximum directivities are observed at three distinct frequencies: 4.35 GHz, 4.4 GHz, and 4.45 GHz, with corresponding values of 4.4 dB, 4.65 dB, and 4.3 dB, respectively.

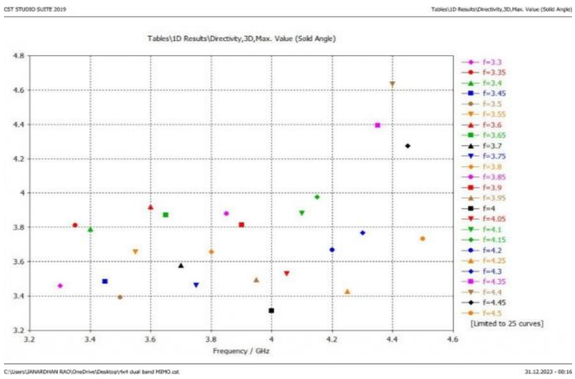

Fig.6 Directivity of Dual band 4X4 MIMO antenna

Figure 7 illustrates the Gain measurements for the presented antenna across a range of frequencies. Notably, the highest gain in the 3.3 GHz - 3.6 GHz range is 3.38 dB, specifically at 3.6 GHz. Furthermore, within the frequency span of 4.3 GHz - 4.6 GHz, the maximum gains occur at three distinct frequencies: 4.35 GHz, 4.4 GHz, and 4.45 GHz, with corresponding values of 3.35 dB, 3.65 dB, and 3.2 dB, respectively.

The efficiency of the suggested antenna can be computed using Equation (1). It is noteworthy that this antenna demonstrates an efficiency of 86.6% across the frequency range of 3.3 - 3.6GHz and a slightly lower efficiency of 78.49% within the frequency range of 4.8 - 5GHz.

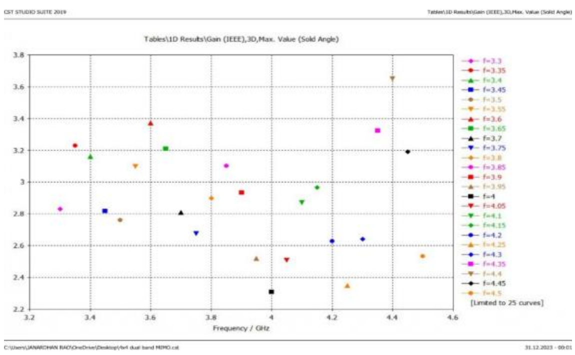

Fig. 7. Gain of Dual band 4X4 MIMO antenna

In Figure 8, the Radiation efficiencies and Total efficiencies for the proposed antenna are depicted across a spectrum of frequencies. Observations indicate that within the frequency range of 3.3 GHz - 3.6 GHz, the radiation efficiency ranges from -0.9dB to -1 dB, while the total efficiency is observed to be between -1.5 dB and -1.7 dB. In the frequency range of 4.8GHz - 5 GHz, the radiation efficiency is observed to range from -3.4dB to -4.6 dB, and the total efficiency falls within the range of -5dB to -5.5 Db

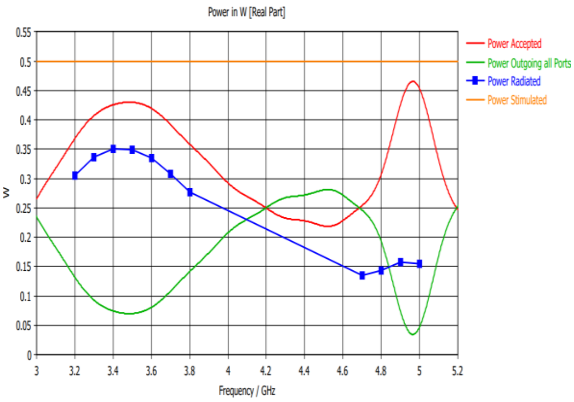

Fig. 8 Radiation efficiency and Total efficiency of Dual band 4X4 MIMO antenna

In Figure 9, the Scattering parameters for the proposed antenna are illustrated across a range of frequencies. The reflection coefficients associated with the reflection of signals are denoted as s_{11} for Port 1, s_{22} for Port 2, s_{33} for Port 3, and s_{44} for Port 4. It is noted that the reflection coefficients for Ports 2, 3, and 4 are all below -6 dB, indicating a relatively low reflection. For Port 1, the reflection coefficient falls within the range of 2dB - 4dB.

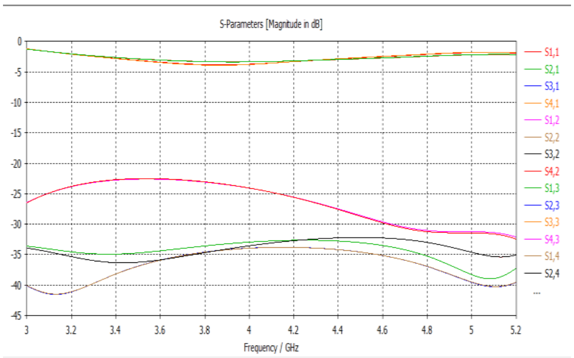

Fig. 9 Scattering parameters of Dual band 4X4 MIMO antenna

In Figure 10, the illustration showcases the powers of stimulation, radiation, acceptance, and outgoing power from all ports. By applying these power values to Equation 3, the isolation is computed. Notably, the highest isolation of 12.041 dB is observed at a frequency of 5 GHz, and at a frequency of 3.6 GHz, the isolation is measured at 9.2 dB

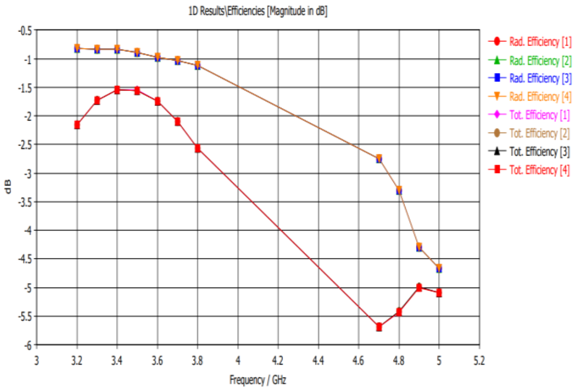

Fig. 10 Power variations of Dual band 4X4 MIMO antenna

In Figure 11, the graphic depicts the envelope correlation coefficient across a spectrum of frequencies. Notably, the ECC is measured at 0.41 for the frequency of 3.5 GHz, while it drops to 0.005 at 5 GHz.

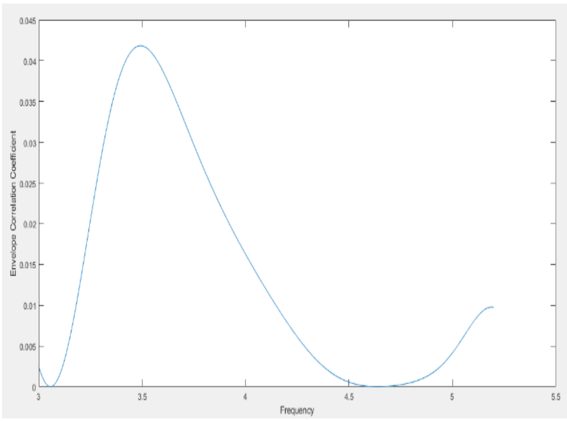

Fig. 11 Envelope Correlation Coefficient of Dual band 4X4 MIMO antenna

A tabular representation of the proposed antenna, along with comparisons to previously reported antennas and their corresponding results and applications, is provided in Table 2.

Table 2. Comparision of Proposed antenna with previous antennas

Ref.	Operating frequency (GHz)	Antenna Dimensions (m^3)	Peak gains (dB)	Substrate	Applications
[10]	3.4 – 3.8	75 × 150 × 1.6	3	FR4	5G
[11]	3.3 –	42 × 42 × 1	No	FR4	5G

	4.2		ne		
[12]	3.3 – 3.6 and 4.8 – 5.0	150 × 70 × 0.8	No ne	FR4	5G
[13]	3.3 – 4.2	37 × 30 × 0 .8	2.5	FR4	5G
[14]	4.37 – 5.5	150 × 72 × 1.2	3.7	FR4	5G
[15]	3.3 – 5.1	60 × 60 × 8	8.1	Rogers RO4003	5G
[16]	3.3 – 3.8	50 × 50 × 3 .5	5.4	F4BK	5G
[17]	4.25 - 5.8	80 × 80 × 6	9.1	F4BME 220	5G
[18]	3.05 – 4.25	38 x 38 x 1.6	3.5	Not given	5G
Propos ed	3.3 - 3.6 and 4.8 – 5	17 x 5 x 3.9 (for single antenna)	3.3 8 and 3.6 5	FR4	5G WLAN

IV. CONCLUSION

The presented dual-band 4x4 MIMO array is designed to cater specifically to 5G smartphone applications, covering two distinct frequency bands. An innovative aspect of this antenna is its strategic placement along the side frame of the smartphone. This location is chosen to achieve a full-screen antenna design, seamlessly integrating with the overall aesthetics and functionality of modern smartphones. This design choice addresses challenges related to the visual and spatial aspects of contemporary mobile devices. A noteworthy performance metric of the antenna is its Envelope Correlation Coefficient (ECC), which gauges the correlation between signals received by different antenna elements. The antenna exhibits optimal ECC results, particularly in the Lower Bands, indicating effective signal independence among its elements.

Despite its compact size, the proposed antenna excels in achieving high isolation, and less reflection coefficient a critical factor in MIMO systems to ensure independent operation of antenna elements without interference. The compact form factor and superior isolation make it well-suited for ultra-thin smartphones, meeting the demand for efficient communication performance in limited space.

The mention of potential improvements in Higher Band efficiency through design modifications inspired by the 6x6 antenna design suggests an adaptable and forward-looking approach. This flexibility indicates the antenna's ability to evolve to meet the demands of different frequency bands or emerging technologies, emphasizing a commitment to continuous refinement and future readiness. The introduced dual-band 4x4 MIMO array not only caters to 5G smartphone applications but also stands out for its thoughtful integration into smartphone frames, optimal ECC results, compact size with high isolation, and a forward-looking design approach.

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Conflict of Interest
Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution
The authors confirm contribution to the paper as follows: study conception and design: Ramineni Padmasree; data collection: Janardhan Rao Duddela, Venu Gogula; analysis and interpretation of results: Ramineni Padmasree, Janardhan Rao Duddela, Venu Gogula; draft manuscript preparation: Ramineni Padmasree, Janardhan Rao Duddela, Venu Gogula. All authors reviewed the results and approved the final version of the manuscript.

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