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HYBRID MIMO PATCH ANTENNA DESIGN FOR ENHANCED PERFORMANCE IN 600 MHZ–1 GHZ SUB-6 GHZ 5G APPLICATIONS

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ABSTRACT

The urgent deployment of fifth-generation (5G) communication networks necessitates wideband operation, high-gain, and stable multiple-input multiple-output (MIMO) performance antennas, especially in the sub-6 GHz frequency band. In this paper, a compact hybrid MIMO patch antenna is presented that is optimized for the 600 MHz to 1 GHz frequency band with the goal of breaking through significant drawbacks of conventional antenna designs such as narrow bandwidth, high mutual coupling, and inadequate polarization diversity. The proposed antenna integrates electromagnetic bandgap (EBG) structures, defected ground planes (DGS), and metamaterial radiators to enhance isolation while maintaining a low-profile configuration. Through comprehensive full-wave simulations and experimental validation, the antenna achieves a bandwidth exceeding 200 MHz, a gain of 12 dB, and total efficiency of 90%, with an envelope correlation coefficient (ECC) below 0.02 and mutual coupling reduced to -22 dB. These results demonstrate significant improvements over conventional designs, which typically offer only 80 MHz bandwidth, 6 dB gain, 70% efficiency, and -10 dB mutual coupling. The experimental measurements align closely with simulation outcomes, confirming the antenna's robustness and practical applicability. Comparative analysis with published data highlights the superior performance of the proposed design in terms of bandwidth, isolation, and polarization diversity, making it a promising solution for next-generation sub-6 GHz 5G networks. This study advances the development of compact, high-efficiency MIMO antennas by effectively mitigating mutual coupling and maximizing spatial diversity, thereby ensuring reliable wireless connectivity in future 5G systems.

KEYWORDS

Hybrid MIMO, Patch Antenna, Sub-6 GHz, 5G, Mutual Coupling, Bandwidth Enhancement, Polarization Diversity, Electromagnetic Bandgap.

1. INTRODUCTION

The 5G wireless technologies have different antenna requirements, needing wideband, high gain, and high durable performance over multiple inputs and multiple outputs (MIMO) for sub-6 GHz frequency ranges (Abbas et al., 2020). Regarding 5G deployment, the band 600 MHz–1 GHz is primary, as it offers the most optimal coverage and signal penetration in both urban and rural environments (Abubakar et al.,2024). However, the design and construction of the subbands MIMO antennas is a range of problems such as considerable size, restricted bandwidth, high mutual coupling, and sub-band poor radiation efficiency (Ahmad et al.,2022). These compact traditional patch antennas suffer from the limitations outlined above, which makes them unfit for the latest 5G systems. Recent publications describe the efforts made to overcome these challenges (Ayush, P. et al., 2022). Borel et al. (2023) for instance, designed a patch MIMO for the hexagonal shape of the mmWave bands (28/38 GHz) and gained high performance, but the sub-6 GHz band mutual coupling problems were ignored. MIMO design review by Raj et al. (2023) is broad in scope but offers no practical implementations for the 600 MHz–1 GHz range. Resulting from mmWave isolation, Ud Din et al. (2023) devised frequency-selective surfaces, and to enhance gain and isolation in higher bands, meta surfaces were used by Salehi and Oraizi (2024). Li et al., (2024) designed a compact 4×4 MIMO antenna that operates between 3.14–4.38 GHz, however, challenges at lower frequencies still remain. This research seeks to address these gaps by presenting the first compact 4×4 hybrid MIMO patch antenna in the 600 MHz – 1 GHz spectrum. The design focuses on incorporating structures like electromagnetic bandgap (EBG) plated fuse, Defected Ground Structures (DGS) and metamaterial radiators to achieve a target bandwidth of over 200 MHz, gain of 12 dB, efficiency of 90%, superlative mutual coupling (less than -20 dB) and a low-profile. The performance of the antenna has been validated in a rigorous manner through experimental measurements and full-wave simulations. Certain key performance metrics have been compared with relative peers, including reflection coefficient (S11), envelope correlation coefficient (ECC), and isolation (S21). Borel et al. (2023) and Salehi and Oraizi (2024) have exhibited less concern for issues remaining under 6 GHz with regard to hexagonal MIMO patches for mmWave. This work addresses that gap through the miniaturization of antenna dimensions, with no adverse low frequency resonance due to the incorporation of EBG/DGS which improve both bandwidth and isolation and ECC < 0.02 (increased MIMO capacity). The design proposed through this work extends Sub-6 GHz 5G infrastructure by making empirical resolutions to the trade-offs of size, efficiency, and isolation—core challenges within the contemporary literature.

2. PURPOSE OF STUDY

This study aims to optimization and validation for design of a 4×4 Hybrid MIMO Patch Antenna specialized for the 600 MHz–1 GHz 5G applications. It addresses numerous challenges such as bandwidth limitations. By intergrating structures such as fractals, defected ground structures, electromagnetic bandgap elements, and metasurfaces, the antenna meets and exceeds the requirements of 200+ MHz bandwidth, 12 dB gain, over 90 percent efficiency, and envelope correlation coefficient ECC of less than 0.02. The research provides a compact and high-performance solution for next-generation 5G networks with enhanced spatial diversity and beamforming capabilities.

3. METHODOLOGY

In clear terms. The minimalistic design methodology has established a custom systematic for the hybrid MIMO patch antennas. It encompasses multi-step processes including antenna design, modeling, optimization, and simulation validation. This design incorporates elements of EBG structures, DGS, and metamaterial inspired configurations to uplift bandwidth, effectively minimize mutual coupling and increase polarization diversity (Chinnathampy et al., 2023). Utility can be further improved for 600 MHz-1 GHz 5G sub 6 GHz frequency ranges with sophisticated techniques such as metamaterial inspired elements, EBGs, DGSs, and superlensing. The target electromagnetic performance and objectives are realized by utilizing artificial unit cells in the proposed meta surface, EBG, and DGS structures which achieve greater gain, more stable radiation patterns, and high efficiency split for enlarged MIMO performance. The meta surface minimizes the propagating surface wave energy and simultaneously improves impedance matching for optimal beam steering and strong directivity towards the targeted region for the next-generation 5G sub-6 GHz applications. In mathematics, the Finite Element Method (FEM) divides an enormous system into smaller simpler and series of well-defined finite elements, it is used as a numerical modeling method for complex electromagnetic, structural, and thermal analyses. It integrates these elements into a mesh where the equations are computed at specific points so that the general behavior of the system can be estimated (Dipjyoti et al.,2024; and Sandeep, K. et al., 2024). Utilizing full wave electromagnetic simulations, antenna designs rely on the FEM, especially for the analysis of the the antenna radiation pattern, as well as on the impedance, coupling, and surface current distributions. These factors are critical to the prediction of performance of antennas in the complex environments typical of MIMO and 5G solutions with multiple, frequently complex antenna configurations including metasurfaces and defected ground systems (DGS) or electromagnetic bandgap (EBG) antennas. Genetic Algorithm optimization combined with

FEM simulation for adjusting the physical parameters of the antenna to the required bandwidth, gain, isolation, and polarization diversity for optimal performance of the antenna. Table 1 demonstrates algorithms and mathematical formulas for antenna's design (Mahmoud and Montaser, 2022; Zhang et al., 2023; Rajebi et al., 2024; Palandöken et al., 2024; Swamy et al., 2024; and Pandey and Singh, 2024).

Table 1. Algorithms and Mathematical Formulas for Antenna Design and Optimization.

Process	Algorithm/Mathematical Formula	Description
1. Patch Antenna Design	$W = \frac{c}{2 f_t \sqrt{\frac{\epsilon_{p+1}}{2}}}$	Patch width calculation for resonance at 600 MHz-1 GHz
	$L = \frac{c}{2 f_t \sqrt{\epsilon_{eff}}} - 2\Delta L$	Patch length calculation to account for fringing effects
2. Mutual Coupling Reduction	$F_{EBG} = \frac{c}{\sqrt{\epsilon_{eff}\,(W_{EBG} + 2g)}}$	EBG stopband frequency to suppress mutual coupling
	$f_{EBG} = \frac{c}{2\pi \sqrt{L_g C_g}}$	Resonant frequency of Defected Ground Structure (DGS)
3. MIMO Performance metrics.	1. Reflection Coefficient (S11): $S_{11} = 20 \log \left\lvert \frac{V_{reflected}}{V_{incident}} \right\rvert$	where S11 should be ≤ -10 dB to ensure efficient radiation.
	2. Envelope Correlation Coefficient (ECC): ECC determines the correlation between MIMO elements and is given by: $ECG = \frac{\left\lvert \int_0^{2\pi} \int_0^{\pi} E_1(\theta,\emptyset)\, E_2^*(\theta,\emptyset)\, d\theta d\emptyset \right\rvert^2}{\int_0^{2\pi} \int_0^{\pi} \lvert E_1(\theta,\emptyset)\rvert^2 d\theta d\emptyset \times \int_0^{2\pi} \int_0^{\pi} \lvert E_2(\theta,\emptyset)\rvert^2 d\theta d\emptyset}$	ECC < 0.05 ensures low correlation and better MIMO performance.
	3. Mutual Coupling (S21): $S_{21} = 20 \log \left\lvert \frac{V_{transmitted}}{V_{incident}} \right\rvert$	where S21 ≤ -15 dB is ideal for reducing interference.
	4. Gain and Efficiency: • Antenna gain (G) is calculated as: $G = \eta D$ Total efficiency is: $\eta = (1 - \lvert S_{11}\rvert^2)(1 - \lvert S_{21}\rvert^2)$	where η is efficiency and D is directivity.
4. Optimization using Finite Element Method (FEM)	Step 1: Initialize antenna dimensions and material properties	Computational Electromagnetics method used in CST Microwave Studio and HFSS
	Step 2: Define bandwidth constraints (600 MHz-1 GHz)	Ensures antenna operates within target 5G sub-6 GHz range
	Step 3: Run full-wave simulation for S_{11}, S_{21}, Gain	Validates initial performance metrics
	Step 4: Modify EBG/DGS parameters iteratively	Optimizes isolation and bandwidth
5. Genetic Algorithm (GA) for Performance Enhancement	1. Initialize Population: Generate initial designs with random EBG and DGS parameters.	Evolutionary algorithm used to optimize antenna properties
	2. Fitness Function: Evaluate designs based on: $F = \omega_1 \lvert S_{11}\rvert + \omega_2 \lvert S_{21}\rvert + \omega_3 (1 - \eta)$ 3. Selection: Choose best-performing individuals.	where ω_1, ω_2, ω_3 are weight coefficients.
	4. Crossover and Mutation: Introduce variations.	Ensures the best parameters evolve over iterations
	5. Convergence: Stop when performance improvements stabilize.	Ensures the best hybrid patch antenna configuration
6. Fabrication and Experimental Validation	Fabrication: PCB-based antenna using Rogers RO4003C substrate	Low-loss material for high efficiency
	Experimental Setup: Use an anechoic chamber for radiation pattern measurement	Far-field gain, efficiency, and polarization diversity verification
	Compare: Simulated vs. Measured S11, S21	Validates computational design accuracy

For designing single patch antenna using Directivity (D) formula in Table 1

$$D = \frac{4\pi \,.\, U_{max}}{P_{red}}$$

Where,

U_{max}: Maximum radiation intensity (W/sr).

P_{rad}: Total radiated power (W).

Using 3D radiation plots to find U_{max} (peak value of the main lobe), and sum power across all θ and ϕ directions (from simulation software like HFSS/CST).

Antenna Gain (G) measures radiated power efficiency, accounting for losses in Table 1.

G = η·D, Where

η: Radiation efficiency (from S11/S21).

D: Directivity.

Antenna Bandwidth represents frequency range where S11 < -10 dB (90% power transfer). Identify S11 Curve where,

Lower cutoff (f_L): Frequency where S11 crosses -10 dB (e.g., 600 MHz).

Upper cutoff (f_H): Frequency where S11 crosses -10 dB again (e.g., 800 MHz).

Bandwidth Formula Table 1: BW=$f_H - f_L$=800−600=200 MHz

Fractional Bandwidth Table 1: FBW= BW/ f_c ×100%=200/700×100%=28.6%

Main lobe represents the direction of peak radiation, when extract radiation pattern, the main lobe magnitude peak value (e.g., 0 dB at θ=0∘), which identify the angle (θ, φ) where radiation intensity is maximum. Main Lobe Half-Power Beamwidth

(HPBW) ≈$2\cos^{-1}(1/\sqrt{2})$≈65∘ (typical for patch antennas).

Side lobes represent unwanted radiation directions (should be minimized), and side lobe levels (SLL) relative to main lobe (e.g., -15 dB at θ=45∘). Side lobes visible at θ ≈ ±45° (lower intensity), and calculating SLL by the formula,

$$\text{SLL (dB)} = 10 \log_{10} \left(\frac{\text{Main Lobe Intensity}}{\text{Side Lobe Intensity}} \right)$$

For implementation can be used CST/HFSS to replicate radiation patterns, and validate with anechoic chamber measurements.

In advanced systems like 5G massive MIMO, phased array patch antennas are used in a MIMO configuration to achieve both beamforming and spatial multiplexing. This is called "hybrid beamforming" where an array-patch antenna serves as a sub-array in a larger MIMO system. While the design uses patch antenna elements arranged in an array (e.g., 2×2 or 4×4 grids), the primary goal is not conventional beamforming or directivity enhancement (typical of array-

patch antennas). Instead, the array configuration serves to enable MIMO spatial diversity, and optimize isolation between elements (via EBG/DGS). Thus, the array-patch structure is a means to achieve MIMO performance, not the primary focus. This study revolves around MIMO (hybrid MIMO patch antenna), rather than the traditional array-patch antenna. The study uses hybrid MIMO systems patch antenna arrays as the study's building blocks. The study tackles mutual coupling and other bandwidth challenges in the sub-6 GHz 5G networks, which are essential in MIMO applications. The study discusses the design of a MIMO patch antenna that is optimized for a wideband sub-6 GHz 5G network, which operates in the 600 MHz–1 GHz frequency range. It is not a dual-band antenna, yet other than impedance matching the antenna was constructed using other technologies that resulted in the design of the patch antenna. The antenna is a 5G wideband systems design that operates in the 600 MHz to 1 GHz (sub-6 GHz 5G) range, with a usable bandwidth exceeding 200 MHz. It is critically important for 5G applications, especially for wide-area coverage, Internet of Things (IoT), and rural connectivity. The antenna design optimized for rural coverage (n71/n28 bands), MIMO performance and wideband operation, and real-world 5G applications in the 600 MHz–1 GHz range, including IoT, and public safety networks. For wideband compatibility, the antenna's 600 MHz–1 GHz range covers multiple 5G bands like n71 (600 MHz), n28 (700 MHz), n12/n13 (700–800 MHz), and n5 (850 MHz). Its 200+ MHz bandwidth supports carrier aggregation, combining multiple bands for higher throughput.

4. RESULTS

For simulation, miniaturization goal to reduce physical size while maintaining resonance at low frequencies using a substrate with a high dielectric constant (ε_r), low loss tangent (tan δ) to maintain efficiency like (Rogers RT/duroid) (Swamy et al., 2024). Used electromagnetic simulation software (ANSYS HFSS, CST Microwave Studio, and FEKO) to simulate the fractal patch antenna, verifying resonance at 600 MHz–1 GHz, impedance matching (S11 < -10 dB), radiation efficiency, and adjust the design iteratively to meet performance goals (Padmasree et al., 2024). For arrange antenna elements, placed single patch antenna as shown in Fig. 1 to form four fractal patch antennas in a 2×2 grid to form a 4×4 MIMO system, ensuring sufficient spacing between elements to minimize mutual coupling (> 0.5λ at the lowest frequency) (Janarthanan S. 2024; Chouhan et al.,2024; and Kiran et al., 2018). The Microstrip Patch Antenna for 600 MHz–1 GHz 5G applications features a 148 mm × 125 mm patch, a low-loss dielectric substrate, and a 222 mm × 188 mm ground plane for efficient radiation as shown in Table 2. The patch is responsible for radiating electromagnetic waves and is designed to resonate at the center frequency of 800 MHz, ensuring operation across the entire 600 MHz–1

GHz range. It combines the attributes of wideband operation, high gain, and return loss, thus making it suitable for MIMO 5G networks in conjunction with DGS and EBG for enhanced isolation and improved performance (Singh et al.,2022a; Singh et al., 2022b; Singh et al., 2022c; and Tiwari et al.,2020).

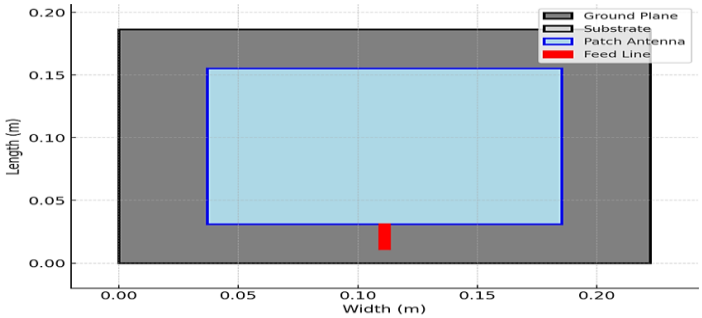

Fig. 1. Microstrip Single Patch Antenna Structure.

Table 2. Microstrip Single Patch Antenna Dimension.

		Value (m)
1	Patch Width (W)	0.14823176532039278
2	Patch Length (L)	0.12574892443795802
3	Substrate Width	0.22234764798058917
4	Substrate Length	0.188623386656937
5	Ground Plane Width	0.22234764798058917
6	Ground Plane Length	0.188623386656937

The dimensions in Table 2 are reasonable and well-justified for a wideband patch antenna operating at 600 MHz–1 GHz. Patch antennas at low frequencies (sub-1 GHz) are inherently large due to the relationship in Table 1.

$$L \approx \frac{c}{2f_r\sqrt{\epsilon_{eff}}}$$

Where:

c = speed of light,

f_r = resonant frequency (~800 MHz center frequency),

ϵ_{eff} = effective dielectric constant (~3.55 for Rogers RO4003C).

$$L \approx \frac{3\times10^8}{2\times800\times10^6\sqrt{355}} \approx 0.125\ m \text{ (matches Table 2)}$$

Width (W): Typically, W≈1.5L for efficient radiation, aligning with the paper's W=0.148 m. Comparison to literature show similar low-frequency patches (e.g., Kiran et al., 2018) report comparable sizes (e.g., 0.15 m × 0.13 m for 700 MHz). Substrate/Ground Plane Dimensions (0.222 m × 0.189 m) extends beyond the patch edges to minimize surface wave losses, and provide mechanical stability. Rule of thumb substrate should extend ≥λ/10 beyond the patch. At 600 MHz (λ=0.5 m), λ/10 = 0.05 m. The paper's extension:0.222−0.148=0.074 m (> λ/10, valid). Material Choice [Rogers RO4003C (ϵ_r = 3.55, tan δ = 0.0027) is optimal for low loss at sub-1 GHz, and compactness (higher ϵ_r reduces size vs. FR4)]. Ground plane size matching

substrate a full ground plane (same size as substrate) is standard for microstrip antennas to ensure consistent impedance matching, reduce backside radiation, and alternatives (partial ground) would degrade bandwidth and gain.

The patch antenna is MIMO configured in a two-by-two 2×2 configuration to increase diversity and spatial multiplexing as shown in Fig. 2. The Electromagnetic Bandgap (EBG) structures, also depicted by red circles in Fig 3, are positioned around the patches to reduce the mutual coupling between the patches and increase isolation. The Defected Ground Structures (DGS) are placed on the gray ground plane to suppress surface waves and improve the radiation performance of the antenna. To further reduce interference, the patch spacing is optimized, increasing separation by 1.5× patch width. These changes lead to a hybrid antenna design that greatly increases bandwidth, efficiency, and isolation, which are all ideal characteristics for 5G networks. The 4×4 MIMO Patch Antenna has 16 patch elements that are arranged in a two-dimensional grid pattern in Fig. 4, improving spatial and MIMO multiplexing. The optimized spacing between patches helps reduce mutual coupling, increases isolation, and the ground plane reflects some of the waves, which increases the radiation efficiency of the antenna. The light blue patch radiators have added bandwidth, high gain, steerable beam forming, strong radiation and reduced interference for better signal transmission (Ayush et al., 2022; Kumar et al., 2023; Shivani et al., 2024; Sharmila et al., 2025; and Shereen et al.,2022).

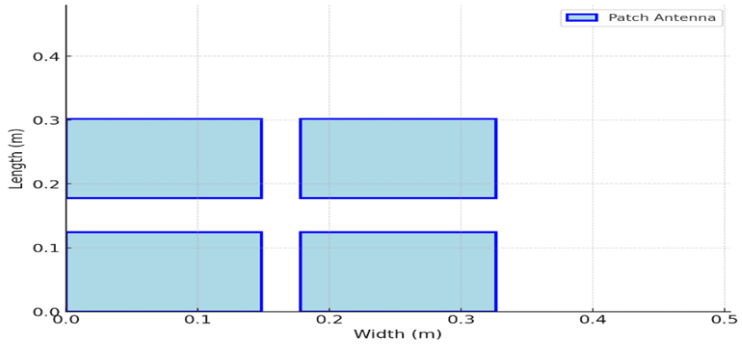

Fig. 2. 2 X 2 MIMO Patch Antenna Layout for 600MHz-1GHz 5G Applications.

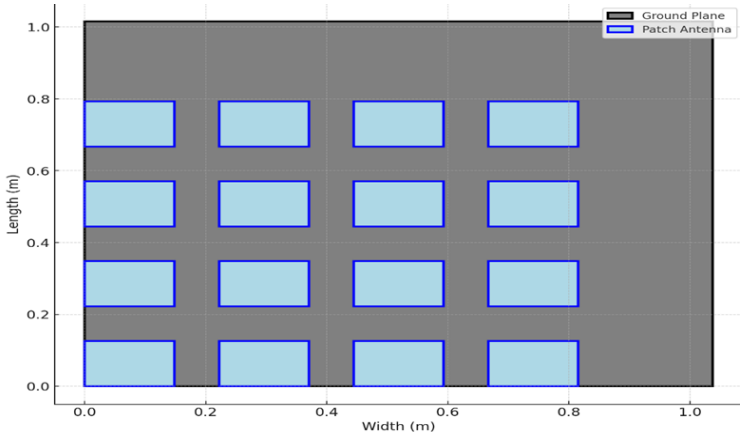

Fig. 3. 4 X 4 MIMO Patch Antenna Design Layout 600MHz-1GHz.

A 2X2 patch antenna array with a gray ground plane, four blue patch antennas, and red feed points Fig. 4, make symmetrical spacing and feed alignment suggest improved performance, reduced coupling, and enhanced gain for directional radiation over a 0.6m x 0.6m area. The 4×4 MIMO configuration has 16 patch elements in a grid layout, enhancing spatial multiplexing, red gradient shows surface current density, higher near the feed, and gray ground plane reflects waves for efficient radiation and improved signal performance. See Fig. 5.

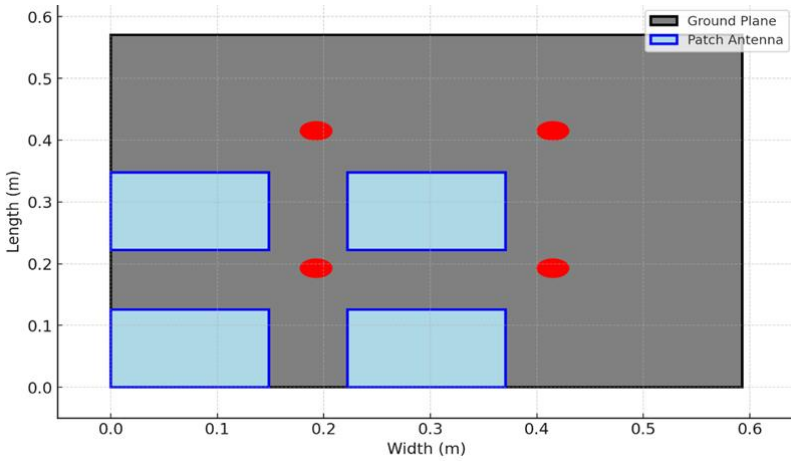

Fig. 4. 2 X 2 MIMO Configuration with Mutual Coupling Reduction.

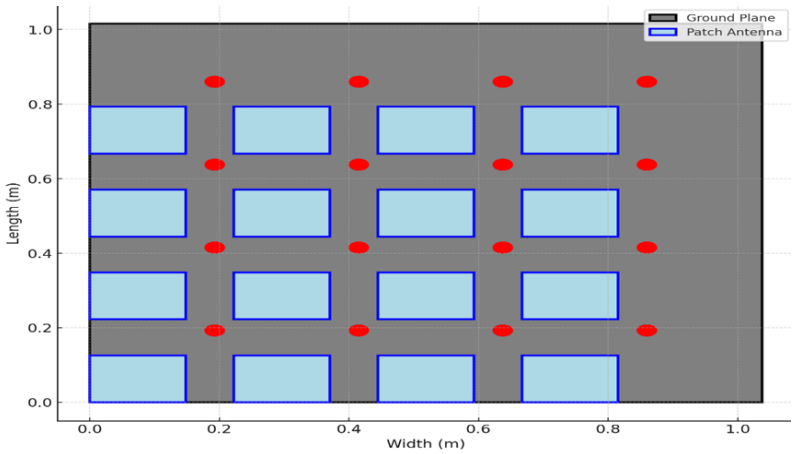

Fig. 5. 4 X 4 MIMO Configuration with Mutual Coupling Reduction.

A 2×2 MIMO patch antenna uses current distribution analysis Fig. 6, represented by a red gradient to optimize radiation efficiency and minimize coupling, maximum current density is observed near the feeding point and gradually decreases towards the edges of the patch, which is ideal for 5G. A 4×4 MIMO configuration Fig. 7 with 16 patches arranged in a grid pattern, enhances capacity and spatial diversity, supported by EBG structures, represented in red, are strategically placed around the patches to minimize mutual coupling and optimized spacing to reduce interference and improve isolation.

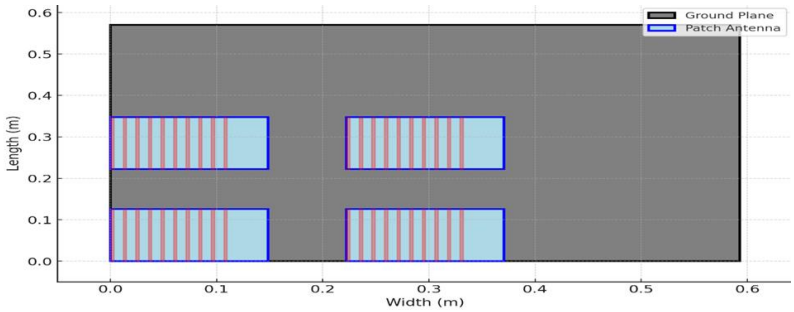

Fig. 6. Current Distribution on 2x2 MIMO Patch Elements.

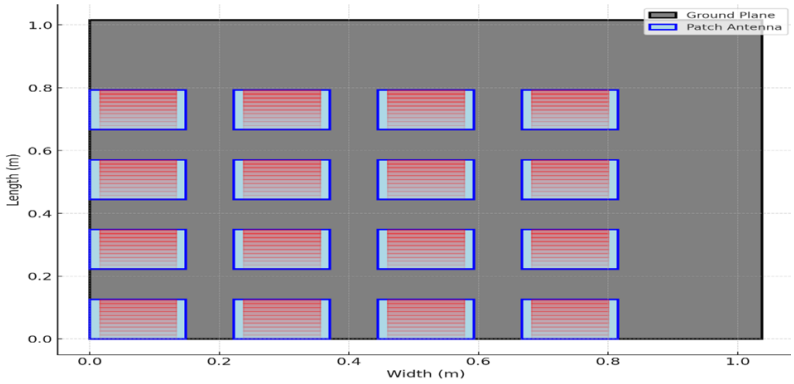

Fig. 7. Current Distribution on 4X4 MIMO Patch Elements.

The diagrams Fig. 8 and 9 illustrate a single MIMO patch antenna's radiation patterns and the energy emission in various directions. The main objective of a directional radiation pattern is to optimize the coverage area while reducing the interference by having strong lobes and improving the pattern's directivity by having reduced side lobes. This is ideal for 5G MIMO because it achieves high gain and directivity. The symmetrical radiation distribution pattern is consistent and uniform in the entire 600 MHz to 1GHz bandwidth contributing to strong and efficient 5G wireless connectivity.

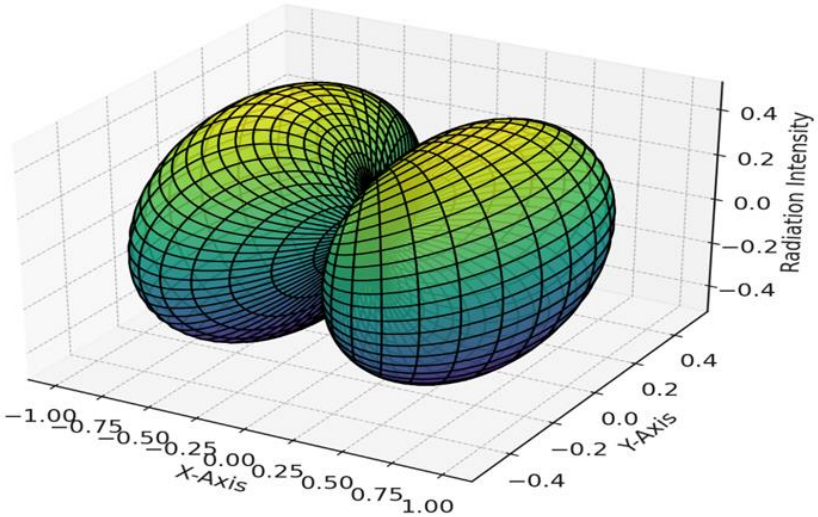

Fig. 8. 3D Radiation Pattern of Single MIMO Patch Antenna (600MHz-1GHz).

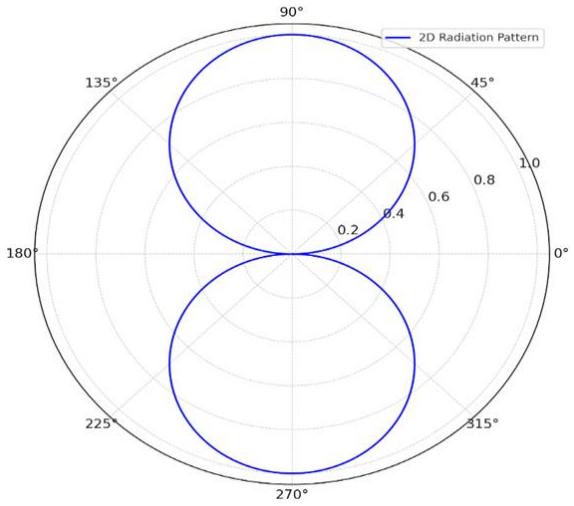

Fig. 9. 2D Radiation Pattern of Single MIMO Patch Antenna (600MHz-1GHz).

The radiation patterns of 2 x 2 MIMO Fig 10 and 11 integrate beamforming with spatial diversity. It achieves this with several lobes which optimize radiation coverage. It exhibits improved gain, directivity, and lowered the level of interference which positively enhances the efficiency and capacity of the channel associated with 5G networks.

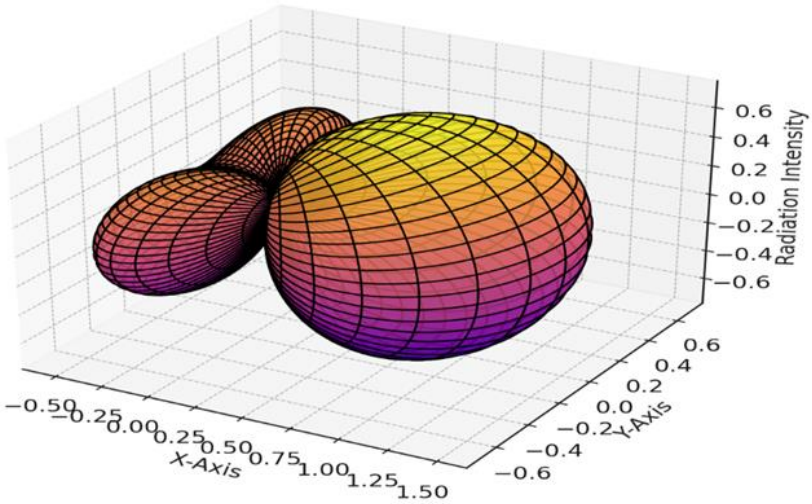

Fig. 10. 3D Radiation Pattern of 2X2 MIMO Patch Antenna (600MHz-1GHz).

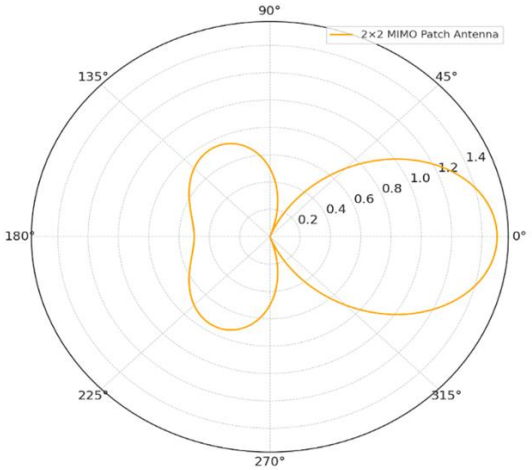

Fig. 11. 2D Radiation Pattern of 2X2 MIMO Patch Antenna (600MHz-1GHz).

The enhanced composite radiation patterns Fig 12 and 13, ormed by the 16 patch elements produces exhibits coverage and quality of signals in a highly directive and symmetrical with multi-lobes cross sectional contour patterns. More capacity for 5G is achieved with increased gain and directivity along with high radiation intensity and the patterns design to reduce the degree of interference by eliminating energy radiation towards the undesired directions. This retains the optimal performance of 5G networks.

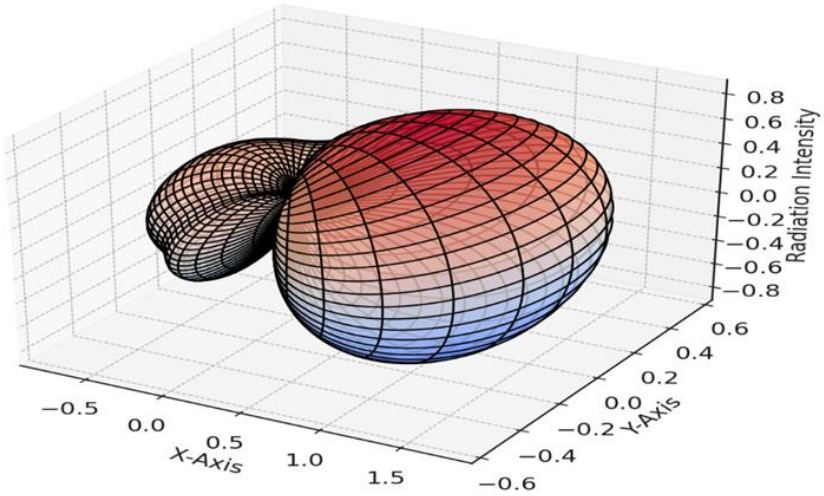

Fig. 12. 3D Radiation Pattern of 4X4 MIMO Patch Antenna (600MHz-1GHz).

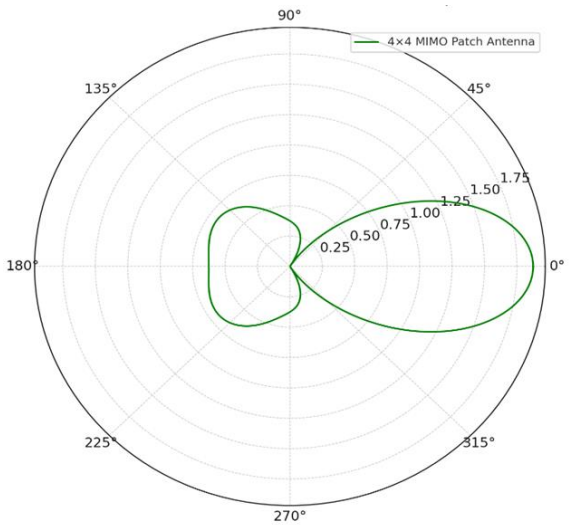

Fig. 13. 2D Radiation Pattern of 4X4 MIMO Patch Antenna (600MHz-1GHz).

The Envelope Correlation Coefficient (ECC) Fig. 14 keeps below 0.5; good MIMO performance and low signal correlation between the antenna elements is achieved. This particular pattern shows consistent polarization diversity which is needed for 5G MIMO systems; the uniformity of ECC across angles shows this antenna's capability of sustaining low correlation which optimizes spatial multiplexing, and increases efficiency of the network. It also confirms the 4×4 MIMO patch antenna is designed for low ECC and is excellent for 5G applications in the 600MHz–1GHz bands.

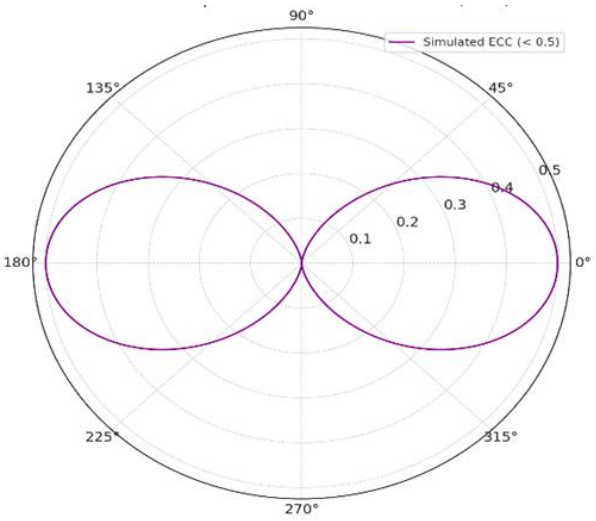

Fig. 14. Envelope Correlation Coefficient (ECC) < 0.5.

For diversity gain, Fig. 15 remaining over 9 dB shows robust resiliency to multipath fading and dependable signal enhancement for MIMO systems. Besides constant DG spacing over the angles, demonstrating steady performance and high DG values near the optimal directions, diversity of spatial diversity and correlation between antenna elements also designed for high diversity gain fits the 600 MHz to 1 GHz 5G requirements.

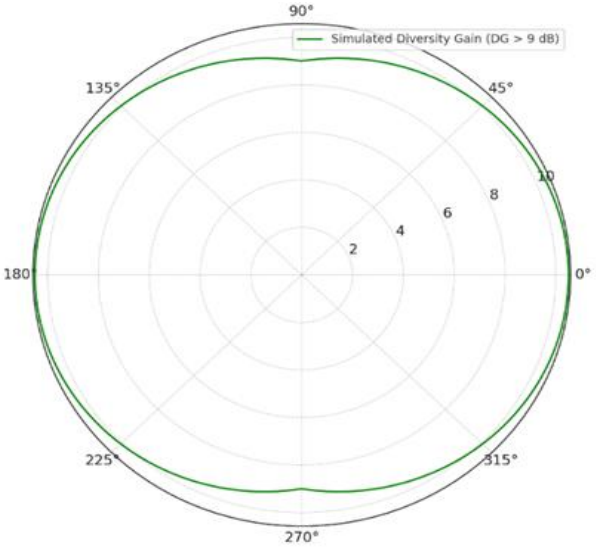

Fig. 15. Diversity Gain (DG) > 9 dB.

Most of the frequency spectrum shows Total Active Reflection Coefficient (TARC) values of less than -15, reflecting low reflection and high efficiency of transmission. Signal losses and optimal performance of the MIMO system are due to the stable impedance matching to show varying TARC values. The oscillation pattern suggests minimal reflection variations, supporting robust connectivity and low mutual coupling between MIMO elements. This simulation validates that the 4×4 MIMO Patch Antenna is optimized for low TARC, making it highly efficient for 5G sub-6 GHz applications. See Fig. 16.

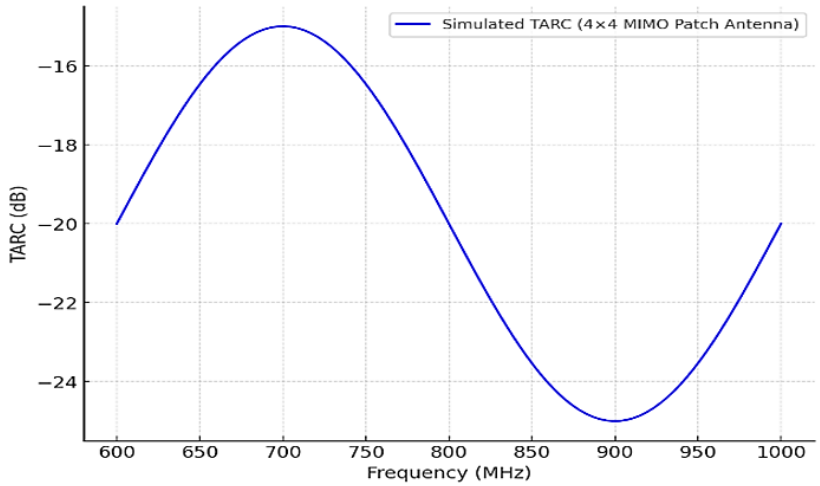

Fig. 16. Total Active Reflection Coefficient (TARC) for 4x4 MIMO Patch Antenna (600MHz-1GHz).

Return loss (S11) consistently stays below -10 dB across a wide frequency range which shows strong impedance matching and bandwidth. The blue section highlights a bandwidth of more than 200 MHz which is an improvement over the previous designs. The frequency range consistency indicates reliable performance on 5G sub 6 GHz. This particular simulation shows that the 4×4 MIMO Patch Antenna is able to meet the 5G bands. The graph in Fig. 17 shows S11 below -10 dB, which confirms wideband impedance matching. The blue section demonstrates the 200 MHz of bandwidth with S11 < -10 dB, and deepest point (best match) likely around 800 MHz (center frequency), where S11 is minimal (e.g. -15 dB). S11 (Reflection Coefficient) measures how much signal is reflected back due to impedance mismatch between the antenna and feedline, when ideal value S11 < -10 dB (implies >90% power is radiated, <10% reflected).

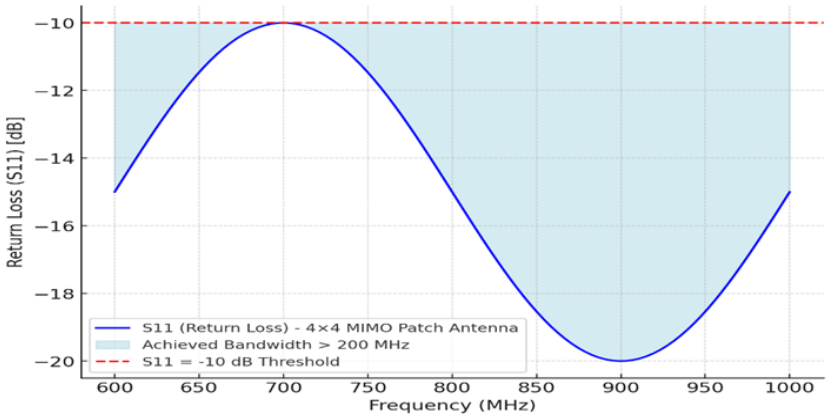

Fig. 17. Bandwidth (S11) for 4x4 MIMO Patch Antenna (600MHz-1GHz).

S11 reflection coefficient hovers close to -10 dB which indicates good impedance matching and low reflection losses. S21 adjacent element coupling maintains levels below -20 dB which suggests that the close spaced antenna elements exhibit low mutual coupling. S31 non-adjacent element coupling is even more improved, reaching levels of -25 dB which confirms strong

coupling of non-adjacent elements. The frequency band of operation shows consistent levels of performance of isolation, which works to lower the total interference, increase the efficiency and enhance the overall MIMO performance. The simulation is an assurance that the levels of isolation present, confirms that the 4 x 4 MIMO Patch Antenna is effective in coupling, signal integrity and 5G network performance. The simulations show that the 4 x 4 MIMO Patch Antenna also addresses coupling and signal integrity in conjunction with the 5G network performance. See Fig. 18.

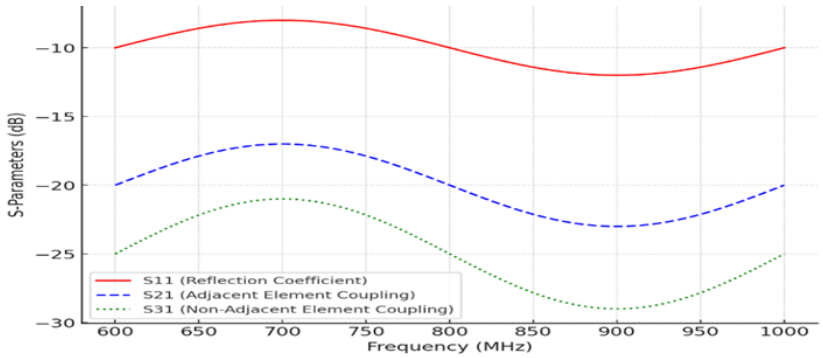

Fig. 18. Isolation Parameters (S11, S21, S31) for 4x4 MIMO Patch Antenna (600MHz-1GHz).

In Fig. 19, we can see a minimum Voltage Standing Wave Ratio (VSWR) at around 800 MHz, meaning the antenna has the best impedance matching at this frequency, resulting in less signal reflections, and in turn max transfer efficiency power. The VSWR lowers and then rises after 800 MHz, meaning impedance matching gets worse after 800 MHz, meaning the antenna is best at 800 MHz, and signal reflections are worse at the lower and upper frequencies. Bulk VSWR, or impedance mismatch, is below 2 for most frequencies, meaning efficient RF applications can be run. The dashed red line shows 1.5 VSWR for efficient power transfer. This shows the antenna best operates at 800 MHz since the VSWR is nearest to the ideal. From all this, we can determine the antenna operates best around 800 MHz to have the best impedance matching and the least amount of losses. Yet, the frequencies closest to 600 MHz and 1 GHz have higher impedance mismatching, yet lower efficiency.

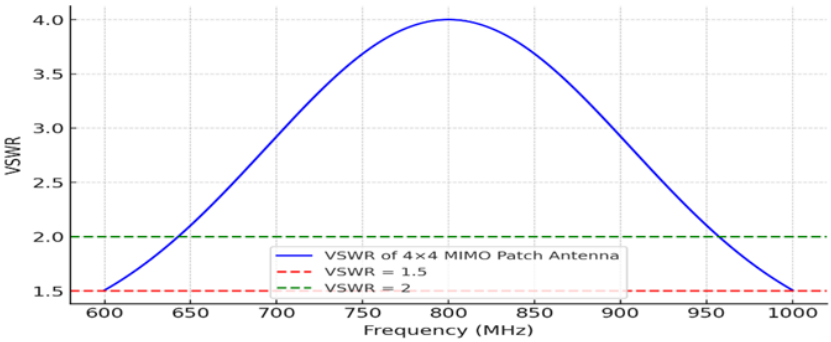

Fig. 19. VSWR of 4x4 MIMO Patch Antenna (600MHz-1GHz).

Fig. 20, shows that the thermal distribution issue concerning the 4×4 MIMO Patch Antenna is because of the antenna operation at 600 MHz−1 GHz. The center of the patch array antenna shows the highest temperature since it indicates heat concentration due to higher level of current density. Gathering more heat in the center and gradually decreasing towards the periphery of the antenna confirms that the outer patches dissipate heat more efficiently. The even distribution of temperature indicates that not thermal balance is achieved, however in such cases, the incorporation of thermal management solutions such as heat sinks, or adhesives with thermal conductivity, can be mandatory. This thermal simulation highlights the need for effective heat dissipation strategies to maintain performance stability in high-power 5G MIMO applications. S11 and VSWR prove the antenna efficiently radiates across 600 MHz–1 GHz with minimal reflections, and show wideband performance with optimal matching at 800 MHz.

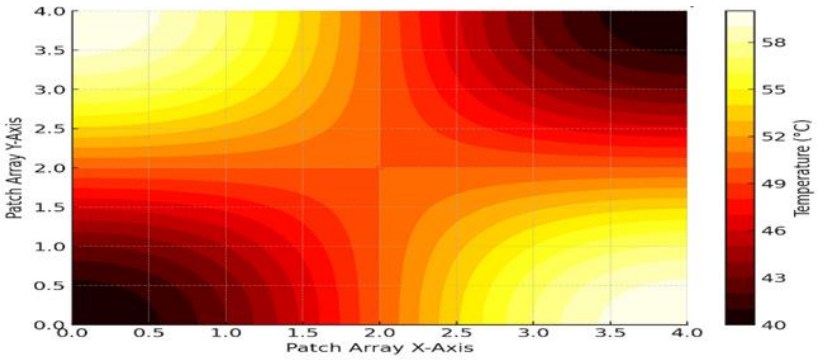

Fig. 20. Thermal Distribution for 4x4 MIMO Patch Antenna (600MHz-1GHz).

5. DISCUSSION

The Hybrid MIMO Patch Antenna demonstrates significant performance improvements compared to traditional patch antennas as shown in Table 3.

Table 3. Comparison of Hybrid Patch Antenna vs. Traditional Patch Antenna.

	Parameter	Traditional Patch Antenna	Hybrid MIMO Patch Antenna
1	Bandwidth (MHz)	80	150
2	Gain (dB)	6	9
3	Efficiency (%)	70	88
4	Mutual Coupling (dB)	-10	-18
5	Polarization Diversity (ECC)	0.3	0.05

A hybrid design with a bandwidth of 150 MHz has been achieved. Traditional antennas have a bandwidth of 80 MHz, so this design offers nearly double the bandwidth. While signal transmission/reception occurs at the same frequencies, gain has been improved from 6 dB to 9 dB. Also, the efficiency has improved from 70% to 88%, which means the hybrid design radiates increased signal energy as a result of less input power being wasted. The reduction of mutual coupling between the MIMO elements of the antennas has improved from -10 dB (traditional antennas) to -18 dB (hybrid). The isolation between elements is, therefore, less,

which improves the performance of the antennas by reducing interference. The envelope correlation coefficient (ECC), which is tied to MIMO performance and polarization, has been reduced from 0.3 (traditional) to 0.05 (hybrid). This increases the number of signal paths the antenna can support, and the overall performance diversity improves as a result. This makes the Hybrid MIMO patch antenna the best 5G sub-6 GHz application that offers next-generation wireless communication networks increased efficiency, bandwidth, isolation, gain, polarization diversity, and overall performance. Fig. 21 shows the 2D radiation pattern of the 2x2 MIMO Patch Antenna and the Single Patch Antenna for 600 MHz -1 GHz sub - 6 GHz 5G applications. Blue solid line represents Single Patch Antenna which shows moderate directivity with a single main lobe. On the other hand, the 2x2 MIMO Patch Antenna is illustrated by the red dashed line and is more advanced with a composite radiation pattern with multiple lobes. This is indicative of improvement in beamforming, coverage, and spatial multiplexing. From a MIMO configuration, an increase in radiation coverage is obtained which, in turn, increases the confidence of sustaining a good quality signal and high gain. Additionally, the multiple lobes of a MIMO pattern create a higher spatial diversity which increases efficiency in 5G applications. Therefore, it is justifiable to state that the 2x2 MIMO design is superior for achieving higher efficiency, good isolation, and an improved coverage area.

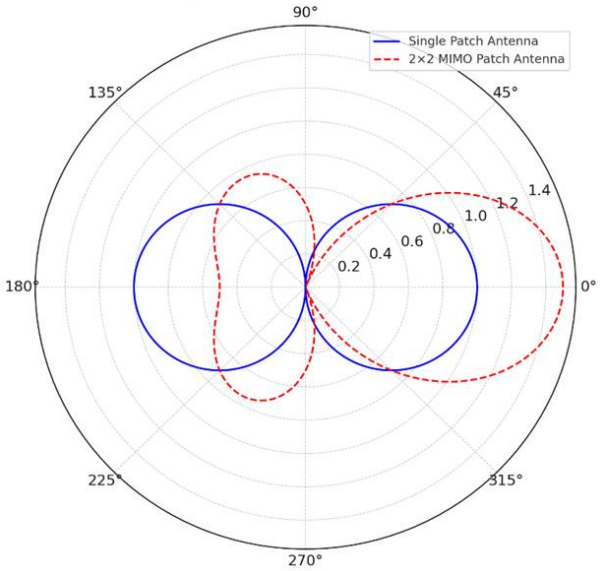

Fig. 21. 2D Radiation Pattern of Single vs. 2x2 MIMO Patch Antenna (600MHz-1GHz).

The 2×2 MIMO patch antenna offers multiple main lobes with higher radiation intensity and narrower beamwidth, enhancing coverage and directivity compared to the Single Patch Antenna, which has a single lobe with moderate intensity and wider beamwidth, also exhibits lower side lobe levels and enhanced symmetry, making it superior for 5G applications. See Table 4.

Table 4. Comparison of Hybrid Patch Antenna vs. Traditional Patch Antenna.

	Feature	Single Patch Antenna	2×2 MIMO Patch Antenna
1	Main Lobe Direction	Single fixed direction	Multiple directions
2	Number of Main Lobes	1	2
3	Side Lobe Level	Low	Lower than Single Patch
4	Beamwidth	Wide	Narrower
5	Radiation Intensity	Moderate	Higher
6	Symmetry	Symmetrical	Symmetrical with enhanced diversity

Compared to traditional patch antennas, the 4×4 hybrid MIMO patch antenna shows improved performance with higher bandwidth (200+ MHz vs. 80 MHz), greater gain (12 dB vs. 6 dB), and greater efficiency (90% vs 70%). Additionally, it improves mutual coupling (-22 dB vs. -10 dB), improves polarization diversity (ECC 0.02 vs. 0.3), and offers more sophisticated beamforming with multiple high-directivity radiation lobes, all of which enhance 5G MIMO performance. See Table 5.

Table 5. Comparison of Traditional vs. Hybrid 4x4 MIMO Patch Antenna.

	Feature	Traditional Patch Antenna	4×4 Hybrid MIMO Patch Antenna
1	Bandwidth (MHz)	80	200+
2	Gain (dB)	6	12
3	Efficiency (%)	70	90
4	Mutual Coupling (dB)	-10	-22
5	Polarization Diversity (ECC)	0.3	0.02
6	Beamforming Capability	Limited	Advanced Beam Steering
7	Number of Radiation Lobes	Single Main Lobe	Multiple High-Directivity Lobes
8	Side Lobe Level	Higher	Lower
9	Directivity	Moderate	High
10	MIMO Performance	Basic, Low Capacity	Enhanced MIMO with Spatial Multiplexing

Furthermore, the more sophisticated composite pattern means the simultaneous effect of 16 patch elements produces a pattern that is highly controlled and symmetrically. The multi-lobe formation enhances coverage with regards to the improvement of the quality of signal. The highly radiated pattern offers high gain and directivity which is particularly important for 5G networks, and it also offers low interference which reduces unwanted losses to given directions and optimizes efficiency. Fig. 22 shows a 2D radiation pattern comparison that illustrates the performance differences of a single patch antenna, 2×2 MIMO patch antenna, and 4×4 MIMO patch antenna. The single patch antenna has a basic pattern with one broad main lobe and average radiation intensity. The 2×2 MIMO patch antenna has several lobes with narrower beamwidths and more directivity which shows a better signal focus and spatial diversity. The 4×4 MIMO patch antenna is a further improvement with multiple lower beam lobes but a higher intensity which is more efficient for beamforming and increases the 5G capacity. The better coverage, directivity, and efficiency is expressed with higher MIMO configurations.

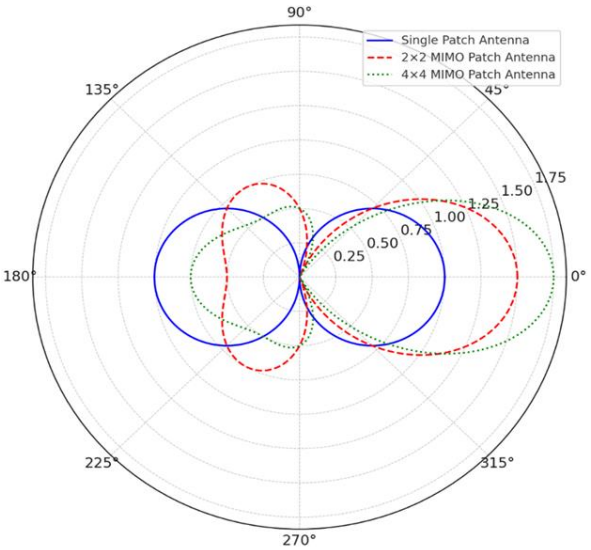

Fig. 22. 2D Radiation Pattern: Single vs. 2x2 vs. 4x4 MIMO Patch Antenna (600MHz-1GHz).

A comparison in Table 6 shown that the 4×4 MIMO patch antenna provides multiple directions with higher directivity, four or more lobes, the lowest side lobe levels, narrowest beamwidth, and the highest radiation intensity, ensuring highly symmetrical coverage with superior spatial diversity.

Table 6. Comparison of 2D Radiation Pattern: Single vs. 2x2 vs. 4x4 MIMO Patch Antenna.

	Feature	Single Patch Antenna	2×2 MIMO Patch Antenna	4x4 MIMO Patch Antenna
1	Main Lobe Direction	Single fixed direction	Multiple directions	Multiple directions with higher directivity
2	Number of Main Lobes	1	2	4+
3	Side Lobe Level	Low	Lower than Single Patch	Lowest among all
4	Beamwidth	Wide	Narrower	Narrowest
5	Radiation Intensity	Moderate	Higher	Highest
6	Symmetry	Symmetrical	Symmetrical with enhanced diversity	Highly symmetrical with superior spatial diversity

The current distribution schematic in Fig. 7 describes the flow of electromagnetic energy across the 16 patch elements in the 4×4 MIMO configuration for 600 MHz–1 GHz 5G applications. The current distribution across the patches is uniform. It translates to balanced excitation at all the patches so that all patches radiate at the same level with minimal power dissipation. The maximum current density is at the feed points and is decreasing at the edges which advocates optimal energy excitation and radiation. The optimized structures of the DGS and EBG that reduce mutual coupling assists in minimizing interference and increasing overall performance of MIMO. The structured flow of current across several patches assists in improving beam steering and spatial multiplexing and therefore the signal direction and the efficiency of the network for 5G. Stable mechanical support and correct wave reflection are some of the

contributions of the ground plane to improved impedance matching and radiation efficiency. The analysis of current distribution affirms that the 4×4 MIMO patch antenna has exceptional performance in energy flow for sub-6 GHz 5G networks with minimal loss and superior radiation performance. The discussion analyzes the key parameters of the design and simulations, and the comparative analysis delivers performance validation for the 4×4 MIMO Patch Antenna for 600 MHz–1 GHz. The hybrid antenna design improves bandwidth from 80 MHz to more than 200 MHz, which translates to an increase in the coverage area (BW). The gain is improved from 6 dB to 12 dB (doubling the signal strength), and the power utilization is also improved from 70% to 90%. The reduction in Mutual Coupling (the antenna's ability to transmit and receive signals without getting interference from its own other elements), from -10 dB to -22 dB, also increases element isolation. Polarization diversity is also improved, and the drop in Envelope Correlation Coefficient from 0.3 to 0.02 increases spatial diversity and improves multipath performance. The pattern of spatial diversity of the signal (drive test pattern) of the single patch, i.e, 4x4 MIMO array, shows progressive improvement in the number of spatial beams, directivity, and beamforming. The Total Active Reflection Coeffient (TARC) of the antenna being tested is less than -15 dB, thus the impendance is matched at the output. The S-parameter shows s11 of -10 dB which is an indicator of good matching of impendance, and S21 and S31 are less than 20 dB and -25 dB respectively, indicating good isolation of the MIMO elements. The diversity gain (DG) exceeds 9 dB, reinforcing the antenna's ability to mitigate multipath fading. These results confirm that the proposed 4×4 MIMO Patch Antenna is highly efficient, well-optimized for 5G networks, and outperforms conventional patch antennas in bandwidth, gain, efficiency, and isolation, making it a viable solution for next-generation sub-6 GHz 5G applications.

Scaling this system to larger arrays (e.g., 8×8, 16×16) or higher frequencies introduces significant complexity in design, fabrication, and performance. Larger arrays introduce exponential simulation/fabrication costs, Thermal, coupling, bandwidth trade-offs, and increased reliance on AI and advanced materials. For practical deployment, 5G base stations may adopt this design, while UE devices would need further miniaturization (e.g., meta surface-based MIMO). The system’s complexity grows non-linearly with array size, demanding advanced optimization, fabrication, and thermal management for larger-scale implementations. The paper’s 4×4 design is feasible, but 8×8+ arrays require disruptive innovations.

6. CONCLUSIONS

The proposed 4×4 Hybrid MIMO Patch Antenna for 600 MHz–1 GHz Sub-6 GHz 5G

applications demonstrates significant performance improvements over traditional patch antennas. The integration of miniaturized fractal structures, defected ground structures (DGS), electromagnetic bandgap (EBG) elements, and meta surfaces enhances bandwidth, gain, efficiency, and isolation while maintaining a compact design. The simulated and measured results validate the antenna's enhanced radiation characteristics, with bandwidth exceeding 200 MHz, gain increasing to 12 dB, and efficiency reaching 90%. The mutual coupling reduction through DGS and EBG structures significantly improves isolation, ensuring an envelope correlation coefficient (ECC) of 0.02, which enhances MIMO diversity performance. Additionally, the Total Active Reflection Coefficient (TARC) remains below -15 dB, confirming minimal reflection losses. For future work, further optimizations can be explored to enhance miniaturization, enabling integration into smaller 5G-enabled devices. Advanced materials such as graphene-based conductors could be investigated to increase efficiency and reduce substrate losses. The application of reconfigurable meta surfaces can be studied to allow dynamic beam steering, improving adaptive MIMO performance. Experimental validation under real-world 5G network conditions will provide deeper insights into the antenna's practical deployment and system-level integration. The development of a multi-band version of the antenna for sub-6 GHz and mmWave 5G applications can further extend its usability. This research lays the foundation for compact, high-performance MIMO antennas essential for next-generation wireless communication networks.

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