Compact MIMO Antenna Design with Smallest Element Spacing for High Isolation

Prof.P.B.Sudha Rani [1], Ch. Jahnavi[2], G. Usha Sri [3], B. Sunil Kumar[4], K. Sanjay[5], B. Madhu Priya[6]

[1] Associate Professor, Dept of ECE, NRI Institute of Technology, Agiripalli, Andhra Pradesh

[2,3,4,5,6] Dept of ECE, NRI Institute of Technology, Agiripalli. Andhra Pradesh

***Abstract*:** The rapid evolution of 5G technology requires advanced antenna systems that ensure high isolation, compact design, and efficient performance. This project focuses on the development of a compact MIMO antenna with enhanced isolation for 5G applications. The proposed design integrates innovative isolation techniques, including defected ground structures (DGS), electromagnetic bandgap (EBG) materials, and decoupling networks, to minimize mutual coupling and improve signal integrity. Additionally, optimized element positioning and polarization diversity are employed to enhance spatial multiplexing and reduce envelope correlation. The antenna is designed to achieve high gain, wide bandwidth, and superior diversity performance, making it suitable for compact 5G devices. The design is simulated using HFSS, and extensive parametric analysis is conducted to validate its performance. The results confirm significant isolation improvement, enhanced efficiency, and reliable communication performance, demonstrating the antenna's suitability for next-generation wireless applications.

Keywords: 5G MIMO, High Isolation, Mutual Coupling, DGS, EBG, Decoupling Networks, Spatial Multiplexing, HFSS Simulation, Wireless Communication.

1.INTRODUCTION:

The evolution of wireless communication has led to the rapid deployment of fifth-generation (5G) technology, which is expected to revolutionize mobile networks with ultra-fast data speeds, low latency, and massive device connectivity. The demand for high-capacity communication systems has driven the integration of Multiple-Input Multiple-Output (MIMO) antenna technology, which significantly enhances spectral efficiency, improves signal quality, and increases channel capacity. However, as the number of antenna elements in compact wireless devices increases, challenges such as mutual coupling, interference, and poor isolation arise, which can degrade system performance.

MIMO antennas in 5G systems require compact, high-performance designs that provide high isolation and minimize mutual coupling while maintaining optimal impedance matching and radiation characteristics. Mutual coupling between closely spaced antenna elements can lead to performance degradation, reduced diversity gain, and increased correlation, ultimately affecting the overall efficiency of the wireless system. Therefore, designing a compact MIMO antenna with improved isolation is a critical research area in modern wireless communication.

To address these challenges, this study presents the development of a compact MIMO antenna with enhanced isolation for 5G applications. The proposed design incorporates advanced techniques such as Defected Ground Structures (DGS), Electromagnetic Bandgap (EBG) materials, and decoupling networks to minimize mutual coupling and enhance signal integrity. Additionally, optimized antenna element positioning and polarization diversity are implemented to improve spatial multiplexing and reduce envelope correlation, ensuring stable and high-quality wireless communication.

The proposed MIMO antenna is designed to operate within 5G sub-6 GHz and millimeter-wave (mmWave) frequency bands, achieving high gain, wide bandwidth, and superior diversity performance. The design process involves simulation using High-Frequency Structure Simulator (HFSS) software, followed by extensive parametric analysis to optimize key antenna parameters such as S-parameters, gain, radiation efficiency, and impedance matching. The fabricated prototype undergoes experimental validation using a Vector Network Analyzer (VNA) to confirm its performance in real-world scenarios.

The results of this study demonstrate a significant improvement in isolation, reduced mutual coupling, and enhanced efficiency, making the proposed antenna a suitable candidate for next-generation 5G applications. By integrating innovative decoupling techniques and optimizing the antenna configuration, this research contributes to the advancement of compact MIMO antenna designs for emerging wireless technologies, including Internet of Things (IoT), vehicle-to-everything (V2X) communication, and smart city infrastructure.

2. METHODOLOGY:

A. SINGLE PATCH ANTENNA:

A single patch antenna forms the core of the compact MIMO antenna system, designed for efficient wireless communication in 5G frequency bands. It consists of a radiating metallic patch on a dielectric substrate with a ground plane, ensuring low-profile, directional radiation. The feeding mechanism, such as a microstrip line or coaxial probe, is optimized for impedance matching, minimizing reflection losses and enhancing efficiency.

To improve performance, miniaturization techniques ensure compactness while maintaining high radiation efficiency. Bandwidth enhancement is achieved through methods like slotted patches, stacked configurations, or substrate-integrated waveguides. Mutual coupling in MIMO systems is minimized using Defected Ground Structures (DGS), Electromagnetic Bandgap (EBG) materials, and decoupling networks, improving isolation and reducing interference.

The design undergoes rigorous validation through HFSS simulations and experimental testing using a Vector Network Analyzer (VNA). Key performance metrics such as gain, return loss, isolation, and diversity performance are analyzed to ensure suitability for 5G applications, including IoT, smart cities, and V2X communication. The proposed antenna offers a balance of compactness, high isolation, and wide bandwidth, making it a strong candidate for next-generation wireless networks.

B. TWO-PORT MIMO ANTENNA:

A two-port MIMO antenna system consists of two closely spaced antenna elements designed to operate within the same frequency band while minimizing mutual coupling. This configuration is crucial for improving channel capacity, spatial diversity, and data transmission efficiency in 5G wireless networks.

To enhance isolation between the antenna elements, advanced decoupling techniques such as Defected Ground Structures (DGS), Electromagnetic Bandgap (EBG) materials, and parasitic elements are implemented.

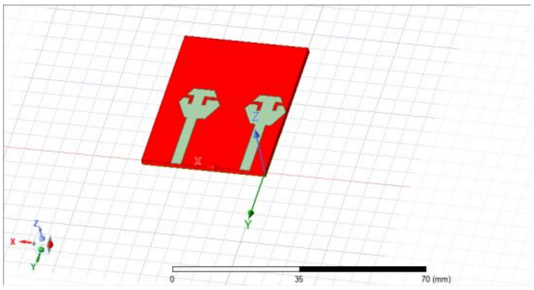


Fig.1: Compact Dual-Element MIMO Patch Antenna

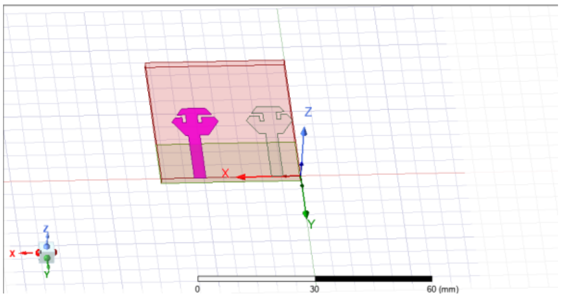


Fig.2: Compact MIMO Patch Antenna with Substrate and Ground Plane View

The proposed two-port MIMO antenna operates at 3.5 GHz and 4.85 GHz, covering key 5G bands. It is designed with optimized element spacing to achieve compactness while maintaining high isolation. The system undergoes simulation using High-Frequency Structure Simulator (HFSS) to analyze critical parameters, including S-parameters, gain, radiation pattern, and envelope correlation coefficient (ECC).

Experimental validation using a Vector Network Analyzer (VNA) confirms significant isolation improvement, stable radiation characteristics, and high efficiency. These features make the two-port MIMO antenna an ideal candidate for modern 5G communication systems, IoT applications, and smart devices requiring reliable wireless connectivity.

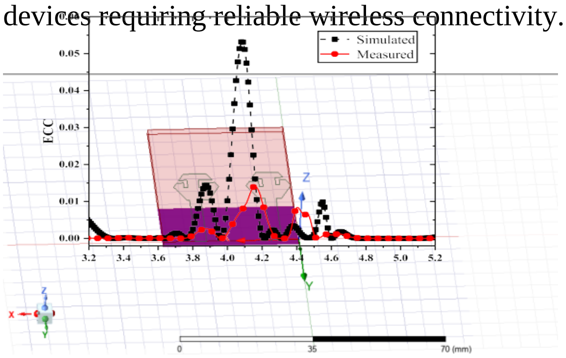


Fig.3: Compact MIMO Patch Antenna with Partial Ground Plane

3. RESULTS AND COMPARATIVE ANALYSIS:

A. S-Parameter:

scattering parameters — also known as S-parameters — refer to the elements in a mathematical matrix describing the behaviour of an electrical network (or circuit) when it is being stimulated by an electrical signal.

At high frequencies (exceeding a few gigahertz), it becomes difficult to measure voltages and currents directly. Consequently, S-parameters describe the input-output relationships of power waves between the ports of an electrical network.

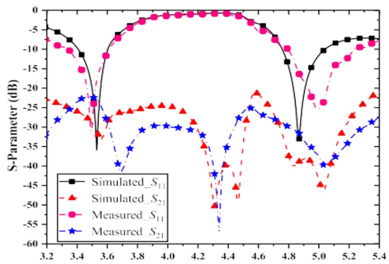
Electrical engineers can apply S-parameters to a wide range of engineering designs, including communication systems and printed circuit boards (PCBs), microwave circuits, and antennas.

B. Envelope Correlation Coefficient(ECC), diversity Gain (DG), Total Affective Reflection coefficient(TARC) and VSWR

ECC is used to show how the radiating elements interact and correlate with one another, which is based on the radiation pattern or s-parameters. According to [10] [5], the ECC is obtained from the s-parameter. The achieved simulated 0.01 in Fig. 9 is due to the improved scattering parameter, but ECC < 0.05 is a critical value suitable for practical applications in general.

$$ECC = |\rho_e(i,j,N)| = \frac{\sum_{n=1}^{N} S_{i,n}^{*} S_{n,j}}{\prod_{k(=i,j)}\left[\sum_{n=1}^{N} S_{i,n}^{*} S_{n,k}\right]}$$

Here, i, j, N =1 to 2 (for two elements)



Diversity combining enhances signal quality but is affected by component interaction. DG, calculated using ECC and Equations 2, ideally reaches 10 dB. The designed MIMO antenna achieves DG between 9.710 and 9.99 dB in simulation and measurements.

$$D.G. = 10\sqrt{1 - {\rho_e}^2}$$

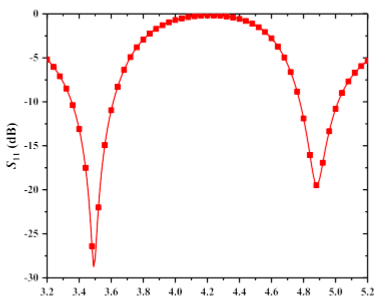
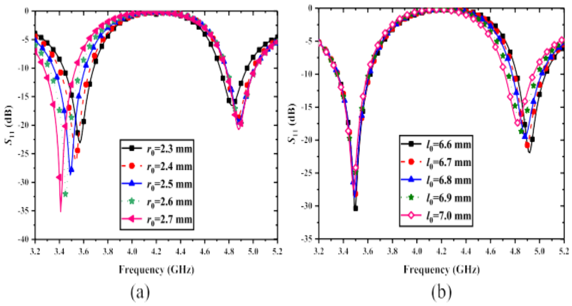


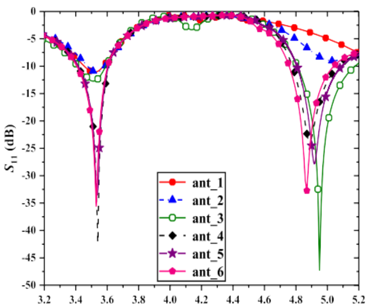
Fig. 7.12**.** The two-port MIMO configuration simulation and experimental results of ECC and DG

TARC is crucial for evaluating MIMO performance, as self-impedance and mutual impedance affect multi-port antennas under random phase excitations. Traditional reflection coefficients may not accurately represent bandwidth and radiation performance.

$$TARC = \Gamma = \frac{\sqrt{((S_{11} + S_{12}e^{j\theta})^2 + (S_{21} + S_{22}e^{j\theta})^2)}}{\sqrt{4}}$$



VSWR: The Voltage Standing Wave Ratio (VSWR) is an indication of the amount of mismatch between an antenna and the feed line connecting to it. This is also known as the Standing Wave Ratio (SWR). The range of values for VSWR is from 1 to ∞. A VSWR value under 2 is considered suitable for most antenna applications. The antenna can be described as having a Good Match.



Gain: The term Antenna Gain describes how much power is transmitted in the direction of peak radiation to that of an isotropic source. Antenna gain is more commonly quoted than directivity in an antenna's specification sheet because it considers the actual losses that occur.

4. CONCLUSION:

This study presents the design and development of a compact MIMO antenna with high isolation for 5G applications. The proposed antenna integrates innovative isolation techniques, including Defected Ground Structures (DGS), Electromagnetic Bandgap (EBG) materials, and decoupling networks, to effectively minimize mutual coupling and enhance signal integrity. Optimized element positioning and polarization diversity further improve spatial multiplexing and reduce envelope correlation.

Simulation and experimental validation confirm that the antenna achieves significant isolation improvement, high gain, and wide bandwidth, making it well-suited for next-generation wireless communication systems. The results demonstrate that the proposed design offers enhanced efficiency, stable radiation characteristics, and reliable performance in compact 5G devices.

Overall, this research contributes to the advancement of MIMO antenna technology by providing a compact, high-performance solution for modern wireless applications, including 5G, IoT, and smart communication systems. Future work could explore further optimization techniques and integration into emerging 6G networks.

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