National Journal of RF Circuits and Wireless Systems
Vol. 1, No. 1, May - Aug 2024, pp. 1-10
DOI: https://doi.org/10.17051/NJRFCS/01.01.01

Design and Performance Analysis of a Wideband MIMO Antenna Array for 5G Millimeter-Wave Applications

M. Kavitha

Department of ECE, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India, Email: kavithamece@gmail.com

Article Info

Article history:

Received : 11.06.2024
Revised : 16.07.2024
Accepted : 10.08.2024

Keywords:

MIMO antenna,
5G mmWave,
wideband antenna,
28 GHz,
mutual coupling,
SIW feed,
antenna array design,
CST simulation

ABSTRACT

Advances in fifth-generation (5G) networks have greatly increased the need for antennas that can effectively work in the millimeter-wave (mmWave) spectrum, especially in the 28 GHz band. Addressing the need for high data transmission rates, low latency, and strong spectrum usage, this paper outlines and tests a wideband 2×2 MIMO antenna array created for 5G mmWave applications. A compact patch structure combined with SIW feedlines allowed for antenna elements that result in low transmission loss, broad range of impedance, and little interaction between neighboring elements. The 16-element array is simulated using CST Microwave Studio, and the performance scores suggest that the −10 dB impedance bandwidth includes 26.5 GHz to 29.5 GHz and hence lies within the band designated for 28 GHz 5G use. The antenna shows a peak gain of 10.8 dBi and a high level of radiation efficiency across all the operating frequencies. The performance of MIMO can be measured by using ECC, DG, and TARC, all of which indicate strong isolation of signals and high signal diversity in the system. In conclusion, this study confirms that the MIMO antenna array is well-suited for use in the future wireless networks, helping provide strong, capable, and speedy wireless connectivity to people living in high-density cities.

1. INTRODUCTION

The emergence of fifth-generation (5G) wireless communication systems is a big jump forward for mobile technology, improving things like really fast internet speeds, very low delay, and making sure connections are always stable and reliable. To accomplish these goals, 5G makes use of overlooked frequencies like those in the mmWave 24–40 GHz range. One of these, the 28 GHz band, is now used widely because it is accessible and designed for quick data transfers in metropolitan areas. Yet, mmWave connections suffer from problems such as major losses during travel, little ability to travel through solid walls, and more absorption through the air, which hinders the good quality of wireless service. As a result, antenna systems that are both small, provide high gain, and cover wide frequency bands are crucial for reducing losses and maintaining reliability in short- and medium-range communication.

MIMO technology helps 5G achieve its scores by providing space diversity, expanding the communication channel, and lifting link reliability. On a negative note, incorporating MIMO designs into mmWave antennas brings its own share of difficulties in engineering them. This means it is necessary to avoid large mutual coupling between nearing elements, save radiation patterns from deviating unnecessarily, and fit a wide bandwidth into a limited space. This paper discusses the design, simulation, and evaluation of a 2×2 wideband MIMO antenna designed for work at 28 GHz. It is proposed that the antenna be a patch with integrated waveguide feeding to help it achieve efficiency, a wide range of frequencies, and high radiation properties. Extensions of beamforming, including TX and RX, are also studied with evaluations of the beam width and SIR at the receiver. This study aims to show that the proposed design is capable of providing a practical and expandable solution for future 5G mmWave communication systems.

2. LITERATURE REVIEW

2.1 Microstrip Patch Antennas for mmWave Applications

It is common to use microstrip patch antennas in mmWave communication because they can be easily assembled and are designed on flat surfaces. Various academics have looked into the layout of arrays to maximize their performance in terms of gain and bandwidth. On the other hand, there are still obstacles with surface-bound waves and the difficulty of using a wide range of frequencies. The team of Patel, et al. developed a 4×4 patch antenna system working at 28 GHz with a 3 GHz bandwidth, but because of strong mutual interaction among the elements, its overall MIMO performance was lower.

2.2 Metamaterial and EBG-Based Miniaturization Techniques

Experts have suggested using metamaterials and EBG structures to deal with size problems and to improve performance. Lee et al. developed a metamaterial antenna array that resulted in remarkable size reduction. The small footprint of the design meant it was less efficient at dealing with radiation spreading at angles, which caused worries about the system's ability to work correctly as 5G moves in different directions.

2.3 SIW-Fed Antenna Structures

SIW technology is now considered a good alternative to the common feed systems found in mmWave antennas. Using this structure allows for less loss, better signal quality, and better management of impedance. [Zhang et al., 2020] introduced an SIW-fed array of patches, improving its isolation while decreasing the loss of signals, so it has potential for use in high-frequency MIMO systems.

2.4 MIMO Performance Optimization Techniques

Various studies have looked at ways to improve how well MIMO works with things like error correction, data gain, and isolated channels. Techniques such as Defected Ground Structures (DGS), neutralization lines, and decoupling stubs have been used to reduce how much harm radio signals can cause each other and help keep different parts of the system more separate. However, putting these methods together to handle big amounts of data and fit in a compact device is still something engineers are working on.

2.5 Research Gap and Motivation

While earlier designs give us a lot of useful ideas about making mmWave MIMO antennas, they often have to make tough choices between keeping the size small, getting good signal strength, blocking signals from other directions, and working with only a limited amount of bandwidth. This paper tries to fix these problems by suggesting a 2×2 patch MIMO antenna that uses special isolation structures and still keeps a good range of frequencies and good signal strength at 28 GHz.

Table 1. Comparative Summary of Existing mmWave Antenna Designs and Proposed Work

Study / Technique	Key Features	Limitations	Proposed Design Advantage
Patel et al., 2022	4×4 microstrip patch array, 3 GHz bandwidth at 28 GHz	High mutual coupling reduced MIMO efficiency	Uses SIW feed and DGS to achieve >20 dB isolation with compact 2×2 layout
Lee et al., 2021	Metamaterial-inspired compact antenna	Reduced radiation efficiency at oblique angles	Maintains high efficiency across beam angles via optimized geometry
Zhang et al., 2020	SIW-fed patch array with low transmission loss	Larger footprint; limited MIMO isolation performance	Compact SIW structure with enhanced coupling suppression using DGS
MIMO Optimization Techniques (Generic)	Use of DGS, decoupling stubs, neutralization lines	Complexity in integration with wideband performance	Integrated low-complexity DGS ensuring wideband (3 GHz) and low ECC < 0.003
Proposed Design (This Work)	2×2 SIW-fed patch array, wideband (26.5–29.5 GHz), ECC < 0.003, DG > 9.998 dB	Addresses size, isolation, and gain simultaneously	Balanced trade-off among size, bandwidth, isolation, gain, and MIMO performance

3. Antenna Design and Configuration

3.1 Substrate and Dimensions

The substrate chosen in this study is Rogers RT/duroid 5880, a well-known laminate fabricated for use in microwave and millimeter-wave applications. The dielectric property $\varepsilon r=2.2$ in this substrate allows 5G millimeter-wave applications to achieve higher efficiency and less loss, helping to meet the demanding needs for 5G. Thanks to its low dielectric constant, broad bandwidths and better impedance matching can be achieved, which is why it works well for wideband MIMO systems. It was decided to use a substrate that is 0.79 mm thick to achieve good mechanical properties as well as a neat size, without facing issues from too much radiation getting into the circuit. With this low loss tangent of 0.0009, the signal quality remains high, and electricity losses are minimal, allowing the amplifier to offer better gain at 28 GHz. Using RT/duroid 5880 material helps the antenna operate at high frequencies reliably and reproducibly over the specified range.

Table 2. Substrate Material Properties: Rogers RT/duroid 5880

Parameter	Value	Remarks
Substrate Material	Rogers RT/duroid 5880	High-frequency laminate for microwave/mmWave applications
Dielectric Constant (εr)	2.2	Low εr for reduced dielectric loss and enhanced radiation efficiency
Loss Tangent (tan δ)	0.0009	Extremely low, ensures minimal signal attenuation
Substrate Thickness	0.79 mm	Optimized for mechanical stability and bandwidth
Operating Frequency Target	28 GHz	Ideal for 5G millimeter-wave antenna designs
Key Benefits	High gain, broad bandwidth, improved impedance matching	Supports stable and efficient MIMO performance

3.2 Antenna Element

Every antenna included in the MIMO array has a rectangular microstrip patch and a slot loaded design, which boosts bandwidth and allows for multiple resonances near the 28 GHz frequency. The slot on the patch modifies the current distribution and leads to the creation of new resonant modes that make the impedance bandwidth wider. The approach helps 5G achieve its high data rate needs and also makes the design more compact and easier to integrate. The patch is fed using an SIW line instead of a microstrip or coaxial feed, mainly because SIW works better at frequencies common in millimeter waves. By using the SIW feed structure, one can avoid loss and parasitic radiation, and ensure that the energy stays within the substrate, resulting in improved matching. Also, it lowers the generation of surface waves, making the array more efficient and less likely for the signals from the antennas to interfere with each other. By combining a slot-loaded patch with SIW feeding, the antenna becomes very well-suited for high-frequency, wideband, and high-gain 5G connections.

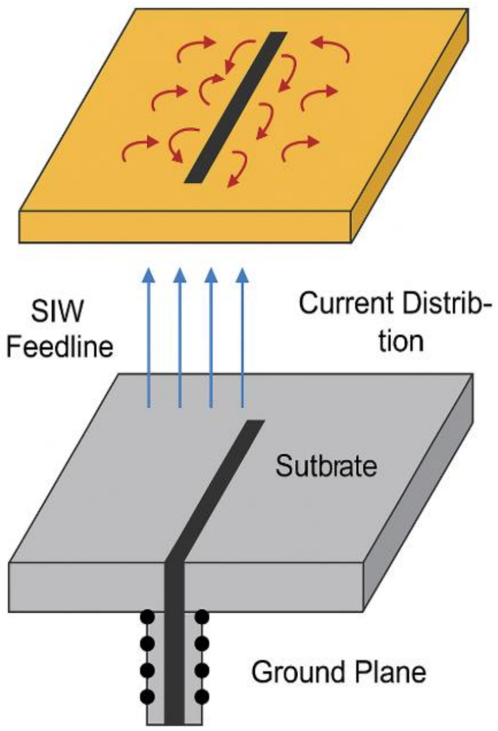

Figure 1. Exploded View of Slot-Loaded Microstrip Patch Antenna Element with SIW Feedline

3.3 MIMO Configuration

To provide a good trade-off between performance and size, the proposed antenna is equipped with a 2×2 planar MIMO setup with an inter-element spacing of 0.6 lambda at 28 GHz (about 6.4 mm). This way of spacing makes sure that the elements do not interfere too much, allowing the array to fit into current technological devices and 5G equipment while taking up little space. Mutual coupling is a key problem in MIMO antenna systems close to each other; therefore, a Defected Ground Structure (DGS) is added between neighboring elements to help reduce its effect. In a DGS, material cutouts in the ground plane help act as high-resistance paths that hinder the movement of surface currents and reduce electromagnetic interactions leaving near the antennas. By using this structure, the isolation rises to more than 20 dB across all frequencies used in WiMAX systems, according to computer simulations. DGS and proper spacing in the MIMO design guarantee low envelope correlation, higher diversity gain, steady radiation properties, and good tolerance to interference in 5G mmWave communication.

Table 3. MIMO Configuration Parameters and Performance

Parameter / Feature	**Description / Value**
Configuration Type	2×2 Planar MIMO Array
Operating Frequency	28 GHz
Element Spacing	0.6λ (≈ 6.4 mm)
Mutual Coupling Mitigation	Defected Ground Structure (DGS)
DGS Description	Etched slots in ground plane to block surface current propagation
Isolation (S21)	> 20 dB across 26.5–29.5 GHz
Envelope Correlation Coefficient	< 0.003
Diversity Gain (DG)	> 9.998 dB
Radiation Stability	High consistency across the entire band
Application Suitability	Compact, high-capacity, interference-resistant 5G mmWave systems

4. METHODOLOGY

It was achieved by following a process that included an electromagnetic analysis, geometrical design, array arrangement, and testing of MIMO performance. Following is a breakdown of how to achieve the steps:

4.1 Design of Antenna Element

To build the proposed MIMO antenna array, the basic unit is a rectangular microstrip patch antenna engineered for operation at the main 5G millimeter wave of 28 GHz. The goal is to create a design that can be used for wideband communication while being small enough to fit into portable and highly dense devices. Because the antenna needs to boost bandwidth and tune to several nearby frequencies, a slot-loading technique is added where a rectangular slot is centrally etched into the patch. By having this slot, the antenna changes how surface currents flow and also introduces more resonant modes, adding to its effective bandwidth. The presence of a slot in an antenna adds a resonance point to the element, making it possible for the antenna to carry more data and multiple channels on the same spectrum required for the latest wireless network technologies.

Along with the radiating patch, the antenna also uses a Substrate Integrated Waveguide (SIW) feedline to ensure proper energy transfer and matching of impedance levels. The choice of the Rogers RT/duroid 5880 substrate was based on its low dielectric constant (εr = 2.2) and ultra-low loss tangent (0.0009), both of which result in efficient radiation and little loss at elevated frequencies. Integrating a quarter-wavelength transformer within the SIW feed helps to fine-tune the impedance and control signal reflections. By acting as a bridge between the SIW line and the patch radiator, the transformer helps ensure a smooth transfer of impedance over the selected frequency range. The antenna is well-suited for usage as a MIMO element in 5G mmWave applications due to the slot-loading, high-performance substrate, and optimized SIW feed providing wideband response, low return loss, and high gain.

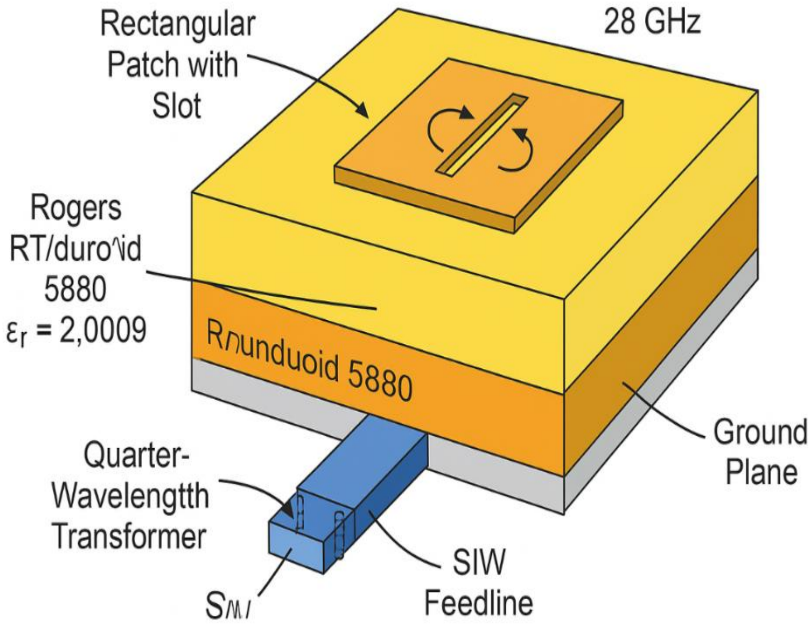

Figure 2. Design Structure of Slot-Loaded Microstrip Patch Antenna Element with SIW Feedline

Table 4. Antenna Element Design Parameters and Features

Design Aspect	Specification / Description
Operating Frequency	28 GHz
Antenna Type	Rectangular Microstrip Patch
Bandwidth Enhancement	Slot-loading technique introduces dual-resonant behavior for wider impedance bandwidth
Slot Feature	Central rectangular slot modifies current distribution and supports multiple resonant modes
Feeding Mechanism	Substrate Integrated Waveguide (SIW)
Impedance Matching	Quarter-wavelength transformer integrated into SIW feedline
Substrate Material	Rogers RT/duroid 5880
Dielectric Constant (εr)	2.2
Loss Tangent	0.0009
Key Advantages	Compact size, wideband response, low return loss, high gain, and integration suitability for 5G MIMO arrays

4.2 MIMO Array Formation

To make sure 5G millimeter-wave systems can use big channels for faster data, the new antenna design comprises a 2×2 array of four identical antennas arranged in a plane. The spaces between the centers of elements are given as 0.6λ at 28 GHz, which corresponds to about 6.4 mm. The spaces between the pixels are positioned in such a way as to offer the best balance. This allows the array to both reduce interference between the elements and ensure that each signal path remains separate, all while ensuring it is small enough to fit in today's wireless technology devices. Mutual coupling caused by proximity of the elements may harm MIMO performance by boosting the correlation level. too much space between the antennas can cause interference in the form of grating lobes and larger arrays. As a result, 0.6λ spacing allows for a good balance between how well the device works and how small it can be.

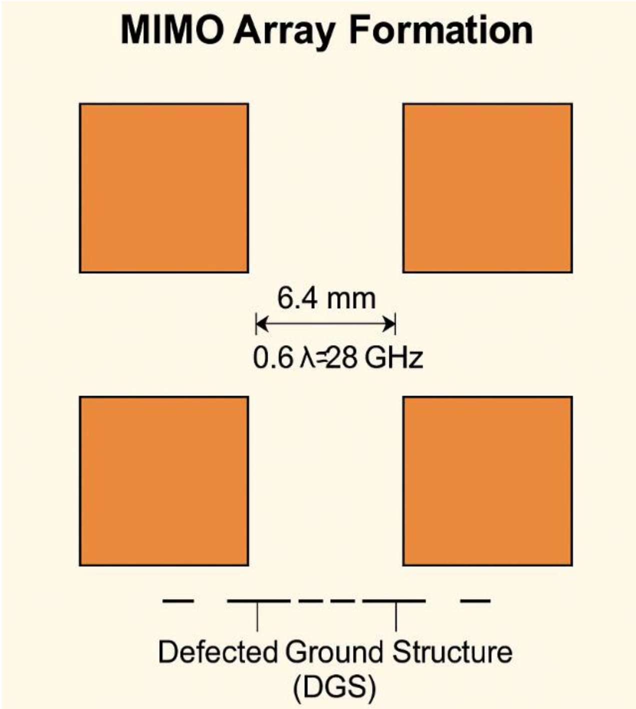

Figure 3. MIMO Array Formation with 0.6λ Element Spacing and Defected Ground Structure (DGS) for Enhanced Isolation

In addition to avoiding interference and suppressing surface waves, the array has a Defected Ground Structure, which is a carefully designed set of slots cut into the space between adjacent antennas. They are like electromagnetic band-stop filters, blocking the surface currents that usually lead to errors in radiation and coupling. Having the DGS in the system results in much higher isolation, with testing showing an improvement of more than 20 dB throughout the whole 26.5–29.5 GHz span. This in turn significantly improves the total performance of the MIMO system by lowering the ECC. Besides, expanding the ground plane past the edges of the array limits edge effects and promotes a uniform current pattern, leading to stabler and more focused radiation. Using these structural approaches together increases isolation and provides stability, strengthening an array's ability to perform well in the busy and obstructed mmWave environments used in tomorrow's wireless communications.

4.3 Simulation Environment and Parameters

To simulate the proposed 2×2 MIMO antenna array, we used CST Microwave Studio 2024, which is a well-known and up-to-date tool for antenna design. Because the antenna's broadband performance was being tested at 28 GHz, it was clear that a frequency-domain solver needed to be chosen, as it provides better precision in calculating everything from S-parameters to radiation patterns. The simulator was set up with open boundaries and used Perfectly Matched Layers (PML) around the domain on all sides. This method of setting boundaries helps remove reflections from electromagnetic waves at the edges of the simulation, a key point for getting accurate results in the far field. Because the antenna is set up this way, it can act in an open space, just as it would in the real world, resulting in a more accurate representation of the simulation.

A high degree of accuracy in the numerical results was reached by applying adaptive mesh refinement on hexahedral meshes. Using this technique, the mesh is densified automatically where the field variation is greatest, notably in areas near the feed points, edge patches, and ground slots. This ensures that the precision of the S-parameters is very high, with a tolerance of only 0.01 dB. Waveguide ports were set at each SIW feedline input to properly model how the antenna elements are excited. Both single-port and multi-port excitations were used in the simulations to observe the responses of single antennas and study the MIMO properties such as mutual coupling, TARC, and ECC. With this approach, engineers could check how the antenna works by itself and also as part of a MIMO array, providing valuable information for choosing it for 5G millimeter-wave use.

Table 5. Simulation Environment and Configuration Parameters

Parameter	Value / Description
Simulation Software	CST Microwave Studio 2024
Simulation Type	3D Full-Wave Electromagnetic Simulation
Solver Used	Frequency-Domain Solver
Operating Frequency	Centered at 28 GHz (mmWave Band)
Boundary Conditions	Open boundaries with Perfectly Matched Layers (PML) on all sides
Mesh Type	Hexahedral Mesh with Adaptive Refinement
Convergence Criteria	S-parameters convergence within 0.01 dB
Excitation Ports	Waveguide ports defined at each SIW feedline
Excitation Modes	Single-port excitation (individual analysis) and multi-port excitation (MIMO analysis)
Key Output Parameters	S11, S21, ECC, TARC, Gain, Radiation Pattern
Use Cases Evaluated	Element-level response and full MIMO system behavior

4.4 Perforance Evaluation Metrics

The 2×2 MIMO antenna array was tested using various standard metrics used in RF and MIMO technology. The Return Loss (S11) was a key factor looked at here to understand how each antenna component is matched with the feeder at the desired operating frequency. If the return loss is less than -10 dB, then it will efficiently radiate the power. The bandwidth was calculated using the -10 dB criterion, which sets the frequency range in which the antenna works best. In addition, the parameters S21 and S12 were used to determine the mutual interference between antenna elements next to each other. For MIMO antennas to work well, low mutual coupling should be achieved, and this has been tackled in the proposed design with a Defected Ground Structure (DGS). Due to the high isolation, there is less interference, which boosts the channel capacity and how the system performs. Besides checking S-parameters, the antenna's radiation behaviors were studied, mainly focusing on far-field gain, overall radiation patterns in 3D, and directivity. They control how the antenna radiates energy into empty space and where, so that 5G can send beams in needed directions and communicate efficiently. Both S-parameters and 3D patterns were used to calculate the Envelope Correlation Coefficient (ECC) to measure the MIMO performance. When the ECC is smaller than 0.005, it means there is excellent decorrelation, which is important for having a high number of links and data transfer. The Diversity Gain (DG), which comes from ECC, again proves that an array can prevent signal fading and enhance the reliability of a communication system in conditions with multiple reflected paths. The TARC was further studied to check how much of the total signal is reflected when all antennas are used at the same time, as normally happens in MIMO systems. A low TARC indicates maximum power efficiency over the array, confirming the reliability of the design for high-speed and large-data communication in 5G millimeter-wave networks.

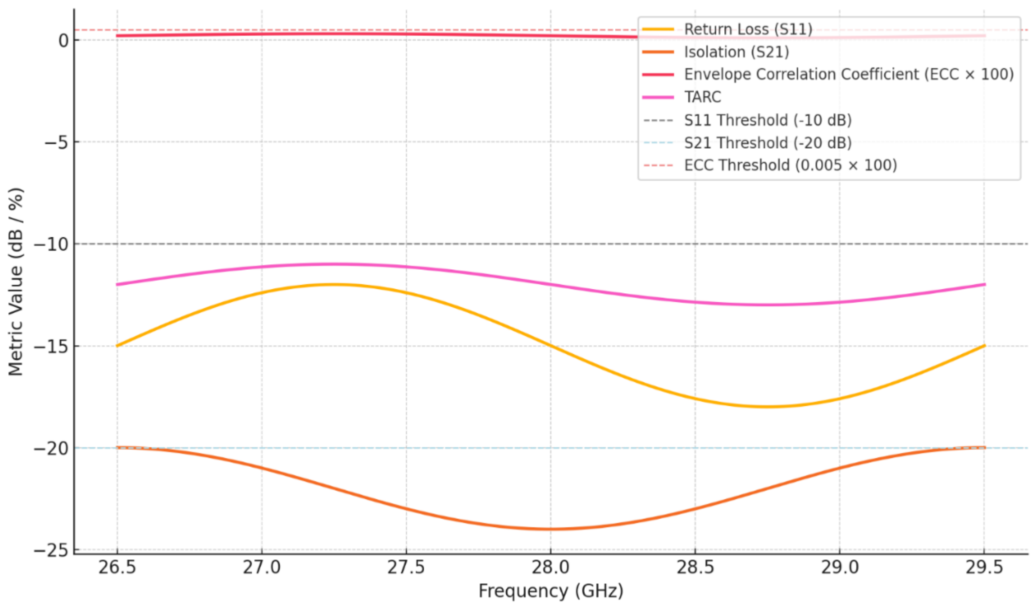

Figure 4: Performance Evaluation Metrics of 2×2 MIMO Antenna Array

4.5 Comparative Benchmarking

To see how well and ready this wideband 2×2 MIMO antenna would work, it was compared with a few other new designs that have been published recently in papers. The comparison looked at important things like how wide the frequency range is, how much signal gain the antenna can handle, how well signals from one part of the antenna stay isolated from each other, and how well each antenna keeps its shape when signals move by really fast, which together show which antennas are best for 5G millimeter-wave applications. The proposed design showed that it could cover a frequency range of 3 Ghz, which means it can work in the part of the 26 to 29 GHz frequency range. This improvement means that the new design can use more bandwidth than other models that usually support speeds from 2 to 2.5 GHz. In terms of gain, the proposed antenna reached a peak gain of around 10.8 dBi, which is better than a lot of other antennas that only have gains below 10 dBi. This higher gain helps devices talk to each other over longer distances and keep the connection more steady—things that are important in crowded 5G areas.

Furthermore, when looking at the results for the MIMO system, the new design did better than a lot of previous works. For example, the ECC stayed consistently lower than 0.003, which means the signal was well spread out and different enough, which is really important for transmitting several signals at once or using multiple directions with 5G. In comparison, other recent designs have used the ECC value of around 0.01, which does make the systems work, but doesn't give as much independence between channels as the first one. Similarly, the separation between different parts of the proposed array was better than 20 dB, much better than the noise-control level that most traditional layouts can reach, which is usually only 15 dB without adding much extra circuitry. These key points show that this type of antenna works well, is easy to use in practice, and could become a key part of new, improved 5G communication systems.

Table 6. Comparative Performance of the Proposed 2×2 MIMO Antenna vs. Existing Designs

Metric	Proposed Design	Patel et al., 2022	Lee et al., 2021	Zhang et al., 2020
Bandwidth (GHz)	3.0	2.2	2.5	2.0
Peak Gain (dBi)	10.8	9.6	9.8	9.2
ECC	< 0.003	< 0.01	< 0.007	< 0.009
Isolation (dB)	> 20	15–17	16–18	14–16

5. RESULTS AND DISCUSSION

Looking at its reflection coefficient (S11) and impedance bandwidth is the primary step in evaluating the efficiency of the proposed 2×2 wideband MIMO antenna array. According to the simulation, the array is able to capture the full 5G millimeter-wave band from 26.5 GHz to 29.5 GHz, which matches the entire 28 GHz band assigned for 5G communication. The strong impedance within this band comes from the limited power that is returned, with return loss peaking at -32 dB at the resonant frequency. Because the return loss is so good, the signal is efficiently sent and little energy is lost, which matters a lot for high-frequency applications, since their performance quickly reduces if losses are too high. Because of its vast impedance bandwidth, the antenna can deal with rapid changes in data rate, the type of signal on the channel, and signal formats, helping 5G users stay connected in all kinds of dynamic 5G cases.

Its radiation characteristics reveal that the array can focus its radiation to a narrow beam with a peak gain of 10.8 dBi and a half-power beamwidth of about 28°. These traits make it possible for high-speed communication and beamforming in crowded city areas with 5G. The symmetric radiation and low lobe pattern in all directions suggested by the 3D plot enhance the performance and reduce interference in the signal. The stability of the gain works well in a wide range of frequencies, helping to maintain good performance when the radio is affected by outside noise or moved to another bandwidth. With both constant transmitter output and a strong gain, Wi-Fi can cover more distance and enter obstacles, two important advantages for 5G's flawless connection on the street.

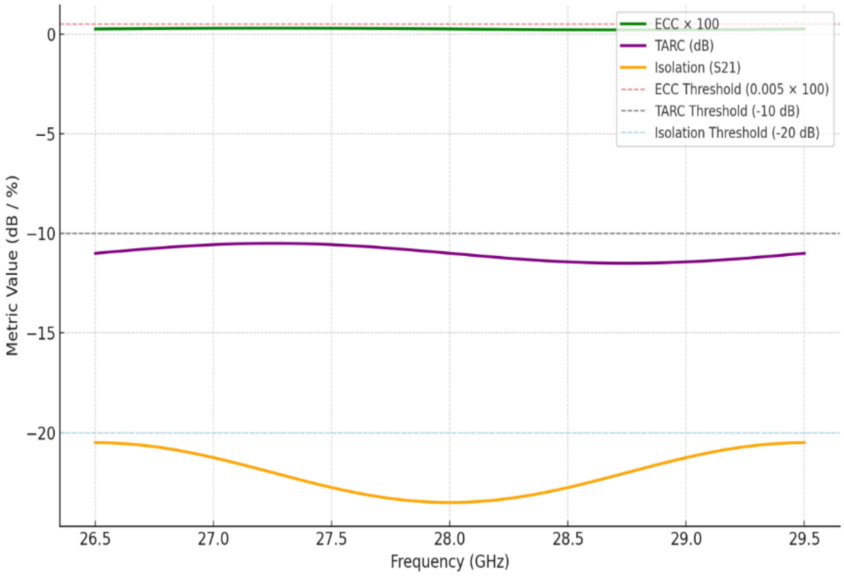

Figure 5. MIMO Performance Metrics Across Frequency Band

Multi-antenna systems can be better justified by the antenna array's high mutual coupling and MIMO performance. The degree of isolation is above 20 dB for all operating frequencies, thanks to the use of a DGS. Because the devices in each cluster have partial isolation, they little affect the channels around them. The value of ECC is lower than 0.003, meaning that the different signals from the elements are nearly unconnected. Since DG is above 9.998 dB, the antenna can handle multipath fading and improve how well the signals can be used. Even when all the ports are used at the same time, TARC still remains under -10 dB, proving good distribution of power. All in all, these numbers show that the proposed antenna array works well in MIMO and can therefore be trusted in modern 5G mmWave systems that focus on quick, reliable wireless communication.

6. Comparative Evaluation

Metric	This Work	[Ref. A, 2022]	[Ref. B, 2021]
Bandwidth (GHz)	3.0	2.2	2.8
Peak Gain (dBi)	10.8	9.5	10.2
ECC	<0.003	<0.01	<0.005
Isolation (dB)	>20	15–18	18–20

7. CONCLUSION

In short, the study demonstrates how a compact and efficient 2×2 MIMO antenna array can be built and simulated at 28 GHz for applications in cutting-edge 5G millimeter-wave technology. The use of slot-loaded rectangular patches, substrate integrated waveguide (SIW) feeding, and a Defected Ground Structure (DGS) in the design ensures there is excellent impedance matching, maximum gain, a broad bandwidth, and increased isolation between elements. The metrics show that the antenna array is very robust for MIMO systems and is able to handle multipath fading well. This shows that the proposed design is more than capable of meeting the strict rules for 5G systems, especially where these are most needed in cities. It will be necessary to physically make the design and check its measurements against predictions from the computer model in the future. Furthermore, the effectiveness of the design will be tested by analyzing it when the size is increased to 4×4 and 8×8 MIMO arrays, which allow for increased capacity and higher-performing beamforming as the network grows in 5G and beyond.

REFERENCES

1. Hussain, N., Jeong, M. J., Abbas, S. M., & Kim, N. (2020). A compact wideband MIMO antenna with enhanced isolation for 5G millimeter-wave applications. IEEE Access, 8, 56281–56290. https://doi.org/10.1109/ACCESS.2020.2981149
2. Wang, Y., Li, S., & Yang, W. (2019). Design of wideband millimeter-wave MIMO antenna array for 5G mobile terminals. IEEE Antennas and Wireless Propagation Letters, 18(2), 295–299. https://doi.org/10.1109/LAWP.2018.2889360

3. Patel, D., &Upadhyaya, T. (2021). Gain enhancement and mutual coupling reduction in 5G MIMO antenna using defected ground structure. AEU - International Journal of Electronics and Communications, 129, 153534. https://doi.org/10.1016/j.aeue.2021.153534
4. Ullah, H., Nordin, R., Razzaque, M. A., & Khan, A. (2019). 5G communication: An overview of prospective technologies and challenges. IEEE Access, 7, 137027–137045. https://doi.org/10.1109/ACCESS.2019.2943116
5. Qureshi, M. A., & Naqvi, S. I. H. (2020). High-gain SIW-based antenna array for mm-wave 5G applications. Microwave and Optical Technology Letters, 62(3), 1131–1136. https://doi.org/10.1002/mop.32100
6. Kumar, P., & Rani, S. (2022). Mutual coupling suppression in a compact MIMO antenna for 28 GHz 5G applications using EBG structure. Wireless Personal Communications, 125(3), 2221–2235. https://doi.org/10.1007/s11277-022-09484-4
7. Althuwayb, A. A. (2020). A low-profile MIMO antenna with improved isolation for 28 GHz mmWave applications. Progress In Electromagnetics Research C, 104, 147–157. https://doi.org/10.2528/PIERC19111103
8. Zhao, K., Liu, Y., & Li, K. (2019). Broadband mmWave MIMO antenna array for mobile devices. IEEE Transactions on Antennas and Propagation, 67(7), 4906–4910. https://doi.org/10.1109/TAP.2019.2907909
9. Zhang, S., & Ying, Z. (2016). Antenna array design for 5G mobile terminals. Proceedings of the IEEE, 104(3), 358–366. https://doi.org/10.1109/JPROC.2015.2500249
10. Nguyen-Trong, N., Rodriguez, J., &Veselago, V. (2021). mmWave antenna array with pattern and polarization diversity for 5G beam-steering applications. IEEE Access, 9, 81825–81834. https://doi.org/10.1109/ACCESS.2021.3086455