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A Dual-Port Wideband MIMO Antenna for Sub-6GHz 5G Applications

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Abstract

This paper presents a dual-port multiple-input multiple-output (MIMO) antenna designed for sub-6 GHz fifth generation (5G) applications. The MIMO antenna features a defected rectangular microstrip patch and a partially grounded structure, contributing to excellent radiation characteristics and superb isolation. It is constructed using Roger-RT5880 substrate's material, which has a relative permittivity (εr) =2.2 and a loss tangent (δ) =0.0009. The dimensions of the antenna are 35 × 90 × 1.5 mm³. The antenna's performance was tested using Computer Simulation Technology (CST), demonstrating operation over a wide frequency bandwidth from 2.76 GHz to 8 GHz, with two operating frequencies at 3.5 GHz and 5.8 GHz. MIMO antenna exhibited strong diversity characteristics, achieving a gain > 4.5 dBi. The results of the simulation were validated, showing an envelope correlation coefficient (ECC) <0.001, a diversity gain (DG)=10 dB, a channel capacity loss (CCL)<0.2 bits/sec/Hz, a mean effective gain (MEG)=-6 dB, and a total active reflection coefficient (TARC)< -10 dB across the bandwidth (BW). These results meet MIMO performance standards satisfactorily. The outstanding effectiveness and performance of the antenna, combined with its compact size, highlight its potential suitability for 5G communication networks.

Keywords: *MIMO antenna; two-port antenna; Sub-6 GHz; 5G applications.*

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1. Introduction

The past two decades have seen significant advancements in the wireless communication industry. Due to the COVID-19 pandemic, billions of wireless communication devices have been utilized, making the transition to 5G technology crucial (Kumar et al., 2024). 100 times faster data rates are possible with 5G technology than the 4G network, thanks to a superior spectrum with lower latency, enhanced bandwidth, and the capacity for beam steering and forming. This technology enables the creation of a new type of network that connects machines, objects, and gadgets enabling virtually everyone and everything to communicate (Ali et al., 2024). A wideband is a transmission channel that operates continuously over a wide passband and has a wider bandwidth than a single voice channel. However, efficient deployment of 5G technologies necessitates using efficient and compact antennas (Sheik et al., 2020).

The rapid evolution of wireless communication technology has ushered in the era of fifth-generation (5G) networks, creating an unprecedented demand for high-performance antenna systems. These systems are essential for achieving faster data rates, superior spectral efficiency, and expansive bandwidths. The sub-6 GHz spectrum stands out as a vital asset for 5G, striking an optimal balance between extensive coverage and exceptional capacity. This mid-band frequency range ensures reliable connectivity in both indoor and outdoor settings while significantly reducing latency. Such performance is critical for transformative applications like augmented reality, real-time video streaming, and industrial automation, positioning 5G as a catalyst for innovation across countless industries (Ahmed et al., 2025).

The 5G network uses two frequency ranges: sub-6 GHz and the millimeter wave range. Due to its ability to work with existing 3G and 4G networks, its long-distance coverage, and its resistance to obstacles, the sub-6 GHz range has garnered more attention. To this end, a microstrip patch antenna is a great option as it is low profile, cost-effective, easy to fabricate and feed, lightweight, and can be used in an array, satellite communications, missiles, cellphones, telemedicine, radar, GPS, and biomedical systems (Kumar, et al., 2020).

The antenna's ground and patch are set up on either side of a dielectric substrate in one particular antenna design known as a microstrip patch antenna. The substrate material is utilized to provide mechanical support and to ensure the required precise spacing between the patch element and its ground plane (Chattha, H. T. 2019).

An antenna's design could be composed of single or multiple-arrangement antennas. MIMO antenna systems have emerged as an effective solution to overcome the limitations and meet the high-speed demands of modern communication systems (Khan et al., 2022). Design arrangement involves positioning several antenna elements on a single substrate and feeding each antenna through a port. Each of these ports is capable of transporting a portion of the system's data and operating at the same carrier frequency (Malviya et al., 2020).

Despite the remarkable progress made in the development of 5G station antennas, it is evident that the current designs do not fully meet all the requirements of the 5G framework. For example, the antenna design suggested in references 3 and 4 faces manufacturing challenges and does not support MIMO technology.

The arrangement of radiating elements is crucial for enhancing isolation in MIMO (Multiple Input Multiple Output) systems. A MIMO system that utilizes dielectric resonators has been proposed for wideband applications [Upadhyaya et al., 2023). In this setup, isolation is significantly improved by using parasitic patches and positioning the radiative elements diagonally. This dielectric resonator MIMO antenna also exhibits circular polarization (Baz et al., 2023). Furthermore, this MIMO configuration allows the conducting ports to be arranged directly opposite one another, rather than in the traditional orthogonal placements. Incorporating slots systematically can further enhance performance. Notably, previous studies in (John et al., 2024). have proposed antennas designed specifically for dual-band and 5G/Wi-Fi/WLAN applications, demonstrating the versatility of these designs. Analysis presented in (Jia et al., 2022) has shown how MIMO systems can greatly enhance channel capacity, highlighting their potential in advanced communication technologies. The literature review highlights several important factors in MIMO system design. Evidence suggests that mutual coupling between conducting patches can significantly diminish antenna performance. Achieving optimal isolation is essential for satisfactory outcomes, with an ideal isolation level of approximately 20 dB. At the same time, it is crucial that key output parameters such as gain, efficiency, and radiation patterns remain within acceptable limits. This underscores the need for careful management of these parameters to ensure robust performance in MIMO systems.

In reference (Ahmed, R., & Islam, M. F. 2014), the authors unveiled a microstrip patch antenna design that achieves a bandwidth ranging from 2.84 to 5.17 GHz, paired with a high impedance of 58% and a central frequency of 4 GHz. This design not only delivers a consistent radiation pattern but also boasts a compact form factor and an average gain of 5 dBi, making it an exceptional choice for a variety of applications. Nevertheless, this significantly impacts the antenna's compactness because the MPA's main structure comprises a dual layer, with a 1st layer comprising triple elements. (Zhao, A., & Ren, Z. 2018) presents a compelling a compact 8-antenna MIMO system, showcasing its remarkable self-isolation properties. These attributes have been validated through rigorous simulations and measurements, proving that effective antenna isolation can be achieved without relying on external isolation elements or complex decoupling techniques. However, this innovative design operates within a limited frequency band of 0.2 GHz (from 3.4 to 3.6 GHz) and boasts an antenna efficiency of less than 70%. These constraints significantly hinder its potential to support a wider range of applications in the realm of 5G technology.

(Chung, M. A., et al., 2025) presents a multi-band antennas that can be configured for laptops, base stations, and smartphones. All three systems utilize the same multi-band MIMO antenna structure, allowing them to operate across multiple frequency bands, including LTE, WiFi, Sub-6GHz, and WiFi 6E. This confirms that each antenna system exhibits excellent transmission performance and strong support for 5G communication technology. (Chung et al., 2025) introduces a multi-coupled MIMO antenna system distinguished by its capability to operate across multiple frequency bands, compact dimensions, ease of manufacturing, cost-effectiveness. Simulations assessing Specific Absorption Rate (SAR) and Power Density (PD) demonstrate that this antenna system does not have harmful radiation effects on the human body. Additionally, the proposed multi-coupled MIMO antenna system is highly flexible, making it well-suited for the future needs of compact and varied wireless communication technologies.

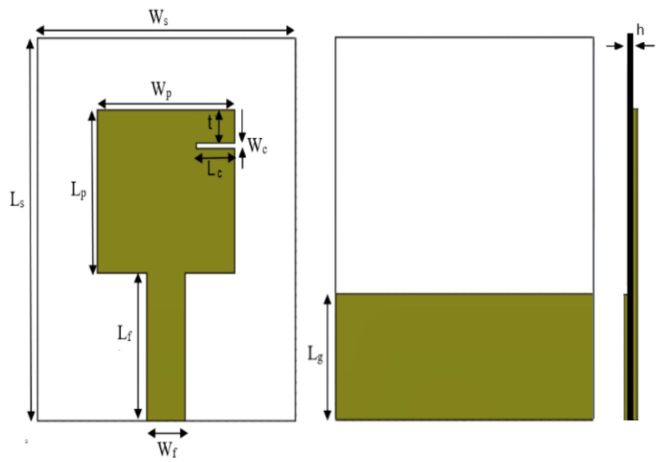
(Hasan et al., 2024) introduces a compact wideband MIMO antenna for 5G NR sub-6 GHz applications, featuring improved isolation, gain, and efficiency with a unique MM structure. It offers high isolation in a small size, a broad bandwidth, and the flexibility to support large MIMO systems. (Pandya et al., 2024) presents a quad-port Multiple Input Multiple Output (MIMO) antenna with high isolation. The design aims to achieve an Ultra-Wideband response suitable for various wireless applications. The antenna's compact size is made possible by the thoughtful integration of vertical and horizontal conductive strips. Additionally, a diagonal radiating strip is incorporated into the patch geometry. The design positions these components orthogonally to enhance performance and provide diverse operational capabilities.

The novelty of our work is to design a small and simple MIMO antenna structure of a wideband antenna in WIMAX 5G applications. The proposed antenna has been designed to have a return loss below -10 dB over 2.76 GH to 8 GHz frequency band, providing a gain of 4.5 dBi, CCL below 0.2-bit/s/Hz, ECC below 0.001 dB, and MEG less than -6dB.

The paper is structured into six sections. Section 1 includes an introduction and a literature review. Section 2 provides an overview of the single-element antenna design. Section 3 proposes a MIMO (Multiple Input Multiple Output) design structure. Section 4 presents the MIMO design results and discusses the main MIMO coefficients. Section 5 demonstrates a comparison between the proposed MIMO antenna and previous works Finally; Section 6 concludes the paper.

2. Single Element Antenna Design

The proposed single antenna is rectangular, made on Roger-RT5880 with a substrate size of 30 × 35 × 1.5 mm as demonstrated in Figure 1.



(a) (b) (c)

Figure 1: The diagram of a single-antenna (a) top view, (b) back view and (c) side view.

CST simulation's key aspects of antenna design were considered, including antenna resonance frequency, S11 curve, BW, and gain. The rectangular microstrip patch antenna is designed to operate at a resonant frequency of 3.5 GHz and 5.8 GHz, using mathematical equations [1:5] typical of conventional microstrip antenna designs. Rectangular patch dimension denoted as Wp for width and Lp for length, can be calculated (Narwade, N., & Sharma, N 2025).

$$w = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r + 1}{2}}} \quad L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \qquad (1)$$

$$\varepsilon_{eff} = \frac{\varepsilon_{r+1}}{2} + \frac{\varepsilon_{r-1}}{2}\left[1 + 12\frac{h}{w}\right]^{-0.5} \qquad (2)$$

$$\Delta L = 0.412h\,\frac{[\varepsilon_{eff+0.3}][\frac{w}{h}+0.264]}{[\varepsilon_{eff-0.258}][\frac{w}{h}+0.8]} \qquad (3)$$

$$\frac{w}{d} = \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_{r-1}}{2\varepsilon_r}\times[\mathrm{Ln}(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}]\right] \qquad (4)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \qquad (5)$$

Where C, f_r, ε_r, ε_{eff} and ΔL are denoted to the velocity of light, central frequency, permittivity of dielectric material, effective dielectric constant and length extension respectively.

Firstly, design a single patch element. Next, a slotted patch is created, featuring a slot measuring 5.5mm x 0.1mm, which is oriented perpendicularly to the feedline on the upper right side of the patch. This design improves the wideband impedance bandwidth. Following the single patch antenna, a MIMO antenna is developed, achieving a high gain that reaches 4.5 GHz, compared to the 3 GHz obtained with the single patch design. This modification offers a wider bandwidth. table 1 provides the dimensions of this design, which underwent several iterations before reaching its current form.

Table 1. The Single Antenna Dimensions.

Antenna Parameter	Dimension (mm)	Antenna Parameter	Dimension (mm)
W_S	30	L_F	13.5
L_S	35	W_C	0.1
W_P	16	L_C	5.5
L_P	15	t	3
W_F	4.4	L_g	11.5

The simulation results of a single antenna element configuration are presented below. The frequency range shows a response that < -10 dB, starting from 2.9:8.15 GHz. Additionally, there are two operating frequencies: 3.5 GHz and 5.8 GHz, as illustrated in Figure 2. Including the slot line defect in the rectangular patch has led to a more stable antenna response (S11).

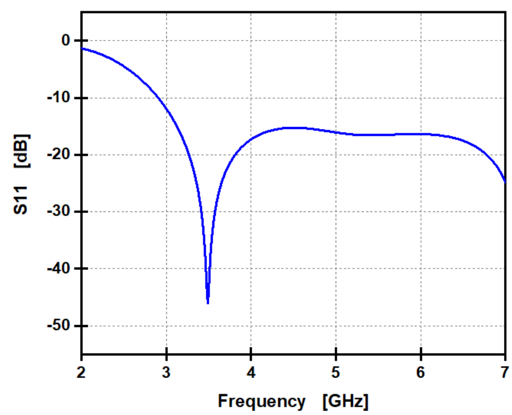
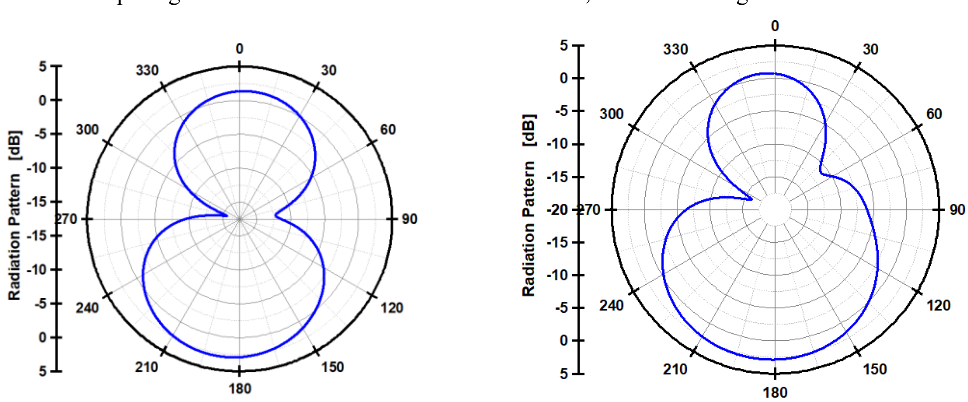


Figure 2: The S11 parameter of the single-element.

Figures 3(a) and 3(b) show the omnidirectional radiation patterns. At 3.5 GHz, the gain is approximately 2.8 dBi at 2.4 GHz and about 2.63 dBi at 5.8 GHz. A peak gain of 3 dBi was also observed at 4.5 GHz, as shown in Figure 4.



(a) (b)

Figure 3: The radiation pattern at (a) 3.5 and (b) 5.8GHz of the single-patch.

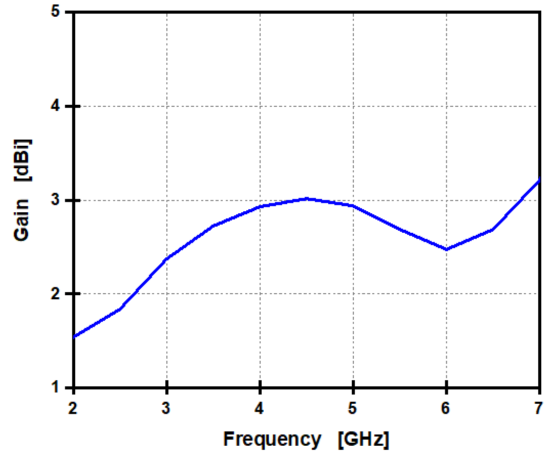
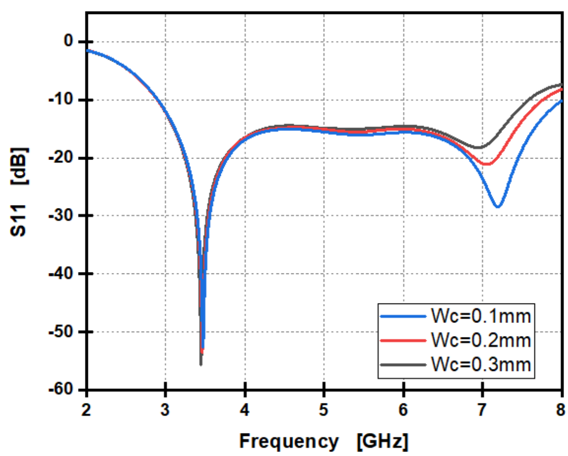
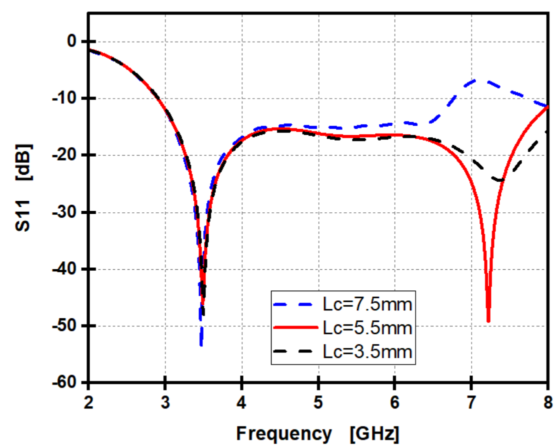


Figure 4: The gain of the single-element.

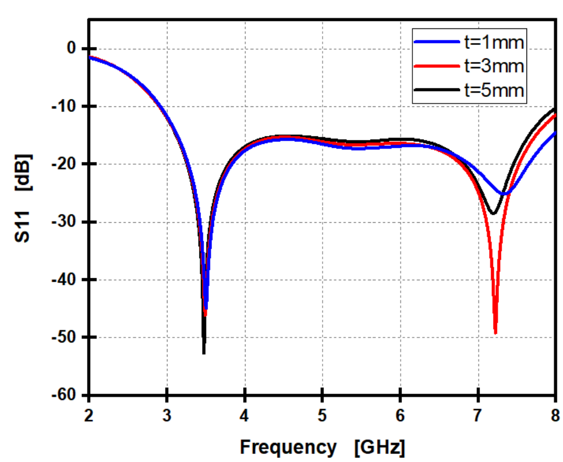
A parametric study was conducted by varying three main parameters: Wc and Lc, which represent the width and length of the rectangular slot, respectively, and t, which denotes the distance from the upper side to the slot, as presented in Figures 5(a), 5(b), and 5(c). The results indicated that a slot width of 0.1 mm, a slot length of 5.5 mm, and a slot position of 3 mm provided the most stable S11 curve across a wider range.



(a)



(b)

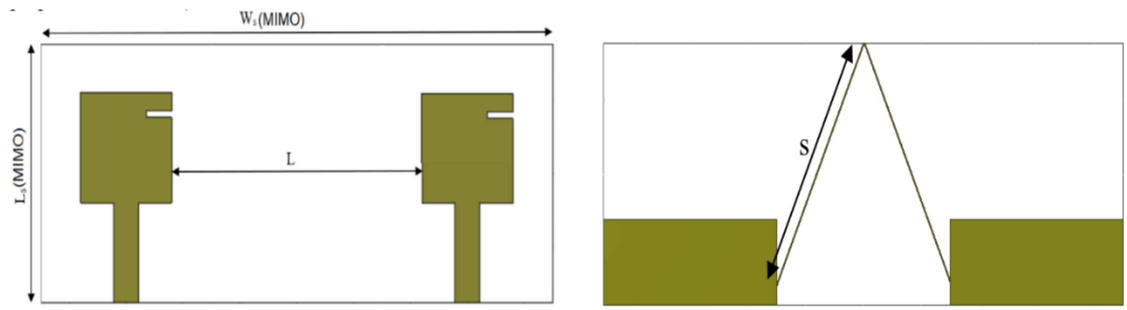


(c)

Figure 5: S11 of the parametric studies for (a) Wc, (b) Lc and (c) t of the single-patch.

3. MIMO Antenna Design

MIMO (Multiple Input Multiple Output) is a wireless technology that uses multiple transmitting and receiving antennas to increase the data capacity of RF (radio frequency) transmissions. In a MIMO system, the same information is sent over the same bandwidth through several different channels. This means each signal takes a unique path to reach the receiving antenna, resulting in more reliable data transmission. Furthermore, having multiple antennas improves the overall signal quality and provides clearer communication channels, which leads to increased data rates. This enhanced throughput allows better video and audio quality, supports additional data streams, and reduces the likelihood of dropped packets. The proposed MIMO design dimensions are illustrated in Figures 6(a) and 6(b), showing the configuration of the proposed patch antennas on the board.



(a) (b)

Figure 6: The schematic diagram of the MIMO antenna (a) front side and (b back side.

A gap of 55 mm exists between the two ports of the radiating elements, while the horizontal distance between the ports is 44 mm. Parallel antenna's arrangement, achieved the concept of self-decoupling, which decreases mutual coupling among antennas. On the MIMO board, each radiating element's ground plane is connected by two intersecting copper lines, each with a thickness of 0.2 mm. This design helps reduce surface wave propagation and minimizes undesired coupling that mutually among elements. The dimensions of MIMO system are 35 x 90 x 1.5 mm^3. Table 2 provides the detailed dimensions of the MIMO antenna's design.

Table 2. The MIMO Antenna Dimensions.

Antenna Parameter	Dimension (mm)	Antenna Parameter	Dimension (mm)
W_s(MIMO)	90	L_s (MIMO)	35
L	44	S	34.7

4. MIMO Results and Discussion

The CST simulation results for the MIMO design configuration are presented below. The reflection coefficients remain below -10 dB across all relevant frequency bands, covering BW from 2.76: 8 GHz, with two key operating frequencies at 3.5 GHz and 5.8 GHz, as seen in Figure 7. Additionally, the transmission coefficients (S12 and S21) are below -20 dB within the operating range, indicating an efficient antenna design, as illustrated in Figure 8. Figures 9(a) and 9(b) show the omnidirectional radiation patterns, at 3.5 GHz and 5.8 GHz frequencies.

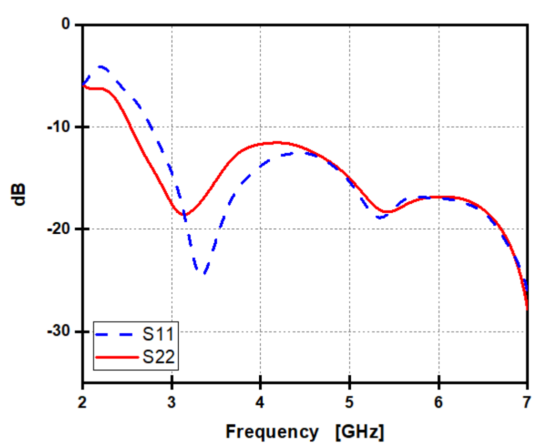


Figure 7: S11 and S22 of the MIMO antenna.

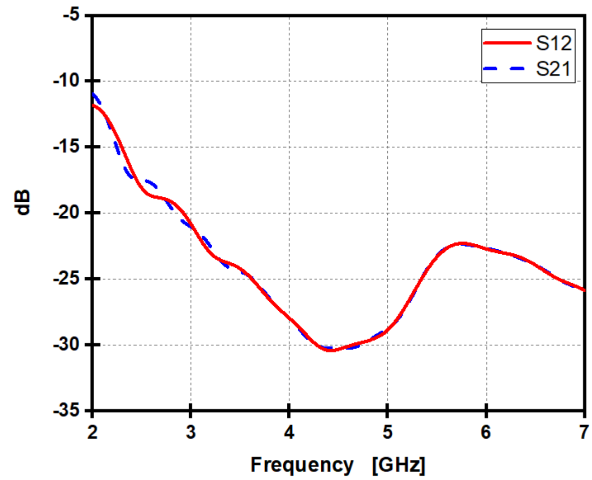


Figure 8: S12 and S21 of the MIMO antenna.

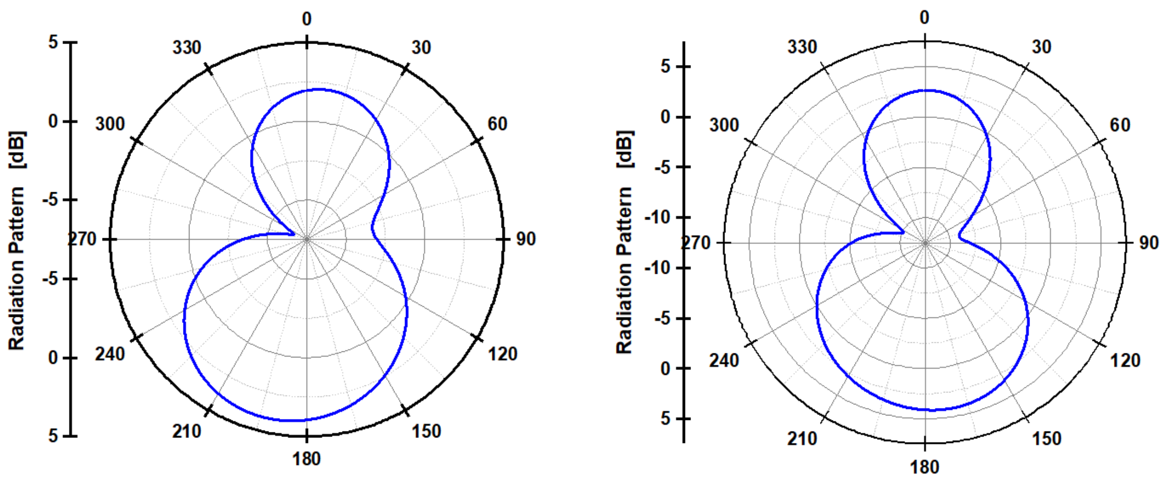


Figure 9: MIMO antenna Radiation patterns (a) at 3.5GHz and (b) at 5.8GHz.

MIMO antenna design increased the gain reaches to 4.5 dBi by using two parallel antennas with connected ground as shown in Fig. 10, instead of 2.98 dBi gain of single element antenna. Five primary MIMO parameters need to be considered (Sharma et al., 2022):

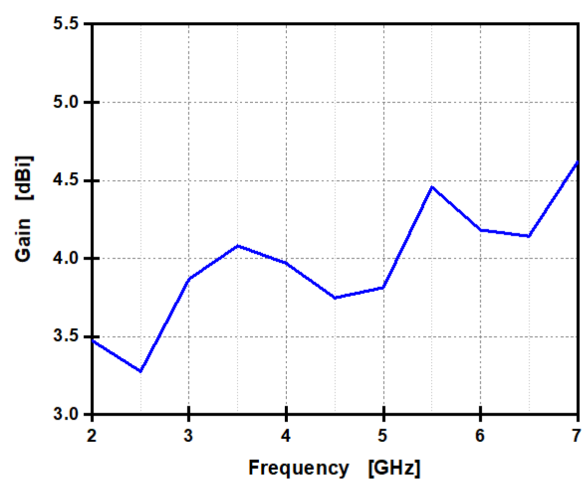


Figure 10: MIMO antenna Gain.

4.1. Channel Capacity Loss (CCL)

CCL is an important metric for assessing the performance of a MIMO antenna. To be considered effective, a MIMO antenna should have a CCL value of 0.4 b/s/Hz or lower. As presented in Figure 11(a), the simulation results indicate a CCL value of less than 0.2 bits/sec/Hz. CCL can be calculated using Equation (6), which expresses the value in terms of S-parameters.

$$\mathrm{CCL} = -\log_2(\det(a)). \quad (6)$$

4.2. Envelope Correlation Coefficient (ECC)

Figure 11(b) illustrates the simulated ECC may estimate from S11, S12, S21 and S22 values of MIMO, with calculated ECC values measuring less than 0.001. Since the ideal ECC should be close to zero, these results indicate satisfactory conditions for good MIMO performance. Equation (7) provides the method for calculating ECC.

$$\rho_{eij} = \frac{S^*_{ii}S^*_{ij} + S^*_{ji}S^*_{jj}}{(1-|S_{ii}|^2 - |S_{ij}|^2)((1-|S_{ji}|^2 - |S_{jj}|^2)}. \quad (7)$$

4.3. Diversity gain (DG)

DG should = 10 dB indicating good MIMO performance as it the same value obtained in Fig. 11(c). Equation (8) can be utilized to determine DG.

$$\mathrm{DG}=10\sqrt{1-|\rho_{eij}|^2}. \quad (8)$$

4.4. Mean Effective Gain (MEG)

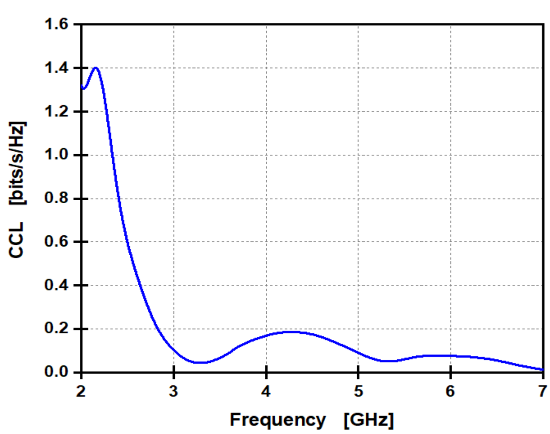
MEG at the two ports in the frequency range that was being performed, Figure 11(d) shows that the MEG <-6 dB as <-10 dB indicating good MIMO performance. Equation (9) can be used to calculate MEG.

$$\mathrm{MEG}_i = \left(1 - \sum_{j=1}^{M} |S_{ij}|^2\right). \quad (9)$$

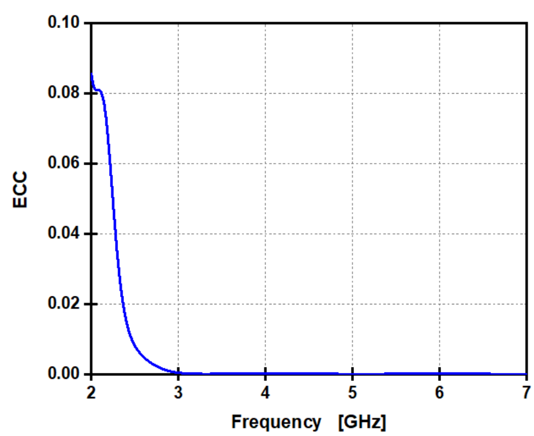
4.5. Total Active Reflection Coefficient (TARC)

TARC< -10 dB means that MIMO antenna was designed is effective. Figure 11(e) shows that less than -10 dB. TARC can be calculated from equation (10).

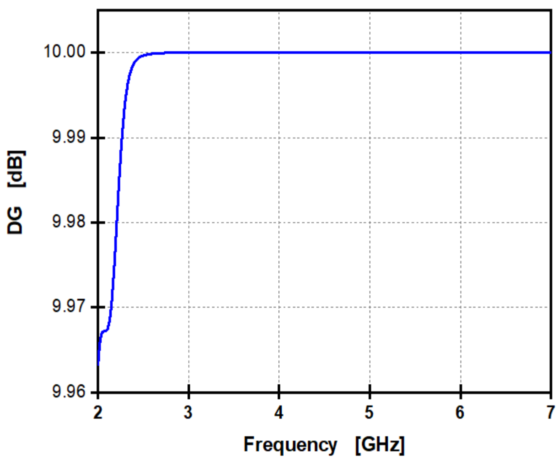
$$TARC = \sqrt{\frac{|(S_{11} + S_{12}\, e^{j\theta})|^2 + |(S_{21} + S_{22}\, e^{j\theta})|^2}{2}}. \quad (10)$$



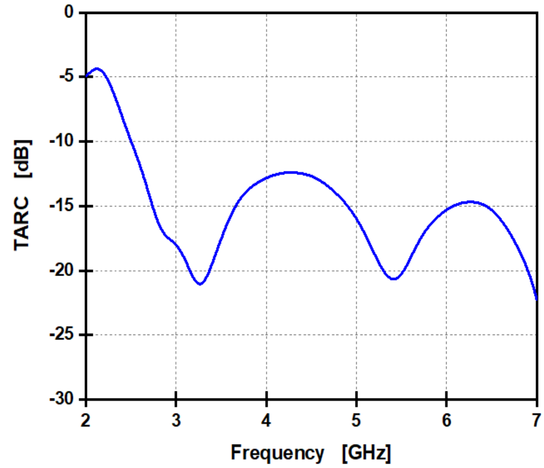
(a)



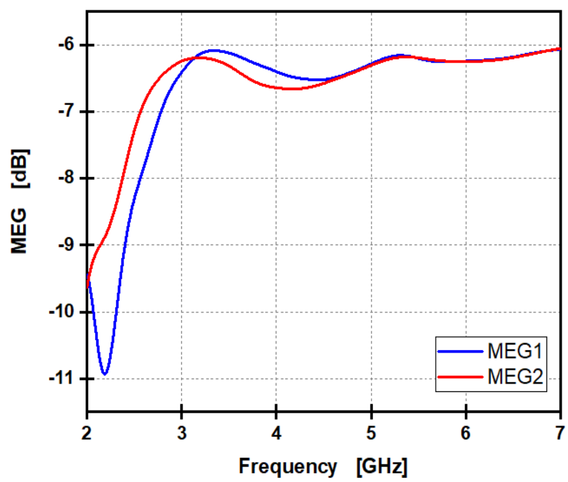
(b)



(c)



(d)



(e)

Figure 11: Parameters of MIMO include: (a) CCL (b) ECC, (c) DG, (d) TARC, (e) MEG.

5. Comparison

The previous works referenced in [15, 16, and 17], as mentioned in table 3, are limited to narrower frequency bands. In contrast, our proposed design operates over a wide frequency range of 2.76 GHz to 8 GHz. Additionally, our design offers a higher gain, reaching up to 4.4 dBi, while maintaining a moderate and suitable size compared to earlier models. Our proposed MIMO design also demonstrates superior performance, with an ECC value of less than 0.001, which is significantly lower than that of the comparable previous works.

While reference [18] presents a larger operational frequency band, it unfortunately falls short with an eager gain of only about 2 dBi, which is less than half of what our design accomplishes. Therefore, our MIMO antenna not only operates over a wide frequency range but also delivers an impressive gain of 4.5 dBi, all while maintaining an optimal and manageable size.

In summary, our MIMO antenna not only excels over a wide frequency range but also delivers an impressive gain of 4.5 dBi, establishing it as a leading solution in the realm of 5G antenna technology for sub-6 GHz applications. This positions our design as a benchmark for performance, innovation, and reliability for 5G applications at sub-6 GHz.

Table 3. A Comparison between the proposed MIMO antenna and previous works.

Ref.	MIMO Size (mm^2)	MIMO Elements	Operating Band (GHz)	Peak Gain (dBi)	ECC	Substrate
Chung, M. A., et al., 2025	220×330 140×70 75×75	10×10 4×4 2×2	0.78-1.08 1.52-2.58 4.61-6.577 7.03-7.26	1.76 3.88 2.92 4.14	<0.5	FR4
Chung et al., 2025	330×220 75×75	10×10 4×4	0.85-1.10 4.47-7.40	2.41 3.63	<0.5	FR4
(Hasan et al., 2024)	52×106	8	3.04-5.05	2.4	<0.006	FR4
(Pandya et al., 2024)	40×40	4	3.20-13.40	2	<0.05	FR4
Proposed	**35×90**	2	2.76-8	4.5	**<0.001**	**ROGER**

6. Conclusions

This paper presents a compact MIMO antenna for sub-six GHz applications, specifically intended for 5G usage, utilizing Roger-RT5880 substrate. The MIMO antenna was simulated using CST software. It demonstrated good impedance characteristics across a frequency range from 2.76 GHz to 8 GHz. The gain reaches to 4.5 dBi and exhibited omnidirectional radiation patterns. A thorough assessment of the mutual coupling between the various ports was performed, as it is a critical parameter for MIMO including ECC < 0.001, DG=10 dB, and CCL<0.2 bits/s/Hz, were evaluated, showing promising performance for 5G communications.

7. References

Kumar, P., Singh, A. K., Kumar, R., Mahto, S. K., Pal, P., Sinha, R.& Al-Gburi, A. J. A. (2024). Design and analysis of low profile stepped feedline with dual circular patch MIMO antenna and stub loaded partial ground plane for wireless applications. Progress in Electromagnetics Research C, 140, 135-144.

Ali, A., Munir, M. E., Nasralla, M. M., Esmail, M. A., Al-Gburi, A. J. A., & Bhatti, F. A. (2024). Design process of a compact tri-band MIMO antenna with wideband characteristics for sub-6 GHz, Ku-band, and millimeter-wave applications. Ain Shams Engineering Journal, 15(3), 102579.

Sheik, B. A., Sridevi, P. V., & Raju, P. R. (2020). E-shaped patch antennas for multitasks/uninterrupted 5G communications. Wireless Personal Communications, 110(2), 873-891.

Ahmed, H., Ameen, A. M., Magdy, A., Nasser, A., & Abo-Zahhad, M. (2025). A Sub-6GHz Two-Port Crescent MIMO Array Antenna for 5G Applications. *Electronics*, *14*(3), 411.

Kumar, S., Dixit, A. S., Malekar, R. R., Raut, H. D., & Shevada, L. K. (2020). Fifth generation antennas: A comprehensive review of design and performance enhancement techniques. *IEEE Access*, *8*, 163568-163593.

Chattha, H. T. (2019). 4-port 2-element MIMO antenna for 5G portable applications. *IEEE Access*, *7*, 96516-96520.

Khan, I., Wu, Q., Ullah, I., Rahman, S. U., Ullah, H., & Zhang, K. (2022). Designed circularly polarized two-port microstrip MIMO antenna for WLAN applications. *Applied sciences*, *12*(3), 1

Malviya, L., Kartikeyan, M. V., & Panigrahi, R. K. (2020). Mimo antennas for wireless communication: Theory and design crc press. *Taylor Francis*.

Upadhyaya, T., Sorathiya, V., Al-Shathri, S., El-Shafai, W., Patel, U., Pandya, K. V., & Armghan, A. (2023). Quad-port MIMO antenna with high isolation characteristics for sub6-GHz 5G NR communication. *Scientific Reports*, *13*(1), 19088.

Baz, A., Jansari, D., Lavadiya, S. P., & Patel, S. K. (2023). Miniaturized and high gain circularly slotted 4× 4 MIMO antenna with diversity performance analysis for 5G/Wi-Fi/WLAN wireless communication applications. *Results in Engineering*, *20*, 101505.

John, D. M., Vincent, S., Nayak, K., BS, S., Ali, T., Kumar, P., & Pathan, S. (2024). A compact flexible four-element dual-band antenna using a unique defective ground decoupling structure for Sub-6 GHz wearable applications. *Results in Engineering*, *21*, 101900.

Jia, Y., Xu, P., & Guo, X. (2022). MIMO system capacity based on different numbers of antennas. *Results in Engineering*, *15*, 100577.

Ahmed, R., & Islam, M. F. (2014). Slotted Microstrip Patch Antenna for Multiband Application. *International Electrical Engineering Journal (IEEj)*, *5*(3), 1293-1299.

Zhao, A., & Ren, Z. (2018). Size reduction of self-isolated MIMO antenna system for 5G mobile phone applications. *IEEE Antennas and Wireless Propagation Letters*, *18*(1), 152-156.

Chung, M. A., Hsieh, M. C., Hsu, C. C., & Lin, C. W. (2025). A Compact Multi-Band MIMO Antenna with High Isolation and Low SAR for LTE and Sub-6 GHz Applications. *IEEE Access*.

Chung, M. A., Huang, S. J., Hsu, C. C., & Lin, C. W. (2025). A Compact and Multi-Coupled MIMO Antenna System Applicable to Various Electronic Devices for Sub6 GHz Design. *IEEE Access*.

Hasan, M. M., Islam, M. T., Alam, T., Kirawanich, P., Alamri, S., & Alshammari, A. S. (2024). Metamaterial loaded miniaturized extendable MIMO antenna with enhanced bandwidth, gain and isolation for 5G sub-6 GHz wireless communication systems. *Ain Shams Engineering Journal*, *15*(12), 103058.

Pandya, K., Upadhyaya, T., Patel, U., Sorathiya, V., Pandya, A., Al-Gburi, A. J. A., & Ismail, M. M. (2024). Performance analysis of quad-port UWB MIMO antenna system for Sub-6 GHz 5G, WLAN and X band communications. *Results in Engineering*, *22*, 102318.

Narwade, N., & Sharma, N (2025). Design and Performance Analysis of 2 and 4-Element MIMO Antennas for Enhanced Gain in Sub-6 GHz 5G Applications.

Sharma, P., Tiwari, R. N., Singh, P., Kumar, P., & Kanaujia, B. K. (2022). MIMO antennas: Design approaches, techniques and applications. *Sensors*, *22*(20), 7813.