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A novel-shaped THz MIMO antenna with high bandwidth for advanced 6G wireless application

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ABSTRACT

This article presents an industrial and innovation highly efficient drone-shaped slotted graphene-based multiple input multiple output (MIMO) antenna with improved isolation, designed for high-speed short-range communication, video rate imaging, medical imaging, and explosive detection in the THz band. The proposed antenna is constructed on an 88×244 μm2 polyimide substrate. Key performance parameters such as reflection coefficient, gain, directivity, radiation pattern, and antenna efficiency are evaluated at the resonating frequencies of 1.7 THz, 3.35 THz, and 5.31 THz, covering a wide bandwidth of 4.88 THz with a reflection coefficient of less than -10 dB. The antenna achieves a maximum gain of 13.92 dB and a radiation efficiency of 95.77% within the resonating band. The MIMO design parameters include an envelope correlation coefficient (ECC) of 0.00015, a diversity gain (DG) of 9.9992, and an isolation of less than -31.55 dB between its elements across the entire bandwidth. The outcomes from CST simulations were verified by designing and simulating a similar resistance-inductance-capacitance (RLC) circuit in advanced design system (ADS), with both simulators producing comparable reflection coefficients. These features underscore the potential of the proposed antenna, utilizing simulations and an equivalent RLC circuit model, as a robust candidate for THz band applications in 6G wireless communication.

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1. INTRODUCTION

The terahertz (THz) multiple input multiple output (MIMO) antenna is emerging as a cornerstone in the evolution of wireless communication, particularly as we transition towards 6G networks. Operating in the 0.1-10 THz range, the THz band offers an expansive and largely untapped spectrum capable of supporting data rates up to terabits per second (Tbps) [1]. This makes it a promising solution to the bandwidth limitations inherent in GHz systems. However, despite its potential, the THz band faces significant challenges, including high atmospheric attenuation, path loss, and material constraints, which limit its practical implementation in wireless networks. The THz band is set to revolutionize a wide range of applications, from satellite and mobile communications to the internet of things (IoT) and advanced medical systems [2]. As the demand for higher data rates and more reliable connections escalates, the integration of MIMO technology within the THz band is crucial. THz MIMO antennas utilize multiple transmitting and receiving elements to significantly enhance the capacity and reliability of wireless networks. These antennas can achieve data rates up to 10 Gbps, far exceeding the capabilities of traditional GHz systems [3]. Existing solutions to overcome the challenges in THz communication include advanced material development, efficient antenna designs, and beamforming techniques. However, these methods often fail to fully address issues like low efficiency, poor isolation, and limited bandwidth in practical scenarios. The THz band's higher data rates and lower signal fading address the challenge of narrow bandwidths in the GHz spectrum, making THz MIMO antennas a key technology for future wireless communication [4].

6G communication networks are envisioned to leverage the THz band to deliver unprecedented performance metrics. With the potential to achieve Tbps data rates, 6G networks will support ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB) [5], [6]. This will enable new applications and services, such as real-time holographic communication, pervasive artificial intelligence (AI), and immersive augmented reality (AR) [7]. Recent progress in THz antenna technology has demonstrated significant advancements, bringing practical implementation within reach. This research aims to address the challenges of low efficiency and poor isolation in THz MIMO antennas by proposing a novel design optimized for dual-band operation and high gain. The proposed antenna is specifically tailored for 6G applications, with the goal of enhancing data rates and improving signal reliability. By exploring innovative antenna structures and materials, this work contributes to advancing the practical deployment of THz MIMO technology in future wireless communication systems. As 6G networks begin to take shape, the deployment of THz MIMO antennas is expected to unlock new possibilities, enhancing existing applications and enabling innovative services that were previously unattainable [8]. The integration of THz MIMO antennas in various sectors, from satellite and mobile communication to IoT and medical systems, highlights their wide-ranging impact and critical role in the evolution of wireless communication [9].

The proposed antenna design, as presented in Table 1, demonstrates remarkable advancements and superior performance metrics compared to existing designs. It achieves significantly broader bandwidths of 4.88 THz, outperforming the bandwidth values of 0.114 THz, 0.4 THz, 0.11 THz, 1 THz, and 1.59 THz reported in the reference works [10]-[14], as well as bandwidth values of 0.038 THz, 0.043 THz, and 0.06 THz in the reference work [15]. The antenna provides a significant gain of 13.92 dB compared to 5 dB, 4.4 dB, 5.49 dB, 4.45 dB, and 11.67 dB in the referenced work [10]-[12], [14], [15]. The proposed antenna's isolation levels surpass -31.55 dB, effectively reducing interference and exceeding the measured levels of ≥17 dB, >-25 dB, >-25 dB, >-23 dB, and >-25 dB cited in [10]-[14], and isolation values of -17 dB, -30 dB, and -23 dB in the referenced work [15]. With an efficiency of 95.77%, the proposed design outperforms the efficiencies of 60%, 94%, 85.24%, 98%, and 76.45% mentioned in studies [10], [11], [13]-[15]. Additionally, the proposed antenna demonstrates exceptional envelope correlation coefficient (ECC) and diversity gain metrics, with an ECC of 0.00015 and a diversity gain (DG) of 9.9992 dB, compared to ECC values of 0.2, 0.006, 0.015, 0.01, 0.004859, and 0.003 found in the literature [10]-[15], and diversity gains of 9.99 dB as stated in [11], [12], [14], [15] and 9.97 in [10]. Notably, the proposed design incorporates resistance-inductance-capacitance (RLC) components, distinguishing it from the referenced designs and further enhancing its performance. Overall, the comprehensive evaluation underscores the significant advancements and superior performance metrics of the proposed antenna design, highlighting its potential to lead the field of antenna technology.

Table 1. Result comparison between the proposed MIMO antenna and other publications

Ref	Resonance frequency (THz)	Bandwidth (THz)	Port	Isolation (dB)	Gain (dB)	Efficiency (%)	ECC DG (dB)	Material	RLC
[15]	2.3, 3.2, 4.5	0.038, 0.043, 0.06	-	-17, -30, -23	5	60	0.2/ 9.99	Polyimide	No
[10]		0.114	4	−17	4.4	94	0.006/ 9.97	RogersRO4835-t	No
[11]	-	0.4	2	–25	5.49	85.24	0.015/ 9.99	Polyimide	No
[12]	1.8	0.11	2	−25	4.45	-	0.01/ 9.99	SiO_2	No
[13]	2.8	1	2	-23	-	98	0.004859/ N/A	Teflon	No
[14]	1.89	1.59	-	-25	11.67	76.45	0.003/ 9.99	Polyimide	No
This work	1.7, 3.35, 5.31	4.88	2	-31.55	13.92	95.77	0.00015/ 9.9992	Polyimide	Yes

2. DESIGNING OF THE SINGLE-ELEMENT ANTENNA AND ITS RESULT

In our quest to develop a cutting-edge antenna for THz applications, we meticulously designed a single-element antenna, refining its structure through three iterative stages to achieve optimal performance. This section outlines the comprehensive design methodology. Figure 1(a) shows the reflection coefficient at each step, while Figure 1(b) depicts the respective gain, and Figure 1(c) presents the final antenna design. Central to our design is the strategic choice of materials. Polyamide was selected as the substrate material due to its favorable dielectric properties, including a dielectric constant of 3.5 and a low-loss tangent of 0.0027. Graphene, renowned for its exceptional conductivity, mechanical strength, and flexibility, was employed as the patch material on top of the substrate [16]. Complementing this, copper was chosen for the ground plane on the opposite side of the substrate to enhance conductivity, facilitating efficient signal grounding and radiation efficiency [17].

In the first stage, we implemented a basic design consisting of a rectangular patch with a central square slot and an additional circular patch in the middle. This initial configuration did not produce any distinct resonance frequency, and the observed gain was notably low, indicating the need for further modifications. The second stage involved adding four rectangular slots at each corner of the central square slot. This modification led to the emergence of two resonance frequencies, but the return loss was still insufficient, and the gain, although improved to 6.3 dB, remained below expectations. In the final stage, we introduced star-shaped slots at the top of the four rectangular slots, significantly enhancing the complexity of the design. This iteration yielded two resonance frequencies at 1.7 and 3.18 THz, with impressive return losses of -52.36 dB and -48.68 dB, respectively. The design also achieved a bandwidth of 3.2 THz, covering both resonance frequencies, and a maximum gain of 9.3 dB, meeting our performance criteria.

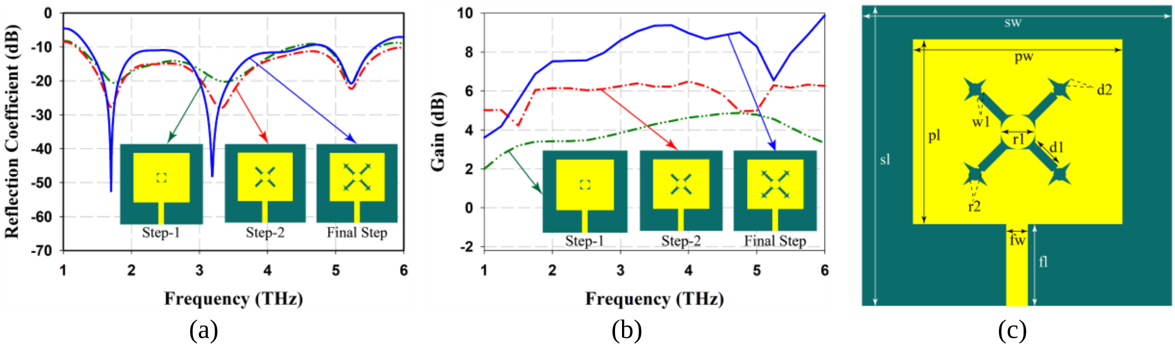

Figure 1. Analysis of the single element antenna: (a) S11 comparison, (b) gain comparison of three steps, and (c) single element antenna

3. DESIGN OF THE PROPOSED ANTENNA AND RESULT ANALYSIS

After designing the single-element antenna, we advanced to a 2-port MIMO configuration to enhance performance. This transition leverages the foundational design to amplify signal reception through multipath exploitation and increased security. The MIMO system is developed to transmit more data over a farther distance while maintaining acceptable MIMO characteristics [18].

Figure 2(a) illustrates the proposed MIMO antenna configuration, where two elements are positioned side by side with a 180-degree orientation relative to each other and we flip the second antenna over. As a result, on the front side, the configuration features the patch of Antenna 1 alongside the ground plane of Antenna 2. Conversely, the back side displays the ground plane of Antenna 1 next to the patch of Antenna 2, as shown in Figure 2(b). This unique arrangement ensures optimal performance by maximizing spatial diversity and minimizing mutual coupling, leading to improved signal quality and reliability. After implementing the MIMO configuration, we observed three resonance frequencies at 1.7 THz, 3.35 THz, and 5.31 THz. A broad bandwidth of 4.88 THz covers these three resonance frequencies, as shown in Figure 2(c). Additionally, Figure 2(d) shows a maximum gain of 13.92 dB, significantly improving compared to the single-element antenna. These values represent the ideal setting of the antenna, all parameters are in µm, sw=90, sl=90, $r1$=10, pw=65, pl=45, fl=25, fw=6, $r2$=4.08, $d1$=10, $d2$=2.94, $d3$=31.31, $d4$=12, $w1$=2.83, $w2$=2.83, D=70, SW=244, and SL=88 µm.

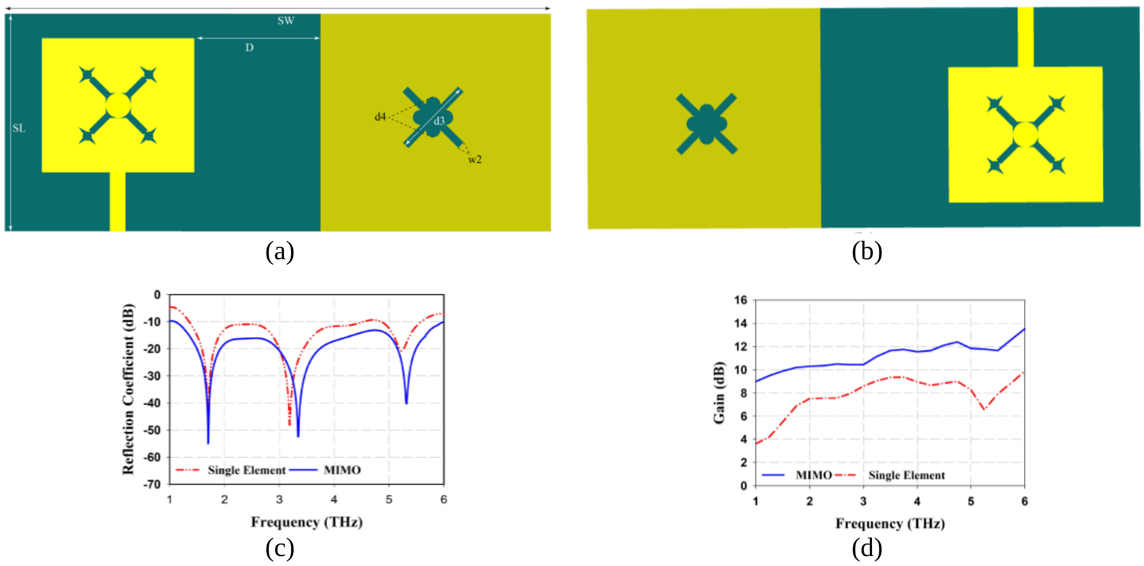

Figure 2. MIMO Antenna overview: (a) front view, (b) back view, (c) S11, and (d) gain comparison

3.1. Reflection coefficient and transmission coefficient

The reflection coefficient, also known as return loss, measures the efficiency of power transfer between the antenna and the transmission line, indicating how well the antenna is matched to its feeding structure [19]. The proposed MIMO antenna exhibits excellent reflection coefficient values across multiple resonant frequencies, showcasing its capability for THz applications, as illustrated in Figure 3(a). The antenna resonates at 1.7 THz, 3.35 THz, and 5.31 THz with exceptionally low return loss values of -55.64 dB, -52.76 dB, and -40.8 dB, respectively. These values indicate minimal signal reflection, thus ensuring efficient energy transfer and robust communication performance. The antenna operates over a wide frequency range from 1.09 THz to 5.98 THz, achieving an impressive bandwidth of 4.88 THz. This broad bandwidth is particularly advantageous for accommodating high-data-rate applications. In terms of isolation, a critical parameter for MIMO systems, the proposed antenna achieves a high isolation value of -31.5537 dB as shown in the same figure of S11. This excellent isolation ensures minimal interference between antenna elements, enhancing the overall system's capacity and reliability [20].

3.2. Gain and efficiency

Gain and efficiency are vital parameters in assessing an antenna's performance. Gain indicates the antenna's ability to direct energy in a particular direction, while efficiency represents the ratio of power radiated to the power supplied to the antenna [21]. The designed antenna demonstrates significant gain and efficiency across the operational frequency range as shown in Figure 3(b). It achieves gains of 10.12 dB at 1.7 THz, 11.32 dB at 3.35 THz, and 11.74 dB at 5.31 THz, with a maximum gain of 13.92 dB within the operating range. These gain values highlight the antenna's effectiveness in directing RF energy, making it suitable for long-range communication and high-resolution imaging applications. The antenna also shows remarkable efficiency, achieving 91.24% at 1.7 THz, 92.82% at 3.34 THz, and 94.4% at 5.32 THz. The maximum efficiency reaches 95.77%, indicating minimal power loss and effective radiation of input power [22].

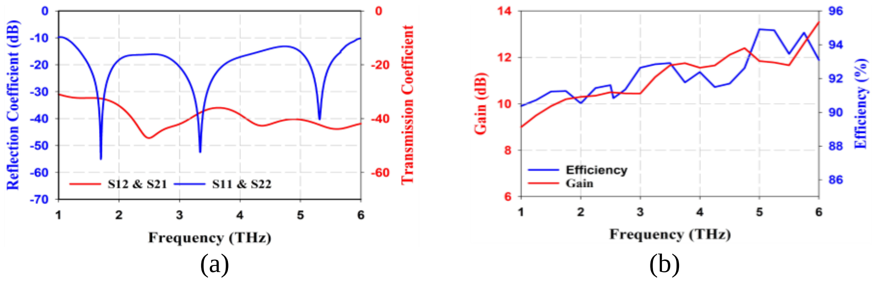

Figure 3. Performance characteristics of the proposed antenna: (a) reflection and transmission coefficient and (b) gain and efficiency

3.3. Envelope correlation coefficient and diversity gain

In a MIMO system, ECC and DG are crucial for evaluating the system's ability to handle multipath environments and improve signal quality. ECC measures the degree of correlation between signals received or transmitted by different antenna elements. The value of ECC can be figured out by (1) [23].

$$\frac{\left|\int_{4\pi}\left[E_1(\theta,\varphi)*E_2(\theta,\varphi)\right]d\Omega\right|^2}{\int_{4\pi}|E_1(\theta,\varphi|^2 d\Omega\ \int_{4\pi}|E_2(\theta,\varphi|^2 d\Omega} \quad (1)$$

Figure 4 demonstrates that the proposed antenna achieves an exceptionally low ECC value of 0.00015, suggesting excellent isolation between the antenna elements and ensuring robust diversity performance. DG quantifies the improvement in signal quality that results from using multiple antenna elements. It represents the system's ability to provide a more reliable signal by combining the received signals from different paths. The value of DG can be determined by (2) [24]. The designed antenna attains a DG value of 9.9992, as shown in Figure 4, which is nearly ideal, confirming the system's excellent ability to mitigate the effects of fading and enhance the overall communication quality.

$$DG = 10\sqrt{1 - ECC^2} \quad (2)$$

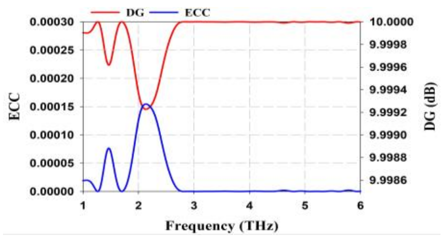

Figure 4. The ECC and DG of the proposed antenna

4. RADIATION PATTERN

Figure 5 depicts that the proposed antenna demonstrates a notable radiation pattern at its resonance frequency of 3.35 THz, characterized by specific E-field and H-field main lobe magnitudes and half-power beamwidths. At $\phi = 0°$, the E-field achieves a main lobe magnitude of 13.5 dBV/m with a 3 dB beamwidth of 30.3 degrees, while the H-field presents a main lobe magnitude of -45.5 dBA/m with a narrower 3 dB beamwidth of 19.3 degrees [25]. In contrast, at $\phi = 90°$, the E-field's main lobe magnitude decreases to 10.9 dBV/m, expanding its 3 dB beamwidth to 61.1 degrees. Concurrently, the H-field's main lobe magnitude is -29.4 dBA/m with a beamwidth of 38.6 degrees. Furthermore, for $\theta = 90°$, the E-field's main lobe magnitude peaks at 21.9 dBV/m with a 3 dB beamwidth of 32.4 degrees, while the H-field's main lobe magnitude is -38.7 dBA/m, featuring a 3 dB beamwidth of 13.5 degrees. This detailed radiation pattern highlights the antenna's efficiency and directional performance across different orientations.

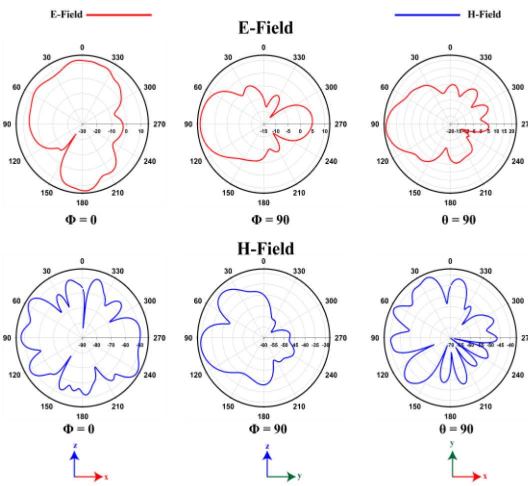

Figure 5. Radiation pattern of the proposed MIMO antenna

5. RESISTANCE-INDUCTANCE-CAPACITANCE EQUIVALENT CIRCUIT AND RESULT ANALYSIS

In our quest to revolutionize antenna technology, we meticulously scrutinized the electromagnetic characteristics of our antenna through an R-L-C circuit model. Leveraging CST Studio, we extracted precise R-L-C parameters from simulations, which we further refined via circuit simulations in Agilent advanced design system (ADS) to comprehensively evaluate antenna performance [26]. To accurately depict the antenna patches, we employed three parallel R-L-C circuits, each representing a distinct resonance. A combination of L9, R9, L10, L11, and C9 symbolizes the slot of the patch. For the feedline, parameters such as resistance (R3), capacitance (C12), and inductance (L9) were integrated to capture its electrical attributes. This constructed model precisely replicates the single-element antenna's behavior. Finally, the model extended to a MIMO antenna as shown in Figure 6 In transitioning to a MIMO configuration, we addressed mutual impedance between antenna elements using a parallel circuit of (L1+C1), R1, (L2+C2), C3, and (L3+R3+L4) to mitigate mutual coupling. Simulating this R-L-C circuit model in Agilent ADS validated its alignment with our antenna design. To ensure accuracy, we compared CST simulation outcomes with parallel circuit simulation results, focusing on the S11 parameter. Figure 7 elucidates this comparison, providing a thorough assessment of our R-L-C circuit model's fidelity in replicating the antenna's behavior.

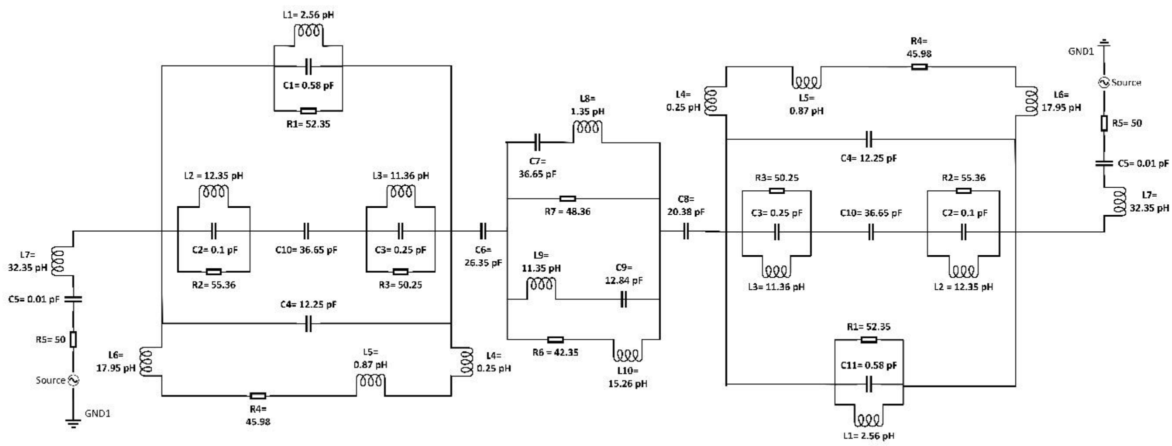

Figure 6. RLC equivalent circuit of the proposed antenna

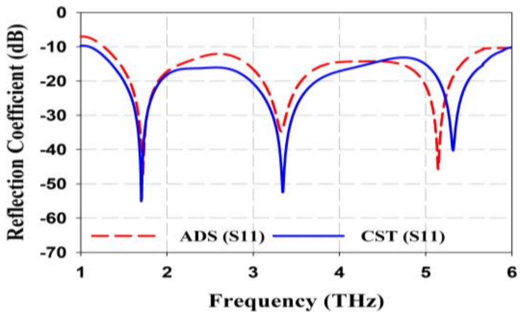

Figure 7. The S11 curve of the MIMO antenna and RLC circuit

6. CONCLUSION

This work presents a high-gain, ultrawide-band microstrip patch antenna designed for multi-frequency operation in the Terahertz band. The inclusion of a slot in the radiating patch activates additional resonant modes, enabling operation at 1.7 THz, 3.35 THz, and 5.31 THz. The design achieves a substantial bandwidth of 4.88 THz, a peak gain of 13.92 dB, and a radiation efficiency of 95.77%. Exceptional inter-element isolation below -31.55 dB ensures reliable performance across the THz frequency range. Diversity metrics, including ECC and DG, confirm the antenna's suitability for MIMO applications. The alignment between CST simulations and the RLC equivalent circuit model validates the design's accuracy and robustness. With its remarkable efficiency, bandwidth, and diversity performance, the proposed antenna is a compelling solution for emerging Terahertz applications, offering transformative potential in areas such as high-speed communication, medical imaging, and industrial sensing. Future research may focus on the use of massive MIMO technologies to increase system capacity and coverage. Additional performance improvements and new functionalities could come from researching metamaterials. Another intriguing approach is to use machine learning techniques to enhance the MIMO antenna’s performance even more. Through the acquisition of big data sets, we want to improve future results by anticipating and optimizing various antenna settings using deep learning models such as convolutional neural networks (CNN) and artificial neural networks (ANN). The findings of the study provide a significant addition to the field and pave the way for future developments in THz communication.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Jamal Hossain Nirob	✓	✓	✓			✓		✓	✓	✓	✓		✓	
Md. Ashraful Haque				✓		✓		✓		✓	✓	✓		
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Md. Sharif Ahammed		✓		✓	✓				✓	✓				
Liton Chandra Paul		✓		✓			✓			✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

REFERENCES

[1] I. F. Akyildiz, C. Han, Z. Hu, S. Nie, and J. M. Jornet, “Terahertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade,” *IEEE Transactions on Communications*, vol. 70, no. 6, pp. 4250–4285, 2022, doi: 10.1109/TCOMM.2022.3171800.

[2] A. S. Alqahtani, “A triple band high gain THz antenna for satellite, space and terrestrial applications,” *Optical and Quantum Electronics*, vol. 55, no. 11, 2023, doi: 10.1007/s11082-023-05257-y.

[3] H. J. Song and N. Lee, “Terahertz Communications: Challenges in the Next Decade,” *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 2, pp. 105–117, 2022, doi: 10.1109/TTHZ.2021.3128677.

[4] M. A. Jamshed, A. Nauman, M. A. B. Abbasi, and S. W. Kim, “Antenna Selection and Designing for THz Applications: Suitability and Performance Evaluation: A Survey,” *IEEE Access*, vol. 8, pp. 113246–113261, 2020, doi: 10.1109/ACCESS.2020.3002989.

[5] B. Hassan, S. Baig, and M. Asif, “Key Technologies for Ultra-Reliable and Low-Latency Communication in 6G,” *IEEE Communications Standards Magazine*, vol. 5, no. 2, pp. 106–113, 2021, doi: 10.1109/MCOMSTD.001.2000052.

[6] S. R. Sabuj *et al.*, "Machine-type communications in NOMA-based terahertz wireless networks," *International Journal of Intelligent Networks*, vol. 3, pp. 31–47, 2022, doi: 10.1016/j.ijin.2022.04.002.

[7] S. Jorwal, S. Singh, and S. Agarwal, "Design of graphene-based terahertz absorber and machine learning prediction model," *Optics Communications*, vol. 554, 2024, doi: 10.1016/j.optcom.2023.130203.

[8] M. K. Sharma, A. Sharma, and R. Kumari, "A CPW THz-MIMO antenna with reduced mutual coupling using Frequency Selective Surface for future wireless applications," *Optical Materials*, vol. 148, 2024, doi: 10.1016/j.optmat.2024.114929.

[9] E. L. D. Priya, A. Sharmila, K. C. Rajarajeshwari, K. R. G. Anand, and A. Naim, "Wearable Proximity Coupled Antenna for IoT Applications," *Springer Tracts in Electrical and Electronics Engineering*, pp. 249–258, 2023, doi: 10.1007/978-981-99-0212-5_20.

[10] T. Okan, "High efficiency unslotted ultra-wideband microstrip antenna for sub-terahertz short range wireless communication systems," *Optik*, vol. 242, 2021, doi: 10.1016/j.ijleo.2021.166859.

[11] K. V. Babu, S. Das, G. N. J. Sree, B. T. P. Madhav, S. K. K. Patel, and J. Parmar, "Design and optimization of micro-sized wideband fractal MIMO antenna based on characteristic analysis of graphene for terahertz applications," *Optical and Quantum Electronics*, vol. 54, no. 5, 2022, doi: 10.1007/s11082-022-03671-2.

[12] G. Varshney, S. Gotra, V. S. Pandey, and R. S. Yaduvanshi, "Proximity-coupled two-port multi-input-multi-output graphene antenna with pattern diversity for THz applications," *Nano Communication Networks*, vol. 21, 2019, doi: 10.1016/j.nancom.2019.05.003.

[13] N. S. Asaad, A. M. Saleh, and M. A. Alzubaidy, "Analyzing Performance of THz Band Graphene-Based MIMO Antenna for 6G Applications," *Journal of Telecommunications and Information Technology*, 2024, doi: 10.26636/jtit.2024.3.1518.

[14] K. V. Babu, G. N. J. Sree, T. Islam, S. Das, M. El Ghzaoui, and R. A. Saravanan, "Performance Analysis of a Photonic Crystals Embedded Wideband (1.41–3.0 THz) Fractal MIMO Antenna Over SiO2 Substrate for Terahertz Band Applications," *Silicon*, vol. 15, no. 18, pp. 7823–7836, 2023, doi: 10.1007/s12633-023-02622-0.

[15] K. Vijayalakshmi, C. S. K. Selvi, and B. Sapna, "Novel tri-band series fed microstrip antenna array for THz MIMO communications," *Optical and Quantum Electronics*, vol. 53, no. 7, 2021, doi: 10.1007/s11082-021-03065-w.

[16] S. A. Khaleel, E. K. I. Hamad, N. O. Parchin, and M. B. Saleh, "MTM-Inspired Graphene-Based THz MIMO Antenna Configurations Using Characteristic Mode Analysis for 6G/IoT Applications," *Electronics (Switzerland)*, vol. 11, no. 14, 2022, doi: 10.3390/electronics11142152.

[17] S. S. Al-Bawri *et al.*, "Machine learning technique based highly efficient slotted 4-port MIMO antenna using decoupling structure for sub-THz and THz 6G band applications," *Optical and Quantum Electronics*, vol. 56, no. 10, p. 1611, Sep. 2024, doi: 10.1007/s11082-024-07249-y.

[18] R. Singh and G. Varshney, "Isolation enhancement technique in a dual-band THz MIMO antenna with single radiator," *Optical and Quantum Electronics*, vol. 55, no. 6, 2023, doi: 10.1007/s11082-023-04811-y.

[19] K. H. Nahin *et al.*, "Performance prediction and optimization of a high-efficiency tessellated diamond fractal MIMO antenna for terahertz 6G communication using machine learning approaches," *Scientific reports*, vol. 15, no. 1, p. 4215, 2025, doi: 10.1038/s41598-025-88174-2.

[20] S. K. Patel, D. Jansari, A. H. M. Almawgani, A. Armghan, M. Irfan, and S. Lavadiya, "Design and optimization of meandered plasmonic MIMO antenna with defected ground structure showing ultra-wideband response and high isolation for 6G/TWPAN communication," *Optical and Quantum Electronics*, vol. 56, no. 1, 2024, doi: 10.1007/s11082-023-05633-8.

[21] M. A. Haque *et al.*, "Performance improvement of THz MIMO antenna with graphene and prediction bandwidth through machine learning analysis for 6G application," *Results in Engineering*, vol. 24, 2024, doi: 10.1016/j.rineng.2024.103216.

[22] M. A. Haque *et al.*, "Regression supervised model techniques THz MIMO antenna for 6G wireless communication and IoT application with isolation prediction," *Results in Engineering*, vol. 24, 2024, doi: 10.1016/j.rineng.2024.103507.

[23] N. Kiani, F. T. Hamedani, and P. Rezaei, "Graphene-Based Quad-Port MIMO Reconfigurable Antennas for THz Applications," *Silicon*, vol. 16, no. 9, pp. 3641–3655, 2024, doi: 10.1007/s12633-024-02939-4.

[24] P. Kumar, T. Ali, A. P. Dongare, A. Chaurasia, S. S. Charith, and R. Kaul, "A DGS-Based Ultra Wideband THz MIMO Antenna for Wireless Communication," in *2024 12th International Electrical Engineering Congress (iEECON)*, IEEE, Mar. 2024, pp. 01–04. doi: 10.1109/iEECON60677.2024.10537808.

[25] S. Seliverstov, A. Kozhukhovsky, S. Svyatodukh, and G. Goltsman, "Terahertz phased array antenna based on integrated taper emitters," *Applied Physics Letters*, vol. 124, no. 12, p. 121106, Mar. 2024, doi: 10.1063/5.0200852.

[26] M. A. Haque *et al.*, "Machine learning-based technique for gain prediction of mm-wave miniaturized 5G MIMO slotted antenna array with high isolation characteristics," *Scientific Reports*, vol. 15, no. 1, p. 276, Jan. 2025, doi: 10.1038/s41598-024-84182-w.

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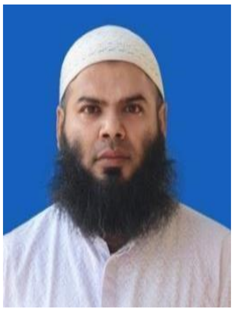

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