

Received 27 April 2026, accepted 10 June 2026, date of publication 15 June 2026, date of current version 1 July 2026.

Digital Object Identifier 10.1109/ACCESS.2026.3703997

RESEARCH ARTICLE

Highly Compact Dual-Band Four-Port Integrated Lens MIMO Antenna for 5G New Radio IoT Devices

BILAL TARIQ MALIK¹, SHAHID KHAN², JAMAL NASIR³,
AND SLAWOMIR KOZIEL^{3,4}, (Fellow, IEEE)

¹Electrical Engineering Department, COMSATS University Islamabad, Islamabad 45550, Pakistan

²Electrical Engineering Department, COMSATS University Islamabad, Abbottabad Campus 22010, Pakistan

³Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, 80-233 Gdansk, Poland

⁴Engineering Optimization and Modeling Center, Reykjavik University, Reykjavik, 101 Iceland

Corresponding authors: Bilal Tariq Malik (bilal_malik@comsats.edu.pk), Shahid Khan (shahid@cuiatd.edu.pk), and Slawomir Koziel (koziel@ru.is)

This work was supported in part by the National Science Centre of Poland under Grant 2022/47/B/ST7/00072 and in part by the Icelandic Research Fund under Grant 2410297.

ABSTRACT This article introduces a highly compact, dual-wideband four-port MIMO antenna with an integrated 3D-printed dielectric lens, tailored for 5G millimeter-wave (mmWave) new radio (NR) IoT applications. The antenna's gain and port isolation are significantly enhanced by placing a hemispherical dielectric lens atop the MIMO structure. The complete integrated lens MIMO antenna (ILMA) measures just $22 \times 22 \times 20 \text{ mm}^3$. Without the lens, the peak gain is limited to 6 dBi and 4.2 dBi at 28 GHz and 38 GHz, respectively. With the lens, gain improves to 10.5 dBi at 28 GHz and 9 dBi at 38 GHz. The antenna also achieves outstanding isolation, over 25 dB at 28 GHz and 30 dB at 38 GHz, with an envelope correlation coefficient (ECC) below 0.02 and diversity gain (DG) exceeding 9.9 dB across both bands. Link budget analysis confirms reliable communication up to 220 m at 28 GHz and 112 m at 38 GHz with 30 dBm transmit power. A fabricated prototype validates simulation results, showing strong agreement in S-parameters, isolation, gain, and radiation patterns. Compared to state-of-the-art designs, the proposed antenna offers superior gain, enhanced isolation, compact size, and cost-effective fabrication, making it well-suited for mmWave 5G NR bands such as n257, n260, and n261.

INDEX TERMS MIMO, 5G antenna, Internet of Things, mm-Wave, dielectric lens, new radio.

I. INTRODUCTION

Fifth-generation (5G) technology promises faster data rates, lower latency, and higher reliability [1], [2]. The mm-wave spectrum, particularly bands like n257 (26 GHz), n260 (38 GHz), and n261 (28 GHz), is central to 5G but faces challenges such as limited penetration, high path loss, and short range [3], [4]. High-gain multiple-input-multiple-output (MIMO) antennas are key to overcoming these issues by improving signal propagation and channel capacity [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13]. However, integrating such antennas into compact, cost-effective devices is challenging. The convergence of 5G with IoT (cf. Fig. 1) and

AI is critical for enabling smart cities, healthcare, agriculture, intelligent transportation systems (ITS), and self-powered IoT devices. Consequently, research focuses on developing compact, high-gain, multi-band MIMO antennas with low mutual coupling that can operate over multiple frequency bands to meet the requirements of mm-wave 5G NR bands [1], [2], [3], [4], [5], [7], [8], [12]. Techniques such as metasurfaces, EBGs, DGS, and dielectric lenses are being explored [7], [14], [15], [16], [17], [18], [19]. For instance, [15] achieved 6 dBi gain with EBG structures in a $27.5 \times 27.5 \text{ mm}^2$ antenna; [7] used metasurfaces to reach 10.44 dBi in $24 \times 24 \text{ mm}^2$; [14] attained 11.5 dBi at 28 GHz but with a larger $51 \times 30 \text{ mm}^2$ size. In [20], a four-port MIMO antenna with 4×1 element arrays achieve 12.5 dBi gain at 28 GHz but requires a large $60.6 \times 31.5 \text{ mm}^2$ footprint. A dual-band

The associate editor coordinating the review of this manuscript and approving it for publication was Yi Ren¹.

(28/38 GHz) MIMO antenna in [16] offers 7 dBi gain and 19 dB isolation within a compact $28 \times 28 \text{ mm}^2$ size. The design in [19] is even smaller ($25 \times 25 \text{ mm}^2$) but with lower gain (5 dBi) and 25 dB isolation at 38 GHz. In [18], a dual-band MIMO antenna (26/37 GHz) with 1×2 arrays per element reaches gains of 18.5 and 16.4 dBi, though at the cost of increased size ($43 \times 32.5 \text{ mm}^2$).

Integrating a dielectric lens with antenna forming an integrated lens antenna (ILA) is a cost-effective method to boost gain by converting spherical wavefronts into planar ones [3], [21], [22], [23]. The dielectric lens enhances antenna gain by converting spherical wavefronts into planar ones, focusing and directing the radiated energy more efficiently. Advances in 3D printing have enabled efficient and affordable ILA fabrication, particularly beneficial for mm-wave 5G bands. For instance, [21] achieved 15.6 dBi gain at 28 GHz using a 3D-printed lens, while [24] increased gain from 6.2 to 13.7 dBi over 27.5–31 GHz for Ka-band applications. However, these designs lacked MIMO capabilities, limiting data throughput. Combining dielectric lenses with MIMO systems, forming integrated lens MIMO antennas (ILMAs) offers both high gain and enhanced channel capacity. The system combines the high gain of a dielectric lens with MIMO's capacity and efficiency, creating a high-performance solution for reliable, high capacity 5G and wireless backhaul applications. In [23], a 12-port circular MIMO lens antenna attained 14 dBi gain and >30 dB isolation at 28 GHz within a 21.5 mm radius but lacked dual-band support. A dual-band ILMA for 5G IoT in [3] achieved 9.5 and 11.4 dBi gain at 26 and 38 GHz, respectively, using a metasurface for improved isolation in a $19 \times 29 \text{ mm}^2$ footprint. Despite progress, compact ILMA designs combining high gain and strong isolation remain scarce. Recent mm-wave MIMO antenna designs primarily focus on compactness, multi-band operation, and isolation enhancement; however, several limitations persist. Many planar designs achieve compact size but exhibit relatively low gain (< 8 dBi) and limited coverage. Isolation improvement techniques such as EBG, DGS, and metasurfaces often increase structural complexity and fabrication cost. Moreover, most reported works lack link-level validation and practical integration considerations for IoT/UAV platforms. These gaps motivate the proposed ILMA, which provides high gain, low mutual coupling, compact size, and validated link-budget performance for practical applications.

This paper presents a compact, cost-effective dual-band 4×4 MIMO antenna for mm-wave 5G NR IoT devices, featuring a novel low-cost 3D-printed dielectric lens that boosts gain by over 5.5 dBi and enhances isolation without increasing antenna size. Matching this gain with a conventional array would require more radiators and a larger antenna. This work aims to develop a MIMO antenna that combines compact size, high gain, low mutual coupling, and multi-band 5G NR operation. Operating at 28 GHz and 38 GHz, the proposed ILMA achieves peak gains of 10.5 dBi and 9 dBi with excellent isolation (>25 dB and >30 dB) in a $22 \times 22 \text{ mm}^2$ footprint. Unlike conventional arrays requiring more

radiators for similar performance, this design offers a unique balance of compact size, high gain, low coupling, and dual-band operation, unmatched in current literature. This level of performance makes the antenna highly suitable for NR IoT devices that need reliable communication with sensor nodes. These features underscore the novelty and uniqueness of our work. Key contributions include:

1. A compact dual-band, four-port MIMO antenna with an integrated dielectric lens for mm-wave 5G NR IoT.
2. A novel extended-height 3D-printed lens design to boost gain and isolation.
3. Performance comparison with state-of-the-art, highlighting advantages in size, gain, isolation, and cost.
4. Experimental validation confirming simulation results.

The article is organized as follows: Section II outlines the design overview; Section III details antenna geometry and analysis; Section IV covers parametric study; Section V presents experimental validation and benchmarking; Section VI evaluates MIMO performance; and Section VII concludes the paper.

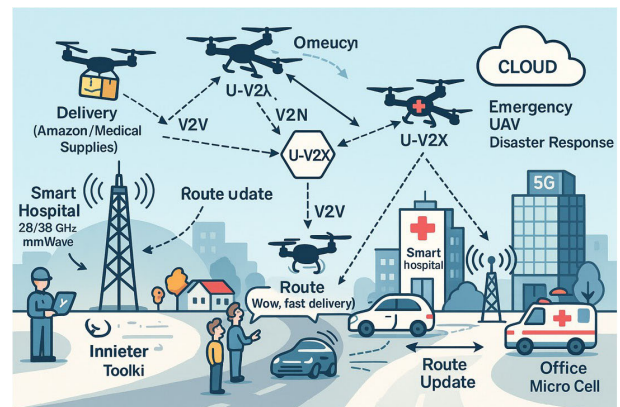


FIGURE 1. AI-generated illustration of a typical 5G network connected IoT devices [35].

II. PROPOSED ILMA DESIGN OVERVIEW

A. MIMO ANTENNA LAYOUT

The top and bottom view of the proposed four-port ILMA layout along with geometric parameters are shown in Fig. 2(a) and Fig. 2(b), respectively. The complete simulation model of proposed MIMO antenna with and without dielectric lens are presented in Fig. 2(c) and Fig. 2(d), respectively. L_s and W_s are the length and width of the substrate. L_p and W_p are the length and width of the patch. S_d is spacing between the four radiating elements and S_p is the dimension of the slot in the radiating patches. S_g is the length and width of square ground slot. R and H are the radius and height of the extended height hemispherical dielectric lens. Arlon AD 250 ($\epsilon_r = 2.55$, thickness 0.76 mm, loss tangent 0.0013) is used as the substrate material for the MIMO antenna. Arlon AD250 was selected over the more commonly used RT/Duroid 5880 due to its favorable trade-off between performance and practicality. Arlon AD250 is more cost-effective and readily available

for in-house prototyping, making it a suitable choice for rapid antenna fabrication. The integrated lens four-port MIMO antenna is designed and simulated using CST Microwave Studio. The optimized dimensions of geometrical parameters are given in Table 1. The proposed ILMA design consists of two components: the planar four elements MIMO antenna, which serves as the radiating sources, and the 3D-printed dielectric lens, which further enhances gain and isolation.

The initial design parameters of the patch were estimated using closed-form equations for microstrip antennas, as detailed in [3], [25], and [26]. The proposed antenna is designed through a systematic multi-stage approach. Initially, a single-element microstrip radiator is developed using transmission-line theory to achieve resonance at 28/38 GHz by appropriately selecting the patch dimensions and feed width. The geometry is then optimized through full-wave simulation to fine-tune impedance matching and bandwidth. In the second stage, a four-port MIMO configuration is formed by arranging identical elements orthogonally to exploit polarization and spatial diversity. Mutual coupling is minimized through careful element spacing and ground-plane modifications, ensuring isolation better than 30 dB. In the final stage, a 3D-printed hemispherical dielectric lens is integrated above the antenna to enhance gain via field collimation. The lens dimensions (radius, height, and placement) are optimized through parametric sweeps to maximize realized gain while maintaining impedance matching and efficiency. The final geometry is obtained by jointly optimizing all parameters to achieve the desired trade-off between gain, isolation, bandwidth, and compactness.

The proposed antenna geometry is derived using transmission-line theory and electromagnetic principles. The initial dimensions of the microstrip radiating element are calculated for the fundamental resonance at f_r . The patch width W , which controls impedance and radiation efficiency, is given by

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

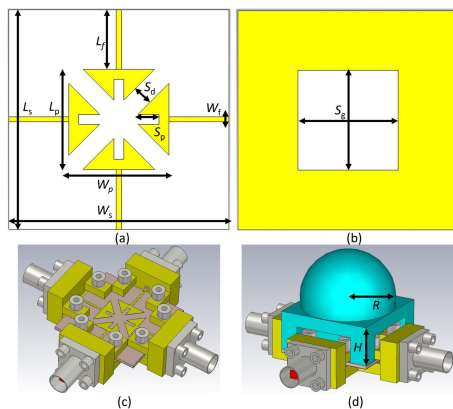


FIGURE 2. Design of the proposed four-port ILMA: (a) top view, (b) bottom view, (c) 3D view with SMA connectors, (d) with dielectric lens.

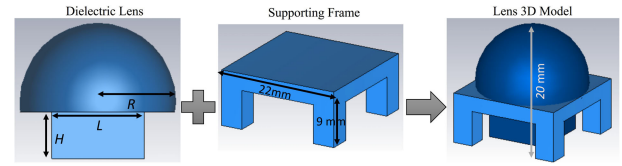


FIGURE 3. Design of the proposed 3D printed dielectric lens with a supporting frame.

The effective dielectric constant ϵ_{eff} and resonant length L , which determine the operating frequency and physical size of the radiator, are calculated as

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W} \right)^{-1/2} \quad (2)$$

$$L = \frac{c}{2f_r \sqrt{\epsilon_{\text{eff}}}} - 2\Delta L \quad (3)$$

These equations directly define the patch dimensions shown in Fig. 2(a), while slot perturbations modify the effective current path to enable dual-band operation and the feedline width is selected to achieve 50- Ω impedance matching.

B. INTEGRATED LENS MODEL

Antenna gain is crucial to counter signal degradation from high path loss at mm-wave frequencies. While conventional gain enhancement methods exist, this paper proposes a novel, compact mushroom-shaped dielectric lens for improved performance. The dielectric lens consists of a hemispherical dome mounted on a rectangular cuboid base. This structure facilitates stable mounting and alignment over the MIMO antenna. An annotated view of the complete lens geometry is provided in Fig. 3. The dielectric lens is fabricated using PLA, which is known to exhibit sensitivity to environmental factors such as moisture and temperature. These effects may slightly alter effective permittivity, leading to minor shifts in resonance and gain overtime. To enhance durability for outdoor applications, protective coatings (e.g., acrylic or epoxy) can be applied to reduce moisture absorption.

A comprehensive set of simulations was conducted comparing different types of dielectric lens profiles. The lenses were designed with equivalent aperture diameters and dielectric constants, and their performance was assessed in terms of realized gain enhancement and 3-dB beamwidth across the operational band. The proposed hemispherical lens provided sufficiently high gain enhancement (≥ 6 dBi), more uniform beam symmetry, as well as simpler fabrication. Its gain G is calculated using [3].

$$G = \eta \left(\pi D / \lambda \right)^2 \quad (4)$$

Alternatively, the maximum directivity D_{max} can be obtained as:

$$D_{\text{max}} = \left(4\pi A / \lambda^2 \right) \quad (5)$$

where $0.5 \leq \eta \leq 0.7$ is the efficiency factor, D is the diameter of the dielectric lens, A is the aperture area of the dielectric lens, and λ is the wavelength at the lowest cutoff frequency.

III. DESIGN EVOLUTION AND ANALYSIS

This section details the design evolution and analysis of the proposed ILMA. It starts with a single square patch antenna (Fig. 4a) with dimensions L_p and W_p obtained using (1) and (4). The patch is split into four triangular radiating elements via two cross slots of width S_d , forming a four-port MIMO antenna (Fig. 4b). Each triangular patch operates independently, enhancing MIMO capabilities. To reduce mutual coupling, a square slot of size S_g is added to the ground plane (Fig. 4c) to improve isolation and impedance matching. Next, rectangular slots of length S_p are introduced at the center of each triangular patch to optimize impedance matching at the lower band (Fig. 4d). Finally, a dielectric lens is integrated atop the MIMO antenna (Fig. 4e). Figures 5(b) and 5(c) show the lens reduces mutual coupling by 2 dB at 28 GHz and 12 dB at 38 GHz, while boosting gain by over 5 dBi at both bands, demonstrating its effectiveness in enhancing gain and isolation across 5G NR bands. The observed drop in gain above 32 GHz is attributed to reduced focus efficiency of the fixed-geometry lens at higher frequencies, along with material dispersion and increased mismatch. While the lens is optimized for peak performance near 28 GHz, its broadband focusing behavior degrades toward 38 GHz. Figure 5(d) presents the realized gain and radiation efficiency of the proposed ILMA.

IV. PARAMETRIC ANALYSIS

A systematic parametric analysis is performed to obtain the final optimized antenna geometry. Key parameters, including patch dimensions, inter-element spacing, slot dimensions, and lens parameters (radius, height, and airgap), are varied independently. Increasing patch length shifts the resonance to lower frequencies, while slot dimensions control dual-band behavior. Element spacing significantly affects isolation, with optimized spacing achieving >30 dB decoupling. The lens radius and height primarily influence gain and beamwidth, where larger dimensions improve directivity but may degrade matching. The final values are selected to achieve an optimal trade-off between reflection coefficient (< -20 dB), high gain (> 10 dBi), and low mutual coupling, ensuring robust performance across both operating bands. Figures 6(a) and 6(b) show that changing the element spacing S_d slightly shifts the resonant frequency and improves isolation at 38 GHz. Figure 6(c) reveals that increasing the slot length S_p enhances impedance matching at the lower band. As shown in Fig. 6(d), increasing the ground slot size S_g shifts the lower resonant frequency higher. The dielectric lens parameters: radius R and height H are key for optimizing gain and isolation. Figures 6(e–f) present the effect of lens radius (R), where increasing R enhances gain, with $R = 11$ mm offering the best performance while maintaining good impedance matching. Figures 6(g–h) show that a lens height of $H = 6$ mm provides

optimal gain stability and improved S -parameters. Figure 6(i) indicates that $L = 10$ mm ensures a balanced gain response, while Fig. 6(j) demonstrates that a feed width of $W_f = 0.5$ mm achieves optimum impedance matching. The gradual reduction in gain at higher frequencies (Fig. 6(e), (g), (i)) results from frequency-dependent focal shift, increased dielectric/conductor losses, and minor impedance mismatch, which collectively lower aperture efficiency. Final optimized dimensions are summarized in Table 1.

TABLE 1. Optimized dimensions of proposed ILMA.

Parameter	Value	Parameter	Value	Parameter	Value
Ls	22 mm	Lf	11 mm	Wp	10 mm
Lp	10 mm	Wf	0.5 mm	Sd	1.8 mm
Sp	1 mm	Ws	22 mm	Sg	10 mm
L	12 mm	R	11 mm	H	6 mm

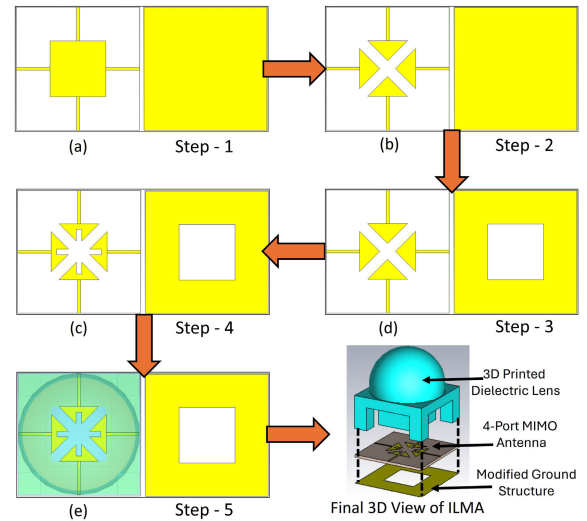


FIGURE 4. Stepwise design evolution of the proposed integrated lens MIMO antenna design.

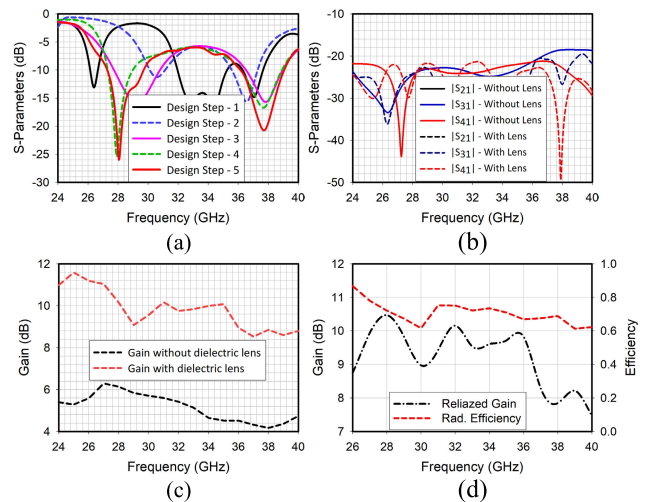


FIGURE 5. (a) $|S_{11}|$ across design steps, (b) isolation with/without lens, (c) gain with/without lens, (d) realized gain and rad. efficiency.

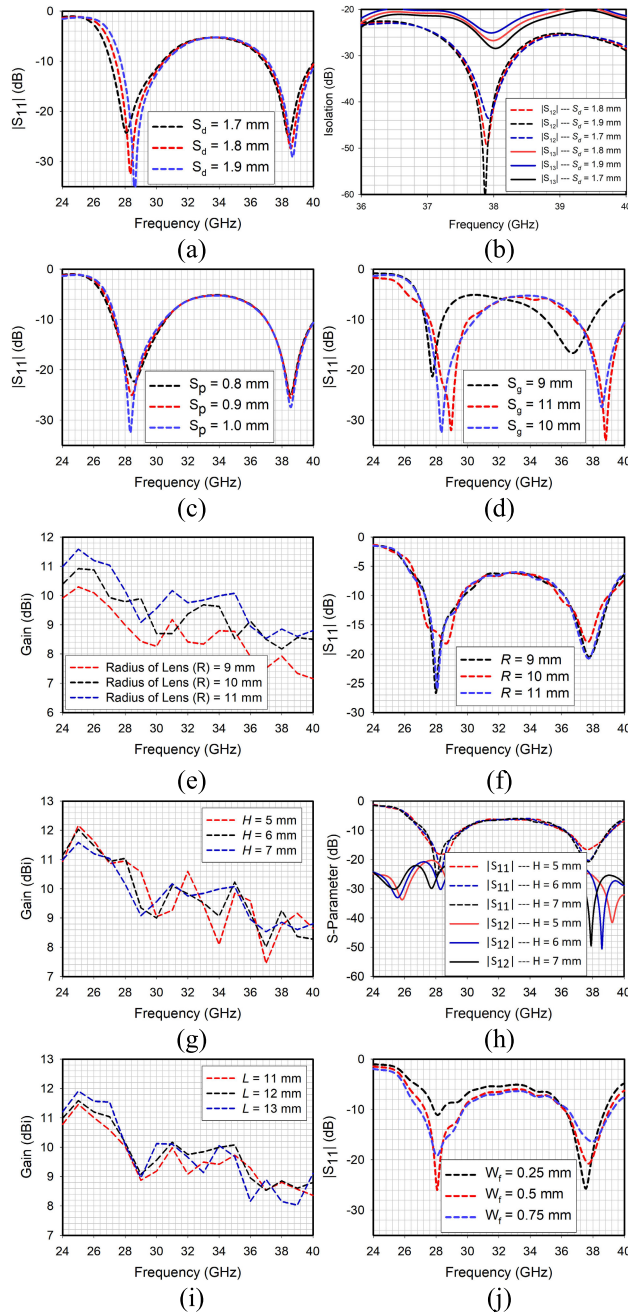


FIGURE 6. Parametric analysis of the proposed ILMA with variations in: (a, b) MIMO element spacing S_d , (c) patch slot length S_p , (d) ground slot size S_g , (e, f) dielectric lens radius R , (g, h) dielectric lens height H , (i) dielectric lens width L , (j) feed width W_f .

V. EQUIVALENT CIRCUIT MODEL

The equivalent circuit model (ECM) of the reported antenna has been developed and is shown in Fig. 7(a). The ECM accurately represents the impedance characteristics and mutual coupling behavior of the proposed four-port dual-band MIMO antenna system. Each antenna element is modeled using two parallel resonant RLC branches to represent its dual-band operation, while the inter-element coupling is represented by mutual inductance and capacitance.

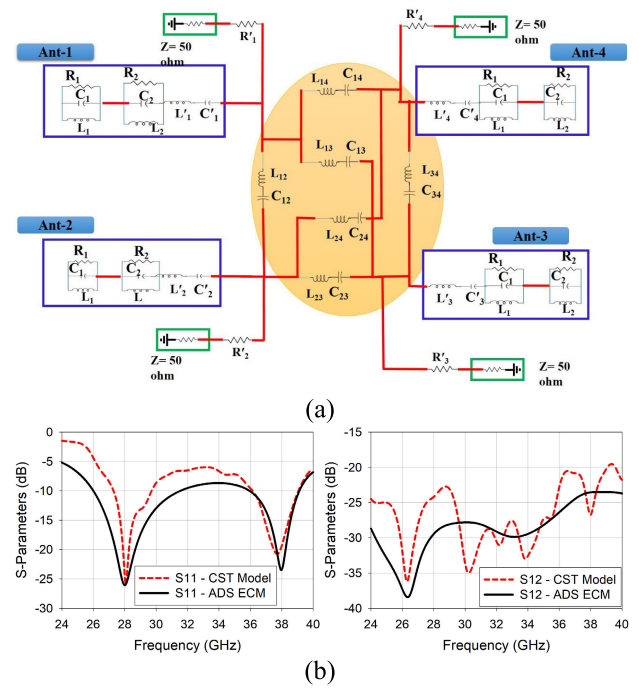


FIGURE 7. (a) Equivalent circuit model of the proposed ILMA, (b) corresponding S-parameters response.

The minor discrepancy between ADS and CST in Fig. 7(b) is expected when a circuit-level model (ADS) is compared with a full-wave EM model (CST). ADS curves represent a circuit-level model (ideal TLs + lumped elements) used for initial matching analysis, while CST presents the full-wave result including radiation, mutual coupling and material dispersion. From the ADS-based equivalent circuit analysis, the extracted lumped element values for 50 Ω input impedance were obtained as $L_1 = 0.2$ nH, $C_1 = 0.2$ pF, $L_2 = 0.035$ nH, $C_2 = 0.5$ pF, $L_3 = 0.35$ nH, and $C_3 = 0.051$ pF, $R_1 = 186\Omega$, $R_2 = 136.8 \Omega$, $C_{12} = 2.99$ pF, and $L_{12} = 1.552$ nH. Owing to the symmetric configuration of the MIMO antenna, the same set of RLC component values is applied to all four radiating elements to ensure uniformity in the circuit representation.

VI. EXPERIMENTAL VALIDATION AND BENCHMARKING

This section covers the fabrication and measurement of the proposed integrated lens MIMO antenna. Key performance metrics include radiation patterns, gain, current distribution, reflection, and transmission coefficients were evaluated at 28 and 38 GHz. A four-port MIMO prototype with a 3D-printed extended-height hemispherical lens was fabricated to validate simulations. Figures 8(a) and 8(b) show the top and bottom view of antenna without the lens, while Fig. 8(c) shows the complete setup with the lens and 2.92 mm SMA connectors. High-precision 3D printing and CNC machining ensured dimensional accuracy. The dielectric lens, designed in CST MWS, was made from polylactic acid (PLA). PLA was chosen for lens fabrication due to its favorable dielectric properties ($\epsilon_r \approx 2.5$, $\tan \delta \approx 0.02$) at mmWave frequencies,

as reported in [21] and [27]. Its 3D printability, structural strength, and low cost make it a suitable material for prototyping of dielectric lenses. The S-parameter measurements were performed using a calibrated vector network analyzer (VNA) over the 24–40 GHz range. A full two-port SOLT calibration was carried out using a standard mm-wave calibration kit to establish the reference planes at the coaxial connectors. High-quality 2.92 mm RF cables and end-launch connectors were used to interface the antenna under test. The measurement setup ensures accurate characterization of reflection and coupling parameters across all ports. Measurements were made using a vector network analyzer (VNA), connecting one port at a time with others terminated by 50 Ω loads for accuracy, as shown in Fig. 8(d). Figures 8(e) and 8(f) show the prototype in an anechoic chamber for radiation pattern measurements with and without the lens.

The measured and simulated reflection coefficients of the proposed MIMO antenna, with and without the dielectric lens, are shown in Figs. 9(a) and 9(b). Without the lens, the lower band shows better impedance matching (Fig. 9a). Adding the lens significantly improves matching across both bands (Fig. 9b). The ILMA operates from 27.2–29.5 GHz and 36.5–39 GHz, with fractional bandwidths of 8.2% and 6.5%, respectively. Simulated and measured results align well, confirming the design's effectiveness, with minor deviations attributed to fabrication and measurement tolerances, ambient noise, and losses in cables and connections. Due to the geometrical symmetry and identical feeding of all antenna elements, the proposed MIMO configuration exhibits uniform electromagnetic behavior across all ports. This is verified through full-wave simulations, where similar S-parameter responses are observed for each port. Minor variations due to fabrication tolerances and manual alignment of the 3D-printed lens are acknowledged but have negligible impact on overall performance.

Figures 10(a–b) shows simulated and measured isolation between MIMO elements. Without the dielectric lens (Fig. 10(a)), mutual coupling is low at operating bands. With the lens (Fig. 10(b)), isolation significantly improves, especially at 38 GHz. Simulated and measured results agree well, with isolation exceeding 25 dB at both resonant frequencies.

Gain and radiation efficiency are the key parameters to evaluate the antenna performance. The realized gain of the proposed antenna is obtained through both full-wave simulation and measurement. Simulated gain is extracted directly from CST by integrating the far-field radiation patterns. Measured gain is determined by using the gain-transfer method in an anechoic environment, where a calibrated standard horn antenna is used as a reference. The antenna under test (AUT) is placed in the far-field region, and the received power is recorded for both the reference antenna and AUT under identical conditions. Figure 11 depicts the comparison between the measured and simulated normalized far-field *E*-plane and *H*-plane radiation patterns of the proposed ILMA at 28 and 38 GHz for Port-1. Due to the symmetry of the MIMO antenna, it is assumed that all

ports exhibit identical radiation characteristics. Therefore, the experimental validation of radiation patterns is limited to Port-1, whereas the performance of the other ports is inferred from the symmetric structure and supporting simulation results. It is apparent from Fig. 11 that both simulated and measured patterns exhibit good agreement in the main lobe direction and overall beam shape, with minor discrepancies in sidelobes, and remain stable at both operating frequencies. Furthermore, the patterns are quasi-omnidirectional, ensuring a stable and reliable communication link in the *E* and *H*-planes. It is important to highlight that, although taking significant precautions to assure accuracy and reliability, minor differences between the simulated and measured radiation patterns were identified. These inconsistencies, largely owing to small misalignments and material irregularities, were within permissible limits and had no substantial impact on the overall performance of the proposed ILMA. This indicates its dependability and suitability for the intended 5G IoT applications.

The proposed dual-band ILMA operates at 28 GHz and 38 GHz, and the surface current distribution provides insight into its performance. To validate the dual-band operation, modal analysis is performed using surface current and electric field distributions. Figure 12 illustrates the surface current distribution when each port is individually excited with the others terminated by a 50 Ω load. The same process is repeated by activating all ports one by one while terminating the remaining three ports. At 28 GHz, the current is primarily concentrated along the main patch edges and feed region, indicating excitation of the fundamental TM_{10} mode, where the effective current path corresponds approximately to half-wavelength resonance. In contrast, at 38 GHz, the current distribution shifts toward the slot/perturbed regions of the patch, forming shorter current paths and indicating excitation of a higher-order resonant mode. The corresponding electric field distributions further confirm strong field confinement at these regions, supporting mode differentiation. This behavior

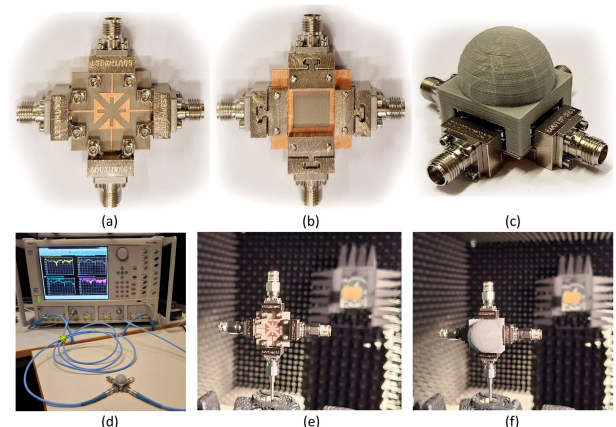


FIGURE 8. Experimental validation of the proposed four-port MIMO: (a) top view, (b) bottom view, (c) perspective view with dielectric lens, (d) S-parameters measurement setup, radiation pattern measurement setup, (e) without dielectric lens, (f) with dielectric lens.

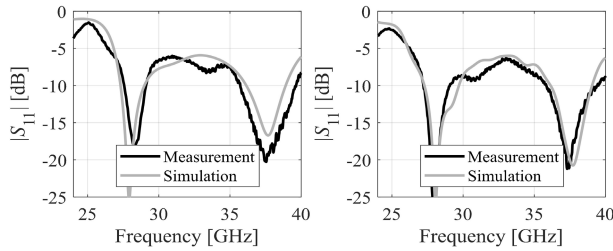


FIGURE 9. Measured versus simulated S-parameters $|S_{11}|$ of proposed ILMA: (left) without lens, (right) with lens.

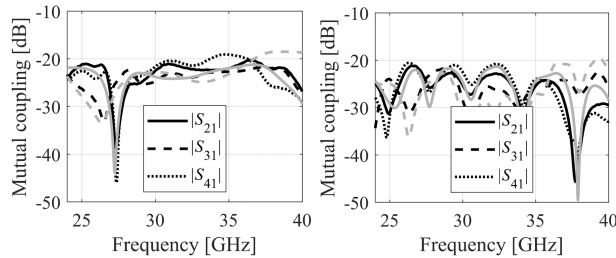


FIGURE 10. Simulated (gray) and measured (black) mutual coupling between the MIMO elements: (left) without lens, (right) with lens.

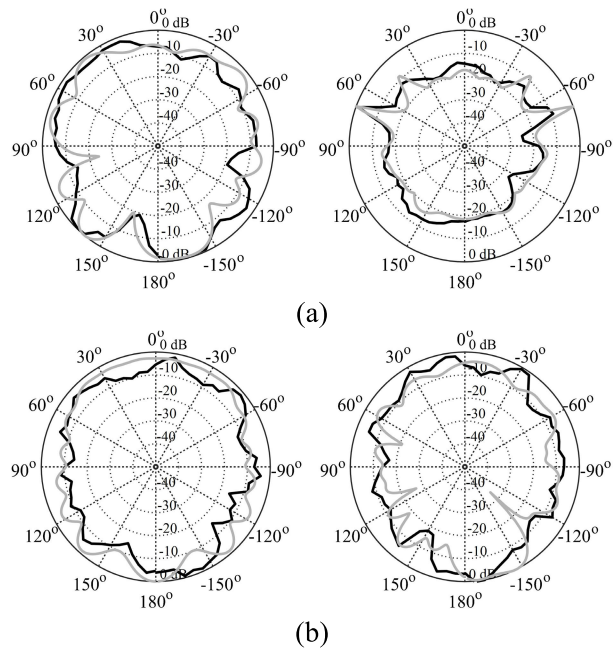


FIGURE 11. Measured (black) versus simulated (gray) normalized E and H plane radiation patterns of the proposed ILMA using Port-1, (top) 28 GHz, (bottom) 38 GHz.

verifies that dual-band operation is achieved through controlled modification of current paths within the same compact radiator, rather than independent radiators.

To explain the isolation mechanism, comparative surface current distributions are analyzed. When a single port is excited, strong induced currents are observed on adjacent elements in the reference design, indicating high coupling. In contrast, the proposed configuration reduces the induced current magnitude on neighboring ports by approximately

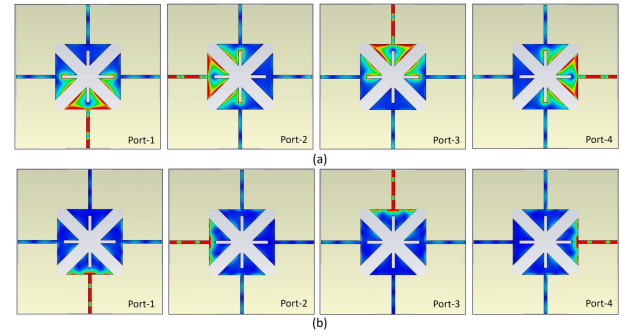


FIGURE 12. Surface current distribution at the resonant frequencies: (a) 28 GHz, (b) 38 GHz.

70–85%, due to orthogonal element placement and disruption of surface current paths. The results confirm low mutual coupling, good isolation, and stable operation across both bands. Symmetrical current patterns indicate consistent excitation, supporting low envelope correlation, high diversity gain, and reliable MIMO performance. The dielectric lens, together with the orthogonal element arrangement and ground slot, further minimizes energy leakage between ports and enhances isolation between the antenna elements.

VII. MIMO PERFORMANCE EVALUATION

This section demonstrates the MIMO performance through diversity features such as envelope correlation coefficient (ECC), diversity gain (DG), channel capacity loss (CCL), mean effective gain (MEG), total active reflection coefficient (TARC), and link budget analysis.

A. ENVELOP CORRELATION COEFFICIENT AND DIVERSITY GAIN

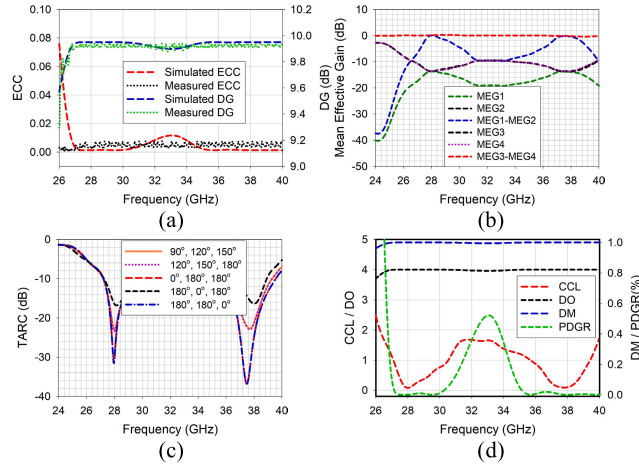
The correlation between communication channels or MIMO elements is evaluated using the Envelope Correlation Coefficient (ECC), which can be obtained from measured far-field patterns. When ECC is zero, the channels are completely independent. $ECC < 0.5$ is considered acceptable. ECC is computed based on the measured far-field patterns of the MIMO antenna elements using the integral formulation given in [3] and [26]:

Figure 13(a) illustrates the calculated ECC of the proposed MIMO antenna, which clearly shows it is significantly lower than 0.05 at both operating bands. This low correlation suggests the antenna elements can effectively operate in a MIMO configuration with minimal mutual interference.

Diversity gain (DG) in a MIMO antenna system refers to the improvement in signal reliability achieved by using multiple antennas at the transmitter, receiver, or both. It quantifies reduction of signal fading probability by using the diversity techniques. The DG was derived from the measured ECC using the standard formula [3], [26], yielding values close to 9.9 dB at both operating bands, as shown in Fig. 13(a), indicating strong diversity performance.

TABLE 2. Parameter values for link budget analysis.

Parameters	Values
P _t (Transmit Power)	21, 24, 27 and 30 dBm
G _t (Tx Antenna Gain)	10.5 dBi @ 28 GHz and 9 dBi@ 38GHz
G _r (Rx Antenna Gain)	10.5 dBi @ 28 GHz and 9 dBi@ 38GHz
f (Operating frequency)	28 GHz and 38 GHz

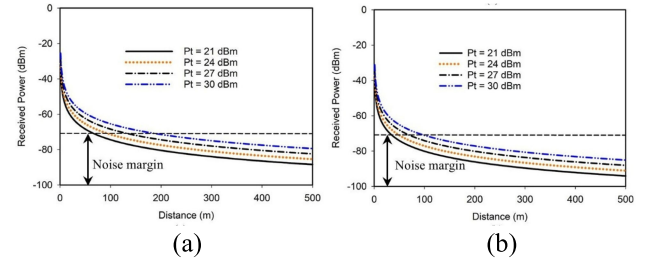
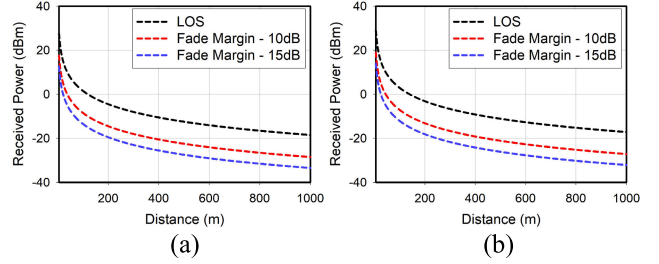
**FIGURE 13.** Diversity parameters of the proposed ILMA; (a) ECC, DG, (b) MEG, (c) TARC, (d) CCL, DO, DM, PDGR.

B. MEG, TARC, CCL, DO, DM, PDGR

The Mean Effective Gain (MEG) quantifies how effectively an antenna receives power in a multipath environment. Figure 13(b) depicts the MEG of the proposed MIMO antenna. The curves show how different configurations perform, with some (e.g., MEG3-MEG4) exhibiting deeper losses, possibly due to mismatches or poor diversity. The Total Active Reflection Coefficient (TARC) demonstrates how different excitation phases influence impedance matching, with certain phase combinations (e.g., 180°, 0°, 180°) achieving optimal performance by minimizing reflections. Figure 13(c) shows the TARC of the proposed MIMO. Lower TARC values indicate better impedance matching and reduced reflections. Meanwhile, the Channel Capacity Loss (CCL) shown in Fig. 13(d) indicates consistently low loss values (near 0 bits/s/Hz), suggesting stable and efficient channel conditions throughout the desired frequency band. The Diversity Order (DO) stays close to the theoretical maximum of 4 across both operating bands, confirming strong spatial diversity. The Diversity Measure (DM) remains above 0.93, indicating highly efficient MIMO operation. The Percentage Diversity Gain Reduction (PDGR) remains below 7%, which verifies minimal degradation in diversity gain and confirms the antenna's suitability for robust mmWave MIMO links.

C. LINK BUDGET ANALYSIS

A link budget analysis was carried out at 28/38 GHz to ensure the successful communication distance of the proposed antenna. The link-budget parameters are selected based on standard mmWave system models and literature. The

**FIGURE 14.** Link budget of the proposed antenna for different power levels, (a) 28 GHz, (b) 38 GHz.**FIGURE 15.** Link budget of the proposed antenna for additional fade margins, (a) 28 GHz, (b) 38 GHz.

transmit power, receiver sensitivity, and path loss model follow 3GPP specifications for 5G NR, while the antenna gain values are obtained from measured/simulated results of the proposed design. The calculations of the link margin were done with all the losses and gains the signal experiences when traveling over the medium. The link margin was calculated by using the widely known equations presented in [3] and [26].

The values of different parameters used are given in Table 2. The noise margin or receiver sensitivity as [28]:

$$MDS = 10 \log_{10} \left(\frac{kT}{1mW} \right) + \text{Noise Figure} + 10 \log_{10} (\text{Bandwidth}) \quad (6)$$

where MDS is minimum detectable signal, T is the temperature, which is 290 Kelvin, and $k = -228 \text{ dBW/(kHz)}$ is Boltzmann's constant. For a bandwidth of 1000 MHz and with a noise figure of 13.87 dB the determined MDS for the presented antenna is -71 dBm . The link budget is represented as:

$$P_t - FSPL + G_t + G_r + G_{MIMO} - L_{other} = P_r + \text{Margin} \quad (7)$$

where $FSPL$ denotes free space path loss, G_{MIMO} denotes MIMO antenna system gain where L_{other} are other losses that are not considered explicitly.

The link margin assessed for different transmitted power levels ($P_t = 21, 24, 27$ and 30 dBm) is given in Fig. 14. Figure 14(a) shows the link margin at 28 GHz which clearly indicates that the presented antenna can maintain a stable communication link up to a minimum distance of 70 m for $P_t = 21 \text{ dBm}$ and up to 220 m for $P_t = 30 \text{ dBm}$ making it suitable candidate for various IoT applications. Likewise,

at 38 GHz (Fig. 14(b)) the proposed antenna can maintain a reliable link up to a distance of at least 40 m and up to maximum distance of 112 m for input power of $P_t = 21$ dBm and $P_t = 30$ dBm, respectively. These results were obtained based on the free-space path models considering ideal LOS conditions without fading, interference, or obstructions, and optimal antenna alignment. The stated results should therefore be interpreted as idealized upper-limit performance, suitable for initial feasibility studies and best-case scenarios. However, practical mm-wave communication, such as for IoT, is notably affected by multipath effects, blockage, and non-line-of-sight (NLOS) propagation. To account for practical deployment scenarios, an additional fade margin of 10–15 dB is introduced to model environmental losses such as blockage, scattering, and misalignment. This margin results in a reduction of the achievable communication range by approximately 20–30%, depending on frequency and operating conditions as shown in Fig. 15(a-b). Despite this reduction, the proposed antenna maintains sufficient link margin for short to medium range mmWave V2X/IoT applications.

VIII. APPLICATION ENVIRONMENTS

The proposed design covers important 5G bands, significant in multiple mm-wave 5G IoT applications for V2X communications, which include precision agriculture, medical emergencies, wildlife conservation, infrastructure inspection, disaster response, maritime surveillance, and network boosters in densely populated zones. Figure 16 illustrates the potential applications of the proposed ILMA in real-time V2X communications. For example, traffic drones relay accident alerts to connected vehicles (V2V) and city infrastructure (V2I), delivery drones use 5G network for seamless urban operations, agricultural drones receive soil moisture data from IoT sensors to optimize crop spraying, autonomous vehicles avoid collisions by sharing flight paths with traffic lights (V2I) and other drones (V2V), post-disaster, drones can locate survivor locations to rescuers (V2X), drones scan RFID tags in warehouses, updating inventory databases in real-time, and temporary “cell tower drones” deployed at festivals, using 5G backhaul [51]. Figure 17 depicts a simulation model of the proposed ILMA on a quadcopter (drone) for V2X communications. The proposed ILMA is well suited for UAV-based V2X applications. A practical deployment analysis is conducted to evaluate the integration of the proposed antenna with real platforms. The antenna is intended for UAV-based IoT applications, where it can be integrated within the plastic body of the drone, which has minimal electromagnetic interference due to its low permittivity. This approach ensures low profile, minimal interference, and stable alignment, making the antenna practically deployable for V2X communications.

To highlight the advantages of the proposed ILMA, its key parameters are compared with recent MIMO antennas in Table 3. The comparison covers gain and isolation improvement techniques, peak gain, isolation, size, and fre-

quency bands. While many designs use complex decoupling methods, the proposed ILMA employs a simple low-cost 3D-printed dielectric lens to simultaneously optimize gain, isolation, and compactness, outperforming several benchmark MIMO antenna designs. The antennas reported in [17], [19], and [33] exhibit slightly compact dimensions but suffer from limited gain (6–7.7 dBi) and moderate isolation levels. Designs in [32] and [33] offer slightly improved gain (8.4–8.5 dBi) and isolation (~ 25 dB), yet they lack any form of gain-enhancement or decoupling mechanism. Unlike the narrowband flexible structures reported in [17] and [19], the proposed design offers a wider bandwidth, improved directivity, and extended link distance without compromising compactness. Furthermore, unlike the sub-6 GHz/mmWave hybrid integration in [34] or the quad-band approach in [32], the ILMA is specifically optimized for 5G NR bands (n257/n260/n261), achieving high gain (>10 dBi), low mutual coupling (< -30 dB), and verified long-range link reliability using a compact form factor. The novelty of the proposed ILMA design lies in a compact, unique, and simple structure with enhanced performance parameters. The link budget analysis and simulation of the proposed design with a UAV for performance stability are the key factors for design novelty. These improvements clearly establish the novelty and performance superiority of the proposed design over existing dual and multi-band mm-wave MIMO antennas.

A. LIMITATIONS

Despite the promising performance of the proposed antenna, several limitations should be noted. First, the use of a

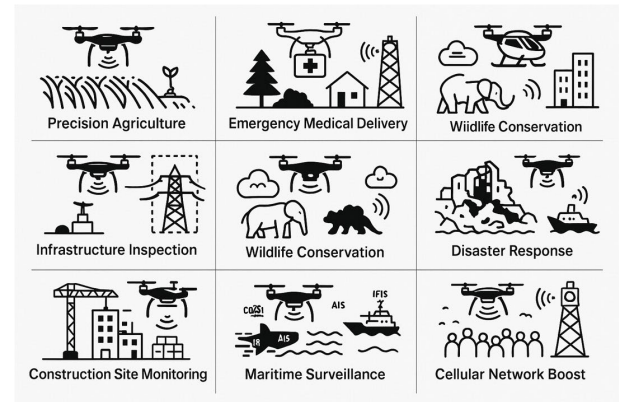


FIGURE 16. Potential applications of the proposed ILMA in V2X communications [35].

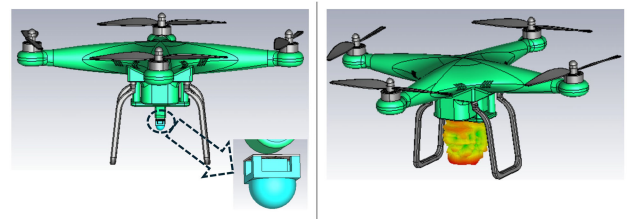


FIGURE 17. Simulated far-field radiation pattern of the proposed ILMA on the base of the drone model for V2X communication.

TABLE 3. Performance comparison of the proposed ILMA with state-of-the-art designs.

Ref.	Ports	Freq. (GHz)	Size (L×W×H) mm ³	Max. Gain (dBi)	Min. Isolation (dB)	Gain Enhancement Technique	Isolation Improvement Method	Link Budget Analysis
[14]	2	28/38	51×30×1.6	11.5	90	N/A	EBG	No
[29]	4	28/38	43.6×43.6×0.4	13.9	20	N/A	DGS	No
[16]	4	28/38	28×28×0.51	7	19	N/A	Ground modification	No
[11]	4	26/37	43×32.5×0.8	16.4	40	Array Layout	N/A	No
[17]	4	28/38	18×8.5×0.25	7.7	20	N/A	N/A	No
[19]	4	28/38	31×42×0.4	6.5	12	N/A	N/A	No
[3]	2	26/38	19×29×13	11.4	22.5	Dielectric Lens	Metasurface	Yes
[30]	4	28/38	29×24.2×0.2	8.1	20	N/A	Parasitic slot	No
[31]	4	28/41	16×12×0.25	6.1	20	N/A	Ground Slot	Yes
[32]	4	28/38	11×44×0.25	8.5	24	N/A	N/A	Yes
[33]	4	28/38	14×14×0.8	8.4	25	N/A	N/A	No
This Work	4	28/38	22×22×20	10.5	30	Dielectric Lens	Dielectric Lens	Yes

hemispherical dielectric lens introduces additional height, which may limit integration in ultra-compact devices. Second, although the lens enhances gain, it also introduces dielectric losses and potential focal shift at higher frequencies, slightly affecting efficiency. Third, the link-budget and coverage analysis are based on standard models and simulated conditions, as full over-the-air mmWave range measurements were not available. Additionally, MIMO performance metrics are primarily validated through simulation with limited measurement-based validation. Finally, fabrication tolerances in 3D printing (PLA material) may introduce minor variations in dielectric properties, potentially affecting repeatability.

IX. CONCLUSION

In this work, a compact dual-band ILMA with a novel mushroom-shaped 3D-printed dielectric lens was proposed for mm-wave 5G NR IoT applications. A 3D-printed dielectric lens is incorporated into the MIMO structure to simultaneously enhance the antenna's gain and port isolation. The design achieves wide impedance bandwidths (27.4–29.1 GHz, 37.2–39.5 GHz), high isolation (>25 dB), and significant gain enhancement (10.4 dBi at 28 GHz, 9 dBi at 38 GHz) within a 22 × 22 × 20 mm³ footprint. The antenna further demonstrates excellent diversity performance (ECC < 0.05, DG > 9.9 dB). Link margin analysis shows that the proposed ILMA supports reliable communication over 70 m to 220 m for transmitting powers between 21 dBm and 30 dBm. Experimental results validate the simulations, confirming that the proposed ILMA outperforms existing designs in gain, isolation, and compactness, making it a strong candidate for low-cost, high-performance 5G IoT applications.

REFERENCES

- [1] A. Ahmad, D.-Y. Choi, and S. Ullah, "A compact two elements MIMO antenna for 5G communication," *Sci. Rep.*, vol. 12, 2022, Art. no. 3608.
- [2] B. A. F. Esmail and S. Koziel, "Design and optimization of metamaterial-based 5G millimeter wave antenna for gain enhancement," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 70, no. 9, pp. 3348–3352, Sep. 2023.
- [3] B. Tariq Malik, S. Khan, J. Nasir, and S. Koziel, "Enhanced gain and isolation dual-band dual-port MIMO antenna with integrated lens for millimeter-wave 5G Internet-of-Things applications," *IEEE Access*, vol. 13, pp. 40859–40874, 2025.
- [4] D. Khan, A. Ahmad, and D.-Y. Choi, "Dual-band 5G MIMO antenna with enhanced coupling reduction using metamaterials," *Sci. Rep.*, vol. 14, 2024, Art. no. 96.
- [5] S. Tariq, S. I. Naqvi, N. Hussain, and Y. Amin, "A metasurface-based MIMO antenna for 5G millimeter-wave applications," *IEEE Access*, vol. 9, pp. 51805–51817, 2021.
- [6] A. E. Farahat and K. F. A. Hussein, "Dual-band (28/38 GHz) wide-band MIMO antenna for 5G mobile applications," *IEEE Access*, vol. 10, pp. 32213–32223, 2022.
- [7] D. A. Sehrai, M. Asif, W. A. Shah, J. Khan, I. Ullah, M. Ibrar, S. Jan, M. Alibakhshikenari, F. Falcone, and E. Limiti, "Metasurface-based wide-band MIMO antenna for 5G millimeter-wave systems," *IEEE Access*, vol. 9, pp. 125348–125357, 2021.
- [8] Y. Zhang, J.-Y. Deng, M.-J. Li, D. Sun, and L.-X. Guo, "A MIMO dielectric resonator antenna with improved isolation for 5G mm-wave applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, pp. 747–751, 2019.
- [9] E. Merlos-Garza, Z. U. Khan, and S. K. Khamas, "A compact MIMO rectangular dielectric resonator antenna for millimeter-wave communication," *Electronics*, vol. 13, no. 16, p. 3280, Aug. 2024.
- [10] B. G. P. Shariff, T. Ali, P. R. Mane, S. Pathan, S. H. Kiani, B. S. Virdee, and H. Mostafa, "High gain narrow beam MIMO array antenna operating at n260 band for millimeter wave applications," *IEEE Access*, vol. 13, pp. 69395–69412, 2025.
- [11] A. Hmamou, F. Kiouach, S. Das, M. El Ghzaoui, T. Islam, and B. T. P. Madhav, "A MIMO antenna array featuring dual wideband and high gain for 5G NR n257/n258/n260/n261 bands applications," *Phys. Scripta*, vol. 99, no. 9, Sep. 2024, Art. no. 095506.
- [12] A. Singh, A. Kumar, and B. K. Kanaujia, "MIMO antenna with improved isolation for 5G millimeter wave applications," *Eng. Res. Exp.*, vol. 7, no. 1, Mar. 2025, Art. no. 015302.
- [13] I. Ud Din, M. Alibakhshikenari, B. S. Virdee, R. K. R. Jayanthi, S. Ullah, S. Khan, C. H. See, L. Golunski, and S. Koziel, "Frequency-selective surface-based MIMO antenna array for 5G millimeter-wave applications," *Sensors*, vol. 23, no. 15, p. 7009, Aug. 2023.
- [14] R. H. Elabd and A. A. Megahed, "Isolation enhancement of a two-orthogonal printed elliptical slot MIMO antenna array with EBG structure for millimeter wave 5G applications," *Discover Appl. Sci.*, vol. 6, 2024, Art. no. 222.
- [15] A. Iqbal, A. Basir, A. Smida, N. K. Mallat, I. Elfergani, J. Rodriguez, and S. Kim, "Electromagnetic bandgap backed millimeter-wave MIMO antenna for wearable applications," *IEEE Access*, vol. 7, pp. 111135–111144, 2019.
- [16] B. A. F. Esmail, D. Isleifson, and S. Koziel, "Dual-band millimetre wave MIMO antenna with reduced mutual coupling based on optimized parasitic structure and ground modification," *Sci. Rep.*, vol. 14, 2024, Art. no. 20507.

- [17] R. N. Tiwari, D. Sharma, P. Singh, and P. Kumar, "A flexible dual-band 4×4 MIMO antenna for 5G mm-wave 28/38 GHz wearable applications," *Sci. Rep.*, vol. 14, Oct. 2024, Art. no. 24009.
- [18] B. Mishra et al., "High isolated 8-port MIMO antenna and 16-port massive antenna for mm wave (5G NR-n260) applications in time division duplex mode," *Sci. Rep.*, vol. 14, Oct. 2024, Art. no. 23274.
- [19] M. Sharma, B. R. Perli, L. Matta, T. Addepalli, K. Sharma, and F. N. Sibai, "Flexible four-port MIMO antenna for 5G NR-FR2 tri-band mmWave application with SAR analysis," *Sci. Rep.*, vol. 14, Oct. 2024, Art. no. 24785.
- [20] S. Ramanathan and A. B. Maria, "A compact four-element MIMO antenna for 5 g millimeter-wave (37–39 GHz) applications," *J. Infr. Millim., THz Waves*, vol. 45, nos. 7–8, pp. 604–620, Aug. 2024.
- [21] B. T. Malik, V. Doychinov, S. A. R. Zaidi, I. D. Robertson, and N. Somjit, "Antenna gain enhancement by using low-infill 3D-printed dielectric lens antennas," *IEEE Access*, vol. 7, pp. 102467–102476, 2019.
- [22] N. Chudpooti, P. Sangpet, T. Pechrkool, N. Duangrit, W. Thaiwiro, P. Akkarackthalin, and N. Somjit, "An additive 3D-printed hemispherical lens with flower-shaped stub slot ultra-wideband antenna for high-gain radiation," *IEEE Access*, vol. 11, pp. 91225–91233, 2023.
- [23] M. Belazzoug, I. Messaoudene, Y. Himeur, B. Hammache, S. Titouni, R. Gadhafi, R. Zerrougui, Y. Braham Chaouche, S. Atalla, and W. Mansoor, "A compact 12-port MIMO dielectric lens antenna with wide-angle beam scanning for Ka-band applications," *IEEE Open J. Commun. Soc.*, vol. 6, pp. 1149–1160, 2025.
- [24] N. Ullah, S. U. Rahman, Y. Liu, and F. Wang, "Corners-slotted wideband patch antenna gain enhancement with a 3D dielectric lens for Ka-band satellite communication," *Int. J. Commun. Syst.*, vol. 37, no. 13, Sep. 2024, Art. no. e5819.
- [25] K. Raheel, A. W. Ahmad, S. Khan, S. A. A. Shah, I. A. Shah, and M. Dalarsson, "Design and performance evaluation of orthogonally polarized corporate feed MIMO antenna array for next-generation communication system," *IEEE Access*, vol. 12, pp. 30382–30397, 2024.
- [26] S. Khan, O. Khan, S. A. A. Shah, J. Nasir, B. T. Malik, S. Khan, and S. Koziel, "Highly compact wideband high-gain four-element MIMO antenna for 5G new radio IoT," *IEEE Internet Things J.*, vol. 12, no. 12, pp. 22350–22365, Jun. 2025.
- [27] G. Boussatour, P.-Y. Cresson, B. Genestie, N. Joly, and T. Lasri, "Dielectric characterization of polylactic acid substrate in the frequency band 0.5–67 GHz," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 5, pp. 374–376, May 2018.
- [28] M. A. Sufian, N. Hussain, A. Abbas, J. Lee, S. G. Park, and N. Kim, "Mutual coupling reduction of a circularly polarized MIMO antenna using parasitic elements and DGS for V2X communications," *IEEE Access*, vol. 10, pp. 56388–56400, 2022.
- [29] B. Aghoutane, S. Das, M. EL Ghzaoui, B. T. P. Madhav, and H. El Faylali, "A novel dual band high gain 4-port millimeter wave MIMO antenna array for 28/37 GHz 5G applications," *AEU-Int. J. Electron. Commun.*, vol. 145, Feb. 2022, Art. no. 154071.
- [30] M. F. Ahmed, M. I. Ahmed, A. A. Ibrahim, and S. M. Gaber, "Quad-port 28/38 GHz antenna with isolation improvement for 5G wireless networks," *J. Infr. Millim Terahertz Waves*, vol. 45, nos. 7–8, pp. 672–693, Oct. 2024.
- [31] N. Hamdan and Ç. Kurnaz, "A novel dual-band four port MIMO antenna design for 28/38 GHz millimeter-wave 5G applications," *Balkan J. Electr. Comput. Eng.*, vol. 12, no. 4, pp. 273–281, Jan. 2025.
- [32] R. N. Tiwari, K. G. Malya, G. Nandini, P. B. Nikhitha, D. Sharma, P. Singh, and P. Kumar, "Quad-band 1×4 linear MIMO antenna for millimeter-wave, wearable and biomedical telemetry applications," *Sensors*, vol. 24, no. 14, p. 4427, Jul. 2024.
- [33] A. D. Tadesse, O. P. Acharya, and S. Sahu, "A compact planar four-port MIMO antenna for 28/38 GHz millimeter-wave 5G applications," *Adv. Electromagn.*, vol. 11, no. 3, pp. 16–25, Aug. 2022.
- [34] A. K. Saurabh and M. K. Meshram, "Integration of sub-6 GHz and mm-wave antenna for higher-order 5G-MIMO system," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 69, no. 12, pp. 4834–4838, Dec. 2022.
- [35] ChatGPT. (2025). *OpenAI*. Accessed: May 14, 2025. [Online]. Available: <https://chat.openai.com/chat>



BILAL TARIQ MALIK received the B.Sc. and M.Sc. degrees in electrical engineering from the Department of Electrical and Computer Engineering, COMSATS University Islamabad, Pakistan, in 2011 and 2014, respectively, and the Ph.D. degree in electronics and electrical engineering from the University of Leeds, U.K., in 2019. He completed his postdoctoral research at Gdańsk University of Technology, Poland, from January 2024 to September 2025. Since 2011, he has been associated with COMSATS University Islamabad. He is currently an Assistant Professor at COMSATS University Islamabad. His research interests include millimeter-wave MIMO antennas, frequency selective metasurfaces, the IoT, and 5G+ communications.



SHAHID KHAN received the B.S. degree in telecommunication engineering from the University of Engineering and Technology Peshawar, Pakistan, the M.S. degree in satellite navigation and related applications from the Politecnico de Torino, Italy, in 2011, and the Ph.D. degree from the University of Lorraine, France, in 2021. He is currently a Research Assistant Professor at Gdańsk University of Technology, Poland. He is working on the metasurfaces, MIMO and dielectric resonator antennas.



JAMAL NASIR was born in Malakand Agency, Khyber Pakhtunkhwa, Pakistan. He received the M.Sc. degree in mobile and satellite communication from the University of Bradford, U.K., in 2007, and the Ph.D. degree in electrical engineering from Universiti Teknologi Malaysia, in 2017. He is currently a Postdoctoral Fellow at Gdańsk University of Technology, Poland. His research interests include meta-materials-based antenna and microwave components, MIMO antennas, dielectric resonator antennas, UWB antennas, and implantable antennas.



SLAWOMIR KOZIEL (Fellow, IEEE) received the M.Sc. and Ph.D. degrees in electronic engineering from Gdańsk University of Technology, Poland, in 1995 and 2000, respectively, and the M.Sc. degree in theoretical physics and the M.Sc. and Ph.D. degrees in mathematics from the University of Gdańsk, Poland, in 2000, 2002, and 2003, respectively. He is currently a Professor with the Department of Technology, Reykjavik University, Iceland. His current research interests include the CAD and modeling of microwave and antenna structures, simulation-driven design, surrogate-based optimization, space mapping, and circuit theory.

• • •