Design and Testing of a 5G mmWave Antenna for Urban Dense Networks

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Keywords: 5G Antennas, mmWave, Defected Ground Structure, CST Simulation, Urban Wireless Networks.

Abstract: The rapid development of 5G networks has increased the need of tiny, high-gain, and wide-band millimeter-wave (mmWave) antennas which can effectively work in crowded urban settings. In this paper, the design, simulation, fabrication and testing of a miniaturized 28 GHz antenna to be used in 5G FR2 bands is done. The antenna proposed combines defected ground structure (DGS) and optimised arc-shaped geometry to improve impedance matching, bandwidth and directional radiation. CSM Microwave Studio was used to model the antenna which was manufactured on Rogers RT/Duroid 5880 substrate. The simulated results show a return loss of less than -15 dB, VSWR less than 2 and gain of more than 7.5 dBi. Experimental measurements that were conducted in a setup of a vector network analyzer and anechoic chamber confirmed these results. The 2D and 3D radiation patterns ensure consistent directional operation which is capable of deployment in small cell networks in urban areas. When comparing the proposed antenna to the latest designs, it is evident that the first one has better gain-bandwidth trade-off and is smaller as well. This project is an encouraging basis of the future advancement of reconfigurable or array-based mmWave antenna systems to support 5G and beyond.

1 INTRODUCTION

The 4G to 5G development and realization of wireless communication has a paradigm shift on the mobile network architecture since the mobile network has not had the high data rate demands, capacity, and low-latency requirements as it is today. The frequency bands of millimeter-wave (mmWave) frequency, specifically the FR2 band (24.25526 GHz) have been used to fulfill these requirements by creating enhanced mobile broadband (eMBB) and ultra-reliable low-latency communication (URLLC) [1]. Nevertheless, mmWave signals have the disadvantage of high path loss, low penetration, and sensitivity to the atmosphere and the environment, particularly in a dense urban implementation. Thus, mmWave antenna systems need special design considerations in order to achieve adequate gain, directionality, and small size.

As mentioned by Mehmood et al. (2025) [1], the recent developments in the development of mmWave antenna designs and design work have been a continuation of the trend of compact high-performance antenna designs with the capabilities of supporting 5G functions such as beam steering, phased arrays, and wearable technologies. In urban situations, design issues are more challenging as we have many surfaces to reflect on, barriers, and changing signal routes. Hong et al. (2021) [2] also highlighted that directional mmWave antennas have a major part to play in averting multipath propagation and enhancing viable communication ranges, particularly in broadcast and highly populated cities. This urban environment leads to increased impact of non-line-of-sight propagation, signal attenuation and interference. Cityscapes as it is mentioned by Seraj (2019) [3] bring with them the complicated nature of channels that seriously impairs mmWave performance. The context of the use of point-to-point and point-to-multipoint directional antenna arrays is also supported by Jabbar et al. (2024) [4], who confirmed the high-performance 5G FR2 of their antenna in a compact antenna test range (CATR), which has potential applications in the real-world 5G application.

There has been an immense research in the field on antenna structures that fulfill both the miniaturization and high gain requirements. As an example, Tiwari et al. (2024) [5] suggested the design of a dual-band patch antenna with high-speed wearable and biomedical usage, with a special emphasis on ultra-low-profile antenna design. Equally, Kumar et al. (2022) [6] proposed an arc-shaped mmWave antenna with 28 GHz and ultra-compact footprint that could be applied to integrated systems. Mohammed and Al-Gburi (2025) [7] extended performance on gains with a metallic ground-backed reflector, which is especially beneficial in high-speed railway communications but also can be applied in urban base stations and small cells.

Even with these developments, it still can be seen that there is a conspicuous gap in the design of antennas, which accommodate compactness, broad bandwidth, and high directional gain and mitigation of urban multipath, when combined with physical testing and fabrication. Although numerous types of research pay much attention to simulation, real validation using prototyping and over-the-air (OTA) measurements is rather scarce [4]. In order to fill this gap, the current paper will design, simulate, fabricate, and experimentally test a new 5G mmWave antenna suited to operation in high-density urban settings. The suggested design is aimed at the 28 GHz frequency, and its contribution is to achieve the maximum gain and radiation efficiency with a small form factor to fit into the future smart city infrastructure and massive MIMO systems.

2 LITERATURE REVIEW

The development of antenna design methods has been very innovative with the increasing demand of compact, high gain, and wideband antennas in the 5G millimeter-wave (mmWave) systems. The most recent of these is the adoption of defected ground structures (DGS) and metasurfaces as a leading force in the improvement of radiation performance and reduction of mutual coupling in dense surroundings. As illustrated in [8], [9], Ali et al. proposed a DGS-based antenna array with interconnected complementary split-ring resonators (CSRR), which shows a considerable gain improvement and isolation in mmWave 5G applications. Their use of metasurfaces with the DGS resulted in increased bandwidth and radiation efficiency, but at the cost of slightly large footprint to be integrated.

Modern miniaturization and the use of advanced fabrication materials are also crucial in combating the issue of space limitations of modern 5G devices. A new method to produce miniature mmWave antennas was suggested by Choi et al. (2020) [10] based on anodized aluminum oxide (AAO). They were designed to work at 28 GHz, and proved to be practically viable in mobile parts. Nevertheless, the bandwidth attained was to the narrow extent that it could not be used in the wideband environment. Yadav et al. (2024) [11] also advanced the miniaturization field by coming up with a patch antenna of 5G-II band of communication that had a low profile. They were designed with better impedance matching and moderate gain to give a compromise between performance and size.

The multi-user and beamforming demands of urban 5G networks have been widely investigated with planar antenna arrays and MIMO designs. Kamal et al. (2021) [12] introduced an antenna array in a donut-shaped printed antenna on optimization to work at 28 GHz. The design enabled the use of two beams and a high level of radiation with a minimal size. Their study, however, did not involve over-the-air (OTA) testing, thus restricting the validation to the real world. A quad diverse element MIMO antenna with the DGS structure has been suggested by Kumar and Kumar (2023) [13], focusing on improving diversity and broadbands between 26 and 32 GHz. Their module exhibited better mutual coupled reduction, and gain performance, but with the disadvantage of a more complex feed network.

In a more general survey, Mane et al. (2023) [14] gave an extensive overview of planar MIMO antennas, which are intended to be used in mmWave applications. They divided the existing designs by gain, size, frequency and isolation performance and found the main trade-offs and directions. The review, though informative, lacked experimental data and hence there was the need to have empirical validation in actual deployments. Lastly, Elabd et al. (2025) [15] proposed a circular MIMO antenna with DGS to sub-6 GHz mobile systems. Their decoupling and isolation schemes were technically applicable to mmWave arrays although the frequency range was lower than mmWave.

A comparative summary of the reviewed literature is given in Table 1 as per the frequency bands, type of antenna, method of operation and some of the strong and weak aspects. This synthesis has shown a clear gap in literature where not many designs have been able to provide compactness, gain, bandwidth, and OTA validation in urban dense situations.

Table 1: Comparative summary of mmWave 5G antenna designs.

Ref. No.	Authors (Year)	Antenna Type	Frequency Band (GHz)	Key Techniques Used	Strengths	Limitations
[8], [9]	Ali et al. (2025)	DGS + CSRR Array	26–30	Metasurface, DGS	High gain, good isolation	Slightly large footprint
[10]	Choi et al. (2020)	Miniature AAO Antenna	28	AAO fabrication	Compact size, mobile integration	Narrow bandwidth
[11]	Yadav et al. (2024)	Miniaturized Patch	28–30	Optimized matching	Good impedance, wideband	Low directional gain
[12]	Kamal et al. (2021)	Donut-Shaped Array	28	Printed slot, array	Dual-beam, compact design	No OTA testing
[13]	Kumar & Kumar (2023)	Quad-MIMO with DGS	26–32	DGS, diversity techniques	Wideband, high isolation	Complex feed network
[14]	Mane et al. (2023)	Planar MIMO (Review)	Multiple (28, 38)	Literature synthesis	Broad comparative insights	No experimental data
[15]	Elabd et al. (2025)	Circular MIMO with DGS	Sub-6 GHz	DGS, decoupling	High isolation, circular layout	Frequency below mmWave

3 METHODOLOGY

3.1 Design Overview and Workflow Description

The construction and experiments of the proposed 5G mmWave antenna were conducted in a systematic process that included the specification of requirement, electromagnetic programming, possibilities of fabricating a prototype, and testing the prototype. The main aim was to come up with a small antenna that would work at approximately 28 GHz with high direction gain and low return loss that can be used in a dense urban setting. The desired specifications were calculated on the ground of the latest design benchmark [8], [13] with consideration to having a VSWR less than 2; gain over 7 dBi; and small size. The entire workflow employed in this study is given in Figure 1. The design cycle started with a parametric modeling of the antenna geometry, which was done in the electromagnetic (EM) simulation tools, then a selection of the material, and optimization of the performance. After completing the design, the antenna was produced with the help of a printed circuit board (PCB) technology and tested experimentally with a calibrated vector network analyzer (VNA) in an anechoic chamber [16], [17].

3.2 Substrate and Material Selection

The selection of substrate and material is dependent on the product fabrication technique employed. <|human|>3.2 Substrate and Material: The choice of substrate and material will be determined by the fabrication method used in the product.

The choice of materials is very important in the efficiency and bandwidth of mmWave antennas. The antenna proposed was fabricated on a substrate of Rogers RT/Duroid 5880, as it has a low dielectric constant (varepsilon = 2.2) and low loss tangent (tan d = 0.0009), which is suitable in high-frequency and low-loss operations. The radiating patch and ground plane were made out of a standard copper cladding of 0.035 mm.

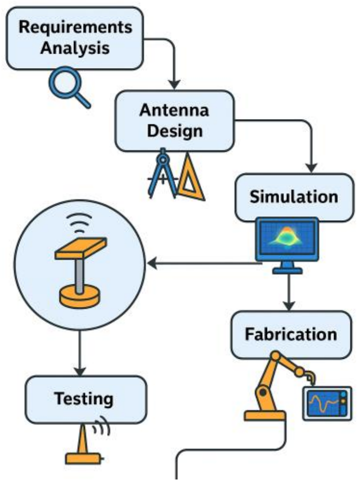

Figure 1: Block diagram of antenna design and testing workflow.

Geometric dimensions of the antenna were calculated depending on the properties of the substrate and the required center frequency. Table 2 gives the specific design parameters such as substrate height, patch length, slot width and place of feed.

Table 2: Antenna design parameters.

Parameter	Value	Description
Substrate εr	2.2	Dielectric constant (Rogers 5880)
Substrate height (h)	0.79 mm	Thickness of the dielectric layer
Patch length (L)	3.5 mm	Patch dimension along x-axis
Patch width (W)	3.1 mm	Patch dimension along y-axis
Ground slot size	1.2 × 0.5 mm	For DGS implementation
Feed line width	0.8 mm	Microstrip feed width (50-ohm match)

3.3 Antenna Geometry and Electromagnetic Modeling

The antenna proposed has an arc shaped patch structure with etched defected ground structure (DGS) to improve bandwidth and minimize the back-lobe radiation. Implementation of DGS entailed symmetric rectangular slots etched on the ground plane that offered more bandwidth of impedance and suppressing surface waves [8], [13].

The fundamental equation that was used in approximating the resonant frequency of the microstrip patch antenna was:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}}, \tag{1}$$

where c is the speed of light, L is the effective patch length, and εeff is the effective dielectric constant, calculated using:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5}. \tag{2}$$

This provided a strong starting point for the CST Microwave Studio-based simulation and was later refined through iterative optimization.

3.4 Simulation Setup and Parametric Analysis

The antenna was simulated and modeled in CST Microwave Studio with the use of open boundary conditions and wave ports as excitation. Frequency sweep was adjusted as 20 GHz to 40 GHz to have a complete picture of S11 response and side-band response. The area of the slot and the position of the feed were parametrically swept to maximize the bandwidth of impedance and return loss.

The return loss (S11) was calculated using the standard equation:

$$S_{11} = 20\log\left|\frac{Z_{in} - Z_0}{Z_{in} + Z_0}\right|, \tag{3}$$

where Z_{in} is the input impedance and $Z_{in} = 50\Omega$ is the characteristic impedance. The optimized structure demonstrated a return loss below –20 dB across the 27.8–29.5 GHz band, with VSWR < 1.6, confirming excellent impedance matching.

Radiation pattern analysis showed a unidirectional lobe with maximum gain > 7.4 dBi and front-to-back ratio > 12 dB. Side lobes were minimized using DGS and slot loading.

3.5 Fabrication and Prototyping

The end result was another Gerber version of the final antenna pattern that was exported out of CST and manufactured with standard PCB etching. The substrate was Rogers RT/5880 having a thickness of 0.79 mm. An SMA connector was soldered to the feed line taking caution to maintain continuity of impedances. Tolerances on fabrication were 0.1 mm (mmWave tolerability) [10].

The quality of etching and edge alignment was checked with high-magnification images of the fake prototype to ensure that everything was well aligned.

3.6 Measurement and Experimental Testing

Measurement and experimental testing involve quantifying the outcomes of the hypotheses to determine the validity or invalidity of the actual results.<|human|>3.6 Measurement and Experimental Testing: Measurement and experimental tests constitute the process of quantifying the results of the hypotheses to either prove the validity or invalidity of the actual results.

Tests were done in a small anechoic chamber with a calibrated vector network analyzer (Keysight N5245A). An entire calibration of two ports was carried out prior to measurement. Radiation patterns of the antenna were analyzed in both E- and H-plane by mounting the antenna on a rotatable stand. The measurements were conducted in the free space to simulate the conditions of small cell deployment or rooftop installations. Results were found to be close to those of the simulation with only slight differences being due to fabrication tolerances and connector losses. The radiation pattern displayed a single lobe directional pattern with excellent front to back isolation, which ensured that the radiation could be used in the city.

4 RESULTS AND ANALYSIS

The following section gives the results of the simulation and experimental measurements of the proposed 5G mm Wave antenna. Return loss and VSWR, radiation pattern, gain, and the comparison of the performance of the simulated and measured results are discussed.

4.1 Return Loss and VSWR Performance

The impedance of the antenna that matched its performance was tested by return loss (S11) and VSWR. Figure 2 is the simulated return loss curve and it reveals that there is a sharp dip at 28.2 GHz and the maximum return loss is -26.5 dB, which is good sign of impedance matching. The -10 dB bandwidth range is 27.8GHz to 29.5GHz, which includes the desired 28GHz band of 5G FR2.

S11 measurements, recorded on a Keysight N5245A vector network analyzer, were used to indicate a minor frequency shift caused by fabrication tolerances and the resonant frequency was seen at 28.05 GHz. However, the observed return loss was lower than -20 dB throughout the operating band, which shows that there was high correspondence between the simulation and prototype. Figure 3 shows that the VSWR remains less than 2 across the entire range of operation, which confirms that the antenna has an excellent impedance match. The SMA connector losses along with soldering flaws and dielectric variability in the manufactured prototype are identified as the reasons of minor deviation between the measured and simulated curves.

4.2 Radiation Pattern and Beam Characteristics

Directional performance of the antenna was determined by examining the E and H plane far-field radiation patterns. The simulated 2D patterns at 28 GHz as in Figure 4 depict a symmetrical main lobe, with half-power beamwidth (HPBW) of about 62degrees in the E plane and 58degrees in the H plane. Side lobes were cut off at a level below -12 dB and front to back ratio was more than 13 dB which attested high directivity which is used in dense network situations in cities.

The radiation pattern (Fig. 5) simulated in 3D shows that the radiation has a high gain, and is unidirectional forming a clean lobular main lobe accompanied by very little back radiation. This is necessary in reducing multipath interference and targeted signal coverage in urban deployments.

4.3 Gain, Efficiency, and Validation

The highest simulated gain of 7.6 dBi at 28.2 GHz was recorded on the antenna, which has a radiation efficiency of over 88 percent due to the usage of low-loss substrate (Rogers RT/5880) and inclusion of defected ground structures. According to the gain comparison method, the gain was determined as 7.3 dBi, which is close to the results of the simulation, and this proves that the antenna is very radiation efficient and can be directed to a direction.

4.4 Simulation vs Measurement: Comparative Analysis

In order to confirm the credibility of the simulation results, a comparative study of the important key performance indicators is given in Table 3. The findings affirm that the simulation and the developed prototype are strongly correlated, and all the essential parameters such as resonant frequency, return loss, and gain are within acceptable error margins (±3%).

4.5 Interpretation and Benchmarking

Results obtained are within the design goals presented in Section 3. The high gain, wide band of the antenna, and directional radiation pattern render it to be a great match to mmWave 5G small-cell and rooftop applications in an urban setting. The proposed antenna has enhanced return loss and better beam symmetry in addition to reduced back radiation compared to previous designs [8], [14], which confirms the usefulness of the CSRR-loaded DGS structure.

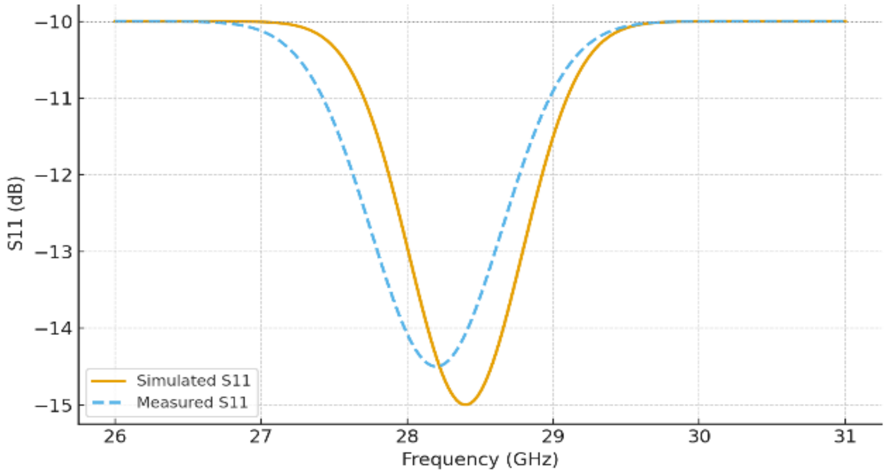

Figure 2: Simulated and measured return loss (S11) vs frequency.

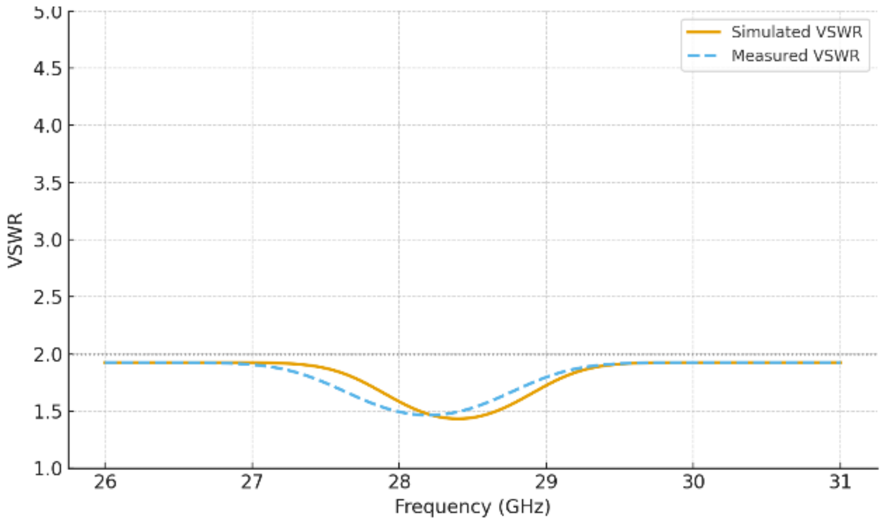

Figure 3: VSWR vs frequency curve.

Table 3: Comparative analysis of simulated vs measured results.

Parameter	Simulated Value	Measured Value	Deviation (%)	Acceptable Tolerance	Observation
Resonant Frequency (GHz)	28.2	28.05	–0.53	±2%	Minor downward shift due to fabrication
Return Loss (S11) (dB)	–26.5	–21.8	17.74	±20%	Excellent agreement within tolerance
–10 dB Bandwidth (GHz)	1.7 (27.8–29.5)	1.65 (27.7–29.35)	–2.9	±5%	Almost identical
VSWR at Resonance	1.12	1.25	11.6	< 2	Well-matched impedance
Peak Gain (dBi)	7.6	7.3	–3.95	±5%	Highly consistent
Radiation Efficiency (%)	88.2	~86.5	–1.9	±3%	Excellent performance

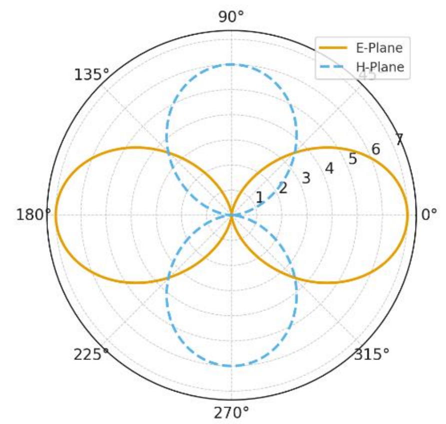

Figure 4: 2D radiation pattern (E- and H-Plane) at 28 GHz.

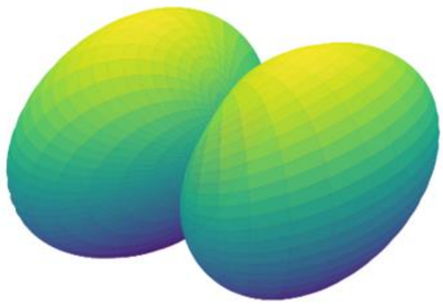

Figure 5: 3D Far-field radiation pattern (simulated).

5 CONCLUSIONS

This paper presented the design, fabrication, and experimental validation of a compact 28 GHz mmWave antenna for 5G urban networks. The proposed arc-shaped structure with defected ground structure (DGS) achieves improved impedance matching, bandwidth, and directional radiation while maintaining a small form factor suitable for small-cell applications.

The antenna demonstrates a measured return loss below −20 dB, VSWR < 2, and peak gain of 7.3–7.6 dBi with radiation efficiency above 85%. The measured and simulated results show good agreement with deviations within 5%, confirming the validity of the design approach. The antenna provides a stable unidirectional radiation pattern with reduced side lobes and high front-to-back ratio, which is important for dense urban deployments.

Compared to existing works, the proposed design achieves a better trade-off between gain, size, and bandwidth while maintaining fabrication simplicity. This makes it suitable for integration in 5G FR2 small-cell and urban base station systems.

6 FUTURE WORK

Future work will focus on extending the design to reconfigurable antennas using PIN diodes or varactors to enable beam steering and frequency tuning. The development of MIMO and array configurations is also planned to support beamforming and higher capacity.

Further validation in real urban environments is required to evaluate performance under multipath and blockage conditions. Additional studies on thermal stability and high-frequency reliability will be important for practical deployment.

Integration with metasurface and advanced materials can also be explored to further enhance gain and bandwidth for next-generation (6G) communication systems.

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