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Design and Optimization of a Wideband 28 GHz Microstrip Patch Antenna Using Rogers RT/Duroid 5880 for 5G Millimeter-Wave Applications

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ABSTRACT
This paper presents the design and simulation of a microstrip antenna operating at 28GHz for 5G communication applications. The antenna was designed and optimized in CST studio, with Rogers RT/Duroid 5880 chosen as the substrate material and a 1.575mm thickness, using the Transmission Line Model (TLM), the patch and feedline dimensions were calculated before optimization. The simulation results demonstrated superior performance, achieving a return loss of -55.37 dB, a wide bandwidth of 4.465 GHz, a VSWR of 1.003, and the highest gain of 7.82 dBi. The antenna exhibited a narrow beamwidth of 33.8° with high directivity of 9.13 dBi, though with a slightly reduced efficiency of 73.9%, which remains within the acceptable operational range. Compared with existing designs in the literature, the proposed antenna demonstrated significant improvements in impedance matching, bandwidth, and gain, making it very suitable for high-speed 5G applications, where wide bandwidth and high gain are required.

Keywords - *28GHz, 5G, CST studio, Microstrip antenna, Millimetre-wave*

I.INTRODUCTION

5G is the fifth generation of wireless technology in mobile communication systems, developed to improve network speed, capacity, and performance compared to its predecessor 4G (Gillis & Gerwig, 2024). It provides tremendous data speeds and low latency, while also connecting many devices in areas such as IoT, smart cities, and self-driving systems. Achieving these features depends mainly on antennas that work well in the high-frequency range of 5G (Patel et al., 2022)

There has been a growing demand for high-speed wireless communication and reliable connectivity in 5G networks, and this has led to significant advancements in antenna technology, particularly in the millimeter-wave (mmWave) frequency range. Microstrip Patch Antennas (MPAs) have emerged as a vital component in 5G systems due to their compact structure, low profile, lightweight nature, and ease of fabrication, making them highly adaptable for portable, wearable (Saravanan et al., 2025; Li, 2023), and integrated communication devices. However, achieving wide bandwidth, high gain (M. Nawaz, 2013), and efficient radiation performance while maintaining compactness continues to be a major design challenge. To overcome these limitations, several design techniques have been investigated, including the use of defected ground structures (DGS) (Suvarna et al., 2021), slotted patches, modified feeding techniques, and artificial materials such as metamaterials (Paul et al., 2017). Another important factor influencing antenna performance is the substrate thickness, which directly affects impedance matching, bandwidth, gain, and radiation efficiency (John et al., 2016)

Some researchers have shown that increased substrate thickness impacts antenna performance metrics such as return loss, gain, bandwidth, and efficiency. Proposing a solution to these challenges will improve the performance and implementation of the 5G network.

Due to the strict requirements for 5G wireless communications, the exploration of MPAs for 28 GHz millimeter-wave applications has been growing considerably in recent years. Researchers currently focus on improving bandwidth, signal strength, and radiation effectiveness by proposing better substrate materials, opening shapes, and feeding structures, sometimes using materials with low signal loss like Rogers RT/Duroid 5880.

Paul and Saha (2021) presented a slotted 28 GHz antenna designed using CST Studio Suite, with two inset gaps near the microstrip feed line. Their use of Rogers RT/Duroid 5880 yielded good impedance matching and wide bandwidth, which would be applicable in mmWave communication. Even though their project exhibits very good impedance performance, it does not fully analyze how each slot contributes to bandwidth improvement; therefore, replication of the design for research on optimization is not possible.

Rana and Smieee (2022) also developed a 28 GHz MPA on Rogers RT/Duroid 5880, demonstrating high signal strength (8.2 dBi), wide bandwidth (3.464 GHz), and low VSWR of 1.02. Their antenna exhibited stable radiation characteristics that further established the suitability of RT/Duroid 5880 for high-frequency applications. However, their work did not investigate manufacturing tolerances, which become critical at mmWave frequencies, where even slight dimensional variations can have a significant effect on performance. Another rectangular wideband patch antenna for 28 GHz, on the same substrate, was proposed by Paul (2021b). He designed two antennas of the same physical dimensions (20×17 mm^2) and carried out simulations in CST Studio. The study has shown a good trade-off between small size and performance with a signal strength of 8.39 dBi and a bandwidth of 2.567 GHz, along with high radiation effectiveness. One of the limitations is that this work focused only on single-layer configurations; multi-layer or metasurface-enhanced designs could have further improved the signal strength and bandwidth, better aligning with current optimization trends.

On the other hand, Teresa and Umamaheswari (2020) presented a low-cost FR-4 substrate for the design of a compact slotted antenna at 28 GHz using HFSS. Even with FR-4 having a high signal loss, this antenna achieved 6.59 dBi in signal strength with an effectiveness of 82.08%. Although the work is commendable for advocating low-cost fabrication, FR-4 is well known for its high dielectric losses at mmWave frequencies. Hence, the design cannot be realistic for actual deployments of 5G communications. However, it does highlight some innovative slot engineering strategies useful for the optimization of compact designs.

Ateeyah (2025) implemented a wearable 28 GHz MPA with a polycarbonate substrate and optimized for flexibility and comfort in 5G-enabled applications. The design was implemented and analyzed using CST Studio. The obtained signal strength was 8.32 dBi, return loss of -22.88 dB, bandwidth of 1.452 GHz, and efficiency of 74.5%, with a VSWR of 1.1, which proves that material selection is crucial for 5G body-worn applications. The performance analysis without wearing on the body is missing, which needs to be considered because human tissue fabric normally detunes mmWave antennas. However, the work offers valuable insight into the behavior of flexible substrates at 28 GHz.

Jiddney (2020) presented a circular MPA on FR-4 substrate ($\varepsilon r = 4.3$, $h = 1.605$ mm) with dimensions of $18 \times 17 \times 1.605$ mm^3 for low-cost 5G systems. This design, which consisted of a circular radiating patch and a partial ground plane, was created and simulated using CST Studio Suite. While the antenna exhibited a wide 7 GHz bandwidth, its efficiency is comparatively low at 55.4%, highlighting some of the drawbacks of using lossy substrates within mmWave bands. Nevertheless, this work demonstrates how geometrical shaping alone can have a profound effect on bandwidth performance.

Geometrical novelties have also been the subject of several studies. Monisha and Padmasine (2024) presented a 3.7 GHz G-shaped antenna proving that changing the shape can result in better bandwidth and compactness. Although it is not operating at 28 GHz, the idea of the design allows confirming that unusual patch geometries contribute to better impedance bandwidth. Also, Yusuf and Ali (2024) presented the optimization of slot-optimized MPAs for 28 GHz using RT/Duroid 5880, yielding good signal strength, effectiveness, and compactness. The study is relevant in optimizing at 28 GHz; however, it does not elaborate on the radiation pattern stability, an issue that is extremely significant in 5G beamforming applications.

Again, Hassan and Khudair (2024) introduced a butterfly-shaped antenna on RT5880 for 50.5 GHz with high signal strength and bandwidth. Although at a higher frequency, the design approach of slot optimization and substrate choice is transferable to 28 GHz, hence conceptually useful. Similarly, Shoaib et al. (2024) evaluated various metals, namely silver and gold, on a Rogers 5870 substrate, arriving at a bandwidth of 5.25 GHz at 25.8 GHz. Their work, while providing material insights, does not aim directly at 28 GHz. Accordingly, it was found that the metasurface-loaded MPAs enhanced the signal strength by more than 10 dBi while keeping the compactness and bandwidth, hence directing the optimization of 28 GHz antennas.

Accordingly, it is evident that, despite the vast amount of progress made in 28 GHz antenna design, there is still a void in the existing body of knowledge on the optimized design of a straightforward, single-layer, and wideband microstrip patch antenna that relies on the optimization of the thickness of the substrate material of the Rogers RT/Duroid 5880 to ensure optimal impedance matching, broad bandwidth, and high directional gain. The void in knowledge is, therefore, filled in this work, in which the design and optimization of the 28 GHz microstrip patch antenna utilizing the transmission line theory and parametric analyses will be performed.

II. MATERIALS AND METHODS

The microstrip antenna was designed to operate at the 28GHz frequency band. The design process began with the selection of the operating frequency within the mm-wave spectrum. This was followed by the choice of Rogers RT/Duroid 5880 as the substrate material due to its low dielectric constant, low loss tangent, and suitability for high-frequency applications. The substrate height chosen was 1.575 mm; this substrate thickness provides an effective trade-off between bandwidth enhancement, gain improvement, and impedance matching

The design procedure involved the calculation of the patch, substrate, and ground plane dimensions using standard transmission line model equations. These equations accounted for the effective dielectric constant, length extension due to fringing fields, and impedance matching requirements. The dimensions for the antenna were calculated using the equations in subsection 2.1 (Design calculations). Thereafter, the antenna structure was simulated in CST Studio Suite 2024 with the Time Domain Solver. A hexahedral mesh type was employed for improved field accuracy and adaptive refinement around the feed region. The boundary conditions were set to open, and the antenna was excited using a microstrip line feed port.

A parametric sweep simulation was carried out to optimize the antenna performance. Key parameters such as substrate thickness, patch length and width, and feedline dimensions were systematically varied to improve the antenna parameters. Then, the performance parameters such as the return loss, bandwidth, gain, and radiation efficiency were analyzed.

2.1 Design Calculations

1. Patch Width (Wp): The patch width represents the main radiating element of the antenna. It influences the input impedance of the antenna. It is calculated from the operating frequency and the substrate material properties as:

$$W_p = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (1)$$

Where c_o is the velocity of the electromagnetic wave in free space, ε_r is the relative permittivity of the substrate, and f_r is the operating frequency.

2. Effective Dielectric constant (ε_{eff}): This occurs due to fringing fields around the patch edges. The effective dielectric constant differs slightly from the actual substrate permittivity. It is expressed as:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1 + 12\frac{h}{W_p}\right)^{-\frac{1}{2}} \quad (2)$$

Where h – height of substrate

3. Effective length (L_{eff}): This is the electrical length required for the antenna to resonate at the desired frequency

$$L_{\text{eff}} = \frac{c}{2f_r\sqrt{\varepsilon_{\text{eff}}}} \quad (3)$$

4. Length Extension (ΔL): Fringing fields at the patch edge cause an additional length beyond the effective length. This is estimated using:

$$\Delta L = 0.412h\frac{(\varepsilon_{\text{eff}}+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varepsilon_{\text{eff}}-0.258)\left(\frac{W_p}{h}+0.8\right)} \quad (4)$$

5. Actual Patch length (L): This is the final length of the patch used in the simulation before optimization

$$L = L_{eff} - 2\Delta L \quad (5)$$

6. Substrate Dimensions: These define the physical size of the substrate; it is made larger than the patch to minimize edge effects, but the same as the ground plane

Length of substrate (L_S) $L_S = L_P + 6h$ 6

Width of substrate (W_S) $W_S = W_P + 6h$ 7

7. Feedline width (W_f): The width of the feedline is designed to match the input impedance of the antenna to the standard 50-ohm impedance of RF systems

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{8h}{W} + \frac{W}{4h}\right) \quad 8$$

Table I shows the antenna design values. Figures 1 and 2 show the design dimensions and the perspective view, respectively

Table 1: Design Value

Parameters	*Calculated Value*	*Optimized Value*
Length of substrate (L_s)	11.98mm	13mm
Width of substrate (W_s)	13.686mm	17mm
Length of patch (lp)	2.53mm	10.5mm
Width of patch (Wp)	4.236mm	12.71mm
Width of feedline(wf)	4.93mm	4.8mm
Length of feedline(lf)	5mm	8mm
Gap	0.60mm	0.79mm
Feedline insertion	5mm	5.8mm
Substrate Thickness	1.575mm	1.575mm

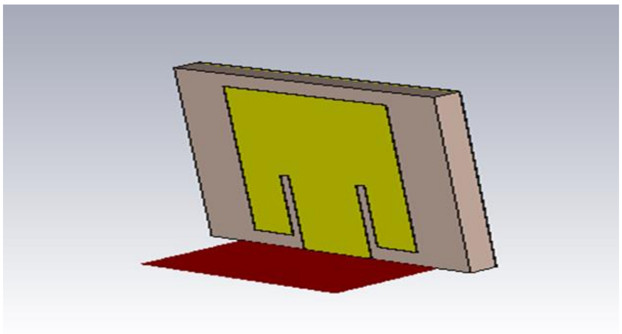


Figure 1: Perspective view of the proposed design

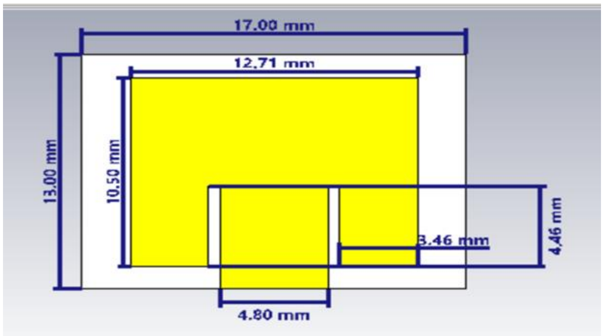


Figure 2: Optimized dimension of the antenna

III. RESULTS AND DISCUSSION

3.1 Results of Design and Simulation

The results of the design and simulation as well as performance parameters and comparisons with other designs are presented herein.

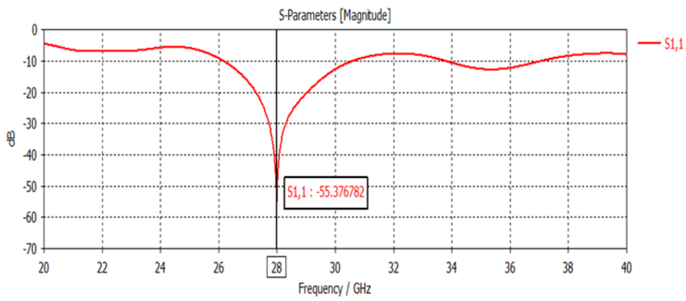


Figure 3: Return loss of the proposed antenna

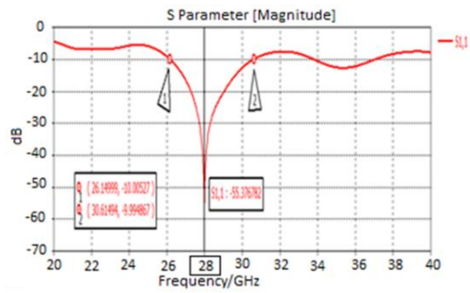


Figure 4: Simulated bandwidth of the proposed antenna

From Figure 3, it can be observed that the antenna design achieved a return loss of -55.376 dB at 28 GHz, in CST studio simulation. This shows that the antenna is very well matched to the feedline. A return loss this low means that almost all the input signal is transferred into the antenna, with almost no energy lost due to reflection. While most studies on 28 GHz microstrip antennas report return loss values between -20 dB and -37 dB, the result for the proposed design achieves a better value. This demonstrates that even with a thicker substrate, the antenna maintains high performance and strong impedance matching, making it suitable for reliable use in 5G applications.

Figure 4 shows the simulated bandwidth of the antenna. It achieves a wide bandwidth, measuring 4.465 GHz across its operating frequency range. This was achieved selecting a high substrate height of 1.575 mm, which significantly enhances the antenna's bandwidth by further increasing fringing fields and reducing the Q factor. Such a wide bandwidth is highly desirable in 5G wireless communication systems.

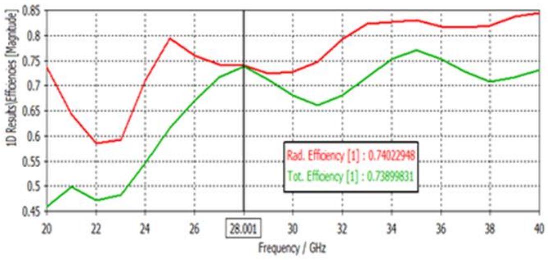


Figure 5: Simulated Efficiency of the proposed antenna

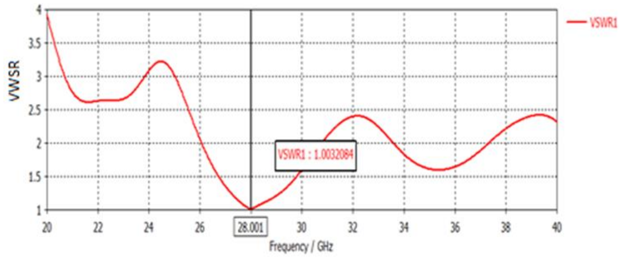
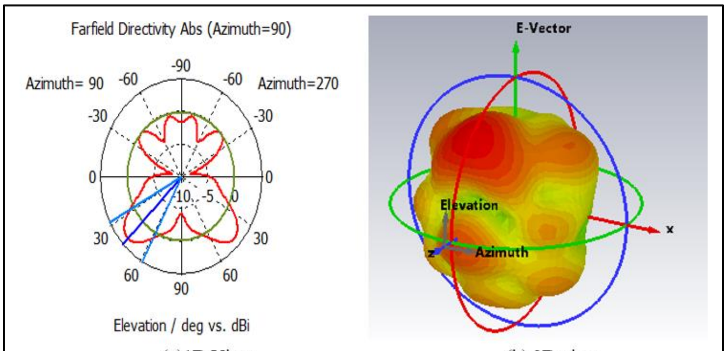


Figure 6: VSWR of the proposed antenna

The total radiation efficiency was recorded as 73.9% (Figure 5) at 28 GHz. This means that 28% of the input power is lost, likely due to increased surface wave excitation, dielectric losses associated with the thicker 1.575 mm substrate. Although 73.9% is still acceptable for many high-frequency applications. The proposed antenna design achieved a VSWR of 1.003 at 28 GHz. This result reflects an almost perfect impedance match, with extremely minimal reflection losses. A VSWR this low is rare in practical antenna designs and highlights the high precision of the feed and patch configuration, despite the substrate thickness.



(a)1D View (b) 3D view

Figure 7: Radiation pattern of the proposed antenna

From Figure 7 it shows that the antenna radiates most of its energy in the direction of the main lobe, which occurs at an elevation angle of 44.0°, with a magnitude of 3.62 dBi. This implies a focused beam, suitable for directional communication. The angular width of the main lobe is 33.8°, indicating a narrow beam spread and a directivity of 9.135dBi. The side lobes are suppressed at -3.7 dB, reflecting moderate leakage of energy in wanted directions.

The radiation pattern in of the 3D view is linear directional, concentrating energy efficiently along the main beam.

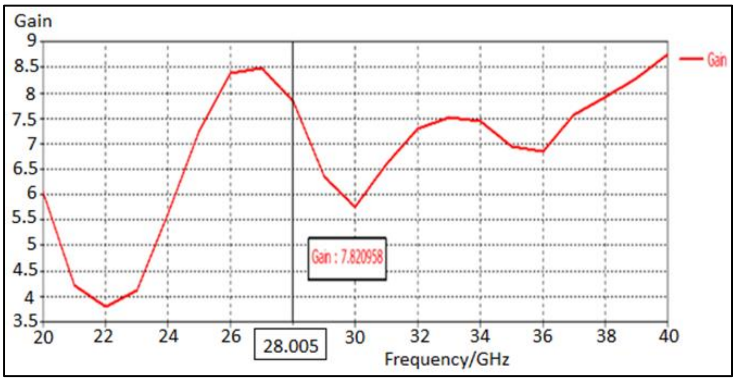


Figure 8: Gain vs frequency plot of proposed design

The antenna design recorded a high gain value of 7.82 dBi (Figure 8) at 28 GHz. This result indicates that the antenna radiates energy strongly in a specific direction, improving signal coverage and transmission strength. A gain of this magnitude reflects effective optimization of the radiating patch, substrate thickness (1.575 mm), and feed structure.

The typical gain range for microstrip patch antennas at this frequency is 5 dBi to 9 dBi, the result from the antenna design is considered high and well-suited for 5G millimeter-wave applications, especially for applications where directional communication and longer range are required.

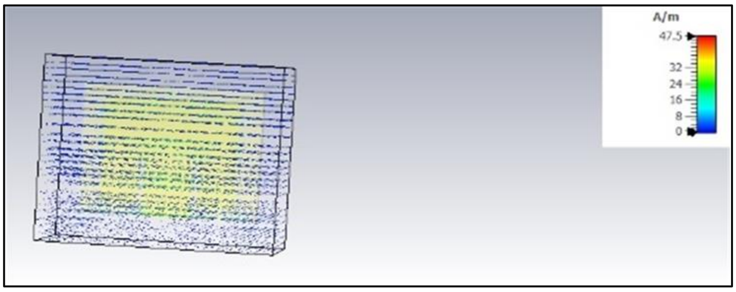


Figure 9: H-field of the antenna design

From Figure 9, the magnetic field (H-field) strength of 58.5633 A/m indicates the intensity of the magnetic component of the radiated wave around the antenna. This value peaks around the edges of the patch and near the feedline, confirming active current flow and radiation.

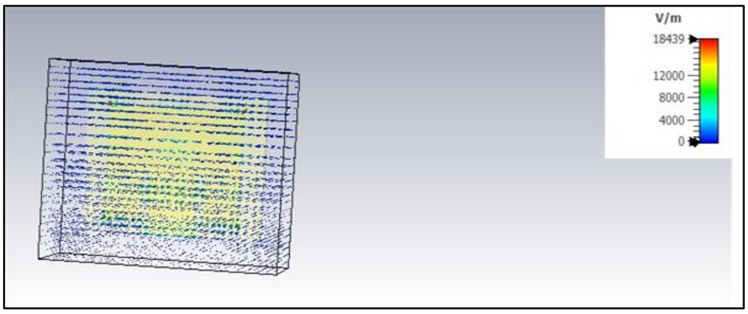


Figure 10: E- field of the antenna design

The electric field (E-field) strength of 21,722.1 V/m (Figure 10) represents the intensity of the electric component of the wave. A high E-field value means the antenna is radiating strong electromagnetic energy, which is essential for transmitting signals over a distance.

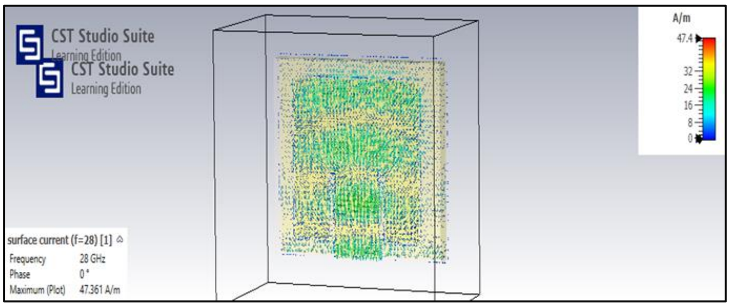


Figure 11: Surface current of the antenna design

The surface current value of 47.461 A/m (Figure 11) in the antenna design shows how much electric current is flowing across the surface of the antenna at resonance. Surface current usually builds up on the radiating patch and the feedline, especially around the edges where radiation is strongest.

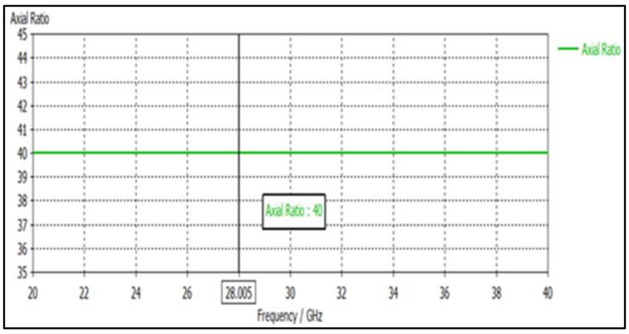


Figure 12: Axial ratio vs Frequency plot of the proposed antenna

The polarization of the antenna design, as shown by CST Studio, is linear, with an axial ratio of 40 dB. Since this value is higher than the thresholds for circular (<3 dB) and elliptical (3-20 dB) polarization, it confirms that the antenna radiates in a single, fixed direction.

3.2 Comparison and validation with the literature

The proposed antenna design operating at the 28GHz achieved a return loss of -55.37dB and a Voltage Standing Wave Ratio (VSWR) of 1.003. Both results surpassed the values reported in the reviewed literature. This demonstrates excellent impedance matching and minimal signal reflection compared to the results in references (Teresa and Umamaheswari, 2020; Ateeyah, 2025). Furthermore, the antenna has a gain of 7.82 dBi, which is

slightly lower than the values in Rana and Smieee (2022); Paul (2021b); Ateeyah (2025), but higher than references Teresa and Umamaheswari (2020) and Jiddney (2020), validating its good radiation performance.
With respect to the bandwidth performance, the proposed design achieved a 4.465GHz. This value surpassed the studies in Rana and Smieee (2022), Paul (2021b), Teresa and Umamaheswari, (2020) and Ateeyah (2025) while being lower than Jiddney (2020).The radiation efficiency is measured at 73.9%, while this is significantly higher than Jiddney (2020), It is lower than Rana and Smieee (2022); Paul (2021b), and Teresa and Umamaheswari, (2020), and closely aligns with the result reported in Ateeyah (2025).

Overall, this finding of these result indicates that while the antenna design performs well in terms of bandwidth and return loss, the thicker substrate may introduce trade-offs that reduce overall efficiency. Nevertheless, the design remains usable in systems where broad bandwidth is prioritized over peak efficiency.

Table 2 Comparison with literature designs

Study	***Freq. (GHz)***	***Substrate***	***Gain (dBi)***	***Return Loss (dB)***	***Bandwidth (GHz)***	***Eff (%)***	***VSWR***
Rana and Smieee	28	Rogers RT 5880	8.2	-38.35	3.464	77	1.02
Paul (2021b)	28	Rogers RT 5880	8.39	-31.68	2.567	84.5	1.05
Teresa and Umamaheswari (2020)	28	Rogers RT 5880	6.59	-27.79	2.6	82.08	1.2
Ateeyah (2025)	28	Polycarbonate	8.32	-22.88	1.452	74.5	1.1
Jiddney (2020)	28	FR-4	5	-	7	55.4	1.023
Proposed design	28	Rogers RT 5880	7.82	-55.37	4.465	73.9	1.003

IV.CONCLUSION

This work presented the design and implementation of an IoT-based weather monitoring system with a communication interface capable of selecting between Wi-Fi and GSM networks based on availability. The system combined modular hardware, adaptive firmware logic, and a cloud-based API and dashboard for environmental data collection and visualization.

The proposed design achieves a high bandwidth of 4.465 GHz and a gain of 7.82 dBi, using a thick substrate at height 1.575mm, making it a very good choice for 5G applications like real-time video streaming, industrial automation, or large-scale IoT deployments, directional mmWave communication and sensing applications, that requires high gain and wide bandwidth, like the new 5G and short-range radar systems. The return loss of –55.376 dB and VSWR of 1.0029 indicate excellent impedance matching. However, the efficiency is lower at 73.9%, likely due to increased surface area and material losses. Its larger size may be a limitation in very compact systems but provides the best bandwidth performance.

AUTHOR(S) CONTRIBUTIONS

Henry E. Amhenrior: Conceptualization, Methodology, Supervision, Writing – review and editing. Data curation; Funding acquisition; Project administration.
Imana Wilfred: Methodology, Software, Validation, Writing – original draft, Data curation; Funding acquisition; Project administration.

AI DISCLOSURE

Artificial Intelligence instruments (Grammarly and ChatGPT) were employed exclusively for the enhancement of linguistic precision and grammatical correction of the manuscript. The research methodology, data analysis, interpretations, and conclusions were comprehensively formulated by the authors. The authors meticulously examined all AI-assisted modifications and assume full responsibility for the content.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper. The authors have no financial, personal, academic, or professional relationships that could have influenced the work reported in this manuscript.

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