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Design and Optimization of a Microstrip Patch Antenna for 5G Wireless Communications Using the Trust Region Framework and Nelder-Mead Simplex Algorithm

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Abstract: Millimeter-wave (mmWave) communication is a key technology in 5G networks, enabling high data rates, improved capacity, and low latency. This study presents a compact microstrip patch antenna designed for mmWave 5G applications, balancing miniaturization and performance. Operating at 24 GHz (23.9–24.2 GHz), the antenna is built on a Rogers RO3006 substrate, chosen for its excellent electrical properties, low signal loss, and high efficiency. With dimensions of 20.45 mm × 10 mm × 0.254 mm, it achieves a directivity gain of 9.41 dBi. To enhance performance, optimization techniques such as the Trust Region Framework and Nelder-Mead Simplex Algorithm are applied, improving radiation efficiency, impedance matching, and bandwidth. This design contributes to the development of compact, high-efficiency antennas for 5G and future wireless technologies.

Keywords: Antenna, 5G Wireless Communication, Trust Region Framework, Nelder-Mead Simplex Algorithm.

I. INTRODUCTION

Antennas play a key role in 5G wireless communication by enabling fast data speeds, low delay, and wide coverage [1]. They help send and receive radio waves, allowing smooth data transfer between devices and network systems. In 5G networks, antennas are crucial for improving speed, capacity, and reducing delays. Their ability to work across different frequency bands, support beamforming, and enhance connectivity makes them essential for various applications and industries [2].

Millimeter-wave (mmWave) technology operates at much higher frequencies than traditional mobile networks, offering large bandwidth and extremely fast data transfer [2]. However, mmWave signals have shorter wavelengths, making them more likely to be blocked by obstacles like buildings and trees, causing signal loss. To overcome this, advanced techniques such as beamforming, phased array systems, and improved antenna designs are used. These methods help direct signals more accurately, improving connectivity and ensuring strong signal transmission in 5G networks [3].

Overall, mmWave communication serves as a cornerstone of 5G wireless technology, unlocking opportunities for high-speed, low-latency connectivity. Its advancements are driving transformative applications across various industries, paving the way for the next generation of wireless communication.

II. OPTIMIZATION TECHNIQUES

A. Trust Region Framework

The Trust Region Framework is an optimization method used to solve nonlinear design problems in antennas, filters, and microwave components. It operates by defining a "trust region," a subset of the parameter space where the model’s predictions are considered reliable. The process begins with an initial guess of design parameters, followed by approximating the objective function within a limited region. Optimization occurs within this trust region using either derivative-free or gradient-based methods. If the new solution shows significant improvement, the trust region expands; if not, it contracts to refine accuracy. This iterative process continues until optimization criteria, such as performance improvement or iteration limits, are met.

B. Nelder-Mead Simplex Algorithm

The Nelder-Mead Simplex Algorithm is an optimization method effective for discontinuous, noisy, or non-differentiable objective functions, commonly used in CST Studio Suite for designing electromagnetic components like antennas, waveguides, and filters. It begins by initializing a simplex with n+1 vertices in an n-dimensional space, evaluating the objective function at each vertex, and ordering them based on performance. The worst vertex is reflected across the centroid to find a potentially better point. If successful, expansion follows; otherwise, contraction towards the best vertex is attempted. If contraction fails, shrinkage reduces the search space. This iterative process continues until the optimization criteria, such as function improvement or minimal changes in the simplex, are met.

III. PROPOSED ANTENNA DESIGN FOR MMWAVE 5G WIRELESS COMMUNICATION

The proposed antenna is designing for 24GHz millimeter-wave (mmWave) communication a critical component of 5G technology is the first stage in this project. The Rogers RO3006 substrate, selected for its exceptional electrical qualities, is used in the construction of the suggested antenna. This substrate is perfect for high-frequency applications because of its low loss tangent of 0.002, dielectric constant of 6.15, and thermal conductivity of 0.61 W/K/m. To optimized the proposed antenna design for better performance the Trust Region Framework and the Nelder-Mead Simplex Algorithm is used.

Figure 1 presents the proposed antenna design, while Table 1 lists the parameters used in the design. This chapter elaborates on the application of these optimization techniques and the resultant improvements in the antenna's performance characteristics.

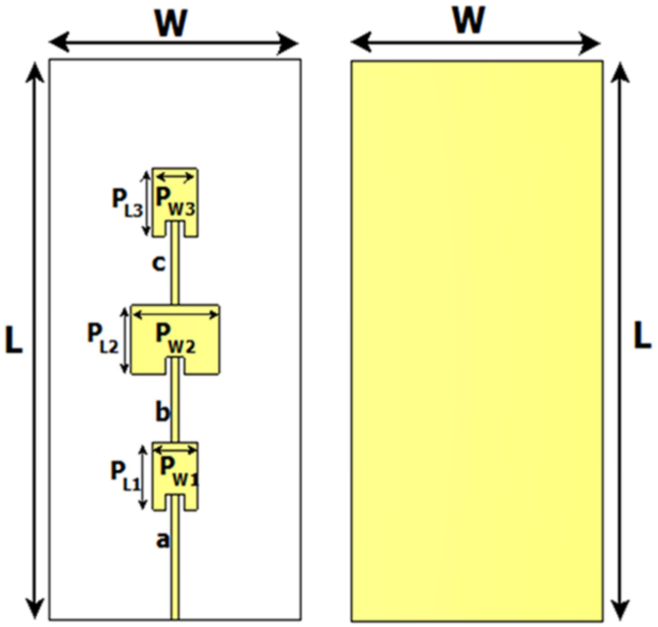

Figure 1: Proposed Antenna Design

Table 1: Parameters used in Proposed Antenna Design

Parameter	**Description**	**Value (mm)**
L	Length of Antenna	20.45
W	Width of Antenna	10.00
PL1	Length of Patch1	2.49
PW1	Width of Patch1	1.75
PL2	Length of Patch2	2.49
PW2	Width of Patch2	3.50
PL3	Length of Patch3	2.49
PW3	Width of Patch3	1.75
a	Length of Feed	4.59
	Width of Feed	0.32
	Length of Insert	0.59
	Width of Insert	0.20
b	Length of Feed	3.08
	Width of Feed	0.32
	Length of Insert	0.59
	Width of Insert	0.20
c	Length of Feed	3.08
	Width of Feed	0.32
	Length of Insert	0.59
	Width of Insert	0.20

IV. RESULTS AND DISCUSSION

The physical dimensions of the proposed antenna are 20.45 mm in length, 10 mm in width, and 0.254 mm in thickness. The simulation results reveal that the magnitude of S11 for the proposed antenna is -43.8 dB at a frequency of 24 GHz, indicating exceptional impedance matching and minimal signal reflection at the target frequency. The graphical representation of this S11 magnitude is shown in Figure 2.

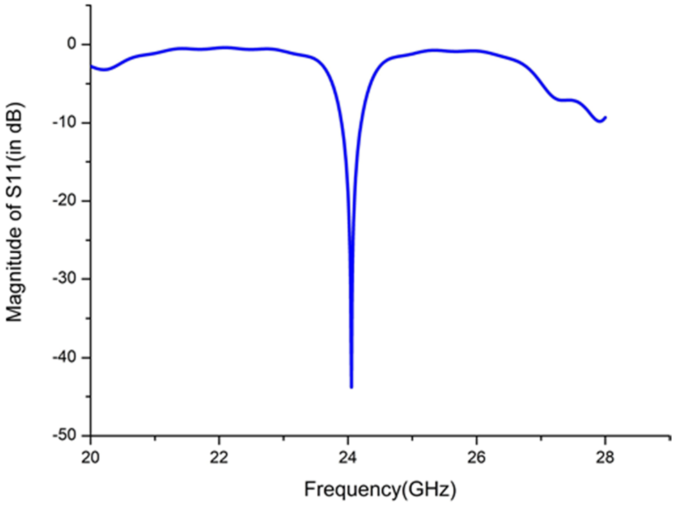

Figure 2: Graphical Representation of Magnitude of S11 of the Proposed Antenna Design

The suggested antenna's simulated far-field gain at Phi 0 and Phi 90, which is 9.41 dBi based on the simulation, is shown in Figure 3. This suggests that the radiation pattern of the antenna has a high directional efficiency. Furthermore, the proposed antenna's 3D radiation pattern is shown in Figure 4, offering a thorough understanding of its radiation properties.

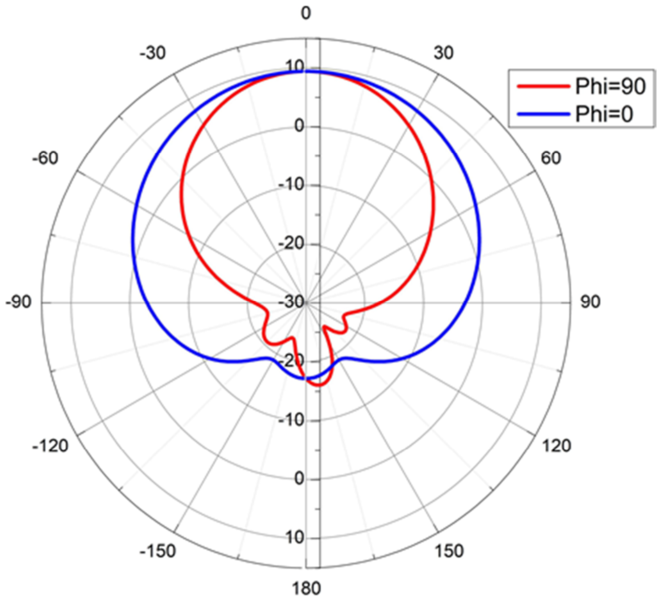

Figure 3: Far-filed Gain of the Proposed Antenna Design

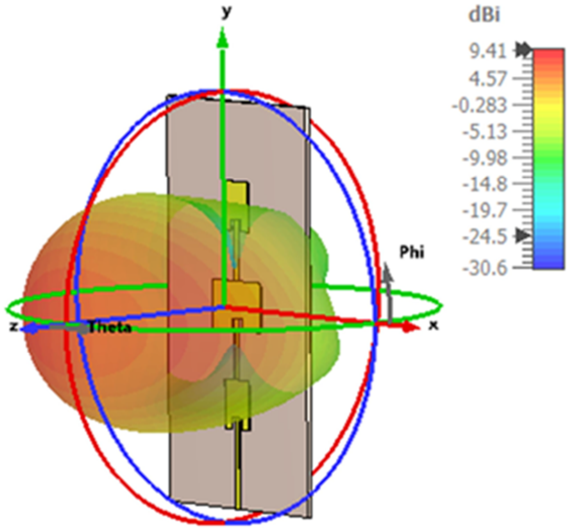

Figure 4: 3D Radiation Pattern of the Presented Antenna

Additionally, the suggested antenna's surface current distribution at 24 GHz is 336.962 A/m. Figure 5 shows this distribution, emphasizing the current flow on the antenna's surface, which is essential for comprehending its functionality and improving its design.

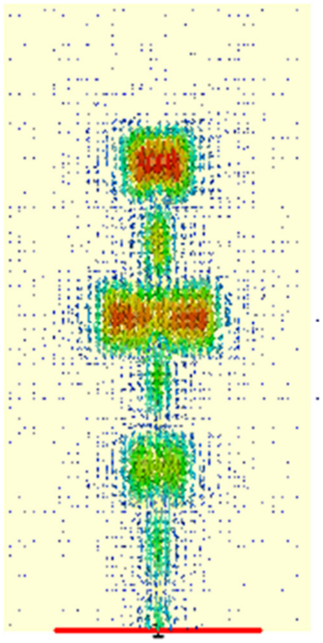

Figure 5: Surface Current of the Presented Antenna

V. CONCLUSION

This study presents a compact microstrip patch antenna optimized for mmWave 5G communication, offering high gain, wide bandwidth, and efficient performance. Designed with the Rogers RO3006 substrate, it operates at 24 GHz with a frequency range of 23.9–24.2 GHz, achieving a gain of 9.41 dBi and a return loss of -43.79 dB. The antenna's small size (20.45 mm × 10 mm × 0.254 mm) ensures suitability for next-generation wireless networks. Performance optimization using the Nelder-Mead Simplex Algorithm and Trust Region Framework confirms its effectiveness in meeting 5G communication requirements.

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