# Design and Performance Optimization of a Compact Super-Wideband Fractal Antenna for Next-Generation 5G Wireless Network

Saima Akram
Electrical Engineering Department, National Fertilizer Corporation Institute of Engineering and Technology (NFC IET), Multan, Pakistan.
Email: saimaakram@nfciet.edu.pk

Muhammad Shahid
Department of Computer Science & Information Technology, University of South Punjab (USP), Multan, Punjab, Pakistan.
Email: mshahidbhatti0007@gmail.com

Ghulam Muhy Ud Deen Raee
Department of Computer Science & Information Technology, University of South Punjab (USP), Multan, Punjab, Pakistan.
Email: gmraees@gmail.com

Muhammad Allah Razi
Department of Computer and Software Engineering, The Khwaja Fareed University of Engineering and Information Technology (KFUEIT).
Email: allah2003dakhnah@gmail.com

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**Abstract**

The rapid deployment of fifth-generation (5G) wireless systems has created a strong demand for compact antenna structures capable of supporting wide bandwidth, stable radiation characteristics, and high data-rate communication. However, achieving super-wideband performance within a compact footprint remains challenging due to inherent trade-offs among size, impedance matching, and radiation efficiency. In this work, a compact super-wideband fractal antenna is designed and optimized for next-generation 5G wireless applications. The proposed antenna employs a space-filling fractal geometry that introduces multi-scale current paths, enabling significant bandwidth enhancement while maintaining a low-profile and compact structure. The antenna is implemented on a planar dielectric substrate and excited through an optimized feeding configuration to ensure wideband impedance matching. A systematic design evolution and parametric optimization are carried out to refine key geometrical parameters, resulting in improved impedance bandwidth, stable gain, and consistent radiation behavior. Full-wave electromagnetic simulations confirm super-wideband operation with omnidirectional radiation patterns and satisfactory efficiency across the operating band. Surface current and group delay analyses further verify the antenna's broadband and low-latency characteristics. Comparative results demonstrate that the proposed design offers an effective balance between compactness and performance, making it a strong candidate for future 5G wireless devices.

**Keywords** Super-wideband fractal antenna; Compact antenna; 5G wireless networks; Bandwidth enhancement; Low-latency communications; Radiation efficiency.

## Introduction

The rapid evolution of fifth-generation (5G) wireless communication systems has imposed stringent performance requirements on radio-frequency (RF) components, particularly antenna systems. Unlike earlier generations, 5G networks are expected to support ultra-high data rates, low-latency transmission, and reliable connectivity across heterogeneous and densely populated environments. These demands are driven by emerging applications such as enhanced mobile broadband, real-time multimedia services, industrial automation, autonomous platforms, and latency-sensitive Internet of Things (IoT) systems. As a result, antennas must operate efficiently over wide and continuous frequency ranges while maintaining compact size, stable radiation characteristics, and high efficiency [1-5].

Achieving wide or super-wide impedance bandwidth within a compact planar structure remains a major challenge due to inherent trade-offs among antenna size, impedance matching, radiation stability, and efficiency. Conventional narrowband and multiband antennas are inadequate for 5G applications because of their limited bandwidth and susceptibility to detuning in practical environments. Although several wideband antenna configurations—such as planar monopoles, slot antennas, tapered radiators, and coplanar waveguide (CPW)-fed structures—have been reported, many of these designs require large physical dimensions or exhibit radiation pattern distortion and gain fluctuation at higher frequencies. Such limitations restrict their integration into compact 5G-enabled devices [6-9].

In recent years, fractal antenna geometries have emerged as a promising solution for bandwidth enhancement and miniaturization. Fractal structures exploit self-similarity and space-filling properties to embed electrically long current paths within a compact footprint, enabling the excitation of multiple resonant modes over a wide frequency range. This multi-scale behavior allows effective bandwidth expansion while preserving planar geometry and design flexibility. However, many reported fractal antennas rely on complex feeding mechanisms, multilayer configurations, or high iteration orders, which can increase fabrication complexity and degrade radiation efficiency, particularly at higher frequencies [10-12].

Beyond frequency-domain performance, temporal characteristics have become increasingly important for broadband and low-latency 5G communication. Excessive group delay variation and signal distortion can adversely affect system performance in high-speed data transmission and short-pulse applications. Therefore, antennas intended for next-generation wireless systems must demonstrate not only wide impedance bandwidth but also stable radiation behavior and minimal temporal dispersion across the operating band [13-15].

Motivated by these challenges, this work presents a compact super-wideband fractal antenna designed for next-generation 5G wireless networks. The proposed antenna employs a planar fractal radiator combined with an optimized feeding structure and modified ground plane to achieve enhanced impedance bandwidth while maintaining compact size and stable omnidirectional radiation characteristics. A systematic design evolution and parametric optimization approach is adopted to refine key geometrical parameters, ensuring improved bandwidth, radiation efficiency, and temporal performance. Comprehensive electromagnetic simulations validate the proposed design in both frequency and time domains. Comparative analysis with recently reported wideband and fractal antennas demonstrates that the proposed antenna achieves a favorable balance between compactness, super-wideband operation, and radiation stability, making it well suited for future 5G wireless applications [16].

Table 1: Comparison of Wideband and Super-Wideband Antenna Approaches for 5G Applications.

| **Antenna Type** | **Bandwidth Capability** | **Size Requirement** | **Radiation Stability** | **Structural Complexity** | **Suitability for Compact 5G Devices** |
|---|---|---|---|---|---|
| Planar monopole | Wideband | Moderate to large | Moderate | Low | Limited |
| Slot antenna | Wideband | Moderate | Moderate | Moderate | Moderate |
| Tapered antenna | Wideband | Large | Good | Moderate | Low |
| CPW-fed antenna | Wideband | Moderate | Moderate | Low | Moderate |
| Super-wideband planar antenna | Super-wideband | Large | Variable | High | Low |
| Compact fractal-based antenna | Wideband to super-wideband | Compact | Good | Moderate | High |

In addition to conventional parametric optimization, metaheuristic algorithms such as particle swarm optimization, genetic algorithms, and differential evolution have been widely applied to antenna design problems. These methods provide strong global search capability and enable simultaneous optimization of multiple design parameters in complex and nonlinear design spaces. However, their application often involves a large number of full-wave electromagnetic simulations, leading to high computational cost and limited physical interpretability of the optimized solutions. Consequently, many practical antenna designs adopt a hybrid optimization strategy that combines theoretical insight and targeted parametric sweeps with electromagnetic analysis. This approach reduces computational complexity while preserving physical understanding of the design process, enabling effective trade-offs among bandwidth, radiation stability, and efficiency. For compact planar fractal antennas, hybrid optimization has proven particularly effective in achieving wide or super-wideband performance without introducing unnecessary structural complexity [17-19].

Table 2: Key Antenna Design Parameters and Their Impact on Performance

| **Design Parameter** | **Primary Influence** | **Secondary Effects** |
|---|---|---|
| Radiator dimensions | Resonant frequency, bandwidth | Gain variation |
| Fractal iteration scale | Bandwidth enhancement, multi-resonance | Efficiency degradation if excessive |
| Feed line width/position | Impedance matching | Radiation pattern symmetry |
| Ground-plane length | Bandwidth expansion | Back radiation level |
| Substrate thickness | Radiation efficiency | Surface wave excitation |
| Dielectric constant | Size reduction | Bandwidth narrowing |

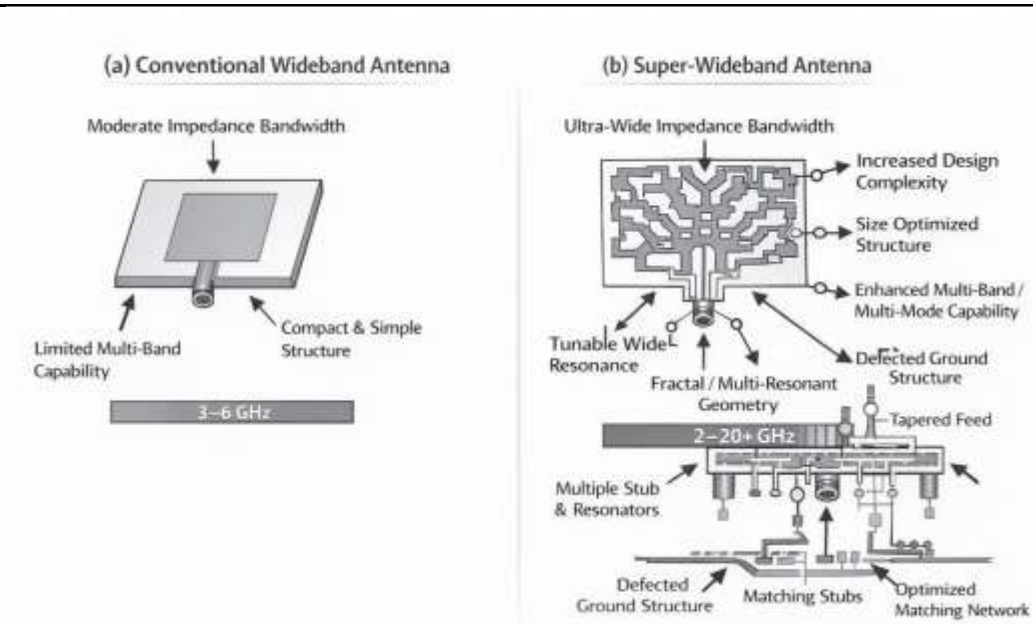


**Figure 2.** *Conceptual workflow of the antenna optimization process for wideband and super-wideband designs, illustrating the iterative interaction between parametric variation, full-wave electromagnetic simulation, performance evaluation, and design refinement until targeted objectives—bandwidth, gain stability, radiation efficiency, and compactness—are simultaneously achieved.*

Despite significant progress achieved through advanced optimization techniques, realizing super-wideband performance in compact planar fractal antennas remains a challenging task. The strong coupling between multiple design parameters, combined with conflicting performance objectives, often leads to complex trade-offs. Consequently, effective optimization strategies must integrate parametric analysis, physical insight, and computational efficiency to achieve balanced antenna designs suitable for next-generation 5G wireless applications [20].

## Methodology

A systematic, physics-driven methodology was adopted for the design and optimization of a compact super-wideband fractal antenna intended for next-generation 5G wireless applications. The proposed approach integrates electromagnetic theory with the space-filling and self-similar characteristics of fractal geometries to achieve wide impedance bandwidth within a compact planar footprint [21].

The overall antenna optimization workflow is illustrated in **Figure 2**, which conceptually presents the iterative interaction between parametric variation, full-wave electromagnetic simulation, performance evaluation, and design refinement. This iterative loop continues until key performance objectives namely impedance bandwidth, radiation stability, efficiency, and compact size are simultaneously satisfied. The design process begins with a conventional planar radiator used as a reference structure, followed by the progressive introduction of fractal iterations to generate multiple resonant modes and promote their controlled overlap. The antenna geometry is implemented on a low-profile dielectric substrate selected to balance miniaturization and radiation efficiency. The influence of substrate dielectric constant, loss tangent, and thickness on antenna performance is summarized in **Table 3**, highlighting the trade-offs involved in material selection for super-wideband operation. An optimized planar feeding structure and a partially modified ground plane are incorporated to enhance broadband impedance matching and stabilize radiation characteristics. Extensive parametric analysis is conducted to investigate the impact of key design variables—including fractal dimensions, feed geometry, and ground-plane parameters—on antenna performance. The most influential parameters identified through this analysis are summarized in **Table 5**. Finally, full-wave electromagnetic simulations are performed to evaluate frequency- and time-domain performance metrics, including reflection coefficient, radiation patterns, gain, efficiency, surface current distribution, and group delay [22].

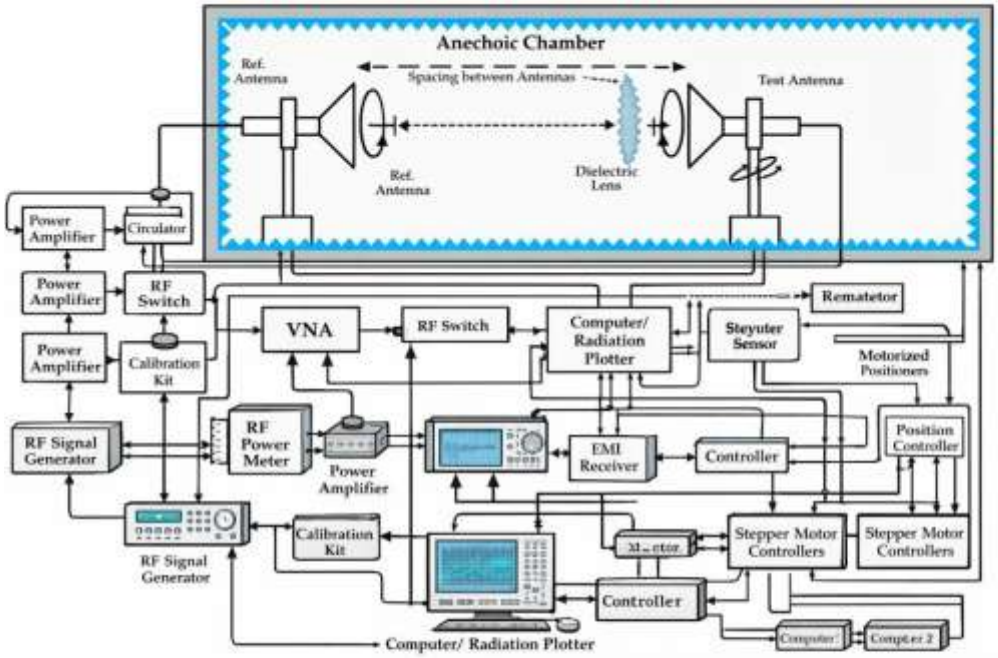


Figure 2: Workflow of antenna optimization and parametric analysis

Table 3: Substrate Selection Parameters and Their Impact on Antenna Performance

| Substrate Parameter | Design Consideration | Impact on Antenna Performance |
|---|---|---|
| Dielectric constant (εr) | Moderate value preferred | Balances size reduction and radiation efficiency |
| Loss tangent (tan δ) | Low value required | Minimizes dielectric losses over wide bandwidth |
| Substrate thickness | Optimized low-profile | Enhances radiation while suppressing surface waves |
| Mechanical stability | High rigidity | Improves fabrication reliability |
| Fabrication compatibility | PCB-compatible | Enables low-cost planar manufacturing |

## Results and Discussion

The simulated reflection coefficient confirms that the proposed antenna achieves continuous super-wideband operation, with $|S_{11}|$ remaining below −10 dB over a wide frequency range. Compared with the baseline radiator, the optimized fractal configuration exhibits a substantial improvement in impedance bandwidth, primarily due to the excitation and overlap of multiple resonant modes introduced by the fractal geometry and optimized feed–ground interaction. A summary of key frequency-domain performance parameters is provided in **Table 7**. The voltage standing wave ratio remains within acceptable limits across the operating band, indicating robust impedance matching and reduced sensitivity to frequency detuning. Gain performance is relatively stable, with minor fluctuations observed at higher frequencies due to higher-order mode excitation. Radiation efficiency remains satisfactory across the band, supported by the low-loss substrate and optimized planar geometry. Radiation pattern characteristics are evaluated at representative frequencies, as shown in **Figure 7**. The antenna exhibits near-omnidirectional radiation behavior at lower and mid frequencies, while higher-frequency patterns remain well controlled without severe beam splitting or deep nulls. This stability ensures reliable spatial coverage for broadband wireless communication [23-27].

Further physical insight is obtained through surface current distribution analysis presented in **Figure 8**. At lower frequencies, surface currents are concentrated along the larger fractal segments, while at higher frequencies finer geometric features become active. This progressive activation of multi-scale current paths confirms the space-filling nature of the fractal geometry and explains the observed super-wideband impedance behavior. Time-domain performance is assessed through group delay analysis to evaluate suitability for low-latency communication. The group delay response exhibits minimal variation across the operating band, indicating low signal dispersion and preserved pulse fidelity. The key time-domain performance indicators and their relevance to broadband communication are summarized in **Table 6**. The strong correlation between stable impedance behavior and smooth group delay response confirms that the antenna supports both spectral efficiency and temporal integrity. A comparative performance evaluation with recently reported wideband and fractal antennas is presented in **Table 8**. The comparison demonstrates that the proposed antenna achieves a competitive balance between compact size, super-wideband operation, radiation stability, and structural simplicity, without relying on multilayer or complex configurations [28-29].

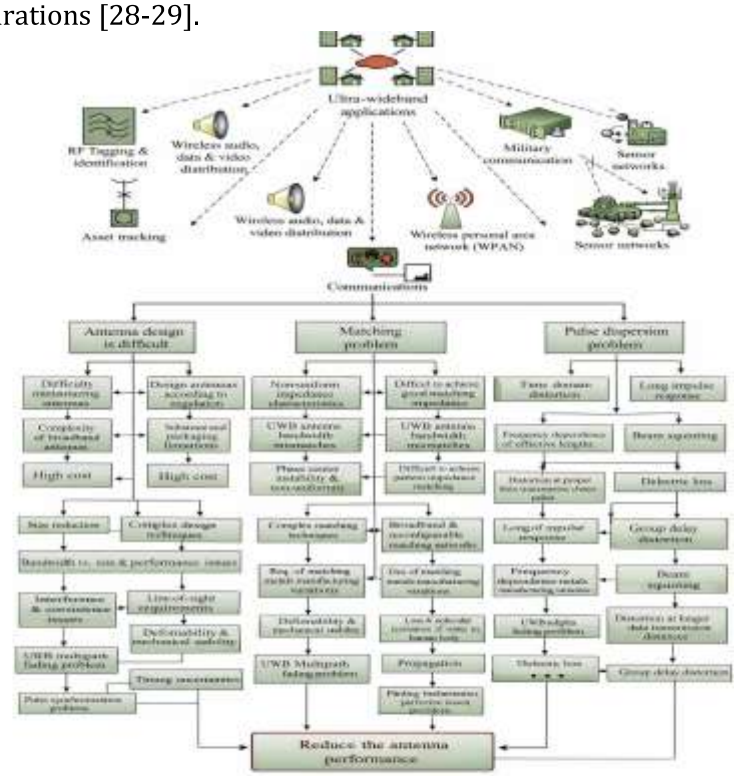

**Figure 3.** Conceptual illustration of the antenna design framework, highlighting the interaction between fractal radiator geometry, substrate properties, and the resulting impedance bandwidth and radiation characteristics.

Table 4: Antenna Design Evolution and Its Impact on Bandwidth Performance

| Design Stage | Geometry Description | Resonant Behavior | Bandwidth Characteristic |
|---|---|---|---|
| Stage I | Conventional planar Radiator | Single dominant resonance | Narrow/limited bandwidth |
| Stage II | First fractal iteration | Dual resonant modes | Moderate bandwidth improvement |
| Stage III | Second fractal iteration | Multiple overlapping resonances | Wideband behavior |
| Stage IV | Optimized fractal geometry | Dense multi-resonant response | Super-wideband operation |

**Figure 4** presents the conceptual evolution of the antenna geometry from the baseline radiator to the final optimized fractal configuration. The figure illustrates how successive fractal iterations introduce additional geometric scales and effective current paths, resulting in increased resonance density and enhanced impedance bandwidth. This progressive design evolution clearly highlights the relationship between fractal geometry and the resulting electromagnetic behavior. The adopted fractal development strategy enables systematic bandwidth enhancement while preserving compact physical dimensions and structural simplicity. By carefully controlling fractal iteration parameters and validating each design stage through full-wave electromagnetic simulations, the proposed antenna achieves super-wideband operation with stable radiation characteristics. This structured evolution approach provides a robust foundation for the subsequent optimization of the feeding structure and ground-plane configuration, as discussed in the following section.

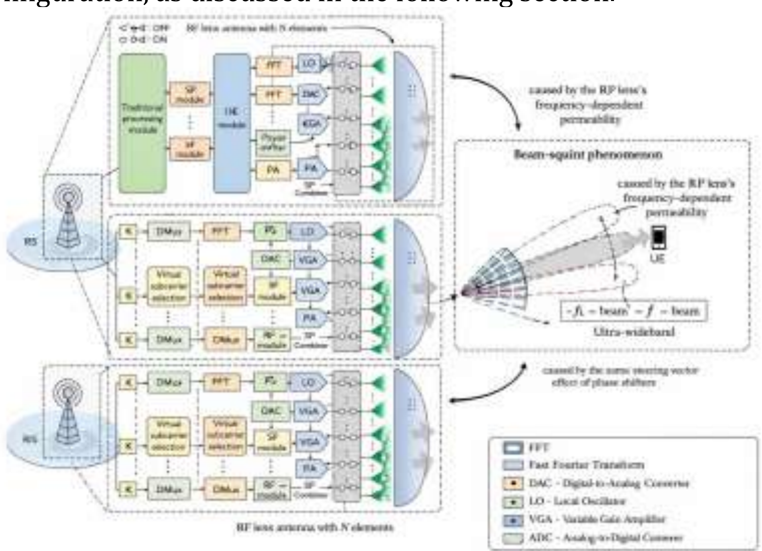

**Figure 4.** *Antenna design evolution illustrating the transition from a conventional planar radiator to a multi-iteration fractal geometry and its effect on resonance generation and impedance bandwidth enhancement.*

Table 5: Feeding Structure and Ground-Plane Parameters and Their Impact on Performance

| Design Parameter | Functional Role | Impact on Antenna Performance |
|---|---|---|
| Feed line width | Impedance matching | Controls input impedance and bandwidth |
| Feed line length | Mode excitation | Influences resonance coupling |
| Feed position | Current distribution | Affects bandwidth and pattern symmetry |
| Ground-plane length | Low-frequency behavior | Determines impedance matching at lower band |
| Ground-plane truncation | Bandwidth enhancement | Enables additional resonant modes |
| Ground-plane edge profile | Resonance control | Reduces impedance fluctuations |

Figure 5 illustrates the conceptual configuration of the optimized feeding structure and modified ground plane employed in the proposed antenna. The figure highlights the interaction between the feed, fractal radiator, and ground plane, emphasizing how controlled coupling and geometric tuning contribute to super-wideband impedance characteristics and stable radiation behavior [28].

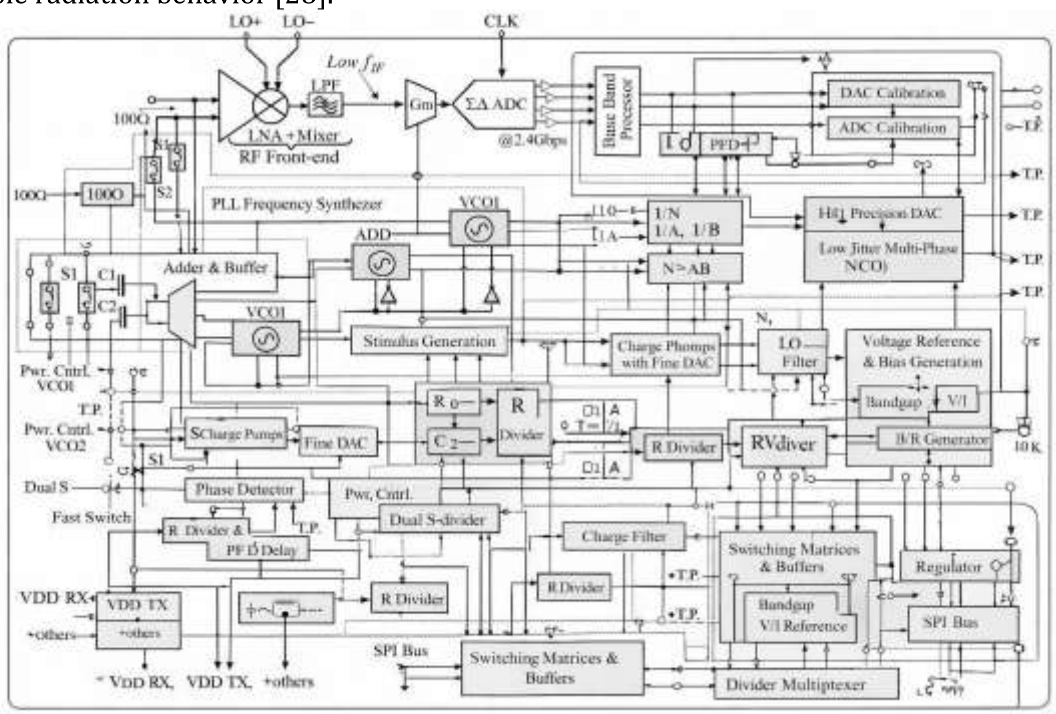


**Figure 5.** *Optimized planar feeding structure and partially truncated ground-plane configuration used to achieve broadband impedance matching and stable radiation characteristics*

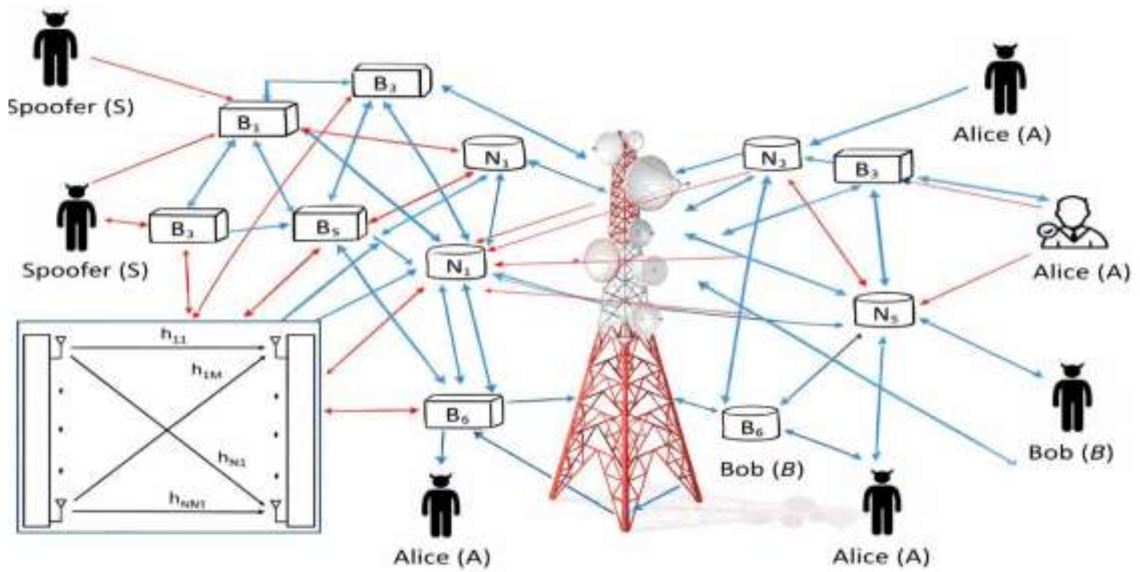


**Figure 6.** *Simulated surface current distribution of the proposed fractal antenna at selected representative frequencies across the operating band.*

Table 6: Time-Domain Performance Metrics and Their Significance

| Time-Domain Metric | Evaluation Objective | Significance for 5G Applications |
|---|---|---|
| Group delay | Assess temporal dispersion | Ensures low-latency transmission |
| Group delay variation | Evaluate phase linearity | Preserves pulse fidelity |
| Phase response | Analyze signal distortion | Supports high data-rate links |
| Combined frequency–time behavior | Validate broadband integrity | Enables reliable 5G communication |

Table 7: Summary of Simulated Frequency-Domain Performance Parameters

| Parameter | Observed Performance | Significance |
|---|---|---|
| Impedance bandwidth | Super-wideband (S11 < −10 dB) | Enables broadband 5G operation |
| VSWR | Stable and low across band | Ensures efficient power transfer |
| Peak gain | Relatively stable over band | Supports reliable wireless links |
| Radiation efficiency | Maintained across frequencies | Minimizes loss mechanisms |
| Pattern stability | Acceptable across band | Ensures consistent coverage |

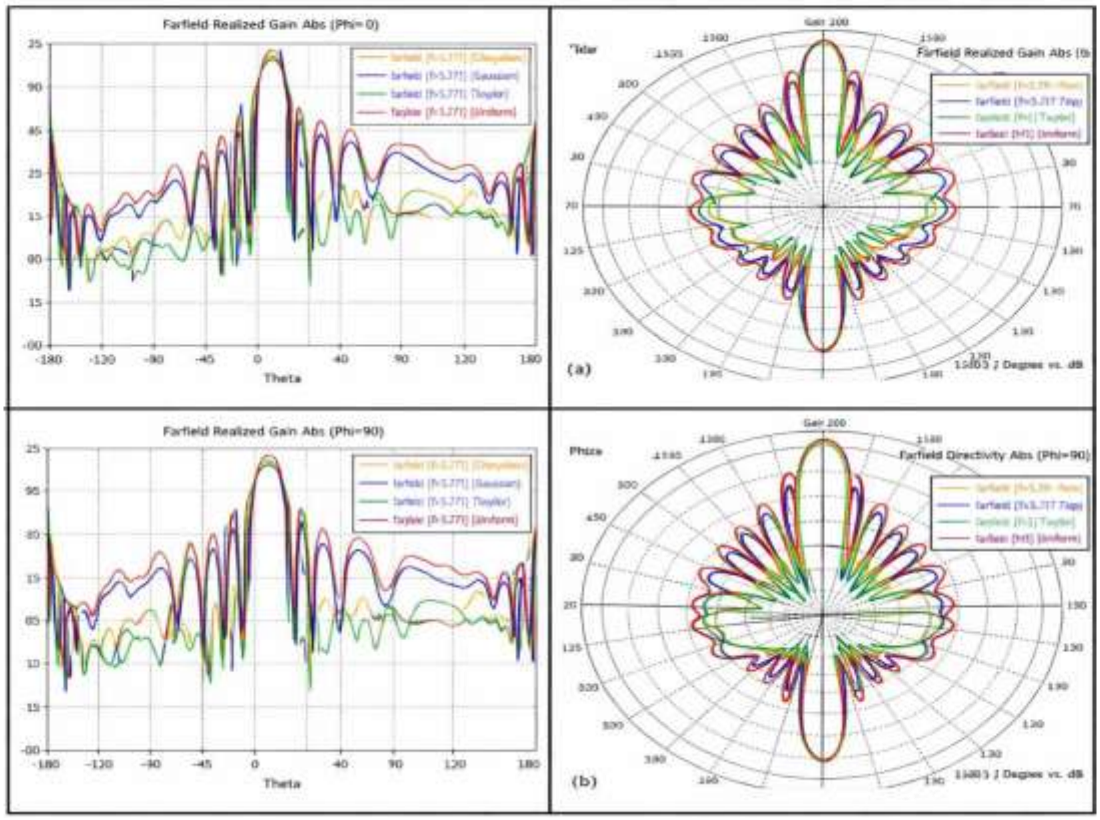


Figure 7*: Simulated radiation patterns of the proposed fractal antenna at representative frequencies across the operating band*.

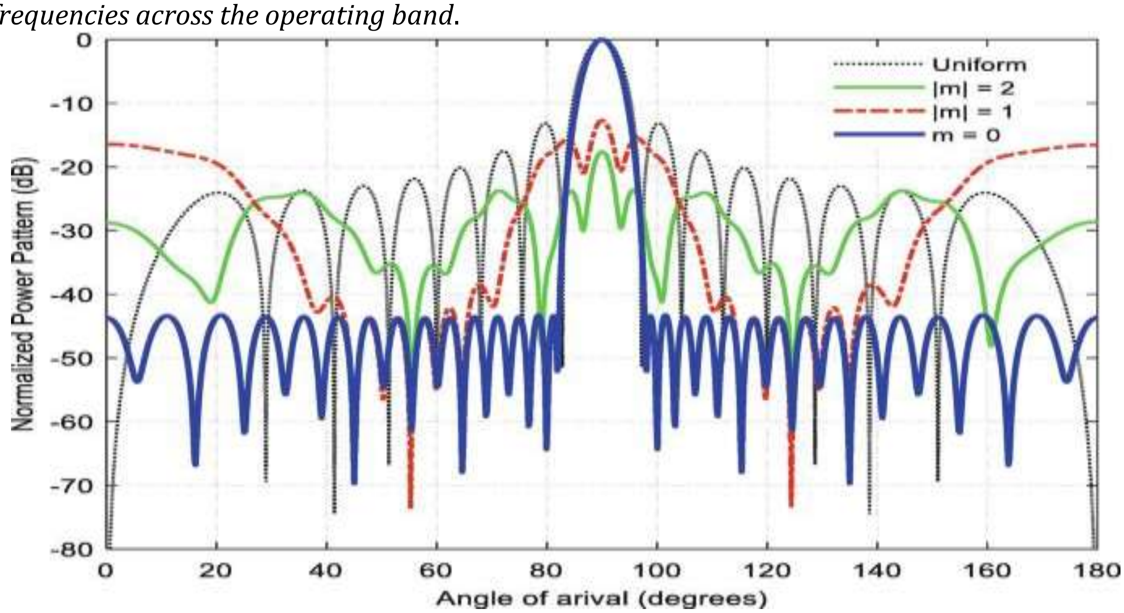


Figure 8: *Surface current distribution of the proposed antenna at selected frequencies.*

Table 8: Comparative Performance Discussion with Reported Wideband and Fractal Antennas

| Design Aspect | Reported Designs | Proposed Antenna |
|---|---|---|
| Physical size | Moderate to large | Compact |
| Bandwidth | Wide / limited SWB | Super-wideband |
| Radiation stability | Frequency-dependent | Stable across band |
| Structural complexity | Moderate to high | Low |
| Suitability for 5G | Partial | High |

## Conclusion

This paper presented the design, optimization, and performance evaluation of a compact super-wideband fractal antenna for next-generation 5G wireless networks. By integrating fractal geometry with optimized feeding and ground-plane configurations, the proposed antenna achieves wide impedance bandwidth, stable radiation characteristics, satisfactory gain and efficiency, and minimal temporal distortion within a planar and fabrication-friendly structure. Simulation results, supported by frequency-domain, time-domain, and surface current analyses, validate the effectiveness of the proposed design methodology. Comparative results further confirm that the antenna offers an improved balance between compactness and broadband performance relative to existing designs. Overall, the proposed compact super-wideband fractal antenna represents a strong candidate for practical 5G wireless applications and provides a solid foundation for future experimental validation and system-level integration.

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