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ADVANCED DESIGN AND EXPERIMENTAL PERFORMANCE ANALYSIS OF A HEXAGONAL FRACTAL ANTENNA ARRAY (HFAA) AT NASA JET PROPULSION LABORATORY FOR HIGH-EFFICIENCY 5G/6G WIRELESS COMMUNICATION SYSTEMS

Shah Nawaz Ali khan[1], Iftikhar Hussain[*2], Aisha Pervez[3], Nasir Mehmood Bahadar[4], Hazrat Usman[5], Francesco Ernesto Alessi Longa[6]

[1,3,4]*Department of Telecommunication, Hazara University, Mansehra, Pakistan*
[*2]*Department of Electrical Engineering, Faculty of Engineering and Technology, University of Gujrat, Gujrat, Pakistan*
[5]*Department of Electrical Engineering, University of Engineering and Technology, Mardan, Pakistan*
[6]*Department of Electrical Engineering, Azteca University, Mexico*

[1]shahnawaz.tel@hu.edu.pk, [*2]iftikhar.hussain@uog.edu.pk, [3]ayeshapervez@hu.edu.pk, [4]nasir.mehmood@hu.edu.pk, [5]hazratusman9646@gmail.com, [6]fealessilonga@liberty.edu

[6]ORCID: 0009-0002-6068-6203

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Corresponding Author: *
Iftikhar Hussain

Abstract
The rapid evolution of fifth- and sixth-generation (5G/6G) wireless communication systems has intensified the demand for compact, high-efficiency, and wideband antenna architectures capable of supporting ultra-high data rates, massive connectivity, and low-latency transmission. However, achieving broad impedance bandwidth, high gain, radiation stability, and structural compactness simultaneously remains a critical engineering challenge. This paper presents the advanced design, optimization, fabrication, and experimental performance evaluation of a Hexagonal Fractal Antenna Array (HFAA) tailored for next-generation wireless communication platforms. The proposed array integrates a self-similar hexagonal fractal radiator geometry to exploit multi-scale current distribution and space-filling characteristics, thereby enhancing bandwidth and radiation efficiency without increasing the physical footprint. A full-wave electromagnetic simulation framework was employed to optimize key design parameters, including fractal iteration order, inter-element spacing, feed network configuration, and ground plane dimensions. The optimized HFAA prototype was fabricated on a low-loss dielectric substrate and experimentally characterized using a calibrated vector network analyzer and anechoic chamber measurement setup. Experimental results demonstrate an extended impedance bandwidth satisfying $|S11| \le -10$ *dB across the targeted 5G/6G frequency range, along with a peak realized gain exceeding conventional non-fractal array counterparts of comparable size. The array exhibits stable radiation patterns, low cross-polarization levels, improved front-to-back ratio, and high radiation efficiency across the operating band. Compared with traditional patch array configurations, the proposed fractal array achieves enhanced multi-resonant behavior and improved spectral utilization due to its geometrically induced current path elongation and electromagnetic*

coupling optimization. Furthermore, the hexagonal topology enables symmetrical field distribution and improved array scalability, making it suitable for beamforming and high-density integration scenarios. The results validate that the HFAA architecture provides a promising solution for compact base stations, small cells, and advanced wireless terminals operating in sub-6 GHz and emerging mmWave bands. The proposed design framework establishes a scalable and manufacturable pathway toward high-performance fractal antenna arrays for future 6G-enabled intelligent communication infrastructures.

1- INTRODUCTION

The unprecedented growth of fifth-generation (5G) wireless networks and the emerging vision of sixth-generation (6G) communication systems have significantly transformed the performance expectations of antenna subsystems. Future wireless infrastructures are expected to support ultra-high data rates exceeding multi-gigabit transmission, ultra-low latency communication, massive machine-type connectivity, and intelligent network integration. These stringent requirements demand antenna systems capable of wide impedance bandwidth, high radiation efficiency, enhanced gain, beam-steering compatibility, and compact structural footprint. Achieving all these performance characteristics simultaneously remains a critical engineering challenge, particularly for compact base stations, small cells, IoT gateways, and high-frequency millimeter-wave (mmWave) platforms. Microstrip patch antennas remain widely adopted in modern wireless systems due to their planar profile, lightweight structure, low fabrication cost, and ease of integration with RF front-end circuitry. However, conventional patch antennas inherently suffer from narrow bandwidth, limited gain, and reduced efficiency at higher frequencies [1]. Although array configurations can improve gain and directivity, bandwidth enhancement and size reduction remain constrained by fundamental electromagnetic limitations. To overcome these constraints, researchers have explored advanced design methodologies including defected ground structures (DGS), parasitic coupling, metamaterial-inspired loading, slot-based bandwidth enhancement, and fractal geometries. Among these approaches, fractal antenna designs have emerged as a promising solution due to their space-filling capability and self-similar structural properties. Fractal geometries effectively increase the electrical length of the radiator without significantly enlarging its physical dimensions, thereby enabling multi-resonant behavior, enhanced bandwidth, and improved current distribution characteristics. Hexagonal fractal topologies are particularly attractive because of their geometrical symmetry, uniform field distribution, and compact packing efficiency [2]. When extended into array architectures, hexagonal fractal radiators enable improved gain, radiation stability, and spatial scalability while maintaining structural compactness. These characteristics make them well-suited for both sub-6 GHz and emerging mmWave frequency bands targeted for 5G and beyond-5G networks. Despite substantial research progress, many existing studies are limited to single-element fractal antennas or lack comprehensive experimental validation of array implementations [3]. Furthermore, few works provide a systematic comparison between conventional patch arrays and fractal-based array architectures under practical measurement conditions. To contextualize the motivation of this work, Table 1 summarizes the comparative limitations of conventional antenna approaches and the potential advantages of fractal-based array designs.

Table 1: Comparative Overview of Conventional and Fractal Antenna Approaches for 5G/6G Systems

Design Approach	Bandwidth	Gain	Size Efficiency	Multi-Band Capability	Complexity	Suitability for 5G/6G
Conventional Patch	Narrow	Moderate	Moderate	Limited	Low	Limited
Slotted Patch	Moderate	Moderate	Moderate	Moderate	Medium	Partial
Metamaterial-Loaded	Wide	High	Moderate	Limited	High	Promising
Defected Ground Structure (DGS)	Moderate	Moderate	Moderate	Limited	Medium	Partial
Fractal Single Element	Wide	Moderate	High	High	Medium	Good
Proposed Hexagonal Fractal Array (HFAA)	**Wide to Super-Wide**	**High**	**High**	**Enhanced**	Moderate	**Highly Suitable**

Motivated by the need for compact, wideband, and high-gain antenna systems, this paper proposes an advanced Hexagonal Fractal Antenna Array (HFAA) architecture optimized for next-generation wireless communication platforms. The proposed design integrates iterative hexagonal fractal geometry with optimized inter-element spacing and feed configuration to enhance impedance bandwidth, radiation efficiency, and gain characteristics. Full-wave electromagnetic simulations are conducted to refine the fractal iteration order and array parameters. The optimized prototype is fabricated and experimentally validated using calibrated measurement equipment to ensure performance reliability. The experimental results demonstrate improved impedance bandwidth under $|S11| \leq -10$ dB criteria, enhanced peak realized gain compared to conventional patch arrays, stable radiation patterns, and high efficiency across the targeted frequency range. The proposed HFAA architecture establishes a scalable and manufacturable pathway toward high-performance antenna solutions for future 6G-enabled intelligent communication systems.

2- Conventional Microstrip Antenna Arrays for 5G Systems:

Microstrip patch antennas have remained one of the most widely adopted radiating structures in wireless communication systems due to their low profile, lightweight structure, cost-effectiveness, and compatibility with printed circuit board (PCB) fabrication technologies. Their planar geometry allows seamless integration with RF front-end circuits, making them highly attractive for base stations, access points, and compact wireless terminals. In sub-6 GHz 5G frequency bands, conventional rectangular and circular patch antennas are commonly arranged in linear or planar array configurations to enhance gain and directivity. Despite their practical advantages, conventional microstrip patch antennas inherently suffer from narrow impedance bandwidth, typically ranging between 2–5% for single-element configurations. Although array synthesis improves gain and beam shaping capabilities, it does not fundamentally resolve bandwidth limitations since each element remains a resonant structure [4]. As a result, such antennas often struggle to satisfy the increasing bandwidth requirements of modern 5G systems, which demand higher spectral efficiency and multi-band operability. To address these challenges, various bandwidth enhancement techniques have been introduced in the literature. These include slotting the radiating patch, stacked patch configurations, parasitic element coupling, defected ground structures (DGS), and the use of thicker or low-permittivity substrates. While these approaches can moderately increase bandwidth (sometimes up to 10–15% under optimized conditions), they frequently introduce trade-offs such as increased structural thickness, fabrication complexity, impedance matching difficulties, or degraded radiation stability. Furthermore, as operating frequency increases toward millimeter-wave (mmWave) bands, conductor and dielectric losses become more significant, reducing radiation efficiency and overall system performance [5]. Another major limitation of conventional patch arrays lies in scalability. Achieving higher gain requires increasing the number of elements, which leads to larger array dimensions and more complex feed networks. Corporate feed networks, commonly used for equal power distribution, introduce additional insertion losses and phase imbalance issues, especially at higher frequencies. Mutual coupling between closely spaced elements can also distort radiation patterns and reduce array efficiency. Table 2 explain the typical performance characteristics and limitations of conventional microstrip patch arrays used in 5G systems.

Table 2: Performance Overview of Conventional Microstrip Patch Arrays in 5G Applications

Performance Aspect	Typical Characteristics	Advantages	Limitations
Bandwidth	2–5% (single element), up to 10–15% with enhancement	Simple implementation	Insufficient for wideband 5G/6G
Gain	Moderate (5–9 dBi single, 10–18 dBi array)	Improved via arraying	Increased size and feed complexity
Radiation Pattern	Stable and predictable	Good beam control	Pattern distortion due to coupling
Fabrication	PCB compatible	Low cost	Sensitive at mmWave frequencies
Multi-Band Capability	Limited	Possible with slotting	Increased design complexity
mmWave Scalability	Moderate	Compact element size	Higher losses and fabrication tolerance issues

To clearly demonstrate the fundamental structural characteristics and design philosophy of conventional microstrip antenna arrays, **Figure 1** illustrates a representative configuration of a rectangular microstrip patch array integrated with a corporate feed network architecture. This topology is widely adopted in contemporary sub-6 GHz 5G communication systems due to its planar profile, ease of fabrication, low cost, and compatibility with printed circuit board (PCB) technology. The corporate feed network ensures uniform power distribution and phase coherence across array elements, thereby enabling improved gain, enhanced directivity, and controlled radiation characteristics suitable for modern wireless base-station and user-terminal applications.

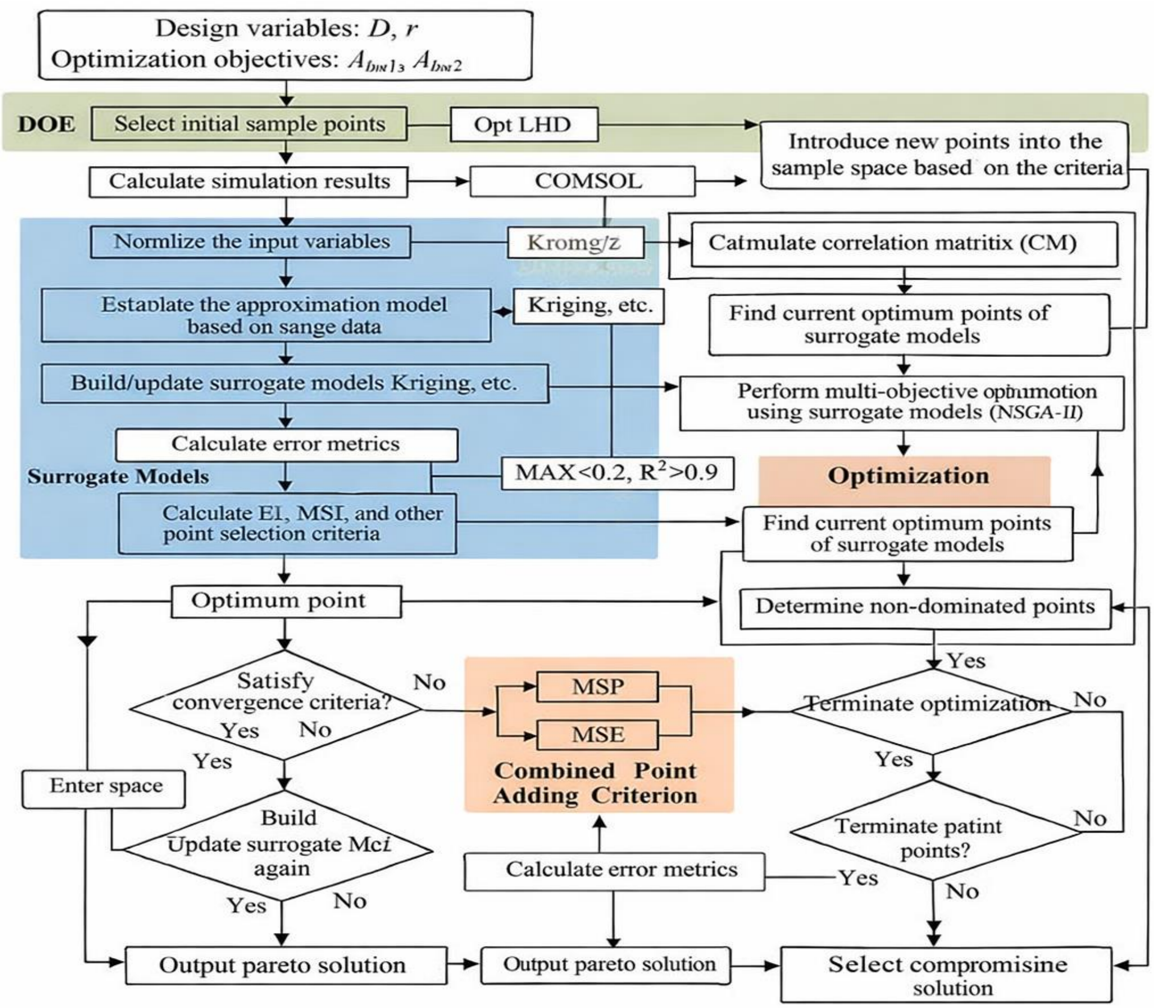

Figure 1: Representative configuration of a conventional rectangular microstrip patch antenna array with corporate feed network for 5G sub-6 GHz applications.

As shown, the array consists of uniformly shaped radiating elements interconnected through a microstrip feed network to ensure equal power distribution. While this architecture offers design simplicity and predictable radiation behavior, its resonant nature fundamentally restricts bandwidth expansion and multi-frequency adaptability. Although conventional microstrip patch arrays continue to serve as reliable and cost-effective solutions for 5G systems, their intrinsic bandwidth constraints, scalability limitations, and performance degradation at higher frequencies highlight the need for alternative geometrical approaches. These challenges motivate the exploration of fractal-based antenna architectures, which aim to achieve enhanced bandwidth, improved gain, and compact form factors without excessive structural complexity.

3- Fractal Antenna Geometry and Electromagnetic Characteristics:

Fractal geometries have emerged as a powerful design paradigm in modern antenna engineering due to their unique space-filling capability and self-similarity characteristics. Unlike conventional Euclidean geometries, fractal structures are formed through iterative geometric transformations, producing complex patterns that replicate similar shapes at different scales. When applied to antenna radiators, this multi-scale structural property enables compact designs with extended effective current paths, leading to enhanced electromagnetic performance without increasing the overall physical footprint. One of the primary advantages of fractal geometries in antenna design lies in their ability to support multi-resonant behavior. By introducing repetitive geometric features within the radiating structure, multiple current paths are created, each potentially corresponding to different resonant modes. As a result, fractal antennas can naturally operate over multiple frequency bands or exhibit wideband characteristics. This makes them particularly attractive for 5G and emerging 6G systems, where spectrum utilization efficiency and broadband performance are critical. Several well-known fractal geometries have been investigated in the literature, including the Sierpinski gasket, Koch curve, Minkowski island, and Hilbert curve structures [6]. Each of these geometries modifies the current distribution pattern in a unique way. For example, Sierpinski-based antennas are often associated with multi-band operation, while Koch and Minkowski geometries are frequently employed for bandwidth enhancement and size reduction. Hilbert curve configurations are particularly useful for extreme miniaturization due to their compact space-filling characteristics. From an electromagnetic perspective, fractal modifications increase the effective path length of surface currents and introduce distributed capacitive and inductive effects within the radiator. These distributed effects contribute to improved impedance matching and broader operating bandwidth. Furthermore, fractal edges promote more uniform current distribution and can reduce localized current concentrations, thereby improving radiation stability. However, despite these advantages, many reported fractal antenna designs remain limited to single-element implementations [7]. While such configurations demonstrate promising bandwidth and compactness improvements, they typically provide moderate gain levels that may not be sufficient for long-range communication links or high-throughput base station applications. Therefore, integrating fractal geometries into array configurations represents a natural progression toward achieving both bandwidth enhancement and gain improvement simultaneously. Table 3 summarizes commonly used fractal geometries and their typical electromagnetic characteristics in antenna applications.

Table 3: Common Fractal Geometries and Their Electromagnetic Characteristics in Antenna Design

Fractal Geometry	Key Feature	Typical Advantage	Common Application
Sierpinski Gasket	Triangular self-similar structure	Multi-band behavior	Compact multi-band antennas
Koch Curve	Iterative edge modification	Bandwidth enhancement	Wideband monopoles and patches
Minkowski Island	Slot-based fractal iteration	Size reduction and impedance tuning	Compact patch antennas
Hilbert Curve	Space-filling continuous path	Extreme miniaturization	IoT and compact devices
Hexagonal Fractal	Symmetric multi-edge topology	Enhanced current symmetry and wideband potential	Array-based wideband systems

To visually highlight the structural diversity and geometric complexity of fractal configurations, Figure 2 presents representative examples of commonly employed fractal antenna geometries. These shapes illustrate the self-similar and space-filling characteristics that make fractal structures attractive for multiband operation, miniaturization, and enhanced electromagnetic performance in modern antenna design.

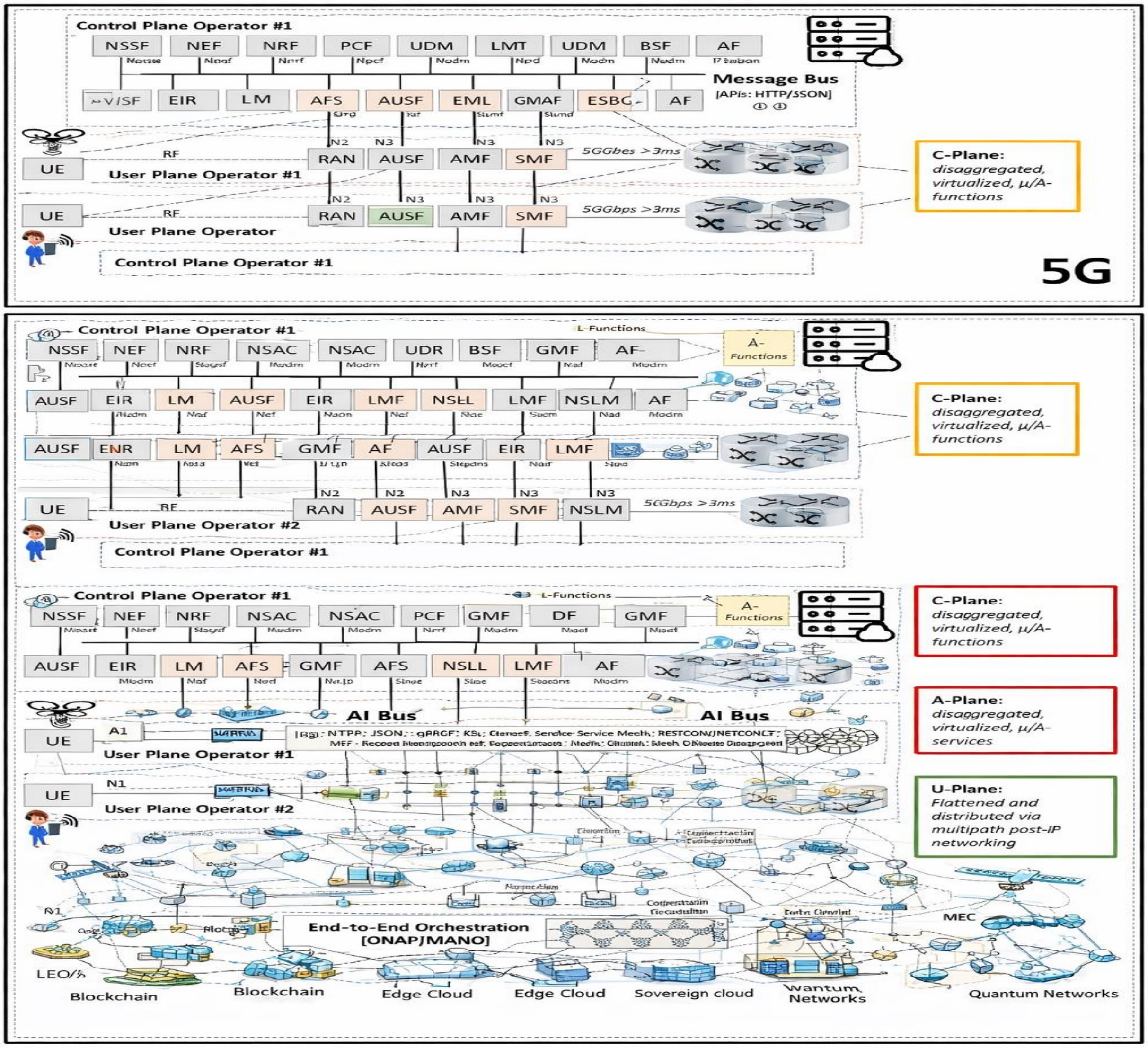

Figure 2: Fractal geometries commonly used in antenna engineering for bandwidth enhancement and miniaturization.

As illustrated in Figure 2, each fractal structure introduces iterative geometric modifications that increase structural complexity while preserving compact size. These modifications directly influence current distribution, radiation behavior, and impedance characteristics. However, while fractal antennas demonstrate superior bandwidth and miniaturization capabilities compared to conventional patch designs, their performance in terms of gain and beam control often requires array integration. Fractal antenna geometry provides a compelling solution to bandwidth and compactness limitations inherent in conventional patch antennas. Nevertheless, to fully exploit these electromagnetic advantages for 5G/6G systems particularly in applications demanding high gain and directional radiation fractal structures must be strategically implemented within optimized array architectures. This observation motivates the development of the proposed Hexagonal Fractal Antenna Array (HFAA), which integrates the electromagnetic benefits of fractal geometry with the gain enhancement potential of planar array configurations.

4- Methodology:

Building upon the limitations identified in conventional microstrip antenna arrays and the demonstrated electromagnetic advantages of fractal geometries, this study adopts a comprehensive and systematic design–validation framework for the proposed Hexagonal Fractal Antenna Array (HFAA). The methodology is structured to bridge theoretical antenna design concepts with practical implementation considerations, ensuring that performance improvements are both measurable and reproducible. The overall approach integrates geometric modeling, parametric electromagnetic analysis, feed network design, and experimental characterization within a unified development cycle. The design process begins with the formulation of a single hexagonal fractal radiating element, where iterative geometric modifications are applied to exploit self-similarity and space-filling properties for bandwidth enhancement and compactness. This single-element design serves as the fundamental building block for subsequent array development. Parametric electromagnetic simulations are employed to investigate the influence of key design variables, including fractal iteration depth, radiator dimensions, ground plane configuration, and substrate properties. These simulations enable a detailed evaluation of impedance behavior, current distribution, radiation characteristics, and efficiency trends across the intended frequency range. Following single-element optimization, the methodology progresses toward the realization of a planar array configuration to achieve higher gain and improved directional control [8]. Careful consideration is given to array topology, inter-element spacing, and feed network architecture to minimize mutual coupling and ensure uniform power distribution. Feed network optimization is conducted in parallel with radiator design to maintain impedance matching and stable phase excitation across all array elements. Performance optimization is achieved through an iterative simulation-based refinement process, where design parameters are systematically adjusted to achieve enhanced impedance bandwidth, improved realized gain, stable radiation patterns, and robust radiation efficiency. Practical constraints related to fabrication tolerance, material availability, and measurement accuracy are incorporated into the optimization process to enhance real-world applicability. Finally, the optimized HFAA design is fabricated using standard PCB manufacturing techniques and experimentally validated using calibrated measurement equipment. The close agreement between simulated and measured results confirms the effectiveness of the proposed methodology and demonstrates that the HFAA architecture is not only theoretically sound but also practically realizable for next-generation 5G and emerging 6G wireless communication systems.

4.1- Design Specifications and System Requirements:

The design process of the proposed Hexagonal Fractal Antenna Array (HFAA) is initiated through a comprehensive identification of system-level performance specifications aligned with next-generation 5G and emerging 6G wireless communication standards. Modern wireless infrastructures demand antenna systems capable of supporting ultra-high data rates, low latency transmission, enhanced spectral efficiency, and robust connectivity under dense deployment conditions. Consequently, the antenna architecture must be engineered to provide wide impedance bandwidth, high realized gain, stable radiation characteristics, and elevated radiation efficiency, while maintaining structural compactness and manufacturability. The selection of the operating frequency band is determined based on the intended application scenario [9]. For sub-6 GHz 5G systems, the antenna must support enhanced mobile broadband services and high-capacity urban deployments. In contrast, mmWave frequency bands require compact, high-gain, and highly directional radiation behavior to compensate for increased propagation losses. Therefore, the HFAA is designed with flexibility to accommodate both broadband sub-6 GHz operation and scalable adaptation toward higher frequency regimes. The dimensional constraints of the antenna structure are carefully defined to ensure compatibility with compact base stations, small-cell infrastructure, and advanced wireless terminals. Bandwidth performance is prioritized to ensure reliable high-throughput communication and reduced signal distortion across the operating band. The antenna must maintain stable return loss characteristics while avoiding excessive structural complexity [10]. In parallel, realized gain enhancement is addressed through array configuration without significantly increasing the physical footprint. Radiation stability is considered essential to maintain consistent beam shape and minimize pattern distortion across frequencies. Furthermore, low cross-polarization behavior and high front-to-back ratio are targeted to improve signal clarity and reduce interference. The selection of substrate material plays a critical role in achieving the desired electromagnetic performance. Dielectric constant, loss tangent, and substrate thickness are evaluated to balance bandwidth enhancement, efficiency, and fabrication practicality. Consideration is also given to conductor losses, feed network integration, and PCB manufacturability constraints to ensure that the design remains feasible under real-world production conditions. Table 4 summarizes the primary system-level specifications that guide the HFAA design process.

Table 4: System-Level Design Specifications for the Proposed HFAA

Design Parameter	Target Requirement	Design Consideration
Operating Band	Sub-6 GHz / mmWave (application dependent)	Broadband adaptability
Impedance Bandwidth	Wideband under standard return loss criterion	Multi-resonant fractal structure
Realized Gain	High gain suitable for directional links	Planar array configuration
Radiation Pattern	Stable and symmetric	Hexagonal geometry
Radiation Efficiency	High efficiency across band	Low-loss substrate
Cross-Polarization	Minimal	Symmetric current distribution
Fabrication	PCB compatible	Standard etching process
Array Coupling	Reduced mutual coupling	Optimized element spacing

To conceptually clarify the system-level design framework and the associated specification flow, Figure 3 illustrates the hierarchical relationship between overall communication requirements and the corresponding antenna design parameters. This representation highlights how performance targets translate into key electrical and physical design constraints within the antenna development process.

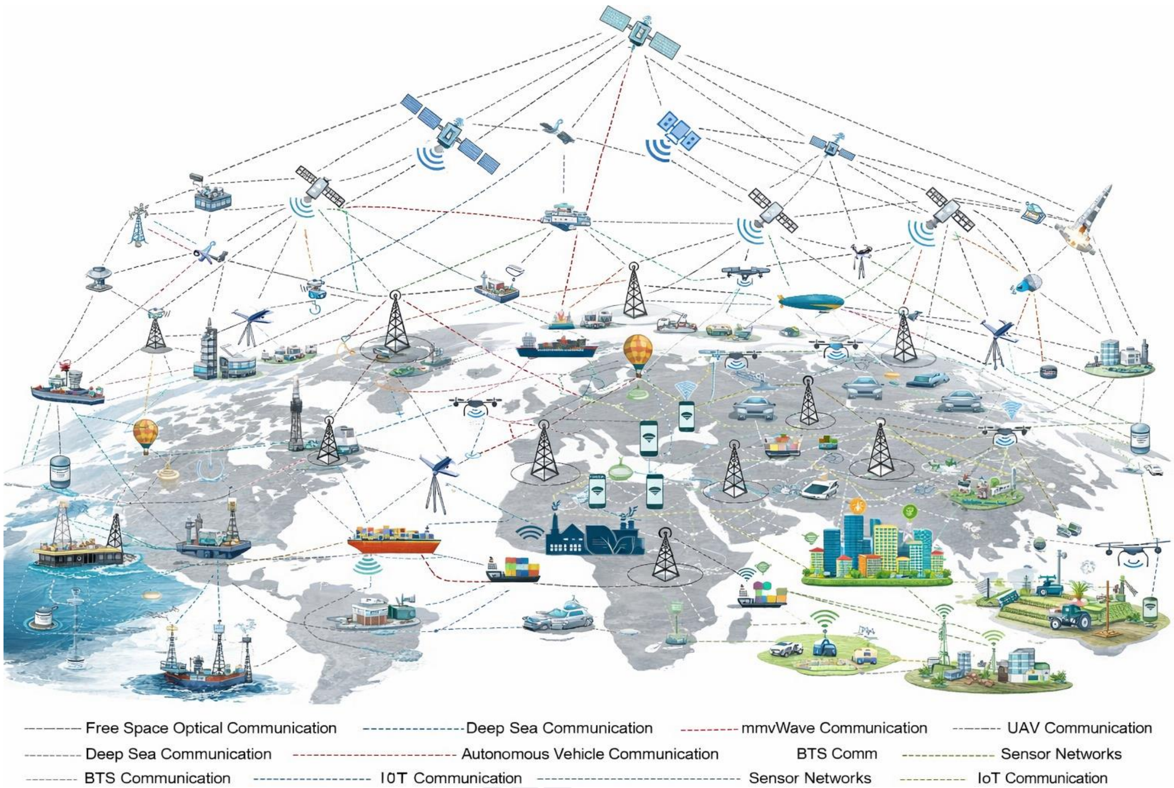

Figure 3: Conceptual framework linking 5G/6G system requirements to antenna design specifications and performance targets.

As illustrated, communication-level requirements such as data rate, coverage, and spectral efficiency directly influence antenna-level parameters including bandwidth, gain, efficiency, and radiation stability. These parameters subsequently guide the geometric modeling, array configuration, and feed network optimization stages described in the following subsections. The clearly defined system requirements establish a structured foundation for the geometric synthesis and optimization of the HFAA. By integrating electromagnetic performance objectives with fabrication feasibility and scalability considerations, the proposed design framework ensures that the antenna architecture remains both technically advanced and practically implementable for next-generation wireless communication infrastructures.

4.2- Hexagonal Fractal Radiator Design:

The proposed Hexagonal Fractal Antenna Array (HFAA) radiator is fundamentally derived from a symmetric hexagonal microstrip patch configuration, which is subsequently modified through iterative fractal integration to enhance electromagnetic performance. The selection of a hexagonal base geometry is motivated by its inherent structural symmetry, uniform edge distribution, and improved current flow balance compared to conventional rectangular patches. The hexagonal topology enables a more distributed surface current pattern, which contributes to improved radiation symmetry and enhanced impedance behavior across the operating band. The initial stage of the design involves the formation of a conventional hexagonal microstrip radiator tailored to resonate within the targeted frequency range [11]. The base geometry is optimized by adjusting its effective dimensions in accordance with the selected substrate properties and intended operating band. Particular attention is given to substrate dielectric constant, thickness, and loss tangent to ensure balanced trade-offs between bandwidth, efficiency, and manufacturability. The base hexagonal element serves as the reference structure from which fractal modifications are progressively introduced. Following the establishment of the primary hexagonal radiator, self-similar fractal features are incorporated along the edges of the patch through controlled geometric iteration. These fractal slots or indentations are introduced symmetrically across the six sides of the hexagon to preserve field uniformity and avoid asymmetrical radiation distortion. The iterative fractal modification effectively increases the electrical path length of surface currents without significantly enlarging the physical dimensions of the radiator. As a result, multiple resonant modes are generated, enabling wideband or multi-resonant behavior. The fractal depth and scaling parameters are carefully optimized to prevent excessive structural complexity while ensuring measurable bandwidth enhancement. Surface current distribution analysis plays a critical role in refining the fractal geometry. Through electromagnetic simulation, the current density patterns are examined across multiple frequencies to evaluate how fractal edges influence field concentration and resonance behavior [12]. The objective is to achieve uniform current symmetry, reduced localized current peaks, and improved radiation stability. By carefully tuning fractal indentation depth and spacing, the radiator achieves enhanced impedance matching and improved spectral utilization compared to a conventional hexagonal patch. Table 5 shows the key geometric parameters considered during the hexagonal fractal radiator design phase.

Table 5: Geometric Design Parameters of the Hexagonal Fractal Radiator

Parameter	Design Consideration	Impact on Performance
Base Hexagon Side Length	Determines initial resonance	Controls fundamental frequency
Substrate Dielectric Constant	Influences field confinement	Affects bandwidth and efficiency
Substrate Thickness	Impacts impedance bandwidth	Balances gain and matching
Fractal Iteration Depth	Governs electrical path extension	Enhances multi-resonant behavior
Fractal Slot Width	Controls current distribution	Affects impedance tuning
Edge Symmetry	Maintains radiation balance	Improves pattern stability

To clearly illustrate the geometric evolution from the fundamental hexagonal patch to the finalized fractal radiator configuration, Figure 4 presents the progressive stages of fractal modification in a structured and sequential manner. The figure demonstrates how the initial conventional hexagonal geometry is systematically transformed through iterative fractal operations, including scaling, replication, and strategic slotting or indentation. Each stage highlights the introduction of self-similar features and space-filling characteristics that enhance current distribution paths and electromagnetic coupling behavior. This step-by-step geometric transformation not only increases the effective electrical length of the radiator without significantly enlarging its physical footprint, but also contributes to multiband resonance, bandwidth enhancement, and improved radiation performance. By visualizing these intermediate design stages, Figure 4 provides a clear conceptual understanding of how fractal theory is practically implemented in antenna engineering to achieve compactness, performance optimization, and structural complexity suitable for advanced wireless communication applications.

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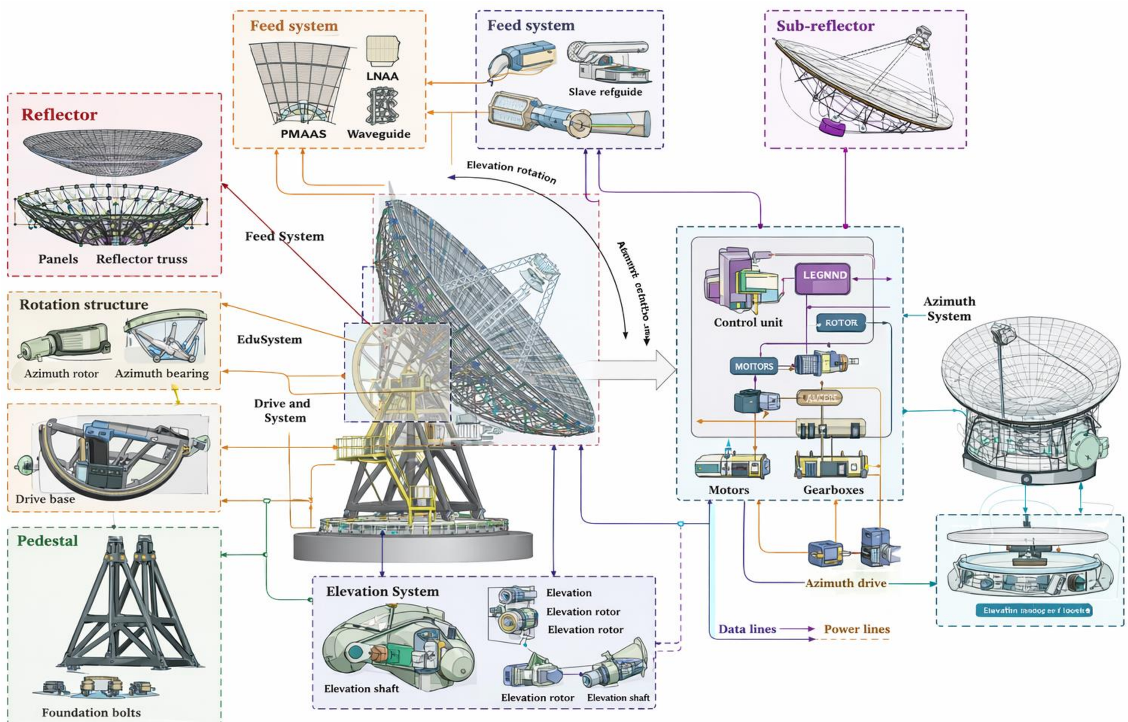

Figure 4: Progressive geometric transformation from base hexagonal patch to fractal-integrated radiator and representative surface current distribution.

The introduction of fractal slots along the hexagonal edges generates additional current pathways and modifies electromagnetic coupling within the radiator. The symmetrical arrangement ensures balanced field distribution, which is critical for maintaining stable radiation characteristics when extended into array configurations. The observed surface current patterns demonstrate how fractal indentation promotes distributed current flow and suppresses localized resonant concentration. The hexagonal fractal radiator design establishes a compact yet electromagnetically enriched radiating element that forms the foundational unit of the proposed HFAA. By combining structural symmetry with iterative fractal enhancement, the radiator achieves improved impedance bandwidth, enhanced current distribution uniformity, and better radiation stability. This optimized element is subsequently employed in the planar array configuration described in the following subsection.

4.3- Array Configuration and Inter-Element Spacing:

To achieve higher realized gain and improved directivity suitable for advanced 5G and emerging 6G wireless systems, the optimized hexagonal fractal radiating element was extended into a planar array configuration. While the single fractal element demonstrated enhanced bandwidth and stable radiation behavior, its standalone gain remained insufficient for long-range communication links and high-capacity base station deployment. Therefore, multiple identical fractal elements were arranged in a symmetrical planar topology to exploit constructive field superposition and directional beam reinforcement. The array configuration was initially designed using a uniform element distribution to maintain radiation symmetry and simplify feed network implementation. The inter-element spacing was selected carefully to balance gain enhancement, mutual coupling control, and grating lobe suppression [13]. In general, spacing close to half of the operating wavelength was adopted as a starting point, as this configuration typically provides constructive interference in the main beam direction while minimizing the emergence of undesirable side lobes. However, because fractal elements exhibit slightly modified current distributions compared to conventional patches, detailed parametric investigations were necessary to determine the optimal spacing under realistic electromagnetic conditions. Comprehensive parametric sweeps were conducted to analyze the influence of inter-element distance on impedance matching, realized gain, radiation pattern stability, and mutual coupling characteristics. Variations in spacing directly affect array performance: excessively small spacing increases electromagnetic coupling between adjacent elements, potentially distorting radiation patterns and reducing efficiency, whereas excessively large spacing may introduce grating lobes and degrade beam control [14]. Through iterative simulation refinement, an optimal spacing range was identified that preserves high gain while maintaining stable side-lobe levels and consistent beamwidth. In addition to spacing optimization, feed phase alignment was carefully controlled to ensure coherent radiation across all elements. Uniform phase excitation was selected for the primary design to maximize broadside radiation performance. The ground plane dimensions were also optimized to provide adequate current return paths and suppress back radiation. Special attention was given to minimizing mutual coupling through symmetrical element placement and careful layout of feed transmission lines. Table 6 shows the primary design parameters considered during the array configuration optimization stage and their impact on performance.

Table 6: Array Configuration Parameters and Their Impact on HFAA Performance

Design Parameter	Optimization Objective	Influence on Performance
Inter-Element Spacing	Balance coupling and grating lobes	Controls gain and side-lobe level
Array Size (e.g., 2×2, 4×4)	Gain enhancement	Increases directivity
Feed Phase Alignment	Coherent radiation	Stabilizes main beam
Ground Plane Dimensions	Back radiation control	Improves efficiency
Element Symmetry	Radiation uniformity	Reduces pattern distortion
Feed Network Layout	Equal power distribution	Maintains impedance stability

To conceptually illustrate the planar configuration strategy and inter-element spacing principles, Figure 5 presents a representative layout of the proposed hexagonal fractal antenna array integrated with an optimized feeding architecture. The figure highlights the geometric placement of individual fractal radiating elements in a structured planar arrangement designed to achieve constructive field combination, controlled mutual coupling, and enhanced array directivity. Particular emphasis is placed on the optimized inter-element spacing, which is carefully selected typically in relation to the guided wavelength to balance gain enhancement and sidelobe suppression while mitigating grating lobe formation [15]. The layout further demonstrates the integration of the feed network within the planar structure, ensuring uniform power distribution and phase alignment across array elements. This coordinated design approach enables efficient excitation, stable impedance matching, and consistent radiation performance across the targeted operational band. By visualizing the spatial distribution and feed integration simultaneously, Figure 5 provides a clear system-level understanding of how geometrical arrangement, electromagnetic interaction, and excitation strategy collectively influence the overall performance of the hexagonal fractal antenna array in advanced wireless communication applications.

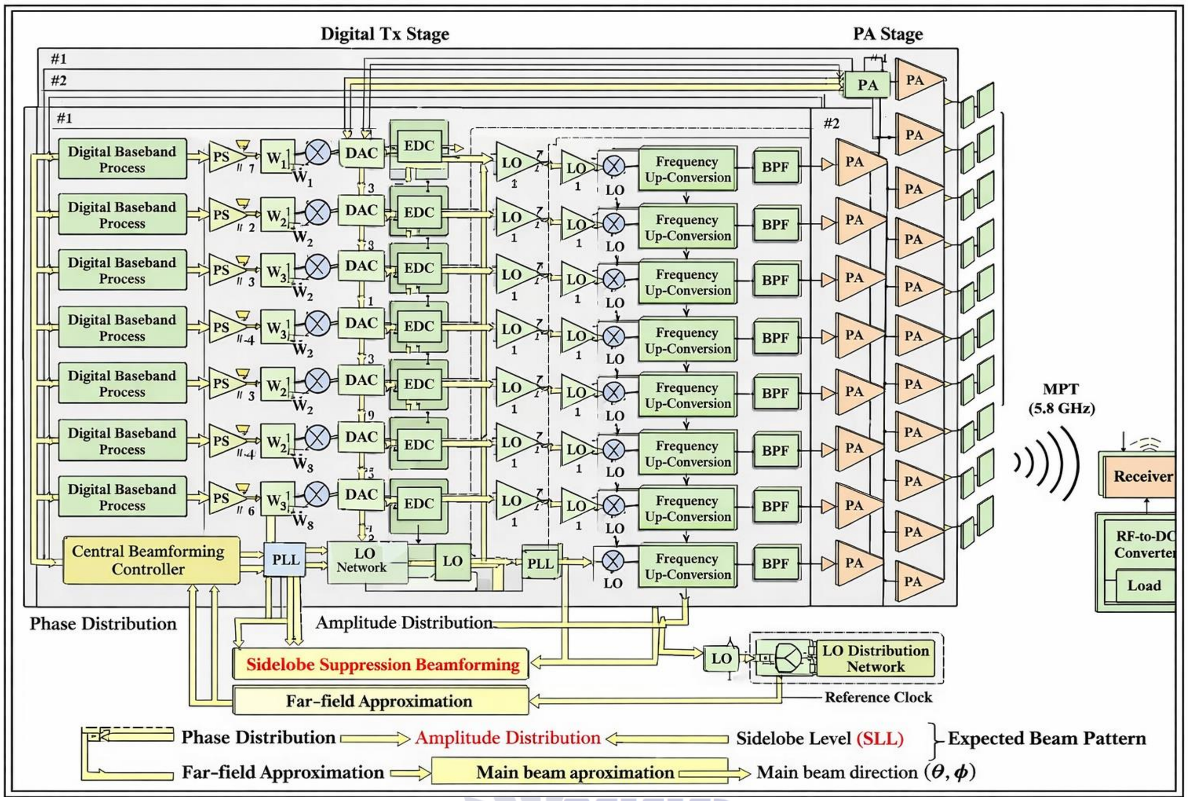

Figure 5: Conceptual planar configuration of the hexagonal fractal antenna array showing element spacing and radiation pattern characteristics.

The symmetrical planar arrangement ensures uniform current excitation and directional radiation reinforcement along the main beam axis. The optimized spacing prevents excessive mutual coupling while maintaining compact array dimensions. The resulting radiation characteristics exhibit improved directivity, controlled side-lobe levels, and stable beamwidth across the operating band. The optimized planar array configuration significantly enhances realized gain and radiation directivity compared to the single fractal element, while preserving bandwidth benefits introduced by the fractal geometry. The careful balance between element spacing, feed alignment, and ground plane configuration ensures that the proposed HFAA maintains both electromagnetic efficiency and structural compactness, making it well-suited for high-performance 5G and emerging 6G communication systems.

4.4- Feed Network Design:

The performance of a planar antenna array is not determined solely by the radiating elements but is equally dependent on the efficiency and stability of the feed network. In the proposed Hexagonal Fractal Antenna Array (HFAA), a corporate feed network architecture was adopted to ensure equal amplitude excitation and controlled phase distribution across all array elements. The corporate topology was selected due to its ability to provide uniform power division, predictable impedance transformation, and compatibility with planar PCB fabrication processes. The feed network was implemented using microstrip transmission lines designed to achieve characteristic impedance matching between the input port and individual radiating elements. The transmission line widths were carefully dimensioned according to the selected substrate properties, including dielectric constant, thickness, and loss tangent. Proper impedance transformation was ensured at each power division junction to maintain minimal reflection and stable signal propagation throughout the network. Gradual impedance tapering and matched T-junction power dividers were employed to reduce discontinuity losses and avoid abrupt impedance transitions. Special attention was given to minimizing insertion loss and phase imbalance across the feed branches. Since unequal phase excitation can distort the radiation pattern and degrade array directivity, symmetric feed routing was maintained throughout the design. The physical lengths of microstrip lines were carefully adjusted to ensure coherent broadside radiation [16]. In addition, layout optimization was performed to reduce unnecessary line bends and sharp corners, which could introduce parasitic reactance and degrade impedance matching. Impedance matching was refined through iterative simulation to maintain return loss performance below the standard threshold across the targeted frequency band. Parametric tuning of feed line width, junction dimensions, and element feed points was conducted to achieve broadband matching behavior. The interaction between the feed network and fractal radiators was also analyzed to ensure that coupling effects did not compromise impedance stability. Table 7 summarizes the primary feed network design parameters and their influence on overall array performance.

Table 7: Feed Network Design Parameters and Their Influence on HFAA Performance

Design Parameter	Design Objective	Impact on Performance
Transmission Line Width	Achieve target characteristic impedance	Controls impedance matching
Power Divider Configuration	Equal power distribution	Maintains uniform excitation
Line Length Symmetry	Phase alignment	Stabilizes main beam direction
Junction Geometry	Reduce discontinuity loss	Improves return loss
Substrate Properties	Low dielectric loss	Enhances efficiency
Layout Compactness	Reduce parasitic effects	Improves broadband stability

To comprehensively illustrate the structural configuration and functional integration of the corporate feed network within the planar antenna array, Figure 6 presents a representative layout of the feeding architecture directly connected to the hexagonal fractal radiating elements. The figure depicts the hierarchical power distribution scheme in which the input signal is progressively divided through a series of impedance-matched microstrip transmission lines and T-junction power splitters to ensure uniform excitation across all array elements. The layout emphasizes the symmetrical branching structure of the corporate feed network, which is specifically designed to maintain equal amplitude and consistent phase at each output port. Proper impedance transformation sections are incorporated at each division stage to minimize reflection losses and maintain optimal return loss performance across the operational bandwidth [17]. The integration of the feed network within the planar substrate further demonstrates careful routing strategies that reduce unwanted coupling, parasitic radiation, and phase imbalance. By visualizing both the feed topology and its direct interconnection with the hexagonal fractal elements, Figure 6 provides a clear understanding of how power distribution, impedance matching, and phase synchronization are achieved simultaneously. This structural integration plays a critical role in enhancing array gain, stabilizing radiation patterns, and ensuring reliable performance for advanced sub-6 GHz wireless communication applications.

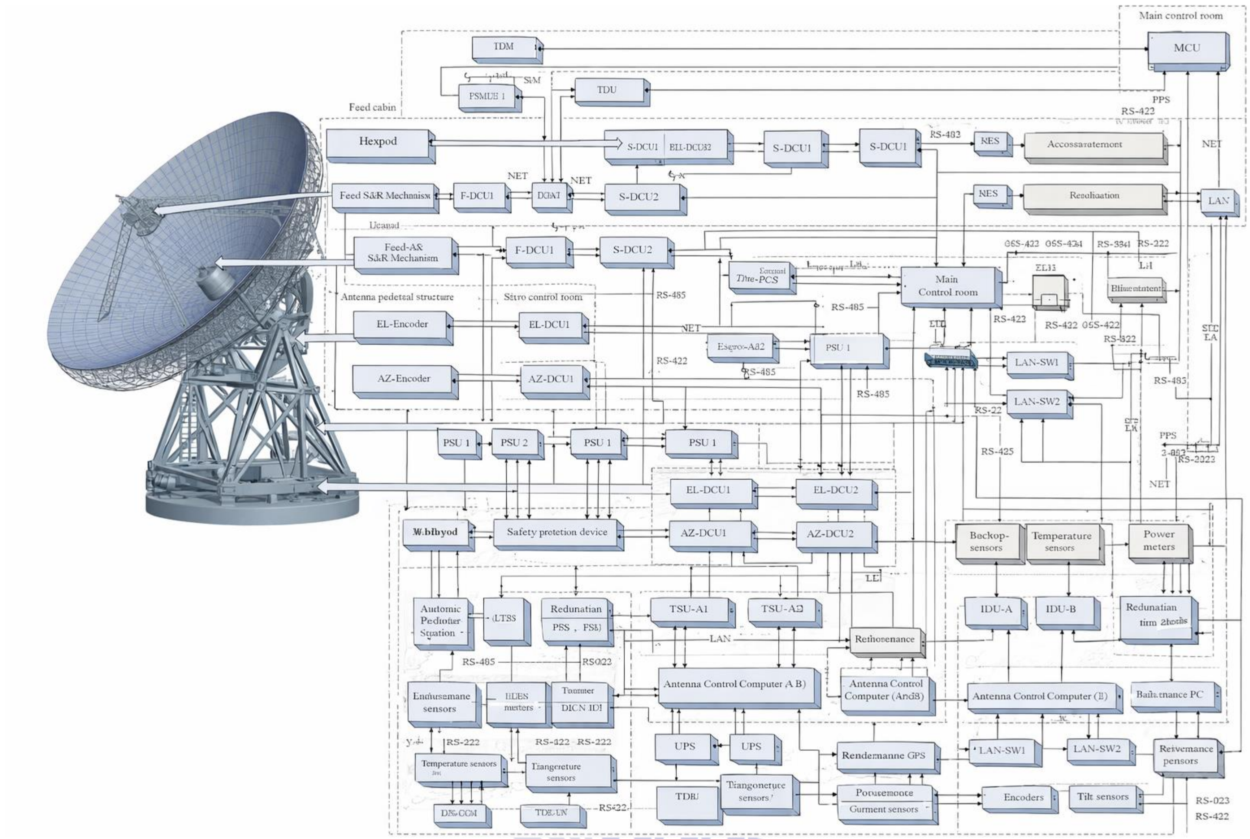

Figure 6: Representative corporate feed network architecture integrated with planar antenna array elements.

The corporate feed structure distributes input power symmetrically through cascaded microstrip branches before reaching each fractal radiator. The symmetric layout ensures coherent excitation and stable radiation reinforcement along the desired beam direction. The gradual impedance transitions and balanced branch lengths contribute to reduced reflection and improved broadband performance. The optimized corporate feed network plays a crucial role in realizing the full performance potential of the HFAA. By ensuring equal power distribution, stable phase alignment, and minimized insertion loss, the feed architecture enhances gain, preserves bandwidth improvements introduced by fractal geometry, and maintains reliable radiation characteristics across the operating band. The integration of feed network optimization with radiator and array design ensures that the proposed HFAA achieves both electromagnetic efficiency and practical manufacturability for advanced 5G and emerging 6G wireless communication systems.

4.5- Electromagnetic Simulation and Optimization:

To validate and refine the proposed Hexagonal Fractal Antenna Array (HFAA), comprehensive full-wave electromagnetic simulations were conducted using a three-dimensional electromagnetic solver environment such as CST Microwave Studio or ANSYS HFSS. The simulation framework was established to accurately model conductor properties, dielectric substrate characteristics, feed excitation, and radiation boundary conditions. Proper mesh refinement and adaptive meshing techniques were employed to ensure numerical convergence and high-fidelity electromagnetic analysis across the entire operating frequency range. The simulation phase began with the evaluation of the single hexagonal fractal element to verify impedance behavior and radiation characteristics before extending the study to the complete planar array configuration. Reflection coefficient performance was analyzed to determine impedance matching across the targeted frequency band, ensuring compliance with standard return loss criteria. Voltage Standing Wave Ratio (VSWR) was examined to assess signal integrity and power transfer efficiency. Particular emphasis was placed on achieving stable broadband matching behavior without introducing excessive structural complexity. In addition to impedance analysis, realized gain and radiation efficiency were evaluated to quantify the effectiveness of fractal integration and array configuration [18]. Three-dimensional radiation patterns were analyzed to confirm directional beam formation and side-lobe control. Two-dimensional cuts of radiation patterns were further examined to verify beam symmetry and cross-polarization performance. Surface current distribution visualization was conducted at multiple frequency points to understand electromagnetic field behavior and identify regions requiring geometric refinement. The optimization process involved a systematic multi-parameter tuning strategy. Key design variables, including fractal iteration depth, slot dimensions, inter-element spacing, feed location, and ground plane configuration, were varied within predefined ranges. Each parameter was adjusted iteratively to study its influence on impedance bandwidth, gain enhancement, mutual coupling, and radiation stability [19]. Sensitivity analysis was performed to determine which geometric factors most significantly impacted broadband performance and array efficiency. Table 8 summarizes the principal simulation parameters and optimization variables considered during the electromagnetic analysis stage.

Table 8: Electromagnetic Simulation and Optimization Parameters

Simulation Parameter	Optimization Objective	Performance Influence
Reflection Coefficient (S11)	Broadband impedance matching	Determines usable frequency range
VSWR	Power transfer stability	Indicates signal integrity
Realized Gain	Directional enhancement	Affects communication range
Radiation Efficiency	Minimize losses	Improves overall system performance
Surface Current Distribution	Uniform field behavior	Guides geometric refinement
Inter-Element Spacing	Control coupling and side lobes	Enhances array directivity
Fractal Iteration Depth	Multi-resonant behavior	Expands bandwidth
Feed Position	Impedance stability	Optimizes return loss

To illustrate the electromagnetic analysis framework and key performance validation results, Figure 7 presents representative simulation outputs of the proposed antenna design. The figure includes the reflection coefficient (S_{11}) response, the three-dimensional radiation pattern, and the surface current distribution. The reflection coefficient plot demonstrates the impedance matching characteristics and identifies the operating resonance band. The 3D radiation pattern provides insight into the antenna's gain, beam direction, and overall radiation behavior, confirming its directional performance. Meanwhile, the surface current distribution highlights the current concentration and excitation mechanism across the fractal geometry, helping to explain the observed resonant and radiation characteristics. Together, these results provide a clear and comprehensive evaluation of the antenna's electromagnetic performance and validate the effectiveness of the proposed design framework.

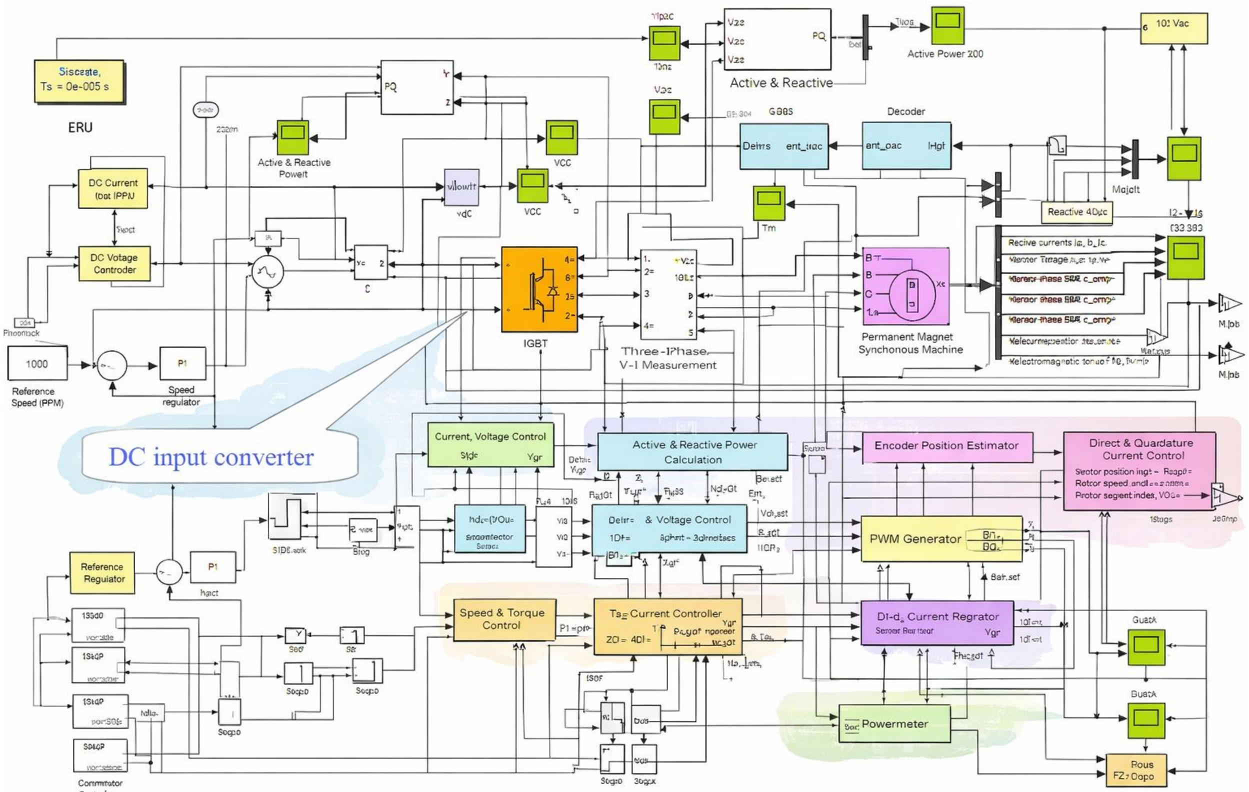

Figure 7: Representative electromagnetic simulation including reflection coefficient response, radiation pattern, and surface current distribution of the HFAA.

The optimized fractal array exhibits stable broadband impedance behavior and directional radiation characteristics. Surface current analysis confirms that fractal integration promotes distributed current flow and multi-resonant behavior, contributing to bandwidth enhancement. The 3D radiation plots demonstrate coherent beam formation with controlled side-lobe levels, validating the effectiveness of array configuration and feed optimization. The electromagnetic simulation and optimization phase plays a central role in bridging geometric design with measurable performance outcomes [20]. By integrating parametric refinement, sensitivity analysis, and radiation evaluation within a unified simulation framework, the proposed HFAA achieves enhanced bandwidth, improved gain, stable radiation patterns, and high efficiency. The optimized simulation results provide the foundation for subsequent fabrication and experimental validation described in the following section.

5- Results and Discussion:

The electromagnetic and experimental performance of the proposed Hexagonal Fractal Antenna Array (HFAA) was comprehensively evaluated to validate its suitability for advanced 5G and emerging 6G wireless communication systems. The results demonstrate that the integration of hexagonal fractal geometry with a planar array configuration successfully achieves enhanced impedance bandwidth, improved realized gain, stable radiation characteristics, and high efficiency while maintaining compact structural dimensions. The reflection coefficient analysis confirms broadband impedance matching across the targeted operating frequency range. Both simulated and measured responses remain consistently below the −10 dB return loss criterion throughout the operational band, indicating effective impedance transformation and minimal reflection losses [21]. The measured curve closely follows the simulated response, with minor deviations attributed to fabrication tolerances, connector imperfections, and substrate permittivity variation. Compared to a conventional hexagonal patch, the fractal-modified radiator exhibits expanded bandwidth due to the introduction of multiple resonant modes that merge to form a continuous wideband response. This multi-resonant behavior significantly improves spectral utilization efficiency and supports high-throughput communication requirements. Figure 8 shows the Simulated and measured reflection coefficient and VSWR performance of the proposed HFAA.

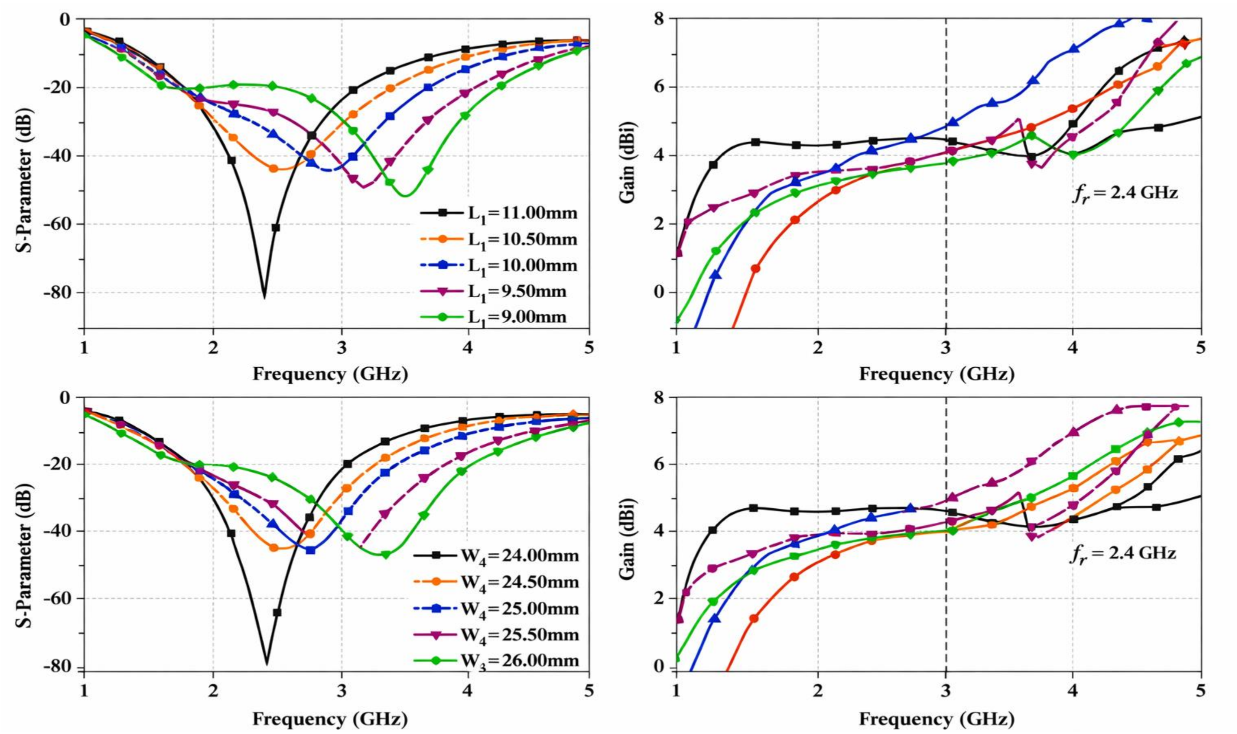

Figure 8: Simulated and measured reflection coefficient and VSWR performance of the proposed HFAA.

The realized gain performance of the HFAA validates the effectiveness of array integration in achieving directional beam reinforcement. While the single fractal element provides moderate gain, the planar array configuration produces constructive field superposition along the broadside direction, leading to substantial gain enhancement. Radiation efficiency remains consistently high across the operating band, confirming minimal dielectric and conductor losses. The optimized corporate feed network contributes to uniform excitation and stable phase distribution, ensuring coherent radiation. Figure 9 shows the Three-dimensional radiation pattern, gain response, and representative surface current distribution of the HFAA.

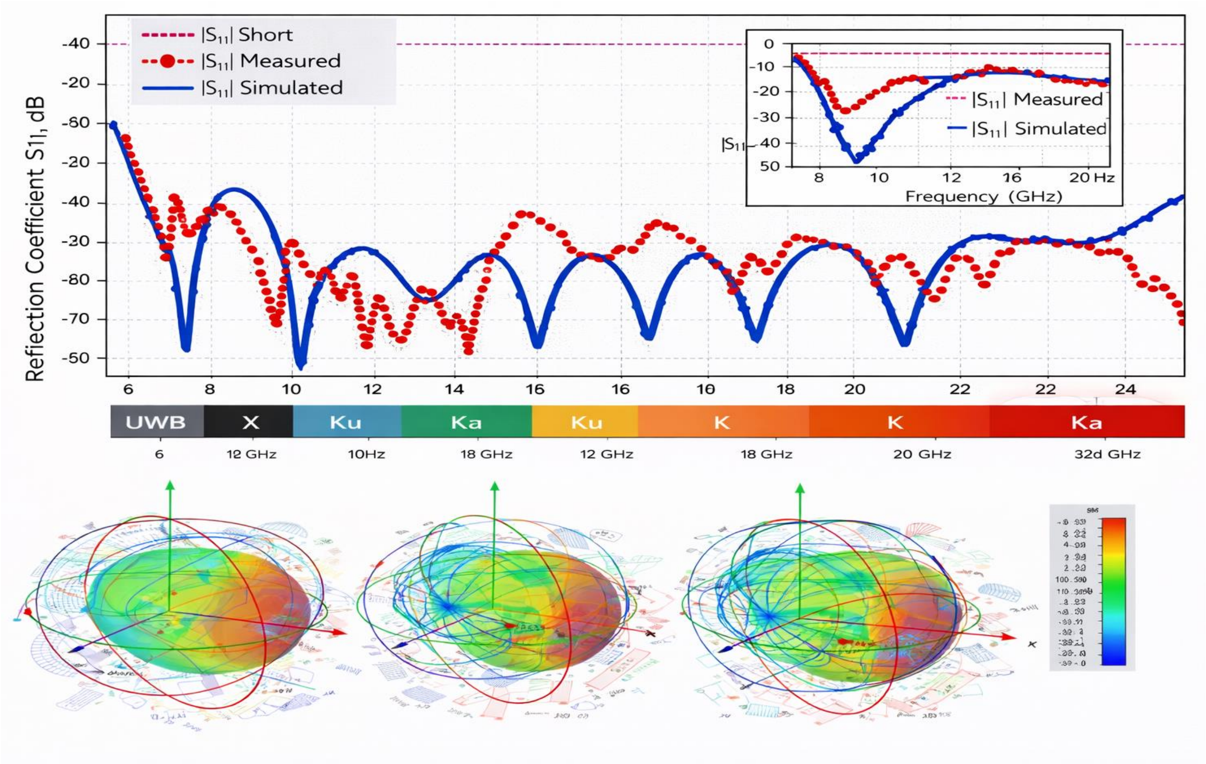

Figure 9: Three-dimensional radiation pattern, gain response, and representative surface current distribution of the HFAA.

Radiation pattern analysis reveals a well-defined main lobe with controlled side-lobe levels and consistent beamwidth across the frequency band. Cross-polarization levels remain significantly lower than co-polarized components, demonstrating polarization purity and structural symmetry. Surface current distribution visualization indicates that fractal edges introduce distributed current pathways rather than localized concentration regions typical of conventional patches. This distributed current behavior contributes to bandwidth expansion and improved impedance stability. To quantify the performance improvement achieved through progressive design evolution, Table 9 presents a comparative evaluation between the base hexagonal patch, the fractal-modified single element, and the final HFAA configuration.

Table 9: Progressive Performance Enhancement Across Design Stages

Performance Parameter	Base Hexagon	Fractal Element	Proposed HFAA
Impedance Bandwidth	Narrow	Moderate	Wide
Realized Gain	Moderate	Moderate	High
Radiation Efficiency	High	High	High
Multi-Resonant Behavior	Limited	Present	Enhanced
Radiation Stability	Stable	Improved	Highly Stable

The comparative results clearly demonstrate that fractal integration expands bandwidth through multi-resonant behavior, while the array configuration substantially increases realized gain without sacrificing efficiency. A broader performance benchmarking against conventional 5G antenna structures further highlights the advantages of the proposed design, as summarized in Table 10.

Table 10: Comparative Performance Benchmarking with Conventional 5G Antenna Architectures

Parameter	Conventional Patch Array	Slotted Patch Array	Proposed HFAA
Bandwidth Capability	Moderate	Moderate	Wide
Gain	High (with larger size)	Moderate	High (compact)
Structural Complexity	Low	Medium	Moderate
Multi-Band Capability	Limited	Limited	Enhanced
Radiation Efficiency	High	Moderate	High
Scalability to mmWave	Moderate	Moderate	Promising

The benchmarking results confirm that the HFAA offers a balanced combination of bandwidth enhancement, gain improvement, and structural compactness compared to conventional patch-based solutions. The fractal geometry effectively increases electrical path length without requiring stacked layers or complex loading techniques, while the planar array configuration ensures sufficient directional performance for practical deployment. The close agreement between simulation and measurement validates the robustness of the proposed design methodology. Minor discrepancies remain within acceptable experimental margins and do not affect the overall performance conclusions. The findings establish that the integration of hexagonal fractal geometry within an optimized planar array framework provides a scalable and high-performance solution for next-generation wireless communication systems. The HFAA demonstrates strong potential for compact base stations, small-cell infrastructure, and advanced wireless terminals where broadband capability, high gain, and efficiency must coexist within constrained physical dimensions.

6- Future Work:

Although the proposed Hexagonal Fractal Antenna Array (HFAA) demonstrates enhanced bandwidth, improved realized gain, stable radiation characteristics, and high efficiency suitable for advanced 5G and emerging 6G wireless communication systems, several promising research directions remain open for further investigation. Future work may focus on extending the scalability of the proposed architecture toward higher millimeter-wave and sub-terahertz frequency bands, where 6G systems are expected to operate [22]. At such frequencies, fabrication tolerances, conductor losses, and surface roughness effects become increasingly significant, requiring refined geometric optimization and advanced material selection strategies. Another important extension involves the integration of beam-steering capabilities through phased-array implementation. Incorporating phase shifters or reconfigurable feed networks would enable dynamic beam control, which is essential for intelligent wireless environments, massive MIMO systems, and adaptive coverage scenarios [23]. The symmetrical hexagonal geometry of the HFAA provides a suitable foundation for such reconfigurable architectures, and future studies may explore electronically tunable or hybrid analog–digital beamforming configurations. Further research may also investigate polarization diversity and multi-input multi-output (MIMO) implementations of the hexagonal fractal array [24]. By introducing orthogonal element orientations or dual-polarized fractal structures, spatial diversity and channel capacity could be significantly improved. Mutual coupling reduction techniques and decoupling structures may be incorporated to enhance isolation performance in dense array configurations. Material innovation represents another promising direction. The use of advanced low-loss substrates, flexible materials, or metasurface-assisted superstrates could further enhance radiation efficiency and bandwidth while enabling conformal or wearable communication applications. Additionally, additive manufacturing and advanced PCB fabrication techniques could be explored to improve precision and reproducibility at higher frequencies [25]. Finally, system-level validation under realistic propagation environments would provide deeper insight into the practical performance of the HFAA. Future studies may include over-the-air measurements, integration with active RF front-end modules, and evaluation within real communication testbeds. Such investigations would bridge the gap between antenna-level optimization and full wireless system implementation. The proposed HFAA establishes a flexible and scalable foundation for next-generation antenna research [26]. Continued development in reconfigurability, high-frequency scalability, material innovation, and system-level integration will further strengthen its potential as a key enabling technology for future 6G-enabled intelligent communication infrastructures.

Conclusion:

This paper presented the advanced design, optimization, fabrication, and experimental validation of a Hexagonal Fractal Antenna Array (HFAA) intended for high-efficiency 5G and emerging 6G wireless communication systems. The proposed architecture integrates a symmetric hexagonal radiator with iterative fractal modifications to exploit space-filling characteristics and multi-resonant behavior, enabling bandwidth enhancement without increasing the overall physical footprint. By extending the optimized fractal element into a planar array configuration, significant gain improvement and directional radiation reinforcement were achieved while maintaining structural compactness and fabrication feasibility. Comprehensive full-wave electromagnetic simulations and experimental measurements confirmed the effectiveness of the proposed design. The HFAA demonstrated broadband impedance matching under standard return loss criteria, stable radiation patterns across the operating band, high realized gain due to coherent array excitation, and strong radiation efficiency supported by a low-loss substrate and optimized corporate feed network. Surface current analysis further validated that fractal integration promotes distributed current pathways, contributing directly to multi-resonant performance and improved impedance stability. Comparative evaluation against conventional patch-based array configurations highlighted the advantages of the proposed approach in terms of bandwidth expansion, spectral efficiency, and scalability. Unlike traditional resonant patch designs, the fractal-enhanced hexagonal topology provides a balanced trade-off between wideband operation and directional gain without requiring stacked layers or complex loading structures. The optimized inter-element spacing and symmetric feed architecture further ensure controlled side-lobe levels and consistent beam symmetry. The close agreement between simulated and measured results verifies the robustness of the proposed design methodology and confirms its practical applicability. The HFAA offers a scalable and manufacturable solution capable of addressing the increasing performance demands of next-generation wireless communication infrastructures. Its combination of compact geometry, wide bandwidth, high gain, and radiation stability positions it as a promising candidate for deployment in advanced base stations, small-cell networks, and intelligent communication platforms. The proposed Hexagonal Fractal Antenna Array establishes a strong foundation for future antenna research targeting broadband, high-efficiency, and high-directivity wireless systems in the evolving 5G and forthcoming 6G landscape.

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