

Design And Investigation Of Self Affine Fractal Antenna

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Abstract

The continuous expansion of wireless communication technologies has generated a strong need for compact, lightweight, and multiband antennas capable of operating efficiently across multiple frequency ranges. Conventional antenna structures often face limitations in achieving size reduction while maintaining satisfactory performance. Fractal antenna technology offers a promising alternative because of its recursive geometry and efficient space utilization. This paper presents the design and performance analysis of a self-affine fractal antenna intended for antenna miniaturization, multiband functionality, and improved electromagnetic characteristics. Self-affine fractal structures differ from self-similar fractals by employing unequal scaling along different axes, enabling greater design flexibility in controlling resonant behavior and physical dimensions. In the proposed model, a rectangular patch is modified iteratively using self-affine transformations. Each iteration increases the effective current path length without enlarging the physical footprint of the antenna. As a result, the antenna demonstrates reduced size and supports multiple resonant frequencies. The antenna model is developed and tested using electromagnetic simulation software. Performance is evaluated through return loss (S11), bandwidth, gain, directivity, radiation pattern, Voltage Standing Wave Ratio (VSWR), and impedance matching. Comparative results between the conventional patch antenna and successive fractal iterations indicate notable improvements in bandwidth enhancement, better impedance characteristics, and additional resonant bands. The proposed antenna is suitable for several wireless communication applications, including GSM, Wi-Fi, LTE, Bluetooth, and Internet of Things (IoT) devices, where compact dimensions and multiband capability are essential. The findings confirm that self-affine fractal geometry is an efficient method for designing small-size antennas with reliable radiation performance. This work contributes to the development of advanced antenna solutions for next-generation communication networks.

Keywords

Self-affine fractal antenna, multiband antenna, antenna miniaturization, return loss, VSWR, wireless communication, patch antenna, IoT devices, bandwidth enhancement, electromagnetic simulation

Introduction

The continuous evolution of wireless communication systems has created a strong requirement for antennas that are compact, lightweight, cost-effective, and capable of operating across multiple frequency bands. Present-day communication platforms such as GSM, LTE, Wi-Fi, Bluetooth, satellite systems, and Internet of Things (IoT) networks depend heavily on antennas that can deliver reliable performance within limited device dimensions. Traditional antenna structures often experience performance degradation when attempts are made to reduce size, especially in terms of bandwidth, gain, and radiation efficiency. As a result, advanced antenna geometries have gained significant attention in recent years. Among these approaches, fractal antenna technology has become an effective method for addressing the limitations of conventional antenna designs. Fractals are mathematical geometries formed through repeated patterns and scaling processes. These structures are mainly categorized into self-similar and self-affine

forms. Self-similar fractals maintain equal scaling in every direction, whereas self-affine fractals scale differently along separate axes. This directional scaling behavior provides additional flexibility for antenna designers, allowing better adjustment of resonant frequencies, impedance matching, and radiation characteristics. Fractal geometries are especially useful in antenna engineering because of two major properties: space-filling capability and multiband operation. The space-filling nature increases the electrical path length of surface currents without requiring a larger physical area, thereby supporting antenna miniaturization. At the same time, repeated geometric patterns generate multiple resonant current paths, which enable operation over several frequency bands. These advantages make fractal antennas highly suitable for compact wireless devices requiring multiband functionality. The development of a self-affine fractal antenna generally begins with a simple base patch structure, followed by iterative geometric modifications to improve performance. By selecting

suitable scaling ratios and iteration levels, the antenna can be tailored for specific wireless applications. Electromagnetic simulation tools are commonly employed to study important parameters such as return loss (S11), bandwidth, Voltage Standing Wave Ratio (VSWR), gain, directivity, and radiation pattern. Through careful optimization, self-affine fractal antennas can achieve high efficiency while occupying minimal space, making them attractive candidates for next-generation wireless communication systems.

Literature Survey

Several researchers have explored fractal antenna structures to improve multiband and wideband performance. Srivatsun and Rani (2011) introduced a compact wideband Cantor-based fractal antenna intended for wireless communication applications. Their design used an FR4 substrate with dielectric constant 4.4 and demonstrated resonant frequencies at 1.1 GHz, 2.2 GHz, 2.5 GHz, and 2.6 GHz. The antenna provided gains ranging from 4.78 dBi to 5.82 dBi, making it suitable for Bluetooth, GSM, UMTS, WLAN, and ISM band operations. The study confirmed the usefulness of self-affine fractal concepts in obtaining multiple resonances within a compact structure. Singh and Surinder Singh (2016) proposed a modified Sierpinski fractal antenna to achieve broadband characteristics. Fabricated on an FR4-epoxy substrate, the antenna exhibited resonances near 4.6 GHz, 6.73 GHz, and 8.01 GHz. It covered an overall operating bandwidth extending approximately from 3 GHz to 9 GHz. The gain varied between 2.07 dBi and 12 dBi depending on frequency. Their results highlighted that fractal optimization can significantly enhance bandwidth while maintaining acceptable radiation performance. Gupta, Christopher, and Koilpillai (2022) developed a circular slot-cut patch antenna for X-band applications. Using an FR4 substrate, the antenna operated around 9.5 GHz and achieved a bandwidth of nearly 2.03 GHz within the 8 GHz to 12 GHz frequency range. The reported gain was approximately 5.5 dBi. This design was considered suitable for radar systems, phased arrays, and X-band wireless applications due to its wide bandwidth and stable beam characteristics. The reviewed studies indicate that fractal-inspired antenna geometries provide effective solutions for compactness, bandwidth enhancement, and multiband operation. These findings support further investigation into self-affine fractal antenna designs for advanced wireless communication environments.

Software Requirements

The design and performance analysis of a self-affine fractal antenna require advanced computational tools capable of accurately solving electromagnetic problems. Since antenna operation depends on Maxwell's equations, simulation software is

essential for predicting field behavior, current flow, impedance response, and radiation characteristics before fabrication. Numerical analysis reduces development time, lowers manufacturing cost, and enables multiple design modifications without the need for repeated physical prototypes. For complex geometries such as fractal antennas, simulation platforms provide a practical and efficient method for evaluating performance under different operating conditions.

Software Requirement: ANSYS HFSS

ANSYS High Frequency Structure Simulator (HFSS) is one of the most widely used full-wave electromagnetic simulation platforms for designing antennas, microwave circuits, waveguides, RF components, and high-frequency electronic systems. The software is based on the Finite Element Method (FEM), which provides accurate numerical solutions for three-dimensional electromagnetic structures. Because of its precision and reliability, HFSS is extensively adopted in academic research, industrial product development, and communication system design. For the proposed self-affine fractal antenna, HFSS is used to create the antenna geometry, assign materials, define feeding methods, and evaluate electrical performance. The software is especially useful for modeling repeated fractal iterations and non-uniform scaling patterns, which are difficult to analyze using manual calculations. By using HFSS, the antenna can be optimized before fabrication, thereby minimizing design errors and improving development efficiency.

Features of ANSYS HFSS

HFSS offers powerful three-dimensional modeling capabilities that allow accurate construction of complex antenna structures. This is particularly valuable in self-affine fractal antenna design, where repeated scaling along different axes must be represented precisely. Parametric modeling features also enable rapid adjustment of dimensions such as patch length, width, substrate thickness, feed dimensions, and fractal iteration depth. The software employs the Finite Element Method solver to compute electromagnetic fields with high accuracy. The structure is divided into many small elements, allowing precise analysis even for irregular and intricate geometries. This capability is important in compact multiband antennas, where small geometric changes can strongly affect resonant frequencies and impedance behavior. Another major advantage of HFSS is adaptive meshing. During simulation, the mesh is automatically refined in regions with strong field variations. This process improves result accuracy while maintaining efficient computational time. Adaptive refinement continues until stable convergence is achieved, making the final solution highly dependable. HFSS also supports accurate material definition. Standard dielectric substrates such as FR4 and Rogers materials can be selected, or custom materials may be created by assigning

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dielectric constant, conductivity, and magnetic properties. This enables realistic representation of substrates, metallic patches, and ground planes, leading to practical simulation results. Boundary condition and excitation settings in HFSS further improve realism. Radiation boundaries simulate free-space conditions, while Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) boundaries can be used for idealized studies. Feeding techniques such as lumped ports, wave ports, coaxial feeds, and microstrip line feeds are supported, allowing flexible antenna excitation methods.

The software provides extensive performance analysis tools. Important parameters such as return loss (S11), Voltage Standing Wave Ratio (VSWR), bandwidth, gain, directivity, and radiation efficiency can be extracted directly. In addition, current distribution, electric field intensity, magnetic field behavior, and far-field radiation patterns can be visualized clearly. HFSS also includes optimization tools that are highly beneficial for fractal antenna design. Parameters such as scaling factor, slot dimensions, patch size, and feed location can be varied automatically to obtain improved impedance matching, desired resonant frequencies, and enhanced bandwidth. These optimization capabilities are valuable for tuning the antenna for practical wireless applications. Finally, the software offers advanced post-processing features such as Smith charts, polar radiation plots, three-dimensional far-field patterns, and export of numerical data for further processing in external platforms such as MATLAB. These features make HFSS a complete environment for antenna design, analysis, and validation.

Design and Investigation of a Self-Affine Fractal Antenna

Iterative Function System

The mathematical foundation of fractal geometry is commonly described using the Iterative Function System (IFS). This method is used to generate repeated geometric patterns through a sequence of affine transformations. In antenna engineering, IFS provides a systematic way to create self-affine fractal structures that can improve antenna compactness and multiband performance. An affine transformation may include scaling, rotation, translation, or a combination of these operations. By repeatedly applying a set of such transformations to an initial geometric shape, increasingly complex patterns are formed. With each iteration, the geometry becomes more detailed and develops multiple current paths that are useful in antenna operation. In simple terms, IFS creates complex fractal shapes from simple mathematical rules. These shapes can then be used as radiating elements or slots in antenna structures. Since self-affine fractals scale differently along separate directions,

they provide greater design flexibility than conventional self-similar fractals. Mathematically, if a set of affine transformations is represented as w_1, w_2, \dots, w_n and the initial geometry is A , the transformed geometry is obtained by combining all transformed copies of A . Repeated application of these transformations produces the final fractal structure after several iterations.

Application of IFS in Antenna Design

The implementation of IFS in fractal antenna design follows a structured sequence. Initially, the required transformations such as scaling and translation are defined mathematically. These operations are then repeatedly applied to a simple starting shape such as a rectangle or patch. Each iteration increases geometric complexity and modifies the electrical current path. After a selected number of iterations, the resulting structure becomes the final antenna patch or ground plane. Matrix representation is often preferred for these transformations because it offers compact mathematical notation and efficient computation. In the proposed work, these steps are used to generate the self-affine fractal patch geometry.

Design Specifications

The proposed antenna is developed as an aperture-coupled microstrip patch structure. A finite ground plane of dimensions $85 \text{ mm} \times 85 \text{ mm}$ forms the mechanical base of the design. The radiating patch is printed on a dielectric substrate having relative permittivity 2.17 and thickness 1.5748 mm. A 3 mm air gap is introduced between the substrate and ground plane to enhance bandwidth performance. The feed mechanism uses a microstrip line printed on the lower substrate surface, while coupling energy to the patch through a rectangular slot in the ground plane. The dimensions of the coupling aperture, feed stub length, and slot position are optimized to achieve efficient energy transfer and impedance matching. To maintain a standard input impedance of 50 ohms, the feed width and feed length are carefully selected. The zeroth iteration consists of a simple rectangular patch. In the first iteration, the patch is divided into six smaller rectangular sections, and the top-middle section is removed. This process is repeated recursively for the remaining sections in higher iterations, producing the self-affine fractal geometry.

Surface Current Distribution

Surface current distribution is one of the most important characteristics in antenna analysis because it directly influences radiation behavior and resonant operation. It describes how electric current flows over the metallic patch during excitation. In fractal antennas, the current follows multiple elongated paths created by the recursive geometry, increasing electrical length while maintaining compact dimensions. For the third iteration of the proposed antenna, current distribution is analyzed at 2.4 GHz, 4.65 GHz, and 10.06 GHz. At each

resonant frequency, strong current concentration appears around the edges, slots, and narrow connecting sections of the fractal geometry. This confirms that the repeated structure contributes to multiple resonant modes and supports multiband operation.

Radiation Pattern of the Antenna

The radiation pattern of an antenna represents the spatial distribution of radiated electromagnetic power. It is a key factor in determining gain, directivity, beamwidth, and overall communication performance. Radiation behavior is closely related to the geometry of the antenna and its current distribution. The proposed self-affine fractal antenna demonstrates stable radiation characteristics at lower frequencies. At higher frequencies, some ripples appear in the radiation pattern due to finite ground plane effects and increased higher-order modes. Nevertheless, the antenna maintains useful radiation coverage suitable for practical wireless systems. Two-dimensional and three-dimensional radiation patterns are evaluated at 2.4 GHz, 4.65 GHz, and 10.06 GHz. The results indicate that the antenna can provide effective directional performance with acceptable beam stability across multiple operating bands. This confirms the suitability of the design for multiband wireless communication applications such as Wi-Fi, Bluetooth, IoT, and other modern RF systems.

Applications

The proposed self-affine fractal antenna has broad applicability in modern wireless systems because of its compact size, multiband behavior, and efficient radiation characteristics. It is well suited for wireless communication equipment that requires operation across multiple frequency bands within limited physical dimensions. Mobile phones, tablets, and other handheld devices can benefit from the planar and miniaturized structure of the antenna, making integration easier without increasing device size. The antenna can also be employed in Wi-Fi and WLAN systems where reliable performance is needed in common wireless frequency ranges. Its compact geometry makes it appropriate for Bluetooth

modules and other short-range communication devices. In Internet of Things (IoT) environments, the antenna can be integrated into low-power sensor nodes, smart appliances, wearable electronics, and embedded communication platforms where space and power consumption are critical factors. In satellite communication systems, the design may be adapted for selected operating bands while maintaining stable radiation properties. The antenna is also useful in RFID systems for compact tags and readers requiring efficient signal transmission. Defense and military communication equipment can benefit from the antenna's multiband capability and reduced size, especially in portable or concealed systems. Microwave radar systems may also use this antenna for selected bands where compact multiband structures are required. In biomedical engineering, the antenna can be integrated into wearable health monitoring systems and wireless medical devices. Vehicular communication systems such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) platforms can employ this design for intelligent transportation networks. Aerospace applications, including unmanned aerial vehicles and lightweight airborne systems, can also benefit from the antenna due to its low-profile and lightweight characteristics. In wireless sensor networks, the antenna supports communication among distributed sensing nodes. Overall, the design is highly promising for next-generation communication systems requiring compact, efficient, and multiband antennas.

Results and Discussion

Results

The proposed self-affine fractal antenna was designed and validated using ANSYS HFSS. MATLAB was used for generating the fractal patch geometry, which was then imported into HFSS for complete electromagnetic simulation. Performance was studied through return loss, gain, and impedance characteristics over multiple iterations of the antenna geometry.

Return Loss (S11) Analysis

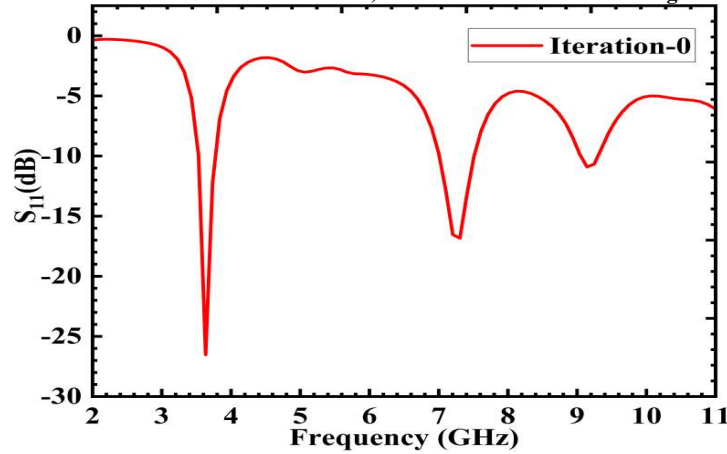


Fig 1: S11 of the zeroth iteration (K0) of self-affine fractal antenna.

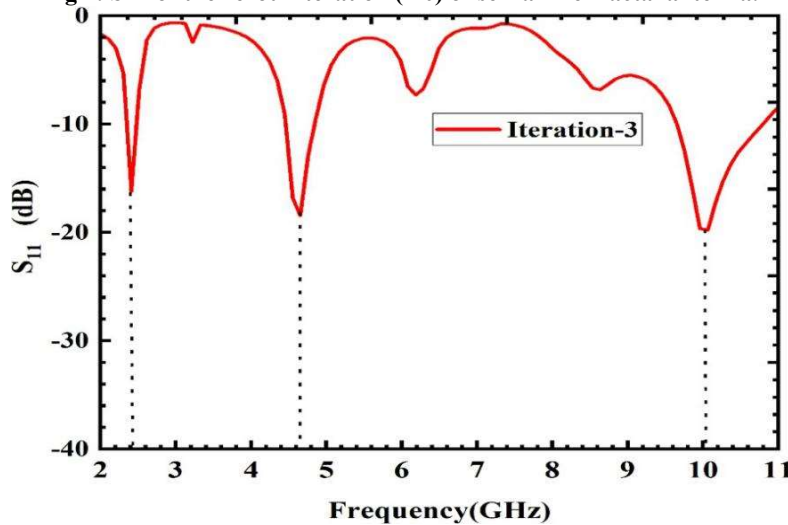


Fig 2: S11 of the third iteration (K3) of self-affine fractal antenna

The zeroth iteration (K0), representing the conventional patch structure, resonated at 3.6 GHz with a narrow bandwidth of 25 MHz. This indicates limited operational flexibility and narrowband behavior. In the first iteration (K1), the antenna exhibited two operating bands. The first resonance occurred at 2.4 GHz with a bandwidth of 130 MHz, while the second resonance was observed at 4.05 GHz with a bandwidth of 330 MHz. The reduction in resonant frequency compared with K0 confirms that the fractal geometry increases the effective current path length. The second iteration (K2)

showed strong return loss values at 2.44 GHz and 3.9 GHz, indicating improved impedance behavior at these frequencies. The third iteration (K3) delivered the best multiband performance with three useful resonances located at 2.44 GHz, 4.65 GHz, and 10.06 GHz. The corresponding bandwidths were 130 MHz, 510 MHz, and 780 MHz respectively. These results confirm that higher fractal iterations significantly improve multiband functionality and usable bandwidth.

Gain Analysis

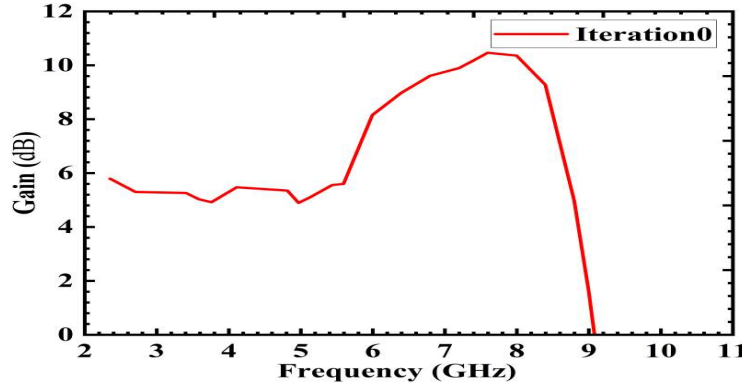


Fig 3: Gain of self-affine antenna for the zeroth iteration.

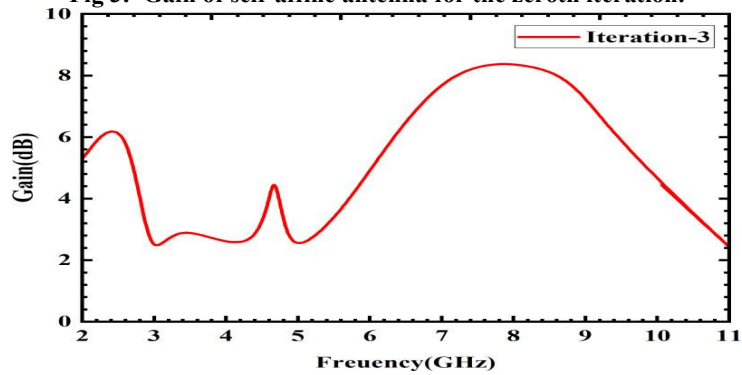


Fig 4: Gain of self-affine antenna for the third iteration

Antenna gain is an important parameter that reflects the ability of the antenna to direct radiated energy efficiently. In the zeroth iteration, the gain was approximately 6 dB at the resonant frequency. For the first iteration, the gain improved to 6.4 dB at 2.4 GHz. Although a second resonant band was present at 4.05 GHz, the gain at that frequency was negative, indicating poor radiation efficiency and making that band less practical for communication use. In the

second iteration, the gain values were about 6.5 dB at 2.4 GHz and 4.5 dB at 4.8 GHz. The third iteration showed gain values of 6 dB at 2.4 GHz, 3.4 dB at 4.65 GHz, and 4.2 dB at 10.06 GHz. These values indicate that the antenna maintains acceptable radiation performance across multiple frequency bands.

Impedance Analysis

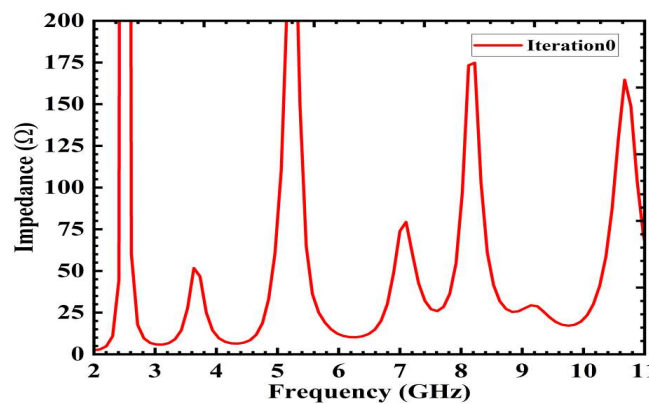


Fig 5: Impedance of the self-affine antenna in zeroth iteration

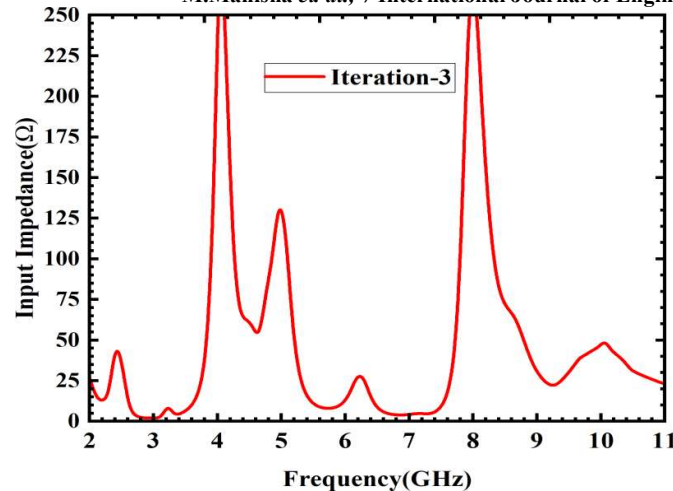


Fig 6: Impedance of the self-affine antenna in the third iteration

Impedance matching is essential for efficient power transfer between the transmission line and antenna. For practical RF systems, a characteristic impedance of 50 ohms is generally preferred. The simulated impedance plots for all iterations indicate that the fractal modifications improve matching at multiple resonant frequencies. Better impedance behavior reduces reflection losses and supports stable antenna performance.

Discussion

The investigation demonstrates that self-affine fractal geometry is an effective technique for achieving compact multiband antennas. The zeroth iteration behaved as a conventional narrowband patch antenna with limited bandwidth. As fractal slots and scaled geometric cuts were introduced in successive iterations, the effective current path increased without enlarging the physical dimensions of the antenna. This geometric modification generated additional resonances and improved bandwidth characteristics. The third iteration provided the best overall performance by supporting three distinct operating bands with wider bandwidths than the earlier stages. These bands are highly relevant for practical wireless applications such as Wi-Fi, Bluetooth, ISM systems, and high-frequency communication links. However, the study also reveals certain trade-offs. Increasing fractal complexity may lead to more difficult fabrication, higher computational requirements, and possible radiation ripples at higher frequencies. Therefore, careful optimization of scaling ratios, slot dimensions, and feed parameters is necessary for obtaining balanced performance.

Comparative Analysis

When compared with previously reported fractal antennas, the proposed design demonstrates competitive multiband behavior with satisfactory gain and improved bandwidth in higher iterations. The ability to generate resonances at 2.4 GHz, 4.65 GHz, and 10.06 GHz highlights its suitability for

both low-frequency and microwave wireless applications.

Conclusion

The design and investigation of the self-affine fractal antenna confirm that fractal geometry is a practical and efficient solution for compact multiband antenna systems. By applying non-uniform scaling along different coordinate directions, the antenna achieves increased electrical length without significantly increasing physical size. This enables antenna miniaturization while preserving useful radiation performance. Simulation studies carried out using MATLAB and ANSYS HFSS verified the effectiveness of the design. The resonant frequency decreased from the conventional patch configuration as fractal iterations were introduced, confirming that the longer current path directly influences frequency reduction. The third iteration produced three resonant bands at 2.4 GHz, 4.65 GHz, and 10.06 GHz with bandwidths of 130 MHz, 510 MHz, and 780 MHz respectively. The results further showed improved impedance matching, multiband operation, and acceptable gain across multiple bands. Although higher iterations increase design complexity, the benefits of compactness, bandwidth enhancement, and operational flexibility outweigh these limitations. Therefore, the self-affine fractal antenna is a promising candidate for future wireless communication systems.

Future Scope

Future work can focus on enhancing bandwidth, gain, and radiation efficiency while preserving compact size. Advanced optimization methods such as genetic algorithms, particle swarm optimization, or artificial intelligence-based tuning can be employed to obtain better design performance. Higher fractal iteration levels may be explored to achieve additional resonant bands or ultra-wideband operation. The antenna can also be

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extended to Multiple Input Multiple Output (MIMO) systems for improved reliability and higher data throughput. Use of metamaterials, flexible substrates, and advanced dielectric materials may further improve performance and create opportunities for wearable or conformal antennas. Fabrication and experimental validation using practical prototypes should also be undertaken to compare measured and simulated results. With continued research, self-affine fractal antennas can play a major role in future compact, intelligent, and high-performance wireless communication technologies.

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