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## REGULAR ARTICLE

# Multiband Omnidirectional Fractal Bow-Tie Antenna for IoT Applications

K. Mohan Krishna[1,2,*], U.V. Ratna Kumari[1]

[1] *Department of ECE, Jawaharlal Nehru Technological University, Kakinada, Andhra Pradesh, India*
[2] *Department of ECE, Kallam Haranadhareddy Institute of Technology, Guntur, Andhra Pradesh, India*

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This paper presents a novel multiband omnidirectional antenna optimized for Internet of Things (IoT) applications, ensuring reliable and seamless connectivity across multiple frequency bands and orientations. The proposed antenna employs a compact planar fractal bow-tie radiator array, which provides highly efficient spectrum coverage for both sub-7 GHz and millimeter-wave (mmWave) 5G bands. Its omnidirectional radiation pattern is achieved through a fractal geometry-based array configuration, enabling robust connectivity in all directions. The antenna effectively covers targeted IoT frequency bands at 4-4.6 GHz, 5.1-5.3 GHz, and 6.3-6.7 GHz, ensuring stable and high-performance wireless communication. With compact dimensions of 100 mm × 40 mm × 1.6 mm, the antenna maintains a return loss better than 10 dB across operational bands and a peak gain ranging between 4 and 8 dB. These characteristics contribute to consistent omnidirectional performance, making the antenna a reliable solution for IoT networks in diverse environments. Furthermore, its low-cost fabrication process and space-efficient design enhance its suitability for seamless integration into scalable IoT deployments. The design also ensures minimal interference and efficient spectrum utilization, which are critical for modern wireless systems. The strong agreement between simulated and measured results validates the antenna's performance, reinforcing its potential for large-scale manufacturing and deployment in next-generation IoT-enabled applications, including smart cities and industrial automation.

**Keywords:** Multiband, Omnidirectional, Fractal bow-tie, IoT applications.

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## 1. INTRODUCTION

Advancements in wireless communication have driven the growth of IoT, connecting a wide range of devices. Integrating IoT with next-generation networks like 5G and beyond provides a flexible framework for applications in smart environments, industrial automation, connected vehicles, and wearable devices [1, 2]. Each application has specific antenna requirements, such as operating frequencies, radiation patterns, and physical profiles. Existing systems in transportation [3, 4] and consumer devices like smartwatches often use antennas with narrow frequency bands and either omnidirectional or unidirectional radiation patterns [5]. Traditional designs often lack the flexibility required for broad IoT deployments, which demand multiband performance and omnidirectional coverage. As IoT expands, compact, low-profile antennas with wide frequency support are essential for reliable connectivity. Designing IoT antennas is challenging due to size, power, and bandwidth constraints, requiring support for multiple communication standards within limited form factors [6]. Furthermore, the adoption of 5G introduces additional design challenges, particularly for high-frequency millimeter-wave (mm Wave) bands, which require innovative approaches to maintain effective radiation characteristics [7]. Traditional multiband antennas often fall short in meeting the broad frequency ranges or delivering consistent radiation patterns across all bands, resulting in increased antenna size or diminished performance. Some recent de- signs incorporate separate modules to cover different frequency bands, which can complicate the structure and lead to larger device footprints with reduced efficiency [8]. For example, Vivaldi and slot antenna designs have been explored to extend coverage to both lower frequencies and mm Wave ranges, yet these configurations often face limitations in terms of compactness and omnidirectional functionality [9]. IoT networks require multiband antennas with omnidirectional radiation patterns for compatibility with various standards. Sub-7 GHz bands support legacy communications, while mm-wave bands enable high-speed 5G data transmission [10]. Omnidirectional patterns improve link stability and coverage, especially for IoT devices without fixed orientations. However, integrating multiband functionality with omnidirectional coverage in a compact form factor presents challenges, as it may affect antenna dimensions, gain, and efficiency [11].

Recent advancements in IoT antenna design have led to compact, low-profile solutions supporting multiple standards within the sub-6 GHz range. These include printed monopole, inverted-F, loop, and patch-based antennas, each tailored to specific frequency bands and applications. Monopole designs,

* Correspondence e-mail: mohankrishnakoppula3@gmail.com





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for example, cover 0.697-5.92 GHz within compact dimensions [12]. Ultra-wideband monopoles support 3-12 GHz with minimal substrate size, while meandered patch designs enhance bandwidth and efficiency using inverse-S meander lines and parasitic patches [13]. Despite progress, most current designs are limited to individual sub-6 GHz or mm-wave bands, restricting omnidirectional coverage across the entire spectrum. Specialized solutions like transparent antennas and rectenna systems offer specific functionality within constrained ranges [14]. However, few IoT antennas integrate both sub-7 GHz and mm-wave capabilities into a single, compact form, with high-frequency solutions like the 60 GHz monopole providing notable performance gains (9.8 GHz bandwidth, 9.6 dB peak gain) [15]. This underscores the need for a unified omnidirectional antenna that combines sub-7 GHz and mm-wave bands, offering 360° coverage and robust connectivity for next-gen IoT applications.

This work presents an innovative multiband planar antenna with an omni- directional radiation pattern, optimized to ensure consistent coverage for IoT devices in all orientations. The core features and contributions of the proposed fractal bow-tie array design are outlined as follows:

1. A multiband omnidirectional fractal bow-tie frequency band. This configuration reduces the need for separate antennas, enhancing integration.
2. The antenna structure employs fractal bow-tie geometry, with multiple bands achievable through this geometry. This results in optimized performance with omnidirectional radiation patterns across each frequency.
3. The antenna design operates effectively within 4-4.6 GHz, 5.1-5.3 GHz, and 6.3-6.7 GHz bands, covering essential ranges for IoT connectivity.
4. The planar design allows simple integration with existing IoT devices and provides flexibility in adjusting operational bands by modifying the fractal structure.

## 2. ANTENNA DESIGN

The proposed antenna comprises a collinear arrangement of four vertically stacked Sierpinski fractal bow-tie radiators as shown in Figure 1. Each radiator is a planar fractal bow-tie element, printed on a dielectric substrate with a relative permittivity $\epsilon_r$ and thickness $h$. The Sierpinski fractal geometry enhances wideband and multiband characteristics through its self-similarity, enabling resonance at multiple frequencies within a compact design. The structure is printed on both the front and back of a rectangular substrate with dimensions $L \times W$ and a total antenna height $H$, minimizing the overall footprint, which is crucial for IoT applications with spatial constraints. Each antenna's front and back sides comprise a single branch of Sierpinski fractal bow-tie radiators, with two complementary Sierpinski fractal bow-tie radiators forming a dipole structure. Each Sierpinski fractal bow-tie radiator serves as an adapted dipole, where radiation results from both direct feed radiation and significant diffraction from the wire ends.

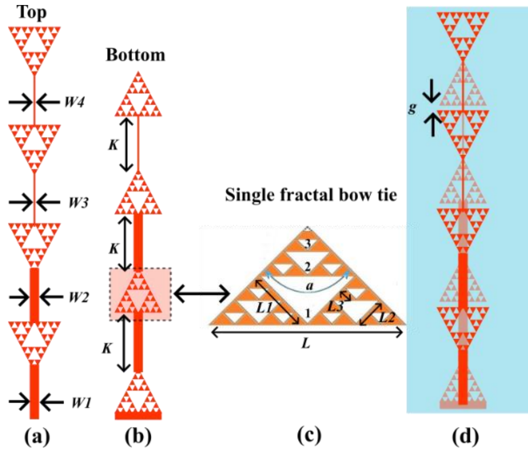


**Fig. 1** – Proposed antenna (a) Top view, (b) Bottom view, (c) Single fractal bow tie element(d) Overall design

The antenna pattern and impedance characteristics are governed by the interaction of the incident and diffracted wave a bowtie introduces additional diffraction sources from the bowtie's edges and corners, which have weaker phase coherence, thus broadening the operational bandwidth. The fractal geometry follows recursive triangular iterations, creating multiple resonant paths that support the target resonant frequencies in a compact design. The fractal structure is recursively scaled, with each iteration side length $L_n$ defined by:

$$L_n = S^n \cdot L^0 \quad (1)$$

where $s$ is the scaling factor, typically 1/2 or 1/3, and $L_0$ is the base side length of the initial triangle. This recursive design facilitates multiband operation, with resonant frequencies $f_n$ approximated as:

$$f_n = \frac{c}{2L_n\sqrt{\epsilon_{eff}}} \quad (2)$$

where $c$ is the speed of light in free space, $L_n$ is the effective length of the $n$th fractal iteration, and $\epsilon_{\text{eff}}$ is the effective permittivity of the substrate. Each bowtie element is connected through half-wavelength printed transmission line sections, ensuring synchronized phase excitation across all elements. The physical dimensions are as follows: $W_t$ = 13.07 mm, $L_a$ = 12.02 mm, $W_b$ = 2.61 mm, $S_a$ = 2.09 mm, $L_{de}$ = 7.83 mm, $W_1$ = 2.61 mm, $W_2$ = 0.52 mm, $L$ = 15.3 mm, $W_d$ = 21.43 mm, $S$ = 26.13 mm, $W_f$ = 2.61 mm, and $S_f$ = 1.04 mm. For practical implementation, the array is connected via a 50 Ω coaxial cable, with the central pin feeding the lower fractal bow-tie element. The feed line uses printed transmission lines to maintain phase coherence, resulting in omnidirectional radiation in the azimuth plane.

## 3. NUMERICAL AND EXPERIMENTAL VALIDATIONS

The fabricated antenna and its experimental setup, as shown in Figure 2, demonstrate the prototype used for evaluating the antenna's performance. The $S$-parameter results, illustrated in Figure 3, provide a comparison between simulated and measured values, indicating good agreement across the operating bands at 4 GHz, 5.2 GHz, and 6.4 GHz. The measured reflection coefficients confirm that the proposed antenna achieves the targeted multiband performance, with $|S_{11}|$ values below – 10 dB at each resonant frequency, affirming effective impedance matching over the desired bands. The 3D radiation patterns simulated at each of the target frequencies (4 GHz, 5.2 GHz, and 6.4 GHz), shown in Figure 4, reveal an omnidirectional pattern in the azimuthal plane and confirm directional gain at low elevation angles.

To further understand the operational characteristics, the electric field distribution at each resonant frequency is shown in Figure 5. The field distributions illustrate strong resonance around the bow-tie edges, which aligns with the multiband response due to the fractal configuration's ability to support multiple resonant paths. This distribution is also validated by the surface current patterns (Figure 5), where the Sierpinski bow-tie structure promotes strong cur- rent paths at each iteration, directly contributing to the antenna's multiband behavior. The radiation patterns in both elevation and azimuthal planes at each of the operating frequencies (4 GHz, 5.2 GHz, and 6.4 GHz) are shown in Figure 6. Both simulated and measured patterns display good agreement, with omnidirectional radiation patterns in the horizontal plane and focused gain in the elevation plane. The patterns confirm that the antenna retains its omnidirectional performance across all operating bands, with minimal azimuthal variations and consistent radiation in the horizontal plane, further validating the design's suitability for IoT applications that require uniform coverage.

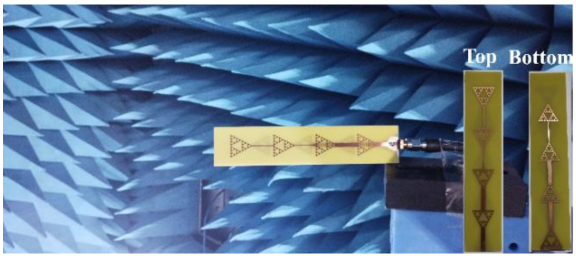


**Fig. 2** – Experimental setup with a fabricated antenna

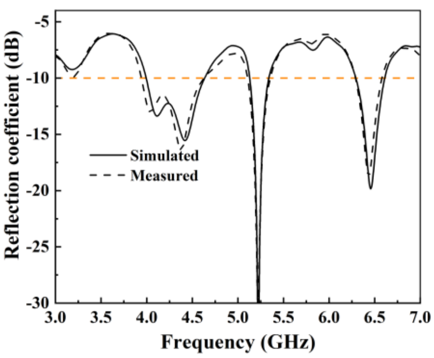


**Fig. 3** – Reflection coefficients of the proposed antenna

The gain performance, depicted in Figure 7, shows both simulated and measured gain values across the operating frequencies. Minimal discrepancies are observed between simulated and measured values. The slight variations can be attributed to fabrication limitations and the effects of the measurement setup. In summary, the results confirm that the proposed antenna achieves the de- sired multiband, omnidirectional performance with stable gain and consistent impedance matching. The Sierpinski fractal bow-tie configuration, in combination with a vertical collinear arrangement, proves effective in delivering reliable coverage across the targeted frequencies, supporting its applicability in IoT applications.

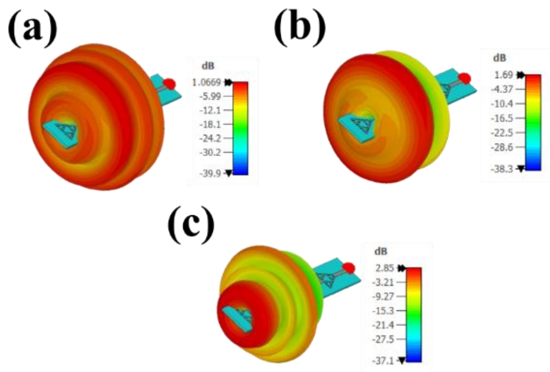


**Fig. 4** – The simulated 3D radiation pattern at (a) 4 GHz, (b) 5.2 GHz, (c) 6.4 GHz

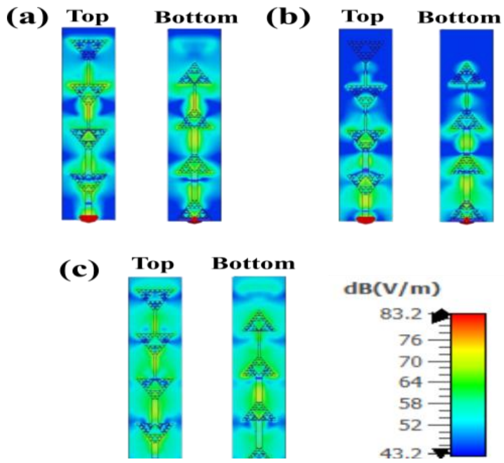


**Fig. 5** – The simulated surface current distribution at (a) 4 GHz, (b) 5.2 GHz (c) 6.4 GHz

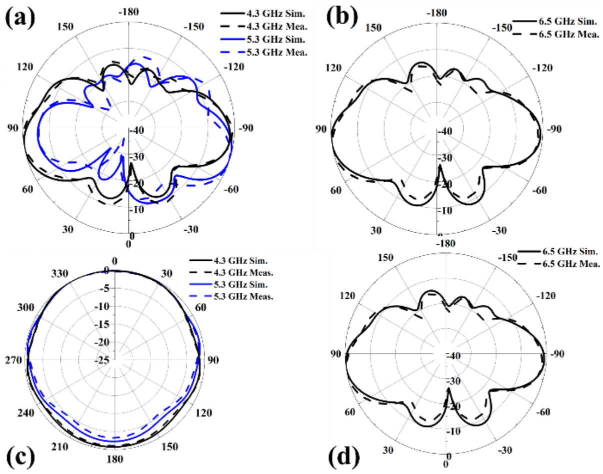


**Fig. 6** – Simulated and measured 2D radiation pattern of the antenna

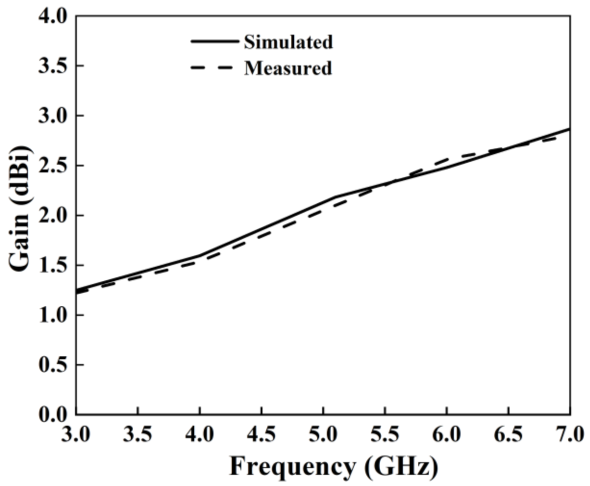


**Fig. 7** – Simulated and measured gain of the antenna

**Table 1** – Comparison of the proposed antenna with some other published works

| Ref. | [16] | [17] | [18] | [19] | This Work |
|---|---|---|---|---|---|
| Ant. Size $mm^3$ | 3.18 × 4.84 × 0.308 | 9 × 11 × 0.25 | 5 × 20.5 × 1.59 | 4 × 5.8 × 0.16 | 100 × 40 × 1.6 |
| Freq. GHz | 60.09 | 60 | 60 | 59.95 | 4.3, 5.3, 6.5 |
| $S_{11}$ dB | – 39.27 | – 33 | – 16 | – 36.41 | – 14 |
| Gain dBi | 8.4 | 4.8 | 5.90 | 9.2 | 3 |
| No. of bands | 1 | 1 | 1 | 1 | 3 |

## CONCLUSION

In conclusion, this paper presents a novel multi-band omnidirectional antenna optimized for IoT applications. The proposed antenna utilizes a compact fractal bow-tie radiator array, efficiently covering both sub-7 GHz and mm Wave frequency ranges critical for next-generation communication systems. Experimental results demonstrate excellent performance characteristics, with reflection coefficients $|S_{11}|$ consistently below – 10 dB across the operational bands of 4-4.6 GHz, 5.1-5.3 GHz, and 6.3-6.7 GHz, while exhibiting a peak gain ranging from 4 to 8 dB, indicative of effective omnidirectional radiation patterns. The low- cost fabrication process, ease of integration with other electronic devices, and the ability to adjust resonant frequencies by modifying the fractal geometry further establish this antenna as a promising candidate for mass production, underscoring its potential to enhance connectivity in the evolving landscape of IoT-enabled applications.

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# Багатодіапазонна всеспрямована фрактальна антена типу "метелик" для застосувань Інтернету речей

K. Mohan Krishna[1,2], U.V. Ratna Kumari[1]

[1] *Department of ECE, Jawaharlal Nehru Technological University, Kakinada, Andhra Pradesh, India*
[2] *Department of ECE, Kallam Haranadhareddy Institute of Technology, Guntur, Andhra Pradesh, India*

У статті представлено нову багатодіапазонну всеспрямовану антену, оптимізовану для застосувань Інтернету речей (IoT), яка забезпечує надійне та безперебійне з'єднання в різних частотних діапазонах та орієнтаціях. Запропонована антена використовує компактну планарну фрактальну решітку випромінювачів типу "краватка-метелик", яка забезпечує високоефективне покриття спектру як для діапазонів 5G нижче 7 ГГц, так і для міліметрових хвиль (mmWave). Її діаграма спрямованості досягається завдяки конфігурації решітки на основі фрактальної геометрії, що забезпечує надійне з'єднання в усіх напрямках. Антена ефективно охоплює цільові частотні діапазони IoT: 4-4,6 ГГц, 5,1-5,3 ГГц та 6,3-6,7 ГГц, забезпечуючи стабільний та високопродуктивний бездротовий зв'язок. Завдяки компактним розмірам 100 мм × 40 мм × 1,6 мм, антена підтримує втрати відбиття краще за 10 дБ у всіх робочих діапазонах та пікове посилення в діапазоні від 4 до 8 дБ. Ці характеристики сприяють стабільній всеспрямованій роботі, що робить антену надійним рішенням для мереж IoT у різноманітних середовищах. Крім того, низьковитратний процес виготовлення та ефективна за простором конструкція підвищують її придатність для безшовної інтеграції в масштабовані системи Інтернету речей. Конструкція також забезпечує мінімальні перешкоди та ефективне використання спектру, що є критично важливим для сучасних бездротових систем. Висока відповідність між результатами моделювання та вимірювань підтверджує продуктивність антени, підсилюючи її потенціал для великомасштабного виробництва та впровадження в наступних поколіннях програм на базі Інтернету речей, включаючи розумні міста та промислову автоматизацію.

**Ключові слова:** Багатодіапазонні, Всеспрямовані, Фрактальні метелики, Додатки для Інтернету речей.