

Analysis of a compact wideband DGS-inspired octagonal patch antenna for sub-6 GHz 5G and IoT wireless systems

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ABSTRACT

The proposed compact wideband antenna is developed to meet the increasing demand for efficient and miniaturized radiators in sub-6 GHz fifth generation (5G) and internet of things (IoT) wireless systems. The design features an octagonal radiating patch integrated with modified H-shaped slots to enhance the current path and impedance matching, while a graded defected ground structure (DGS) is introduced to improve bandwidth (BW) and suppress unwanted surface wave effects. Fabricated on an FR4 substrate and energised by a simple stripline feed, the antenna maintains a compact size of 18×15 mm² without compromising performance. It achieves a wide fractional BW of 42.81% spanning 3.1–5.8 GHz, with a resonance centered at 4.6 GHz and obtained reflection coefficient of –36 dB, indicating excellent impedance matching. Additionally, the suggested antenna provides the maximum gain of 3.14 dB and an overall radiation efficiency of 80.5%, demonstrating stable radiation characteristics while making it ideal for small, low-profile 5G and IoT communication devices.

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1. INTRODUCTION

The rapid expansion of cellular services necessitates increased capacity and quicker data rates. A new spectrum with increased bandwidth (BW) and fifth generation (5G) technology. Its frequency range spans from millimeter-wave (mm-wave) to sub-6 GHz. The benefits of the this 5G frequency range include increased coverage, reduced fading in the rain, and faster data rates. The conceptualization of planar antennas for 5G sub-6 GHz band of frequencies increases overall system performance significantly. Microstrip patch antennas (MPA) have intrinsic features that make them an excellent choice for 5G communication networks [1], [2]. Although microstrip antennas have many benefits, such as cheap, tiny area, planar construction, ease of fabrication, and suitability for arrays, their main drawbacks include their relatively large size at low frequencies, low gain, and narrow BW. Because of their improved performance and design, microstrip antennas are becoming more and more common. Antennas are essential for establishing a communication link in wireless technologies [3].

The necessity for small, wideband antennas which can meet the demands of high-speed connectivity in applications with limited space has increased due to the recent spread of sub-6 GHz 5G communication technology [4]–[6]. This issue is more noticeable in embedded wireless communication equipment and internet of things (IoT) nodes, where the antenna's dimension has a big impact on the system's overall functionality. The impedance matching qualities of the antenna must be guaranteed while minimizing the space occupied by the antenna because contemporary IoT and embedded wireless communication devices work in dynamic situations [7].

One of the biggest complexities in integrated and reconfigurable antenna is still achieving a large impedance BW while maintaining small dimensions. While wideband patch antennas can escalate complexity of design or dimensions, conventional downsizing strategies often result in lower BW or worse radiation efficiency. Many current defected ground structure (DGS)-based patch antennas are made to operate independently, despite the fact that DGS approaches have been extensively investigated to increase BW and improve impedance matching [8]–[11]. Compatibility with reconfigurable hardware, IoT modules, or very large-scale integration (VLSI)-based radio frequency (RF) front-ends has received little attention, and their performance frequently deteriorates when incorporated into embedded systems. Investigating various patch shapes in addition to ground plane adjustments is another interesting approach to solving the problems. Without significantly expanding the patch's size, the geometry-based current control and DGS patterns can be useful for the wideband properties. The aforementioned methods are broad approaches to creating wideband antennas that can be used to embedded systems, IoT devices, and VLSI-based RF systems for sub-6 GHz 5G networks [12].

An antenna designed for sub-6 GHz operations are crucial in modern wireless networks including 5G communications, wireless-fidelity (Wi-Fi), long-term evolution (LTE), and IoT. Consequently, these antennas have been intended to perform efficiently below 6 GHz and often cover frequency bands such as 3–3.85 GHz for 5G (n77/n78), 2.4 GHz for ISM applications, and 1.8/2.1 GHz for LTE [13]. The primary objectives of sub-6 GHz antenna design are wide BW, high radiation efficiency, and small size to enable integration into portable and embedded systems. Monopoles, dipoles, MPA, and planar inverted-f antennas (PIFA) was among many different types of antennas that are employed. Nowadays, techniques like fractal geometry, coplanar waveguide (CPW) feeding, and DGS have been employed to minimize antenna size and maximize the BW without compromising performance [14]–[16]. For dependable connectivity, minimal latency, and high data rates in settings where mm-wave signals may experience propagation constraints, these antennas are essential. Sub-6 GHz antennas are therefore still the foundation of wireless systems, especially in indoor and urban installations.

Many scientists throughout the world are working on different kinds of antennas. Patch antennas are an extremely frequently employed type of antennas due to its essential features. Patch antennas are favored for their simplicity, robustness, integrated compatibility, cost-effectiveness, energy efficiency, compact size, and simple manufacturing. MPAs are a better device for sub-6 GHz wireless communication because of these key characteristics [17]–[19]. In terms of their usability and requirements, they are changing independently with many designs created by contemporary researchers. An MPA can be designed using a variety of techniques, and DGS is one of the most widely utilized approaches to improve the MPA's radiation properties. Because of its adaptability and structural independence, DGS is a highly used technology [20].

In efficient antenna design, it is commonly known that BW and antenna size must be trade-off. An antenna's capacity to perform better over a broad range of resonances typically declines with decreasing size. The ability of smaller antennas to accommodate wideband transmissions is sometimes limited by their smaller surface area and shorter current channels. As a result, small antennas are sometimes only suitable for specific frequency bands due to their narrow BW [21]. Consequently, larger antennas can be effectively covering a wider variety of BW because they can manage longer current courses and more intricate designs. When building antennas for contemporary communication systems, striking a balance between small size and sufficient BW is a significant challenge, especially when multi-band capabilities and space constraints are both crucial.

With the aid of an insert linked feeding mechanism, a tiny antenna measuring $20.5 \times 17.5 \text{ mm}^2$ with a high BW between 2.8 and 5.6 GHz [22]. One of the designs surrounds the radial component with a rectangular shaped patch containing a U-shaped slot [23]. The proposed antenna achieves triband characteristics with the initial band from 4.8–6.2 GHz, another band from 5.1–5.3 GHz, and the third resonance lies on 5.72–5.82 GHz [24]. Artificial periodic structures with unusual characteristics that do not arise naturally are known as metamaterials. Metamaterials are primarily used to improve antenna performance, including impedance, directivity, and BW gain. The MPA incorporates a metamaterial split ring resonator [24]–[26]. A 0.4 GHz BW obtained from 4.802 GHz and 5.21 GHz for that planned design. A circular slip ring resonator was suggested in another research as a way to achieve 87% antenna miniaturization. Consequently, the greatest possible reduction of the antenna may be demonstrated by utilizing a metamaterial [27]. Another circular shaped planar antenna for Sub-6 GHz wireless applications is intended to improve the performance. The planar antenna, with its most basic form and lack of lumped elements, spans a broader BW of 3.05–5.82 GHz [28].

An innovative antenna design with a 2.2 GHz BW, a -20 dB reflection coefficient, and a 4.8–7 GHz resonant range is being developed. Using a small $30 \times 26 \times 1.42$ mm³ structure, the finished prototype with both barium strontium titanate (BST) and a DGS had a higher reflection coefficient of -25 dB and a longer operating range of 1.8 to 6 GHz [29]. This led to a 4.2 GHz increase in BW. The antenna has an overall footprint of 36×31 mm² and efficiently functions in the 3.3–3.6 GHz and 4.3–5.2 GHz frequency ranges, offering a peak gain of about 7.1 dB. A special theta-shaped patch antenna (TSPA) with dimensions of $35 \times 34 \times 1.6$ mm³ integrates a particular DGS [30], offering dual-band operation at 4.2 GHz and 4.9 GHz, making it suitable for 5G NR frequencies n77 (3.34–4.21 GHz) and n79 (4.3–4.9 GHz) [31]. With a small shape of $42 \times 42 \times 1.6$ mm³, another design achieves resonance between 2.07 and 5.8 GHz by utilizing a semicircular DGS slot to increase BW and decrease size [32]. Furthermore, dual-band operation in the 1.8–3.7 GHz and 4.05–5.5 GHz frequency bands is supported by an antenna with the same footprint (42×42 mm²) [33]. For sub-6 GHz 5G NR applications, especially for the n77 (3.2–4.15 GHz) and n78 (3.34–3.84 GHz) bands, compact antennas have become crucial [34].

A handful of investigations have successfully achieved wide BW, compact dimensions, and high radiation efficiency together in the sub-6 GHz frequency range, despite the fact that numerous compact and DGS-based antenna designs have been documented in the literature. Existing designs frequently increase one parameter at the expense of another; for instance, broader BW solutions usually ask for larger physical dimensions, while miniaturized antennas frequently suffer from reduced BW. Specifically, it is still rather rare to find antennas that can achieve radiation efficiency above 80%, retain dimensions less than 20 mm, and provide more than 40% fractional BW. This limitation reveals a glaring research need, particularly for sub-6 GHz 5G communication networks, which demand lightweight, reliable, and wideband antennas for embedded and IoT-based wireless technologies.

This article describes a technique for increasing the impedance BW and decreasing the dimension of the antenna that is suited for 5G applications. In order to enhance the efficient current path without expanding the antenna structure, an octagonal patch has been picked for the design suggested, allowing for reduced dimensions while maintaining high radiation performance. In order to disrupt surface currents and produce more resonant channels, which aid in expanding the impedance BW, H-shaped slots were added to the patch. To enhance impedance matching, control ground current spread and facilitate more size diminution, a stepped DGS has been incorporated. The suggested antenna having a total volume of $18 \times 15 \times 1.6$ mm³. With the middle frequency of 4.6 GHz, the broader BW of the proposed antenna is attained up to 2.7 GHz (from 3.1 to 5.8 GHz). The analyzed antenna is an excellent choice for sub-6 GHz 5G operation due to its high peak gain, outstanding radiation characteristics, and current distribution. The following is an additional explanation of the article's structure: section 2 describes the antenna's geometry and design in depth. Section 3 elaborates the design of the proposed antenna. Section 4 presents the results of the simulation of the suggested antenna together with measurement analysis. Section 5 concludes by summarizing the significant findings and contributions of the paper.

2. DESIGN METHOD

Substrate selection based on factors including printed circuit board (PCB) compatibility, thickness, dielectric constant, and cost, standard microstrip theory is used to perform preliminary patch size calculations, which are then refined by parametric analysis. To enhance BW characteristics, DGS modifies ground planes. For ease of integration and manufacture, a microstrip line feed is utilized. A simple design and simulation flow diagram describes the design process, and full-wave simulations are carried out for optimization has been given in Figure 1. The flow diagram shows how to use computer simulation technology (CST) software to create and optimize structured antennas. First, the antenna design specifications, such as frequency, BW, and size constraints, are defined. Next, the substrate material is selected based on its relative permittivity, thickness, cost, and PCB compatibility. The microstrip antenna's starting dimensions are then established using traditional microstrip antenna theory and modeled in CST. DGS is then added to increase the impedance BW after the boundary conditions and excitations have been established. In order to optimize the antenna size and DGS, the full-wave electromagnetic simulation is used to simulate the antenna with the proper solver settings and parametric evaluation.

Good impedance matching for the recommended antenna is achieved by feeding the basic octagonal patch antenna with a 50 Ω impedance microstrip feed. This suggested antenna's full architectural construction and optimum dimensions are shown in Figure 2. The microstrip feed line's total length and width are 2.4 mm and 6.6 mm, respectively. It also makes use of an inexpensive FR4 substrate with a height of 1.6 mm and relative dielectric constant (ϵ_r) of 4.4, that is frequently used because of its affordability, accessibility, and suitability for rapid IoT experimentation. The design is compatible with standard PCB fabrication techniques, enabling simple, and reliable manufacturing. A modified H-shaped slot on an octagonal patch and a stepped DGS in the ground plane make up the suggested antenna. The patch has an octagonal shape and measures

8 mm on each side. 11.5 mm is the radius of the radiating patch's modified H-shaped slot. A DGS is mounted at the ground surface to vary the impedance matching properties and achieve the necessary radiation performance. The stepped ground plane of the suggested DGS structure is made up of five strips of varying sizes. Each ground strip is 1 mm long, and its breadth varies accordingly. The front and back view of the suggested antenna is shown in Figures 2(a) and (b), respectively. The design will result in higher efficiency of the antenna specifications if the appropriate impedance is used. Table 1 clearly shows the general specifications of the proposed antenna.

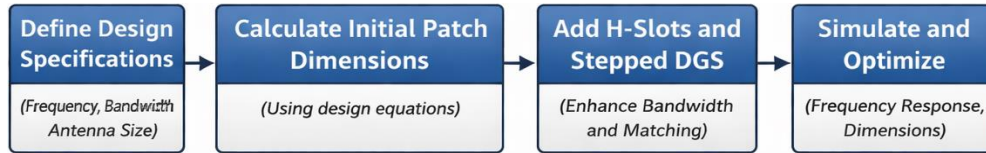


Figure 1. The flow diagram of the proposed antenna design

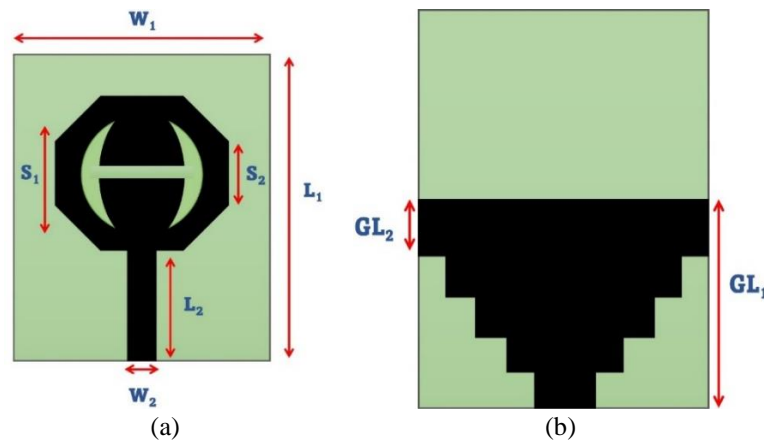


Figure 2. Geometrical view of the proposed antenna; (a) front view and (b) back view

Table 1. Detailed parameter of the proposed antenna

Parameter	W1	L1	W2	L2	GL1	GL2	S1	S2
Size (mm)	15	18	2.4	6.6	9	2.3	5	6.5

The octagonal patch design is favored for uniform current distribution and many resonant routes to maximize BW within a restricted region. In order to change the ground plane currents and provide impedance matching for greater BW without enlarging the antenna with a crucial aspect for IoT devices with use of DGS is recommended. Because the structure is planar, the computational problem's complexity is also manageable, opening the door to the possibility of designing scalable reconfigurable antenna arrays. Because of its small size and broadband performance, the designed antenna is best option for sub-6 GHz 5G systems for smart sensors, and embedded IoT devices.

3. EVOLUTION STAGES

The proposed octagonal patch antenna's evolution is illustrated in detail in Figure 3. The evolution starts with basic hexagonal shaped patch antenna for 3.6 GHz and ends with proposed hexagonal shaped patch antenna with H-shaped slots.

Step 1: the design structure of the antenna is measured from the fundamental design equation of a circular shaped antenna with a full ground plane (1):

$$f_r = \frac{c}{4\pi S_1 \sqrt{\epsilon_{eff}}} \tag{1}$$

where c is the velocity, S_1 is the sidelength of the octagonal patch, and ϵ_{eff} is the equivalent dielectric constant shown in (2) [35]:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-1/2} \quad (2)$$

where, ϵ_r is the substrate permittivity, h is the substrate thickness, and W is the patch width. For $f_r=3.6$ GHz, the octagonal patch's sidelength is initially fixed at 18.3 mm. The 3.6 GHz narrow band frequency is covered by the traditional antenna. Figure 3 illustrates the development of the suggested antenna. Iteration 1's antenna design is large and has a limited BW, is shown in Figure 3(a).

Step 2: slots based on literature are used to modify this basic construction to elaborate the BW and minimize the overall volume of the designed antenna. Around the octagonal patch's perimeter and the entire ground plane, the current distributions are more prevalent. This slot increases the current path and disrupts the octagonal patch's surface current distribution. Consequently, Figure 3(b) shows that the antenna's acquired BW is roughly 1.6 GHz between 4.2 and 5.8 GHz.

Step 3: to cover a wider BW in Iterations 3, the stepped DGS structure might be substituted with the complete ground plane. Figure 3(c) illustrates how the antenna's overall BW is enhanced by the inclusion of these stepped-shaped DGS. The BW of the antenna has been attained is higher, spanning from 3.1 to 5.6 GHz, or about 2.5 GHz. The designed antenna's overall specifications have also been reduced to 18×15 mm².

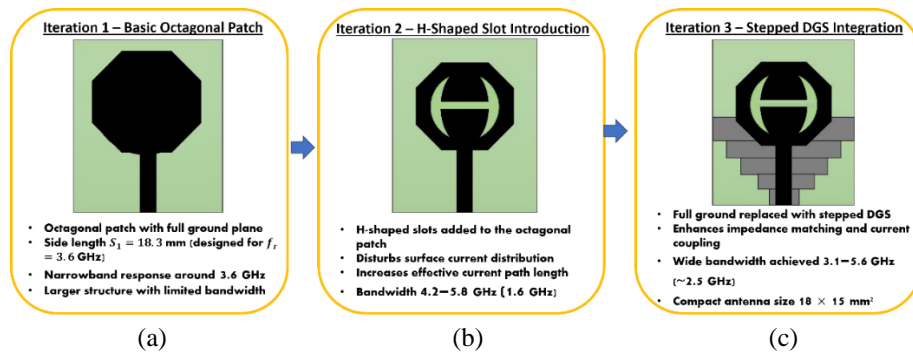


Figure 3. Design of the proposed antenna at different stages; (a) stage 1, (b) stage 2, and (c) stage 3

4. RESULTS AND DISCUSSION

An agilent vector network analyzer (VNA) can be assessed to evaluate the operation of the designed antenna structure, focusing on parameters such as BW and normalized gain. Radiation characteristics can be measured in an anechoic chamber. Figure 4 depicts the designed prototype as well as the measuring instruments. Manufacturing tolerances and cable losses are the primary reasons of the little differences between the observed and simulated results, which normally match substantially. Key metrics of performance for antennas include peak gain, radiation pattern, and reflection coefficient has been analysed. The presented design's reflection coefficient is simulated and evaluated across the entire frequency spectrum using CST microwave studio, where the model used approximately 25,000–35,000 mesh cells to ensure accurate electromagnetic field computation. A typical frequency sweep simulation required about 6–10 minutes on a standard workstation. When the antenna size is reduced, BW, and radiation efficiency slightly decrease.

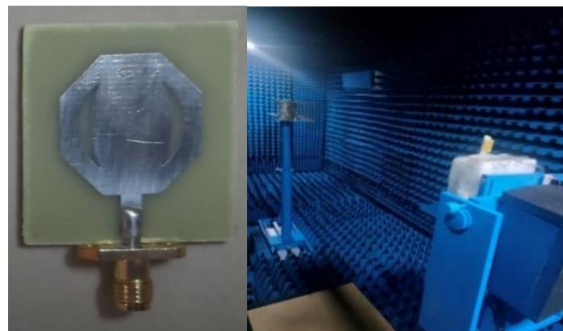


Figure 4. Prototype and measurement setup of the proposed antenna

A computed and analysed reflection coefficient of this developed antenna has been evaluated at the 4.6 GHz resonant frequency. Figure 5 illustrates improved impedance matching of the suggested antenna and has an increased reflection coefficient of -38.4 dB over the whole band. The intended antenna's resulting BW is observed between 3.1 GHz and 5.8 GHz, yielding a 41.5% fractional BW. The reflection coefficient in this range shows effective radiation and strong impedance matching, falling below -10 dB. The function of the antenna over the intended resonance is demonstrated by the close relationship between simulation and measurement. Small variations in the physical construction of the antenna or practical measuring conditions may be the cause of the two values' slight variations. However, fabrication tolerances, particularly in the slot dimensions and ground strip widths, can slightly affect impedance matching and BW performance. Due to its compact size and PCB compatibility, the antenna can be easily integrated into IoT modules, portable devices, and embedded wireless systems.

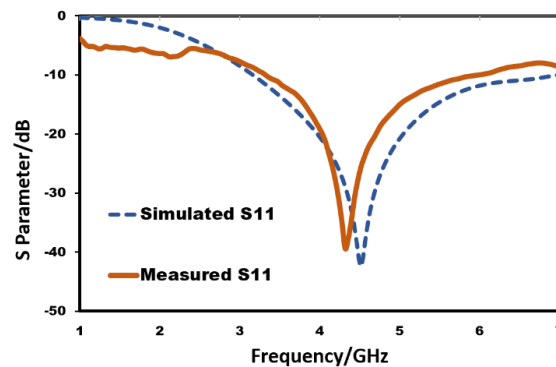


Figure 5. Simulated reflection coefficients of the proposed antenna

Analysis is done on simulated current densities for the octagonal antenna resonated at 4.2 GHz. As seen in Figure 6, a high current flow has been seen on both sides of the modified H-shaped slots in the octagonal patch at full resonant frequencies. By inserting the H-shaped slots to the radiation element, the total length of the current path will be increased, shifting the natural resonance to lower frequencies and creating lots of resonant phases that will expand the BW. Because of the numerous inductive and capacitive effects introduced by the stepped DGS, the current concentration on the ground layer changes, increasing the impedance BW. This is because the current path will be changed by the structural changes, which will decrease the degree of symmetry. The antenna's frequency resonated most effectively at 4.2 GHz, according to this pattern.

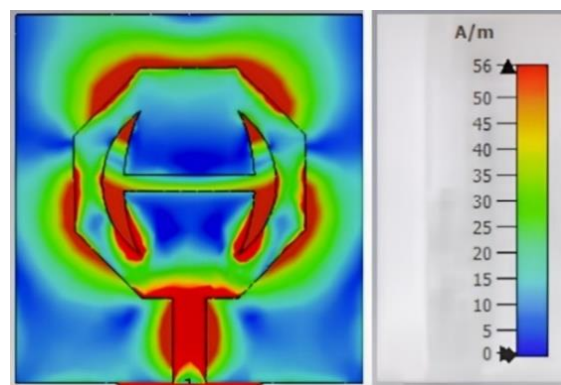


Figure 6. Simulated surface current density at 4.2 GHz

Radiation stability analysis evaluates whether an antenna maintains consistent radiation characteristics across frequency, operating conditions, and environment. Consider reflection coefficients (S_{11}) results acquired by altering substrate permittivity and thickness to have an analysis of the antenna's

performance under various operating scenarios has been illustrated in Figure 7. If $\epsilon_r=2.2$ is taken into account in the substrate permittivity variation analysis, it resonates at 5.2 GHz with a shallow S_{11} of almost -22 dB. The designed antenna resonates at 4.9 GHz with a deeper reflection coefficient of around -35 dB when the permittivity value is increased and $\epsilon_r=3.3$ is taken into consideration in Figure 7(a). At $\epsilon_r=4.4$, the operating band is 4.6 GHz, with a profound reflection coefficient of roughly -42 dB. In terms of substrate tolerance, a thinner substrate ($H_s=0.5$ mm) exhibits resonance at 4.8 GHz with a S_{11} of around -36 dB, whereas an increase in substrate thickness ($H_s=1$ mm) improves matching and reaches around -41 dB at 4.68 GHz. It is also clear that the optimal value of 1.6 mm produces the deepest resonance of about -40 dB at 4.6 GHz is shown in Figure 7(b).

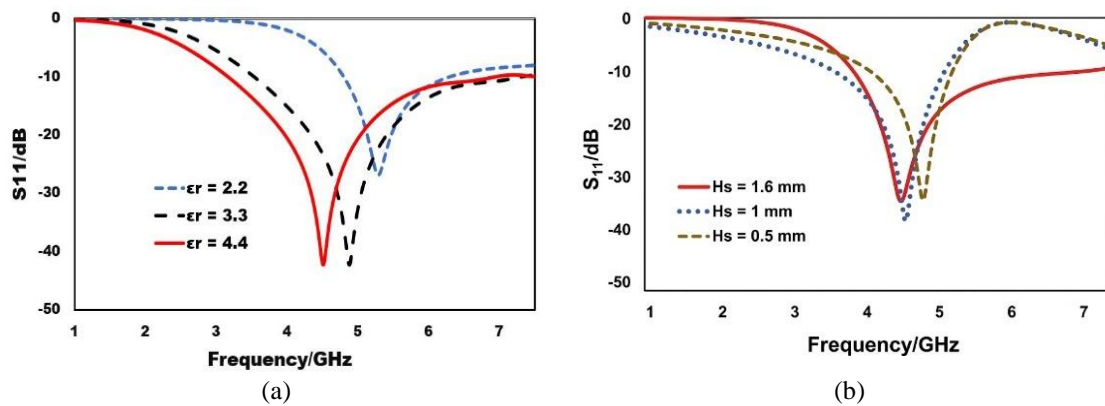


Figure 7. Antenna performance under different operating conditions; (a) parametric study of substrate permittivity's impact on S_{11} and (b) substrate height's impact on S_{11}

Beyond impedance matching, the evaluation of radiation efficiency and antenna gain is essential for testing the antenna's practical functionality. The gain measurement is crucial to verify the antenna's capacity to send and receive data over the intended area. It's obvious that an antenna performs better throughout operational frequencies is noteworthy. Figure 8 shows the suggested antenna's 3.14 dB gain and 81% maximum radiation efficiency at the lower resonance of 4.5 GHz. Thus, the proposed design's easy construction, tiny dimensions, enhanced gain, and radiation efficiency make it an appropriate solution for the sub-6 GHz 5G NR band.

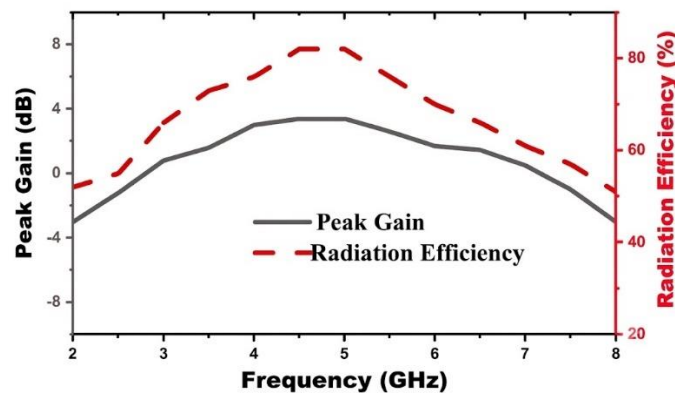


Figure 8. Simulated peak gain and radiation efficiency of the proposed antenna

Table 2 illustrates the trade-off between antenna miniaturization and antenna BW in the sub-6 GHz resonance region. The initial instance demonstrates the performance of a larger-sized conventional microstrip antenna, which has a narrow BW because of its fundamental shape and ground plane. In the second instance, the antenna's compactness is increased due to its smaller size. However, a number of methods, including ground modification and antenna shape optimization, are needed to increase the antenna BW. In the third scenario, the suggested octagonal DGS-based antenna offers a greater BW and is more compact. It is evident that the suggested antenna design offers the necessary antenna BW and compactness for 5G and IoT device design.

Table 2. The trade-off between antenna miniaturization and antenna BW

Antenna type	Antenna size (mm ²)	Operating frequency (GHz)	Miniaturization (%)	Bandwidth (GHz)
Conventional	36×30	4.5	-	1.8 (3.6–5.4)
Without DGS	22×18	4.6	~55	2.3 (3.3–5.6)
With DGS	18×15	4.6	70	2.7 (3.1–5.8)

To reduce distortion and unwanted side lobes while guaranteeing efficient signal availability and acquisition in the accurate orientations, a well-planned radiation analysis is required. Figure 9 depicts the radiation characteristics of the constructed antenna, which have been determined at 4.6 GHz and 5.1 GHz in the XOZ and YOZ planes, correspondingly. The H-plane aligns with the XOZ axis in the magnetic field, while the E-plane is part of the YOZ axis in the electric field has been illustrated in Figures 9(a) and (b), respectively. The antenna's consistent bidirectional and omnidirectional behaviour throughout its operational range is demonstrated by the radiation patterns along both planes.

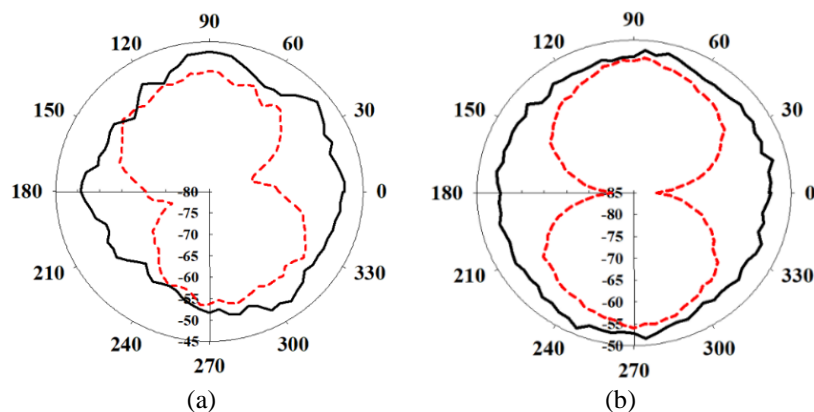


Figure 9. Measured 2D radiation patterns of the antenna; (a) 3.6 GHz and (b) 5.1 GHz

Table 3 contrasts the designed antenna with the small antennas that are currently published, as reported in the brief literature, based on the antenna size, substrate, peak gain, and fractional BW. Additionally, the accompanying table demonstrates that the suggested antenna achieves a good reduction in size and gain for whole bands when compared to earlier experiments. The suggested antenna's dimensions, 15×18×1.6 mm³, are significantly smaller than those of the antennas detailed in [22]–[34]. All of the antennas discussed in these articles range in size from 20.5×17.5 mm², as reported in [22], to a significantly greater size of 42×42 mm², as detailed in [32], [33]. Despite having a broad BW of 1.8–6 GHz, the antenna described in [30] is substantially larger and has a lower peak gain of 0.5 dB. Although the dual band properties are given in the antennas described in [23], [30], [31], [33], the antennas described in these articles have a significantly bigger dimension and a much narrower BW. The antennas described in [30], [32], [33] have a higher peak gain, but they are also larger in size. However, employing a small substrate material such FR-4, the work reported here has a wide frequency range from 3.1 GHz to 5.8 GHz with a BW of 2.7 GHz and a peak gain of 3.14 dB. The work described here is equivalent in terms of BW while having a substantially lower size, which is advantageous for compact sub-6 GHz 5G and IoT wireless applications.

Table 3. Comparison with previously published wideband antennas for sub 6-GHz applications

Reference	Antenna size (mm)	Substrate used	Operating frequencies (GHz)	Bandwidth (GHz)	Peak gain (dB)
This work	15×18×1.6	FR-4	3.1–5.8	2.7	3.14
[12]	20.5×17.5	FR-4	2.8–5.6	2.8	2.95
[13]	27×29×1.6	FR-4	4.8–5.2, 6.7–6.9	0.4, 0.2	-
[19]	30×26.5×1.42	Rogers RT 5880	1.8–6	4.2	0.5
[20]	36×31×0.8	FR-4	3.3–3.6, 4.4–5.2	0.3, 0.8	7.17
[21]	35×34×1.6	FR-4	3.3–4.2, 4.4–5	0.9, 0.6	1.51
[22]	42×42×1.6	FR-4	2–5.8	3.8	8
[23]	42×42×1.5	FR-4	1.8–3.7, 4–5.5	1.9, 1.5	8.5
[24]	40×20×1.6	FR-4	3.3–4.2	0.9	2.5

5. CONCLUSION

A sub-6 GHz 5G (n77/n78/n79) antenna with a modified ground configuration is constructed and investigated in this paper. A stepped DGS is included in the suggested antenna design to increase BW range for 5G applications that use frequencies lower than 6 GHz. With a total volume of $18 \times 15 \times 1.6 \text{ mm}^3$, the suggested antenna offers a beneficial solution of compact size and excellent BW. With a middle frequency of 4.35 GHz, the proposed antenna's broader BW is attained up to 2.7 GHz (from 3.1 to 5.8 GHz). Validation of the simulated results using the experimental results revealed excellent agreement. This wideband operation, improved gain, and efficiency proved it ideal for integration into successful IoT systems. Notably, lower 5G bands are a good fit for the proposed structure. For Sub-6 GHz wireless systems, the intended antenna is a good option due to its better peak gain, and high efficiency as well as its omnidirectional radiation properties. In the future, the antenna will be evaluated in real-world IoT applications such wearables, smart meters, and embedded RF modules. Furthermore, the integration of reconfigurable RF front-ends and IoT gateways can be examined to determine the antenna's adaptability, positioning, and beyond.

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AUTHOR CONTRIBUTIONS

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.




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