

Design and Miniaturization of a 10-GHz Microstrip Patch Antenna Using a Metamaterial-Patterned Wired Defected Ground Structure

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Abstract

To address the growing demand for compact and high-performance X-band components, a novel metamaterial-patterned wired defected ground structure (MMP-WDGS) operating at 10GHz is proposed and investigated in this study. The proposed antenna design begins with a basic rectangular patch configuration, which is then enhanced through the introduction of a wired dumbbell-shaped defect and a metamaterial-patterned ground structure. The antenna design is optimized in HFSS using parametric variation of key dimensions. The results show a return loss of about -33dB, and a bandwidth close to 33% compared to the conventional design. The proposed antenna achieves significant miniaturization while maintaining stable radiation performance. The overall antenna area and radiating patch area are reduced by 72.95% and 72.40%, respectively. Furthermore, curve fitting and sensitivity analysis are employed to evaluate parameter effects on resonant frequency, reducing the need for repeated simulations during the design process. Due to its compact structure and performance, the antenna can be considered for applications in satellite communication, radar, and high-frequency wireless systems. Finally, the assessment of the antenna's reflection and radiation responses is imported into a MATLAB real-time simulation environment to test the feasibility of the structure for satellite communication with the presence of environmental losses.

Keywords: *Defected Ground Structure, Meta-Material Structure, Miniaturization, Performance Parameters, Sensitivity Analysis, Satellite Communication.*

1 Introduction

The rapid advancement of wireless communication technologies has increased the demand for compact and efficient antennas. Among the available antenna types, microstrip patch antennas (MPAs) are widely used for their low-profile, lightweight construction, ease of integration with microwave circuits, and ability to operate across multiple frequency bands. Antenna miniaturization is a significant topic in the antenna industry. The growing demand for secure and efficient wireless communication systems has led to an increased adoption of microstrip patch antennas in X-band applications. These systems require compact, low-profile antenna structures capable of transmitting high-quality information reliably over wireless channels. Miniaturization techniques for antennas can be broadly systematized into two main types: material-based and topology-based approaches. The performance of an antenna is largely determined by the radiation produced by the accelerated charges within the excited antenna. This means that by precisely managing how current flows on the antenna and by adjusting its electrical size, you can fine-tune the antenna's resonance and radiation patterns while keeping its physical size as small as possible. Over the years, several methods have been developed to reduce antenna size. These include adding slots to the radiating elements, utilizing materials with high dielectric constants, and disrupting the surface current distribution through defects in the ground plane.

There are various techniques used for enhancing the radiation properties while reducing the antenna size, such as material loading, stacking, using meta-materials, frequency-selective surfaces, electronic band gap (EBG), photonic band gap, and creating defects on the ground plane referred to as defected ground structures (DGS) [1-4]. DGS is generally a defect etched in a periodic or a single pattern on the Microstrip patch antenna's ground plane. Antennas with DGS have gained more popularity when compared with other structures due to their simple fractal designs. Single or multiple etched slots on the ground plane of microstrip patch antennas are designated as DGS. At the outset, DGS is used as a filter underneath the microstrip line to reduce the higher-mode harmonics and to enhance the band-stop characteristics. The success rate of DGS in the field of filters has given rise to various applications. Park et al. [2] proposed the DGS technique to explain a single dumbbell-shaped defect. DGS is a substantial form of EBG structure, thereby revealing a band-stop property [3]. A microstrip patch antenna designed with a Minkowski Fractal DGS beneath the patch at the ground plane of the antenna is addressed in [4]. The proposed fractal DGS reduces the size of the antenna by 68% with enhanced bandwidth and radiation efficiency operating at 10GHz resonant frequency. There are various structures patterned on the ground plane of the antennas under the microstrip line that are presented in the literature. To

increase the effective inductance, a novel one-dimensional (1-D) dumbbell-shaped defective ground unit lattice is suggested in [5]. In [6], controlling the cutoff frequency characteristics is made simple by increasing the effective inductance. Excellent cut-off and stop band properties are provided by the DGS. The study investigates how arrowhead-shaped DGS slots influence the performance of microstrip low-pass filters (LPFs). Notably, a three-pole LPF incorporating an arrowhead-shaped DGS slot achieves a 67% reduction in length compared to a traditional three-pole LPF. This design maintains an insertion loss of 0.5dB and offers a 15dB rejection in the stop band, extending up to three times the cut-off frequency. Kim et al. [7] introduced an equivalent circuit model for a microstrip line featuring a spiral-shaped DGS etched into the metallic ground plane, along with a method for extracting its parameters. The spiral DGS design achieves sharp rejection characteristics using a single spiral-shaped defect. In [8], researchers have introduced U-slot and V-slot DGSs in microstrip lines to achieve enhanced band-rejection characteristics with improved quality factors (Q-factors). These configurations are characterized by their simplicity compared to traditional DGS designs and offer steeper rejection profiles. For the U-slot DGS, reducing the spacing between the parallel slots increases the Q-factor, while for the V-slot DGS, decreasing the slot angle results in a higher Q-factor. Experimental implementations of filters incorporating three cascaded U-slot DGSs have demonstrated a Q-factor of 38.6, indicating a sharp and selective band-rejection performance. Similarly, filters with three cascaded V-slot DGSs have effectively suppressed signals in the 3.5 to 4.3GHz frequency range, achieving more than 20dB attenuation. A compact defected ground structure (DGS) has been introduced for microstrip lines, effectively reducing the filter's length by at least 26.3% compared to conventional designs [9]. Cross-shaped defected ground structures are also used to design filters [10], and anticipated performance indicates an expanded and intensified stop band beyond the low-pass region. Researchers have introduced a DGS design featuring concentric circular rings [11] to enhance stop band performance in microstrip circuits. This configuration incorporates a metallic shield on the reverse side of the DGS to mitigate radiation leakage, making it particularly advantageous for microwave circuit applications, and the design has proven effective in reducing mutual coupling within microstrip patch antenna arrays. DGS can also be used in designing various electronic devices such as filters, diplexers, transponders, etc. Some compound structures are designed, including meander line structures [12], where the resonant frequency of the slot can be easily controlled by changing the length of the structure. A novel form of backward coupling has been identified between two parallel microstrip transmission lines situated over a defected ground plane featuring slot split-ring resonators (SSRRs) [13, 14]. This method enhances the coupling between the two lines even when the lines are separated by a considerable gap. The coupling is frequency-selective, showing strong interaction at a specific target frequency on one channel, while coupling at other frequencies is controlled through a different channel. This configuration facilitates the design of innovative couplers that allow for relaxed spacing between lines, presenting potential applications in devices such as diplexers and transponders. Fractal DGS are also used for designing Microstrip patch antennas and filters [15]. In [4, 16], the authors explain the fundamental concepts of DGS with its analysis and applications. DGS is helpful in the reflection and radiation responses of the antenna. It is also beneficial in the reduction of mutual coupling and impedance matching between the elements of the antenna in the antenna array structures. Since the field current distribution is perturbed due to DGS, the antenna size is reduced. The equivalent circuit of the MPA consists of both inductance and capacitance, which are connected in parallel to each other. The disturbance in the field current will disturb the value of the capacitance and inductance, which gives rise to the resonant frequency. The defects on the ground plane disturb the current distribution in the ground plane; this disturbance changes the characteristics of the transmission line by comprising slot resistance, slot inductance, and slot capacitance, to the line resistance, line inductance, and line capacitance, respectively. The addition of lumped inductance proposed by DGS helps in the reduction of the phase velocity of the wave and gives rise to the slow wave effect. The slow-wave phenomenon lowers the resonant frequency of the antenna by increasing its effective electrical length. As a result, a physically smaller antenna can be realized while maintaining the desired operating frequency [4, 17-18]. The slow wave factor is defined as the ratio of propagation constant (β) and free space wave number (k) [19]. Maximum slow wave effect can be obtained by combining DGS and Fractals, which makes replicated geometric patterns to etch the ground plane, hence, behaves like DGS and is termed as DGS Fractals [20]. Here, the authors have proposed an antenna size reduction of 44.74%.

X-band operation has gained significant importance in modern wireless, radar, and satellite communication systems due to its wide bandwidth, high resolution, and compact antenna size. A novel approach is introduced for designing compact microstrip patch antennas for 10GHz wireless communication applications [4]. This method achieves antenna miniaturization by integrating a highly capacitive modified Minkowski fractal DGS-II directly beneath the centre of the radiating patch, leading to a significant reduction in the antenna's resonant frequency from 16.832GHz to 10GHz without altering its physical dimensions. This technique not only facilitates size reduction but also enhances antenna performance, making it suitable for space-constrained applications in the X-band spectrum. Several studies have explored the miniaturization of antennas by lowering their resonant frequency without altering their physical dimensions. The resulting frequency often varies depending on the design. For example, H. Elftouh et al. [21] designed a conventional antenna that initially resonated at 5.7GHz, and by incorporating a DGS, they were able to shift the resonant frequency down to 3GHz. Nosrati et al. [22] proposed a circularly polarized antenna array integrated with a meta-surface. Prakasam et al. [23] designed a circular microstrip patch antenna array, while Ayn et al. [24] investigated the impact of an air gap in a 2×2 antenna array configuration. Farooq et al. [25] developed a 1×4 antenna array utilizing a coplanar waveguide (CPW) feeding technique. Additionally, Attia et al. [26] enhanced the radiation performance of an antenna array by incorporating magnetic superstrates. Authors in [27] investigated a conventional C-band array alongside its miniaturized counterpart, which utilizes a DGS to achieve resonance at the S-band while preserving the overall physical volume of the antenna array. Similarly, [28] explored antenna miniaturization by incorporating both a DGS and a meander structure. In their study, the originally designed antenna resonated at 15GHz; however, the introduction of these techniques enabled dual-band operation at 7.26GHz and 9.42GHz. Rebyiy et al. [29] demonstrated a dumbbell-shaped DGS incorporating circular slots, which effectively shifted the resonant frequency from 5.8GHz to 2.45GHz. Similarly, A Ghaloua et al. [30] introduced a modified patch antenna array featuring a dumbbell-shaped DGS to achieve a more compact array design, also resulting in a frequency shift from 5.8GHz to 2.45GHz. Ali et al. [31] employed rectangular complementary split ring resonators (RCSRR) to achieve antenna miniaturization, attaining a size reduction of approximately 46.8%. A design methodology for converting an L-shaped stub into a U-shaped stub antenna utilizing a DGS is designed in reference [32]. The proposed models achieved fractional bandwidths of 5.7% and 6.89% at resonant frequencies of 3.5GHz and 5.8GHz, respectively. The resonant frequency in an MPA can be controlled using the DGS concept, keeping substantial performance; consequent size reduction can also be achieved. Sierpinski carpet fractal slots to the ground plane of a Wi-Fi application-based MPA are used for reducing the size of the antenna. [33]. Recently, an inter-digital structure and further DGS were used by loading a metamaterial structure complimentary split ring resonator (CSRR), to optimize the compactness of the antenna, and metamaterials are playing a major role in synthesizing materials with desirable features for the size reduction of the antenna, using double negative materials and artificial magnetic materials in the form of split ring resonators (SRR). Since our focus is on the size reduction of the antenna from the literature, it is noticed that M. Karahan et al. [34] designed a microstrip patch antenna having dimensions of (16x16)mm² with a resonant frequency of 10GHz and return loss of -23.34dB. B.N. Demirkoparan et al. introduced a 17x15mm² microstrip patch antenna having a gain of 4.1dB [35]. In [36], an ultrawideband MPA is designed with a resonant frequency of 11.2GHz, and the antenna size is 23.9x29mm². In [37], the authors proposed a circularly polarized MIMO patch antenna that resonates at a frequency of 9.1GHz with an improved gain of 6dB. The value of the return loss is 21dB with a compact size of 40x15mm² designed for wearable applications. A Dual-polarized beam-steerable filtering patch antenna is designed in [38] with a gain of 5.8dB that resonates at 10GHz, having a size of 136x136mm².

Here, a miniaturized MPA is designed by incorporating a dumbbell-shaped DGS with meta-material characteristics. At first, in Section-2, the antenna is designed for X-band operation around 10GHz, where compact size and reliable performance are achieved. The antenna design is carried out and optimized in HFSS using parametric variation of key dimensions. In addition, curve fitting and sensitivity analysis are used to study how different parameters affect the resonant frequency to reduce repeated simulations during the design process. In Section-3, the optimized results are shown with a return loss of about -33dB, indicating good impedance matching, along with a bandwidth close to 33%. A comparison is made among other designs from the literature with the proposed design in the same section. Finally, the reflection and radiation responses of the antenna are imported to MATLAB real-time simulation environment to test the feasibility of the structure for satellite

communication in the presence of several key environmental loss factors in Section-4. At last, the paper is concluded in Section-5.

2 Methodology: Miniaturized MPA design

While designing the microstrip patch antenna for a specific frequency, the antenna's wavelength plays an important role. Generally, the higher the frequency, the shorter the wavelength. Conventional microstrip antennas typically have dimensions close to half the wavelength ($\lambda/2$) of the operating frequency. Given the resonant operating frequency $f_r = 10\text{GHz}$ and the speed of light $c = 3 \times 10^8 \text{ m/s}$, the wavelength λ can be calculated accordingly. For a microstrip patch antenna, the length and width can be determined using the formulas in Equations (1) and (2) [1, 39]:

$$L = \frac{c}{2f_r\sqrt{\epsilon_{reff}}} - 2\Delta L \quad (1)$$

$$W = \frac{c}{2f_r\sqrt{\frac{\epsilon_r+1}{2}}} \quad (2)$$

The effective length, L_{eff} , and the length extension, ΔL , are key design parameters. The term ΔL accounts for the difference between the actual physical length of the patch and its effective electrical length is illustrated in Equations (3) and (4),

$$\Delta L = 0.412h \frac{(\epsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\epsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)} \quad (3)$$

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} \left[1 + 12 \frac{h}{W}\right]^{-1}, \frac{W}{h} > 1 \quad (4)$$

The Equations (3) and (4) define the relationships among f_r , c , relative permittivity (ϵ_r), effective relative permittivity (ϵ_{reff}), substrate thickness (h), and patch width (W). Equations (5) and (6) are employed to determine the dimensions of the ground plane (length: L_g and width: W_g). Since the substrate typically shares the same dimensions as the ground plane, a separate calculation is deemed unnecessary.

$$L_g = 6H + L \quad (5)$$

$$W_g = 6H + W \quad (6)$$

The antenna configuration should be tuned to accomplish the ideal exhibitions. The standard detail of the antenna to have the return coefficient S11 less than -10dB, as the outcome 10% of the transmitted signal is reflected back. The antenna is viewed as useful as required. In the process of optimizing the design of an antenna, the "trial and error" process is a frequently utilized technique. Additionally, the commonality and instinct of the researcher in designing an antenna are important and efficient. Here, we have used a parametric optimization technique, which is essential for achieving optimal performance by systematically adjusting key design parameters. Since the length and width of the patch affect the resonant frequency, the parametric optimization ensures the antenna operates at the desired frequency. Instead of manually changing dimensions and running multiple simulations, the parametric optimization allows HFSS to automatically adjust variables within a defined range. This saves time and ensures a more efficient design cycle. Fig. 1 shows the optimized antenna's front view and back view with DGS.

This work investigates the application of a DGS for the miniaturization of MPA and examines the impact of DGS geometrical parameters on the antenna's resonant behaviour. The antenna model is developed and analyzed using ANSYS HFSS. An edge-feeding configuration is employed, where a 50Ω coaxial probe is connected to the radiating patch through a properly matched microstrip feed line to facilitate efficient power transmission. The proposed antenna is implemented on a Rogers RO3003 dielectric substrate characterized by a relative permittivity of 3, a thickness of 0.5 mm, and a loss tangent of 0.0013. The target operating frequency is 10GHz in the X-band region. The metallic ground plane is positioned on the underside of the substrate. Initially, a conventional microstrip patch antenna resonating at 10GHz is designed based on standard transmission-line

formulation. To achieve antenna size reduction through the incorporation of the proposed metamaterial-inspired DGS, a second reference antenna is designed for operation at 17GHz ($\lambda = 17.63$ mm). The DGS is then introduced into the ground plane of the higher-frequency antenna, resulting in a downward shift of the resonant frequency toward the desired 10GHz band. This approach enables significant miniaturization while preserving the required operating characteristics. Then, a modified wire-shape dumbbell DGS with a square split ring resonator meta-material structure is etched on the ground plane of the antenna as presented in Fig. 1 (b). The metamaterial-pattern-based DGS configuration demonstrated improved electromagnetic performance compared to a conventional patch antenna. The etched ground structure modified the effective inductance and capacitance of the antenna system, which contributed to enhanced resonance and compact antenna behaviour. In this work, a metamaterial-inspired geometry was incorporated into the DGS region. The metamaterial name assigned to the structure was based on the geometrical pattern of the resonator rather than the actual substrate material properties. In metamaterial antenna design, structures are commonly named according to their physical shape or resonator configuration, such as SRR, CSRR, circular ring, hexagonal ring, or fractal pattern structures. These artificial electromagnetic structures exhibit unique wave manipulation characteristics because of their geometry and periodic arrangement. In the proposed design, when the DGS patterns are carefully etched, the resulting structure mimics the structural equivalent pattern of metamaterials. For instance, the DGS can lead to band-stop characteristics, slow-wave effects, and negative effective permittivity/permeability at the 10GHz frequency range. The dimensions of the proposed antenna are shown in Table 1. Due to the effect of DGS, the small antenna is now resonating at 10GHz, along with balanced performance characteristics.

(a) (b)
Fig. 1 (a) 1 Front View (b) Back View of the proposed MMP-WDGS patch antenna.

Table 1 Parametric values of the proposed antenna

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
L	4.279	H	0.25
W	5.436	L_1	k
L_{f1}	2.473	W_1	k
W_{f1}	0.628	S	0.3
L_{f2}	2.584	D	0.75
W_{f2}	0.141	PP	0.5
Lamda (for 17GHz)	17.63	S_f	0.5

3 Results and Discussion

The S11 plots for the conventional 10GHz and 17GHz, along with miniaturized 10GHz MPA, are shown in Fig. 2. A more negative S11 gives a higher return loss (RL) (since $RL = -S11$), signifying less reflection and better impedance matching. From the graph, it is noted that the designed antenna has a return loss of -27.06dB. This indicates that 2.9% of the power is reflected, while 97.81% is successfully transmitted, which results in good impedance matching. The real and imaginary parts of impedance are shown in Fig. 3 for the miniaturized 10GHz antenna. This dB indicates how well the power is transmitted with a perfect impedance match. The designed antenna has a bandwidth of 33%. The radiation characteristics of the same miniaturized 10GHz MPA are depicted in Fig. 4 in polar representation. The same figure includes both Co and Cross polar radiation responses for both E- and H-planes. The proposed MPA has a gain of 2.85dB at 10GHz.

Fig. 2 Return Loss S11 vs. frequency plot for conventional (10GHz and 17GHZ) and miniaturized (10GHz) MPA.

Fig. 3 Real and Image part of impedance vs. frequency plot for miniaturized 10GHz MPA.

Fig. 4 Radiation patterns of the miniaturized 10GHz MPA.

Fig. 5 Sensitivity analysis of $L1$, $W1$, S , and D for the minimum of S11 value at resonant frequency.

Fig. 6 Sensitivity analysis of PP , SF , and k for the minimum of S11 value at resonant frequency.

Figures 5 and 6 illustrate the sensitivity behaviour of the proposed microstrip patch antenna with respect to the DGS parameters L_1 , W_1 , S , D , PP , SF , and k , which play critical roles in determining the resonance characteristics of the structure. The antenna is constructed to operate at 10GHz using a meta-material-inspired DGS technique to achieve miniaturization while maintaining acceptable impedance matching and radiation characteristics. A systematic parametric sweep of L_1 was performed within the range of approximately 0.8 mm to 4.5 mm, since the meta-material structure we designed comes beneath the patch within the respective range of L_1 . In this design methodology, L_1 represents the effective resonant length of the patch, and its variation directly influences both the resonant frequency and the return loss S11 performance.

To obtain a continuous analytical representation of the simulated data, a second-order polynomial curve fitting method was employed using the least-squares regression approach. The polynomial model was selected due to the smooth nonlinear dependency observed between the antenna length parameter and the resonant characteristics. The fitted curve approximates the relationship between L_1 and the minimum value of S11 at the resonant frequency as a quadratic function, capturing the gradual reduction in frequency with increasing length up to an optimum point, followed by a gradual increase beyond that region. Examining each parameter independently across a broad range of values would result in an extremely large number of computations and require substantial memory for the simulation. Therefore, to address this issue, a sensitivity analysis is performed in HFSS for each parameter. A sensitivity analysis was performed to quantify the influence of the antenna length parameter on the performance metrics of the antenna. From both Figures 5 and 6, it can be clearly seen that for all the selected values of all considered design parameters, the minimum values of S11 are well below -15dB goes below up to -35dB. This proves the authenticity of parameter range selection for antenna miniaturization. Then, to observe the effect of these design parameters on antenna miniaturization, the resonant frequencies are evaluated based on the same sensitivity analysis and curve fitting method.

Fig. 7 Sensitivity analysis of L_1 , W_1 , S , and D for resonant frequency.

Fig. 8 Sensitivity analysis of PP , SF , and k for resonant frequency.

The Fig. 7 and 8 illustrate the curve-fitting-based parametric analysis of several key geometrical parameters of the proposed antenna structure and their influence on the resonant behaviour. The plot compares the fitted responses of the critical design parameters L_1 , W_1 , S , D , PP , SF , and k with respect to the resulting resonant frequency. Each parameter is represented by a distinct marker and curve style, as shown in the legends of both figures. These curves are generated using polynomial curve fitting based on the discrete simulation data obtained from the parametric sweep of each geometrical parameter. The figure demonstrates how the resonant frequency varies as each structural parameter is modified. The polynomial regression technique was applied to approximate the nonlinear relationship between the antenna dimensions and the resonant frequency. The least-squares fitting method was used to obtain smooth curves that represent the overall trend of the simulated data. This approach helps to identify the optimal design points while minimizing the number of required electromagnetic simulations. From the plot, it can be observed that the parameter L_1 exhibits a strong nonlinear behaviour. As L_1 increases, the resonant frequency initially decreases and reaches a minimum around $L_1=2.5\text{mm}$, corresponding to a resonance frequency of approximately 7GHz. Beyond this point, the frequency increases rapidly, indicating that L_1 has a high sensitivity to dimensional changes. In contrast, the parameters L_1 and k exhibit relatively lowest resonating frequencies. The curve representing L_1 shows minor fluctuations around the resonance region, indicating that the antenna length parameter maintains relatively consistent performance across the analyzed range. Similarly, the curve corresponding to the parameter k remains, suggesting that variations in this spacing parameter have maximum influence on the resonant frequency within the investigated range. This analysis helps the researcher to give a clear insight into the selection of design parameters and their values based on the requirements of the application.

In this section, we discussed the experimental work in more detail. The points discussed here are the comparison of performance between the conventional antenna and the designed antenna with a defective ground structure. For the primary point, the worries will be what the impacts on the antenna execution are assuming the area of the transmitting plane has been manipulated and how much size decrease is accomplished on each layer

level of the designed antenna, for example, the radiating patch level, substrate level, and ground level. The actual structural compactness in a microstrip patch antenna using Defected Ground Structure refers to minimizing the physical dimensions of the antenna, like enhancing its electrical performance, such as resonance at a desired frequency, bandwidth, and impedance matching. The presence of slots increases the apparent length due to fringing fields, which is the effective electrical length of the antenna. By introducing the defected ground structure (DGS), the current path is altered because of the increase in inductance and capacitance, affecting the fringing field. Our designed meta-material slot or etching in the ground plane increases the inductance and capacitance, which further increases the effective electrical length. That means the same resonant frequency can be achieved with a small physical patch. The physical antenna dimension is the actual measured size of the antenna, whereas the effective electrical length is the virtual size the antenna behaves as due to fringing fields and substrate effects. By optimizing fringing fields using Meta-material DGS, the size of the antenna is reduced. The miniaturized MPA has a reduction in size of around 72.95% in overall antenna surface area and a 72.40% reduction in radiating patch area. The performance and size of the proposed antenna (with DGS and without DGS) are compared with other literature (Table 2).

Table 2 Performance Comparison among the proposed design and other similar designs from the literature

Reference	Antenna dimension (mm)	Patch dimension (mm)	f_r (GHz)	S11 (dBi)	Gain (dB)	Bandwidth (GHz)
Karahan et al. [34]	(16x16)	(7.5x9.9)	10	-23.34	6.8	0.283
Demirkoparan et al. [35]	(17x15)	(15.3x13.3)	11.1	-27.1	4.1	4.8
Kolusu et al. [36]	(23.9x28)	Irregular open loop shape	11.2	-24.47	2.6	11.4
Gloria et al. [37]	(40x15)	Radius=6mm (113.1)	9.1	-21	6	0.3
Huang et al. [38]	(136x136)	(45x45)	10	-25	5.8	2.5
Proposed Antenna (Without DGS)	(16.28x20.76)	(8.2x10.28)	10	-24	4.28	0.16
Proposed Antenna (With DGS)	(8.436x10.836)	(4.279x5.436)	10	-33	2.84	0.05

4 Performance evaluation of MPA

Nowadays, wireless telecommunication still struggles to ensure smoother communication in urban connectivity gap areas. This connectivity gap arises due to high-rise buildings, which block the 5G or mm-wave signals. Another reason for the connectivity issue is the signal shadow zones in the communication network. A satellite network configured for data from space helps to achieve uninterrupted communications in such cases for dense urban areas. The solution is to use 5G as the primary network and to use LEO satellite communication as a backup and for load balancing of the network. This will help to establish reliable connectivity across the network without any tower congestion or signal overlaps.

Fig. 9 Radiation pattern (3D) matching between HFSS and MATLAB for the proposed design (a) HFSS (b) front view-MATLAB (c) side view-MATLAB.

Fig. 10 Complete flow of work for real-time test of Proposed MAP and its array in MATLAB simulation environment.

To evaluate the proposed MPA for such a condition, a simulation environment is created in MATLAB with the LEO satellite, with Iridium NEXT constellations and ground stations (GSs) placed in twelve important locations of an urban city in Bhubaneswar, Odisha. After the design and optimization of the MPA, the S11 range and the 3D radiation pattern values for different azimuth and elevation angles are imported to MATLAB. Using these reflections and radiation characteristics, the MPA design is replicated again in MATLAB using a custom antenna algorithm. Then, to validate this replica, the radiation pattern of both the platforms matched carefully with the main lobe, side lobes, and back lobes in Fig. 9. Now, after the exact matching from the figure, this design in MATLAB

can be considered as the same MPA design at 10GHz from HFSS, and its performance can now be evaluated in the real-time simulation environment. The complete flow of work involved in this study is depicted in Fig. 10.

At first, a satellite system model is constructed in MATLAB with 66 LEO satellites and 12 GSs using Satellite Communication Toolbox. All the 66 LEO satellites are placed on 6 orbital planes with 11 satellites in each, with an approximate inclination of 86 degrees between planes, as shown in Fig. 11. However, many satellites exist at the backside of the Earth, which is not visible in Fig. 11. Then, the GSs are created using Lat/Long (Location) coordinates on the earth's surface using the Google Earth tool. The main aim here is to test for uninterrupted data transmission between GS and Satellites. All 12 GS with their locations are shown in Fig. 12. To make the simulation environment more realistic and practical, the elevations of these 12 GS are taken differently based on different building heights. The elevation values are calculated in meters, where the ground floor is considered as 4 meters, and the next floor onwards are considered as 3 meters each. Some GS are also taken at ground level with elevation as zero. This makes the perfect criteria for this study.

Fig. 11 Sixty-six LEO Satellites with Iridium NEXT **Fig. 12** Twelve GSs are placed in different important constellations orbiting around the Earth. areas of an urban city.

Fig. 13 Antenna array design in MPA (a) 8x8 rectangular array pattern (b) Side lobe suppression (c) Back lobe suppression.

For satellite communication, generally antenna array is required to point highly directive radiation beams towards the GS to overcome any kind of attenuation. In such cases, the single proposed MPA may not be suitable to be used as a transmitter (Tx) antenna at satellites. Hence, an 8x8 uniform rectangular array (URA) is designed in MATLAB considering the proposed MPA as the array element. The radiation pattern of the URA is shown in Fig. 13 (a). Now, Chebyshev window is used to taper all the side lobe levels in the radiation pattern as depicted in Fig. 13 (b). As the radiation pattern is a broadside pattern, the array is now modified to orient its radiation pattern towards a single direction in Fig. 13 (c). Now the array design is mounted at the transmitter to all LEO Satellites. Similarly, to validate receiver (Rx) signal strengths at the GS locations, the proposed single MPA is added at all twelve GSs. Fig. 14 depicts the satellite transmitter radiation patterns after adding a designed array to LEO Satellites. Similarly, the GS radiation patterns can be realized from Fig. 15. The whole simulation environment scenario is created in MATLAB at a frequency of 10GHz.

The main objective of this section is to evaluate the satellite communication scenario for the urban area network. Thus, all the specifications like transmitter power, Noise figure, different losses, half-power beam width, centre beam elevation angle, satellite altitude, Gain, etc., are added as per the real-time satellite scenario in MATLAB. To evaluate the performance of the proposed antenna and its array for satellite communication, the signal strength at each of 12 GSs is measured. To make the simulation environment more practical, certain attenuation factors like rain, cloud, and foliage are also added, and their loss are also considered. Standard engineering approximations are considered as propagation models for these attenuation factors. ITU-R P.838 is taken for the rain propagation model. Similarly, ITU-R P.840 is considered for the cloud propagation model, and foliage is taken as an empirical log model. The received signal strength values of 12 GS are given in Table 3. From the table, the analysis revealed that for all receivers (GS-1 to GS-12), the signal strength values were around -80 to -85dB_w without considering any losses. These values are almost the same for all the GSs as the LEO satellite is directly above the location and all the 12 GS are placed very close to the beam centre at a particular point of time. After adding all losses due to rain, cloud, and foliage, these signal strengths are now in the range between -85 and -90dB_w. Even with all kinds of environmental losses, this range of signal strength at all GS can be considered ideal conditions for quality satellite connectivity. Fig. 16 depicts the received power comparison and individual loss components for all 12 GSs. From this figure, it can be observed that the loss due to foliage varies around 3dB and is maximum among others. Attenuation loss due to rain is around 2dB for 12 GSs. Similarly, the loss for cloud is observed near 0.1dB, which lowest among all. It can also be observed from the same figure that the loss for cloud remains almost the same for all 12 GSs due to very little sensitivity at the elevation levels. These good signal strength levels prove the feasibility of the proposed MPA and its array for satellite communication. The details of the various received power and losses are summarized (Table 3).

Table 3 Received signal strength (RSS) at all twelve GSs without and with losses.

GS Locations	Received Power (without Loss) (dBw)	Losses (dB)			Total Loss (dB)	Final Received Power (dBw)
		Rain	Cloud	Foliage		
1	-83.01	1.39	0.04	2.86	4.29	-87.30

2	-83.01	1.95	0.04	3.06	5.04	-88.06
3	-83.01	1.87	0.04	2.18	4.09	-87.10
4	-83.01	2.13	0.04	1.65	3.82	-86.84
5	-83.01	1.84	0.04	2.92	4.8	-87.81
6	-83.01	1.91	0.04	2.83	4.78	-87.79
7	-83.01	2.07	0.04	2.38	4.49	-87.50
8	-83.01	1.61	0.04	2.53	4.17	-87.18
9	-83.01	1.46	0.04	2.45	3.95	-86.97
10	-83.01	1.99	0.04	2.64	4.67	-87.68
11	-83.01	2.22	0.04	3.04	5.3	-88.31
12	-83.01	2.1	0.04	2.37	4.51	-87.52

Fig. 14 Radiation patterns (3D) of Tx after adding the proposed MPA array to LEO Satellites.

Fig. 15 Radiation patterns (3D) of Rx after adding the proposed MPA single antenna to GSs on earth.

Fig. 16 Received power and individual loss of twelve GSs due to rain, cloud, and foliage attenuations.

5 Conclusion and future work

This study presents the design of a compact microstrip patch antenna using a dumbbell-shaped defected ground structure with meta-material characteristics for operation at 10GHz in the X-band. By introducing the DGS beneath the patch, the current path is altered, which effectively lengthens the electrical length of the antenna and enables size reduction without shifting the operating frequency. The modified antenna shows improved impedance matching, with a return loss close to -33dB , along with reasonable bandwidth and stable radiation performance. When compared to a conventional design, the proposed structure achieves a smaller size while maintaining similar operational characteristics, highlighting the usefulness of the DGS technique for antenna miniaturization. The use of a parametric study, along with curve fitting and sensitivity analysis, helps in understanding how different design parameters influence the resonant behaviour. This also minimizes the number of repeated simulations required during the design process, making it more efficient. Overall, the proposed antenna design can be considered suitable for compact high-frequency applications such as satellite communication, radar, and modern wireless systems. Further work may focus on improving gain and bandwidth by exploring different substrate materials or alternative DGS configurations.

List of Abbreviations:

MMP-WDGS: metamaterial-patterned wired defected ground structure

MPA: Microstrip patch antennas

EBG: Electronic band gap

DGS: Defected ground structure

LPF: Low-pass filter

Q-factor: Quality factor

SSRR: Slot split-ring resonator

CSRR: Complementary split-ring resonator

MIMO: Multiple input, multiple output

HFSS: High frequency structure simulator

RL: Return loss

GS: ground station

LEO: Lower earth orbit

URA: Uniform rectangular array

ITU-R: International telecommunication union radiocommunication sector

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Shibanee Dash contributed to the conceptualization, methodology, antenna design, equivalent circuit modeling, simulation, and preparation of the original manuscript draft.

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