Wideband Minkowski fractal antenna using complementary split ring resonator in modified ground plane for 5G wireless communications

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Abstract
In this paper, the enhancement of gain and bandwidth of a Minkowski fractal antenna (MFA) with defected ground structure is investigated. The antenna characteristics are studied for first and second iterations by considering complementary split ring resonators in the L-shaped modified ground plane. The dimensions of the MFA are optimized with computer simulation technology software and the fabricated antenna characteristics are measured using Vector Network Analyzer and Wave and Antenna Training System. From the simulation, the maximum gain of our proposed antenna has been found 5.2 dB. Both bandwidths obtained from simulation and measurement exceed 2 GHz. The results of simulation are in good agreement with measured ones. This proposed antenna is suitable for the applications of various 5G wireless communications.

KEYWORDS
5G, CSRR, DGS, fractal antenna, wideband

1 | INTRODUCTION
The demands of compact size, low cost, and high-performance antennas are increasing day-by-day for both civilian and military applications. For telecast real-time events, video conferences, AI-based vehicles, and air-traffic control, 5G technology is needed to transfer high-speed data up to 20 Gbps. To get a wideband, compact size and multi-channel antenna for 5G applications with good efficiency, it is needed to modify the structure of the microstrip patch antenna. Various types of modifications such as slot-loaded and metamaterial-loaded patch, linear and nonlinear fractals, meandering line, fork-shaped patch, differential feeding technique, and so forth, are used in recent research works. The use of fractal geometries in these antennas has shown to be a good strategy in order to obtain log periodical multiband behavior. This is mainly due to the self-similarity property of fractals. There are many fractal curves such as Koch curve, Cantor curve, Minkowski curve, Sierpinski gasket and each of them has space-filling property. For the first iteration, both Koch Curve and Minkowski loop fractal antennas can provide gain and bandwidth of about 3.2 dB and 200 MHz, respectively. Lots of research works have been carried out for the enhancement of gain and BW. By adding metamaterial, these
parameters can be improved further. Yi Hong Xie in Reference 15 has proposed an antenna with a metamaterial unit cell (CSRR) in the ground plane for dual band operation, but both the bandwidths are very narrow. Hui Zhang mentioned two types of CSRRs where one is perpendicular and the other is parallel. Perpendicular CSRR is useful for generating wide bandwidth whereas the parallel type CSRR is useful for generating dual bands.

In this research work, the Minkowski fractal antenna (MFA) behavior is investigated with the aim to improve the gain, bandwidth, and return loss characteristics. First, the initiator is transformed into a fractal antenna by the first and second iterations with a full ground plane. Then to increase the bandwidth the ground plane has been modified with an L-shaped structure. With the proposed defected ground structure (DGS), bandwidth has been increased from the MHz order to GHz. And to enhance the gain, complementary split ring resonators (CSRRs) are incorporated in the ground plane. Antenna characteristics have been studied for two types of ring resonators. Our proposed antenna will operate in the frequency range of 1.9–4.9 GHz which exists in the Unlicensed National Information Infrastructure (U-NII) band within Lower-5G. Considering the FR-4 substrate, the geometry of the proposed antenna is designed with Computer Simulation Technology (CST) software. The first iteration MFA is fabricated in our lab for measurement of return loss and radiation pattern. Antenna parameters are measured using Vector Network Analyzer (VNA) and Wave & Antenna Training System (WATS). It is found that better MFA characteristics are obtained by adding a ring resonator in the DGS compared to the conventional one with a full ground plane.

The paper is organized as follows. The design and optimization of the proposed MFA are presented in Section 2. Simulation and measured results are discussed in Sections 3 and 4, respectively. Finally, a concluding remark is provided in Section 5.

2 | Design and Optimization of MFA

 Basically, there are two classes of fractals such as deterministic and random fractals. The deterministic fractals are again characterized as Linear and Non-Linear geometry. Linear geometry is derived by using the Iterative Function System. Under Linear geometry, there are many fractal curves such as Koch curve, Cantor curve, Minkowski curve, Sierpinski gasket, and many more. The dimensions of the initiator are designed for 3.5 GHz. Two fractal iteration stages have been considered. The obtained $-10$ dB bandwidth range is found approximately from 2 to 5 GHz for both iterations. The antenna BW and gain specifications are expected to satisfy various applications in different countries.

2.1 | Design of fractal patch

The antenna is designed using FR-4 substrate ($\varepsilon_r = 4.3$) with a thickness $h_s$ of 1.6 mm. For the design of a square fractal patch, the most important parameter is the side-length, $L$ of the initiator and is expressed as

$$L = 2L_{i1} + W_{i1}$$  \hspace{1cm} (1)

where subscript $i$ represents the iteration number. The side-length, $L$ and the resonant frequency, $f_r$ of the initiator are related as

$$f_r = \frac{1}{4} \left( \frac{C_0}{2L} \right)$$  \hspace{1cm} (2)

where $C_0$ is the speed of light ($3 \times 10^8$ m/s). The square substrate length, $L_s$ is taken as

$$L_s = 2L = \frac{C_0}{2f_r}$$  \hspace{1cm} (3)

For $f_r = 3.5$ GHz, $L = 21.42$ mm, and $L_s$ is 42.85 mm. After optimization using CST the side-length of the initiator is found, $L = 20$ mm. Thus the optimized dimension of the substrate is 40 mm and the final substrate size becomes $40 \times 40$ mm.$^{2,21}$

Generally, a fractal antenna is made from a square patch initiator by using one or more iterations as shown in Figure 1. Using the optimized value of $L$, all parameters of the first and second iterations are calculated from Equation (1). The optimized parameters regarding the MFA initiator have been given in Table 1.
TABLE 1 Optimized parameter of Minkowski fractal initiator

| Parameter | Side length of patch | Gap of the inset feed | Feedline width | Feedline length |
|-----------|----------------------|-----------------------|----------------|-----------------|
| Symbol    | \( L \)              | \( g \)               | \( W_f \)      | \( F_i \)       |
| Unit (mm) | 20                    | 0.8                   | 2.0            | 12              |

2.2 | Design of DGS

In this paper, the MFA with full ground plane is referred to as a conventional one. To increase the BW, the full ground plane is modified. Making the ground plane in different geometrical shapes such as M-type, H-type, T-type and L-type, BW increment has been observed. Comparing the results, L-shaped DGS has shown the highest increment of the BW. The L-shape is again modified by varying the length keeping width the same to obtain better impedance matching characteristics. Moreover, different shaped slots (rectangle, square, triangle) have been incorporated in various positions and the best performance has been found when V-notch (isosceles-triangle) is placed in the middle of the L-shaped ground plane as shown in Figure 2.

The width of the L-shaped DGS is taken one-fourth of the substrate (which is \( W = 40 \) mm). The V-angle of the V-notch is taken \( \alpha = 90^\circ \) and each of the sides of V-notch becomes 4 mm, that is, one-tenth of the substrate width. Thus, the V-opening \( L_v = 5.6 \) mm which is about one-seventh of the substrate width.

2.3 | Design of CSRR

To study the effect of metamaterial on the antenna characteristics, two types of CSRR are introduced at the ground plane. By replacing space with copper and copper with space of SRR, CSRR of the same dimension of SRR is made.\(^{22}\) According to the duality theorem, the frequency response of the SRR, which has negative permeability, is similar to the response of its complementary unit cell with negative permittivity. To keep the resonance at the same frequency, the metamaterial unit cell is designed at 3.5 GHz.
For both CS-SRR (Complementary Square Split Ring Resonator) and CC-SRR (Complementary Circular Split Ring Resonator) the resonant frequencies are $f^r_s$ and $f^r_c$, respectively and are expressed as

\[
f^r_s = \frac{1}{2\pi \sqrt{L_T \left[ \left( 2x_{avg} - \frac{d_s}{2} \right) C_{pul} + \frac{\varepsilon_0 s h_s}{2d_s} \right]}}
\]

\[
f^r_c = \frac{1}{2\pi \sqrt{L_T \left[ \left( \frac{\pi r_i - d_c}{2} \right) C_{pul} + \frac{\varepsilon_0 S h_c}{2d_c} \right]}}
\]

where $L_T$ is the total inductance of the SRR, $C_{pul}$ is the capacitance per unit length and $x_{avg}$ (CS-SRR) is the distance from the center point to the middle portion of the outer ring. $C_{pul}$ is calculated as

\[
C_{pul} = \frac{\sqrt{\varepsilon_{eff}}}{C_0 Z_0}
\]

where $\varepsilon_{eff}$ is the effective permittivity of the medium and $Z_0$ is the impedance of the medium. $L_T$ is expressed as

\[
L_T = 0.0002l \left( 2.303 \log_{10} \frac{4l}{t_c} - \gamma \right)
\]

where $l$ and $t_c$ is the length and the width of the outer circular ring, and the constant $\gamma$ is 2.451. The parameter $l$ is also expressed as

\[
l = \begin{cases} 
2\pi (r_0 - t_c) - d_c & \text{for Circular ring} \\
4 \times 2 \times x_{avg} - d_i & \text{for Square ring}
\end{cases}
\]

The structures of the CS-SRR and CC-SRR are shown in Figure 3. The outer and inner sides of the complementary square split ring resonator (CS-SRR) are found $8 \times 8$ and $6 \times 6$ mm$^2$, respectively. For the complementary circular split ring resonator (CC-SRR), the outer-radius and the inner-radius are found $4$ mm and $2$ mm, respectively. All the parameters of both CS-SRR and CC-SRR such as $t_s$, $t_c$, $S_s$ and $S_c$ are found $1$ mm except $d_s = 0.4$ mm and $d_c = 0.5$ mm.

The two CSRR unit cell structures are simulated in CST MWS. For satisfying the Double Negative property, the value of permittivity should be negative in the desired frequency range. In this work, Nicolson–Ross–Weir (NRW) technique has been used to obtain the values of permittivity of square and circular SRR. This is a very popular technique to convert S-parameters and it provides easy as well as effective formulation and calculation. Therefore, the simulated S-parameter values from CST are exported to Matlab environment. Then NRW method is used to extract the permittivity of the CSRR unit cell. The permittivity vs frequency graph for both CS-SRR and CC-SRR are shown in Figure 4. It is seen that both real and imaginary components of permittivity are negative in the frequency range from 3.6 to 4.6 GHz for CS-SRR and from 3.1 to 4.8 GHz for CC-SRR, respectively.

To study the behavior of the antenna characteristics, the number of CSRR in the L-shaped DGS has been varied from 1 to 8. However, satisfactory results have been found by placing a single CSRR. The positions of the single CS-SRR and
CC-SRR are considered for different places. In Figure 2 these positions are shown by dotted square and circular box. For CS-SRR and CC-SRR, the best results are found by placing them in the position shown in Figure 2 by solid square and circle, respectively.

2.4 Design of inset feed port

Using the values of port extension coefficient, substrate height, dielectric constant and width of the transmission line (see Table 1), 50 Ω impedance matching has been achieved. For the simulation of both first and second iteration, 50 Ω impedance matching is considered. In Figure 5, inset feed port structure of the first iteration MFA is shown. SMA connector will be fixed with this inset feed port after fabrication.

3 RESULTS AND DISCUSSION

MFA is simulated for first and second iteration with various ground structures. In Figure 4, simulated first iteration MFA structure has already been shown and second iteration MFA structure will also be similar. first as well as second iteration MFA characteristics have been studied by incorporating seven types of ground structures. These ground structures are: conventional full GP, L-shaped GP, V-notch in L-shaped GP, L-shaped GP with V-notch plus CSRR and CSRR in full L-shaped GP with V-notch. This CSRR is of two types (square and circular) and has been considered in the DGS only.

From the simulation results of first iteration with a full ground plane (GP), the return loss magnitudes are found −8.42 dB and −5.02 dB at 3.52 GHz and 4.59 GHz, respectively. Similarly, the return loss magnitudes of the second iteration with full GP are obtained −6.083 dB and −3.208 dB at 3.64 GHz and 4.77 GHz. Since the above-mentioned magnitudes of $S_{11}$ are always above −10 dB, the ground plane has been modified.

After modifying the ground structure with L-shape, bandwidth and gain have increased and to observe the improvement further, V-notch is added in the DGS. The simulated parameters for L-shaped GP with V-notch provide much...
improved results than L-shaped GP without the notch. Without the V-notch in L-shaped GP, the bandwidth was 1.97 GHz and 2.1 GHz for the first and second iteration, respectively.

For L-shaped GP with V-notch, the return loss magnitude has increased remarkably for the first iteration. Almost 3 GHz bandwidth is observed, having operating frequency range from 1.9 to 4.9 GHz for both first and second iteration MFA. All characteristics of third modification is presented in the first row of the Table 2. It should be noted here that no BW is found for zero iteration. The results of the fourth modification with square and circular SRR are shown in the second and third rows of Table 2. Using CS-SRR and CC-SRR 3.01 GHz and 3.03 GHz bandwidth is found for first iteration and 2.88 GHz and 2.87 GHz bandwidth is found for second iteration, respectively (see Figure 6).

The increment of the gain is the main focus of our interest. Without modification, the gain is found less than 2 dB. With modification, increased gain has been noticed for both first and second iteration. Using CS-SRR and CC-SRR, almost 5.2 dB is found at 4.73 GHz for the first iteration and 4.6 dB is found at 4.5 GHz for the second iteration. The range of the gain is shown in Table 2.

In Figure 7, the gain characteristics graph for different frequencies has been shown (solid line indicates the first iteration and broken line indicates the second iteration results). It is observed that incorporating CS-SRR and CC-SRR in the DGS for both first and second iteration the highest gain is noticed approximately at 4.7 GHz and the value of about 5.21 dB is found for the first iteration by incorporating CS-SRR.

| Ground plane                      | Fractal patch (Iteration No.) | Frequency range (GHz) | Bandwidth (GHz) | Min-max gain (dB) |
|-----------------------------------|--------------------------------|-----------------------|-----------------|-------------------|
| V-notch in L-shape DGS            | First                          | 1.94–4.93            | 2.99            | 1.84–5.24         |
|                                   | Second                         | 2.00–4.86            | 2.86            | 0.99–4.69         |
| L-shaped with V-notch & CS-SRR    | First                          | 1.93–4.94            | 3.01            | 1.87–5.214        |
|                                   | Second                         | 1.97–4.87            | 2.88            | 1.093–4.6        |
| L-shaped with V-notch & CC-SRR    | First                          | 1.92–4.95            | 3.03            | 1.9–4.75         |
|                                   | Second                         | 1.99–4.87            | 2.88            | 0.969–4.48       |

**TABLE 2** Simulated results of our proposed MFA with DGS

**FIGURE 6** Return loss characteristics of different ground structure for (A) first and (B) second iteration

**FIGURE 7** Gain over frequency of V-notch in L-shaped DGS for first and second iteration with (A) CS-SRR and (B) CC-SRR
Radiation efficiency for both first and second iterations is observed within the frequency range from 1 to 6 GHz (see Figure 8). The solid line indicates the first iteration and the broken line shows the second iteration. It is noticeable that for both CS-SRR and CC-SRR the radiation efficiency is above 80% in our desired frequency range.

The radiation patterns for two principal planes (E-plane and H-plane) are shown in Figure 9. Simulated radiation patterns have been observed for four resonant frequencies such as 2.2, 2.9, 3.67, and 4.75 GHz in the range from 1.9 to 4.9 GHz. It is found that the radiation patterns for Cross-polarizations of E-plane is always omnidirectional and it is dominant at Y-Z direction. Radiation pattern is also existing in X-Y directions. And the H-plane radiation pattern has changed from omnidirectional to hemispherical. This means that the proposed antenna is circularly polarized. This phenomenon has a number of benefits for areas such as satellite applications and it helps overcome the effects of propagation anomalies, ground reflections and the effects of the spin that occur on many satellites.

For four different ground structures, MFA bandwidths of first and second iterations are shown in Figure 10. Greater MFA bandwidths have been observed for the first iteration except the first one in the bar graph. For the second iteration of MFA, bandwidths are also very close to the first iteration. However, the gains found for the first iteration are far better than that for the second iteration as explained above. So, the first iteration MFA has been chosen for prototype.

Figure 11 shows the surface current distribution on the Minkowski fractal patch for both CS-SRR and CC-SRR at 4.73 GHz. The direction of the field line is uniform in four sectors of the patch. With the increase of field lines in the patch, more gain can be achieved. The field lines in the DGS are denser around the ring resonators. This denser field lines help to steer the beam forming effectively.

The antenna characteristics have also been studied for the array of CS-SRR and CC-SRR in the L-shaped DGS. It is found that bandwidth and gain have not improved significantly. However, best results (as shown in Table 2) are found for a single unit cell of CSRR on the selective place (see Figure 2) of the proposed DGS. For this reason, first iteration MFA with a CSRR is considered for fabrication.

4 MEASURED RESULTS

After studying the simulation results of various MFAs, the best two types of antennas which have better gain and bandwidth are fabricated for measurement. Both antennas are fabricated for first iteration Minkowski fractal structure. In one MFA, L-shaped DGS consists of a square-CSRR in the position as shown in Figure 2(A) and in another MFA circular-CSRR is made in the L-shaped DGS as shown in Figure 2(B). The antennas are fabricated on FR-4 substrates in our laboratory using a photolithographic method. After etching and cleaning, SMA port is connected with the microstrip feed line. In Figure 12 the photographs of MFA are shown. The return loss ($S_{11}$) and the radiation pattern of the fabricated antennas are measured using VNA (Rohde & Schwarz—ZVH8) and WATS (Man & Tel Co.), respectively. The photographs of the experimental setup for measurement of $S_{11}$ and radiation pattern are shown in Figure 13.

The results of measured $S_{11}$ are shown in Figure 14.

It is clearly noticeable that both fabricated antennas will operate from 2.7 GHz to 4.8 GHz with a bandwidth of almost 2.1 GHz. The operating frequency range and bandwidth are found very close to the simulation results which are 1.8 to 4.8 GHz and 3 GHz, respectively. Fabricated antennas show great value of return loss magnitude up to $-37$ dB at the frequency of 4.1 GHz for CS-SRR and $-39$ dB at 4.3 GHz for CC-SRR whereas both $S_{11}$ are found $-50$ dB below in simulation.

The radiation patterns of the fabricated MFAs are shown in Figure 15. Measured pattern of CS-SRR is found very similar to the figure 11. (See attachment) simulation one, but for CC-SRR the radiation pattern is like digit eight which
FIGURE 9 Radiation pattern of V notch in L-shaped DGS with CS-SRR (left) and CC-SRR (right) for first iteration (A), (B) at 2.2 GHz; (C), (D) at 2.9 GHz; (E), (F) at 3.67 GHz; and (G), (H) at 4.75 GHz, respectively.
**Figure 10** Bandwidths for different ground structures for first and second iterations

![Graph showing bandwidths for different ground structures for first and second iterations.](image)

**Figure 11** Surface current distribution at 4.73 GHz for DGS with (A) CS-SRR and (B) CC-SRR

![Surface current distribution at 4.73 GHz for DGS with (A) CS-SRR and (B) CC-SRR.](image)

**Figure 12** Photograph of the fractal (left side) and the modified Ground Plane (right side) of the fabricated (A) CS-SRR and (B) CC-SRR antennas

![Photograph of the fractal (left side) and the modified Ground Plane (right side) of the fabricated (A) CS-SRR and (B) CC-SRR antennas.](image)

**Figure 13** Experimental setup for measurement of (A) $S_{11}$ and (B) radiation pattern

![Experimental setup for measurement of (A) $S_{11}$ and (B) radiation pattern.](image)
FIGURE 14  Measured S-parameters of fabricated first iteration MFA for (A) CS-SRR and (B) CC-SRR

FIGURE 15  Measured radiation pattern of fabricated antennas (A) CS-SRR and (B) CC-SRR

TABLE 3  Comparison of simulated and measured results of the first iteration MFA with DGS

| CSRR in the Ground plane | MFA with first iteration | Frequency range (GHz) | Bandwidth (GHz) | Return loss (dB) |
|--------------------------|--------------------------|-----------------------|-----------------|-----------------|
| CS-SRR in the DGS        | Simulation               | 1.93–4.94             | 3.01            | −66.15          |
|                          | Measurement              | 2.66–4.9              | 2.24            | −37.01          |
| CC-SRR in the DGS        | Simulation               | 1.92–4.95             | 3.03            | −49.36          |
|                          | Measurement              | 2.56–4.92             | 2.44            | −39.36          |

is similar to an omnidirectional pattern. The radiation pattern for CS-SRR at 0° is found slightly less than the simulated one which should be maximum (see Figure 14(A)). CC-SRR are shifted 45° than that of the simulated ones where CS-SRR shows no shift.

The measured patterns may be called bidirectional which can be used in V2V communication, GPS and WLAN. The results of simulated and fabricated antenna characteristics are given in Table 3 for comparison.

Operating frequency range of the fabricated antenna is shifted towards higher frequency compared to the simulated antenna frequency range. In fabricated antennas return loss value decreased 34%. Bandwidth of fabricated antenna is decreased about 30% from the simulated antenna. As we used liquid etching process for the fabrication of our proposed antenna, slight deviations have been found compared to the simulated results. Though the highest possible precaution is taken during measurement, the absence of the anechoic chamber has made some alteration in the measured results.

The performance of our antenna is compared with the earlier research works in the Table 4. It is found that our antenna has higher gain with large bandwidth and compact size.
TABLE 4 Comparison table of our proposed antenna with other reported fractal antennas

| Reference | Dimension (L × W × t) (mm³) | Fractal type          | Total bandwidth (GHz) | Max gain (dB) |
|-----------|------------------------------|-----------------------|-----------------------|---------------|
| 2         | 58 × 40 × 1.6                | Wheel shape fractal    | 2.94                  | 5.2           |
| 4         | 48 × 36 × 1.58               | Hybrid fractal         | 2.83                  | 9.0           |
| 8         | 265 × 270 × 1.6              | Koch fractal           | 0.6                   | 5.0           |
| 11        | 94 × 94 × 1.6                | Koch fractal           | 1.4226                | 5.52          |
| 24        | 40 × 40 × 1.6                | Minkowski fractal      | 1.6625                | 3.84          |
| 25        | 112 × 100 × 1.6              | Star shape fractal     | 0.124                 | 1.058         |
| Proposed (CS-SRR) | 40 × 40 × 1.6            | Minkowski Fractal      | 3.01                  | 5.21          |

5 | CONCLUSION

For 5G wireless communication systems, fractal antennas become more popular due to their frequency independent characteristics and wide BW. In this research work, a compact wideband MFA has been proposed for 5G applications. By considering ring resonators in the L-shaped modified ground plane, the antenna characteristics are studied for first and second iterations. All the MFAs have been optimized by CST simulation software and first iteration with CSRR antennas are fabricated in our lab for measurement on FR-4 substrate. Due to the proposed DGS with CSRR, the bandwidths have been increased from MHz order (200 MHz for conventional) to GHz order (more than 2.2 GHz for our antenna). The simulated gain of our proposed antenna varies from 1.8 dB to 5.2 dB within the operating frequency band. The bandwidths of our fabricated MFAs (first iteration) are found 78% of the simulated ones which are obtained 3 GHz. The radiation patterns of the simulated and measured MFAs are obtained bidirectional. The MFA characteristics have been improved by using CSRR in the DGS. It is found that the antenna characteristics for both CS-SRR and CC-SRR are almost the same. The operating frequency range of our proposed antenna is 1.9 to 4.9 GHz. As the proposed antenna is small in size, less weight, and easy to fabricate for its simple design, it can be used for various wireless applications like Wi-Fi, Wi-MAX, and WLAN in the cellular devices.

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AUTHOR CONTRIBUTIONS
Md. Ashfaq Ohi: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; writing-original draft; writing-review and editing. Zahid Hasan: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; writing-original draft; writing-review and editing. Shadman Fuad Bin Faruque: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; writing-original draft; writing-review and editing. Abdul Kawsar: Formal analysis; investigation; methodology; resources; software. Anis Ahmed: Formal analysis; investigation; project administration; supervision; validation; visualization; writing-original draft; writing-review and editing.
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