Computational analysis of a dual-port semi-circular patch antenna combined with Koch curve fractals for ultra-wideband systems

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Abstract
This paper presents a two-port microstrip-fed semi-circular patch antenna integrated with Koch curve fractals and common ground with defected ground structure for the effective implementation in handheld ultra-wideband (UWB) systems. The proposed array is engraved on a 1.57 mm thick FR-4 substrate with an overall array size of $30.5 \times 47 \times 1.64$ mm$^3$. The parametric analysis of the proposed array indicates that the two optimized Koch curve fractal (second iteration order) radiators (upper substrate layer) provides an optimum matching performance in a wide operational band (4.395–10.184 GHz, 79.4%) and minimizes the patch area by 41.2% as compared to the conventional circular patch. To realize good port-to-port isolation ($S_{21}/S_{12} \leq -16.8$ dB), the reduced ground is slotted and incorporated with a funnel-shaped decoupling structure at the center. The prototype of the proposed array is fabricated and experimentally tested to justify the simulated S-parameter results. All diversity metrics like envelope correlation coefficient, diversity gain (DG), mean effective gain, channel capacity loss, and total active reflection coefficient lie within their acceptable limits which affirm a high signal-to-noise ratio and the proficiency of the proposed array in the development of high data-rate UWB communication devices.

KEYWORDS
defected ground structure (DGS), Koch curve fractal, multiple-input multiple-output (MIMO), ultra-wideband (UWB)

1 | INTRODUCTION

Over the last few decades, the wireless telecommunication industry has been evolving significantly from the first generation (1G) analog networks to the forthcoming fifth generation (5G) technology to comply with the escalating user demands of reduced cost, fast Internet speed, reduced delay time, reliable network connectivity, high channel capacity, and enhanced communication security in an intensely scattered environment. The unlicensed sub-6GHz band of the emerging 5G technology plays a crucial role in the Internet of things (IoT)-based industry applications like automated guided vehicles, surveillance cameras, industrial robotics, sensing systems, head-mounted display for workers, and control services like electricity grids, power plants, and so forth. In 2002, the Federal Communication Commission (FCC)
has allocated the usage of unlicensed radio spectrum from 3.1 to 10.6 GHz with 109.5% fractional bandwidth (FBW) at 6.85 GHz center frequency for commercial ultra-wideband (UWB) applications. Apart from the admirable properties of UWB technology, conventional UWB radio systems suffer from the problem of co-channel fading and interference due to multipath wave propagation from the transmitter to the receiver end. To curb the adverse effects of multipath fading, the UWB devices are designed with multiple-input multiple-output (MIMO) wireless technology which multiplies the capacity of the radio channel using multiple antennas at transmitter and receiver. The integration of UWB-MIMO technologies has become an essential part of modern wireless systems to achieve a high data-rate (about 1 Gbps), superior radio-link reliability, broad communication range and little interference in a rich multipath environment.4

The physical size constraints of the portable and handheld gadgets pose a challenge to the antenna designers to develop small-sized and low-profile MIMO antennas. To meet these specifications, a microstrip patch antenna (MPA) is a suitable choice due to its innate benefits of light-weight, simplicity, less cost, mechanically robust and planar/non-planar surface conformity.5 For modeling compact user equipment, the inter-element spacing in the MIMO configuration is reduced which in turn degrades the array performance due to increased mutual coupling and alters the radiation pattern of actively radiating elements. Therefore, it is favored to incorporate fractal geometries in MPAs to achieve the desired compactness and multiband/wideband operation in a given restricted area due to its inherent self-similar, self-affine and space-filling characteristics.6 In recent years, numerous approaches namely neutralization line,7 defected and protruding ground structures,8 parasitic elements,9 electronic bandgap structures,10 and so forth have been introduced in MIMO antenna design to mitigate the effect of mutual coupling between the array elements. Also, the combination of defected ground structure (DGS) with fractal MIMO antennas helps in realizing the desired size reduction, improved operational bandwidth and enhance isolation between the actively radiating patches.11

In the past, several research studies have been reported by the antenna designers to employ the concept of recursively iterated geometries such as Sierpinski gasket,12 Hilbert curve,13 Minkowski curve,14 Koch curve,15 and so forth, for designing 2 × 2 MIMO antennas with the ultimate goal to achieve the smaller dimensions and multiple operational bands. In Reference 12, a 136 × 136 mm² microstrip-fed complementary Sierpinski gasket fractal array with a plus-shaped DGS (in the reduced ground plane) is designed to achieve 8.2% FBW (4.7434–5.1514 GHz) with minimum inter-port isolation of 10 dB. In Reference 14, a 50 × 100 mm² hybrid (Minkowski and Koch curve) fractal array with a grooved ground plane and T-shaped decoupling structure is proposed for dual-band operation (1.65–1.9 GHz and 2.68–6.25 GHz) with the port-to-port isolation less than 10 dB and 15 dB in the two frequency bands respectively. In Reference 16, a 40 × 50 mm² coplanar-waveguide fed sunflower fractal MIMO antenna is designed in combination with a DGS technique to operate in dual-frequency bands (2–2.9 GHz, 5–10 GHz) with an overall envelope correlation coefficient (ECC) ≤ 0.05 and maximum efficiency of 65% and 85% in the two frequency bands respectively. In Reference 17, a 41 × 99.4 mm² aperture-coupled-fed complementary Sierpinski gasket fractal array integrated with two modified complementary Archimedean spiral-shaped DGS is reported to cover a wide operational range from 4.3 to 11.6 GHz (91.8% FBW) with $S_{11}/S_{12} \leq -15.8$ dB and ECC ≤ 0.007. All the aforementioned fractal MIMO antennas12–17 occupy a large surface area with a low degree of inter-port isolation, therefore, they cannot be considered as a good choice for the implementation in the modern portable electronic gadgets, functioning in a highly scattered surrounding. Also, some of the reported MIMO antennas16,17 covers the frequency band outside the FCC’s allocated UWB band, which can further give rise to interference problems. Table 1 presents the shortcomings of the formerly investigated UWB-MIMO antennas as compared to the proposed fractal MIMO antenna.

With the goal of solving the trade-off among the high operational bandwidth, antenna compactness and good inter-port isolation characteristics,12–22 a 2 × 2 miniaturized Koch curve fractal MPA array with a higher operational range and significant diversity performance is presented in this research. The proposed fractal array is modeled on a 1.57 mm thick FR-4 lossy substrate with relative permittivity ($\varepsilon_r$) and loss tangent (tan $\delta$) of 4.4 and 0.024 respectively. Two $\lambda/2$ separated Koch curve fractals (iterated up to second order) are positioned on the top of two microstrip-fed semi-circular radiators (front side of the substrate) to reduce the patch area by 41.2% (as compared to conventional circular patch) and cover a large operational band (simulated) from 4.395 to 10.184 GHz (79.4% FBW) with minimal mismatch losses. By introducing a funnel-shaped decoupling structure and two distinct slots in the reduced ground plane (lower side of the substrate) of the proposed array, a high degree of isolation ($S_{21}/S_{12} \leq -16.8$ dB) is realized between the two actively radiating fractal patches. A peak simulated gain of 3.84 dB (at 8.9 GHz) and overall radiation efficiency ≥ 74% is realized for the entire working range. The modeling and simulation of the proposed fractal array is carried out in the microwave studio of computer simulation tool version 18 software with open boundary conditions. To justify the array performance for the realistic UWB-MIMO applications, the proposed array is fabricated (using photolithography process) and experimentally tested for S-parameters ($S_{11}$, $S_{22}$, $S_{21}$, $S_{12}$) using a vector network analyzer (VNA). The measured FBW of 77.7% (4.6–10.45 GHz, $S_{11}$) and 77.6% (4.55–10.32 GHz, $S_{22}$) with an overall $S_{21}/S_{12}$ (dB) ≤ −19.3 dB is realized which symbolizes
TABLE 1
Comparison of proposed fractal MIMO antenna with the formerly designed MIMO antennas

| Reference | No. of elements | Operating band (GHz) | Substrate size (mm²) | Peak gain (dBi) | Peak efficiency (%) | Minimum isolation (dB) | Weak points |
|-----------|-----------------|----------------------|---------------------|-----------------|---------------------|------------------------|-------------|
| 12        | 2               | 4.74–5.15            | 136 × 136           | 3.9             | 68                  | 10                     | Small impedance bandwidth, large size, high mutual coupling, low efficiency |
| 13        | 2               | 2.4–2.489, 5–6       | 121.8 × 68.45       | NA              | NA                  | 20                     | Multiband operation, large size, efficiency and gain values are unstated |
| 14        | 2               | 1.65–1.9, 2.6–6.45   | 100 × 50            | 1.35, 7.3       | NA                  | 15                     | Multiband operation, large size |
| 15        | 2               | 0.9–1, 1.73–1.8, 2.6–2.8, 3.6–3.7, 4.2–4.4, 5.5–5.6, 5.9–6.1 | 40 × 82             | 4.65            | NA                  | 17                     | Multiband operation, large size, efficiency is not reported |
| 16        | 2               | 2–2.9, 5–10         | 40 × 50             | 5               | 85                  | 20                     | Multiband operation, large size |
| 17        | 2               | 4.3–11.6             | 41 × 99.4           | 4.7             | NA                  | 15.8                   | Large size, efficiency is not reported |
| 18        | 2               | 0.4–0.46, 2.39–2.5, 3.92–4, 4.58–4.8, 5.46–5.98 | 51 × 50             | 6.1             | NA                  | 16                     | Multiband operation, large size, efficiency is not reported |
| 19        | 2               | 2.34–2.5, 5.45–5.75  | 70 × 30             | 2.37, 3.34      | 75                  | 15                     | Multiband operation, large size |
| 20        | 2               | 3–4, 4.3–5.6, 8.4–9.5 | 35 × 60             | 5               | 90                  | 16.5                   | Multiband performance, large size |
| 21        | 2               | 2.24–2.5, 3.6–3.99, 4.4–4.6, 5.71–5.9 | 37 × 56             | 4.2             | 83                  | 14                     | Multiband performance, large size, low inter-port isolation |
| 22        | 2               | 3.1–7.2              | 42 × 40             | NA              | NA                  | 15                     | Large size, gain and efficiency values are unstated |

This work 2 4.395–10.184 30.5 × 47 3.84 88 16.8 —

a good agreement with the simulated results. The adequacy of the proposed fractal array for enhancing the signal-to-noise ratio (SNR) (using diversity combining methods) is analyzed in terms of MIMO performance metrics like low ECC, high diversity gain (DG), high mean effective gain (MEG), low channel capacity loss (CCL) and stable total active reflection coefficient (TARC).

2 | FRACTAL ARRAY DESIGN

Figure 1(A),(B) shows the geometry of the proposed 2 × 2 semi-circular MPA array with Koch curve fractals and a minimized ground with DGS for MIMO implementation in UWB radio systems. The proposed fractal array is modeled on an economical FR-4 lossy substrate (εr = 4.4, tan δ = 0.024 and ht = 1.57 mm) with the total volumetric size of 30.5 × 47 × 1.64 mm³. As illustrated in Figure 1(A), the top substrate surface is composed of two semi-circular radiating patches where the upper edge of each radiator is combined with a Koch curve fractal (iterated up to second order) geometry. The proposed fractal array is fed using two microstrip transmission lines, each with a characteristic impedance of 50 Ω. A λg/2 horizontal stub is loaded at the lower portion of each feedline to realize an enhanced matching performance in the excited operational band. Taking array compactness and good inter-port isolation into consideration, the separation distance between the fractal patches is fixed at λ/2 (21.2 mm).

Figure 1(B) presents the common ground configuration of the proposed fractal array integrated with a DGS technique (rear view of FR-4 substrate). To realize a wideband operation from the proposed array, the length of the common ground
plane is reduced to 12.5 mm (‘Wg’). A funnel-shaped decoupling structure extends vertically (at an angle of 90°) from the reduced ground plane to obstructs the steady flow of current between the two fractal patches and hence minimizes the effect of cross-coupling. To match 50 Ω characteristic impedance from the proposed array, the upper edge of the reduced ground is defected with two mirror-imaged rectangular slots (situated behind the feedline). The base of each rectangular slot is further combined with a horizontal L-shaped slot to realize a high degree of isolation between the two ports of the proposed array. This is described in more detail in Section 3.2. The parametric values of the optimized fractal array are mentioned in Table 2.

### TABLE 2 Parametric values (mm) of the proposed fractal array

| Parameter | Ls | Ws | a   | b   | c   | v  | s  | l  | r  |
|-----------|----|----|-----|-----|-----|----|----|----|----|
| Dimensions| 30.5| 47 | 12.3| 2.4 | 1.489| 5.5| 4.466| 13.4| 6.7 |
| Parameter | Wg | m  | n   | o   | g   | h  | i  | k  | t  |
| Dimensions| 12.5| 2.5| 7.11| 15  | 29.22| 2  | 18 | 5  | 4.5 |

3 | STUDY ON GEOMETRICAL VARIATIONS OF PROPOSED FRACTAL ARRAY

3.1 | Optimization of Koch curve fractal radiators

Figure 2 demonstrates the stepwise approach followed to realize the final Koch curve fractal patch geometry (up to second order of iteration) and the corresponding impedance bandwidth ($S_{11}/S_{22}$) characteristics (versus frequency) of the proposed fractal array are presented in Figure 4. The recursive procedure followed to reach the second order of iteration of the Koch curve fractal is shown in Figure 3. Initially, the array design starts with the circular radiating patches (Level I), each with optimized radius ‘$r$’, computed for a higher order of resonance ‘$f_r$’ (black curve in Figure 3) using Equation (1).23

$$r = \frac{87.94}{f_r \sqrt{\varepsilon_r}}$$  (1)

Level II is constructed by cutting off the upper half of circular patches resulting in semi-circular patch geometry, designed to excite lower as well as a higher order of resonances at 5.4 GHz and 9.2 GHz respectively (orange curve in Figure 4). Further, a horizontal stub is inserted at the lower end of each feedline (Level III) to provide a dual-band operation from

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**Figure 1** (A) Microstrip line fed Koch curve fractal radiators. (B) Reduced ground with DGS

**Figure 2** Intermediate design steps for the construction of final optimized fractal radiators
**FIGURE 3** Design procedure for construction of the Koch curve fractal up to second iteration

**FIGURE 4** Comparison of $S_{11}/S_{22}$ (dB) characteristics for geometrical variations in the patch

4.7 to 6.1 GHz and 7.35–10.2 GHz (blue curve in Figure 4). Level IV and Level V represent the proposed array structures after the application of the first and second order of iteration of the Koch curve fractal geometry at the upper edge of semi-circular radiators (Level III). As illustrated in Figure 3, to construct the Koch curve fractal, initially, a straight line of length '$l$' is considered (0th order of iteration). The length '$l$' is further cut into three equal segments (each of length '$l/3$') where the central segment is replaced by the two other segments of an equilateral triangle (each with length '$l/3$') resulting in the first order of iteration. This process is iterated recursively to form the higher order of iterations. The self-similar repetitions of the proposed Koch curve fractal can be generated by the iterated function system (IFS) approach, defined by generalized matrix Equation (2) using the set of affine linear transformations 'W'.

$$W \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} e \\ f \end{bmatrix} \tag{2}$$

where the variables 'a', 'b', 'c', and 'd' deals with rotation ($\theta$) and scaling ($s$) operations and variables 'e' and 'f' deals with translations.

Using $a = \cos \theta/s$, $b = -\sin \theta/s$, $c = \sin \theta/s$, and $d = \cos \theta/s$ where $s = 1/3$ and $\theta = 60^\circ$ for two segments of equilateral triangle (one in clockwise, other in anticlockwise direction), the required IFS transformation for Koch curve fractal is calculated by Equations (3)–(6).24

$$W_1 \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1/3 & 0 \\ 0 & 1/3 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \text{ for } \theta = 0^\circ. \tag{3}$$

$$W_2 \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1/6 & -\sqrt{3}/6 \\ \sqrt{3}/6 & 1/6 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 1/3 \\ 0 \end{bmatrix} \text{ for } \theta = 60^\circ. \tag{4}$$

$$W_3 \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1/6 & \sqrt{3}/6 \\ -\sqrt{3}/6 & 1/6 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 1/2 \\ \sqrt{3}/6 \end{bmatrix} \text{ for } \theta = -60^\circ. \tag{5}$$

$$W_4 \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1/3 & 0 \\ 0 & 1/3 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 2/3 \\ 0 \end{bmatrix} \text{ for } \theta = 0^\circ. \tag{6}$$

The self-similarity dimension ($D$) of the proposed Koch curve fractal is calculated using Hausdorff-Besicovitch dimensionality.24 In the proposed fractal configuration, four new non-overlapping copies ($N$) are generated with the scaling factor ($s$) of 1/3, resulting in a fractal dimension ($D$) of 1.262.

The red colored curve in Figure 4 (for Level IV) covers a wide functional band from 4.57 to 10.13 GHz (75.6% FBW) but exhibits a poor impedance matching performance. To minimize the mismatch losses in the excited frequency range, the
Koch curve fractal is iterated up to the second order. The final Koch curve fractal array (Level V) operates in the frequency band from 4.395 to 10.184 GHz (79.4% FBW) with an optimum matching characteristic (green colored curve in Figure 4). Therefore, it can be concluded that the array geometry proposed in Level V helps in size miniaturization as it reduces the circular patch area by 41.2% (Level 1) and provides better matching characteristics across the entire range of operation due to the increment in the effective length of the surface current path by the introduction of fractal geometry.

3.2 | Optimization of the common ground plane with DGS

Figure 5 demonstrates the evolutionary stages of the common ground plane with DGS to realize a wide functional band with a low degree of mutual coupling for a fixed Koch curve patch geometries (second iteration). Their corresponding $S_{11}/S_{22}$ (dB) and $S_{21}/S_{12}$ (dB) performances (relative to the frequency) are depicted in Figures 6 and 7 respectively. Stage I demonstrates a full ground plane configuration of the proposed fractal array, responsible for exciting the resonances at 7.8 GHz and 9.6 GHz respectively (black curve in Figure 6) with a high degree of port-port isolation (black curve in Figure 7). Generally, reducing the ground along Y-direction results in more fringing and therefore improves the bandwidth of operation. So, the ground is reduced to an optimized length of 12.5 mm (Stage II) to cover the frequency range from 4.58 to 9.33 GHz (orange curve in Figure 6) with $S_{21}/S_{12} \leq -9.5$ dB (orange curve in Figure 7). Further, to enhance the isolation and matching performance of the proposed array (blue curve in Figures 6 and 7), a vertical stub is elongated (at an angle of 90°) from the middle of the reduced ground plane (Stage III). Stage IV is constructed by embedding an upturned isosceles triangle at the upper end of the vertical stub. This funnel-shaped decoupling structure provides a dual-band operation from 4.44 to 5.97 GHz and 6.79–9.9 GHz (red curve in Figure 6) with a low degree of isolation ($S_{21}/S_{12} \leq -14$ dB) between the two ports (red curve in Figure 7). To minimize the effect of mismatch losses and mutual coupling in the working frequency band, the upper edges of the reduced ground are defected with two mirror-imaged rectangular slots (behind the feedlines), each combined with a horizontal L-shaped slot (Stage V). This ground plane configuration provides the best-optimized results with the widest impedance bandwidth of 5.789 GHz and $S_{21}/S_{12}$ (dB) $\leq 16.8$ dB (green curve in Figures 6 and 7 respectively).

**FIGURE 5** Geometrical variations in the ground plane geometry of the proposed fractal array

**FIGURE 6** Comparison of $S_{11}/S_{22}$ (dB) performance (versus frequency) for variations in ground plane geometry

**FIGURE 7** Comparison of $S_{21}/S_{12}$ (dB) performance (versus frequency) for variations in ground plane geometry
4 | SIMULATED AND MEASURED RESULTS

To validate the antenna performance in a real practical scenario, the proposed fractal array is fabricated using a photolithography process. The fabricated prototype of the proposed fractal array is tested for S-parameters \( (S_{11}, S_{22}, S_{21}, S_{12}) \) values using VNA E 5063A (100 kHz-18 GHz) under normal laboratory conditions. Figure 8(A),(B) shows the snapshot of the front and back view of the fabricated fractal array respectively. To energize the fractal patches, a 50 Ω female subminiature version A connector (frequency range up to 18 GHz) is soldered at the termination of each feedline. Figure 8(C) shows the snapshot during the measuring of the reflection coefficient on VNA.

4.1 | Return loss \( (S_{11}/S_{22} \text{ (dB)}) \), voltage standing wave ratio and isolation \( (S_{21}/S_{12} \text{ (dB)}) \) characteristics

Return loss is used to estimate the power absorbed by the antenna from the transmission line. VSWR is defined as the ratio of peak voltage to the minimum voltage in the standing wave pattern that sets up in the transmission line due to impedance mismatches. The value of voltage standing wave ratio (VSWR) should lie between 1 and 2 for the maximum transfer of power from the feedline to the antenna. Equation (7) shows the relationship between return loss and VSWR.\(^{25}\)

\[
\text{Return loss (dB)} = -20 \cdot \log_{10} \left( \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \right)
\]  

(7)

Figure 9 shows the variation of the simulated and measured reflection coefficient \( (S_{11}/S_{22} \text{ (dB)}) \) and the transmission coefficient \( (S_{21}/S_{12}) \) as the function of frequency. The proposed fractal array covers a simulated operational band from 4.395 to 10.184 GHz (79.4% FBW) and a peak \( S_{11}/S_{22} \text{ (dB)} \) of \(-54.5\text{ dB}\) at 9.4 GHz frequency. The measured results on a VNA show a frequency band from 4.6 to 10.45 GHz (port-1, \( S_{11} \)) and 4.55-10.32 GHz (port-2, \( S_{22} \)) with the FBW of 77.7% GHz and 77.6% respectively. The simulated and measured \( S_{11}/S_{22} \text{ (dB)} \) responses show an acceptable similitude of 95% match at the lower frequency band and a 97% match at the higher frequency band. A good port-to-port isolation \( (S_{21}/S_{12} \leq -16.8\text{ dB (simulated)} \) and \( S_{21}/S_{12} \leq -19.3\text{ dB (measured)} \)) is achieved for the entire operational band from 4.395 to 10.184 GHz.

**FIGURE 8** Snapshots of the fabricated fractal array showing (A) Fractal radiators (B) Ground view (C) Testing of reflection coefficient on VNA

**FIGURE 9** Comparative plot of simulated and measured \( S_{11}/S_{12} \text{ (dB)} \) and \( S_{21}/S_{12} \text{ (dB)} \) relative to the frequency
As shown in Figure 10, the proposed fractal array achieves a good match with the feedlines and power loss is minimal as simulated and measured VSWR values are less than 2 for the entire operational band. It validates the suitability of the proposed fractal array for UWB-MIMO applications.

4.2 Broadband gain, radiation efficiency, and radiation patterns

Antenna gain quantifies the maximum distance that can be covered by the electromagnetic (EM) wave. Figure 11(A) shows the variation of antenna gain (in the broadside direction) for the activated port-1 in the functional range from 4.395 to 10.184 GHz. Owing to the symmetrical arrangement of the antenna elements in the proposed array, gain values remain unchanged for the activated port-2 (with port-1 ceased by a 50 Ω load). Therefore, for the energized port-1, the proposed fractal array shows a maximum gain of 3.84 dB at 8.9 GHz frequency (simulated) and 3.81 dB at 9.25 GHz frequency (measured) with an average simulated gain of ≥1.2 dB. The radiation efficiency for port-1 is measured using the Wheeler cap method (as explained in the study by García-García) and compared with the simulated one as shown in Figure 11(B). The proposed fractal array radiates with an overall radiation efficiency ($\eta_{rad}$) ≥ 74% (simulated) and ≥ 72.2% (measured) throughout the operational band. Hence, the proposed fractal array exhibits good UWB properties as the overall simulated gain and radiation efficiency variations are ≤2.9 dBi and ≤14% respectively.

Figure 12(A)-(C) shows the simulated and experimental 2D far-field radiation patterns (co- and cross-polarization) for the proposed fractal array in the two reference planes, E-plane (y-z) and H-plane (x-z) at the three resonances of 5.4 GHz, 7.78 GHz, and 9.47 GHz for excited port-1 and port-2 connected with 50 Ω load. For activated port-1 and port-2 terminated (at all three resonances), it is observed that the proposed fractal array exhibits a directional far-field pattern in the y-z plane and an almost omnidirectional far-field pattern in the x-z plane. The measured far-field patterns show a reasonable resemblance with the simulated ones. Some deviations between the simulated and measured far-field patterns are because of the spurious radiations resulting from the fabrication errors and certain cable effects. Therefore, the proposed array is suitable for a variety of wireless communication applications supported by the unlicensed UWB spectrum.

![Figure 10](image1.png)  
**Figure 10** Variation of simulated and measured VSWR against frequency

![Figure 11](image2.png)  
**Figure 11** Variation of simulated and measured (A) gain (B) radiation efficiency against the frequency for the activated port-1
4.3 Surface current distribution

To determine the influence of mutual coupling between the two array elements, Figure 13(A)-(D) shows the current distribution at 5.4 GHz and 9.47 GHz resonances for the activated port-1 and port-2 respectively. It is observed that the funnel-shaped stub and slotted ground plane decouples the energy from the fractal radiators and are mainly responsible for improving the isolation level between the two ports. This is also validated by the parametric analysis of the ground plane presented in Section 3.2. For port-1 excited by simulated 1 W of power at the feed point (port-2 deactivated by 50 Ω load), the decoupling structure (inserted in the ground plane) allows a very small amount of current to flow through
the non-activated antenna element (port-2) for the two resonances. For activated port-2 and port-1 terminated, a similar reduction of coupling current is observed. Hence, the proposed fractal MPA array exhibits good isolation performance throughout the UWB of operation. For better analysis, the effective electrical length of the surface current is estimated from the current density plots presented in Figure 13(A)-(D) and compared with the wavelength at 5.4 GHz and 9.47 GHz using Equations (8) and (9).\(^{27}\)

\begin{align*}
\lambda_g &= \frac{c_0}{f_r \sqrt{\varepsilon_{\text{eff}}}} \quad \text{(8)} \\
\varepsilon_{\text{eff}} &\equiv \varepsilon_r + \frac{1}{2} \quad \text{(9)}
\end{align*}

where \(\lambda_g\), \(c_0\), \(f_r\), \(\varepsilon_{\text{eff}}\), and \(\varepsilon_r\) is the guided wavelength, light speed (\(=3 \times 10^8 \text{ m/s}\)), resonant frequency, effective dielectric constant and dielectric constant of FR-4 substrate respectively. The wavelength (\(\lambda_g/2\)) computed at 5.4 GHz frequency (using Equation (10)) is 16.905 mm and based on the current distribution presented in Figure 13(A), it is approximately equal to 16.26 mm (4.76 + 5 + 2 + 4.5 mm) with an error of 3.81%. At 9.47 GHz frequency, as displayed in Figure 13(C), more magnitude of the current is concentrated along the path length of 9.796 mm (5.956 + 2 + 1.84 mm) which is nearly identical to the mathematically computed wavelength (\(\lambda_g/2\)) of 9.64 mm with an error of 1.62%. It is also noticed that at low resonances, the smaller sections of Koch fractal geometry provide little contribution to the overall radiation due to the large wavelength of electromagnetic (EM) waves. Although at high resonances, the size of Koch segments gets analogous to the wavelength which considerably improves the antenna radiation performance.

### 4.4 Diversity characteristics

To characterize the feasibility of the proposed dual-port fractal array for UWB-MIMO systems, various diversity performance metrics such as ECC, DG, MEG, CCL, and TARC are analyzed in this section.

For a two-element MPA array, ECC is a crucial diversity parameter to quantify the amount of correlation between the signals received from adjacent communication channels. DG is defined as the figure of merit to determine the potency of the applied diversity scheme. For any practical MIMO application, the acceptable limit of ECC and DG to receive uncorrelated signals is less than 0.05 and greater than 9.95 respectively.\(^{6,28}\) ECC (\(\rho_e\)) can be computed from S-parameters using Equations (10) and (11) defines the relationship between ECC and DG.\(^{29}\)

\[
\rho_e = \frac{|S_{11}S_{12} + S_{21}S_{22}|^2}{((1 - (|S_{11}|^2 + |S_{21}|^2))(1 - (|S_{22}|^2 + |S_{12}|^2)))} \quad \text{(10)}
\]

\[
\text{DG} = 10\sqrt{1 - \rho_e} \quad \text{(11)}
\]

Figure 14(A), (B) shows the variation of ECC and DG against the frequency for the proposed fractal array. It illustrates a low level of ECC (\(\leq0.0021\) (simulated), \(\leq0.0023\) (measured)) and a high degree of DG (\(\geq9.989\) (simulated), \(\geq9.988\) (measured)) for a complete operational range which affirms a good diversity performance of the proposed MPA array.

CCL is the third significant diversity parameter that determines the degree of deterioration of array performance as a result of the correlation in the MIMO channel. For a MIMO antenna system with high SNR, the expression for CCL (as given in Equation (12)) is derived from the correlation matrix (as reported in the study by Ho Chae et al\(^{29}\)) and should be less than 0.4 bits/s/Hz for a good diversity performance.

\[
\text{CCL} = -\log_2 \det \begin{pmatrix} 1 - (|S_{11}|^2 + |S_{12}|^2) & -(S_{11}S_{12} + S_{21}S_{22}) \\ -(S_{21}S_{22} + S_{12}S_{11}) & 1 - (|S_{22}|^2 + |S_{21}|^2) \end{pmatrix} \quad \text{(12)}
\]

Figure 14(C) shows that the value of CCL is \(\leq0.4\) bits/s/Hz (simulated and measured) for the entire operational range which indicates high port-to-port isolation between the array elements.

MEG is another important diversity metric as it determines the antenna gain performance by taking into account the real fading scenario. Assuming a uniform Rayleigh environment with identical vertical and horizontal polarization
differences, MEG is equal to half of the radiation efficiency (as explained by Nasir et al.\textsuperscript{30}). Therefore, Equations (13) and (14) are used to determine MEG for both the ports of the proposed array based on radiation efficiencies and S-parameter values. For good diversity performance, the difference in the magnitudes of MEG for two ports should be less than 3 dB.\textsuperscript{31}

\begin{equation}
\text{MEG}_{\text{port}1} = 0.5(1 - |S_{11}|^2 - |S_{12}|^2) \quad (13)
\end{equation}

\begin{equation}
\text{MEG}_{\text{port}2} = 0.5(1 - |S_{21}|^2 - |S_{22}|^2) \quad (14)
\end{equation}

As shown in Figure 14(D), a maximum MEG of −3.018 dB (simulated) at 5.88 GHz frequency and −3.011 dB (measured) at 6.2 GHz frequency is observed with an overall MEG ≥ −3.7 dB (simulated) and ≥ −3.85 dB (measured). The difference between the MEG for the two ports is 0 dB (simulated) and 0.69 dB (measured). This makes the proposed fractal array feasible for MIMO employment in UWB radio systems.

TARC is an essential MIMO metric which determines the impact of random phases of incoming signals on impedance bandwidth and resonating frequencies of the antenna array.\textsuperscript{29} TARC can thus be deemed as the apparent return loss of the whole MIMO antenna system and for a two-port lossless MIMO antenna, TARC is mathematically computed from S-parameters using Equation (15).

\begin{equation}
T_{\text{AR}} = \sqrt{\frac{[(S_{11} + S_{12}e^{\theta})]^2 + [(S_{11} + S_{12}e^{\theta})]^2}{2}} \quad (15)
\end{equation}

where ‘θ’ is the input feeding phase angle.\textsuperscript{31}
As shown in Figure 14(E), (F), TARC (dB) curves are plotted for variation in ‘θ’ (0°, 30°, 60°, 90°, 120°, 150°, 180°) against the frequency (GHz). For an efficient operation of the UWB-MIMO antenna, TARC < 0 dB is generally required. The simulated and measured TARC values < −10 dB and < −8.9 dB respectively are observed for all variations of ‘θ’. The simulated and measured TARC resonance curves (at ‘θ’ = 30°) show a good resemblance with the simulated and measured $S_{11}$/$S_{22}$ (dB) curves respectively. The simulated and measured TARC curves show a slight deviation in resonant characteristics (as compared to simulated and measured S-parameter curves) because TARC considers the effect of mutual coupling and feeding phase of the incident wave.

4.5 | Time domain analysis

Group delay is a crucial time-domain performance metric used to estimate the degree of pulse dispersion in the course of data transmission and reception by a UWB antenna. For evaluating the group delay performance, a pair of similar proposed fractal arrays (with the activated port-1 and port-2 terminated by 50 Ω load) have been set-up in a face-to-face arrangement at the far-field distance, ‘F’, computed according to Equation (16).

$$F \geq \frac{2D^2}{\lambda}$$

where ‘D’ is the largest dimension of the proposed fractal array (=56.03 mm) and ‘λ’ is the wavelength (=29.458 mm) relative to the highest operating frequency (=10.184 GHz). For the proposed fractal array, the calculated far-field distance (‘F’) is 21.3 cm. While measuring group delay using VNA, the two antenna arrays are separated by a distance of 25 cm (far-field region).

To realize a distortion-less signal transmission from the proposed fractal array, the group delay variations should be less than 1 ns for the entire band of operation. Figure 15 illustrates the variation of simulated and measured group delay against the frequency. It reveals that the proposed fractal array exhibits an optimum linear phase performance with almost constant values of group delay (with variation < 1 ns) for the entire working band from 4.395 to 10.184 GHz. Some deviation between the simulated and measured group delays is noticed as a result of measurements in a free-space environment. Hence, the proposed fractal array is an appropriate choice for implementation in UWB communication systems with good pulse-handling potential.

5 | CONCLUSION

A compact dual-port microstrip fed fractal MPA array is proposed for portable UWB-MIMO systems in this article. The proposed array consists of two semi-circular patches (each joined with second order Koch curve fractals) and a reduced ground with DGS, occupying an overall area of 1433.5 mm². The simulated results show a wide frequency band of 4.395–10.184 GHz (79.4% FBW) with $S_{21}/S_{12} \leq 16.8$ dB and provide a peak radiation efficiency of 88.8% (at 6.2 GHz) with the overall variations < 15%. The measured S-parameter results cover the frequency band from 4.6 to 10.45 GHz (port-1, 77.7% FBW) and 4.55–10.32 GHz (port-2, 77.6% FBW) with minimum isolation of 19.3 dB. The simulation and experimental diversity characteristics like ECC, DG, MEG, CCL, and TARC lie within the standard levels and show a good
resemblance. Hence, it is concluded that the proposed fractal MIMO antenna complies with the UWB-MIMO criteria of miniaturized geometry, high FBW, high inter-element isolation, and adequate diversity characteristics which make the designed array an appropriate choice for high data-rate portable UWB systems.

ACKNOWLEDGMENT
We would like to thank the Thapar Institute of Engineering and Technology, Patiala for providing the necessary infrastructure and facilities to support this research work.

PEER REVIEW INFORMATION
Engineering Reports thanks Amer Tawfeeq Abed and José Alfredo Tirado Méndez for their contribution to the peer review of this work.

PEER REVIEW
The peer review history for this article is available at https://publons.com/publon/10.1002/eng2.12378.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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REFERENCES
1. Shoaib N, Shoaib S, Khattak RY, Shoaib I, Chen X, Perwaiz A. MIMO antennas for smart 5G devices. IEEE Access. 2018;6:77014-77021. https://doi.org/10.1109/ACCESS.2018.2876763.
2. Bajracharya R, Shrestha R, Jung H. Future is unlicensed: private 5G unlicensed network for connecting industries of future. Sensors. 2020;20(10):1-18. https://doi.org/10.3390/s20102774.
3. Zhao H, Zhang F, Wang C, Zhang X. A universal methodology for designing a UWB diversity antenna. J Electromagn Waves Appl. 2014;28(10):1221-1235. https://doi.org/10.1080/09205071.2014.911667.
4. Chouhan S, Panda DK, Gupta M, Singhal S. Multiport MIMO antennas with mutual coupling reduction techniques for modern wireless transreceive operations: a review. Int J RF Microw Comput Aid Eng. 2018;28:e21189. https://doi.org/10.1002/mmce.21189.
5. Balanis CA. Antenna Theory: Analysis and Design. 4th ed. Hoboken, NJ: John Wiley & Sons; 2016.: https://www.wiley.com/en-us/Antenna+Theory%3A+Analysis+and+Design%2C+4th+Edition-p-9781118642061.
6. Gurjar R, Upadhyay DK, Kanaujia BK, Sharma K. A novel compact self-similar fractal UWB MIMO antenna. Int J RF Microw Comput Aid Eng. 2019;29:e21632. https://doi.org/10.1002/mmce.21632.
7. Tiwari RN, Singh P, Kanaujia BK. A compact UWB MIMO antenna with neutralization line for WLAN/ISM/mobile applications. Int J RF Microw Comput Aid Eng. 2019;29:e21907. https://doi.org/10.1002/mmce.21907.
8. Sohi AK, Kaur A. Hexa-band suppression characteristics from a fork-shaped UWB-MIMO antenna loaded with complementary split-ring resonator and slots. J Electromagn Waves Appl. 2020;34(16):2194-2219. https://doi.org/10.1080/09205071.2020.1809533.
9. Khan MS, Capobianco AD, Shafique MF, Ijaz B, Naqvi A, Braaten BD. Isolation enhancement of a wideband MIMO antenna using floating parasitic elements. Microw Opt Technol Lett. 2015;57:1677-1682. https://doi.org/10.1002/mop.29162.
10. Kumar N, Kiran KU. Meander-electromagnetic bandgap structure for UWB MIMO antenna mutual coupling reduction in E-plane. AEU-Int J Electron C. 2020;127:153423. https://doi.org/10.1016/j.aeue.2020.153423.
11. Arya A, Kartikeyan MV, Patnaik A. Defected ground structure in the perspective of microstrip antennas: a review. Frequenz. 2010;64:79-84. https://doi.org/10.1515/FREQ.2010.64.5-6.79.
12. Kaur A, Gupta S. A complementary Sierpinski gasket fractal antenna array for wireless MIMO portable devices. Microw Opt Technol Lett. 2019;61:436-442. https://doi.org/10.1002/mop.31584.
13. Peristerianos A, Theopoulou A, Koutinos AG, Kaifas T, Siakavara K. Dual-band fractal semi-printed element antenna arrays for MIMO applications. IEEE Antennas Wirel Propag Lett. 2016;15:730-733. https://doi.org/10.1109/LAWP.2015.2470681.
14. Choukiker YK, Sharma SK, Behera SK. Hybrid fractal shape planar monopole antenna covering multiple wireless communications with MIMO implementation for handheld mobile devices. IEEE Trans Antennas Propag. 2014;62(3):1483-1488. https://doi.org/10.1109/TAP.2013.2295213.
15. Rajkumar S, Sivaraman NV, Murali S, Selvan KT. Heptaband swastik arm antenna for MIMO applications. IET Microw Antennas Propag. 2017;11(9):1255-1261. https://doi.org/10.1049/iet-map.2016.1098.
16. Abed AT. Novel sunflower MIMO fractal antenna with low mutual coupling and dual wide operating bands. *Int J Microw Wirel Technol.* 2020;12(4):323-331. https://doi.org/10.1017/S1759078719001375.

17. Sohi AK, Kaur A. A complementary Sierpinski gasket fractal antenna array integrated with a complementary Archimedean defected ground structure for portable 4G/5G UWB MIMO communication devices. *Microw Opt Technol Lett.* 2020;62:2595-2605. https://doi.org/10.1002/mop.32356.

18. Rajkumar S, Srinivasan N, Natesan A, Selvan KT. A penta-band hybrid fractal MIMO antenna for ISM applications. *Int J RF Microw Comput Aid Eng.* 2018;28:e21185. https://doi.org/10.1002/mmce.21185.

19. Cui S, Liu Y, Jiang W, Gong SX, Guan Y, Yu ST. A novel compact dual-band MIMO antenna with high port isolation. *J Electromagnet Waves Appl.* 2011;25:1645-1655. https://doi.org/10.1080/09205071.2011.1599311797164765.

20. Babu KV, Anuradha B. Design of MIMO antenna to interference inherent for ultra-wide band systems using defected ground structure. *Microw Opt Technol Lett.* 2019;61:2595-2605. https://doi.org/10.1002/mop.32356.

21. Chouhan S, Panda DK, Kushwah VS, Singhal S. Spider-shaped fractal MIMO antenna for WLAN/WiMAX/Wi-Fi/Bluetooth/C-band applications. *AEU-Int J Electron C.* 2019;110:152871. https://doi.org/10.1016/j.aeue.2019.152871.

22. Joo E, Kwon K, Park J, Choi J. On-body UWB MIMO antenna for UWB application. Paper presented at: Proceedings of the 2013 Asia-Pacific Microwave Conference Proceedings (APMC). Seoul, South Korea: IEEE; 2013:1130–1132. https://doi.org/10.1109/APMC.2013.6695045.

23. Sohi AK, Kaur A. UWB aperture coupled circular fractal MIMO antenna with a complementary rectangular spiral defected ground structure (DGS) for 4G/WLAN/radar/satellite/international space station (ISS) communication systems. *J Electromagnet Waves Appl.* 2020;34(17):2317-2338. https://doi.org/10.1080/09205071.2020.1813638.

24. Vinoy KJ, Abraham JK, Varadan VK. On the relationship between fractal dimension and the performance of multi-resonant dipole antennas using Koch curves. *IEEE Trans Antennas Propag.* 2003;51(9):2296-2303. https://doi.org/10.1109/TAP.2003.816352.

25. Elrashidi A, Elleithy K, Bajwa H. Input impedance, VSWR and return loss of a conformal microstrip printed antenna for TM01 mode using two different substrates. *Int J Netw Commun.* 2011;2(2):13-19. https://doi.org/10.5923/j.ijnc.20120202.03.

26. García-García Q. Patch-antenna efficiency based on Wheeler cap and measured Q factor. *Microw Opt Technol Lett.* 2004;40:132-142. https://doi.org/10.1002/mop.11307.

27. Srivastava K, Kumar S, Kanaujia BK, Dwari S, Choi HC, Kim KW. Compact eight-port MIMO/diversity antenna with band rejection characteristics. *Int J RF Microw Comput Aid Eng.* 2020;30:e22170. https://doi.org/10.1002/mmce.22170.

28. Das G, Sharma A, Gangwar RK. Dual port aperture coupled MIMO cylindrical dielectric resonator antenna with high isolation for WiMAX application. *Int J RF Microw Comput Aid Eng.* 2017;27:e21107. https://doi.org/10.1002/mmce.21107.

29. Chae SH, Oh S, Park S. Analysis of mutual coupling, correlations, and TARC in WiBro MIMO array antenna. *IEEE Antennas Wirel Propag Lett.* 2007;6:122-125. https://doi.org/10.1109/LAWP.2007.893109.

30. Nasir J, Jamaluddin MH, Khalili M, Kamarudin MR, Ullah I, Selvaraju R. A reduced size dual port MIMO DRA with high isolation for 4G applications. *Int J RF Microw Comput Aid Eng.* 2015;25:495-501. https://doi.org/10.1002/mmce.20884.

31. Fritz-Andrade E, Jardon-Aguilar H, Tirado-Mendez JA. The correct application of total active reflection coefficient to evaluate MIMO antenna systems and its generalization to N ports. *Int J RF Microw Comput Aid Eng.* 2019;30:e22113. https://doi.org/10.1002/mmce.22113.

32. Jafri SI, Saleem R, Shafique MF, Brown AK. Compact reconfigurable multiple-input-multiple-output antenna for ultra-wideband applications. *IET Microw Antennas Propag.* 2016;10:413-419. https://doi.org/10.1049/iet-map.2015.0181.

33. Hasan MN, Chu S, Bashir S. A DGS monopole antenna loaded with U-shape stub for UWB MIMO applications. *Microw Opt Technol Lett.* 2019;61:2141-2149. https://doi.org/10.1002/mop.31877.

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**How to cite this article:** Sohi AK, Kaur A. Computational analysis of a dual-port semi-circular patch antenna combined with Koch curve fractals for ultra-wideband systems. *Engineering Reports.* 2021;e12378. https://doi.org/10.1002/eng.212378