Fractal geometry-based chakra-shaped microstrip patch antenna array for vehicular communications under 5G environments

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ABSTRACT
In this paper, fractal geometry-based two-printed antenna structures are proposed for vehicular communication in 5G wireless communication networks. Initially, a 48 × 39 mm² single element fractal patch antenna is designed and tested which shows dual-band resonance at around 28.1 and 32.5 GHz. In order to improve different antenna characteristic number of fractal radiating elements have been increased to four and constructed an array of patches such that it can be used for multiple applications in the field of vehicular communications. The proposed array model is fabricated on a Rogers RT duroid 5880tm material of size 115 × 82 mm² and tested using Agilent Technologies N5247A VNA. The measured results confirm the validity of the designed model for intended applications. The proposed array antenna operates at distinct quintuple bands in the frequency range of 25–36 GHz for vehicular communication within the proposed lower fifth generation (5G) channel. The proposed array configuration shows a good peak gain of 6.72 dB within the operating bands.

1. Introduction
Traditionally from first generation to fourth generation, there was an impact on the hardware advancements only, but as per the latest technology of 5G, there is a direct impact on software (Rogalski, 2021). With the advancements of software, the level of computational capacity has increased which provides a scope of automobile communication. This provides the technology to be self-configure, self-healing and self-analysis. Location information can be accessed very easily as the technology has very good self-informative system available in itself (Cao et al., 2021). This all is achieved as the technology has a direct impact on software accessing and development. Using cooperative localization, device-to-device communication is enabled to its highest position where multiple applications are entitled to it (Jeong et al., 2020). Internet of things (IoT) is another field in which the impact is directly observed as the sensors are intact.
with the 5G communication, where the latency can be reduced and the active time of the device can be improved. The range of communication can be increased with the milli-metre technology incorporated using 5G (Kbashi et al., 2021). Health and medical sciences are another areas where the impact of 5G is directly seen as the high frequency can be used to scan the organs and give a better understanding of the health of the patient (Zhan, 2021). Vehicular communication is another area where the impact is seen as a vehicle to everything is largely exposed to the technology which includes communication using Vehicle to Vehicle (V–V), vehicle to infrastructure (V–I), vehicle to pedestrian (V–P) and vehicle to the user (V–U) (Rahim et al., 2020). This has brought the automobile industry to its highest technology-based movable vehicles. The communication unit is set up at different vehicles, roadside units and other objects which are needed to provide the information. These units are to be in contact and should provide the information continuously (Rahim et al., 2019). The information regarding the roads, the way the curves are ahead, weather information, and other necessary information are stored in the cloud which can be accessed by the vehicle to provide the information to the user (Li et al., 2020). As the information is endless and continuous which is very much needed for the user to understand the vehicle and the road better, there is an emergency need of having a proper end-to-end connection. Wireless communication comes to existence as it provides information via wireless connectivity (Li, 2020).

In this era, it is very much clear that the technology surrounded with 5G has an impact on the luxury, safety, security and comfort of the individual (Rahim et al., 2019). Society is benefitted from this technology which makes it as an essential commodity for day-to-day life. Table 1 provides the information regarding the proposed Spectrum under 5G.

At these frequencies, there is a very much need for an antenna that should have a good gain, multi-band, highly directive with compact in size.

The best antenna for the fulfilment of this is a microstrip patch antenna, which can be used for very high frequencies, but the drawback of the antenna is, it possesses low gain, low bandwidth which will have an impact directly on the performance of the antenna. There are many ways to overcome these drawbacks such as fractal geometry which provides self-similarity and improves the performance of the antenna (Singh et al., 2019). The alternate is to design a multi-patch that increases the antenna dimensions yet can be used for multiple applications. The antenna patch can be implemented using fractal designs like Sierpinski carpet, Minkowski island, snowflake (Rahim et al., 2019), these designs are based on fractal geometry which is an endless, self-similar design (Rahim & Malik, 2021). Over the years, these shapes are used in the design of antennae at frequencies not greater than 10 Giga Hertz (GHz) (Bisht & Malik, 2022).

Table 1. Proposed spectrum under 5G for various countries (Rogalski, 2021).

| Countries            | Channel-1     | Channel-2     | Channel-3     | Channel-4     |
|----------------------|---------------|---------------|---------------|---------------|
| US Proposed Spectrum | 24.25–27.5 GHz | 31.8–33.4 GHz  | 37–40.5 GHz   | 40.5–42.5 GHz |
| EUROPE Proposed Spectrum | 27.5–29.5 GHz | 37–40.5 GHz   | 47.2–50.2 GHz | 50.4–52.6 GHz |
| SOUTH KOREA Proposed Spectrum | 28.4–32.4 GHz | 41.25–43.75 GHz | 59.3–71 GHz | – |
| CHINA Proposed Spectrum | 31.75–33.54 GHz | 45–47 GHz     | 59–64 GHz     | – |
In this paper fractal geometry-based single and multi-patch antenna are presented. The antennas are simulated and measured at futuristic 5G frequencies for vehicular applications, where the size of the single patch is 39 mm × 48 mm × 0.55 mm and 2 × 2 array antenna is 82 mm × 115 mm × 0.55 mm. The antennas are tested under frequency range of 25 GHz–35 GHz. The advantage of 2 × 2 array antenna is its miniaturized dimensions achieved by using fractal geometry, antenna resonates at multiple bands with enhanced operating bandwidths, a maximum gain of 6.72 dB with Voltage Standing Wave Ratio (VSWR) of 0.715 and reflection coefficient of −27.71 dB at the frequency of 32.8 GHz. The antennas are simulated using High Frequency Structure Simulator (HFSS) v15 and measured using N5247A Vector Network Analyzer (VNA).

2. Related works

In this section, the latest research works carried out by various researchers in the domain of vehicular communications, fractal antennas, and 5G communications are presented. The focus is majorly on the parameters of the antenna and the behaviour of the antenna at futuristic frequencies. The authors (Patil et al., 2018) proposed a Hexagonal shaped ultra-wide bandwidth Fractal dipole antenna for frequency range 0.5–12 GHz. The simulation is carried out to focus on the gain of the antenna which was around 6.9 dBi for various angles of penetration. The proposed fractal module is very tiny in its size and shape which can be used for vehicular communications. A minimum reflection coefficient of 29.19 dB was achieved and the VSWR was in the range of 4 dB. In the next analysis, the author (Malik & Singh, 2019) proposed a triangular-shaped fractal geometry antenna for UWB applications. The self-complementary principle is applied at the first iteration of the planner triangular monopole antenna for its enhancement. Through this principle, it is observed that the reflection coefficient is reduced to below 10 dB for a frequency range of 4–11 GHz. The triangle patch is compared with single and multiple patches in which the performance level was enhanced up to 30%. The idea of studying this antenna leads us to design antenna both single and multi-layer patch. One of the key features of the antenna is to design such that it can be used for multiple applications. The author proposed Fractal based Hexagonal wide slot antenna for super wide-band applications. The proposed antenna achieves a ratio impedance bandwidth 15:19 for a frequency range of 3–30 GHz for VSWR ≤ 2. The achieved bandwidth is double when compared with the required bandwidth of SWB operation. For bandwidth enhancement, even at lower frequencies, the author proposed a hexagonal tuning stub loaded at microstrip feed line which is a very good idea for the compact antennas which can be placed on a vehicle (Malik et al., 2020).

The latest requirements of the antenna are to make it wearable and conformal which can be placed on the human body for providing the required information. The author (Atanasov et al., 2019) proposed a wearable Fractal monopole antenna embedded with a reflector for better antenna performance and SAR reduction. The proposed antenna shows improved bandwidth of 130 MHz in the free space and 128 MHz when mounted on a flat homogeneous phantom at an operating frequency of 2.36–2.50 GHz. The bandwidth of the antenna is the most important feature for any
application and the author (Benavides et al., 2018) had proposed about Fractal antenna with a modified hexagonal shape with multi-band notch characteristics for UWB applications. The antenna is fabricated using FR4 Epoxy which leads to obtaining a bandwidth of 2.36 GHz in the frequency range of 9.8 GHz–15 GHz with $S_{11}$ is less than $-10$ dB over the entire UWB range (Saputro & Chung, 2016). The author mentioned that these improved features provide several applications in the field of telecommunication and vehicular communications. The above-related work has provided a lot of understanding regarding the design of the proposed work to make it useful for multi-band applications in vehicular communications under 5G environments (Shaik & Malik, 2020). The slots have been introduced in the design to achieve wide-band and to achieve multi-band characteristics with wide impedance. The antenna is also designed using a single patch and multi-patch design which is described in the next section.

3. Antenna design

3.1. Microstrip patch antenna with single patch

The single element patch antenna is designed using a self-similar pattern with the same dimensions as the rectangular patch of 39 mm $\times$ 48 mm. The antenna is designed using the Rogers RT duroid 5880tm, with a relative permittivity of 2.2. The patch is of circular shape and internally made of seven iterations, with each iteration radius is reduced by 1 mm as shown in Figure 1. The single element fractal antenna resonates at dual band due to the suggested antenna geometry.

Figure 1. Microstrip patch antenna with a single patch.
3.2. Microstrip patch antenna with 2 × 2 patch

The antenna is configured using the same single patch structure with the extension of 2 × 2, the antennas are arranged in the matrix form with two rows and two columns. The feed lines are drawn row-wise and connected in a column to match the impedance between the four single patch antennas. The antenna substrate is measured at 82 × 115 mm with a 2 × 30 mm of the feed line. The antenna is designed using the Rogers RT duroid 5880tm, with a relative permittivity of 2.2 (Figure 2 and Table 2).

The antenna dimensions are calculated as per the circular patch with radius of \( r \), and the mathematical formulation is as follows:

\[
R = \frac{Qr}{w_0C}
\]  
(1)

\[
L_1 = \frac{1}{w_0^2C_1}
\]  
(2)

\[
C_1 = \frac{LWx0ee}{2h} \cos^2 \left( \frac{x_0}{L} \right)
\]  
(3)

![Figure 2. Microstrip patch antenna with 2 × 2 array.](image)

| Table 2. Dimension of single patch and multi-patch antennas(dimensions in mm). |
|---|---|---|---|---|---|---|---|---|---|---|
| L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | R1 |
| 21 | 8 | 4 | 5.5 | 7 | 8.5 | 39 | 7 | 82 | 10 |
| W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 | R2 |
| 44 | 52 | 1.6 | 115 | 90 | 8 | 50 | 33 | 25 | 9 |
in which \( L \) = Patch length, \( W \) = Patch width, \( x_0 \) = feed point location, \( h \) = substrate thickness.

\[
Q_r = \frac{c \sqrt{\varepsilon_r \varepsilon_m}}{f h}
\]

(4)

where \( f \) = frequency of the designed antenna, \( c \) = light velocity, \( \varepsilon_r \) = effective permittivity of medium.

\[
\varepsilon_e = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2} \left( 1 + \frac{12h}{W} \right)^{-1/2}
\]

(5)

4. Design evolution of the proposed 2 × 2 patch antenna

In the proposed design, five inner circles are loaded in the circular patch each decreasing continuously by a factor of 1 mm and three stages are implemented where the antenna is first designed using a single patch, then the antenna is designed using a 1 × 2 patch format and finally the antenna is designed using 2 × 2 patch as shown in the Figure 3.

The iterations and number of circular cross-sections are mentioned in Table 3 with the impedances of fractal antenna is shown in Figure 4.

The equivalent input impedance of the chakra-shaped fractal antenna with single, 1 × 2 and 2 × 2 patch are provided in Equation (6), as for single patch there are six circular slots, for 1 × 2 patch there are 12 circular slots and 24 for 2 × 2 patch, respectively (Li et al., 2020).

\[
Z_{\text{total}} = \frac{1}{Z_p} + \frac{1}{Z_q} + \frac{1}{Z_r} = \frac{1}{Z_{sp}} + \frac{12}{Z_{sq}} + \frac{24}{Z_{sr}}
\]

(6)

where \( Z_p, Z_q \) and \( Z_r \) are the equivalent impedance of similar circular slots loaded on to

Table 3. Comparison of number of slots for the designed antenna.

| Iterations            | Chakra shape           |
|-----------------------|------------------------|
| \( N \)th stage       | 6 \( \times 2^{(n-1)} \) Circular Slots |
| First stage (single patch) | 6 \( \times 2^0 = 6 \times 1 = 6 \) |
| Second stage (1 × 2 patch) | 6 \( \times 2^1 = 6 \times 2 = 12 \) |
| Third stage (2 × 2 patch) | 6 \( \times 2^2 = 6 \times 4 = 24 \) |
the antenna of different stages and can be calculated as

\[
Z_p = \frac{1}{\frac{1}{Z_{sp1}} + \ldots + \frac{1}{Z_{sp6}}} = \frac{Z_{sp}}{6}; \quad Z_{sp} = Z_{sp1}\ldots
\]

(7)

\[
Z_q = \frac{1}{\frac{1}{Z_{sq1}} + \ldots + \frac{1}{Z_{sq12}}} = \frac{Z_{sq}}{12}; \quad Z_{sq} = Z_{sq1}\ldots
\]

(8)

\[
Z_r = \frac{1}{\frac{1}{Z_{sr1}} + \ldots + \frac{1}{Z_{sr24}}} = \frac{Z_{sr}}{24}; \quad Z_{sr} = Z_{sr1}\ldots = Z_{sr24}; \quad \text{(third stage with 24 slots)}
\]

(9)

Figure 4. Circuit diagram of designed antenna.
The antenna performance parameters can be calculated using total input impedance for all the three stages combining as \( Z_{\text{total}} \)

\[
\text{Reflection Coefficient, } \Gamma = \left( \frac{Z_{\text{total}} - Z_0}{Z_{\text{total}} + Z_0} \right)
\] (10)

4.1. **Parametric study of \( S_{11} \) parameter for different antenna configurations**

The parametric investigations are performed to observe the variations of reflection coefficients for different design evolution stages. Figure 5 provides the parametric study of \( S_{11} \) for all the designed antenna structures, single patch, 1 × 2 patch and 2 × 2 patch configurations. It can be observed that as the numbers of elements are increased, the reflection coefficient is reduced and number of resonating points has increased. So, with the suggested 2 × 2 patch array configuration, the antenna resonates at multiple bands with enhanced operating bandwidths.

The design and analysis execution flowchart of the proposed 2 × 2 multi-patch antenna models is presented in Figure 6.
Figure 6. Detailed design and analysis flow chart of the designed antennas.
5. Results and discussion

5.1. Simulation

The simulation studies are performed using HFSS EM solver, with the operating frequency from 25 GHz to 36 GHz and the analysis has been carried out on single patch and multi-patch antenna separately. Figure 7 shows the surface current all over the patch, the electrical field is strong throughout the antenna and provides good stability, and radiates maximum energy which is received at the port. Maximum current distribution is available at the centre of the proposed multi-patch antenna with high magnitude at the edges of the patch for the resonating frequency of 32.8 GHz.

The antenna design is simulated for the frequency ranging from 25 GHz to 36 GHz and for the process of calculating the bandwidth, the first step is to find out the $S_{11}$ of both the antennas. Figure 8 represents the reflection coefficient vs. frequency characteristics of the single patch and multi-patch antennas. It is evident from the portrayed figure that the suggested multi-patch antenna provides better performance and multiple resonating frequencies compared to the single patch antenna structure. As observed in Figure 8(a), the single patch antenna provides dual-band resonant characteristics as per observation below $-10$ dB level of $S_{11}$ parameter. However, very good reflection coefficient is observed at higher resonance with a highest attained value of $-18$ dB at the resonant frequency of 31.6 GHz. As per Figure 8(b), the multi-patch antenna provides penta band operation considering $S_{11} \leq -10$ dB with significant bandwidths at each operating bands of 27.1, 28.5, 30.1, 32.8 and 34.8 GHz with the reflection coefficients of $-20.01, -18.36, -14.96, -27.71$ and $-24.19$, respectively. The best value of reflection coefficient is recorded as $-27.71$ dB at the frequency of 32.8 GHz in the operating frequency.

The VSWR values are shown in Figure 9. As indicated in Figure 9(a), VSWR of the single patch antenna is computed the values are within the maximum applicable limit of 4 in vehicular communication for the resonating points. The minimum VSWR for single patch antenna is observed at 31.6 GHz with a value of 1.08. On the other hand, due to the incorporated feed geometry, the proposed multi-patch antenna shows improvement in impedance matching and as a result minimum VSWR of 0.423 is obtained at 34.75 GHz.
The acceptable VSWR confirms that well impedance matching the designed structures and ensure low mismatch losses associated with the suggested designed antenna models such that these antenna models can be used practically.

Figure 10 provides the radiation pattern of $2 \times 2$ antenna at operating bands of 27.1, 28.5, 30.1, 32.8 and 34.8 GHz for both E-plane and H-plane of multi-patch antenna.

At 27.1 GHz, 7.63 dB gain is achieved with the theta ranging from $-20^\circ$ to $+20^\circ$ with the phi value of $90^\circ$, and at 28.5 GHz, 9.43 dB gain is achieved with the theta ranging from $-40^\circ$ to $+40^\circ$ with phi value of $0^\circ$. At 32.8 GHz, 9.17 dB gain is achieved with the theta ranging from $-30^\circ$ to $+30^\circ$ with the phi value of $0^\circ$ and at 34.8 GHz, 5.27 dB gain is achieved with the theta ranging from $-30^\circ$ to $+30^\circ$ with the phi value of $0^\circ$. The achieved values imply that the radiation pattern is best suitable for vehicular communication as it is spread out in forward directions and for moving vehicles the radiation should be towards the target with at least $20^\circ$ (Zhu & Langley, 2009) and the proposed design is suitable with a range of at least $40^\circ$ overall.
Figure 11 provides the details about total gain with the primary sweep of frequency at theta and phi at 0°. The gain of the single patch antenna reaches the maximum gain of 8.2 dB, and for most of the frequency range, the gain is greater than or equal to 3 dB. The range starts from 25 GHz and stays greater than 3 dB till 34.5 GHz. The gain of the multi-patch antenna reaches the maximum gain of 6.72 dB at resonating frequency of 32.8 GHz and 6.69 dB at 28.5 GHz, respectively.

5.2. Fabrication and measured results

The process for fabrication starts with exporting both patch and ground separately in the form of dxf files by keeping z-axis as zero and dip trace software is used to combine both the patch and ground as single entity and then exported with an extension used is grb. This file is then opened in eagle software which is used to interface the single-sided CNC machine for fabrication which consists the precision of 95% efficiency and the material used for fabrication is Rogers RT duroid 5880tm. The time required for fabrication depends on the layers of antenna and the structure of patch. The proposed antenna took around 60 min for fabrication. Then the fabricated antenna models are connected with an SMA connector. The prototypes of the fabricated antennas are shown in Figure 12.

The antenna after fabrication is tested under an experimental confined laboratory with a highly précised Vector Network Analyzer of Agilent Technologies N5247A with a range of 1 GHz–50 GHz with both 1 dB and 2 dB sweep which is very much helpful for the futuristic frequencies. Figure 13 provides the snapshot of the measurement set up of antennas connected with VNA. The simulated and measured values are compared to provide information regarding the deviation of obtained results. The comparisons of measured and simulated $S_{11}$ parameters for the single patch antenna and proposed array antenna are shown in Figures 14 and 15, respectively. The detailed results are summarized in Table 4. The measured and simulated $S_{11}$ results are almost similar and the array
antenna with multi-patch elements possesses better results compared to the single patch and the performance has improved in reflection coefficient, number of operating bands, and bandwidth.

Figure 10. Radiation patterns for E-plane represented in black and H-plane represented in red colour of multi-patch antenna at (a) 27.1 GHz, (b) 28.5 GHz, (c) 30.1 GHz, (d) 32.8 GHz, (e) 34.8 GHz.
Table 4 provides the comparison between the simulated and measured $S_{11}$ for both the single patch and multi-patch antenna. It can be concluded that due to the suggested array configuration, the antenna operates at more number of distinct operating bands with enhanced impedance bandwidths. In fact, the number of resonating frequencies has increased from two to five which makes the proposed array configuration suitable for multiple applications at the lower band spectrum of the upcoming 5G technology.

Table 5 provides a detailed comparison between the proposed antennas and work carried out by various researchers under fractal antennas, 5G and multi-band applications. The 2 × 2 antenna achieved penta bands in the frequency ranging 25 GHz–36 GHz, and a combined simulated bandwidth of 4650 MHz with a peak gain of 6.72 dB. The proposed design is able to achieve higher bandwidths compare to other models but unable to enhance the total gain of the antenna but the gain is in acceptable range. This comparison clearly indicates that the proposed antenna performance is better in

Figure 11. Total gain of single patch and 2 × 2 antennas.

Figure 12. Fabrication of (a) single patch (b) multi-patch antenna.
Figure 13. Testing of (a) Single patch antenna (b) multi-patch antenna.

Figure 14. Comparison of measured and simulated $S_{11}$ of the single patch.

Figure 15. Comparison of measured and simulated $S_{11}$ of proposed multi-patch antenna.
the area of bandwidth and good standing wave ratio compare to the antennas provided as reference.

6. Conclusion

A single patch and $2 \times 2$ patch fractal geometry-based chakra-shaped microstrip patch antenna for vehicular communications is investigated and discussed in this paper. The $2 \times 2$ patch covers five operating bands in the range of 25 GHz–36 GHz. The gain of the antenna reaches the maximum gain of 6.72 dB at resonating frequency of 32.8 GHz and 6.69 dB at 28.5 GHz respectively. The reflection coefficients of $-20.01$, $-18.36$, $-14.96$, $-27.71$ and $-24.19$ respectively achieved at operating bands of 27.1, 28.5, 30.1,
32.8 and 34.8 GHz. Maximum current distribution is achieved at the centre of the proposed multi-patch array antenna with high magnitude at the edges of the patch for the resonating frequency of 32.8 GHz. A good agreement between the experimental and simulated results justifies the suitability of proposed antenna for vehicular communications as it needs multi-band antennas for its communication with good peak gain and better bandwidth. The proposed antenna has enhanced the overall bandwidth to 4650 MHz in the 5G proposed lower band spectrums for vehicular communications.

Acknowledgements

This paper and the research behind it would not have been possible without the exceptional support of my supervisor. His enthusiasm, knowledge and exacting attention to detail have been an inspiration and kept my work on track. We thank our colleagues from Lovely Professional University, Phagwara, Punjab, India who provided insight and expertise that greatly assisted the research. We are also immensely grateful to all our friends for their comments on the preparation of the manuscript, although any errors are our own and should not tarnish the reputations of these esteemed persons.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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