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High Gain Automobile Antenna for Vehicular Communication of IoV Systems in 5G Network

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Abstract

A tetra-circle fractal feeder for conventional Vivaldi antenna (CVA) is designed, simulated, fabricated and measured. The antenna is designed to full cover of frequency bands of sub-6 GHz band with channels n78 (3.3 GHz - 3.8 GHz), n77 (3.3 GHz - 4.2 GHz), n79 (4.4 GHz - 5 GHz), and n46 (5.150 GHz - 5.925 GHz). These bands are used for fifth-generation (5G) New Radio (NR) bands. The novelty of the proposed antenna is focused on fractal feeder approach for gain improvement in the low frequency band of CVA antenna while maintaining gain performance in 5G NR frequency bands and within vehicular applications. Wideband, high gain, good directivity, and low-profile design are achieved. The proposed antenna is designed based on a CVA as a reference antenna and then a fractal-shaped feeder is introduced for the CVA. The antenna is simulated in free space as well as over voxel model of vehicle body then fabricated. The measured frequencies 3.3 GHz - 6.5 GHz (3.2 GHz bandwidth) are achieved with a minimum reflection coefficient of -28.52 dB and maximum gain of 7.6 dBi, respectively. The simulation and measurement results are compared. Moreover, the measured results are compared with Wideband based MIMO antenna array, Quad-band based modified Vivaldi antenna, Fractal loaded based two- and eight-element MIMO, and Cross-Joint based Vivaldi antenna pair. The proposed tetra-circle fractal feeder for CVA antenna overcomes these works in terms of high gain over operating bandwidth, good matching impedance and high front to back ratio with comparable size.

Keywords: conventional Vivaldi antennas, scanning antenna, fractal, vehicle to everything (V2X), vehicular antennas.

1.Introduction

Due to the rapid and increasing development of wireless communications applications for vehicles with the beginning of the 5G [1]. The Vehicle-to-everything (V2X) has become a part of this system. Therefore, V2X allows to communicate between vehicles or a vehcile and the infrastructures around it. This gives the vechile early knowledge of traffic signals, road congestion, road signs, status of other vehicles, and pedestrians[2], [3]. V2X has the potential issue of ensuring good coverage to support multiple services with 5G[4].

5G technologies have become significantly interesting in data rates speeds with lower latency and greater reliability. In addition, it have been developed into a 5G NR which enabling the devices to communicate wirelessly over the 5G network [5], [6], [7]. A wide band of compact planar antennas are the appropriate solution for V2X to meet the performance requirements of 5G NR networks[8], [9].

In recent decades, the researchers have become interest in the upper mid-band of 5G NR which refers to the frequency range between 3.5 GHz to 6 GHz [10]. This band is crucial for 5G NR deployment as it provides a good balance between coverage and capacity [8], [11], [12]. Therefore, maintaining a good directive antenna is reqired to ensure that this balance is achieved. While providing reasonable coverage, frequencies in this range allow for faster data speeds and better performance [13], [14]. Furthermore, wide band with high gain of planar antenna is the appropriate solution for the development of 5G NR technologies in V2X requirements with wireless communications and then their association with cloud services [15], [16], [17].

In this work, a directional of Vivaldi antenna shape with new feeding technique is designed, simulated, and fabricated. The Computer Simulation Technology - Microwave Studio (CST-MW) is used as the simulation software. The proposed antena contains new feeding design approach to achieve high gain of wide band with tetra-circle fractal patch antenna. The design initially begins with a CVA of traditional feeding technique, radial stub feed (RSF). Then intermediate steps of feeding design have successfully applied to get a gain enhancement for the upper mid-band of frequency spectrum, circular fractal feed (CFF). The CFF enables to expand the impedance matching toward the upper mid-band of 5G NR. The CFF significantly enhancing the gain without increasing antenna size when compared with the RSF.

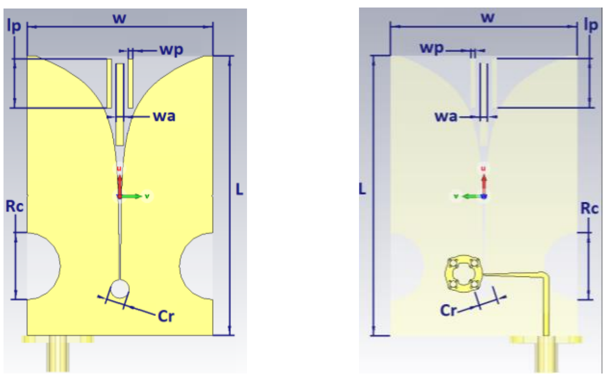
Finally, the antenna was fabricated and the measurement results were compared with the simulation results as well as the comparison with four recently published works which are wideband based MIMO antenna array [8], quad-band based modified Vivaldi antenna [15], fractal loaded based two- and eight-element MIMO [18], and Cross-Joint based Vivaldi antenna pair [19].

2.Antenna Desing

A wide band, low profile, directivity over frequency range, high front-to-back ratio, good gain, high durability, and scan angle capabilities are required for V2X applications. Therefore, the antenna is designed to resonate from 3.5 GHz to 6.4 GHz to meet the IoV requirements with 5G NR technology. Theoretical equations of CVA are used to estimate the minimum frequencies range, substrate dimensions, the length of opening tapered curve, and other basic parameters. Due to the variables limitation which is used in the theoretical equations of CVA, CST-MW software is used to simulate, analyze, and optimize the proposed antenna design. This software uses a large number of variables required during the simulation process. Moreover, the simulation results are been more accurate and dependable for the fabrication process.

In this paper, a new geometrical feeder configuration design is proposed with CVA of coplanar waveguide (CPW) shape approach. It maintains a wideband antenna bandwidth which covers the upper mid-band of 5G New Radio (5G NR) band (between 3.5 GHz to 6 GHz) services. The antenna design provides a vehicular scannable directive roof top antenna with wide bandwidth of the resonant frequency to cover 3.5 GHz - 6.4 GHz of sub-6 GHz frequency range band services.

The proposed antenna design is based on three steps of a procedure, starting with the traditional Vivaldi antenna (step 1), then the fractal feed concept based on the zero- and order of annular-shaped structure (step 2), and finally three parallel-shaped line as parasitic element with embedded semicircular patch elements are inserted (step 3). The geometrical steps of the proposed antenna configuration are shown in Figure 1. The antenna is designed using a Sub-Miniature version A (SMA) connector and a flame retardant (FR-4) substrate with 4.3 relative permittivity of dielectric constant (ε_r) and 0.025 of dielectric loss tangent (tan δ) coated by annealed copper of 0.035 mm on both sides, with thickness 0.78 mm and having dimensions 75 × 50 mm^2 (L x W). The optimized values of the proposed antenna dimensions are summarized in Table 1.



(a) (b)

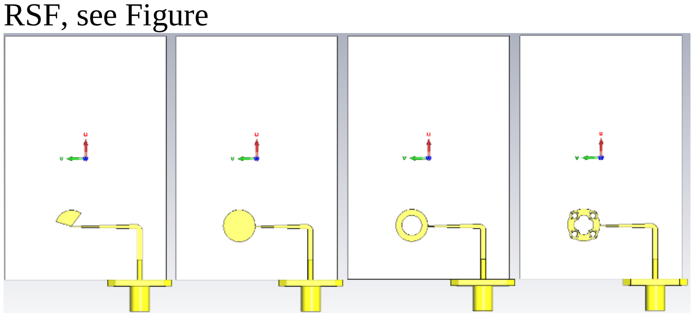
Figure1. Configuration of the proposed fractal antenna structure: (a) GND layer (front view) and (b) feeder layer (back view).

Table1. Antenna design parameters.

Antenna parameter	Dimensions (mm)
L	*75*
W	*50*
l_p	*10.69*
w_a	*1.62*
w_p	*0.97*
C_r	*4*
R_c	*14.58*

The geometrical model is started with the following steps:

Step one, the CVA was designed for wide band antenna based on a sector-shaped area of the RSF, see Figure



(a) (b) (c) (d)

Figure2. Geometry of the proposed feeder (a) RSF (feed0), (b) CSF (feed1), (c) ASF (feed2), and (d) TCS (feed3).

The CVA are designed as reference planar antenna with RSF, feed0. The following formula of CVA are used for the proposed antenna to define the exponential equation, as shown below [20] and [21]:

Tapered curve profile:

$$y_A = S_1 e^{R1} + S_1 \quad (1)$$

$$y_B = S_2 e^{R1} + S_2 \quad (2)$$

Length of the opening tapered profile:

$$S_1 = \frac{X_2 - X_1}{e^{R2y2} - e^{R1y1}} \quad (3)$$

$$S_2 = \frac{X_2 e^{R2y2} - X_1 e^{R1y1}}{e^{R2y2} - e^{R1y1}} \quad (4)$$

The length (L) of the CVA:

$$0.2\lambda \leq L \leq 0.5\lambda \quad (5)$$

Opening width of tapered curve:

$$2w < \frac{c}{fH\sqrt{\varepsilon_e}} - d \quad (6)$$

$$0.06\lambda \leq d \leq 0.09\lambda \quad (7)$$

Substrate height (H):

$$H \gg 0.003\lambda \quad (8)$$

Where ε_r, λ, (x_1, y_1), and (x_2, y_2) are represented the dielectric constant, the wavelength of operating frequency the starting and ending point of the exponential curve profile, respectively.

Step two, The RSF was redesigned in order to improv the gain for wide band of CVA, based on circular-shaped feeder (CSF), feed1, and zero-order annular-shaped feeder (ASF), feed2, are presented. CSF is a reference feeder while ASF is fractal concept design of zero-order feeder, see Figure 2. They are closely related to each other where the parameters values and the size dimension of them are equal. Consequently, it is approximately equal to twice the value of the effective radius ($2r_e$) structure with the following circular formula:

$$r = \frac{K}{\sqrt{1 + \frac{2H}{\pi \varepsilon_r K}\left[ln\frac{\pi K}{2H} + 1.7726\right]}} \quad (9)$$

$$K = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}} \quad (10)$$

The effective radius of patch is given by

$$r_e = r\sqrt{1 + \frac{2H}{\pi \varepsilon_r r}\left[ln\left(\frac{\pi r}{2H}\right) + 1.7726\right]} \quad (11)$$

The resonant frequency

$$(f_r) = \frac{1.8412 \times c}{2\pi r_e \sqrt{\varepsilon_r}} \quad (12)$$

where c is the speed of the light in free space.

After that, first-order fractal structure of the ASF, as Figure 3 shows, is derived by loading the tetra-circle-shaped (TCS) fractal feeder for CVA, feed3. These four circles' slots are centered equidistantly at the middle of the circumferential portion of the larger circle, feed3. The outer diameter of central slot, feed2, is measured with S diameter so the outer diameter of the first-order is scaled with $S/3$.

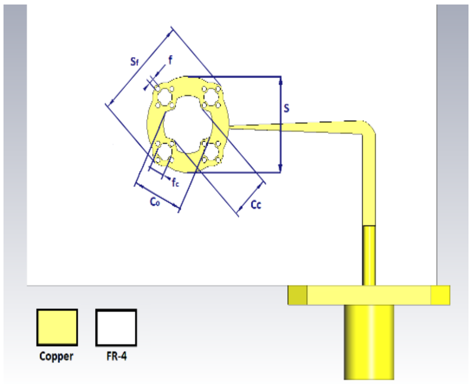


Figure3. Configuration of the TCS feeder for CVA structure.

The optimum performance of the fractal feeder is achieved by ASF and TCS fractal feeder. This parametric study carried out by CST-MW and the optimized values of feeder dimensions are listed in Table 2. Based on TCS optimization values where the value of S=10 mm from simulation, the values of maximum and minimum of effective radius are 11.3 mm and 4.7 mm, respectively.

Table2. Antenna feeder dimensions.

Antenna parameter	Dimensions (mm)
S	9
S_f	9.2
f_c	1.45
C_o	4.86
f	0.437
C_c	3.08

Step three, in order to increase the radiation performance of CVA characteristic with TCS feeder, three parasitic element's structure was added at the focal antenna area as well as two semicircles are embedded besides, as shown in Figure 3.

3.Simulation Results

The proposed antenna is beam steerable antenna through rotating motor outside the roof of the vehicle. Hence, This steerable antenna ensure the possibility of signal tracking. Moreover, strongest connection point is achieved within the 5G NR services. As shown in Figure 4, the proposed antenna is located at the back end of the vehicle roof at a distance of 6 mm above the vehicle body to avoid contact with the vehicle's metal surface. Using CST-MW software the simulation process followed by optimization technique to achieve good simulation results are listed in Table 3.

As a result, return loss, $S11$ curve in Figure 5 shows that the CVA with TCS feeder has upper frequency (f_u) ≅ 6.4 GHz and lower frequency (f_l) ≅ 3.3 GHz. Therefore, the proposed antenna is successively designed to cover the upper mid-band of 5G NR for V2X applications.

Furthermore, the parameters study, radiation pattern, gain, matching impedance, and F/B ratio are evaluated.

(a) (b) (c) (d)

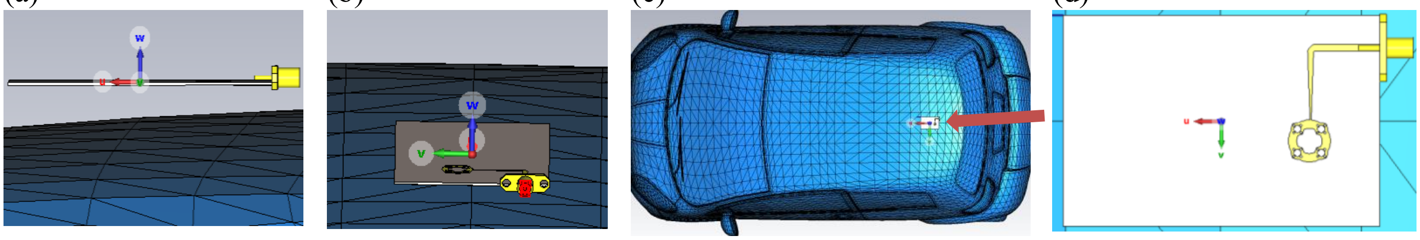


Figure4. Proposed antenna location (a) side view (b) rear view (c) arrow shows the antenna position (d) top view.

Table3. Simulated results of the CVA with different antenna feeder.

Feeder (Unit)	**Frequency band (GHz)**	**Bandwidth (GHz)**	**Matching impedance (dB)**	**Gain (dBi)**	**F/B**	**Linear Efficiency (%)**	**Dimensions (L × W × H) (mm³)**
Feed0							
Feed1							
Feed2							
Feed3	3.31-6.42	3.11	-33.45	8.08	8.78	97.98	75×50×0.78

From Table 3, it can be seen that the proposed antenna is designed to cover the upper mid-band of 5G NR. This band generally range from around 3.5 GHz to 6 GHz to serve the 5G NR frequency bands applications. The proposed antenna ensures that it can be moved at a 360-degree angle to obtain the highest possible signal with wide band antenna. The proposed antenna is designed to full coverage of 5G NR spectrum (sub-6-GHz Band) with channels n78 (3.3 GHz - 3.8 GHz), n77 (3.3 GHz - 4.2 GHz), n79 (4.4 GHz - 5 GHz), and n46 (5.150 GHz - 5.925 GHz) with high S_{11}value of the wide bands. The simulated F/B ratio and gain results of the proposed antenna are plotted in Figure 6. The simulation reveals that the proposed antenna has good F/B ratio of 11.77 and maximum gain of 8.08 dBi over sub-6 GHz bands of 5G NR spectrum, respectively.

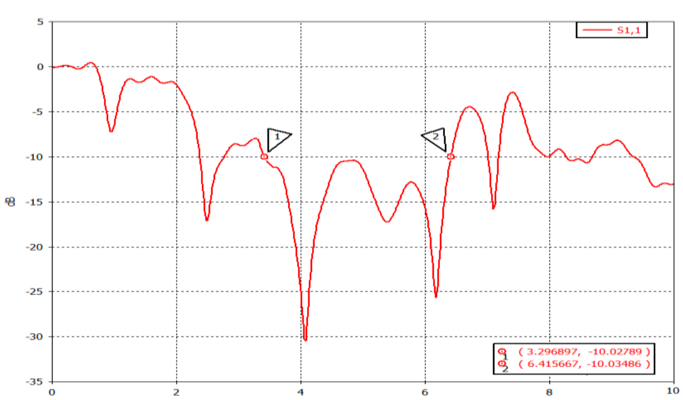


Figure6. Simulated F/B ratio (solid line) and maximam gain (dashed line) over frequencies for the proposed antenna.

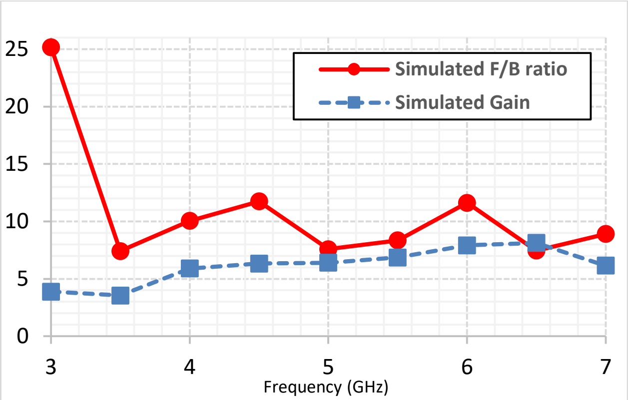
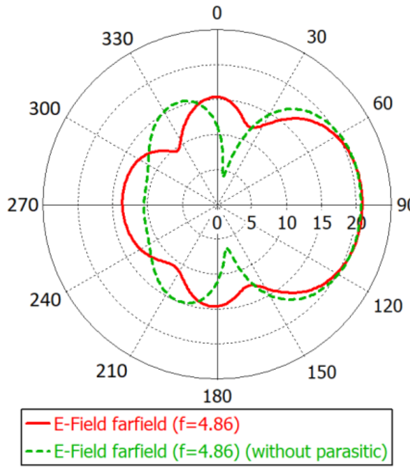
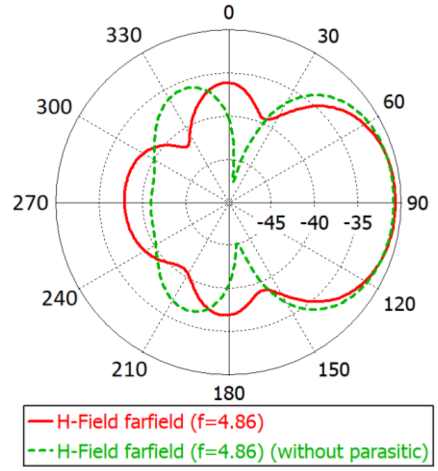


Figure5. CST simulated return loss, S_{11} curves of CVA with TCS feeder.

The simulated far-field radiation patterns directivities of the proposed antenna at resonance frequency are shown in Figure 7. As seen, these plots confirm that the main direction of the radiation pattern is achieved in 90° for both H- and E-plane with ($xxxx$-axis) and ($yyyy$-axis), respectively. Therefore, the proposed antenna works as beam steerable of an end-fire antenna at z-axis propagation direction. Finally, the simulation results for the proposed antenna are revealed a new design of steerable directive beam antenna for V2X applications. Therefore, this design ensures that it can be oriented at a 360-degree angle with a directive radiation pattern. Furthermore, good signal strength is achieved to meet the requirements of 5G NR with V2X services over a wide band range.



(a)



(b)

Figure7. The radiation patterns of farfield with (solid line) and without (dashed line) parasitic element at 4.85 GHz of resonant frequency (a) E-plane (b) H-plane.

4.Measurement Setup

The simulation results yielded good results, and using photo-etching technology, the proposed antenna was fabricated on a FR-4 substrate, as shown in Figure 8. The fabricated antenna has the same dimensions as the simulation, with a thickness of 0.78 mm and a permittivity of 4.3 + j 0.025. Although this type of substrate is lossy material. However, many researchers use this material because of its availability, low cost, and ability to withstand vibration.

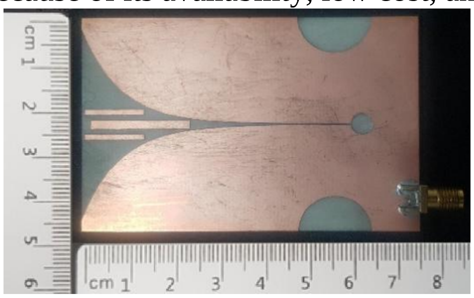


Figure8. Fabricated proposed antenna with dimensions

The proposed design employed CVA with TCS fractal feeder design. The proposed antenna produces a steerable directive beam with wide band antenna. From Figure 8, it can be shown that there is a single SMA connector used to feed the TCS of CVA with 50Ω port connection. In this work, the proposed antenna of CVA with TCS feeder design is fabricated and measured to evaluate the ability of the proposed antenna for achieving the requirements of the 5G NR band for V2X applications.

The measurement setup, illustrate in Figure 9, is used to measure all the practical parameters values, such as the resonant frequency, bandwidth, matching impedance, etc.; Vector Network Analyzer (VNA) (Agilent model E5071C) with two dual polarization horn antennas were a part of this setup. Also, frequency generator (Agilent model N5183A), frequency analyzer (Agilent model E4440A), and microwave absorber chamber played an important role to complete this setup. The rotation process was modeled through the use of a laboratory rotary stepper motor. Finally, the measurement results are clarified and compared with the simulation results as well as with recently works in the next section.

(a) (b) (c)

Figure9. Fabricated proposed antenna (a) on rotator steper motor (b) measurement setup and (c) S_{11}measurement result.

5.Comparison

Figure 10 shows the relationship between the simulation and measurement results. In addition, it can be shown that the manufactured antenna covers the frequencies range of n77, n78, n79 and n46 band, with a slight difference between them. The measurement and simulation results for the proposed antenna are compared and summarized in Table 4.

From Figure 11, it can be seen that the fabricated antenna has closely matching results as compared to the simulation ones. These significant matching results between the simulation and measurement can be attributed due to use high mesh cells during the simulation process, manufacturing precision, real dimension of the substrate thickness, SMA connector losses, and the antenna isolated with an anechoic chamber.

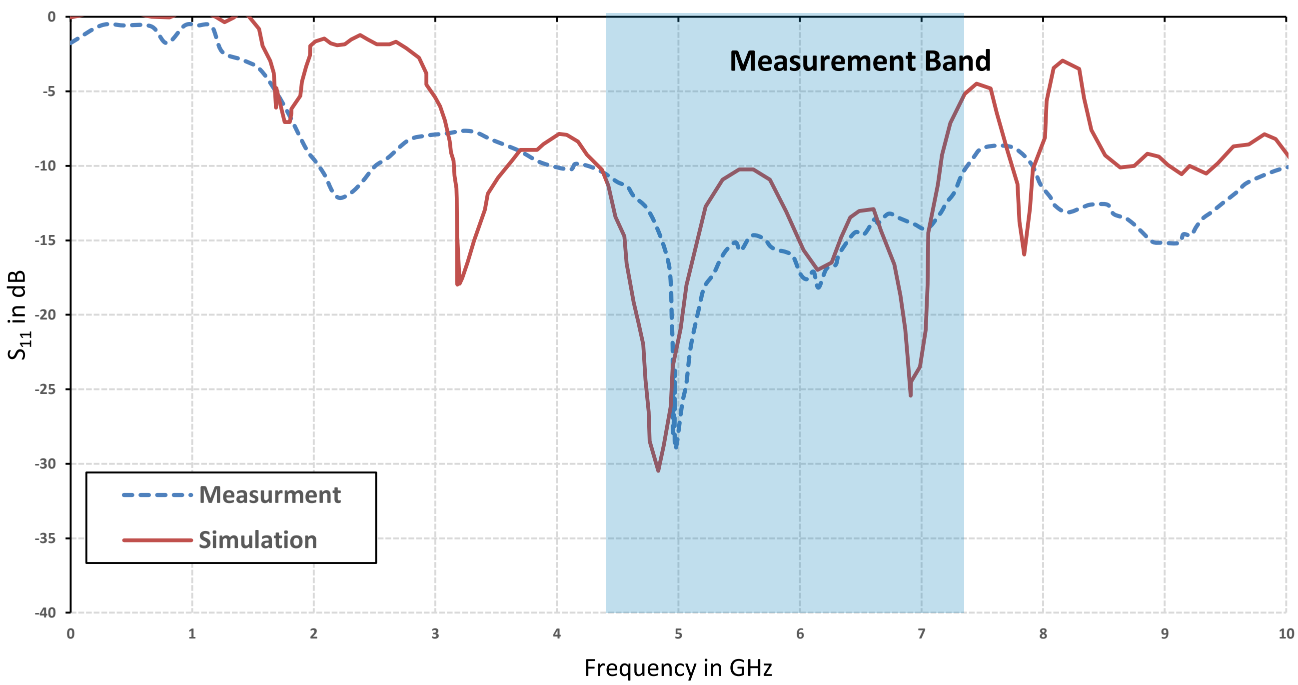


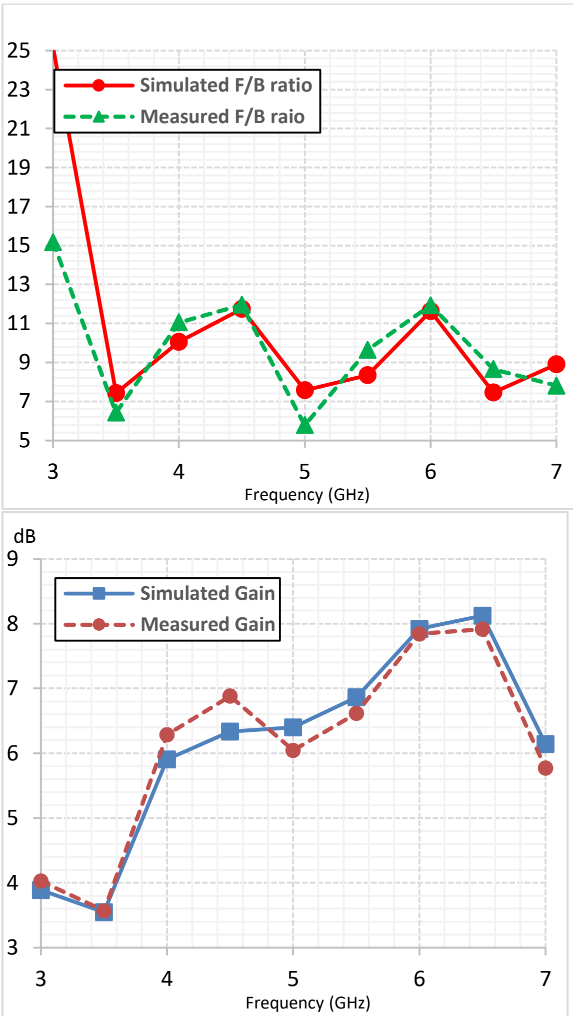
Figure10. Simulation and measurement comparison of S_{11} results.

Table4. The simulated and measurement results comparison.

	Resonant frequency (GHz)	S_{11} (dB)	Frequency band (GHz)	Bandwidth (GHz)	Gain (dB)
Simulation	4.865	-33.45	3.31-6.42	3.11	8.08
Measurement	4.9	-28.52	3.3 - 6.5	3.2	7.6

Moreover, entering a real value for the relative permittivity in CST-MW, which is measured by impedance analyzer. Furthermore, the SMA connector is simulated with the actual dimension instead of using the automatically generated port.

In order to evaluate the CVA with TCS fractal feeder antenna that is proposed in this work, Table 5 lists the performance of the proposed designed antenna with some other antennas that are serve 5G NR of V2X band. Thus, the antenna outperforms them in terms of matching impedance, good gain over wide bandwidth, and comparable size. The Proposed antenna is compared with wideband based MIMO antenna array [8], quad-band based modified Vivaldi antenna [15], fractal loaded based two- and eight-element MIMO [18], and Cross-Joint based Vivaldi antenna pair [19]. It should be noted that these antennas in [8], [18], [15], and [19] resonate at multi bands. However, the proposed antenna full covers of 5G-NR and LTE-4G (or WLAN) frequencies and it has the ability to be scannable beam antenna for V2X applications.



(a) (b)

Figure 11. Proposed antenna with simulated (solid line) and measured (dashed line) of (a) F/B ratio (b) maximam gain over frequencies.

Table 5. Comparison of the proposed antenna performance terms with similar frequency bands structures.

Reference	**Operating Band**	**Frequency band (GHz)**	**Bandwidth (GHz)**	**Matching impedance (dB)**	**Gain (dBi)**	**F/B ratio**	**Substrate**	**Support WLAN/ 5G-NR**	**Dimensions (L × W × H) (mm^3)**	
[8]	n77/n78/n79/ n46	3.25-5.93	2.68	-26	-	- - -	FR-4	Yes/Yes	103.8×68×7	49,408.8

						-				
[15]	Quad band	3.64-4.08 4.15-5.40 5.58-6.16 6.51-7.32	0.41 1.21 0.59 0.41	-21 -28 -15 -13	7.5 6.4 8.5 7.2	- - - -	FR-4	No/Yes	118×85×1.5	15,045
[18]	n77/n78 /n79/n46	3.3-6.0	2.7	-41	>2.5	-	FR-4	Yes/Yes	72×72×1.6	8,294.4
[19]	n77/n78 /n79/n46	2.63-7.15	4.52	-22	5	-	FR-4	Yes/Yes	143×60×0.76	6,520.8
This work	n77/n78 /n79/n46	3.3-6.5	3.2	-28.52	7.9	11.13	FR-4	Yes/Yes	75×50×0.78	2,925

6.Discussion And Conclusions

A tetra-circle fractal feeder of conventional Vivaldi antenna (CVA) has been designed, studied and experimentally investigated. With the first-order fractal radiating structure, TCS feeding the CVA for enhancing the gain over wide bandwidth. The proposed antenna is designed to operate at the n77, n78, n79, and n46 bands of 5G-NR and LTE-4G (or WLAN) frequencies requirements. As required, a new feeding design approach comprising in three steps is introduced to achieve compact high gain over wideband antenna. Starting from wideband reference antenna, CVA. The proposed antenna is characterized by relatively small size (76×46×0.78 mm3) with a device mounted on top of the vehicle.

Instead of a flexible substrate, the suggested antenna is constructed with a rigid substrate of CVA with TCS feeder. However, the mechanical support is especially necessary. Furthermore, unlike a flexible substrate, the vehicle's vibrations will not be affected on the resonance frequency or any other antenna characteristic.

This antenna is suitable for use in V2X communication systems band of 5G-NR and LTE-4G (or WLAN) applications.

From Table 5, it can be seen that the main band which focused on is the sub-6 GHz band with channels n78, n77, n79, and n46 (or 5 GHz WLAN). The proposed antenna has a wider bandwidth than [8], [15], [18] by 0.52 GHz, 0.59 GHz, and 0.5 GHz, respectively. But less than [19] by 1.32 GHz. Moreover, the proposed antenna has the advantage of being single wideband and not divided into several bands. Furthermore, the proposed antenna is smaller in size than [8], [15], [18], [19] by 46,483.8 mm^3, 12,120 mm^3, 5,369.4 mm^3, and 3,595.8 mm^3, respectively.

The gain is one of the important parameters which is considered an issue for the small antenna size. The proposed antenna gain is greater than [18], [19] by 5.4 dBi and 2.9 dBi, respectively, that are located within the n78, n77, and n79 bands. Meanwhile, the proposed antenna gain is less than [15] by 0.6 dBi within the n46 band of the proposed antenna. These results are considered comparable for the small size of the proposed antenna since the antenna is fabricated with the lossy material, FR-4. It is used for both layers of proposed antenna which is considered very cheap and available material. However, it is very difficult to design a highly efficient antenna using this material and maintain both bands.

The main important point is that the proposed antenna reaches a high performance of maximum F/B with 11.3 upper mid-band of 5G NR, with good directivity. By increasing this ratio, signal-to-noise ratio is enhanced. This will increase the antenna's ability to focus its reception or transmission in a specific direction without using a reflector layer. Thus, the propagation field is directed outside the vehicle body. Consequently, the effective range is increased for the propagation field communication.

Therefore, the proposed antenna shows important features that is more applicable in V2X applications with 5G NR bands as compared to the wideband based MIMO antenna array, quad-band based modified Vivaldi antenna, fractal loaded based two- and eight-element MIMO, and Cross-Joint based Vivaldi antenna pair in terms of bandwidth, gain, matching impedance, and high F/B ratio with small antenna size.

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