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A Twelve-Beam Steering Low Profile Patch Antenna with Shorting Vias for Vehicular Applications

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Abstract—A low-profile twelve-beam printed patch antenna is presented for pattern reconfigurable applications. The patch is fed at the four sides using coaxial feeds. Diagonal lines of vias are inserted on the patch surface to restrict currents to the edges. Whilst majority of patch antennas have an axial beam pattern, the proposed antenna produces twelve different tilted beams. When one of its four feeds on the sides is excited and the remaining feeds are open circuited, the antenna generates a linearly polarized tilted beam (6.2 dBi, $\theta_{max} = 30^\circ$). This beam is directed away from feeding patch corner. Therefore, the antenna can steer its tilted beam in four different space quadrants in front of the antenna by exciting one feed at a time. The antenna is also capable of generating eight other beams using multiple feed excitations. They are four additional titled beams (6.03 dBi, $\theta_{max}=30^\circ$), two tilted-twin beam (6.5 dBi, $\theta_{max}=\pm 36^\circ$), one semi-doughnut beam (5.8 dBi) and one axial beam (8.2 dBi). The antenna is designed to operate at test frequency of 2.4 GHz and has a height = 1.5 mm ($\lambda_0/83$). The impedance matching to 50 Ω is achieved using right angle slots etched on the patch antenna.

Index Terms—Microstrip patch antenna, SIW antenna, low-profile antenna, pattern reconfigurable antenna, beam steering, tilted beam.

I. INTRODUCTION

Beam steering antennas are gaining tremendous attention for a variety of different applications, such as cellular and satellite communication, radar system, and Wireless Local Area Network (WLAN) [1]-[3]. These antennas can provide an efficient way to mitigate the multi-path fading phenomena since they can form the beam toward the intended direction, enabling the network to avoid the interference and noise sources. Consequently, they offer higher Single to Noise Ratio (SNR), higher diversity gain and higher rate data-transmission. With smart cities and sensor technology developing to improve our lives we now need, more than ever before, steerable antennas for enabling sensors to achieve longer ranges, higher throughputs and lower power consumption (longer battery up times).

Typically, large wireless networks can use phased array antennas [4] for beam steering and pattern reconfiguration. However, phased array antennas are heavy and expensive, require multiple antenna elements, phase shifters (with

inevitable losses) and complex signal processing for their operation. Therefore, they are not suitable for low price modern commercial portable wireless transceivers.

As an alternative, single element Beam Steering Antennas (BSAs) [5]-[21] have been proposed recently for manoeuvring antenna radiation beam in space. Being single element, these antennas are small, lightweight, require small signal processing and either need no or diminutive phase shifters. The rectangular spiral antenna [5]-[8] was the initial one in this class. To steer its beam, the current distribution over the spiral arm is varied using switches, but the antenna has limited beam steering capability and suffers from pattern variations. Four space quadrant consistent patterns switching were achieved using star [9] and printed square loop antennas [10]-[13]. These employed four feeds which are switched one at a time. The same concept was exploited by [14]-[16]. Another antenna, quasi feed switching antenna, employing p-i-n diodes to switch the pattern in four different space quadrants is reported in [17]. In [18] circular patch surrounded by four parasitic patches that act either as reflector or director depending on the p-i-n diode switching arrangement steers its beam up to nine different angular directions. In [19], a 4-port antenna is proposed for providing four distinct beams. In [20], four microstrip patches are excited by 4-ports to provide two beams which are either linearly polarized conical beam or circularly polarized axial beam. In [21], a 2-port circular microstrip patch antenna is proposed, capable of producing steerable dipole-like radiation patterns for scanning entire azimuth plane. This, however, failed to cover the axial directions. All these approaches provided only tilted beams and no other possible radiation patterns. This meant a large space above the antenna was left uncovered within the 3dB of the main lobe. To fill the gap, this new work focuses on multiport antennas to cover nearly all spatial zones using multi beam radiation.

In this work, we have exploited a specially grounded square patch antenna with four ports for generating 12 different beams to cover most of the space above the antenna. They are 8 tilted, two tilted-twin, one semi-doughnut and one axial. The first 11 beams are either single or multiport feed but do not require any phase shifters. Only the last axial beam requires three fixed phase shifters.

The proposed antenna is of a low-profile design (1.5mm at 2.4 GHz $\sim \lambda_0/83$) which is capable of effective beam steering in

both E and H planes. Similar to [9]-[16], it keeps patterns, polarization and VSWR the same for all switched beams. We have exploited edge radiations from the microstrip square patch antenna to produce tilted beams, which can be steered in space using RF switches. To encourage edge radiation, the square patch has rows of shorting vias, similar to partial SIW [22]-[29], which forces current to stay on the edges. Further, we have undertaken slot matching for edge feeding the patch, similar to [30], which helps the antenna to have low profile. The antenna performances are simulated using CST Microwave studio based on Finite Integration Technique in Time Domain (FIT-TD) [31]. Table I provides a comparison of this work with those of similar works [14]-[16] and [25]-[26]. It shows that this work is new from the aspect of low profile structure, highest tilt, and multiple reconfigurable radiation beams.

Table. I. Performance comparison between the proposed antenna and antennas reported in [14], [15], [16], [25] and [26].

	This work	[14]	[15]	[16]	[25]	[26]
Operating frequency GHz	2.4	2.4	2.9	3.5	10.8	5.2
No. of achievable beams	12	4	5	4	1	1
Height	$\lambda_0/83$	$\lambda_0/19$	$\lambda_0/12$	$\lambda_0/29$	$\lambda_0/18$	$\lambda_0/37$
Size	$0.8\lambda_0 \times 0.8\lambda_0$	$0.8\lambda_0 \times 0.8\lambda_0$	$0.7\lambda_0 \times 0.7\lambda_0$	$0.8\lambda_0 \times 0.8\lambda_0$	$1.43\lambda_0 \times 1.25\lambda_0$	$0.7\lambda_0 \times 0.7\lambda_0$
Tilt angle (degree)	30-43	36	28	31	35	0
Gain (dBi)	5.7-8.2	5.34	7.2	8.27	7.13	7.04
Polarization	LP	LP	LP	LP	CP	CP
Beam steering	Yes	Yes	Yes	Yes	No	No
Patterns consistent in four quadrants	Yes	Yes	Yes	Yes	No	No

II. ANTENNA CONFIGURATION AND REFLECTION COEFFICIENT

Fig. 1 shows the top and side views of the proposed antenna. The square patch is etched on a Taconic [32] TLP-5 substrate ($\epsilon_r=2.2$, $\tan \delta=0.009$) having an area $100 \text{ mm} \times 100 \text{ mm}$ and a thickness of $h=1.5 \text{ mm}$. The whole antenna structure is backed by a ground plane. Each side of the square patch has a length $l_3=76 \text{ mm}$. From the bottom, the patch is fed at four sides using the coaxial line. The feeding points are A, B, C and D and each of them is located at a distance $l_1=32.2 \text{ mm}$ from one corner and $l_2=43.8 \text{ mm}$ from the other corner. Four right-angle shaped slots with dimensions $l_4=5 \text{ mm}$, $l_5=4.9 \text{ mm}$, $l_6=2.4 \text{ mm}$, $l_7=2.1 \text{ mm}$, $l_8=1.2 \text{ mm}$, $l_9=1.6 \text{ mm}$, $l_{10}=1 \text{ mm}$ $g_1=2.3 \text{ mm}$ and $g_2=2 \text{ mm}$ are cut (formed) in the vicinity of feeding points for achieving 50 Ω impedance match, Fig. 1.

Also, as seen in Fig. 1, the four rows of periodic conducting vias shorting the patch to the ground are placed diagonally between the two successive feeding points making an angle

$\alpha=45^\circ$ to the edge of a side. The first via is placed at a distance $d_1=5.2 \text{ mm}$ away from the edge of the horizontal slot. Each set of periodic vias consist of 23 conducting (copper) rods having a diameter of $r=0.6 \text{ mm}$ and the distance between the two consecutive vias is $d=2 \text{ mm}$.

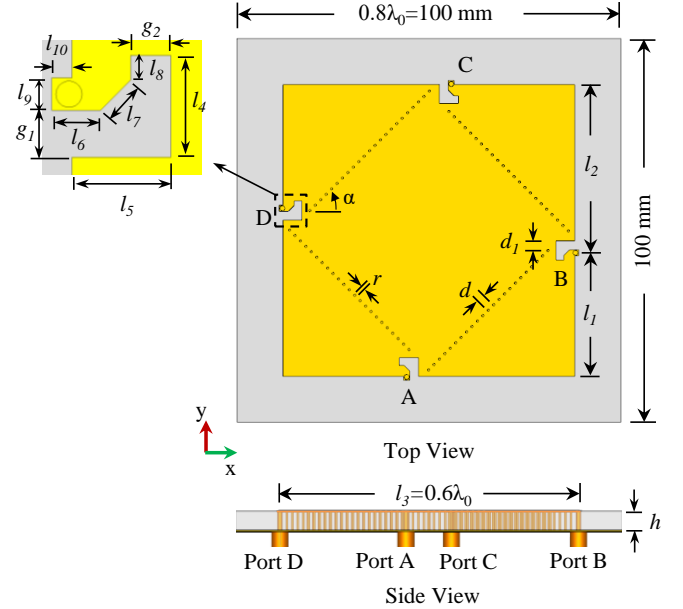


Fig. 1. Top and side views of the proposed antenna.

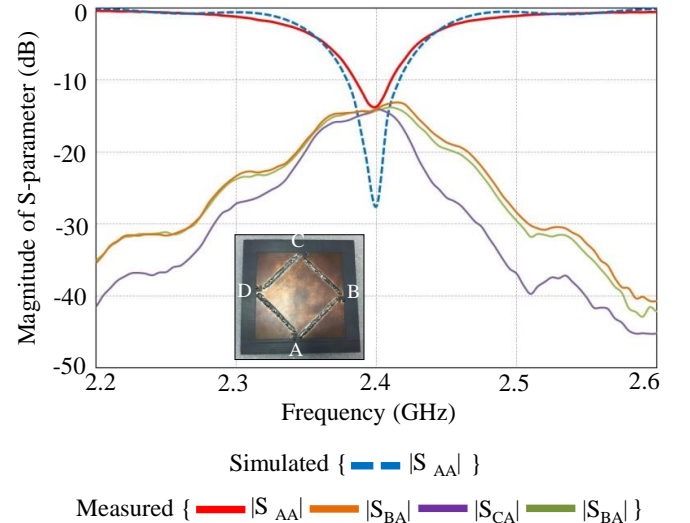


Fig. 2. Simulated and measured reflection coefficients of the antenna for port A excitation and measured isolation at other ports. (Inset) prototype antenna.

Fig. 2 shows the reflection coefficient ($|S_{AA}|$) of the antenna when only port A is excited and remaining ports (B, C and D) are open circuited. The antenna operates in 2.4 GHz (802.11b/g/n) license free band and covers the frequency range from 2.38 GHz to 2.42 GHz. Since the other ports are symmetrical with respect to the antenna structure the reflection coefficient of those ports are expected to be similar to that of port A. The measured isolation (e.g. $|S_{BA}|$) between port A and the remaining ports are more than 15 dB.

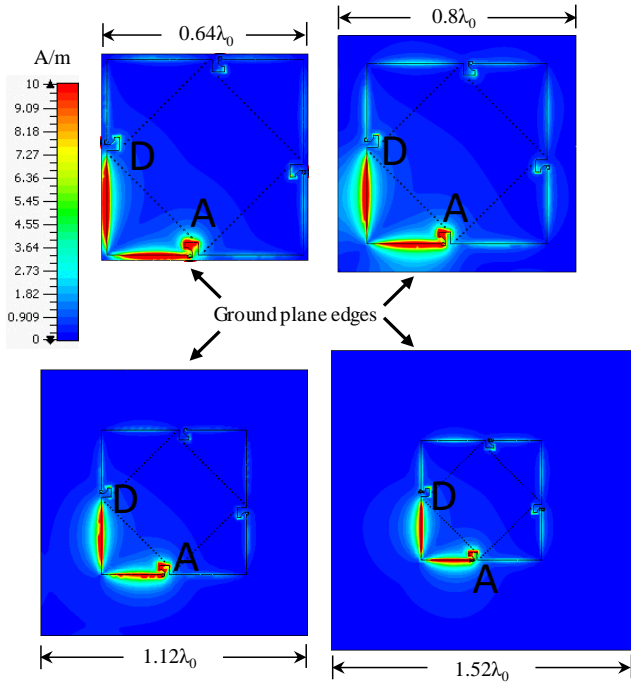


Fig. 3. Simulated current distributions for port A excitation for different sizes of ground plane of the antenna. (Patch dimensions constant at $0.64\lambda_0 \times 0.64\lambda_0$ for all four cases).

III. RADIATION PATTERN RESULTS

Fig. 3 shows the current distributions of the antenna for different sizes ($0.64\lambda_0 \times 0.64\lambda_0$, $0.8\lambda_0 \times 0.8\lambda_0$ etc) of the grounded-substrate (Fig. 1) used in the antenna when port A is excited and the remaining ports are open circuited. It provides a qualitative display of how a tilted beam is formed. Considering Fig. 3, the formation of the tilted beam can be attributed to the interaction of the ground edges with the field from the aperture of the antenna. The periodic vias in the antenna, Fig. 1, behave as a short-circuited electric wall and consequently block the current flow to the other parts of the patch. Therefore, the currents due to port A excitation are concentrated just around the A-D edges of the patch. These A-D edge currents produces antenna aperture fields which interact with the ground plane side edges. This interaction produces a tilted far field beam directed away from A-D corner of the patch. It was further found that it was the size of the ground that influenced the beam tilt angle, as shown in Fig.4.

Fig. 4 shows the variation of the beam tilt of the maximum radiation in both elevation (θ_{max}) and azimuth (ϕ_{max} at cut angle of $\phi = 45^\circ$) planes for different dimensions of the ground plane. It is found that when the side length of the square ground plane is increased from $0.6\lambda_0$ to $0.8\lambda_0$, the tilt angle increases from 16° to 30° . The tilt angle decreases, with a larger dimension than $0.8\lambda_0$ and the radiation pattern becomes axial (axial beam) beyond the dimension of $1.2\lambda_0$. The direction of the maximum radiation in the azimuth plane remains constant at 45° . Since, the ground plane dimension of $0.8\lambda_0 \times 0.8\lambda_0$ (100mm \times 100mm) exhibits the maximum tilt, $\theta_{max}=30^\circ$, it is selected for designing the proposed antenna.

Fig. 5 shows polar cuts of the normalized radiation pattern of the antenna at the operating frequency of 2.4 GHz when only

port A is excited and remaining ports (B, C and D) are open circuited. The antenna generates a tilted beam with the maximum radiated field located at $\theta_{max}=30^\circ$ away from the zenith (z-axis) and directed away ($\phi_{max}=45^\circ$) from the adjacent corner. The antenna has a maximum gain of 6.2 dBi in the direction of maximum radiated field. The main lobe is linearly polarized (E_θ) and the cross-polarized components (E_ϕ) are approximately 25 dB down in the direction of the main beam.

Since ports A, B, C and D are symmetrically located around the patch, the associated radiation patterns of any of these ports are similar. Therefore, by exciting A, B, C or D individually (one at a time), the antenna can steer its linearly polarized tilted radiation ($\theta_{max}=30^\circ$) in four quadrants of ($\phi_{max}=45^\circ$, $\phi_{max}=135^\circ$, $\phi_{max}=225^\circ$ and $\phi_{max}=315^\circ$).

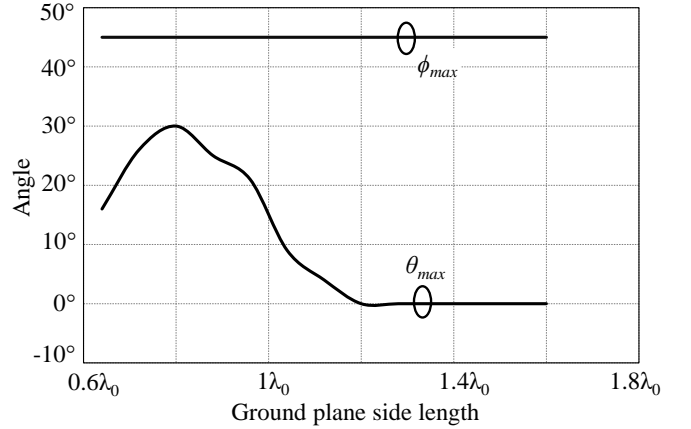


Fig. 4. Variation of the radiation pattern tilt angle with the variation of ground plane dimension. (Patch dimensions constant at $0.64\lambda_0 \times 0.64$).

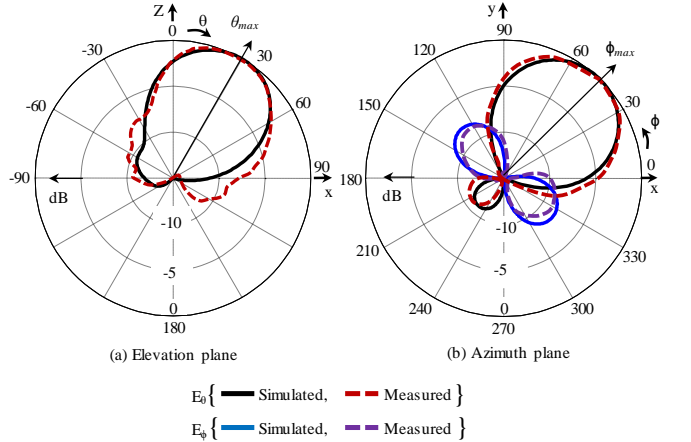


Fig. 5. Tilted beam at 2.4 GHz with only Port A excited (a) Elevation cut at $\phi_{max}=45^\circ$, (b) Azimuth cut at $\theta_{max}=30^\circ$.

IV. MULTI-PORT FEEDING FOR ADDITIONAL BEAMS

As discussed in the previous section, the proposed antenna can generate four tilted beams by switching through its feed. However, in the middle of two beams ($\phi_{max} = 0^\circ, 90^\circ, 180^\circ$ and 270°) the gain of the antenna drops by 5 dB (Fig. 4(b)). This creates signal power drops (holes) in the full azimuth beam steering. In addition, the maximum gain in the zenith direction is only 4 dBi. This is a drawback if axial transmit / reception services are required. These limitations of the antenna can be

overcome by exciting multiple ports simultaneously. In fact, in this way, the proposed antenna can provide eight additional new beams. They are four tilted beams directing towards the power-dropped azimuth directions, two tilted-twin beams, a semi-doughnut beam and an 8.2dBi high gain axial beam.

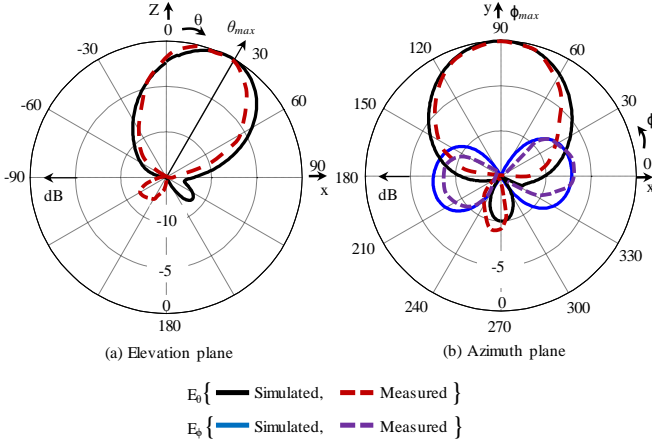


Fig. 6. Tilted beam at 2.4 GHz with ports A and B excited simultaneously, (a) Elevation cut at $\phi_{max} = 90^\circ$, (b) Azimuth cut at $\theta_{max}=30^\circ$.

A. Additional four new tilted beams to enable seamless azimuth beam steering using dual feeding

To recover the signal in power dropped zones two adjacent ports of the antenna are fed simultaneously with equal amplitudes and phases. This dual feeding generates a tilted beam directing towards a quadrant opposite to that of the left feeding port (observing from the top). For instance, if port A and port B are fed simultaneously, the antenna radiates a tilted beam of $\theta_{max}=30^\circ$ in the direction of $\phi_{max}=90^\circ$ (opposite to that of feeding port A). Fig. 6 shows the polar cuts of this new linearly polarized (E_{θ}) tilted beam with a gain of 6.03dBi. Similarly by dual feeding port B and C, C and D, and D and A, a 6.03 dB tilted beams can be generated in three quadrants $\phi_{max}=180^\circ$, $\phi_{max}=270^\circ$ and $\phi_{max}=0^\circ$, respectively. Therefore, a complete seamless (signal power drop holes of less than 0.5 dB) full-azimuth steering can be realized by combining both single and dual feeding configuration. This is shown in Fig 7.

B. Tilted-twin beams using dual feeding

Tilted-twin beams provide a theoretical doubling of network capacity without substantially increasing cost and size. At the same time, it can improve throughput and provide better, faster and consistent Quality of Services (QoS) to the subscribers [33]. We find that if two opposite ports are fed together with the same amplitude and phase, twin beam is generated. This twin beam has a gain of 6.5 dBi, same as that of single fed tilted beam. The direction of the twin beam is at the left diagonal to the line joining the two feeds (observing from the top). For instance, if ports A and C are excited together, the antenna provides a tilted-twin beam with $\theta_{max}=\pm 36^\circ$ in the direction of $\phi_{max}=45^\circ$ and 225° (noted as $45^\circ/225^\circ$). Fig. 8 shows the 3D pattern and polar cuts of tilted twin-beams due to ports A and C and each beam has a gain of 6.5dBi in the direction of maximum radiation. Similarly, another tilted-twin beam can be

generated in the direction of $\phi_{max}=135^\circ/315^\circ$ by exciting ports B and D simultaneously with equal amplitude and phase.

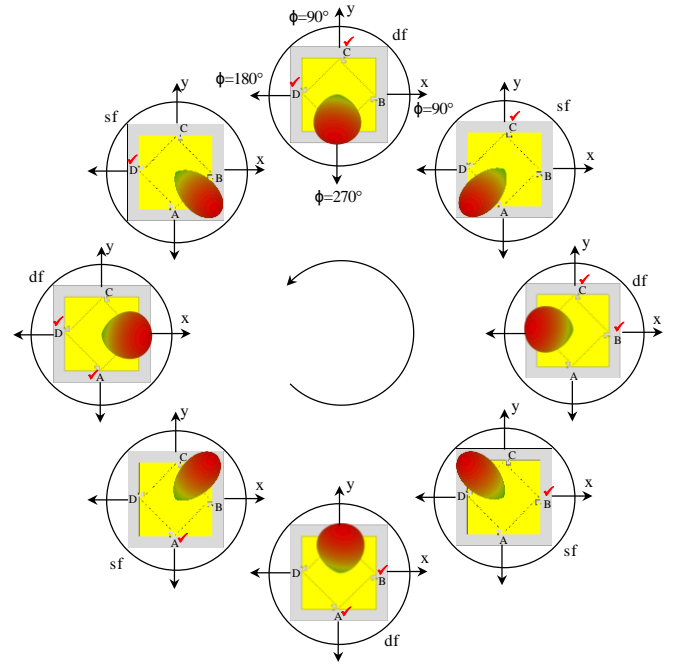


Fig. 7. Demonstration of beam steering with tilted beams using sf ('single feed' configuration) and df ('dual feed' configuration).

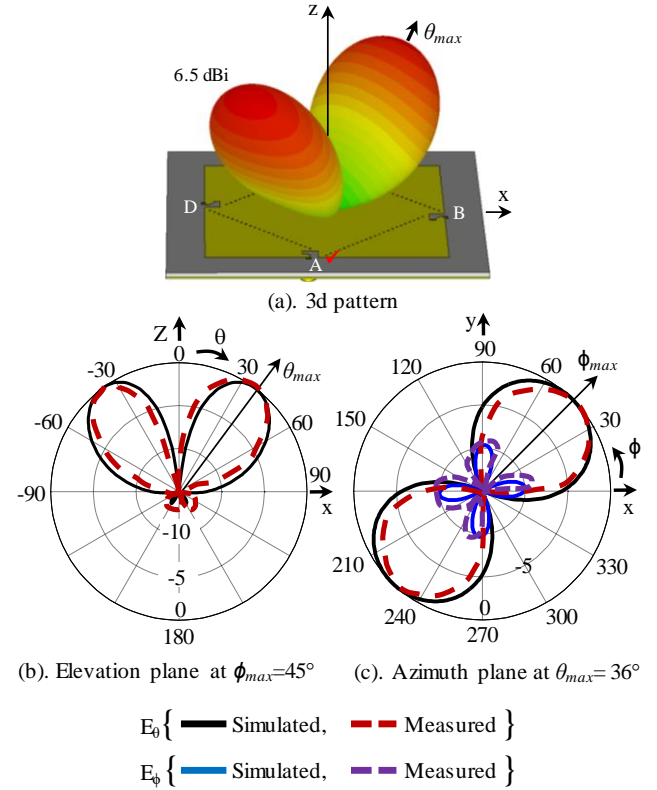


Fig. 8. Tilted-twin beams at 2.4 GHz with port A and C excited together; (a) 3D pattern, (b) Elevation cut at $\phi_{max}=45^\circ$ and (c) Azimuth cut at $\theta_{max}=36^\circ$.

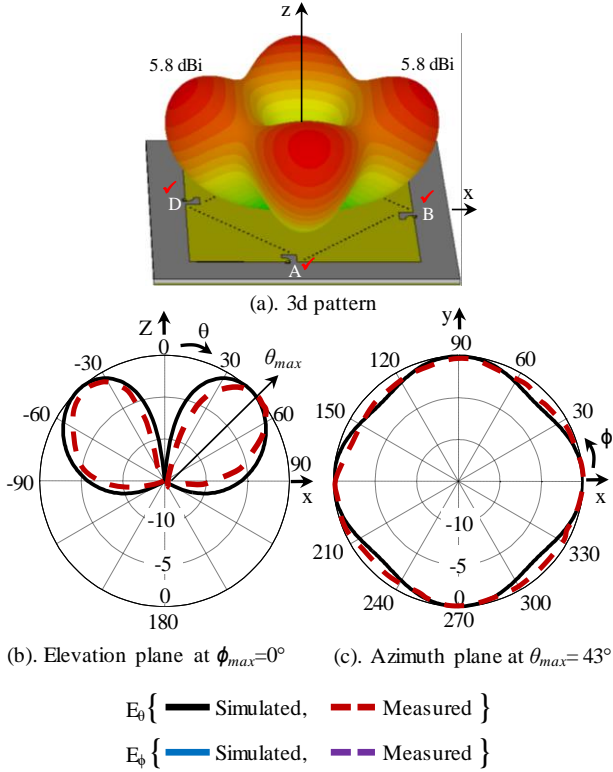


Fig. 9. Semi-doughnut beam at 2.4 GHz; (a) 3D pattern, (b) At $\phi_{max}=0^\circ$, and (c) at $\theta_{max}=43^\circ$.

C. Semi-doughnut beam using four port feeding

Ideally, the antennas for vehicular communication systems have a radiation pattern which receives signals from all the side directions and nothing from top. This condition requires a semi-doughnut pattern [34]. It is found that besides having steerable tilted beams and tilted-twin beam, the antenna would provide semi-doughnut pattern. This is achieved by simultaneously exciting all the four ports with currents of equal amplitude and phase. Fig. 9 shows the 3D pattern and polar cuts of the semi-doughnut pattern. The antenna achieves the highest gain of 5.8 dBi in the directions $\theta_{max}=43^\circ$ and $\phi=0^\circ, 90^\circ, 180^\circ$ and 270° . The magnitude of side lobes is well below (<-20 dB) that of the main lobe. The azimuth cut at $\theta_{max}=43^\circ$ represents an excellent omnidirectional coverage and uniform gain over all azimuth angles (ϕ).

D. Axial beams using four port feeding with phase shifters

The off-boresight tilted beams and semi-doughnut beam are not suitable for the systems where signals may arrive directly from the top, such as from overhead low earth orbit satellite, balloon or an UAV. It is found that the proposed antenna can provide both linear and circular polarized axial beams. A linear polarized axial beam can be formed by exciting all four ports A, B, C and D simultaneously with currents of equal amplitude and phase values of $0^\circ, 0^\circ, 180^\circ$ and 180° , respectively. Fig. 10 shows 3D pattern and polar cuts (xz - and yz -plane) of the axial beam. The main beam has a gain of 8.2dBi and cross polarized components are 40 dB down from that of the main beam. A circular polarized axial beam of gain 8.2 dBi can also be

generated if the phases for the four ports are in phase quadrature ($0^\circ, 90^\circ, 180^\circ$ and 270°) [35].

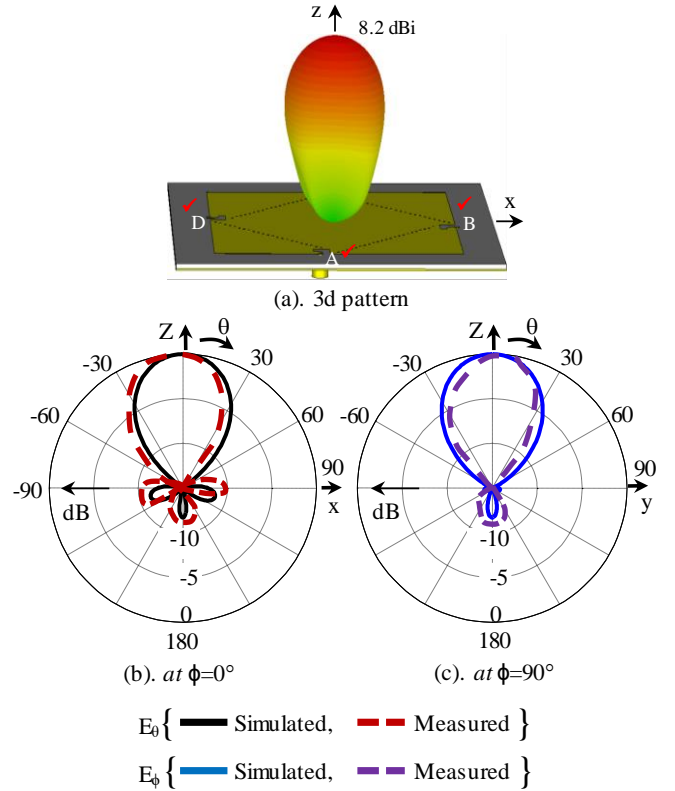


Fig. 10. Axial beam at 2.4 GHz; (a) 3D pattern, (b) At $\phi_{max}=0^\circ$, and (c) at $\phi_{max}=90^\circ$.

V. FREQUENCY RESPONSE OF GAIN AND EFFICIENCY

Fig. 11 shows the variation of the total antenna efficiency for all five types of radiation beams: four single feeding tilted, four dual feeding tilted, two tilted-twins, one semi-doughnut and one axial beam. It is found that in a range of 2.384 to 2.412 GHz the antenna exhibits a total efficiency of greater than 70% for all radiation beams, which is defined as 'Net efficient pattern bandwidth' = 28 MHz (1.16 % bandwidth). This means that the proposed antenna is suitable for narrow band communications, especially for the narrow band Internet of Things (IoT) at lower frequency spectrum. For a higher frequency operating band, a scaled antenna for satellite communications at 30 GHz (Ka band) would offer a net 350 MHz bandwidth. This is more than sufficient for even 4k high throughput internet access. At the test frequency of 2.4 GHz, single feeding tilted, dual feeding tilted, tilted-twin, semi-doughnut and axial beam have efficiencies of 87%, 85%, 89%, 78% and 82%, respectively. Within the net pattern bandwidth, it is observed that the antenna gain in the direction maximum radiation varies from 5.77 dBi to 6.64 dBi for single feeding tilted beam configuration and it varies from 6.16 dBi to 5.97 dBi for dual feeding tilted beam configuration, as shown in Fig. 12. The gain of the tilted-twin beams and semi-doughnut beams are found to be constant at 5.77 dBi and 5.82 dBi. The gain of the axial beam shows a little variation from 8.3 dBi to 8.1 dBi within the net pattern bandwidth.

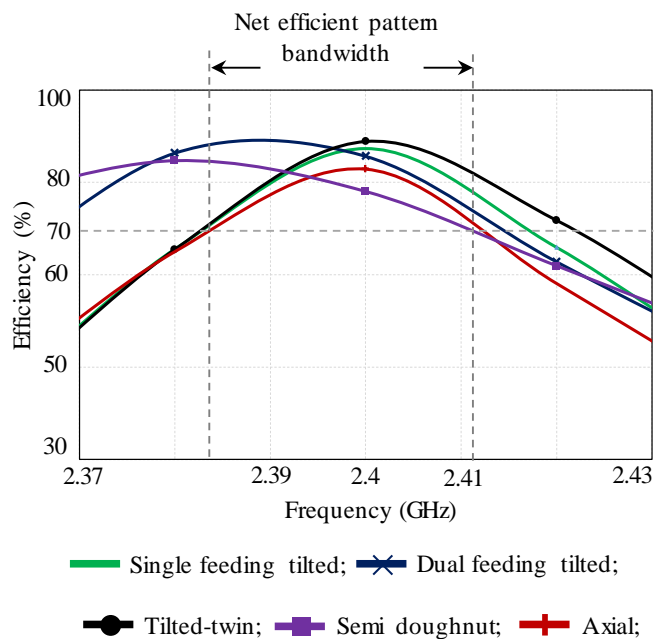


Fig. 11. Total efficiency of the antenna for different types of beams presented in sections III and IV.

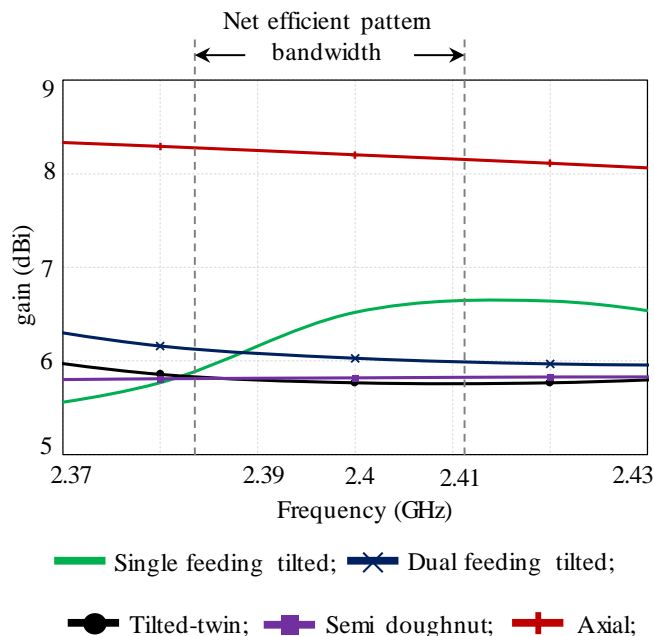


Fig. 12. Gain of the antenna in the maximum direction of the radiation for different types of beams presented in sections III and IV.

VI. APPLICATION

From application stand point the proposed antenna is designed for the next generation of vehicular applications. The proposed architecture aims to transform the internet access from High Throughput Satellites (HTS) and base stations, especially in weak electromagnetic environments. In these weak signal zones, conventional enhancement technologies like omni antenna based MIMO (Multiple Input Multiple

Output) struggle to provide significant gains. Being low profile the proposed antenna can easily be placed on the panoramic roofs of vehicles which are now are being made of variety of non-metallic surfaces. A depiction of how directive multiple beams can enable high SNR, and provide an ability to communicate with both satellite and terrestrial infrastructure is shown in Fig. 13.

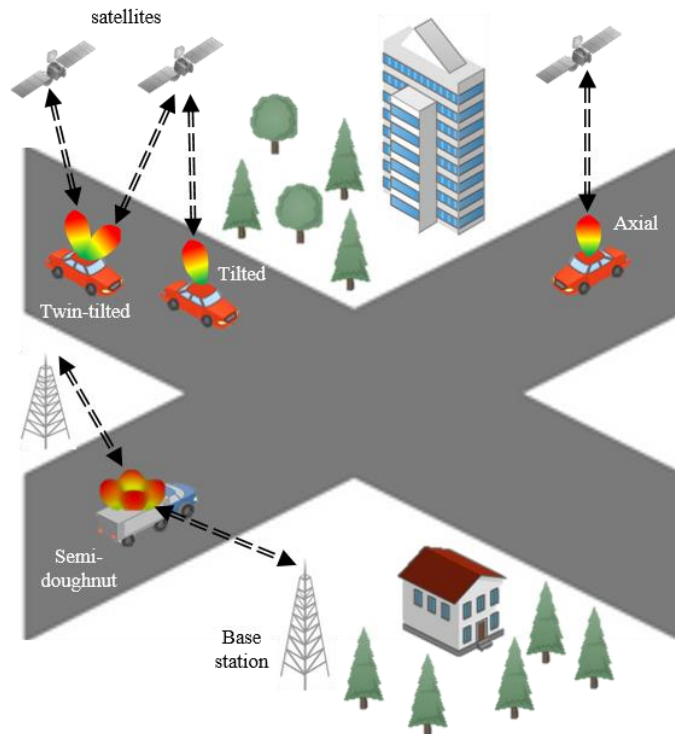


Fig. 13. Vehicular networking using multiple patterns to improve connectivity.

VII. CONCLUSION

A twelve-beam low-profile ($\lambda_0/83$) printed patch antenna is presented for pattern reconfigurable applications. The antenna was designed to operate over a test frequency of 2.4 GHz (802.11b/g/n) WiFi band. The antenna exploits edge currents on the corners of the patch to produce eight tilted beams. The same antenna using dual feeding is also capable of generating two tilted-twin beams. Using four ports feeding it also generates a semi-doughnut radiation and an axial beam. Thus, with a total of twelve beams and a low profile structure the proposed antenna is an excellent candidate for future high throughput vehicular commutations. In addition, the ability of same antenna to communicate with both satellite and terrestrial infrastructure will enable vehicles to offer connected cars with IoT automotive cloud services

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