Progress In Electromagnetics Research C, Vol. 143, 169-180, 2024 PIER C

(Received 27 February 2024, Accepted 10 May 2024, Scheduled 1 June 2024)

Recent Trends in Compact Planar Antennas at 5G Sub-6 GHz and mm Wave Frequency Bands for Automotive Wireless Applications: A Review

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ABSTRACT: 5G wireless communication offers higher channel capacity, high data rate, sufficient bandwidth, enhanced coverage, and reliable link as compared to the previous generation mobile networks. Also, 5G becomes more relevant with the recent launches of low earth orbit satellites by various ventures like starlink, amazon, one web, etc. As these satellites have heights up to the range from 300 km to 1000 km, the free space path loss decreases drastically which in turn improves the signal reliability and efficient communication at dead spots. With these advancements, antenna researchers have the freedom to design compact, easy to manufacture, with adequate gain user equipment terminal antennas which can be easily integrated in the modern passenger car body. This paper will focus on the recent development in the design considerations of the compact antenna design at sub-6 GHz (n78 frequency band) and mm wave (n278 frequency band) according to 3gpp standards. This manuscript also discusses various design specifications like selection of material for antennas, design complexity, feeding methods, fabrication and measurement challenges and performance parameters which include reflection coefficient, gain, polarization, axial ratio, cross polarization discrimination, radiation efficiency, radiation pattern shape, etc. The proposed antenna design considerations will facilitate the possible integration into the various parts of the car body according to the recent vehicular applications for uninterrupted communication.

1. INTRODUCTION

In today's era of 5G/6G, there is utmost significance of reliable, high speed, and uninterrupted connection in rural areas and while travelling. These features can be implemented with the high data rate and low free space path loss between the sender and receiver [1, 2]. These two features entirely depend upon link budget calculations which describe the various input parameters of both the antenna networks. These parameters include the distance between two communicating antennas, output power, size and gain of the antennas, atmospheric effects, signal bandwidths, and spectral efficiency. Among them, the distance between elements and gain of the antenna are the deciding factors for high data rate and free space path loss [3]. Initially, the orbital height of satellite antennas is very large. For instance in the case of geostationary and medium earth orbit satellites, the height ranges from 2,000 to 35,786 km [4]. As the distance between user equipment antenna on earth and satellite antenna is large, the free space path loss increases significantly. Therefore, the introduction of new ventures of lower orbital height of the satellite like starlink, one web, amazon etc. reduces the free space path loss as the free space path loss is directly proportional to the orbital height, which in turn provides the freedom to design and fabricate the miniaturized size, medium gain, and low-cost antennas for various automotive 5G/6G applications [5–7]. For the initial antenna design considerations, there are multiple options with the types of antennas according to applications. As this manuscript highlights compact and planar antennas, microstrip patch antennas are the prime choice among researchers to achieve aforementioned characteristics. The structure of the patch antenna consists of the substrate material sandwiched between two metal plates. The top metal plate is considered as the radiating patch and the bottom layer considered as ground structure [8]. The dimensions of the patch antenna is entirely characterized by the choice of frequency bands [9].

As the discussion is initially started with 5G/6G, according to third generation partnership project (3GPP) two frequency bands have been chosen which include sub 6 GHz (C-band) and mm wave (Ka-band) [10, 11]. To be more specific, sub-6 GHz band includes n77/78/70 band (3.3 to 5 GHz), and mm wave frequency band includes n257 band (26.5 to 29.5 GHz). To cover the overall 5G spectrum for both terrestrial and satellite com-

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munications, one needs to design the antenna that covers both the frequencies, but the separation between the two frequency bands is very large; therefore, antenna designers may face the challenge to achieve such a large bandwidth along with appropriate radiation properties. Thus, one solution is to design different antennas at the two frequencies individually and then arranged on the same platform in the form of multi-input multi output (MIMO) configuration [12].

MIMO configurations is one of the prominent solutions to enhance the channel capacity along with the advantages of high data rate in current and future wireless communications [13]. This type of configuration requires large bandwidth for the concurrent operation of multiple antennas. However, the challenge in this structure is to reduce mutual coupling effect and high isolation in the closely packed multiple antennas, which ultimately reduces the side lobe level and improves the antenna performance [14].

Another significant feature of the antenna design is polarization which is very relevant for the uninterrupted communication for the longer period of time. If both the antennas have same polarization, then the chances of signal loss are minimum. Generally, the polarization of satellite antennas or base station antenna is either circular or dual polarizations. It is more imperative to use the same polarization in the user equipment antennas at ground side. For circular polarization (CP), two orthogonal modes must be excited in the radiation patch [15, 16]. The circular polarization of the antennas can be evaluated by a parameter called axial ratio. The value of axial ration should be less than 3 for achieving the circular polarization according to the literature [17, 18]. Another possibility is to design antennas with dual polarizations. Dual polarizations are necessary in modern wireless communication to increase the reliability of the link and reduce multipath fading losses.

2. LINK BUDGET CONSIDERATIONS

Link budget calculations reveal the specifications of the user equipment antennas by considering various factors like atmospheric losses, free space path losses, satellite antenna power, gain, etc. The low altitude of satellites will reduce the free space path loss [19].

$$FSPL = 32.44 \text{ dB} + 20 \times \log(freq) + 20 \times \log(dis) \quad (1)$$

$$P_{rec} = G_{total} + P_{trans} - Losses \quad (2)$$

Finally, signal to noise ratio (SNR) has been evaluated from Equation (2)

$$SNR = P_{rec} - (173 \text{ dBm} + NF + 10\log(B)) \quad (3)$$

Here, NF is noise figure in dB, and B is the bandwidth in MHz.

The spectral efficiency can be calculated from the best suited modulation and coding schemes, and the data rate is expressed using Equation (3) [20].

$$DR = SE \times B \quad (4)$$

where DR is the data rate in Mbit/s, and SE is the spectral efficiency in bit/s/Hz.

3. CIRCULARLY POLARIZED SUB-6 GHZ ANTENNAS

For various applications, compact size, simple design, ease in fabrication and CP operations, patch antennas are most commonly used. However, poor impedance beamwidth and narrow axial ratio bandwidth are some of the issues, which restrict the application of presently working antennas. Researchers have suggested a variety of slots, structures, and shapes to overcome the issue of limited beamwidth. In such approaches some of the researchers use co-plane waveguide (CPW) feedline structure with radiating element as shown in Figure 1(a) [21]. This type of structure shows a significant impedance bandwidth of 472 MHz and AR bandwidth of 484 MHz [21]. The authors provide a parametric analysis on various dimensional parameters like feed width, gap between radiator, CPW, etc. The final design has been fabricated, measured, and compared with other similar works. Similar attempts have been made by other researchers at different frequency bands to achieve the wide axial ratio bandwidth correspondingly configuring the circular polarization. These different design considerations can be visualized in Figure 1. Figure 1(b) [22] shows a similar design but with different slots in the CPW structure, and the design is chosen to resonate in C-band and X-band with wide reflection and CP purity bandwidths. To investigate the optimal value, a parametric study of the multiple dimensional elements in antenna design is carried out. Each of the slots' dimensions around the square patch's perimeter has individual effects (such as slot width and length) that are tuned to get the lowest axial ratio and the widest possible impedance bandwidth. In another design as shown in Figure 1(c) [23], a little modification has been performed in the slots to achieve the multiband and wideband characteristics in sub-6 GHz frequency band. This publication presents a multiband multi-sense CP slot antenna. This antenna produces a triple-band CP wave by using an L-shaped patch and a defected ground plane. The proposed design in Figure 1(c) is more suitable for WLAN applications. A very similar and simple design is presented by the authors as shown in Figure 1(d) [24] which was optimized to operate in sub-6 GHz frequency bands. In this structure, both left-handed circular polarization and right-handed circular polarization have been achieved with a fractional impedance bandwidth of 90.2% and fractional AR bandwidth of 40%, which is feasible for wireless applications in the C-band, including WLAN and WiMAX applications. In another design of this type as shown in Figure 1(e) [25], a productive CP antenna for C-band applications has been created by the authors. On the substrate's ground plane, a variety of square strips, notches, slits, and stubs have been added, and an inverted L-shaped patch element is taken as a radiating element. This design exhibits 16.9% fractional bandwidth and 16.2% axial ratio bandwidth. By adding a stub to the ground plane, the suggested antenna's power loss is decreased, and its bandwidth is improved. With an extremely low price of FR4 substrate, the suggested antenna has a pretty high impedance bandwidth (50.9%) and an acceptable gain (5.35 dBi). The final suggested antenna is based on a traditional CPW-feeding antenna, which has 2.75 GHz as center frequency as depicted in Figure 1(f) [26]. The final suggested antenna is based on a traditional CPW-feeding antenna, which produces 2.75 GHz

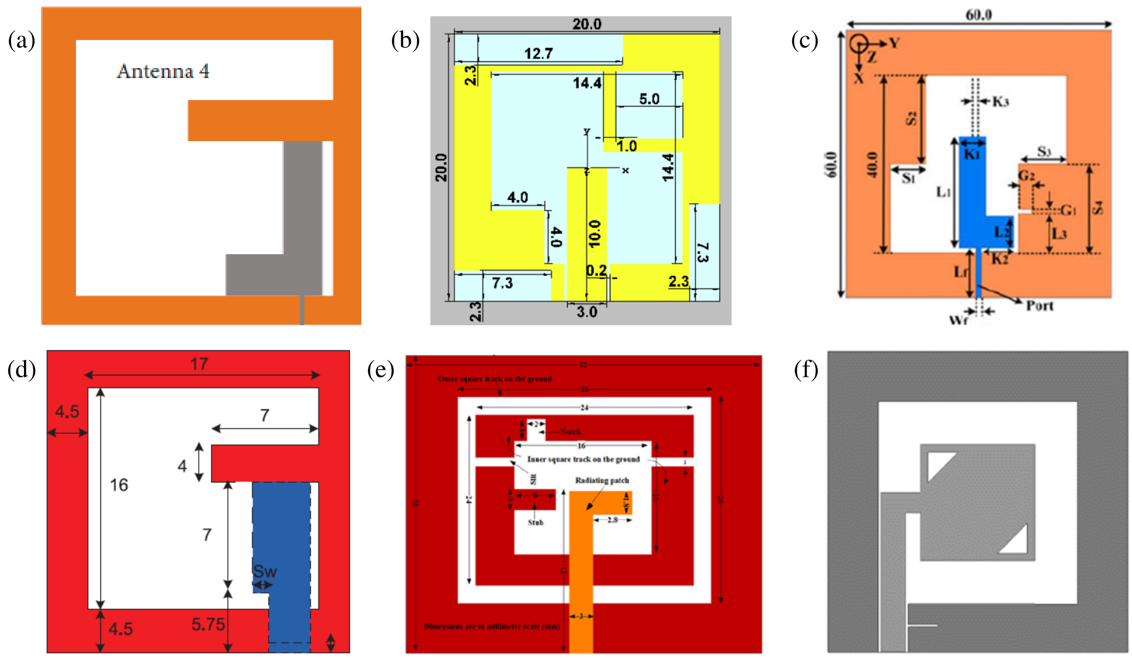

FIGURE 1. CPW based circular polarized antennas (a) [21]. (b) Square slot antenna [22]. (c) L-shaped radiator [23]. (d) [24]. (e) [25]. (f) [26].

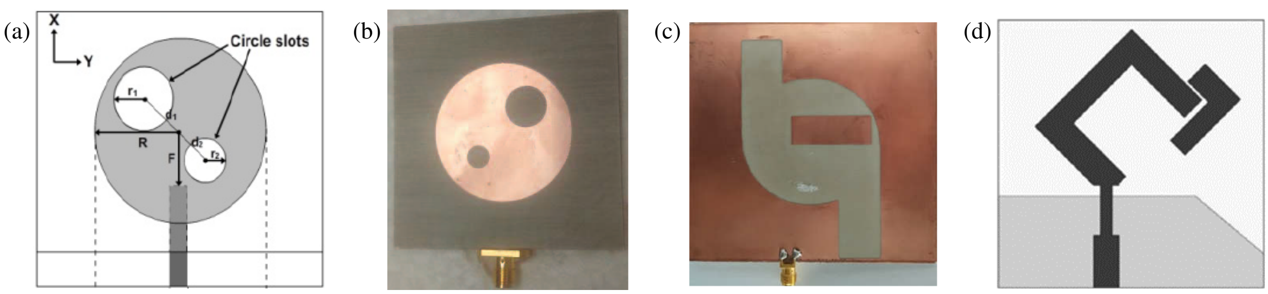

FIGURE 2. Other methods to achieve CP in antennas (a) [27]. (b) [28]. (c) [29]. (d) [30].

as center frequency. After that by the technique of symmetrical disorder, two triangles have been cut diagonally, which achieve circular polarization with very narrow 3-dB axial ratio bandwidth. The CPW-fed line is moved to the left, changing the antenna's radiation modes, to increase bandwidth even more. However, the axial ratio remains unsatisfied when compared to impedance. Hence, the last version features a reduced slot in the ground plane. Consequently, there is an efficient improvement in the axial ratio and a slight improvement in the impedance bandwidth. Satellite direction finding systems, Bluetooth, Wi-Fi, and wireless transmission applications can benefit from the given antenna. Some researchers have used a circular patch with simple circular cut placed at some optimized distance to achieve the circular polarization as shown in Figure 2(a) [27]. In this design, two unbalanced slots are etched on the circular patch at 45°. The dimensions and relative position of the slots have been analyzed to assess the performance parameters. Moreover, the presented design consists of two substrate layers, and a circular patch is on the top while the bottom substrate consists of a feeding line. The single design is converted into a 2×2 antenna array. The measurement result for single element shows the return loss of more than 20 dB at 2.45 GHz and measured minimum axial ratio of 0.21 dB. In another similar design, the antenna is made to resonate at 2.4 GHz for RF energy harvesting as shown in Figure 2(b) [28].

Throughout the 3-dB axial proportion frequency array of 2.36 GHz to 2.40 GHz, the antenna demonstrates a gain of greater than 6.0 dBic. Wide-beam CP radiation is a feature of the projected antenna that makes it desirable for RF energy harvesting applications. In another research paper, a circularly slotted antenna is presented in [29], and the design is shown in Figure 2(c). This research aimed to develop a design for enhancing a circularly slotted antenna's CP performance in order to achieve wide 3-dB axial ratio bandwidth and a higher gain at 2.4 GHz. Further, a very unique design is discussed for dual bands and dual circular polarizations as shown in Figure 2(d) [30]. The dual operational frequency bands of the proposed antenna, i.e., 1.54–2.08 GHz for linearly polarized radiation and 3.96–8.4 GHz for CP radiation are verified by the mea-

TABLE 1. Comparative analysis of the circularly polarized sub-6 GHz antennas.

Reference	Size (mm^3)	Peak Gain (dB)	Impedance Bandwidth (MHz)	Axial Ratio Bandwidth (MHz)	Applications
[21]	120×120×1.6	4	473	460	UHF RFID
[22]	20×20×1	4.4	5400	4800	C-band
[23]	60×60×1	4.2	5000	530	WLAN and X-band
[24]	25×25×1.6	4.5	5750	2300	WLAN and Wi-Max
[25]	32×32×1.6	5.35	2380	830	C-band downlink
[26]	60×60×1	N.A.	1360	1110	Bluetooth, Wi-Fi, WiMAX
[27]	7×80×1	10.8	200	140	WLAN
[28]	60×60×1.6	6	135	40	RF energy harvesting
[29]	95×100×1.6	5	1039	787	Wideband Applications
[30]	32×32×1.6	4.14	540	4420	GPS and GSM-1800

sured findings. All the parametric values of the circularly polarized sub-6 GHz antennas are illustrated in Table 1.

4. CIRCULARLY POLARIZED ANTENNA ARRAYS

In the above section, only single element antennas are discussed, and the sole element antenna has a limited gain over the required bandwidth. But as discussed in Section 2, the data rate indirectly depends upon the gain of the antenna. Therefore, various researchers have designed and analyzed circularly polarized antenna arrays utilizing various techniques to enhance the overall gain of the antenna.

For instance, one of the most prominent methods to design a circularly polarized antenna array is to use a sequential phase network. Various authors use this method in either single layer substrate or multilayer substrate. In [31], a 2×2 dual fed circularly polarized antenna array is designed at 5.9 GHz as visualized in Figure 3(a). Simulated annealing has been used to optimize the feed; the resultant structure has a voltage standing wave ratio of 2 : 1 and a bandwidth of 9.8%. Similarly, in next various articles, both sequential feeding and metasurface techniques have been utilized to achieve circular polarization and improved gain of the antenna array. In [32], a CP single element antenna is extended into 256 element antenna array, and a subarray is provided in Figure 3(b). The projected design achieves excellent impedance and axial ratio bandwidth in the mm wave frequency band. A series-parallel sequential rotation feeding method can achieve high gain, increase bandwidth, enhance CP purity, and drastically lower RF loss. In another research paper [33], a single element CP antenna is arranged into 8×8 elements with sequential rotation feeding method on the lower substrate which is an aperture coupled through slot in the ground plane as shown in Figure 3(c). The measurements result in a bandwidth of 41.45% and an AR bandwidth of 23.16%. In a similar research paper [34], a 4×4 CP antenna array is designed to operate in the X-band as shown in Figure 3(d). The impedance bandwidth of the projected layout is greater than 19.5%, and axial ratio is 8.8%. Another metasurface based sequential feeding network is discussed by [35]. The proposed design composed of sequential fed 2×2 CP antenna elements which is covered by the 8×8 metasurface elements as depicted in Figure 3(e). The planned design has an inclusive size of approximately $1.26\lambda_o \times 1.26\lambda_o \times 0.046\lambda_o$ at 5.9 GHz, fractional impedance bandwidth of 58.06%, and axial ratio bandwidth of 41.67%. A slotted circular 2×2 patch antenna array of 45 mm×45 mm at center frequency of 5.75 GHz is shown in Figure 3(f) [36]. Despite miniaturized size, a peak gain of 8.2 dB is achieved over the range 5.1–6.3 GHz. In the last paper of this discussion, [37] proposes a 4 element CP antenna surrounded by metasurface patch elements. The measured operating bandwidth of the final design is 36.4% (4.5–6.5 GHz), with a measured gain ranging from 9.5 to 11.5 dBic. In another article presented in [38], a CP antenna with series fed is analyzed with two 90° phase shift between L-probes. Moreover, axial ratio has been improved with the utilization of parasitic patches. In [39], a six-element conventional truncated antenna is presented demonstrating beam forming capabilities in S-band. Moreover, the proposed design also exhibits an axial ratio less than 3 dB in the design range of frequencies. In another paper [40], an aperture coupled patch antenna is discussed to operate in Ka-band with maximum gain of 28.7 dBi. In [41], a 2×2 CP antenna has been proposed for mm wave frequency range with the analysis of axial ratio, gain parameters, and beamforming capabilities The proposed work demonstrates an excellent impedance matching with reasonable significant gain. In [42], an inverted S-shaped antenna is proposed for wide axial ratio bandwidth and impedance bandwidth in C-band, and further the design has been extended into a 4-element array. In [43], an aperture coupled antenna array is presented with the utilization of multilayer substrates, and the design is optimized to operate in the Ka-band. In [44], an aperture coupled 2×2 patch antenna array is proposed with the use of a sequentially rotated CPW feeding network, and the proposed design is analyzed based on resonance, axial ratio and radiation patterns. Further, in [45] a sequentially fed CP antenna array has been projected for wideband modern wireless applications. The design possesses a circular cut in the top layer and feeding

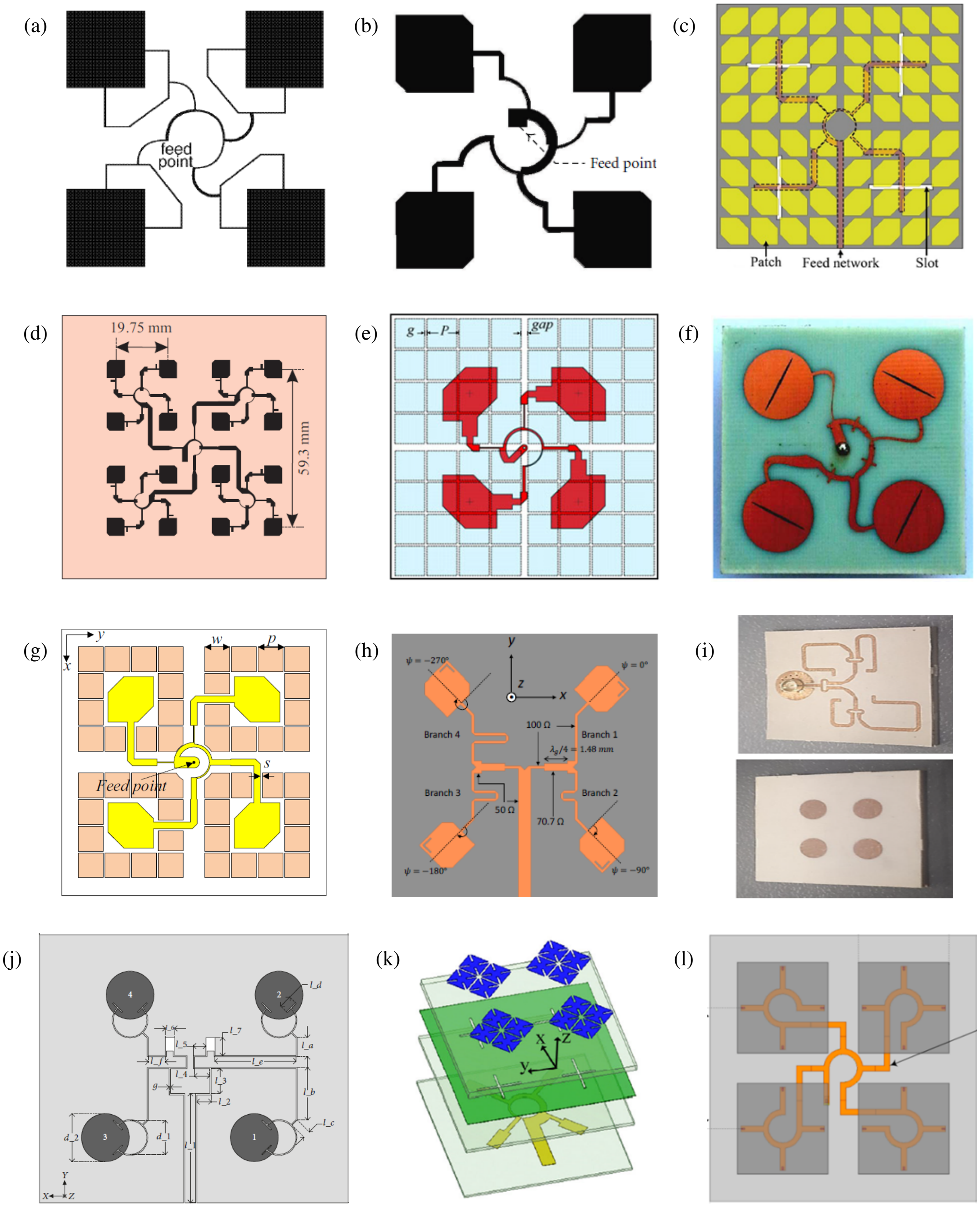

FIGURE 3. CP antenna arrays (a) [31]. (b) [32]. (c) [33]. (d) [34]. (e) [35]. (f) [36]. (g) [37]. (h) [41]. (i) [43]. (j) [44]. (k) [47]. (l) [48].

in the bottom layer of the design. In [46], a 10×10 linear array for CP radiation has been proposed to achieve the high gain of 17.4 dBi for SAR applications. In [47], a metasurface-based antenna array has been proposed along with the Specific Absorption Rate (SAR) analysis in the frequency range of C-band. Further, in [48], a 2×2 antenna array is proposed for ultra-high frequency (UHF) radio frequency identification (RFID) applications with sufficient gain, impedance bandwidth, and axial ratio. However, the performance of the design is enhanced by introducing an air gap and insertion of copper probes. The performance parameters of the circularly polarized antenna arrays are outlined in Table 2.

5. AUTOMOTIVE ANTENNAS AND ASSOCIATED CHALLENGES

As the application scenarios are increasing day by day in the automotive industry. It is necessary to install a number of antennas while maintaining the aesthetic appearance of the modern passenger cars. However, embedding antennas in plastic parts or glass material in the various parts of the car body may

TABLE 2. Comparative analysis of the circularly polarized antenna arrays.

Reference	Size (mm^3)	Peak Gain (dB)	Impedance Bandwidth (MHz)	Axial Ratio Bandwidth (MHz)	Applications
[31]	152×152×0.79	12.4	400	200	Modern wireless
[32]	9×9×0.254	30	4330	1550	RADAR and satellite
[33]	1.6×1.6×0.065	13.5	4120	2200	X-band applications
[34]	59.3×59.3×1.27	11.5	1600	720	Satellite application in Ku-band
[35]	64×64×2.33	12.08	3600	2500	Wideband communication
[36]	45×45×1.6	8.25	1750	900	C-band
[37]	82×82×2.72	11.5	2000	2000	C-band
[38]	144×144×5	12.1	2530	2340	Sub-6 GHz
[39]	530×200×3.048	N.A.	120	30	Beam Steering Applications
[40]	N. A	28.7	2290	$\theta = \pm 50°$	Portable Satellite Communication
[41]	N. A	11.47	6290	4000	Millimeter wave
[42]	59.9×25.8×0.5	14	2100	2150	GNSS
[43]	18.5×18.5×1.02	12.1	6500	6200	Phased Array RADAR
[44]	85×74×1	10.11	850	400	Aerospace
[45]	46×46×1.6	7.5	5300	4040	Modern wireless applications
[46]	325×55×3.2	17.4	400	2200	Side looking SAR applications
[47]	40×40×6	9.2	5190	3470	SAR applications
[48]	440×440×20	12.5	120	166	UHF RFID

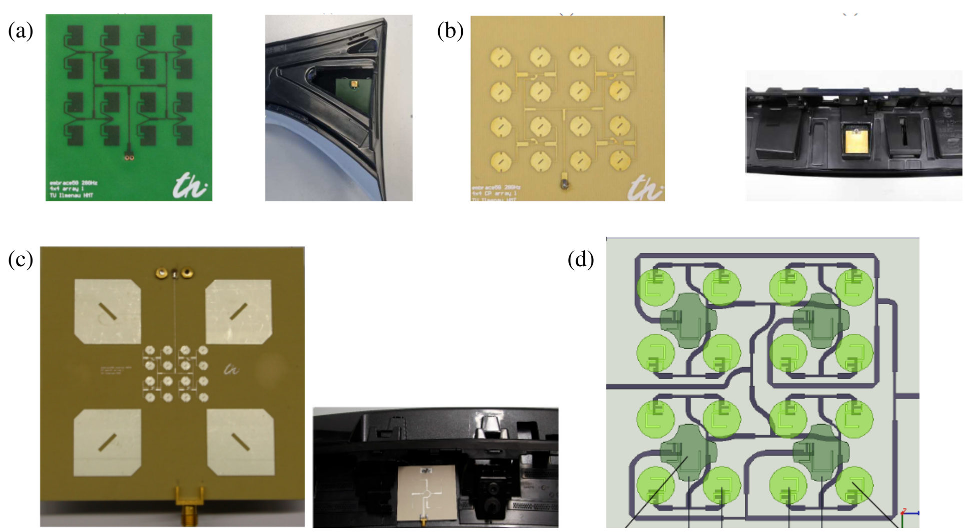

FIGURE 4. (a) Linearly polarized antenna array [40]. (b) Circularly polarized antenna array [41]. (c) Nested antenna array [42]. (d) [54].

impact the performance characteristics of the antennas. Various research groups have specifically worked upon the embedded antennas in the automotive sector. In such attempts, a multi-band patch antenna with horizontal arrangement is presented by the authors in[49]. The design is optimized to resonate at multiple frequencies ranging from 1.7 to 2.6 GHz covering various mobile communication bands. This design is novel in nature in terms of enhancement in bandwidth by merging the processes of corner feeding and horizontal placement. An adequate antenna optimization will be needed, depending on how much the antenna is de-tuned by the plastic embedding. In another attempt, a low gain 2 × 2 antenna array is designed which is embedded into the B-column of a modern passenger car [50]. The proposed design offers 9.3 dBi maximum gain and 1.4 GHz bandwidth. The array's main beam is steered by $\pm 16°$ with sidelobe level (SLL) < -10 dB. In the continuation of the previous research, the design has been extended into a 4×4 linearly polarized antenna array [51]. The proposed design is embedded into a back spoiler arm as shown in Figure 4(a). When high-gain satellite antennas are taken into account, a 4 Mbit/s

TABLE 3. Comparative analysis of the circularly polarized antenna arrays.

Reference	Size (mm^3)	Peak Gain (dB)	Impedance Bandwidth (MHz)	Axial Ratio Bandwidth (MHz)	Applications
[49]	175×47×1.6	4.8	980	N.A.	LTE
[50]	35×35×0.51	9.3	1420	N.A.	Ka-band
[51]	27×30×0.51	11.2	750	N.A.	Ka-band automotive applications
[52]	30×30×0.51	13.6	4000	900	
[53]	90×90×1.25	13.7	4000	1500	C-and Ka-band
[54]	110×110×4.6	17	800	500	C- and X-band satellite communications
[55]	36.4×66.7×0.81	12.2	3500	N.A.	Tx and Rx of SRR systems
[56]	N.A.	N.A.	7000	3000	Automotive Applications
[57]	54×54×6.8	10	90	65	Vehicular GNSS

uplink data rate can be anticipated for miniaturized ground station antennas with a modest gain of 13 dBi. Consequently, a straightforward, small, and vehicle-integrated 4×4 patch antenna array architecture was put out, exhibiting encouraging performance metrics for non-terrestrial 5G automobile uses. Additionally, the implanted array provided a maximum gain of 11.2 dBi, which may be used to calculate an achievable data rate of 2 Mbit/s for a variety of Internet of Things applications. Further, in its extension, the linearly polarized antenna is transformed into circularly polarized antennas as envisioned in Figure 4(b) [52]. The projected design is embedded into the back spoiler of the car. The antenna array satisfies favorable performance metrics, such as a measured impedance bandwidth exceeding 4 GHz and a circularly polarization bandwidth of 900 MHz, for satellite 5G vehicle use cases. With a projected data rate of 6 Mbit/s, the implanted array provided a maximum gain of 12 dBi, a number that is practical for numerous vehicle wireless applications. Moreover, another research paper of the same group discussed a nested antenna array for both 3.5 GHz and 28 GHz as visualized in Figure 4(c) [53]. The 28 GHz circularly polarized antenna array is placed in the center of the 3.5 GHz circularly polarized antennas with feeding on the bottom layer. In order to provide next-generation mobile services to every place on the planet, merging lower and higher frequency bands promotes scale effects across regions with diminishing network concentration. Promising performance metrics are met by the nested user equipment (UE) antenna array for satellite 5G automobile applications. Embedded into the rear spoiler, the n78-band has a bandwidth of 160 MHz with a circular polarization bandwidth of 100 MHz. In a similar work of nesting, antennas for C- and X-bands have been presented in [54]. The proposed design is a multilayer structure in which top layer consists of a 2×2 antenna array for 3.5 GHz, 4×4 antenna array for X-band in the bottom layer of the upper substrate, and the feeding network is on the bottom layer of the lower substrate material. The proposed design exhibits excellent performance in terms of reflection coefficient, axial ratio, gains, and efficiency. In [55], a 1×8 antenna array has been developed for 24 GHz with linear polarization property with a maximum gain of 12.2 dBi. Various performance and dimensional aspects of the automotive antennas are illustrated in Table 3.

6. CHALLENGES IN DESIGNING THE ANTENNAS FOR SATELLITE COMMUNICATION IN AUTOMOTIVE SECTOR

In the above sections, a thorough investigation has been done in order to examine circularly polarized antennas and their performances with the compact features of the antennas.

However, there are various challenges associated with these antennas which are discussed as follows:

- The first challenge in the design of a circularly polarized antenna is to optimize the antenna parameters to achieve the exactly same 3-dB axial ratio bandwidth as -10 dB impedance bandwidth. A lot of parametric optimization processes have to be adopted to achieve the same frequency bands.
- Another challenge is to design a 5G antenna for both sub-6 GHz and mm wave applications as both the frequency bands have large gap in between, so it is tedious to design an antenna for such high bandwidth. Therefore, the solution is to combine the two different antennas on single platform with minimum isolation.
- The next challenge in the design of 5G antennas is to achieve high data rate which is directly related to the gain of the antenna and hence the size of the antenna. So, researchers cannot design large sized antenna which may face difficulty during the embedding in the various parts of a modern passenger car. Therefore, a compromise has to be made among the size, gain, and data rate of the antenna system in the desired application.
- Further, to enhance the gain of the antenna, an array would be a feasible solution, but at mm wave frequency bands the size of the antenna is miniaturized, and there are various challenges to be faced in order to reduce the mutual coupling between closely packed radiating elements.

TABLE 4. Detailed analysis of antennas for terrestrial communication link.

Reference	Size (mm^3)	Peak Gain (dBi)	Isolation (dB)	Frequency Band (MHz)	Applications
[58]	55×25×2	5	6–10	698-960 & 1710–2690	4G LTE
[59]	59.5×44.3×21	N.A.	20–25	850, 2400, 5900,1575	LTE, GPS, WLAN, WAVE
[60]	165×40×50	5.8	23	5750–6100	V2X
[61]	48.5×30×49.5	N.A.	6–10	617–960 and 1710–6000	5G-Diversity
[62]	90×10×25.7	N.A.	N.A.	1217–1238 and 1565–1586	5G, LTE, WLAN, FM and Bluetooth
[63]	111×71×65	2.25	38	5850-5925	GPS, LTE, UM TS, DSRC
[64]	175×75×19	N.A.	10	2500–4500	LTE/5G Cellular
[65]	194.5×75×65	6.3	> 11	617–960 and 1700–6000	5G Mobile Services
[66]	70×35×65	Linear average Gain (-3.0 to -0.6)	N.A.	1920–5000	Sub-6 GHz 5G
[67]	70×40.5×64	N.A.	N.A.	617–5000	Sub-6 GHz cellular bands
[68]	88×55×1.5	N.A.	> 15	824–960 & 1710–2690	MIMO LTE
[69]	76×25×1.53	2	N.A.	698–2690	LTE, GSM and UMTS
[70]	120×70×0.1	4.6	N.A.	800 and 5900	LTE and C-V2X
[71]	15×6.5	N.A.	N.A.	87-5900	Automobile Applications
[72]	78×58×29	N.A.	25	300–5900	SDARS and GNSS
[73]	110×80×1.6	9.34	N.A.	3620–7320	LTE, IoT, 6G, IoV

- Another challenge is to optimize the antenna many times as there are variations in the resonant and radiation characteristics after embedding in the car. This is because overall dielectric constant changes which can cause shift in the resonating frequency and impedance matching. Therefore, to readjust the parameters the antenna needs further optimization using various optimization algorithms available in the literature.
- To find the appropriate location for embedding the antenna in a car is another challenge faced by the automotive antenna engineers. The placement of the antenna will depend upon the application requirement. If the antenna is designed for the terrestrial communication, then it needs to be an omnidirectional radiation pattern, and if it is designed for satellite communication, then the radiation pattern should point towards zenith, i.e., broadside in nature.
- Substrate material is the foremost parameter to assess the size and performance of the antenna. Therefore, the availability of the substrate material is the next challenge for the design of the antenna. If we are targeting compact size antennas, then we have to consider high index substrate material which is expensive and rarely available.

7. ANALYSIS OF AUTOMOTIVE ANTENNAS FOR TERRESTRIAL NETWORK APPLICATIONS

It is evident that with the rapid growth of various applications in automotive industry, modern passenger cars need to be equipped with various components, e.g., Radio, Navigation, and Bluetooth. Moreover, the looks and aesthetic appearance are also equally significant regarding the integration and installation of these antennas. So, one possible and most widely utilized solution is to use shark fin housing for different antennas. However, it might be challenging to house the low frequency antenna designs in the limited space of shark-fin. Because at such lower band of frequencies, the size of the antenna will be comparatively large. Still researchers have found various solutions to address these issues as illustrated in Table 4. For instance, different versions and designs of MIMO antenna incorporated in shark fin Module are presented in [58–73].

After the critical analysis of the terrestrial antennas, various challenges and suggestions in designing the antennas for terrestrial network communications are outline below:

- For terrestrial network communication, the size of a cellular antenna is extremely significant as the frequency of operation is extremely low in the range of MHz. Therefore, the size of the antenna would be comparatively large, and integration in the limited space would be a challenge. Researchers have to explore innovative solutions to resolve this problem.
- Another major requirement of a terrestrial link antenna is the omnidirectional nature of the radiation pattern to cover the maximum area and ensure the reliable connection throughout the journey.
- The next challenge in designing an antenna for terrestrial communication link is in the choice of optimum space for the integration of the antenna. The space is chosen in such a way that the link could be established for longer period of time with minimum losses, and for that, there are various spaces available in the car, e.g., Rooftop, side mirror, and B-column.
- As per the analysis done in Table 4, multiple antennas are integrated into Shark fin module; therefore, to keep the

higher isolation between these elements would be another major challenge. Various methods like defected ground structure (DGS), metasurfaces, common ground, etc. can be utilized to achieve maximum isolation.

- At last, to cover the various frequency bands, e.g., LTE, sub-6 GHz, WLAN, WiMAX, GPS, UMTS, and DSRC, multiple antennas are required and need to installed at specified locations. Therefore, antenna designers need to focus on the design of single element antenna which resonates at multiple frequencies to cover all these low frequency bands.

8. SUGGESTIONS OF INNOVATION ANTENNA DESIGN AND INTEGRATION WITH AUTOMOTIVE TECHNOLOGY

Based on the analysis and discussion about the satellite and terrestrial antennas, some of the innovative antenna design suggestions are outline as follows:

- The very first innovation in the antenna design for this particular application is to design multilayer antennas for different frequency bands as it resolves the issue of limited space in the modern passenger car.
- The use of metasurface in the antenna design will enhance the gain of the antenna within limited size of the radiating element, which in turn improve the data rate in satellite communications according to the link budget calculations.
- Another innovative idea is the shared aperture antennas for both sub-6 GHz and mm wave frequencies in the form of MIMO structure on single platform so that the overall antenna can cover the minimum space.
- One of the potential spaces for the installation of antenna in the automobile will significantly impact the signal strength throughout the connection. Therefore, antenna designers should find some of the innovative ideas to install the antennas at optimum location.
- After integrating the antenna in the car, the material (plastic, glass, etc.) of the part impacts the performance of the antenna. Therefore, the antenna substrate material should have very low loss tangent value so that the performance of the antenna should not alter after embedding into various parts of the car body.
- The antenna should also be tested on the basis of electromagnetic compatibility (EMC) to prevent the human exposure to radiation. Therefore, antenna designers should ensure compliance from various regulatory bodies.

9. FUTURE RESEARCH INSIGHTS IN ANTENNA DESIGN FOR AUTOMOTIVE INDUSTRY

The antenna design for automotive industry continuously evolves as the vehicles are approaching towards continuous connectivity and autonomy. Future research and ideas in the designing of these antennas will focus on various subareas to meet the requirements of next generation vehicles

- As the automotive industry advanced towards the automated and connected driving, it needs a greater number of antennas within the available and potential spaces in the automobiles. Antennas are already placed in the form of shark-fin module which covers the multiple monopole antennas for LTE, SDRS, sub-6 GHz, etc. along with the circularly polarized GPS antenna developed on ceramic substrate. Therefore, with respect to the future directions, more antennas can be integrated into the plastic, glass parts of the automobile. But it will impact the performance of the antenna as the dielectric constant of the car body material can cause the shift of the resonance frequency.
- Moreover, terrestrial link antenna can be integrated with a satellite antenna to cover the minimum space. Both the antennas have different requirements in terms of radiation pattern. Satellite antenna should have broadside radiation pattern pointed towards zenith with moderate or high gain, and terrestrial antenna should have omnidirectional radiation pattern.
- As 5G demands more reliable and high channel capacity, MIMO antenna will fulfil these requirements after critically analyzing the various parameters like Envelope correlation coefficient (ECC), Mean Effective gain (MEG), Channel Capacity Loss (CCL), and Total Active Reflection Coefficient (TARC).
- Moreover, beamforming in antenna design is another future direction for the maximum coverage, improved signal quality, and reliability.
- The material should be selected in such a way that it can withstand harsh environmental conditions which include temperature, moisture, vibrations, and dusting environment. For instance, ceramic material is used for GPS antenna due to its longer stability.

10. CONCLUSION

This article has discussed various recent trends, challenges, and requirements of the antennas for various sub-6 GHz and mm wave frequency bands for automotive wireless applications. The discussion starts with link budget considerations, single element circular polarization antennas and its arrays, and plastic embedded automotive antennas for n78 and n258 frequency bands. It has been inferred that for reliable and uninterrupted signal in satellite communications, circular polarization is the foremost requirement in the design of antennas. Along with the polarization, gain is another significant parameter to achieve the required data rate for effective 5G communication which can be achieved with the design of antenna array while maintaining circular polarization purity in the antenna arrays. Moreover, compactness of the antennas should not be compromised as these antennas have to installed in limited space. At last, various challenges have been discussed in the plastic embedding of the antennas in automotive industry. In the conclusion, the antenna designers should be very careful while designing the antennas with its compactness, enhanced gain, circular polarization, plastic embedding, etc. for ensuring the reliable and uninterrupted signal throughout the communication.

ACKNOWLEDGEMENT

The authors extend their appreciation to the Deanship of Scientific Research at Northern Border University, Arar, KSA for funding this research work through the project number "NBU-FFR-2024-1578-01".

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