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Fifth Generation Antennas: A Comprehensive Review of Design and Performance Enhancement Techniques

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ABSTRACT The intensive research in the fifth generation (5G) technology is a clear indication of technological revolution to meet the ever-increasing demand and needs for high speed communication as well as Internet of Thing (IoT) based applications. The timely upgradation in 5G technology standards is released by third generation partnership project (3GPP) which enables the researchers to refine the research objectives and contribute towards the development. The 5G technology will be supported by not only smartphones but also different IoT devices to provide different services like smart building, smart city, and many more which will require a 5G antenna with low latency, low path loss, and stable radiation pattern. This paper provides a comprehensive study of different antenna designs considering various 5G antenna design aspects like compactness, efficiency, isolation, etc. This review paper elaborates the state-of-the-art research on the different types of antennas with their performance enhancement techniques for 5G technology in recent years. Also, this paper precisely covers 5G specifications and categorization of antennas followed by a comparative analysis of different antenna designs. Till now, many 5G antenna designs have been proposed by the different researchers, but an exhaustive review of different types of 5G antenna with their performance enhancement method is not yet done. So, in this paper, we have attempted to explore the different types of 5G antenna designs, their performance enhancement techniques, comparison, and future breakthroughs in a holistic way.

INDEX TERMS SISO, MIMO, wideband, multiband, 5G communication, metamaterial, corrugations, dielectric lens, defected ground structure (DGS), antipodal Vivaldi antenna (AVA), multi-element antenna, monopole, dipole, magneto-electric(ME) dipole, loop, fractal, inverted F antenna (IFA), planar inverted F antenna (PIFA).

I. INTRODUCTION AND MOTIVATION

In last few years, economic and social development is greatly influenced by the advancements in the field of mobile communication. As a result, 5G technology has emerged as a pedestal of the future 2020 generation. 5G technology is an emerging technology with evolutionary and revolutionary services. It is the next generation of technology to provide ultra high data rates, very low latency, more capacity, and good quality of service. It is worth mentioning that 5G technology will unleash new opportunities to leapfrog traditional barriers to development. As 5G technology supports IoT also, it gives leverage of a major societal transformation in the fields of education, industry, healthcare, and other social sectors. 5G technology is expected to unlock an extensive IoT ecosystem wherein many devices will be connected and by maintaining a trade-off between latency, cost, and speed a network can suffice the communication needs.

The 3GPP standards undergo continual change. The 3GPP investigates an organized release of new functionality and is responsible for new releases of standards as per the planned schedules. The 3GPP has stated three different usage scenarios of 5G communications which are as follows [1]:

- **Enhanced Mobile Broadband (eMBB):** It provides ultra high speed indoor and outdoor connection. It supports good and uniform quality of service at the edge

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of the cell, on highways, in aircraft, and train. Also, it gives high data rates upto 20 Gbps in the indoor area and 2 Gbps in the outdoor area.

- **Massive Machine Type Communications (mMTC):** It supports the Internet of Things (IoT) to interconnect a very large number of devices. A single base station can support 10000 or more devices for different applications like smart power grids, smart cities, etc.
- **Ultra-reliable and Low Latency Communications (uRLLC):** It has stringent the requirement such as low latency (below 1 ms) and low packet loss (1 in 10000 packets). Some instances are remote medical surgery, safety in transportation, and wireless control of manufacturing process.

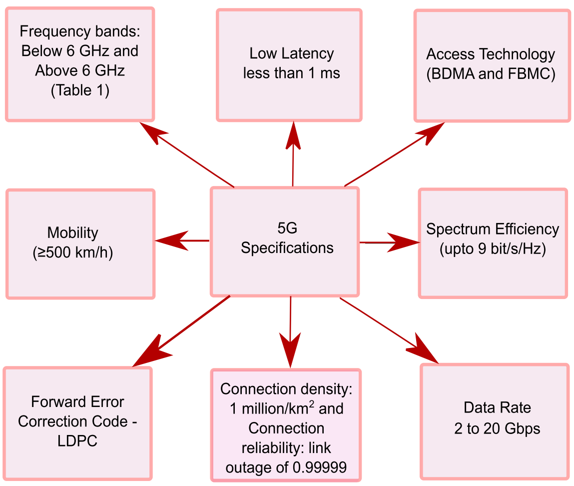

FIGURE 1. Specifications of 5G technology [2], [3].

As shown in figure 1, 5G technology is driven by eight specification requirements namely frequency bands, mobility, data rate, forward error correction, access technology, latency, spectral efficiency, and connection density taking into account the connection reliability [2], [4], [5] . The use of shorter frequencies (millimeter waves between 30 GHz and 300 GHz) for 5G networks is the reason why 5G can be faster. It can operate in both lower bands (e.g., sub 6 GHz) as well as mmWave. 5G is comparatively faster than 4G, delivering up to 20 Gbps peak data rates and 100 plus Mbps average data rates. To achieve low latency, low density parity check (LDPC) codes are used as a forward error correction code in 5G technology. Mobility denotes maximum mobile station speed at which a defined quality of service (QoS) can be achieved and is more than 500 km/h. As per International Telecommunications Union Radiocommunication Sector (ITU-R) the average spectral efficiency also termed as spectrum efficiency is up to 9 bit/s/Hz [2]. The 5G technology supports beam division multiple access (BDMA) and filters bank multicarrier (FBMC). The highly directive beams of radio transmission signals help to achieve space division multiple access which can be termed as BDMA. The BDMA can handle many users in 5G systems thereby increasing the system capacity. In FBMC, a bank of filters is used and provides better spectral efficiency. The low latency feature of 5G technology is driving new ways of using high quality video in real time. The use of artificial intelligence (AI) along with video analytics is more likely to turn high definition camera streams into actionable information. The data rate expected from 5G technology is 2 to 20 Gbps. It also provides a connection density of one million per square kilometer and connection reliability (link outage of 0.99999) [6]. As per the ITU-R, 5G frequency spectrum is classified in two broad categories below 6 GHz (FR1) and above 6 GHz (FR2) respectively as shown in table 1 and table 2.

TABLE 1. Frequency bands of 5G for below 6 GHz (frequency range 1 (FR1)) [7], [8].

Frequency Range (MHz)	Frequency Band
470-698	n71
698-960	n5, n8, n12, n14, n15, n20, n25, n28, n29, n81 - n83, n89, n91 - n94
1427-1518	n50, n51, n74 - n76, n91 - n94
1710-2025	n1 - n3, n34, n39, n65, n66, n70, n84, n86, n95
2110-2200	n65, n66
2300-2400	n30, n40
2500-2690	n7, n38, n41, n90
3300-3400	n77, n78
3400-3600	n48, n77, n78
3600-3700	n48, n77, n78
3700-4200	n77
4400-4990	n80

TABLE 2. Frequency bands of 5G for above 6 GHz (frequency range 2 (FR2) [5], [9].

Frequency Range (MHz)	Frequency Band
24250-29500	n257, n258, n261
37000-43500	n260
45500-47000	–
47200-48200	–
66000-71000	–

One of the pivotal parts of the 5G device is an antenna which is required to work at an enhanced gain, bandwidth, and lesser radiation losses. So, antenna design for 5G devices becomes very crucial while maintaining the above mentioned parameters for 5G communication. Till date, there is no such review paper available in the literature which covers a review of design and performance enhancement techniques of recent

TABLE 3. Summary of important acronyms.

Acronyms	Meaning
IoT	Internet of Things
3GPP	Third Generation Partnership Project
eMBB	Enhanced Mobile Broadband
mMTC	Massive Machine Type Communications
uRLLC	Ultra-reliable and Low Latency Communications
QoS	Quality of Service
FR	Frequency Range
SISO	Single Input Single Output
MIMO	Multiple Input Multiple Output
EBG	Electromagnetic Bandgap
DRA	Dielectric Resonator Antenna
DGS	Defected Ground Structure
CSRR	Complementary Split Ring Resonators
CR	Cognitive Radio
PIFA	Planar Inverted F Antenna
IFA	Inverted F Antenna
ECC	Envelope Correlation Coefficient
ME	Magneto Electric
AVA	Antipodal Vivaldi Antenna
FMA	Folded Monopole Antenna
PRS	Partially Reflective Surface
GSM	Global System for Mobile
LTE	Long Term Evolution
UMTS	Universal Mobile Telecommunications System
DCS	Distributed Control System
LB	Low Band
MHB	Middle High Band
HB	High Band
FSS	Frequency Selective Surfaces
MC	Mutual Coupling
RAN	Radio Access Network
D2D	device to device
UE	user equipment
CoMP	Coordinated Multipoint Processing
CRAN	centralized Radio Access Network
NFV	network function virtualization

5G antennas. So, in this paper, we have tried to explore all 5G antennas in a holistic way that were proposed in recent years considering their performance enhancement techniques. The paper also aims to direct the researcher for further advancement in the 5G antenna design as per their applications.

The structure of the paper is as follows: section II elaborates on different classifications and performance enhancement methods of 5G antenna. The comprehensive review of the different designed antenna is given in section III. The findings of 5G antenna classification are summarized in section IV. The future breakthroughs of different antenna types are provided in section V. At the last, all findings are concluded in section VI. The summary of acronyms is given in table 3.

II. OVERVIEW OF 5G ANTENNA: CLASSIFICATION AND THEIR PERFORMANCE ENHANCEMENT TECHNIQUES

A. CLASSIFICATION

In recent years, lots of 5G antenna designs are proposed employing different performance enhancement techniques. In this section, we have classified these designs based on input output ports and the antenna types.

1) CLASSIFICATION BASED ON INPUT OUTPUT PORTS

We found that the simplest way of classifying antenna is based on input output ports as shown in figure 2. The antenna can be broadly classified as:

- **Single Input Single Output (SISO)** Some researchers have implemented the SISO antenna which is either a single or multi-element antenna for 5G applications. The SISO antenna is easy to design and implement. Also, it can be easily integrated into 5G communication devices. To achieve a high gain, the size of a single element antenna is large [10]. At above 6 GHz frequency bands, the signals suffer from higher propagation losses and quality of service degrades. So, to achieve a uniform and good performance, it is required to replace a single element antenna by a multi-element antenna [11]. A multi-element antenna is mainly used to enhance the gain of an antenna at the cost of increased size and design complexity [12].
- **Multiple Input Multiple Output (MIMO)** The wireless communication is prone to interference, multipath fading, and radiation losses. Also, it becomes severe at higher frequencies. To overcome these issues, the utilization of multiple input multiple output (MIMO) antennas becomes very important as it enhances the transmission range without increasing the signal power. Thus, MIMO design can be used in 5G to achieve low latency, maximum throughput, and large efficiency. In MIMO more signals can be launched intelligently by using multiple antennas and thus enhancing channel capacity significantly.
  The method used to reduce the number of an antenna in MIMO is to use multiband antennas that provide coverage of different wireless applications [13]. Further, the MIMO antennas can be classified depending upon their frequency band as wideband and multiband antennas. The wideband and multiband antennas can be further classified into multi-element with a metal rim and multi-element without metal rim antennas. The metal

rim antenna provides excellent mechanical strength as well as aesthetic appearance to mobile phones.

Additionally, in compact devices for achieving a higher transmission rate, the MIMO antenna with improved isolation is preferred [14]. Different types of enhancement techniques are used in various antenna structures to increase the gain, improve isolation (mutual coupling) among antennas, bandwidth, envelop correlation coefficient (ECC), and efficiency. The electromagnetic interaction between antenna elements in the MIMO is called as mutual coupling (MC). In this process, energy is absorbed by the receiver of one antenna when another antenna is radiating energy. Hence it is very much essential in MIMO to reduce mutual coupling between antenna elements. It can be calculated mathematically as follows [15]:

$$MC_{mn} = exp(-\frac{2x_{mn}}{\lambda}(\alpha + n\pi)), \quad m \neq n \tag{1}$$

$$MC_{mn} = 1 - \frac{1}{N}\sum_{m}\sum_{m \neq n} MC_{mn} \tag{2}$$

where MC_{mn} and x_{mn} are the mutual coupling and the distance between m^{th} and n^{th} antenna elements respectively. The parameter α controls the coupling level and N is the number of MIMO elements. It is generally calculated in the form of scattering parameters and measured in dB.

Another important parameter of MIMO is envelop correlation coefficient (ECC) which represents the correlation between incoming signals at the MIMO ports. The ECC can be calculated by using following formula [15]:

$$|p_{mn}(e)|^2 = 1 - \frac{\eta_{max}}{\eta_m \eta_n} \tag{3}$$

where $p_{mn}(e)$ is the correction coefficient between m^{th} and n^{th} ports, η_{max} represents the maximum efficiency whereas $\eta_m\eta_n$ represents total efficiency of the radiating elements. This value of ECC should be less than 0.5 [15].

2) CLASSIFICATION BASED ON ANTENNA TYPES

Another important method of classification can be based on antenna types as shown in figure 3. As per the literature, different types of antennas suitable for 5G applications are as follows:

- **Monopole Antenna:** It consists of a straight microstrip line of λ/4 length where λ is the wavelength of the resonant operating frequency of an antenna. As found in the literature, several modifications were proposed which change the basic structure into new shapes like conical, spiral and others as per the applications and requirements [16], [23].
- **Dipole Antenna:** It consists of two straight microstrip lines each of λ/4 length and feeding is provided in between two microstrip lines So, the total length of dipole antenna is λ/2 [17], [24].
- **Magneto-Electric (ME) Dipole Antenna:** It consists of a planar electric dipole and vertically shorted planar magnetic dipole. The feeding is provided to the magnetic dipole from the bottom side of the substrate [18], [25], [26].
- **Loop Antenna:** It consists of a circular, rectangular, square or any other shape of a ring. The radius of the loop antenna is smaller than wavelength [8], [27].
- **Antipodal Vivaldi Antenna (AVA):** It consists of two conductors on both sides of the substrate and they are mirror images of each other. The upper conductor acts as a radiator whereas bottom conductor acts as a ground [12], [28]–[30], [34].
- **Fractal Antenna:** It consists of a repetition of the same structure multiple times. It is designed by using an iterative mathematical rule. The fractal antenna can be of different shapes like rectangle, circle, star, triangle, and leaf [20], [31].
- **Inverted F Antenna (IFA):** It consists of a microstrip line with one bend and feeding is given to the straight part of the microstrip line. The feed point is near to the bent part and hence the overall look of an antenna is of inverted F type [21], [32].
- **Planar Inverted F Antenna (PIFA):** It consists of the patch antenna and ground plane which are connected by using shorting pin and feeding is provided from the bottom side of the substrate. As it resonates at quarter wavelength, it requires less space [22], [33].

The advantages and disadvantages of different antennas are presented in table 4.

B. PERFORMANCE ENHANCEMENT TECHNIQUES

Many researchers have employed various performance enhancement techniques in antenna designs which aim to target one or more parameter enhancement like bandwidth, gain, efficiency, reduction in the mutual coupling, and compact size. Figure 4 shows different antenna performance enhancement and decoupling techniques for SISO and MIMO antennas in which the enhanced parameters are also mentioned below the performance enhancement techniques. These performance enhancement techniques and decoupling techniques are explained below:

1) ANTENNA PERFORMANCE ENHANCEMENT TECHNIQUES

Figure 4 shows the important antenna performance enhancement techniques which can be employed for 5G antennas while their advantages and disadvantages are listed in table 5. These techniques are:

- **Substrate Choice:** The main requirement of an antenna implementation is the appropriate selection of a substrate. Various substrates with different permittivity and loss tangent are available for antenna fabrication. To increase gain and reduce power loss a substrate with less relative permittivity and low loss tangent must be selected [30].

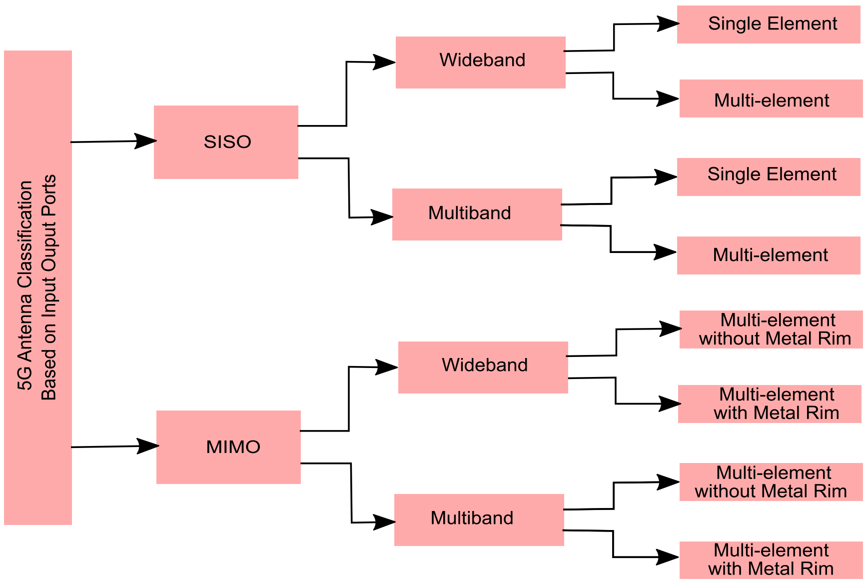

FIGURE 2. 5G Antenna classification based on input output ports.

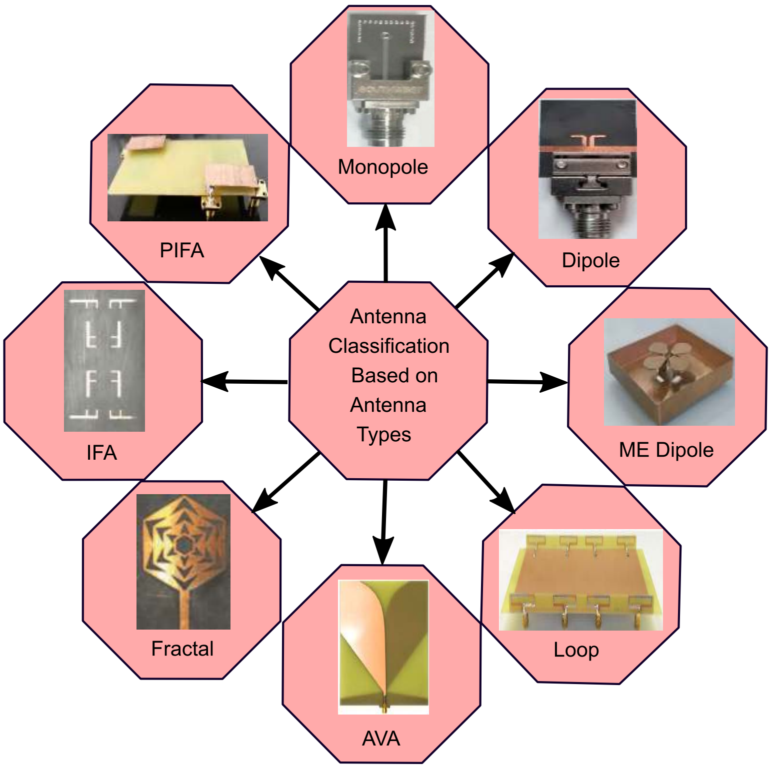

FIGURE 3. 5G Antenna classification based on antenna types [8], [16]–[22].

- **Corrugation:** The corrugation means removal of a metal part (rectangular, sine, triangular, or square shape) from the edge of a radiator. It helps to improve bandwidth and front to back ratio. [12]
- **Multi-element:** Further gain of an antenna can be increased by the multi-element antenna. It also enhances the antenna bandwidth and efficiency [30]. Applications where a single element antenna cannot Fulfill the requirements like high gain and wide bandwidth, a multi-element is more effective.
- **Dielectric Lens:** Electrostatic radiation is transmitted in one direction by the dielectric lens which leads to

TABLE 4. Advantages and disadvantages of antenna types.

Ref. No.	Antenna Type	Advantages	Disadvantages
[16], [23]	Monopole	• Simple to design and fabricate • In multi-element monopole antenna design, it can be easily rotated in any direction.	• Less gain • Requires large area of ground • Gives poor response in bad weather condition
[17], [24]	Dipole	• Simple to design and fabricate • Receives balanced signal	• Less gain • Cannot be used for long range communication • Low bandwidth
[18], [25], [26]	Magneto-Electric (ME) Dipole	• High front to back ratio • Low side lobe and back lobe level • Wide bandwidth • Low cross polarization	• Design and fabrication is complex • Costly
[8], [27]	Loop	• Easy to design • Provides good channel capacity	• As single element loop antenna cannot meet the 5G requirements, multi-element loop antenna is required. • Low gain
[12], [28]–[30]	Antipodal Vivaldi Antenna (AVA)	• Enhances the gain • Provides wider bandwidth • Gives stable radiation pattern	• Requires more space • Low gain at lower frequencies
[20], [31]	Fractal	• It helps to miniaturize antenna size. • Provides wider bandwidth • Good impedance matching • Provides consistent antenna performance over the operating range.	• Design is complex • Limitation on repetition of fractal design
[21], [32]	Inverted F Antenna (IFA)	• Smaller in size • Good impedance matching due to intermediate feeding	• Narrow bandwidth • Low gain
[22], [33]	Planar Inverted F Antenna (PIFA)	• Low profile • Good impedance matching • Enhances front to back ratio	• Narrow bandwidth • Low gain

increase in gain and directivity of an antenna. There are different shapes of a dielectric lens and it is designed by using the same or different substrate material with the same or different substrate [30].

- **Mutual Coupling Reduction Techniques:** In multi-element antenna design, the antenna elements effects the performance of each other. To reduce this, researchers have incorporated different mutual coupling techniques in the MIMO antenna which is also named as isolation or decoupling techniques in the literature. Few of these important techniques are explained in the next section.

2) MUTUAL COUPLING REDUCTION (DECOUPLING) TECHNIQUES

The decoupling techniques play a vital role to achieve the optimum performance of MIMO antennas. These techniques are an unavoidable part of the MIMO antenna design. These techniques are explained below, and their advantages and disadvantages are presented in table 6.

- **Neutralization Lines:** Using metallic slit or lumped element, neutralization lines pass electromagnetic waves between antenna elements to reduce mutual coupling. It reduces the antenna area and improves bandwidth when connected between ground planes. With the change in the location of a point on the neutralization lines, impedance changes thereby changing the effective bandwidth [15].
- **Decoupling Network:** In decoupling network, cross admittance gets transformed to purely imaginary value by adding discrete components or transmission lines. This technique employs a plane decoupling network which acts as a resonator to reduce mutual coupling. The decoupling network includes pattern diversity for multi-elements, dummy load, and coupled resonators technique. It is a cost effective solution to improve isolation [15].
- **Electromagnetic Bandgap (EBG) Structure:** It is acting as a medium for the transmission of electromagnetic waves. EBG structure is made up of dielectric or metallic material and having a periodic arrangement. Because of

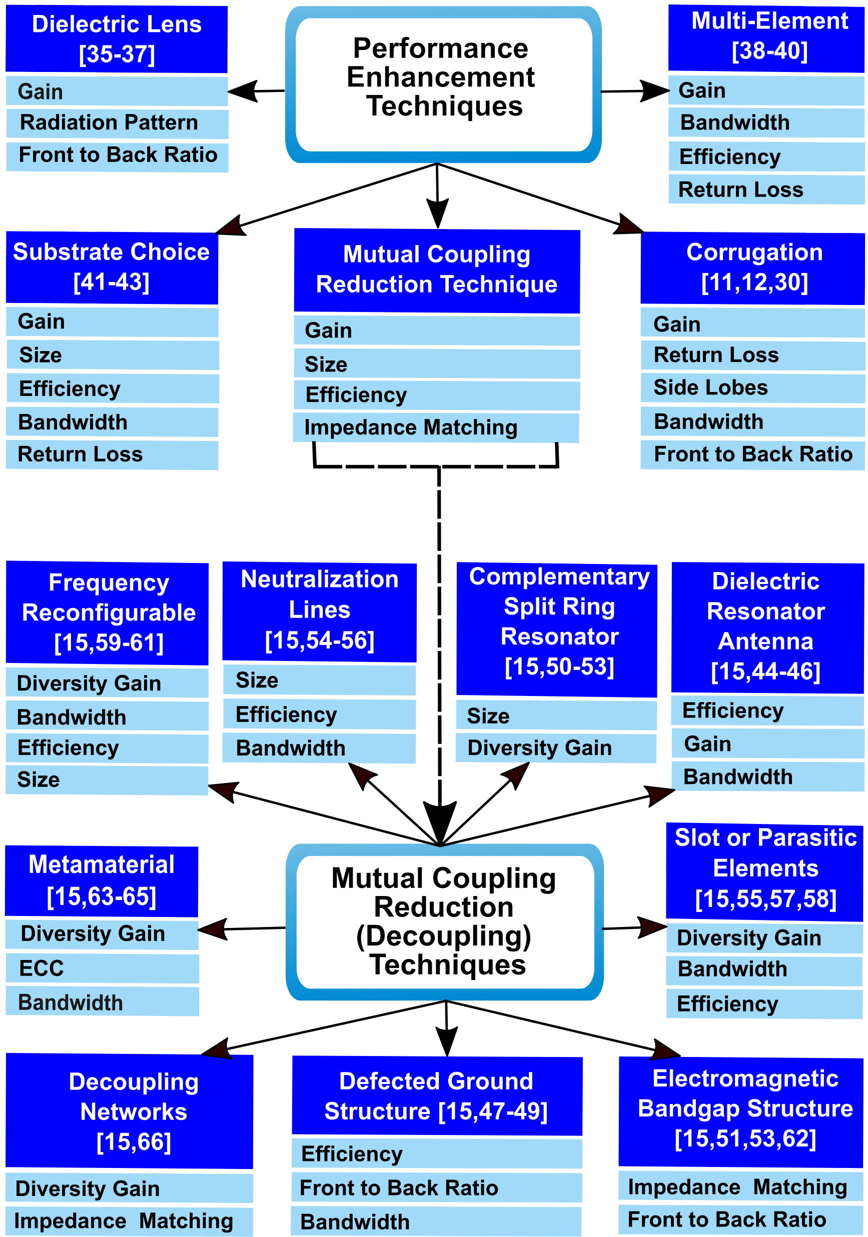

FIGURE 4. Various performance enhancement techniques for 5G antenna.

this periodicity independent resonance, it can produce more than one bandgap. EBG structure provides low mutual coupling and high efficiency [15].

- **Dielectric Resonator:** An antenna that contains dielectric resonator is called as dielectric resonator antennas (DRA). DRA provides high gain, high radiation efficiency, and low loss. DRA can also provide high isolation with dual-band property [15].
- **Defected ground structure (DGS):** It is the structure where the slots or defects consolidated on the ground plane of the antenna. DGS can be used to provide maximum efficiency, low mutual coupling, and wide bandwidth [15].
- **Metamaterial:** It contains an electromagnetic characteristic. Different types of metamaterials are a single negative, electromagnetic, electromagnetic bandgap, double negative, anisotropic, isotropic, terahertz, chiral, tuneable, photonic, frequency selective surface based, nonlinear, and tunable metamaterial. Metamaterials are designed manually by using two or more materials. Using metamaterial, it is possible to have an antenna with low mutual coupling, high gain, bandwidth, and compact size of an antenna [15], [30].
- **Slot Elements:** It is used to enhance impedance bandwidth using the coupling method in the ground plane or the radiation patch. The slot antenna is used to

TABLE 5. Advantages and disadvantage of performance enhancement techniques.

Ref. No.	Performance Enhancement Techniques	Advantages	Disadvantages
[35]–[37]	Dielectric Lens	It enhances the gain, improves front to back ratio, provides stable radiation pattern, and radiates the maximum energy in the front direction.	It increases the size of an antenna.
[38]–[40]	Multi-element	It improves the gain, efficiency, return loss, and bandwidth.	It is difficult to design the feeding network and increases the size of an antenna.
[11], [12], [30]	Corrugation	It provides improved gain, return loss, and bandwidth. Also, as it reduces side and back lobe levels, the front to back ratio increases.	It reduces input impedance.
[41]–[43]	Substrate Choice	A substrate having low permittivity gives enhanced gain, efficiency, wide bandwidth, and a compact antenna while a substrate with high permittivity improves the return loss.	A substrate having low permittivity is costly and they are not easily available.
[15], [44]–[46]	Mutual Coupling Reduction	It enhances the gain, efficiency, and input impedance matching. Some mutual reduction techniques reduces the size of an antenna.	It increases the complexity of antenna design.

provide wide bandwidth, high gain, high efficiency, and high mutual coupling value [15].

- **Complementary Split Ring Resonators (CSRR):** CSRR is used for isolation improvement, to perform filtering function, and to provide lower mutual coupling. CSRRs are also used to provide high efficiency with miniaturizing the size of the antenna [15]. CSRR is made up of two concentric ring structure with slots opposite to each other.
- **Frequency Reconfigurable:** It is based on switching techniques. In reconfigurable antenna to increase frequency range and to increase envelop correlation coefficient; varactor diodes, MEMS switches, and p-i-n are used. The reconfigurable antenna structure can provide lower mutual coupling, a high value of diversity gain, and efficiency [15].

III. PERFORMANCE ENHANCEMENT OF 5G ANTENNAS: COMPARATIVE AND PARAMETRIC ANALYSIS

This section elaborates on the different types of antenna in more detail. The antenna can be broadly classified as SISO and MIMO based on input output ports. The MIMO antennas are further classified based on their design which is multi-element without metal rim and multi-element with metal rim for both wideband and multiband applications. It is not possible to cite and analyze each 5G antenna research paper, but we have done a comparative analysis for most of the recent antenna designs.

A. SISO WIDEBAND ANTENNAS

After a literature survey on SISO antennas for 5G applications, it is found that the researchers have designed antenna for optimizing its different parameters like size, gain, bandwidth, front to back ratio, etc. These antennas are either a single element or multi-element. So, the SISO antennas for 5G applications can be categorized into a single element and multi-element antennas.

1) SINGLE ELEMENT

The single element antenna is easy to design, implement, and fabricate. To reduce the size of an antenna, some researchers have used dipole antenna [41], [69]. AVA proposed in [34] which contains a conductor and ground as a mirror image of each other can be one of the best candidates in the tapered slot category for 5G applications. In [28], by using a windmill shape of AVA, the authors have achieved wide bandwidth of 10-160 GHz which covers all above 6 GHz bands of 5G communication. A compact antenna of size 10 mm $\times$ 12 mm $\times$ 1.48 mm is designed on the transparent substrate Plexiglas, but its gain is only 1.94 dBi [70]. The resonance based reflector antenna is designed by using three metallic layers with the substrate as a sandwich in between two layers to provide wider front to back ratio (FBR) bandwidth [71]. The 3D antenna is designed in [72] and it is metalized by using a spray coating technique to produce a compact, lightweight, and rigid antenna. A daunting task of integrating a single element SISO antenna in a smartphone can be achieved by using a conformal technique that is a thin exponentially tapered layer of copper is used as a reflector to procure a high gain of 8-9 dBi [67]. In [36], a compact Quasi-Yagi antenna with a dielectric lens is proposed to achieve a 14-15 dBi gain and wide bandwidth of 24-40 GHz.

Further, to reduce the size of an antenna with acceptable performance parameters, some researchers have implemented multilayer antennas [35], [73]. A five layer antenna using a planar array of the rectangular shaped metasurface

TABLE 6. Advantages and disadvantage of mutual coupling reduction (decoupling) techniques.

Ref. No.	Mutual Coupling Reduction (Decoupling) Techniques	Advantages	Disadvantages
[15], [47]–[49]	Defected Ground Structure	It is easy to implement, to enhance the bandwidth, to improve the front to back ratio, and to increase the efficiency.	It's analysis is the challenging issue.
[15], [44]–[46]	Dielectric Resonator Antenna	It enhances efficiency, bandwidth, and gain.	It's structure is complex.
[15], [50]–[53]	Complementary Split Ring Resonator	It improves diversity gain and reduces antenna size.	It provides low bandwidth.
[15], [54]–[56]	Neutralization Lines	It is a compact antenna. It gives wider bandwidth and enhanced efficiency.	It's structure is complex.
[15], [55], [57], [58]	Slot or Parasitic Element	It enhances diversity gain, bandwidth, and efficiency.	It is difficult to design and to decide the position of slot or parasitic element.
[15], [59]–[61]	Frequency Reconfigurable	It provides compact size and supports multiple wireless standards. Also, it improves diversity gain, bandwidth, and efficiency.	It required external components.
[15], [51], [53], [62]	Electromagnetic Bandgap Structure	It provides good front to back ratio and impedance matching.	It's structure is complex.
[15], [63]–[65]	Metamaterial	It enhances the diversity gain, bandwidth, and ECC. Also, it is compatible for integration with another components.	It is difficult to design and decide the position of metamaterial unit cells.
[15], [66]	Decoupling Network	It improves diversity gain and impedance matching.	It's gain is low and the design is complex.

TABLE 7. Comparison of single element antennas (SISO wideband).

Ref. No.	Substrate	Size (mm^3)	No. of Substrate Layers	Gain (dBi)	Frequency Band (GHz)	Antenna Type
[41]	FR4	40 x 10 x 1	1	2-2.5	3.08 to 5.15	Dipole
[34]	FR4	40 x 24 x 1.6	1	5-9.53	25 - 33.4	Antipodal Vivaldi antenna
[67]	Nelco NY9220	20 x 16 x 0.508	1	8 - 9	20 - 28	Circular slot
[43]	RO4003C, Taconic TLX-9	90 x 96 x 2.878	2	8.59-10.43	3.24-3.8	Microstrip patch
[26]	Arlon 25N	40 x 40 x 10.516	2	6-8	4.98-6.31	ME dipole
[68]	Teflon, ceramic, Rogers 5880	75 x 75 x 15.428	3	6- 9.2	3.1 - 5.1	Dielectric resonator antenna
[42]	RT/Duroid 5880	12 x 12 x 1.02	2	9.5-11	24-34.1	Microstrip patch

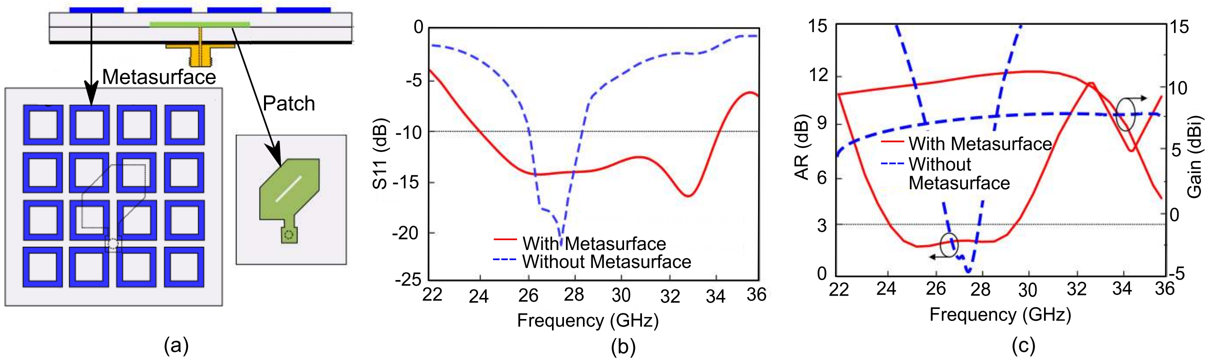

FIGURE 5. Multilayer antenna design [42] (a) Antenna design (b) Return loss (c) Gain and axial ratio.

is designed in [74] to operate over 1.63-3.68 GHz frequency band which includes 2G, 3G, LTE, and 5G bands. In [75], a five layer antenna is designed by incorporating symmetrical E shaped patch antenna, slots, and substrate integrated waveguide (SIW) to operate an antenna in both TM_{10} and TM_{20} modes with nearly same resonance frequencies. It also yields low cross polarization and stable radiation pattern.

The detailed comparison of the 5G antennas for single and multilayer, SISO is given in table 7. This comparison is based on the type of substrate, size, the number of substrate layers, gain in dBi, and operating frequency range in GHz. As per the table 7 the cost effective 5G antennas are designed in [34], [41] which are fabricated on FR4 substrate and they are of moderate size. A compact antenna is designed in [67] and its gain is moderate. To enhance the gain of a compact antenna, the researchers design a multilayer antenna. The last four rows present the comparison of a single element, multilayer 5G antennas. Out of these multilayer antennas, the antenna designed in [42] is very compact and with high gain.

The multilayer and circularly polarized antenna design [42] is shown in figure 5. In this, figure 5(a) depicts the design of an antenna that contains two substrates of RT/Duroid 5880 and three layers of copper. Out of these three layers, the top layer is the metasurface layer and it designed by 4×4 square rings. The middle copper layer is the radiator patch and the bottom copper layer is a ground. The square ring of the metasurface is a series combination of capacitor and inductor which affects the resonance frequency and hence the bandwidth of an antenna. As depicted in figure 5(b), the bandwidth of antenna without metasurface is 24.6-28.7 GHz whereas the bandwidth of antenna with metasurface is 24-34.1 GHz. Further, metasurface also improves gain (9.5-11 dBic) and axial ratio bandwidth (24.1-29.5 GHz) as shown in figure 5(c). This gain enhancement of a compact wideband antenna is possible because of multilayer and metasurface enhancement technologies.

2) MULTI-ELEMENT ANTENNAS

The most important requirements of 5G antennas are high gain, stable radiation pattern, and wider frequency band. These requirements cannot be satisfied by a single element antenna and hence a multi-element antenna is designed by most of the researchers for 5G applications [12], [79]. A 1×16 multi-element antenna presented in [25] has used a substrate integrated coaxial line (SICL) feeding network to achieve a very high gain of 15-19 dBi and wide bandwidth of 25 - 41 GHz. A multilayer and 42 elements parasitic antenna is designed in [40] to obtain a high gain of 21.4-22 dBi and side lobe level (SLL) better than −18 dB. Next, a significant gain enhancement by 3 dB is done in [37] by placing a 3D, U-shaped lens in front of an antenna. Importantly, the SIW technique can be incorporated in the 5G antenna to enhance the isolation level [16], [80]. In [38], SIW is incorporated all three substrates of 8×8 planar antenna to obtain a very high gain of 24.7 - 27.8 dBi and wide bandwidth of 56.1 to 70.6 GHz with a compact size. Further, a metasurface is used in [81] to enhance the bandwidth of low profile antenna.

The comparison of the wideband 5G multi-element antenna is given in the table 8. The single substrate layer antennas presented in [76] and [31] are of moderate size, gain, and bandwidth. To improve the performance of a multi-element antenna the multilayer antenna is designed in [39], [77], [78] but, the overall size of antennas is large. In [39], proximity coupled multi-element antenna is designed to enhance the gain at the cost of increased size. From table 8 it is observed that a very compact 1×4 multi-element AVA is designed in [12] by incorporating corrugations to achieve wide bandwidth.

The effect of the corrugation technique on the return loss and gain [12] is shown in figure 6. In figure 6(a), 1×4 multi-element AVA design is shown in which corrugations are incorporated at the flat edges of AVA flares. After incorporating these corrugations, the electric path length of the current at the flat edges increases due to the introduction of inductor(L), resistor(R), and capacitor(C) at the flat edges. This extra RLC circuit changes the resonance frequency of an antenna as shown in figure 6(b). Figure 6(b) proves that the bandwidth of an antenna is increased after incorporating corrugation in it. Further, as the current density increases at the edges, the antenna radiates more energy in the end-fire direction which in turn enhances the gain as depicted in

TABLE 8. Comparison of multi-element antennas (SISO wideband).

Ref. No.	Substrate	Size (mm^3)	No. of Substrate Layer	Gain (dBi)	Frequency Band (GHz)	Antenna Type
[12]	RT/ Duroid 5880	28.8 x 24 x 0.254	1	8.2 - 13.2	24.04 - 40.85	Antipodal Vivaldi antenna
[76]	RT/ Duroid 5880	37.6 x 14.3 x 0.254	1	8.5- 10.7	23.41 - 33.92	Antipodal Vivaldi antenna
[31]	RT/ Duroid 5880	32 x 12 x 0.254	1	7.8-10.9	25.28 - 29.04	Fractal
[77]	RT/ Duroid 5880	30 x 35.62 x 4.9	4	10.6 - 12.61	27.12 - 29.5	Dipole
[39]	Taconic TLY-5	96.1 x 50.5 x 1.016	2	13.83 - 14.31	26.4 - 28.92	Microstrip patch
[78]	RT/ Duroid 5880, Acrylic Polymer	32.1 x 37.45 x 2.124	2	10 - 12	23 - 32	Microstrip patch

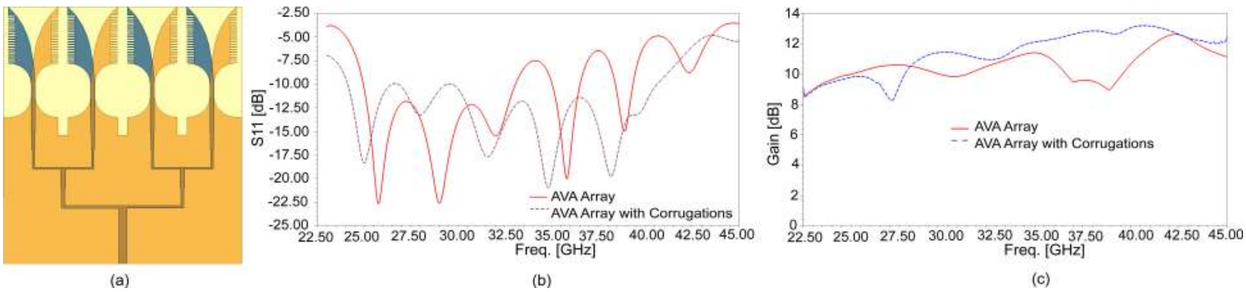

FIGURE 6. Antenna design with corrugations [12] (a) Antenna design (b) Simulated return loss (c) Simulated gain.

figure 6(c). Thus, the corrugation performance enhancement technique is very useful for bandwidth and gain enhancement.

B. SISO MULTIBAND ANTENNA

SISO multiband antennas can be also classified as a single and multi-element antenna. After a deep literature study, it is found that very few research work is done on multiband SISO antennas as it provides less gain and bandwidth [82], [83]. In [82], a dualband antenna operates at 28 GHz and 38 GHz with a low bandwidth of only 3.65 and 2.19 GHz, respectively. In [83], a triband antenna is implemented by incorporating a slot technique but the gain is less. Hence, SISO multiband is not a good choice for 5G applications.

C. MIMO WIDEBAND ANTENNAS

MIMO wideband antennas can also be categorized as mulit-element without metal rim and multi-element with a metal rim.

1) MULTI-ELEMENT WITHOUT METAL RIM ANTENNAS

In the literature, it is found that lots of work have been carried out in MIMO wideband antennas without metal rim. These designs mainly focus on either dual element or multi-element antennas. Both antenna categories are explained below:

- ***Dual Element Antenna without Metal Rim***

This section deals with the MIMO antennas consisting of similar antenna structures with distinct feeding lines. In MIMO antennas, DRAs are used because of high efficiency, improved isolation, and enhanced gain. In the MIMO system, the major requirement is to increase the isolation between antenna elements. Lots of research is done to increase isolation between MIMO DRAs like frequency selective surfaces (FSSs) [87], metasurface shields [88], and hybrid feeding mechanism [89]–[91]. These techniques are used to resist the current displacement within antenna elements. Also, isolation can be improved by adding a metal strip on the upper surface of the dielectric resonator [84]. This added metal strip moves a strong coupling field away from adjacent slots resulting in alleviated ECC value and higher diversity gain.

Isolation in a MIMO system is a big challenge because of limited space inside the mobile. The neutralization line [92], [93] and decoupling techniques [32], [94] are suggested for isolation improvement. In addition, good isolation is achieved by using a pair of antennas with a self-decoupled structure [85]. This structure is achieved by placing two antenna elements on common ground which not only improves isolation but also increases the antenna effective length. This self-decoupled antenna structure provides efficiency around 58% and the ECC value is less than 0.1. Thus, the self-decoupled structure provides improved isolation, low ECC, good efficiency, and compact size.

In [95] four port MIMO antenna is designed which provides low gain and omnidirectional pattern. 3D antennas are also available in literature, but it takes more space for four elements four-port antenna [96]. PIFAs can be used in cellular applications and 5G IoT. PIFA antenna has two elements and four ports [22]. It provides a minimum bandwidth of 900 MHz, minimum isolation between ports is −13 dB.

TABLE 9. Comparison of dual element without metal rim antennas (MIMO wideband).

Ref. No.	Size (mm^3)	Gain (dBi)	Isolation (dB)	Frequency Range (GHz)	Efficiency (%)	Antenna Type
[84]	20 x 20 x 2.54	9.9	24	27.25 - 28.59	Not Given	DRA
[85]	150 x 75 x 0.8	Not Given	17	3.4 - 3.6	58	Monopole
[22]	50 x 100 x 3.00	3	25	2.7 - 3.6	80 to 92	PIFA
[86]	60 x 60 x 8	8.2	25	3.3 - 4.36	89.5	ME Dipole

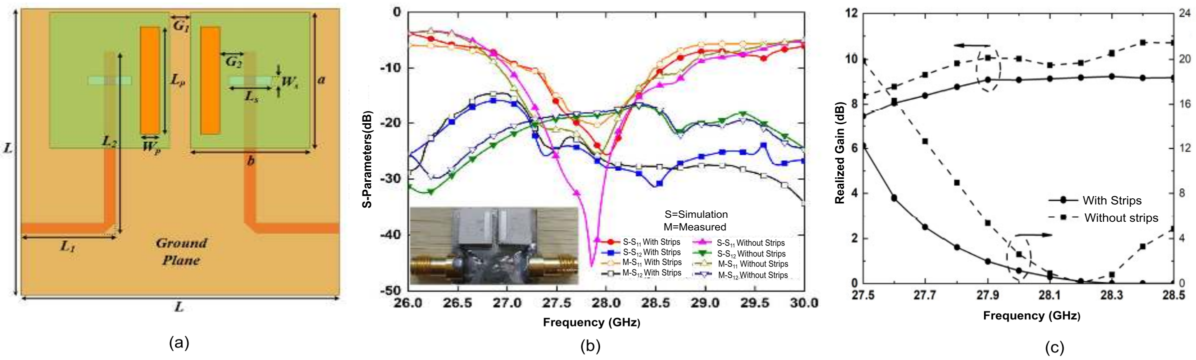

FIGURE 7. Dielectric resonator antenna design [84] (a)Top view of MIMO DRA (b) S parameters (c) Gain and ECC.

To reduce mutual coupling between different elements filtering antennas are used without using a decoupling network or duplexer. ME (Magnetoelectric) dipole antennas have advantages like stable gain, wide bandwidth. Dual polarized low-profile ME dipole antenna provides wide bandwidth [86]. ME dipole antenna contains four patches which are shorted one. Short aperture in between these patches forms a magnetic dipole. The Center frequency of this antenna obtained is 3.83 GHz with 27.6% of impedance bandwidth.

Table 9 provides a comparative study of various MIMO wideband antennas suitable for 5G applications. The comparison is done based on various performance parameters like antenna size, gain, frequency band, isolation, efficiency, and antenna type used. It shows that the efficiency of the MIMO wideband antenna can be increased by using PIFA [22], and ME dipole antenna [86] whereas the gain enhancement is achieved by using DRA [84] and ME dipole [86] antenna. Additionally, the self-decoupled [85] require more space as compared to the other antennas. It is observed that antenna designed in [84] by using DRA provides a higher gain, optimum isolation, much lower ECC value by maintaining a compact size, and high radiation efficiency in millimeter wave band.

Figure 7 shows the DRA structure, S parameter, gain, and ECC for MIMO DRA [84]. As shown in figure 7 (a) two rectangular shape DRAs are mounted on Rogers 5880 substrate. To enhance the isolation metal strip is printed on the top surface of the DRAs. Figure 7 (b) depicts S parameter where it shows isolation is improved after adding the metal strip. A large diversity gain and channel capacity are achieved as shown in figure 7 (c). The ECC value achieved is less than 0.013 in 28 GHz band and diversity gain is greater than 9.9 dB.

- ***Multi-element Antenna without Metal Rim***

MIMO multi-element antenna is used to enhance the gain and the transmission range of the signal which is a prime requirement of any high speed communication applications. In this section, an extensive literature study is carried out for wideband multi-element without metal rim along with their applications.

In the literature, it is found that extensive research has been carried out by several authors for designing MIMO multi-element antenna like structured monopoles, slot antennas, dual and tri polarized antennas for 5G applications. Along with MIMO cognitive radio (CR) is also the core technology for 5G communication but, the design of an antenna using both CR and MIMO is a daunting task. In [106], MIMO antenna having four ports is designed for underlay and interweave CR. Also, a wideband MIMO antenna is designed in [98] by adding a multipurpose filter within the microstrip feeding part. Because of the multipurpose filter which incorporates varactor diode, frequency tuning is also possible. A combination of CR and MIMO creates a more efficient system called filtenna which provides increased spectrum efficiency and data rate, respectively. Further, the parametric analysis shows that the ECC value is below 0.5 within the frequency range of 2.50 - 4.20 GHz and gain is greater than 1.5 dBi. Next, to enhance data throughput and radiation efficiency many researchers have designed Monopolar Patch Antennas (MPAs) that generates monopole radiation pattern [107]–[112]. In [97] MPAs are combined in Y type structure for MIMO operation with an efficiency of 88% and ECC around 0.1. This antenna is suggested for 5G access point applications.

MIMO advantages can be realized provided mutual coupling is minimized. For this various mutual coupling

TABLE 10. Comparison of multi-element without metal rim (MIMO wideband).

Ref. No.	Frequency Range (GHz)	Isolation (dB)	ECC	Channel Capacity (bps/Hz)	Antenna Type
[97]	3.3 - 4.2	15	0.1	16.5	Monopole
[98]	2.5 - 4.2	15	Less than 0.5	Not Given	Filtenna
[99]	3.4-3.6	10	0.2	35 to 38	Monopole
[100]	5.1-5.9	17	0.01	Not Given	Monopole
[101]	2.55-2.65	12.5	0.15	38 to 40	Monopole
[102]	3.4-3.6	12.5	0.2	57	SIW Antenna
[103]	3.4-3.6	17.5	0.05	40.8	Slot
[104]	2.5-7.0	17	0.1	39	Inverted F
[105]	24.35-31.13	20	Not Given	Not Given	Microstrip Patch

reduction techniques have been proposed like polarization diversity, orthogonal polarization, DGS, and neutralization lines. MIMO antenna which is uniplanar and uses polarization diversity reduces mutual coupling which further makes 5G antenna more resistant for interference and fading [14].

Inverted monopole antenna with the parasitic strip is used in [99] for designing an eight element antenna which utilizes neutralization lines and ground middle slots for decoupling purpose. For the rejection of wireless LAN band and to provide good isolation, four monopole antennas along with common ground are used to form a multi-element antenna that behaves like a band stop filter [100]. In [103], the multi-element antenna yields balanced slot mode, and to obtain high isolation the polarization diversity technique is used. In addition to this, the channel capacity enhancement technique is verified with the help of the Kronecker channel model.

The printed wideband antenna which consists of three slots, connecting lines, and symmetric antenna elements for mobile terminals is presented in [113]. Reflection coefficient improvement and mutual coupling reduction are obtained with this arrangement. This dual antenna operates at different GSM and LTE bands. Neutralization line and ground slots are used to enhance isolation by using a MIMO multi-element antenna in [114]. These eight elements antenna structure provides good efficiency, bandwidth, channel capacity and have a small size, hence it is a potential candidate for 5G applications. The self curing technique is used for decoupling purposes, to improve matching conditions, flexibility, ease of application, and compatibility in commonly used antennas like a loop, monopole, and inverted F antenna (IFA) [115]. IFA can be decoupled by placing one of the antennas in excited mode whereas the second antenna at a stable null point [116]. High isolation and compact antenna can be obtained by using J shaped slits [117].

A comparison of the MIMO wideband multi-element antenna is shown in table 10. This comparison is based on the type of mutual coupling reduction technique, frequency range used, isolation, ECC, and channel capacity. For getting high isolation and lower value of ECC, the polarization technique is used in [100]. Enhanced channel capacity is obtained with orthogonal polarization [102]. It is observed that enhanced isolation is achieved by using polarization diversity [100], [103] and F shaped stub [104]. Out of these antennas, the antenna designed in [105] provides high gain, stable radiation pattern, enhanced isolation, and wider bandwidth.

Fabricated 16 element multi-element antenna and its performance parameters are shown in figure 8 [105]. This 16 element antenna is designed by using two multi-element antennas in which two substrates of equal size are used. The patch present on the bottom substrate is used as a radiator whereas the patches present on the top substrate are utilized as parasitic patches for enhancement of bandwidth as shown in figure 8 (a). For decreasing mutual coupling between antenna elements, feed lines and radiating patch allowed to rotate 180 degrees out of phase. In figure 8 (b), return loss S11 and frequency plot is shown with and without a feeding network. This feeding network operates at a definite phase difference to obtain E plane and H plane gain. This antenna provides a very high gain of 19.88 dBi and impedance bandwidth of 5.37 GHz. Hence, this antenna is suitable for 5G applications.

2) MULTI-ELEMENT WITH METAL RIM ANTENNA

Metal rim based MIMO antennas are the key elements in the design of smartphone antennas suitable for 5G communication. Loop antennas and slot antennas are widely used to incorporate all the required LTE bands along with new 5G bands. Typically, the metal rim MIMO antennas can be either fixed type or reconfigurable for wideband and multiband applications. Figure 9 represents the smartphone metal shell structure. Figure 9(a) represents the 3D view of the smartphone metal shell whereas, figure 9(b) represents the corresponding side view. As shown in the figure, a metal shell consists of a substrate, metal rim, and a 2 mm wide single ring slot. It can be observed that a metal ground present below the substrate is firmly surrounded by an unbroken metal rim. The antenna is designed along the rim of the metal ground.

Additionally, MIMO metal rim antennas are of two types which are reconfigurable and fixed antennas. The important

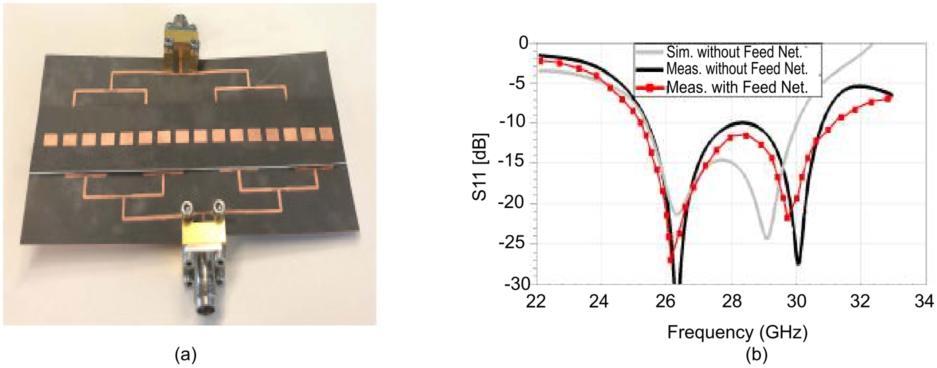

FIGURE 8. Fabricated multi-element antenna with performance parameters [105] (a) Fabricated MSA with parasitic element (b) Simulated S11 with and without feeding network.

feature of a reconfigurable antenna is that it is a frequency tunable antenna whereas the frequency band is not variable in a fixed type of an antenna. Compared to fixed type metal rim antenna, the reconfigurable (tunable) metal rim antenna increases functionality in communications and radar applications without increasing the size and cost of the system. Also, the reconfigurable antenna provides multi-frequency operation, polarization diversity. The tunable antennas can be realized using pin diodes and varactor diodes, MEMS devices (switches, phase shifters), and tunable materials like liquid crystals.

In [120] along with wideband, the metal rim MIMO multi-element antenna is characterized by reduced antenna size due to inverted-F antenna design along with tuning stubs. The multi-element antenna design consists of eight elements that cover 3.3-7.1 GHz and uses the FR4 substrate. This 8 × 8 metal rim multi-element antenna is a suitable candidate for 5G applications because of its wideband, efficiency above 47%, and ECC less than 0.09. By varying the stub length, the operating frequency of the inverted F antenna (IFA) can be controlled.

In [121] a metal rim wideband MIMO multi-element antenna consists of 4 modules of dual band antenna elements (shared radiators) resulting in an eight element antenna structure. Each module consists of two antenna elements (for example module1 consists of Ant1 and Ant2). Along with metal rim, a combination of monopole and dipole antennas in orthogonal mode provides a wideband in low frequency band whereas the use of slots in orthogonal mode provides wider bandwidth in a high frequency band. The use of orthogonal mode also enhances isolation. The parametric analysis of multi-element antenna exhibits ECC below 0.11 with Ant1 and Ant2 efficiencies as 58.9-88.6%, 31.6-76.7% respectively and isolation above 12 dB. Since the bandwidth is 3.3-5 GHz the MIMO antenna design is suitable for 5G applications.

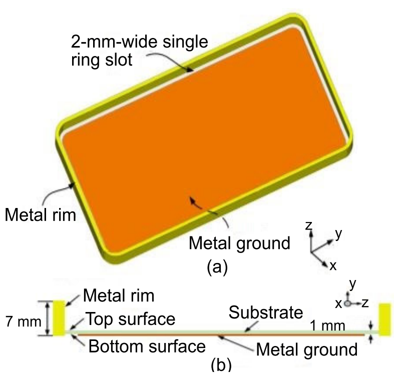

FIGURE 9. The smartphone metal shell: (a) 3D view; (b) Side view [148].

In [119], four elements and eight elements MIMO antenna design integrated with metallic bezels operating at a frequency of 3.5 GHz with a bandwidth of 3.4 to 3.6 GHz are presented and discussed. The basic radiating element is a dual antenna pair consisting of slit and slot on bezel and ground respectively providing spatial reuse and is excited via symmetrical feeding network. Moreover, the antenna pair referred to as co-frequency pair integrated with metallic bezels is suitable for smartphones. The 4 × 4 MIMO multi-element antenna is fabricated and the performance parameters exhibit ECC below 0.13, isolation better than 12.7 dB with efficiency 35.2-64.7%.

In [122], the metal frame eight elements multi-element antenna consists of two types of antenna structures namely open slot and closed slot and the antenna is fabricated on the FR4 substrate. Further, Ant1 and Ant5 represent open slot with coupled line whereas Ant2, Ant3, Ant4, Ant6, Ant7, and Ant8 represents closed slot with the coupled line. Compared to closed slot mode, the open slot mode provides better bandwidth enhancement. The MIMO eight element antenna provides a bandwidth of 3400-3600 MHz and is suitable for metal rim 5G antenna design. The performance parameters show that the isolation is better than 13 dB with ECC less than 0.15. Also, the efficiency is greater than 42%.

Table 11, provides a comparative summary of various MIMO wideband metal rim antennas suitable for 5G smartphone applications. The comparison is done based on various performance parameters like antenna type, type of substrate used, efficiency, ECC, and the frequency bands covered. From the above table 11, it is observed that a wideband of

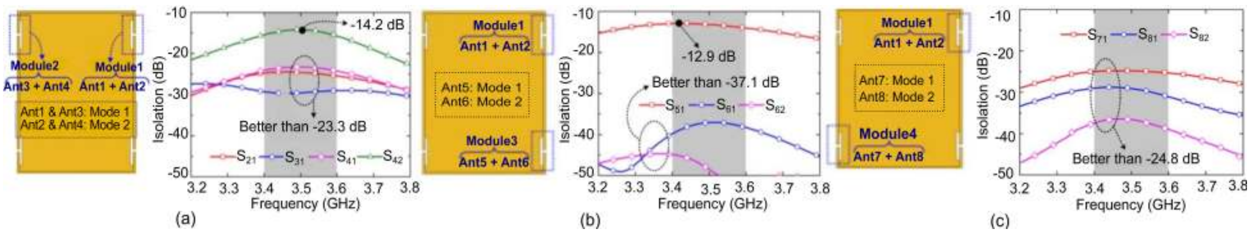

FIGURE 10. Wideband metal rim eight element MIMO antenna [119] (a) Isolation Between Module 1 and Module 2 (b) Isolation between module 1 and module 3 (c) Isolation between module 1 and module 4.

TABLE 11. Comparison of mutli-element with metal rim antennas (MIMO wideband).

Ref. No.	Efficiency (%)	Isolation (dB)	ECC	Frequency Band (MHz)	Antenna Type
[120]	47-70	more than 11	less than 0.09	3300 - 7100	Hybrid IFA
[121]	57.8 -74.7	more than 12	less than 0.11	3300-5000	Monopole
[119]	35.2-64.7	more than 12.7	less than 0.13	3400-3600	Slot
[122]	greater than 42	greater than 13 dB	less than 0.15	3400-3600	Slot

about 3300-7100 MHz is provided but isolation is comparatively low [120]. It is also observed that [122] provides isolation better than 13 dB. Taking into account all the parameters discussed in table 11, [119] provides better performance.

In [119], a fixed type 4 × 4 MIMO wideband multi-element antenna integrated with the metal rim is designed and fabricated. The dual antenna pair supports in-phase current mode and slot mode resulting in a polarization orthogonal mode thereby enhancing diversity performance. One of the key factors for high isolation includes a symmetrical feeding network. Figure 10 represents wideband metal rim eight element MIMO antenna. As shown in figure 10, A two antenna pairs in three possible configurations as module 1: top right and module 2: top left (figure 10.a), module 1: top right and module 3: bottom right (figure 10.b) and module 1: top right and module 4: bottom left (figure 10.c). The plots summarize the simulation results of the 8 element antenna. The parametric analysis shows that the isolation of the MIMO multi-element antenna in three possible configurations is better than 23.3 dB, 23.3 dB, and 24.8 dB. Thus, the design provides isolation enhancement, and the ECC is less than 0.13.

D. MIMO MULTIBAND ANTENNAS

Wireless communication plays an important role in the rapid growth of information technology where channel capacity is a major issue. The solution for the same is multiband antennas as it is very difficult to use separate antennas for different applications. Multiple frequencies supported by a single antenna is more suitable for wireless and mobile communication applications because of the compact size requirement.

1) MULTI-ELEMENT WITHOUT METAL RIM ANTENNAS

The MIMO multiband antennas are very beneficial to reduce the required number of antennas for different applications. This section includes the details of multiband antennas without metal rim and they can be further classified into dual element and multi-element antennas without metal rim.

- ***Dual Element Antenna without Metal Rim***

In the literature review, wide research is available in dual polarized multiband antennas [129]–[131]. A compact size, simple structure, stable radiation pattern, and polarization performance are the advantages of reconfigurable antennas over traditional antennas. In [123], a U-shaped structure and PIN diode low profile reconfigurable dual polarized antenna is used for 5G application with the isolation of more than 25 dB within two bands. The MIMO multiband antenna structure is a key factor to reduce antenna size [132]. The tapered slot antenna design [124] provides wider bandwidth and ECC less than 0.001 that can be used for the 5G mobile terminal applications.

For dualband, the 5G antenna main prerequisite is compact size, low-profile structure, and Full Duplex system [133], [134]. For dualband application, PIFA is used for MIMO half duplex and MIMO full duplex 5G system [125]. To reduce mutual coupling between antennas, a metamaterial-based system is used in recent years [135]. To reduce mutual coupling and improve efficiency by 15% decoupling method based on metasurface is proposed in [126]. Also, the isolation is greater than 25 dB with ECC of about 0.08 at 2.6 GHz and 0.01 at 3.5 GHz.

Dual Folded Monopole Antenna (FMA) system with compact size provides multiple resonances [127]. Further, a square patch of FSS is a decoupling structure used to suppress mutual coupling between antenna elements.

Many metasurface based antennas with a low profile are used in a broadband application that operates in the S band [136]–[140]. Furthermore, dualband metasurface based antennas are also demonstrated in [140]. Shared aperture antennas structure for dualband operation is formed by

TABLE 12. Comparison of dual element without metal rim antennas (MIMO multiband).

Ref. No.	Gain (dB)	Isolation (dB)	Frequency Range (GHz)	Efficiency (%)	Antenna Type
[123]	6.86 8.14	25	3.24 - 4.03 4.44 - 5.77	Not Given	Dipole
[124]	3 7	16 25	1.8 - 2.6 27.5 - 40	70 to 90 60 to 85	Tapered Slot
[125]	4.8 3.9	20 35	2.5 - 2.7 3.4 - 3.8	80	PIFA
[126]	7.8 8.6	25	2.5 - 2.7 3.4 - 3.6	Not Given	Microstrip patch
[127]	9 7.5 6.5 4 7	30	2.4 - 2.48 2.91 - 3.49 3.27 - 3.97 3.4 - 3.8 5.15 - 5.85	55 to 65	Folded Monopole
[128]	7.3 - 10.4 11.8 - 14.6	70 21.5	3.2-4.05 26.8-29.55	Aperture efficiency -61 %	Fabry- Perot resonator antenna (FPRA)

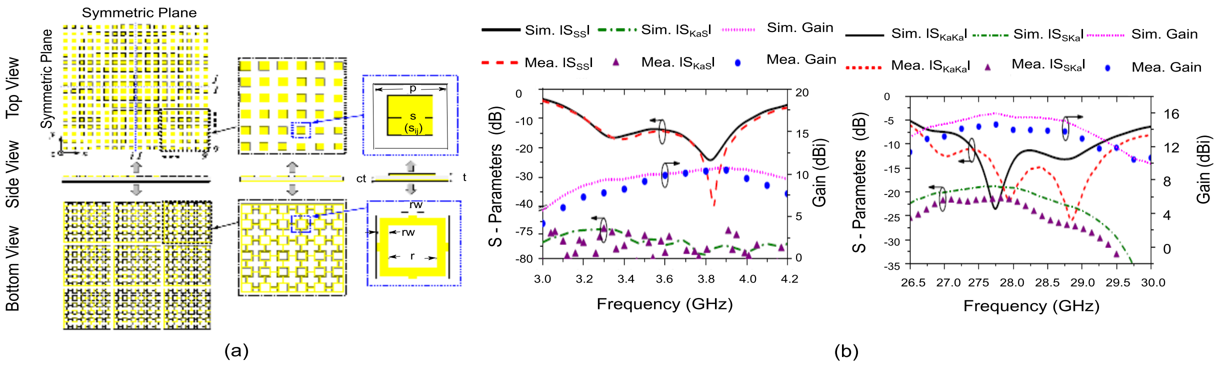

FIGURE 11. Shared-surface Antenna [128] (a) Shared surface antenna (b) Simulated and measured S parameters and gain.

integrating metasurface and partially reflective surface (PRS) at S band and Ka band respectively [128].

Table 12 provides a comparative study of various MIMO Multiband antennas for 5G applications. The FMA design provides the maximum gain of 9 dBi and maximum isolation of 30 dB but less efficiency [127]. PIFA design provides better efficiency and isolation but lesser gain [125]. The reconfigurable antenna provides better isolation and gain [123]. Further, the tapered slot antenna gives moderate gain and good isolation [124]. Optimum gain and maximum isolation are provided by metasurface based dualband aperture antenna [128].

Figure 11 shows the shared surface antenna, S parameter, and gain [128]. As shown in figure 11(a) this antenna is a combination of PRS unit cell and metasurface element. The advantage of a shared surface is that it changes the electrical and physical parameters of an antenna which allows resonant modes at Ka band and S band. Figure 11 (b) depicts S parameter where it shows return loss less than −10 dB with 23.45% measured bandwidth for S band and 9.76% for Ka band. It provides maximum measured isolation greater than 70 dB at 3.6 GHz (S band) and 21.5 dB at 28 GHz (Ka band). The maximum broadside gain is 7.3 to 10.4 dBi over impedance bandwidth of 3.2 to 4.05 GHz and 11.8-14.6 dBi over the band of 26.8 - 29.55 GHz by maintaining a compact size.

- ***Multi-element Antenna without Metal Rim***

Multiband multi-element antenna is the panacea of the rapid development of wireless communication which demands heterogeneous network simultaneous accessing two or more technologies like WiFi, GSM, Bluetooth, 4G, and 5G. In [141], multimode in mobile terminals is obtained by using the hybrid structure which consists of U shaped slots and lumped elements. This antenna can cover GSM, LTE, and UMTS applications with good isolation and better efficiency for both lower and higher frequency bands. To improve isolation, slot length has been decreased significantly with the insertion of lumped capacitors at the slot edges but inductance is introduced by increasing electrical length of U shaped slots and adding L shaped slots. The performance of the decoupling structure largely depends upon the lengths of U and L shaped slots whereas merely depends upon their widths. Impedance matching of these two antenna elements depends upon this hybrid decoupling structure.

The neutralization line is used in [142] to cancel reactive coupling between two radiating elements of multiband MIMO antenna which is used for GSM, LTE, and distributed control system (DCS) applications. For mutual coupling reduction, the ground plane is etched with four slits and two small rectangles. Folded monopole and rectangular metal patch which acts as radiating elements produces different frequency modes for multiple applications. After this compared their powers as well as uploading and downloading speeds. This antenna provides good impedance matching, diversity gain, and radiation efficiency. An octaband compact monopole antenna is presented in [143] without using a lumped element and very small nonground portion. Nonuniformity in surface currents at a different location can be used for impedance matching.

A comparison of the MIMO multiband multi-element antenna is shown in table 13. The comparison is done based on various parameters like isolation enhancement technique, frequency range used, isolation, ECC, efficiency, and size of the antenna. For getting a small value of ECC in sub 6 GHz, the eight element MIMO system is used [147] with polarization diversity. To design a compact, PIFA is used in [33] with a vertical metallic patch as an isolation enhancement technique. The maximum efficiency is obtained in twelve port MIMO antenna with a slotted ground structure [145]. It can be seen from the table 13 that most of the MIMO multi-element antenna designed is compact and the frequency range is sub 6 GHz which is suitable for 5G application in mobile terminals. The effect of polarization diversity on efficiency and channel capacity is shown in figure 12 [146].

Dimension and geometry of the proposed ten element antenna is shown in figure 12 (a). The substrate material used here is FR4 with a size of 150 mm × 80 mm × 0.8 mm which is compatible with smartphones. The ten antenna elements are located along edges of the substrate and each antenna element can cover uplink and downlink frequency range required for LTE bands. T shaped slot is formed in a rectangular slot which is a couple fed by L shaped feeding strip and generates two resonant modes. Antenna efficiency is measured in the low band (LB) and high band (HB) as shown in figure 12 (b). In the case of LB, 42-65% efficiency is obtained whereas in HB efficiency is 62-82%. These values of efficiency are suitable for achieving low capacity loss. Assuming the same power is fed to each transmitting antenna, the ergodic channel capacity is obtained which is shown in figure 12 (c). In the case of LB, the peak channel capacity is reached up to 48 bps/Hz whereas in the HB it is 51.4 bps/Hz.

2) MULTI-ELEMENT WITH METAL RIM ANTENNAS

The demand for multiband metal rim antennas is rapidly increasing because of the advancement in modern devices like smartphones and smartwatches. A 2 × 2 MIMO antenna design representing a main antenna and diversity antenna is discussed in [149]. Here the transmission rate has enriched using carrier aggregation technique. Further for an LB of 824-960 MHz, the measured efficiency is 31-38% whereas for an HB of 1710-2690 MHz the measured efficiency is 42-69%. The metal rim antenna design is suitable for smartphone applications and consists of a dual loop structure. Furthermore, in [154] the MIMO antenna designed is integrated with carrier aggregation (CA) to enhance data rates and cover LTE and Wi-Fi bands. In addition, the antenna designed in [155] uses orthogonal characteristic modes to achieve antenna diversity as well as to enhance the antenna performance. The metal frame MIMO multi-element antenna suitable for sub 6 GHz applications is discussed in [156]. Here, the multi-element antenna consists of two 8 elements and each radiating element represents a slot antenna integrated with a feedline of 50Ω. The bandwidth is enhanced by incorporating a tuning stub into a feedline.

In [118], multiple antennas enhance the communication link capacity and supports multipath propagation. The antenna structure is characterized by a reconfigurable feature because of the use of varactor diode for switching between the frequency bands. Also, the metal rim MIMO antenna design is novel and operates in the frequency band of 698-960 MHz and 1710-2690 MHz, respectively. The switching feature enables the open slot antenna design to support 8 frequency bands. In [157], a metal rim 2 × 2 MIMO reconfigurable multi-element antenna for smartphone application is proposed. Here the antennas are designed along the long edges of the phone and are fabricated on the FR4 substrate. Another reconfigurable antenna design includes a switch based reconfigurable MIMO metal rim antenna for the LB, middle HB (MHB), and HB application [158]. This MIMO antenna designed utilizes the theory of antenna clusters consisting of many radiating elements that are fed diversely.

In [148], the antenna design consists of a ring slot that is realized in the space separating metal ground and rim. This antenna provides a reconfigurable design for the 4G band. For 5G communication below 6 GHz, a MIMO antenna consisting of 4 elements is discussed and the type of antenna structure used is a slot antenna. Thus, an antenna designed integrates 4G and 5G bands and provides isolation enhancement. The substrate used is Taconic RF-30. The design provides isolation greater than 13 dB and ECC of 0.07 respectively.

A metal rim reconfigurable MIMO antenna is presented in [150]. Here, the use of 3 switches provides a reconfigurable antenna structure capable of covering seven WWAN/LTE frequency bands. The antenna structure incorporates two loop

TABLE 13. Comparison of multi-element without metal rim antenna (MIMO multiband).

Ref. No.	Frequency Range (GHz)	Isolation (dB)	ECC	Efficiency (%)	Size(mm^3)	Antenna Type
[144]	0.740-0.965,1.380-2.703	10	0.5	40-67.2	95 x 60 x 0.8	Microstrip Patch
[145]	3.4-3.8,5.15-5.925	12	0.15	41-82	150 x 80 x 0.8	Slot
[146]	3.4-3.8,5.15-5.925	11	0.15	42-82	150 x 80 x 0.8	Slot
[33]	2.5-2.7, 4.85-5.15	10	0.2	Not Given	17.30 x 5.76 x 4.61	PIFA
[147]	1.88-1.92,2.3-2.4,2.54-2.62	10	0.1	40-65	136 x 68.8 x 1	PIFA

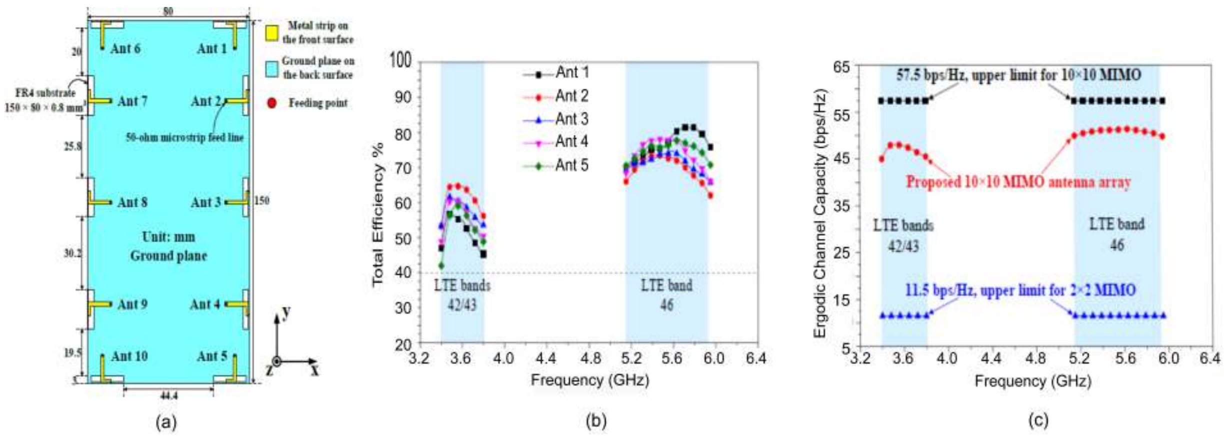

FIGURE 12. Multiband antenna multi-element (MIMO) [146] (a) Structure of MIMO multi-element antenna (b) Measured total efficiency (c) Channel capacity.

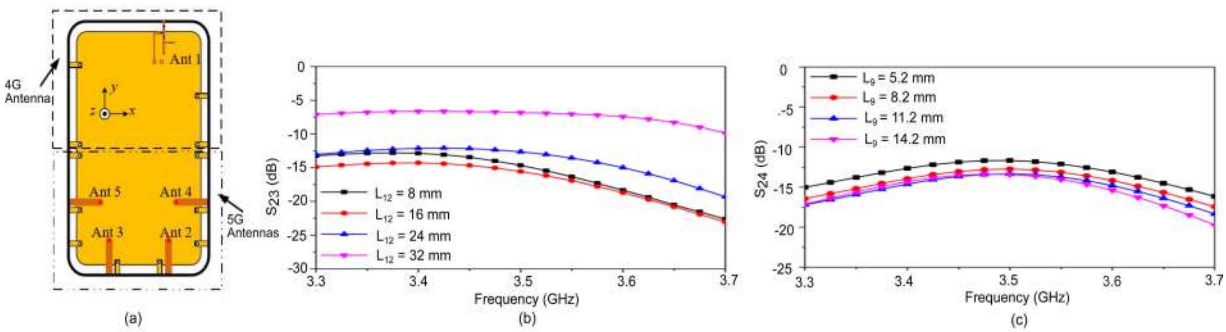

FIGURE 13. Multiband metal rim 5G MIMO antenna [148] (a) A single ring slot based antennas for metal rim 4G/5G smartphones. (b) Mutual coupling between Ant 2 and Ant 3 for different values of L12 (c) Mutual coupling between Ant 2 and Ant 4 for different values of L9.

TABLE 14. Comparison of multi-element with metal rim antennas (MIMO multiband).

Ref. No.	Substrate	Efficiency (%)	Isolation (dB)	ECC	Frequency Band (MHz)	Antenna type
[149]	FR4 substrate	LB: 31-38, HB: 42-69	less than 18	less than 0.11	LB: 824-960, HB:1710-2690	Loop
[118]	FR4 substrate	above 50	14	LB<0.15, HB< 0.05	LB: 698-960, HB: 1710-2690	Slot
[148]	Taconic RF-30	4G: 40-90, 5G: 60-75	more than 13	less than 0.07	4G: 698-960 and 1710-2690 5G: 3400-3600	Loop
[150]	FR4 substrate	LB: above 43, HB: 59-72	more than 17	LB< 0.02, HB< 0.4	LB: 824-960, HB: 1710-2690	Loop
[151]	FR4 substrate	20-60	more than 12	LB < 0.4, HB < 0.1	LB: 704-960, HB: 5150-5875	Slot
[152]	FR4 substrate	LB: 48-66, HB: 44-59	more than 10	LB < 0.2, HB < 0.05	2496-2690, 3400-3800	Monopole

antennas and excites four loop modes. MIMO antennas are designed on the FR4 substrate and provide a gain of 0.32-1.4 dBi and 1.6-4.8 dBi in the lower band and higher band, respectively. The corresponding ECC values in the lower and upper bands are 0.02 and 0.4 with overall efficiency above 43% and 59-72%. Isolation is less than 17 dB.

TABLE 15. A summary of 5G antenna design.

Ref. No.	Antenna Types	Trivial Points
[34] [43] [42]	SISO: Single Element	• It is easy to design and fabricate. • A compact antenna provides low gain and narrow operating bandwidth. • To achieve enhanced gain, bandwidth, and other antenna parameters, the size of antenna should be large. • The enhancement in gain and bandwidth is achieved by using multilayer and corrugation technique.
[12] [76] [78]	SISO: Multi-element	• The single element antenna gain can be manifolded after implementing multi-element antenna. • It also enhances return loss and hence the bandwidth of an antenna. Further, it provides a stable radiation pattern. • It increases the size of an antenna. Also, the design of the feeding network is complex, and it is the daunting task to achieve 50Ω input impedance. • The metamaterial and corrugations are suitable for improvement in the gain and radiation pattern of an antenna.
[84] [22] [128] [153]	MIMO: Wideband Dual element without Metal Rim	• It provides high efficiency. • The design of these antennas is complex. • Isolation among wideband antenna elements are effectively improved by using DRA and sharing common ground between antenna elements.
[99] [101]	MIMO: Wideband Multi-element without Metal Rim	• Using monopole antenna, the designed multi-element is light in weight, small, and easy to design. • Impedance matching is a tedious task. • Channel capacity and isolation can be improved by orthogonal polarization and polarization diversity receptively.
[120] [121] [119]	MIMO: Wideband Multi-element with Metal Rim	• Supports antenna miniaturization along with improved ECC and isolation. • Compact antenna design along with wideband operation is possible due to reactance loading and impedance matching. • The effect of user's hand abates isolation and hence affect the overall efficiency. • Orthogonal polarization enhances isolation and provides diverse performance.
[127] [128]	MIMO: Multiband Dual element without Metal Rim	• Provide optimized gain, wide bandwidth, high efficiency, good isolation with compact size. • The design of feeding network is complicated for dual polarization. • Increase in gain and isolation can be achieved using metasurface based antenna.
[144] [33] [147]	MIMO: Multiband Multi-element without Metal Rim	• Compact antenna size is obtained with low ECC value. • It provides marginal values of isolation. • Slotted ground structure can be employed to get better efficiency and to alleviate ECC, polarization diversity technique can be used.
[149] [150] [152]	MIMO: Multiband Multi-element with Metal Rim	• Use of varactor diodes, ON/OFF switches provide reconfigurable antenna design • Device aesthetic properties sometimes restrict the design process. • Reconfigurable antenna uses a switching mechanism hence the design is complex. • MIMO antenna design along with carrier aggregation technique enhances data rate.

In [151], MIMO antenna design along with carrier aggregation provides a high data rate. The main antenna and the diversity antenna occupy the space along the adjacent edges of the smartphone. The antenna consists of L-shaped structures along with slot antennas. The frequency bands include LTE along with GPS and Wi-Fi bands. The mutual coupling is less than −12 dB with an efficiency of around 20-60%. The ECC for the lower band and higher band are less than 0.4 and 0.1 respectively.

In [152] a MIMO multi-element antenna consisting of 8 elements is integrated with the metal frame for 5G mobile phones. The 8×8 MIMO antenna consists of four exactly the same structures where each structure encompasses dual antenna thereby covering LTE bands. The multi-element antenna exhibits an efficiency of 48-66% in the lower band and 44-59% in the higher band. ECC in the two bands is less than 0.2 and 0.05, respectively with isolation greater than 10 dB.

Table 14 provides a comparative summary of various MIMO multiband metal rim antennas suitable for 5G smartphone applications. The comparison is done based on various performance parameters like antenna type, type of substrate used, efficiency, ECC, and the frequency bands covered. From table 14, it is observed that, under fixed type, antenna design provides better isolation of near about 18 dB with ECC value well below 0.5. The efficiency is comparatively unsurpassed [149]. Under reconfigurable design type, it is observed that compared to fixed type design the ECC can be reduced further and the efficiency can be enhanced [118], [148]–[152]. It is also observed that in [148] along with the low value of ECC the efficiency is above 70% in both the bands.

Figure 13 represents a multiband metal rim 5G MIMO antenna [148]. As shown in figure 13(a), the 4G antenna is designed in the upper section whereas 5G MIMO multi-element antenna consisting of 4 elements is designed in the lower section of the smartphone. A 2 mm wide ring slot antenna element is realized in the space separating metal ground and rim of the mobile phone. Stubs are used to connect the metal ground to the metal rim thereby splitting the ring slot into many radiating elements resulting in better isolation. The stubs are loaded on the upper side of the substrate. Here for 5G MIMO antenna, slot 4 is divided into 4 elements (Ants2-5) and each element is fed via microstrip line. Figure 13 (b) and (c) highlights that isolation between Ant2 and Ant3 as well as between Ant2 and Ant4 is enhanced by more than 14 dB by adjusting L12 to 16 mm and L9 to 11.2 mm, respectively.

IV. SUMMARY

The concise review of classifications of 5G antennas and their performance enhancement techniques is presented in this section. This review paper provides an easier path for the upcoming researchers to select the antenna type and enhancement method to satisfy the requirements of different 5G applications. The SISO antenna can be employed in compact devices where the size of an antenna plays an important role. Further, to enhance the gain and bandwidth SISO multi-element antenna can be used. Hence, SISO antennas are easy to integrate into 5G devices which supports IoT except for smartphones. For smartphone applications, MIMO antennas are the best candidate as it supports beamforming. The MIMO multiple patch antenna is comparatively simple to design and implement for smartphones and cognitive radios. To enhance the antenna parameters further, a multi-element antenna can be implemented in MIMO. Also, after the addition of metal rim to MIMO antennas, fundamental and higher order resonance frequencies are generated which results in bandwidth enhancement. Such MIMO antennas with metal rim are suitable for smartphones and smartwatches. Moreover, the next advancement of MIMO i.e. massive MIMO is used at base stations to provide better throughput and spectrum efficiency. The design of antennas with their performance enhancement techniques are summarized in table 15.

V. FUTURE BREAKTHROUGHS

Increasing user demand for the smarter and faster network which is fully secure has escalated the need for higher data rates. To provide all the users with enhanced data rates, more resource allocation is obligatory in the spectrum. In addition, the deployment of ultra dense networks and small cells can provide network flexibility in 5G. The evolving new mobile technology is getting more compact and smarter by considering account the performance parameters such as connectivity, compatibility, and scalability. Further, the 5G technology in mobile communication is energy efficient and offers high throughput, low latency, increased scalability, and reliability. Also, the key technologies such as cloud based Radio Access Network (RAN), massive MIMO (mMIMO), device to device (D2D) communication, network densification, and virtualization of resources plays a vital role in fulfilling the requirements of 5G system. The focus of future breakthroughs are summarized for applications like smartphones, base stations and mobile terminals followed by 5G-IoT in the table 16.

- **Smartphones:** Multiband MIMO antenna design is also suitable for smartphone applications but designing multiband antennas in the limited space of the smartphone is a challenge for antenna engineers. Hence, antenna designs such as MIMO with multimode loop antennas, monopole antennas, IFA are apt for 5G smartphones due to their compactness, ease of integration and manufacturability [159], [160]. Many such compact multiband MIMO antenna designs suitable for 5G mobile terminals and smartphones are summarized in this manuscript.
- **Base stations and Mobile Terminals:** Compact multiband MIMO antenna design is proposed for mobile terminals to meet the demand of integrating more wireless services in the limited space of the mobile terminals. Along with high data rates the 5G base stations and mobile terminal also demand increased channel capacity. Hence, mMIMO antenna design technology can provide both increased data rate and channel capacity. High channel capacity in mMIMO is possible by having many antennas at the base station side. Further, mMIMO also reduce the latency and increase energy efficiency. In mMIMO the number of antennas at the base station side will be very large for higher channel capacities. Also, using mMIMO will increase energy efficiency and reduce the latency [163]. Moreover, the antenna designs fitting the 5G Base station and mobile terminals include MIMO multi-element antenna with DGS, mMIMO antenna system with switched beamsteering [162], [163]. Compared to traditional mMIMO networks, recently cell-free (CF) mMIMO network has been proposed wherein the user equipments (UEs) are served simultaneously by all antennas. Also, CF mMIMO network provides exceptional coverage than the conventional collocated mMIMO system and uncoordinated small cells [167]. Multiple antenna technologies are looked upon as futuristic gateway for 5G network because of adaptive beamforming and spatial multiplexing resulting in improved capacity, coverage, and quality of service (QoS). In years to come, this technology has better prospects in the revolutionary field of smartphones and base stations [161].
- **5G-IoT:** Considering the need for a faster network along with high data rate 5G-IoT is an emerging field. The 5G technology supports one million devices that can be connected over 0.38 square miles whereas only two thousand devices can be connected with 4G technology.

TABLE 16. Future breakthroughs of 5G antennas.

Sr.No.	Applications	Focus of future breakthroughs	Ref.No.
1	Smartphones	Antenna categories: MIMO with multimode loop antennas, monopole antennas,IFA Technology used: beamforming modules, carrier aggregation, multiple antenna technology.	[159]–[161]
2	Base stations and mobile terminals	Antenna categories: MIMO multi-element antenna with DGS, mMIMO antenna system with switched beamsteering. Technology used: multiple antenna technology, millimeter wave Radio Access Network (RAN), Cell-free (CF) mMIMO.	[161]–[163]
3	5G-IoT	Antenna categories: UWB monopole antenna, phased multi-element antennas with beamforming network, massive MIMO. Technology used: centralized RAN (CRAN), software-defined wireless sensor net- working (SD-WSN), network function virtualization (NFV) and cognitive radios (CRs)	[164]–[166]

The performance and deployment of various 5G-IoT applications are boosted by various key technologies which include mMIMO, coordinated multipoint processing (CoMP), D2D communication, centralized RAN (CRAN), network function virtualization (NFV) and cognitive radios (CRs) [166]. The antenna categories suitable for 5G-IoT includes UWB monopole antenna, phased multi-element antennas with beamforming network, mMIMO [164]–[166]. The major challenge faced in the successful deployment of IoT includes the scarcity of a universal platform, protocol, and a programming language. The viable solution is the development of universal coding language and platform. Another challenge faced by future 5G-IoT is the ability to support substantial device connectivity thereby providing prominent and consistent QoS. The access to the 5G network is dependent on the characteristics of the devices connected, hence identification of a perfect system parameter configuration best suited for a specific IoT use case is also a big challenge [166]. Soon artificial intelligence (AI) and 5G-IoT together can play a vital role in developing a smart system capable of tuning its configurations according to the needs or parameters of the environment change.

VI. CONCLUSION

In this paper, a comprehensive review of different 5G antennas is done with the comparison and analysis of their performance enhancement techniques. Also, 5G communication requirements are elaborated. While doing a review of 5G antennas, it is found that the 5G antenna architecture can be classified into two major categories i.e. SISO and MIMO based on input output ports. Both are further classified as wideband and multiband based on their frequency response. Next, the SISO antennas can be classified into a single element and multi-element antennas. The SISO antennas are suitable for integration with 5G devices that support IoT. The MIMO antennas can be categorized into a multi-element antenna with and without metal rim for both wideband and multiband. The MIMO antennas are the best candidate for smartphones while the massive MIMO antennas can be used at base stations. In MIMO metal rim antenna design the use of carrier aggregation reinforces transmission rate. Also, design features like orthogonal polarization boost isolation thereby enhancing the overall efficiency. Additionally, antennas can be classified based on their types. All these antenna types are elaborated in detail with its performance enhancement technique. These enhancement methods create a profound effect on the electrical and physical properties of an antenna which in turn enhances the overall performance of an antenna. The paper also focuses on a future breakthrough which includes 5G smartphones, 5G-IoT, base stations, and mobile terminals. This review paper is useful to 5G antenna designers for selecting a suitable antenna with an enhancement method to accomplish all requirements of 5G applications.

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