International Journal of Microwave and Wireless Technologies

cambridge.org/mrf

Tutorial and Review Paper

Cite this article: Ishteyaq I, Muzaffar K (2022). Multiple input multiple output (MIMO) and fifth generation (5G): an indispensable technology for sub-6 GHz and millimeter wave future generation mobile terminal applications. *International Journal of Microwave and Wireless Technologies* **14**, 932–948. https://doi.org/10.1017/S1759078721001100

Received: 17 October 2020
Revised: 21 June 2021
Accepted: 24 June 2021
First published online: 28 July 2021

Keywords:
Electromagnetic effects; massive MIMO; mobile antenna designs; multiple input multiple output antennas; specific absorption rates

Author for correspondence:
Insha Ishteyaq,
E-mail: insha.ishteyaq@islamicuniversity.edu.in

Multiple input multiple output (MIMO) and fifth generation (5G): an indispensable technology for sub-6 GHz and millimeter wave future generation mobile terminal applications

Insha Ishteyaq and Khalid Muzaffar

Department of Electronics and Communication Engineering, Islamic University of Science and Technology, Awantipur, Jammu and Kashmir-192122, India

Abstract

The in-depth exploration in the future 5G technology symbolizes a revolution in technology for antenna designers to encounter the all time increasing need as well as demand for higher data rate wireless communications. The paper gives out an exhaustive review of the evolution and characteristics of the 5G spectrum allocations, the MIMO antenna design with regard to mutual coupling reduction techniques and safer user applications. It precisely covers almost all the aspects of 5G which mainly include the types of antenna designs and their performance parameters related to MIMO design. The paper also presents a brief description of massive MIMO technology for base station applications. The main aim of the paper is: (1) to emphasize the frequencies allocated for the 5G including sub-6 Ghz and mm-wave bands; (2) to underline the suitable antenna designs for MIMO applications for mobile devices and base stations; (3) to highlight the mutual coupling effects in MIMO designs and its reduction techniques; (4) to consider the gaps in the literature and the challenges for reducing SAR effects for the safety of the users. This review paper has been an attempt to explore the evolution of 5G bands and antenna designs for 5G applications, comparison based on the literature, and the techniques implemented for enhancing the MIMO antenna performances.

Introduction

With the escalation in demand for high data rate communication systems along with commercialization of the fourth generation (4G) networks, there is an emergence of research related to ongoing fifth generation (5G) technologies. The initiatives have been taken and programs launched by a number of organizations worldwide that aim at the key technologies for 5G. There is an ongoing study that suggests the major requirements for 5G include high spectral efficiency (SE) and energy efficiency (EE), low latency, and greater number of node connections. The SE in the available spectrum is considered to be the prioritized design constraint for wireless networks considering the increasing capacity demand. There has been an improvement of data rates from Kilo-bits per second (Kbps) in 2G to Giga-bits per second (Gbps) toward 5G. There is an overall 70% of the total power consumed by the radio access networks. The improvement in the EE is lagging with the overall growth of data traffic in the networks. There is a need of reliable wireless networks for future generations that will be both spectrally efficient as well as in terms of energy. Thus the optimization of SE and EE together is very critical related to 5G technology research [1].

There is a target of deploying 5G in 2020 and beyond with regard to International Telecommunications Union (ITU) radio communication standards sector. One of the most important issues related to 5G deployment is the availability of spectrum required for 5G which could be managed and used efficiently. In view of this, the institutions for 5G research are paying greater attention on the available spectrum to be utilized for 5G deployment. Some of the global institutions include IMT-2020 promotion group of China (IMT-2020 PG), Europe's EU-FP7-METIS project, etc. [2]. Some of the requirements for specifying the 5G technology include frequency allocation bands, data rates, density of connectivity and reliability, spectral density, latency, and mobility as depicted from Fig. 1 [3–5].

The emerging potential frequency bands include the bands above and below 6 GHz. 5G is able to operate in millimeter-wave frequency bands in addition to lower frequency bands of below 6 GHz. In comparison to 4G with the delivering data rates of around 20 Gbps (maximum) and the average of more than 100 Mbps (minimum), the 5G is considered to be very fast. The lower latencies in 5G are achieved by using low density parity check coding as the error correcting code in the forward direction. The maximum speed at the mobile station which refers to the mobility is around 500 kilometers per hour in case of 5G. In 5G, the capacity of the systems is increased by utilizing beam division multiple access and filters bank multicarrier thus handling more number of users at a particular instant of time. In addition to the higher data rates of 2–20

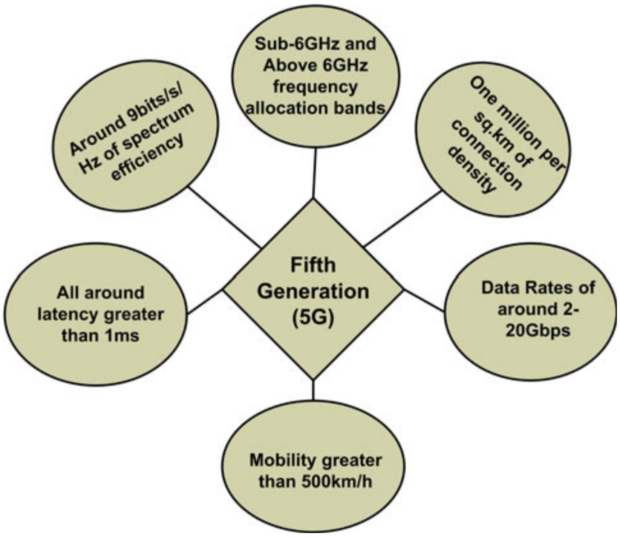


Fig. 1. Specification requirements for the 5G technology.

Gbps, the 5G provides 1 million/km^2 of connection densities and the reliability with the outrage link of approximately 0.999 [6]. The study showed that by the year 2021 the demand for mobile data rate traffic will be 78%. To ensure this growth 5G networks employing multiple input multiple output (MIMO) technology is going to play a key role. The MIMO technology ensures broader bandwidths in comparison to 4G/long-term evolution-advance [7]. There has been continuous advancement in the antenna design technologies viz, for 3G applications single-user MIMO and for 4G multi-user MIMO have been employed while the 5G is going to employ massive MIMO technology which promises the data rates upto 20 Gbps. For an efficiently performing MIMO antenna design, the number of closely spaced antennas must be placed in a way to make the antenna compact with reduced correlation effects for mobile applications [8,9].

In view of enabling the roaming across the world for up to the scale economy, there are in-process a number of activities to visualize the standard spectrums to be allocated for 5G globally. The 5G bands have been divided by the ITU-R mainly into two categories, i.e. FR1 that refers to sub-6 GHz frequencies and FR2 that refers to the frequencies above 6 GHz generally called millimeter-wave band. The FR1 and FR2 bands allocated for 5G are generalized in Table 1.

The paper follows a holistic approach to render almost all the aspects related to the MIMO technology with the application to 5G for mobile hand-held devices. The organization of the paper is as follows: section "MIMO antenna technology" and section "Comparison of massive MIMO and the existing systems" discuss the MIMO antenna technology explaining the basics while traveling from 3G to the ongoing 5G systems. The antenna design considerations have been explained for massive MIMO applications in section "Antenna design considerations in MIMO technology". The performance enhancement analysis is described in section "Analysis for performance enhancement in the antennas for 5G applications". Effects of mutual coupling and correlation are discussed in the section "Mutual coupling in MIMO antennas" and section "Methods to reduce mutual coupling in MIMO antennas"; also section "Isolation enhancement in massive MIMO" and "SAR in reference to the safety of users" explains the specific absorption rates (SAR) while handling the mobile devices for the safe application of users. The challenges, summary, and future scope of MIMO design consideration approaches have been adequately addressed in sections "Challenges in the design of MIMO for 5G applications", "Critical review on 5G design aspects and summary", and "Conclusion", respectively.

Table 1. Table representing frequency range-1 and 2 (FR-1 and FR-2) for sub-6 GHz 5G applications and mm-wave applications

Bands for 5G sub-6 GHz	Frequency range [10]
n71	(470–698) MHz
n81-n83, n91-n94	(698–960) MHz
n74-n76	(1.427–1.518) GHz
n65, n66	(2.11–2.2) GHz
n30, n40	(2.3–2.4) GHz
n38, n41, n90	(2.5–2.69) GHz
n77	(3.3–4.2) GHz
n78	(3.3–3.8) GHz
C-Band/LTE-42	(3.4–3.6) GHz
n79	(4.4–5) GHz
LTE-46/LTE-U	(5.15–5.925) GHz
Bands for 5G mm-wave	Frequency range
n257, n258, n261	(24.25–39.5) GHz
n260	(37–43.5) GHz
–	(45.5–71) GHz

MIMO antenna technology

Evolution

The antenna designers have been using the advanced up to date techniques in order to develop the wireless communication networks with the improved speeds for data transfer. There has been a timely evolution of the technology fulfilling the requirements of efficient data transmission. Going from 3G (third generation) to the present day 5G (fifth generation) there has been a continuous progress in developing the MIMO technology The evolution of the MIMO technology is shown in Fig. 2.

The single user MIMO was being used for 3G networks that utilized the concept of transmitting simultaneously a number of parallel data streams to a single user from the base station. Then for 4G systems, the multi-user MIMO technology was employed where the multiple number of data streams were being assigned to multiple users keeping in view the system capacity and performances. The single and multiple user MIMO are specifically shown in Figs 3 and 4, respectively.

In the recent times the massive MIMO technology has been introduced for 5G applications. Initially in 2010, the concept of massive MIMO was proposed by a scientist "Marzetta" of Bell Laboratory. The concept implies to the base stations with hundreds of antennas that serve the multiple number of users simultaneously on the same frequency source.

Comparison of massive MIMO and the existing systems

Antenna arrays with large number of elements at the base stations are believed to play a key role in the upcoming wireless networks.

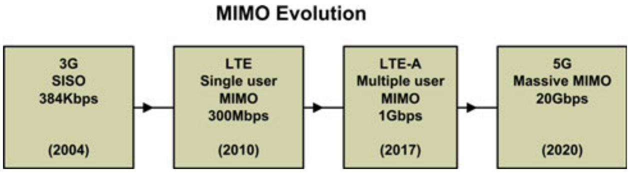


Fig. 2. Timely evolution of MIMO technology.

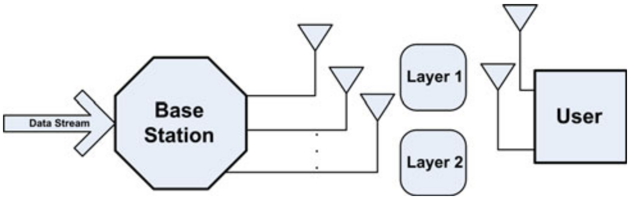


Fig. 3. Single user MIMO where the data are transmitted simultaneously on parallel streams going to single user.

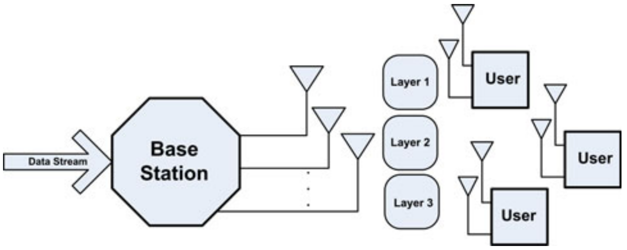


Fig. 4. Multiple user MIMO where the various users are assigned with the separate data streams.

They exploit the use of multiple antennas at each base station in order to furnish higher spectral gains. The technology enables beam-forming by using spatial filtering at transmitter as well as receiver side [11]. The comparison of massive MIMO with all other technologies has been briefly summarized as follows:

Traditional MIMO and massive MIMO

The comparison of the traditional MIMO used for 4G LTE and the massive MIMO employed for recent 5G technology is summarized in Table 2.

The massive MIMO technology has a number of technical advantages which include:

i. Reduced power consumption by the antennas in massive MIMO technique which is because for an antenna the power transmitted is inversely proportional to the square of the number of antennas.
ii. With the increase in the number of antennas there is a decrease in thermal noise effects and small-scale fading. The above effect is almost eliminated that results in the improvement of system performance.
iii. On increasing the number of antennas in the base station, the signals transmitted are concentrated to a certain point in space by beam-forming technique. With this the base station is able to distinguish the individual users accurately thus resulting in the improved spatial resolution.

Table 2. Table explaining the features of traditional MIMO and massive MIMO technologies

Parameter	Traditional MIMO	Massive MIMO
Number of antenna elements	Approximately up to 8	More than 100
Channel matrix requirement	Low	High
Channel capacity	Low	High
Noise resistance	Low	High
Diversity gain	Low	High
Correlation among antenna elements	Low	High
SER (symbol error rate) performance	High	Low

Due to the number of advantages of massive MIMO technology, its going to play a key role for fifth generation (5G) applications. In addition to above advantages, it can also improve the channel capacity EE and SE to a great extent [12].

mm-waves and massive MIMO

With the advent in applications for mm-wave frequencies, massive MIMO technology involves the use of large number of antenna array elements for wider applications such as beam forming/beam steering and spatial multiplexing for multiple user systems [13]. For mm-wave propagation such an antenna system is required which will enhance the propagation within the higher frequency band and also enhances both energy as well as spectral efficiencies. The requirement is fulfilled by employing the Massive MIMO at base stations [14]. The mm-wave frequency band provides greater bandwidths with very high gains in comparison to sub-6GHz frequency range [15]. But there is also larger effect of noise power for higher frequency bands. Thus in view of achieving high SNR, high gain beam steerable antennas with directional patterns are essentially required. In comparison to recent technologies employed for wireless communications, mm-wave technology offers number of advantages which mainly include broader bandwidths and high capacities, less intercepting probabilities, antennas of very small dimensions, etc. [15,16].

Sub-6 GHz and massive MIMO

In order to achieve the targeted 5G data rates of order of 20Gbps, it seems that the use of mm-wave spectrum might be necessary. However, there are a number of challenges that need to be addressed before mm-wave can be realized for the use in mobile communications. The original equipment manufacturers are continuously working on mm-wave technology; however, in the near term, sub-6GHz is going to be the key spectrum for 5G networks. With the capability of transferring high data rates along longer distances in rural as well as urban areas, the sub-6GHz frequencies are going to play an important role. The interference problems will be solved by sub-6GHz massive MIMO to a large extent. This can be realized by the use of more number of antennas in the base stations which enables them to serve majority of users in the urban areas [17].

Antenna design considerations in MIMO technology

The design of antennas for the wireless mobile communication systems is a very challenging task for the antenna designer community. The communication systems trending toward 5G require wide band and multi band antennas in order to sustain the operation of mobile services and reduced system complexity. In addition to this, the challenges for the antennas include compact physical size, feasibility of integration with hand-held devices, operation of multi-antenna system, and efficient MIMO operation. The basic steps required for designing the MIMO antenna system are generally divided into two sections [18]:

1. Physical design of antenna.
2. Performance enhancement analysis.

The conceptualization of the basic idea for designing a MIMO is shown in Fig. 5. The foremost step while designing a MIMO is to select the proper operating frequency. The throughput and gain of the system widely depend on the number of antenna elements employed in the design. So its important to take the trade-off among these used characteristics. Another important aspect to be considered while designing includes the calculation of the channel capacity and to reduce the mutual coupling thereby increasing port isolation between the antenna elements. In order to improve the throughput of the system, more number of elements are required that also improves the bandwidth of the system design [11].

Classification of 5G MIMO

One of the important means for classification of 5G MIMO design is based on the type of antennas used. The most widely used antenna types suitable for 5G applications can be summarized in Table 3. In Table 4 are given some important advantages as well as disadvantages of different types of antenna applicable for 5G systems.

The 5G antennas can also be classified in terms of the applied ports viz, antennas with single input and output ports and antennas with multiple input and output ports as shown in Fig. 6. The 5G antenna designs on the basis of number of I/O (input-output) ports are defined briefly as follows:

SISO antennas

The type of antenna is quite simple in terms of design and implementation. It has been reported in literature that these antennas are implemented either with a single element or multiple elements employed for 5G mobile applications. Single input single output (SISO) antennas have an advantage of easy integration into the 5G mobile devices. For the frequencies above 6 GHz, the single antenna service quality gets degraded by the effect of propagation losses which the signals are prone to. So in order to overcome those losses multiple antenna system forms a better option [14]. The single antenna due to its larger size becomes incapable for mobile terminal devices. Single antenna provides high gain but at the cost of larger size [13].

Table 5 summarizes briefly the SISO multiple element mobile terminal antennas reported in the literature. It can be generalized from Table 5 that the technique of making slots etched from the ground planes acting as main radiating elements enhances broadband operation required for cellular communications. But some of the drawbacks of using these techniques include the introduced complexities in the design procedure in addition to the larger sizes of the antenna designs which add to the interference with all other circuit elements present on the mobile PCB devices.

MIMO antennas

In mobile wireless communication systems, there are a number of unwanted factors that include maximum interference, more radiation losses, multi-path fading, etc. which go increasing as we approach toward the higher frequencies. To minimize all the related issues, MIMO antennas are proving a good option. In MIMO technology, the key challenges to be addressed include high efficiency for each element and low correlation between the elements [7]. Table 6 shows the antenna features of the MIMO antennas structured for hand-held devices according to the literature. With very small space between the antenna elements, the mutual coupling between them is quite prominent. The coupling arises due to the presence of surface waves, free space radiations, and surface currents. In antenna arrays, coupling is mostly due to free space radiations and surface currents whereas for micro-strip antennas it is because of surface waves only. This has an adverse effect on the reflection coefficient of the MIMO antenna systems. MIMO system strengthens the range of transmission without any increase in the power of a signal. The application of MIMO in 5G reduces latency, increases efficiency and throughput with the enhanced channel capacity. Depending upon the frequency, MIMO antennas can be multi band as well as broad band including the MIMO antennas that posses a metal rim and those which do not have any metal rim [43].

Double and multi-element MIMO antennas without metal rim

The MIMO designs having two elements or multiple number of elements without metal rims around the mobile terminals are extensively present in the literature. The MIMOs consist of same structures of antenna elements with prominent separate feed for the individual elements. There is an important factor of attaining maximum isolation between the antenna elements for the whole MIMO designs to function efficiently. Dielectric resonator antenna (DRA) elements are used in MIMO designs as they provide high gain, comparable isolation as well as enhanced efficiency. In MIMO DRAs, the isolation can be increased by using shields such as meta-surfaces [51], feeding mechanism with hybrid techniques [52–54], FSS (frequency-selective surfaces), etc. These isolation techniques aim at changing the current densities among the elements of the MIMO antenna. The isolation among the DRA elements can also be increased by loading the metal strips over the resonator surfaces. It reduces the correlation between the adjacent elements by diverting the coupling field away from each other. In order to reduce mutual coupling between the antennas, neutralization lines and several other decoupling techniques are employed [55–59]. A neutralization line is embedded in between the elements of MIMO antenna in different ways applicable to enhance isolation [60,61]. Better isolation can also be achieved by using the antennas possessing self decoupled structures [62]. Table 7 summarizes the comparison of MIMO antenna design without metal rim.

Mobile terminal antennas with metal rim

In current world, there is an increase in the development of mobile smart-phones with metal rims that mostly employ MIMO antenna structures. They are becoming the key technologies that are mainly suited to 5G wireless applications. Such antennas with metal rims are offering high level robustness

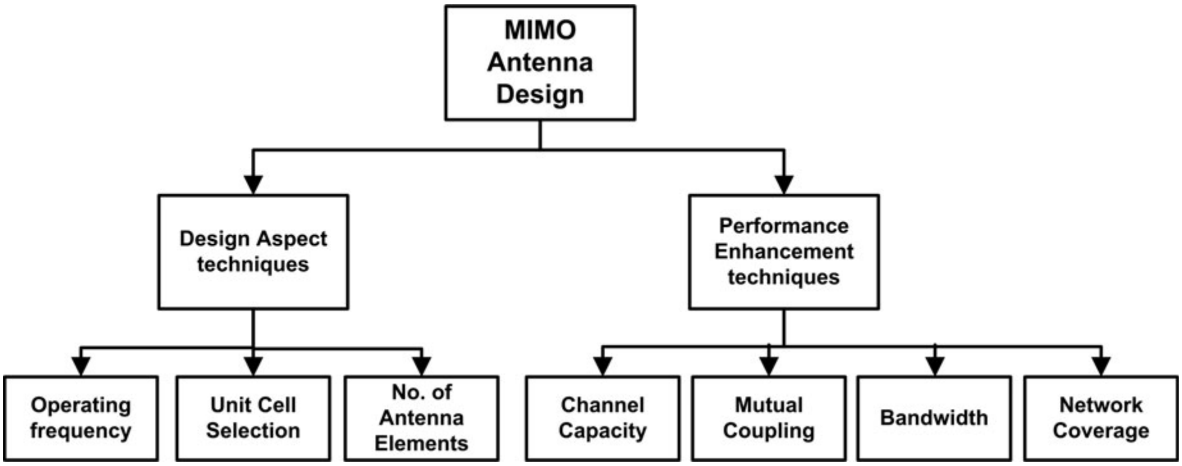


Fig. 5. Design aspects of MIMO antennas.

Table 3. Table explaining the features of the different antenna types used for 5G applications

Antenna types used in MIMO	Brief explanation
Monopole	Basically it consists of a “λ/4” micro-strip line but a number of modifications have been reported which involves spiral, conical, L-shaped structures represented in accordance with the applicability and MIMO requirements [19].
Dipole	Being an extension to monopole antenna it consists of two “λ/4” strip lines fed in between them. Number of dipole antenna arrays are presented for 5G applications [20,21].
ME dipole	The antenna possess two types of dipoles viz, planar electric and other vertical magnetic shorted. The feed is placed on the bottom side of substrate and it excites the magnetic dipole first [22–24].
Fractal	The same structure is repeated number of times following the mathematical rule of iteration. The patches are of different shapes [25,26].
IFA	An antenna formed from micro-strip lines forming inverted F-shape by the bending of two lines with respect to one vertical line. The feed mostly co-axial type is mainly given to the vertical line [27].
PIFA	It is a type of miniaturized patch antenna where two planes are connected by the shorting vias and is mostly fed from bottom side [28].
AVA	Two conductors of similar shapes are placed on top and bottom of substrate where the conductor on top forms a radiator and ground is formed by the part on the bottom [29–33].
Slotted loop	The rings of different shapes such as square, diamond, circular, or any applicable shape form these kind of antenna. The slots act as main radiators in such antennas [34,35].

ME, magneto-electric; IFA, inverted-F antenna; PIFA, planar inverted-F antenna; AVA, antipodal vivaldi antenna.

along with the attractive external appearance. A loop antenna having two parallel loops is loaded on the ground which is excited by coupled feed line of L-shape [68]. An antenna with three patches having a small gap that connects it to the ground plane is presented in [69,70] It is a MIMO metal rim antenna of compact size because of IF (inverted-F) design in addition to the stubs required for tuning. Table 8 summarizes the comparison parameters for metal rim MIMO antennas.

With the increasing demand for the higher data rates that too when there is a shortage of bandwidth in the available spectrum, the smart-phones employing efficient antennas are being widely required for 5G applications. In view of the 5G standardization, the design of mobile terminal antennas is very critical. In [75] an integrated antenna having substrate with ME dipole is presented for 4.98–6.04 GHz range. A printed broadband antenna for MIMO applications for 5G 3–9 GHz has been presented in [76]. A MIMO mobile terminal with four ports has been investigated for 5G in [77].

Analysis for performance enhancement in the antennas for 5G applications

In order to enhance the performance and meet the requirements for 5G technology, the parameters of MIMO antenna design that include efficiency, gain, bandwidth, reduction in mutual coupling, size miniaturization, etc. need to be optimized. In Table 9, we have summarized the standard techniques that enhance the performance of the antennas to a considerable extent.

The techniques employed for enhancing the performance of antenna designs have some merits and demerits which can be quantified in terms of certain antenna parameters as shown in Table 10.

The parametric metrics important for the better performance of the MIMO antenna designs include envelope correlation coefficient (ECC) and mean effective gain (MEG). The important linked metrics are evaluated by using ECC and MEG. For wireless mobile communications, ECC is treated as one of the most

Table 4. Brief description of advantages and disadvantages of different types of antennas

Antenna types used in MIMO	Advantages	Disadvantages
Monopole [19]	1. Easy to design, fabricate, and characterize. 2. In case of multi-element designs, the monopole elements can be rotated in any direction with ease.	1. Large ground area is required. 2. Gain is less and response is poor during adequate weather.
Dipole [20, 21]	1. Easy designing and fabrication. 2. Accepts balanced signals.	1. Gain is low. 2. Not suitable for extended communication range. 3. Bandwidth is small.
ME dipole [22–24]	1. Side and back lobe levels are small. 2. Front to back ratio is high. 3. Low cross-polarization levels, broader bandwidth.	1. Antenna fabrication and design is complex. 2. Design is overall costly.
Fractal[25, 26]	1. Overall size miniaturization of antenna is achieved. 2. The antenna performance is consistent over the working range.	1. Complex to design. 2. Limitation for repetition on fractal design.
IFA[27]	1. Quite small in size. 2. Because of intermediate feeding mechanism, impedance matching is good.	1. Lesser gain achieved. 2. Narrow bandwidth.
PIFA[28]	1. Front to back ratio is enhanced. 2. Good impedance matching is achieved. 3. Antenna is of low profile.	1. Less bandwidth. 2. Small gain.
AVA [29–33]	1. Broader bandwidth. 2. Enhanced gain. 3. Radiation patterns are stable.	1. Large space area required. 2. Gain is less for lower frequencies.
Slotted loop [34,35]	1. Antenna design is easy. 2. Channel capacity is quite appreciable.	1. For 5G applications, multiple element loop antenna is required. 2. Gain is small.

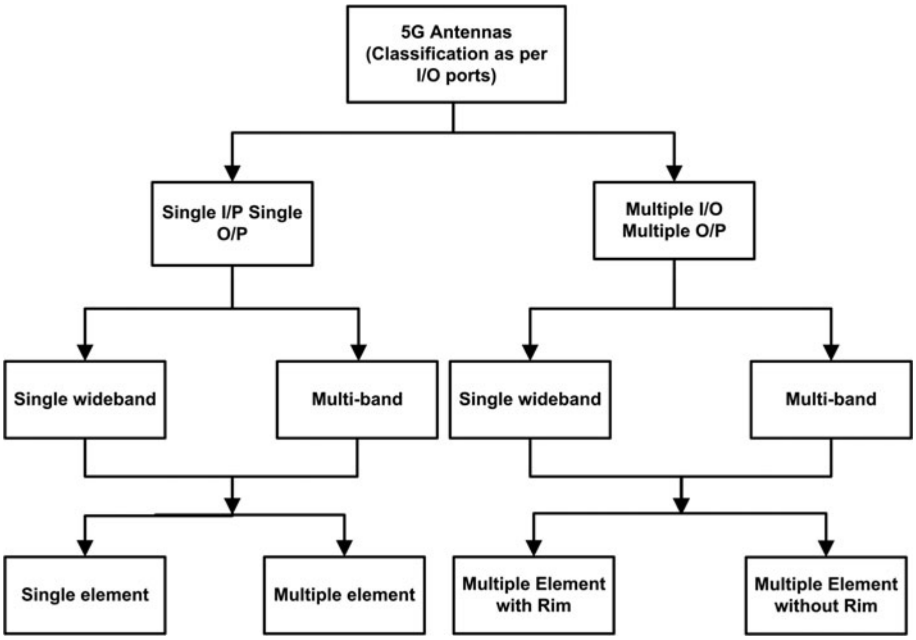


Fig. 6. Classification of 5G antennas based on I/O ports

important parameters [89]. ECC can be defined as the amount of field correlated between the antenna elements in a MIMO design. In order to obtain high capacity and high diversity gain, ECC must be very low [90]. The acceptable amount of ECC is 0.5 however in case of 4G communication systems the revised value is 0.3 [91,92]. ECC in case of multi-antenna system is evaluated either from *S*-parameters or radiation patterns in the far field. The *S*-parameters method is not efficient in most of the cases while as in the far-field pattern method those disadvantages can be overcome [93]. The efficiency of the antenna elements is determined by the ratio of power radiated to the power transmitted into the free space. From the standard far-field radiation pattern method, the efficiency can be calculated as [94]:

$$\eta = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left[E_\theta E_\theta^* + E_\phi E_\phi^*\right]\sin(\theta)d\theta d\phi$$

Table 5. Table explaining the single input single output antennas applicable for communication devices

Ref.	SISO antenna design	Operating frequency band (GHz)
[36]	An antenna with a monopole conical sleeve and a helix type structure are proposed on the antenna top.	0.3–0.7
[37]	The antenna which differs from PIFA (conventional) in terms of having coupled feed instead of contact feed is shown.	0.82–3
[38]	An antenna for double-band operation is proposed in which resonances are achieved by using strips as coupling networks.	0.7–0.96
[39]	The antenna elements with compact size employing a contour is proposed.	2.27 - 2.52 5.29–5.53
[40]	A slot is introduced on the top of PIFA radiating element of U-shape for the increased bandwidth is presented.	0.8–0.97 1.5–5.9
[41]	The antenna utilizes the operation of combined radiators for PIFA with one longer and other shorter radiating elements.	2.39–2.49 5.07–5.88
[42]	The antenna is designed for wide band operation in the lower ultra high frequency (UHF) band.	0.88–0.96 1.85–1.99

Table 6. Table explaining the multiple input multiple output antennas applicable for 5G communication devices

Ref.	MIMO antenna design	Operating frequency band (GHz)
[44]	An antenna with two monopole slot elements having symmetric geometry were proposed for achieving the diversity.	1.85–2.31
[45]	A double-band antenna was proposed by utilizing an electro-magnetically coupled feed network.	1.7–2.75
[46]	A diversity antenna has been proposed by using combined magnetic slot of square shape with an electric dipole.	2.0–5.6
[47]	The antenna fed by L-shaped strip lines with chamfered corners having PIFA have been proposed.	5–6
[48]	An antenna having radiating elements of the shape of rhombus with a modeled T-shaped stub used to enhance isolation is presented.	3.34–3.87
[49]	An antenna with a Y-shaped structure integrated with three monopole patch antennas (MPAs) is presented.	3.3–4.2
[50]	An eight-element antenna having open L-slot and fed by using a tuned stub is proposed.	3.24–5.82

where, E_θ represents field pattern in the vertical direction. E_ϕ represents field pattern in horizontal direction. Another important parameter to evaluate antenna efficiency is to quantify the amount of energy collected by the antenna from its surroundings [94]. The far-field radiation pattern method used to calculate the efficiency in terms of mean effective gain can be written as $\eta = 2(MEG)$. The performance enhancement parameters of a MIMO design are specifically shown in Fig. 7

Mutual coupling in MIMO antennas

In terms of energy, coupling may be defined as energy absorbed by a non-radiating antenna which is in the vicinity to a radiating antenna. It is observed to change the reflection coefficient, radiation patterns as well as input impedance of the antenna elements in an array. In [95], the empirical model of coupling was presented as:

$$C_{mn} = exp - \frac{2d_{mn}}{\lambda}(\alpha + j\pi),\ m \neq n$$

$$C_{mn} = 1 - \frac{1}{N}\Sigma m \Sigma n \neq m C_{mn}$$

where, C_{mn} → mutual coupling, d_{mn} → distance between m^{th}andn^{th} antenna elements, α → coupling level control factor, N → number of elements in the array. Practically, mutual coupling depends on the configuration of the elements of antenna array as well as on the excitations of the rest of the elements. The S-parameter factor (dB valued) between the m^{th}andn^{th} elements represented by $20\log_{10}(|S_{nm}|)$ is used to quantify the coupling factor. [96] explains the mutual coupling effects in transmitting mode and receiving modes.

Table 7. Comparison parameters of the MIMO antennas without metal rim

Ref.	Isolation (dB)	Type of antenna	Frequency range (GHz)
[63]	25	ME dipole	3.3–4.36
[62]	17	Monopole	3.4–3.6
[64]	25	PIFA	2.7–3.6
[65]	12.5	SIW antenna	3.4–3.6
[66]	17	Inverted-F	2.5–7.0
[67]	17.5	Slot antenna	3.4–3.6

Table 8. Comparison parameters for MIMO antennas with metal rim

Ref.	Isolation (dB)	Type of antenna	Frequency range (GHz)
[71]	>12.7	Slot antenna	3.4–3.6
[70]	>11	Hybrid IFA	3.3–7.1
[72]	>12	Monopole antenna	3.3–5.0
[73]	>13	Slot antenna	3.4–3.6
[74]	>10	Monopole antenna	2.496–2.690 3.4–3.8
[68]	<18	Loop antenna	0.824–0.96 1.71–2.690

Table 10. Merits and de-merits of different techniques used for performance enhancement of MIMO design

Technique used	Merits	Demerits
Coupling reduction [84,85]	1. The impedance matching, efficiency, and gain of antenna are enhanced. 2. In various cases these techniques help in size miniaturization of antenna.	1. Large ground area is required. 2. Gain is less and response is poor during adequate weather.
Type of substrate [86]	1. Substrate of high permitivity enhances return loss parameter. 2. A low permitivity substrate enhances efficiency, gain with broad bandwidth, and compact size.	Low permitivity substrates are expensive, thus scarcely available.
Multiple antenna elements [87]	It helps in the improvement of gain, bandwidth, return loss, and efficiency.	1. Overall size of antenna is increased. 2. Designing a feed network for multi-element system is difficult.
Corrugation [32]	1. The method reduces back side lobe levels thus increasing front to back ratio. 2.Improved efficiency, bandwidth, and gain.	Reduced input impedance
Dielectric lens [88]	1. Improved front to back ratio with stable patterns and maximum energy radiated in front direction. 2.Gain is enhanced.	Size of antenna is increased.

Table 9. Techniques employed in MIMO antennas to enhance their performance

Methods to enhance performance	Explanation
Reducing mutual coupling/ maximizing isolation by using different techniques [78,79]	By reducing the mutual coupling between the antenna elements, antenna gain and efficiency are enhanced in addition to the induced good impedance matching between feed and radiator. Some of these techniques also help in the size miniaturization of the design.
The selection of the substrate used [80]	For antenna design, the substrates of different permitivity and loss tangents are available. Lower the permitivity and loss tangent, lesser will be the power loss and more will be the gain parameter. The right choice of substrate enhances bandwidth of the antenna.
Use of multiple antenna elements [81]	With the increase in the number of antenna elements, the gain is increased in addition to the increased efficiency and wider bandwidth
Method of corrugation [32]	Removing the metal parts of different shapes from the edge of the radiator of antenna broadens the bandwidth and improves f/b (front to back) ratio. There is also reduction in side lobe levels which further enhance antenna performance
Use of dielectric lens [82,83]	Dielectric lens of the same material as that of substrate or a different material designed as structures as per applicability are used over or by the side of antenna surfaces. The technology enhances the gain with the improved f/b ratio and stable patterns.

Transmitting mode effect

In case of multi-antenna system, multiple ports may possess phase excitations of random order during the transmission mode. It has a prominent impact on impedance matching as well as mutual coupling of the elements of the antenna system. total active reflection coefficient (TARC) may be defined as the square root of total power generated subtracted from the total power generated by all phase excitations divided by total power generated [97]. TARC is the parameter required to measure reflection coefficient of a MIMO antenna array having different phase excitations at the multiple element ports. Under the multiple phase excitations at different ports, TARC takes the account of impedance matching, mutual coupling, and radiation efficiency. TARC is worse because of high mutual coupling.

Receiving mode effect

When the antenna element is in the receiving phase, the antenna performance can be investigated by exciting one element while terminating the other element by the load of 50Ω. The mutual coupling between the antenna elements in a multi-antenna system has a prominent effect on the antenna parameters which mainly include ergodic channel capacity [98], diversity gain [99], throughput [100], reflection coefficient and radiation parameters, and error rates [101]. Figures 8(a) and (b) depict the mechanisms of mutual coupling in transmitting mode and receiving mode. As an example if we take two elements in antenna array such as “p” and “q” and assuming an attached source to “q”, the energy generated by source 1 is radiated into space 2 toward the p^{th} element. A part of this received energy by p^{th} element is re-scattered to the space 4 and rest is traveled toward 5. A small part of this energy 4 is being picked up by the q^{th} element. This process of mutual interaction is indefinitely continued which explains the mutual coupling mechanism in the transmitting mode. While as in the receiving mode, if we assume wave 1 impinging on to this array it is seen to induce some current first in the element “p”. A fraction of this goes to receiver 2 and rest will be scattered into space 3 of which a part might be directed toward 4 where it is added to plane wave 5. The antenna performance can be investigated by exiting one element by another one that is ended on a 50Ω load [102].

Methods to reduce mutual coupling in MIMO antennas

A number of techniques reported in literature are being used to count for maximum isolation among the antenna elements in a MIMO system. One of the simple methods to achieve the greater

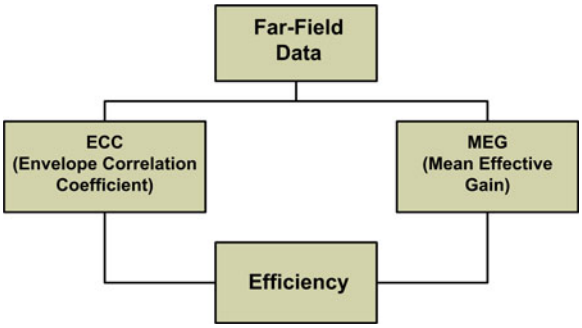


Fig. 7. Performance enhancement parameters for MIMO design.

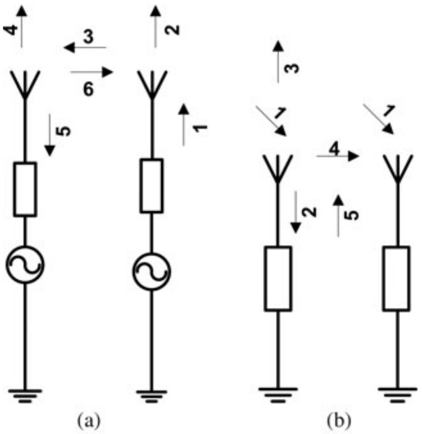


Fig. 8. Mutual coupling mechanism in (a) transmitting mode and (b) receiving mode.

isolation is to increase the distance between the antenna elements; due to minimum space inside the mobile device, the method is not much feasible. Another method is to employ the polarization diversity but this too has an adverse effect on the gain parameter of the antenna and on the evaluation of spatial multiplexing in case of MIMO devices. The techniques employed to reduce the mutual coupling or to enhance the isolation between antenna elements largely depend on the antenna structure. The techniques used must not largely effect the other parameters to a greater extent. The techniques used for decoupling that are present in the literature include the use of neutralization lines between the antenna elements placed in accordance of producing the better results [103], ground strips and stubs of different shapes based on mode of antenna operation [104], slots in the ground and the defected ground structures, parasitic elements capable of changing surface current paths for improving isolation [105]. In addition to these, the use of de-coupling networks [106], meta-material structures, meta-surfaces [51] aid in the improvement of isolation in MIMO antennas.

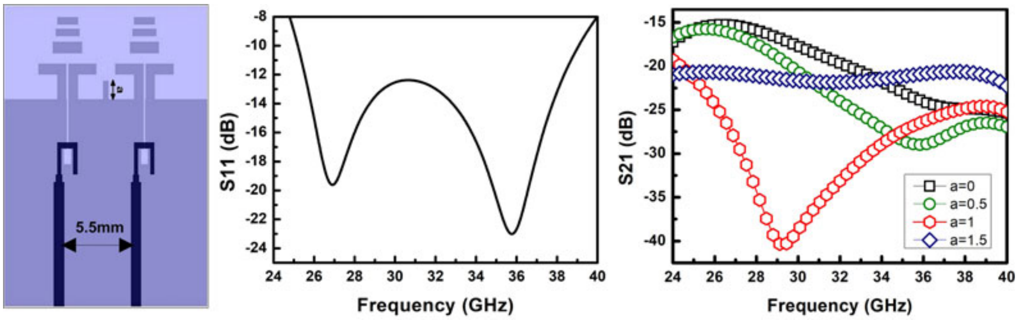
Neutralization lines (NL) introduce opposite phase having same amplitude, which cancels out the coupling between the elements. The NL when connected between the planes enhance size miniaturization as well as bandwidth [107]. In [108], the ground slots are connected by the NL where the transmitted conductive current on the line is neutralized by the current induced resulting in the reduced coupling between antenna elements. A neutralization line consisting of two strips and a disc has been used to create different number of current paths for decoupling as presented in [109]. The lines of different lengths create paths to cancel out the coupling field and enhance isolation. The ground strips have also been employed for increasing the isolation between the dipole antenna elements for 5G applications in. A Quasi yagi MIMO antenna having two elements has been proposed in [104] where a ground stub has been placed in between the elements in order to reduce the mutual coupling in the MIMO design. The MIMO antenna design and the resulting parameters are shown in Fig. 9. Electromagnetic band gap structures act as a transmission medium for the electromagnetic fields that enhance the efficiency and reduce the mutual coupling among antenna elements. In [110], the mushroom-shaped integrated EBG structures have been proposed among the antenna elements for reducing the mutual coupling. The decoupling networks transform the admittance to an imaginary value and acts as a resonator for decoupling between multiple elements. A parasitic element having H-shape have been incorporated for reducing the mutual coupling in [111]. In [112], the four-element antenna array has been loaded with the reactive parasitic structures for enhancing isolation. A DRA with dual-polarization with wide band operation and enhanced isolation has been presented in [113]. The modifications in the ground plane suffice to provide the characteristics same as that of band stop filter. In this technique, mostly a slot is made in between the MIMO elements on the ground plane. The slot restrains the fields to couple between antenna elements thus reducing coupling [114]. Meta-materials of different structural shapes and meta-surfaces are able to reduce the mutual coupling to a large extent in the MIMO antennas [32]. Split ring resonator structures also form an effective means for reducing the mutual coupling between the antenna elements. The different techniques used for reduction of mutual coupling between the antenna elements is shown in Fig. 10. Table 11 briefly summarizes the merits and de-merits of the different isolation enhancement/decoupling techniques.

Isolation enhancement in massive MIMO

Massive MIMO is an extended version of MIMO technology with more than hundred antennas forming an array with directivity to be considered an extra dimension for freedom. The technology is mainly employed at the base stations focusing to form an essential means for 5G wireless mobile communication systems. In this part, a brief review about the basic decoupling techniques for enhancement of isolation between the antennas in the massive MIMOs at the base stations has been summarized. In massive MIMO antennas, the coupling must be <-30 dB in accordance to the industry thumb rules. In [123], a high gain stacked patch antenna having dual polarization with very low coupling between the antenna ports is presented. The massive MIMO structure is composed of 144 total ports having patches pointing in different orientations. The isolation can be enhanced by using array antenna decoupling surfaces [124], thin planar meta-material-based lens [125] and so on in case of massive MIMO antenna designs.

SAR in reference to the safety of users

To meet the requirements for the deployment of 5G wireless bands, the antenna designers have capitalized for the antenna array systems. The sub-6 GHz frequency band is becoming the band of interest for 5G communication in most of the countries worldwide [126]. The MIMO antenna performance has a



(a) (b) (c)

Fig. 9. Two-element quasi-Yagi MIMO antenna design. (a) Antenna schematic, (b) S_{11}dB, (c) mutual coupling [104].

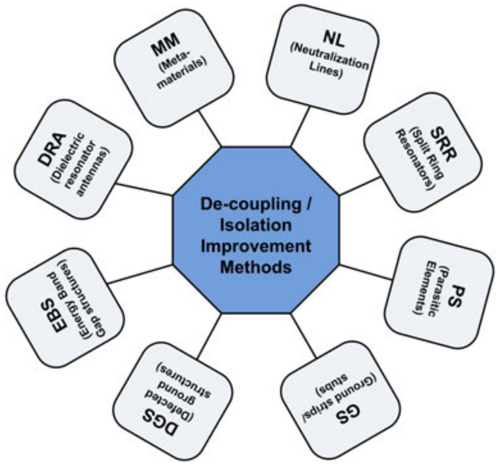


Fig. 10. Techniques for reduction of mutual coupling.

prominent influence by the housing effects inside the mobile terminal and also in the vicinity of the users hands [127,128]. The antenna designers need to take into account the influence of human biological tissues on the antenna performance and *vice-versa*. Its not feasible to decrease the transmitting power levels and sensitivity toward the receiving levels. The coupling of EM fields between the antenna and the human needs to be reduced considerably for the safe user handling of the device [129]. The EMW radiations pose hazardous effects on the human health wherein the energy being absorbed by the body gets changed into heat causing the rise of temperature and thermal effects on it [130]. An important parameter that evaluates this energy absorption is determined by the SAR. [131] presents four-band antenna array that has been loaded on different positions on the mobile PCB and it has been studied that SAR values need to be very low mainly at a distance where the antenna is faraway from human head. An antenna with the rectangular radiating slot and T-slot for dual band operation has been analyzed for SAR effects in [132]. It has been proposed in the literature that for users' safety the SAR value must be <2 W/kg for the mobile terminal antennas in order to prevent them from the harmful exposure to EM waves. The work in Fig. 11 shows the MIMO antenna design having closed loop parasitic elements as decoupling networks. The resulting parameters and the schematic of the design are shown in the respective figure. The parasitic elements have reduced the coupling to <−20 dB and also the SAR result is acceptable, i.e. < 2 which is considered to be very safe for the user applications.

Table 11. Merits and de-merits of isolation enhancement techniques in MIMO antennas

Technique used	Merits	Demerits
NL [115]	1. It helps in antenna miniaturization. 2. It improves efficiency and provides broader bandwidths.	The antenna design becomes complex.
DGS [116]	1. The design is easy to implement. 2. It enhances bandwidth, increases efficiency, and helps to improve front to back ratio.	It becomes challenging to analyze the whole concept.
EBG [117]	It helps in the improved impedance matching and provides good f/b ratio.	Complexity of structure.
MM [118,119]	1. It improves the ECC values, bandwidth, and diversity gain. 2.It provides good compatibility for integration with rest of the components.	Complex to design and positioning of meta-material unit cells in the overall antenna design.
DRA [79,120]	Antenna efficiency is enhanced along with wide bandwidth and improved gain.	Design of whole structure becomes complex.
PE [84,85]	Bandwidth, diversity gain, and efficiency of the antenna are enhanced.	The placement of parasitic element with respect to other components becomes difficult.
CSRR [121,122]	Antenna size is reduced with the improvement of diversity gain.	Bandwidth achieved is low.

Challenges in the design of MIMO for 5G applications

In order to enable essential trends, few remarkable challenges in antenna design are needed to overcome. The section summarizes some major challenges that are required to be addressed.

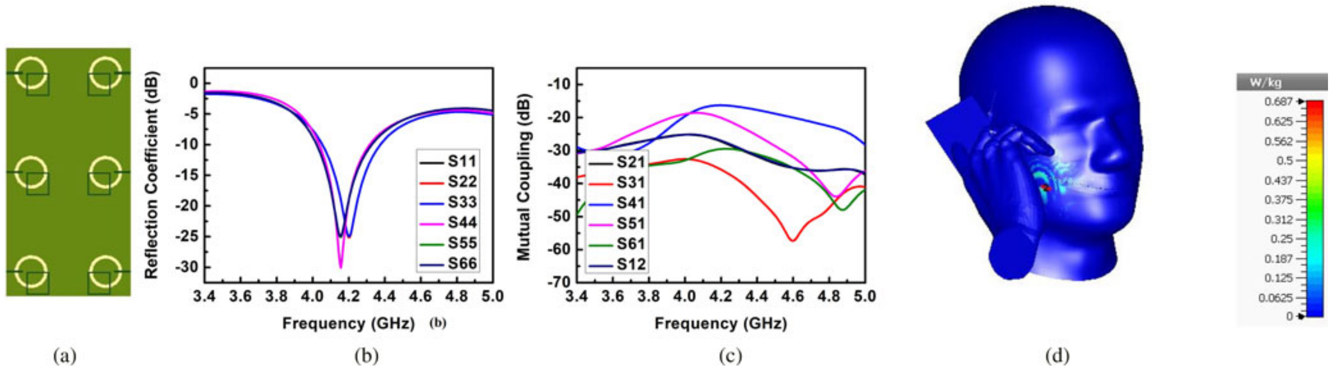


Fig. 11. Six-element MIMO antenna. (a) Antenna schematic, (b) S_{11}dB, (c) mutual coupling, (d) SAR [133].

Table 12. Summary of the MIMO antenna parameters for 5G wireless applications

Ref	Frequency (GHz)	η (%)	Isolation	ECC	Antenna type
[137]	2.55–2.68 3.42–3.8	41–84	12	>0.15	Loop antenna
[138]	2.55–2.6	48–63	11	>0.15	Slot antenna
[139]	3.4–3.6	62–78	10	>0.20	Inverted-F
[140]	0.63–0.96 1.88–1.92 2.30–2.62	40–60	10	<0.15	Inverted-F
[141]	1.8–2.6 3.4–3.6	50–70	10	<0.4	Slotted MIMO
[142]	3.45–3.8 5–5.45	70–76	17	<0.05	Slot antenna
[143]	3.3–3.9	60–80	17	<0.01	Diamond slot
[144]	3.3–4.4	65–80	16	<0.005	CPW type
[145]	3.4–3.6	50–80	15	< 0.2	Waveguide type
[108]	3.3–3.6	40	15	< 0.02	Loop element
[146]	3.4–3.8	60	25	<0.01	Square ring slot
[147]	3.4–3.6	35–50	11	<0.40	QAL array
[148]	3.4–3.6	60–70	18	<0.015	U-shaped slot
[149]	304–3.6	50–70	17	<0.07	Monopole with edge fed dipole

(1) 5G is intended to hold up a wide range of user cases that include massive IOT, critical control mission, and enhanced mobile broadband. To ensure the availability of the spectrum, 5G should be able to work on diversified bands and spectrums including shared band, licensed bands, unlicensed bands, and lower sub-6 GHz to millimeter-wave bands. An important challenge for 5G antenna designs is the delivery of most capable interface to support the requirements of spectrum and user cases.

(2) One more challenge for the 5G antenna design is to allow the continuous technological evolution in addition to compatibility in forward direction. The major components to be analyzed for wireless applications can be shown as:

  (a) The flexibility in the spectrum is needed for supporting the devices operating on different spectral bands.
  (b) In order to support the large range of expected end points, scalable air interface is needed.
  (c) For technological evolutions and supporting future requirements, air interface having forward compatibility is essential.

(3) There is an inevitable demand for massive connectivity for wireless systems with the development of IOT devices in the coming time. This ever-increasing demand for more connectivity of machine to machine devices is mainly specified by high reliability, less complexity of transmission, extremely low power consumption, low latency, etc. These challenges need to be addressed and it is expected that 5G networks designed need to be more network centric, less scalable, and mostly targeted for human-based applications.

Since the mm-waves have promised the high speed point-point communications, there is a problem of blocking these signals by atmospheric oxygen and rain which makes it specific to short-range communication. One of the methods to harness this spectrum is beam-forming wherein a beam is directly targeted on a device. For this, the antennas at base-stations or in the devices need to be designed in such a way to handle this complexity for directing a beam to the target in cellular overcrowded environment with a number of obstructions. These 5G systems require such antennas with high gain mainly to overcome the atmospheric losses. To design high gain antennas at the limited available energy has been a challenge ever since for the designers.

Critical review on 5G design aspects and summary

The 3GPP (third generation partnership project) has released the upgradation of the 5G network standards from time to time which has enabled the research community to clarify their objectives mainly to commit toward the development. It is not only smart-phones that will support the 5G technology; rather the IOT devices will be in need of the supportive antennas with stable patterns, low path losses, low latency for providing wide range of services such as smart city, etc. The 5G technology is going to unleash more opportunities to break the traditional boundaries toward the development. Since the technology is supporting IOT, there will be a transformation in major fields including healthcare, education, and many more social sectors. To suffice the needs for better communication, 5G technology will decipher pervasive IOT system where numbers of devices are to be connected while maintaining network speed, cost, latency trade-offs. The 3GPP standards are continuously undergoing some changes. For 5G wireless networks, the 3GPP has defined three usage schemes stated as follows: [134]

(1) **MTC (massive machine type communications):** The scheme supports the IOT in order to connect more number of devices, as thousands of devices can be supported by a single base-station for smart-grid, smart-city applications.
(2) **eMBB (enhanced mobile broadband):**It supports the extremely high speeds for both indoor as well as outdoor connectivity providing around 20Gbps data-rates for indoor and 2Gbps for outdoor areas.
(3) **uRLLC (ultra-reliable and low latency communications):** It possesses an inflexible requirement of low latency <1ms and a packet loss of 1 in 1000 packets. Some of the occurrences include the safety in the transportation, manufacturing process control, and medical surgery.

The problems of multipath fading interference and radiation losses are prominent in wireless communications which become quite severe at the high frequencies. In order to overcome these problems, the application of MIMO technology has become quite important because it enhances the range of transmission without much increase in the power of a signal. In 5G, the MIMO antenna technology is used to accomplish the good efficiency, lower latency, and maximum throughput. The MIMO technology can be efficiently utilized to launch more signals while using multiple number of antennas thereby improving the channel capacity. Based on the operating frequency bands, the MIMO antennas have been classified as multi-band and wideband, which are further classified as multi-element antennas without rim and multi-element antennas with rim.

Antennas with metal rim provide the mechanical strength to smart-phone devices in addition to their aesthetic look. When the number of radiating elements in the transmitter or receiver side is very large, the MIMO is referred to as massive MIMO system [135]. In massive MIMO technology, because of large number of antenna elements, there is an enormous increase of SE. One of the important methods for improving the throughput of the MIMO antennas is beam-forming by the antenna array. Beam-forming refers to the regulation of the phase of the transmitting signal to get a major beam in one particular desired direction. The beam-forming can be performed both in analog as well as digital domain. The analog domain beam-forming is applied for single-user systems while as remaining two are used for multi-user systems [136].

A brief review for the MIMO antenna technology toward the application for future 5G wireless communication networks has been summarized in the given section. The paper is supposed to provide an easy path for the new researchers to design the antennas taking into account all the parameters responsible for enhancing the performance of MIMO antennas for 5G applications. The paper gives an insight to the different types of antennas that mainly include SISO antennas which are mostly employed in the devices where compactness in the physical size of antenna is critical. The MIMO antennas form an important part for smart-phones in reference to their support for beam-forming, etc. An important advancement to MIMO is massive MIMO technology ensuring better spectrum efficiency as well as throughput mainly for the base station application. One of the most crucial factors for MIMO applications is the effect of mutual coupling on the antenna performance. A number of techniques are being used for reducing the coupling effect between the multiple elements in a MIMO design. It is desirable that there must be low correlation of field power among the elements. Table 12 summarizes briefly almost all the crucial parameters for the MIMO antenna designs that are present in the literature.

Conclusion

In the paper, a thorough review of SISO antennas, single-user MIMO, multi-user MIMO, and massive MIMO technologies is presented for 5G wireless systems. The antennas have been reviewed by analyzing some important parameters that mainly include the effects of mutual coupling on the antenna performance in addition to the safe user handling of the mobile device. The review paper has been devised with the aim to provide a summary of MIMO antenna design for 5G applications implemented for smart-phones as well as for base stations. The main focus is to review the spectrum evolution toward 5G that includes both mm-wave and sub-6 GHz bands in addition to their pros and cons. Based on the properties and availability of the spectrum, the design of the antennas has been focused on. The MIMO antennas for mobile terminals are mostly designed with metal-rimmed edges or without metal rims. The effects of mutual coupling due to close spacing of MIMO antenna elements and its impact on the correlation are determined by ECC. The main take-aways of this review are categorized as:

Evolution of spectrum toward 5G

The main focus of the future researchers is to use the 5G spectrum bands in parallel to all other existing cellular frequency bands. Most of the countries worldwide have intensified their research for 5G applications. 5G spectrum allocation of bands include sub-6 GHz range and mm-wave range. The sub-6 GHz bands include mainly n77 (3.3–4.2) GHz, n78 (3.3–3.8) GHz, n79 (4.4–5) GHz, LTE-U (5.15–5.925) GHz; however, majority of the work is focused on (3.4–3.6) GHz and (5.15–5.925) GHz bands. The millimeter-wave bands include (24.25–39.5) GHz, (37–43.5) GHz, (45.5–47) GHz, (47.2–48.2) GHz, (66–71) GHz. The technology operating in both high- and low-frequency bands offer quite higher data rates of around 20 Gbps and more than 100 Mbps on an average. 5G specifies low latency, high mobility, supports more number of users at a time with enhanced antenna gains, broader bandwidths, and minimum radiation losses.

Mutual coupling and antenna performance

The MIMO antenna designs for mobile and base station applications and the decoupling techniques are being presented. The isolation improvement techniques include the use of neutralization line, slotted and defected ground structures, parasitic elements, ground strips, meta-materials, etc. The techniques applied depend on the design of MIMO antenna elements in addition to their frequency of operation. The correlation between the antenna elements is also explained along with their effect on the antenna performance. The paper also presents the promising coupling reduction techniques for base station antennas in addition to mobile terminal antennas.

SAR in terms for safe user handling

The antennas for mobile terminals should also take into account the effects of proximity of the user during the working of device. Due to the properties of biological tissues related to absorption of electromagnetic waves, SAR becomes an important parameter. The paper has discussed a number of antennas in the literature, analyzed for the SAR values. For the safe application of the mobile devices, work is being done to make the SAR values <2. The 2 W/kg has been set as the safety limit by the IEEE. The review sets a better understanding of all the aspects for the design of MIMO mobile antennas for 5G applications.

Future applications

The increasing demand for faster, smarter, and completely secure networks has increased rapidly the requirement for high data rates. The 5G is proving to be efficient in terms of energy and offering low latency, more scalability, high throughput, and more reliability. The main requirements for 5G networks are fulfilled by some notably important technologies that mainly include massive MIMO, densification of networks, radio access networks, device to device communication, and resource virtualization. The future applications for 5G can be briefly summarized as:

(1) **Cloud computing/IOT fog for 5G** The 5G-IOT is becoming an emerging field keeping in consideration with the need for higher data rates and faster communication networks. With 4G technology, only up to 2000 devices could be connected; however, 5G supports high connection density of around 1 million devices over 0.38 sq. miles [150]. The most suitable antennas for 5G IOT are multiple-element phased antennas having beam-forming networks, ultra-wide band monopole antennas, and massive MIMO [151,152]. In the near future, the combination of AI(artificial intelligence) and 5G-IOT is going to play an effective role in the development of smart systems.

(2) **Smart-phone application** For smart-phone applications, multi-band MIMO antennas are generally suitable; however, it also becomes a challenge to put these multiple elements in the limited space. Thus, the antennas that include monopole antennas, multi-mode loop, IFA are appropriate for smart-phone applications because of easy integration and compactness [153,154].

(3) Mobile platforms and base-stations In addition to high data rates, there is an increase in demand of more channel capacity for mobile platforms and 5G base-stations. The requirement can be full-filled by employing massive MIMO technology. Due to more number of base station antennas, it is possible to achieve high channel capacity in mMIMO. Besides capacity increase, mMIMO reduce energy consumption as well as latency, thus increasing EE [18]. Multi-antenna systems are going to provide a gateway for 5G network because of spatial multiplexing and high beamforming that is going to improve capacity, increase coverage, and QoS (quality of service).

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Insha Ishteyaq received her bachelors in Electronics and Communication Engineering in 2013 from the University of Kashmir and her Masters in 2017. She is currently working toward her Ph.D. degree from Islamic University of Science and Technology with research interests in antenna design for 5G standards. She has published few papers in international journals and conferences. Her research interests include modern day antenna design, millimeter-wave antennas, microelectronics, and related applications.

Khalid Muzaffar received his B.Tech in Electronics and Communication and M.Tech. in Communication and IT from NIT Srinagar, India in 2004 and 2006, respectively. He worked in Ericson India pvt ltd. From July 2006 to July 2007 as a field and maintenance engineer. He joined IUST Awantipora as an assistant professor in August 2007. He received Ph.D. from CARE, IIT Delhi, India in June 2017. His research interests are microwave antenna design, applications of thermal imaging for microwave field imaging.