Chapter

Antennas for 5G and 6G Communications

Syeda Iffat Naqvi and Niamat Hussain

Abstract

An antenna is of substantial importance for a communication system as the design of an air interface is mainly reliant on the antenna design. With the significant wireless evolution from 1G to 6G, technologies and network capacities are also evolving to fulfill the promptly growing customer demands. These continually increasing demands have gone concurrently with extensive technological accomplishments of the antenna design community. This chapter discusses the sub-6 GHz and millimeter-wave (mm-wave) fifth-generation (5G) antennas, including antenna arrays, multiple-input, multiple-output (MIMO) technology, beam-steering techniques, metasurfaces, and other techniques to achieve the current and impending fast connectivity. Moreover, the design specifications, research directions, various technologies expected to be involved, and challenges in the design, fabrication, and measurement of the sixth-generation (6G) antennas at the THz band have also been presented. In addition, antenna-in-package (AiP) and antenna-on-chip (AoC) technologies with proper technology solutions have also been discussed.

Keywords: 5G, 6G, millimeter-wave, 5G antennas, THz antennas, MIMO, beam steering, 5G communication

1. Introduction

Over the years, wireless and mobile communication standards have developed, where each phase brings more intriguing and innovative services and capabilities to the end-user. Since 1980, wireless and mobile networks have been evolving, and after almost every decade, a new generation has been established. Beginning with first-generation (1G) featuring analog modulation techniques, circuit switching, Frequency Division Multiple Access (FDMA), and developing 2G and 3G on the way, the wireless network generations have matured into IP-based 4th generation (4G)/Long-Term-Evolution (LTE), with the internet as a core network [1]. Although higher data rates have been achieved with 4G/LTE standards, however, exponentially growing data rates requirement led by the rapidly increasing number of wireless devices and limited potential of the existing technologies to administer the impending technologies such as high definition (HD) video streaming, cloud services, Internet-of-Things (IoT), and device-to-device communication [2–6], instigated substantial development in establishing fifth-generation (5G) standards for commercial mobile and broadband wireless communication services [7]. As all the radio communication
services, such as GPS, AM/FM radio, cellular, Wi-Fi, and satellite communication are operating in the microwave spectrum (300 MHz - 3 GHz), this resulted in the congestion and bandwidth inadequacy at the widely used microwave frequency band. Consequently, the underused millimeter-wave spectrum draws the attention of researchers in order to support 5G communication systems and applications.

Although the commercial deployment of 5G is underway in the world’s major countries, the rapidly increasing higher data rates and ultra-high-speed communication requirements have led to the introduction and development of sixth-generation (6G) wireless communication technology. The 6G wireless communication system is expected to emerge around 2030, and it is envisioned that at that time, the number of connected devices will increase by 500 billion [8, 9]. It is expected that 6G will offer ultra-reliable low-latency communication emphasizing internet machines, the use of Artificial Intelligence for wireless communication, and the enhancement of mobile broadband [10]. In order to fulfill these increasing demands, communication systems are shifting towards the higher frequency bands i.e., millimeter-wave and terahertz (THz) bands, as shown in Figure 1 [11, 12]. Both millimeter-wave and THz bands will play an essential role in the 6G wireless communication [13–15]. Some of the prominent proposed applications for THz band wireless communication are the internet of nano-thing (IoNT), health monitoring system, entertainment services, military, ultra-high-speed on-chip communication [14], augmented reality, and heterogeneous networks [15].

An antenna is substantially important for any communication system as the design of the air interface is mainly dependent on the antenna design. With the evolution of wireless generations, technologies, and network capabilities provided by the manufacturers, the antenna design community has also shown extensive technological development to meet the continuously increasing customer requirements. This chapter describes the challenges associated with 5G communication and antenna designing. Also, it presents numerous literary works exploring various technologies and design methodologies to meet the users’ necessities for 5G antennas. In addition, design specifications, research directions, different technologies expected to

Figure 1.
Mobile cellular spectrum from 1G (1980s) to 6G (predicted around 2030s) [12].
be involved, and challenges in the design, fabrication, and measurement of the 6G antenna at the THz band are discussed in this chapter.

2. 5G mobile communication

Mobile communication is considered one of the paramount innovations of the last few decades as it has played a significant role in the social and economic development of the countries. Due to the rapid upsurge in connected devices, the growth of data traffic is remarkable. The latest traffic anticipated by Cisco Systems, Inc., due to the increase in mobile devices is illustrated in Figure 2. It is noted that the number of global mobile devices is predicted to grow from 8.8 billion (in 2018) to 13.1 billion by 2023, with an 8% compound annual growth rate (CAGR) [16]. Due to this anticipated growth of connected devices and also due to the more value-added services such as virtual reality, ultra-high-definition video, cloud services, smart vehicles, etc., the industry progressed towards the 5G networks to provide the 1000x more capacity as compared to 4G, so that the incessantly growing data rates requirement can be met.

The system specifications targeted by International Telecommunication Union (ITU) for 5G to meet the consumer requirements are demonstrated in Figure 3. Figure 3 depicts that 5G communication systems should have high data rates such as 10 Gbps, mobility up to 500 km/h, spectral efficiency near to 10 bits/s/Hz, as compared to 4G these systems should be 10× more cost-effective, and latency should be less than 1 ms [17]. Moreover, 5G must permit massive device connectivity by connecting a huge number of devices simultaneously to the network for the Internet of Things (IoT).

2.1 5G spectrum allocation

The officially allocated 5G bands at the ITU World Radio-communication Conference 2019 (WRC-19), are illustrated in Figure 4 [18]. The allocated spectrum for 5G considers low bands i.e., 700 MHz, and Sub-6 GHz bands, including 3.3–4.2 GHz and 4.4–5 GHz bands. The most potential technique to enhance the capacity and data rates in mobile and wireless communication systems is to increase the bandwidth [19]. As higher frequencies offer more bandwidth, therefore, higher

![Figure 2](https://example.com/figure2.png)

*Figure 2.* Global growth of mobile devices (Values in parenthesis refers to the years 2018 & 2023) [16].
5G and 6G Enhanced Broadband Communications

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Frequency bands i.e., mm-wave band covering 26 GHz, 28 GHz, 37GHz, 39 GHz, 47 GHz, and 60 GHz, have been widely considered for 5G applications. It is expected that at the ITU World Radio Conference in 2023 (WRC-23), some additional IMT identifications could be approved across several bands between 3.3 GHz and 10.5 GHz for 5G [20].

2.2 5G Antenna Design Considerations

With the immense technological advancements in the reliability, capacity, availability, and latency that which 5G mobile communication standard put forward, the regulatory bodies such as European Telecommunication Standards Institute (ETSI) and 3rd Generation Partnership Project (3GPP) also set antenna specifications and

Figure 3.
Requirements for 5G Communication [17].

Figure 4.
5G frequency bands (Licensed, Unlicensed/shared, Existing band [18].

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requirements for 5G systems. This requires the identification of new technologies for 5G mobile antenna design [21]. The foremost areas to be considered for the 5G mobile antenna design are illustrated in Figure 5 [22]. The following sub-sections discuss the 5G antenna design considerations.

2.2.1 Antenna design

The rapid evolution of mobile communication systems towards 5G demands the multi-band and wide-band antennas to support the interoperability, provide more coverage, and lessen the complexity of the system [23–25]. Especially at mm-wave frequencies, a 5G mobile antenna should be compact in size, complying with the bandwidth and radiation efficiency requirements. The mm-wave spectrum suffers more path loss due to increased atmospheric absorptions and attenuations at higher frequencies [26]. Therefore, the 5G antennas should have high gain with increased directivity in order to overcome the path loss. In addition, another challenge in mobile communication at both microwave and mm-wave frequencies is that the orientation and location of the mobile device are not consistent. Thus, the direction of communication is not known. Therefore, to mitigate the path losses, for better spatial coverage, and to obtain high directivity and gain, antenna arrays, and beam-steerable antennas are widely identified as key enablers for the 5G mobile and broadband communication. Moreover, to meet the higher capacity requirement and for a broader coverage area, MIMO technology has been extensively explored recently for 5G communication [27]. MIMO is one of the enabling technologies to achieve 100 times more bandwidth as compared to 4G/LTE systems.
2.2.2 Antenna integration with RFIC

At the mm-wave spectrum, the conductive and dielectric losses are higher as compared to the microwave spectrum [28]. At microwave spectrum, the Radio Frequency Integrated Circuit (RFIC), antenna, and modem chips are categorized as separate design blocks, and the whole radio system establishes a horizontal integration known as a multiple-chip module, as shown in Figure 6a [29, 30]. This configuration increases the chip area, thus limiting the suitability of this approach for the cellular and other wireless devices as the device size follows the trend of continuous reduction with the development of technology. As the antenna has to be interfaced with the electronic circuitry, whether in a discrete or integrated manner, therefore impedance should be matched at the antenna circuit interface to ensure maximum power transfer from one component to the other. Thus, the standard interconnects elements such as coaxial cables, C-clips, and RF switches with specific impedance values (50 Ω) are used to establish a stable feeding network.

However, at mm-wave frequencies, the signal attenuation characteristics of the RFIC components are degraded radically, and consequently, the noise figure has deteriorated. Moreover, contrary to the current mobile antennas, the antennas should essentially be placed in close proximity to RFIC for 5G mm-wave devices. Therefore, for 5G mm-wave mobile antennas, highly integrated and compact antenna packaging schemes are characterized into two major groups [29, 31] i.e., the antenna in package (AiP) and Antenna on Chip (AoC).

**Antennas in package:** In this scheme, the RFIC, antenna, and other components are brought together into one system by stacked integration technology with vertical interconnects, as shown in Figure 6b. In AiP, buried and through vias are used, which reduces the lateral size of the mm-wave antenna module. However, at higher frequencies integrating these technologies become challenging as the losses between interconnects are high. On the other hand, AiP is beneficial for heterogeneous design and integration schemes as it offers the liberty to use different substrates and fabrication methods.

![Figure 6](image)

*Figure 6.* An illustration of (a) Multi-chip module, (b) Antenna in package, and (c) Antenna on chip [29].
Antennas on chip: With the advancements in technology, the Antenna-on chip (AoC) scheme has gained much attention, as it brought the integration of RF front end and digital baseband on a single chip, as depicted in Figure 6c. The co-design of antennas and circuits alleviates the need for a matching network. The on-chip methodology also reduces the interconnect losses, as the metal interconnects interface the IC directly to the antenna feed point. Also, it lessens the design complexity by minimizing the use of components, thus saving space and cost. At the mm-wave spectrum, as the antenna size is kept miniaturized by up to a few millimeters, therefore, on-chip implementation is most suitable at such higher frequencies [32]. On the other hand, a number of challenges also exist for on-chip antennas, such as layout constraints due to metallization density rules, low antenna gains due to losses in silicon substrates, and challenges of on-wafer characterization [29]. In order to overcome these hurdles and achieve a proper RF SoC solution, extensive research is underway.

2.2.3 Co-existence with preceding standards

On the path of technology evolution, there is the transition from microwave communication to mm-wave 5G communication. The existing technologies such as 3G/4G/ Wi-Fi and sub-6 GHz 5G will co-exist with mm-wave 5G. Consequently, this has provoked microwave engineers to design antennas for mobile devices with backward compatibility. Moreover, it is expected that 5G will continue to evolve, for example, as 5G+, just like 4G where LTE became to LTE-Advanced. Therefore, it is also essential to implement the forward-compatible integrated antennas in addition to backward compatibility. The smartphone illustrated in Figure 7 exhibits the expected placement of different antennas supporting various wireless standards in a smartphone. Although integrated antenna solutions are necessary, however, to design such integrated antenna modules are quite challenging for microwave engineers [33].

2.2.4 Effects of the electromagnetic exposure

International regulatory bodies like Federal Communication Commission (FCC) and International Commission on Non-Ionizing Radiation have established some
regulations and standards regarding human safety and exposure to electromagnetic radiation [34, 35]. Thus, wireless devices have to comply with these standards. Specific Absorption Rate (SAR) and Power Density (PD) are two important parameters to measure human exposure to electromagnetic waves [36]. Power density demonstrates the density of power carried towards the tissue. As the human body is conductive and absorbent, therefore, it will significantly affect the mobile antenna performance if hindered in the path of antenna radiations. At mm-wave frequencies, it is expected that the overexposure to the electromagnetic radiations can cause only superficial burns and no serious injuries in tissues, as the radiations are concentrated at the surface tissues only [37, 38].

3. Sub-6 GHz 5G antennas

In order to design an efficient antenna for 5G communication devices, several challenges are required to be addressed at the microwave spectrum. As microwave frequencies have to go through high latency, low data rate, and low capacity, therefore, in order to meet the relentless customer needs, antenna design is of considerable importance. In recent years, substantial research has been carried out to design antennas for 5G devices in the sub-6 GHz range of the spectrum. The antennas reported in the literature for lower 5G bands are usually large in size and are monopole antennas. Considering the structure, antennas are categorized as a single element, array, and MIMO configurations. This sub-section describes the 5G single elements, arrays, and MIMO antennas operating at lower 5G frequencies.

Some of the literary works have reported a single element antenna for 5G applications [40–46]. The 5G antenna reported in [39] is a magneto-electric dipole antenna with tapered H-shaped ground, operating at a sub-6 GHz band. By employing the tapered ground technique, the height of the antenna is reduced. The peak gain obtained by this antenna is 6.8 dBi. Similarly, the work in [40] presents a single compact antenna supporting a 5G sub-6 GHz band. The proposed antenna is a slotted antenna with U and E-shaped slots with a full ground plane. This antenna attains a peak gain of 1.1 dBi. Moreover, a flexible co-planar waveguide (CPW) fed circular-shaped single antenna [41], as shown in Figure 8, is proposed for sub-6 GHz 5G applications, whereas a peak gain of 3 dBi is achieved for the proposed antenna. The antenna design reported in [42] is a hexagonal-shaped frequency reconfigurable antenna operating at the sub-6 GHz frequencies for 5G systems. The reported antenna is an omnidirectional antenna with a peak gain of 1.5 dBi. Likewise, another frequency reconfigurable single element antenna, as depicted in Figure 9, is presented for 5G devices [43]. Gain for this antenna ranges from 1.2 to 3.6 dBi at the operating frequencies. The antenna proposed in [44] is a printed low-profile antenna with frequency and pattern reconfigurability. PiN diodes are used to control the beam; thus, depending on the state of the switches, the antenna can steer the beam in seven different directions. The antenna gain for different switch states ranges from 1.7 to 3.8 dBi. Another work reported a triangular-shaped monopole antenna for 5G sub-6 GHz devices [45], featuring frequency reconfiguration, as illustrated in Figure 10. The peak gain obtained by this antenna in different switch states is above 2.5 dBi. It is observed from the literature review that it is easy to design a single-element antenna, and also it can easily be integrated into 5G communication devices. However, the peak gain obtained by the single antennas is low.
Figure 8.
Flexible CPW fed 5G antenna (a) Perspective view, (b) Fabricated prototype [39].

Figure 9.
Frequency reconfigurable multi-band 5G antenna with biasing circuit [43].

Figure 10.
Top and bottom view of fabricated sub-6 GHz 5G antenna [45].
In order to overcome the propagation losses due to atmospheric attenuations and absorptions, high gain antennas are required for 5G communication. As a single-element antenna cannot obtain high gain, therefore, multi-element array configuration is one of the principal methodologies to deal with this issue. In an array, multiple antenna radiations are added constructively to enhance the gain of the antenna, thus, administering the path loss to some extent [46]. Recently, various antenna array designs have been reported for 5G sub-6 GHz systems [47–50]. The strategy proposed in [47] is a four-element antenna consisting of four hybrid antennas, as illustrated in Figure 11, operating at a sub-6 GHz band for 5G. The proposed geometry obtained a peak gain of 8.4 dBi, which is considerably high for 5G devices. Likewise, in [48], a dual-band filtering antenna array with dual polarization is presented. The presented geometry, as shown in Figure 12, is a 1 × 4 array, which attained a very high gain of 17.7 dBi, thus making it suitable for 5G base station systems operating at sub-6 GHz. Another work [49] reported a metasurface-based 4 × 4 antenna array for sub-6 GHz 5G applications. The reported antenna is a low profile and high gain antenna with a peak gain of 7.2 dBi. Moreover, the sheet array consists of capacitively coupled elements placed over a ground plane have made a new contribution in antenna engineering to overcome the problems associated with narrow bandwidth and low gain [50]. The performance of the proposed antenna array is tested by placing it at different body parts such as the palm, knee, backhand, etc. The peak gain obtained is nearly 6 dBi. It is observed that antenna arrays reported in literary works discussed in this section have obtained high gain (which is required for 5G communication) at the cost of increased size and design complexity.

MIMO antenna system is a system with multiple radiating elements employed at both the transmitting and receiving terminals, as illustrated in Figure 13. MIMO is considered to be the pivotal solution for capacity enhancement of a channel as compared to the conventional Single-Input-Single-Output (SISO) wireless systems [51, 52]. Although MIMO technology offers several benefits, however, placing multiple radiators in close proximity to each other increases the coupling between the adjacent radiators. As a result, the diversity performance of the antennas is compromised [53]. Therefore, designing a MIMO antenna with better diversity is indeed a challenge for antenna designers. Along with essential parameters to measure the antenna performance, such as gain, bandwidth, efficiency, etc., a few other parameters are also necessary to be inspected to measure the MIMO characteristics. These parameters are Envelope Correlation Coefficient (ECC) [54, 55], Diversity Gain (DG) [56], Mean Effective Gain

Figure 11.
The geometry of antenna: (a) single antenna, (b) four-element array [47].
(MEG) [57], Total Active Reflection Coefficient (TARC) [58, 59], and Channel Capacity Loss (CCL) [58].

As MIMO allows multiple antennas to radiate simultaneously, enhancing the channel capacity and data rates with multi-Gbps throughput (required for 5G systems), therefore, it draws the attention of researchers, and in recent years MIMO has been widely studied. Numerous works have been reported with MIMO antenna designs operating at 5G sub-6 GHz [60–66]. Sarkar et al. [60] suggested a four-element MIMO structure consisting of inverted L-shaped monopole antennas, as shown in Figure 14. The recommended design obtains inter-element isolation of $\geq 11$ dB, while
not involving any complex decoupling technique. This MIMO structure received a wide operating band and an average gain of 4 dBi. Authors have also investigated ECC and MEG to analyze the MIMO performance. The work in [61] reported a two-element MIMO configuration, where each element is a bow-tie antenna with a T-probe feeding structure. In order to decouple the antenna elements, a compact metasurface superstrate is employed, as shown in Figure 15. The introduction of the metasurface layer not only improves the isolation between the MIMO antennas but also enhances total efficiency and ECC between the two antennas; thus, ascertaining the suitability of this design for 5G sub-6 GHz devices. Another work [62] presented a four-element dual-polarized MIMO configuration. The main antenna is coupled and fed by the two pairs of differentially driven feed lines. The presented structure demonstrates port isolation of more than 35 dB. Parchin et al. [63] proposed a four-element MIMO antenna system for sub-6 GHz 5G devices, where each antenna is a diamond-ring slot antenna placed at the corners of the printed circuit board, as shown in Figure 16. Due to the orthogonal placement of L-shaped microstrip feed lines, pattern and polarization diversity are obtained. The data-mode/talk-mode characteristics are explored. The work in [64] introduced a ten-element MIMO structure for smartphone applications, operating at a 5G sub-6 GHz frequency band. The antenna structure is a shorted...
half-wavelength loop antenna placed in a 2D array configuration. In this work, ECC and channel capacity are calculated to analyze the MIMO characteristics. In addition, the impact of the user’s hand on the antenna performance and SAR analysis is also carried out. Another MIMO antenna system composed of four dielectric-loaded horn antennas is reported in [65] for vehicle-to-everything communication at 5G sub-6 GHz frequencies. Likewise, the study in [66] reported a four-element MIMO antenna system for 5G devices with the orthogonal placement of antennas. In order to reduce mutual coupling, four different structures i.e., electromagnetic bandgap
(EBG) structure, capacitive elements, defected ground structure (DGS), and neutralization lines (NL) are investigated. To analyze the MIMO characteristics, ECC, DG, MEG, and TARC are also inspected.

4. Mm-wave 5G antennas

Recently, several works reported antenna designs for mm-wave 5G communication devices. At mm-wave spectrum, atmospheric losses are high, therefore, high gain antennas are required for 5G systems. As single patch antennas have low gain, therefore, a lot of work has been done to improve the performance of the antenna in terms of bandwidth, gain, and coverage area [67–71]. Lin et al. in [67] proposed an omnidirectional circular polarized antenna for 5G device-to-device communication by integrating electric and magnetic dipoles in a disc-shaped structure such that they have parallel orientation. In another work [68], a cross dipole antenna is reported, as shown in Figure 17, where an electric and magnetic dipole are integrated to enhance the antenna performance. Similarly, the work in [69] presented a circularly polarized patch antenna. In order to improve the antenna performance in terms of gain, bandwidth, and axial ratio, a square ring-shaped metasurface is mounted above the patch antenna, as illustrated in Figure 18. Likewise, in order to increase the spectral efficiency, an antenna with a switchable beam for 5G mm-wave applications is proposed in [70]. In this work, beam switching is achieved by incorporating the two PIN diodes at the ground plane. Tahir et al. in [71] suggested a wide-band antenna for 5G mm-wave communication devices, where high gain is achieved by using a corporate fed four-element linear antenna array, as shown in Figure 19.
As MIMO is a key enabler for 5G mm-wave communication, therefore, recent research widely explored MIMO antenna designs to obtain higher channel capacity. However, a drawback associated with MIMO configuration is coupling between the multi-elements. Various techniques such as EBG [72], DGS [73], frequency selective surfaces (FSS) [74], metasurfaces, and metasurface corrugations [75–77], have been used to reduce the coupling effects and also to improve the radiation characteristics of the recently reported MIMO antennas.

5. Integrated antennas for 5G handheld devices

As the mm-wave 5G antennas are expected to be compatible with the previous technologies such as 4G/LTE, therefore, integrated or co-existing 4G/LTE and mm-wave 5G antennas will be an effective solution for long and short-range communication. On the other hand, designing such antennas is really challenging due to increased coupling effects between closely packed antennas. Some of the recent studies [78–81] reported antenna designs for handheld devices where 4G/LTE and mm-wave 5G antennas co-exist on the same substrate board. The integrated antenna solution proposed in [78] is a two-element MIMO antenna system at microwave frequencies and an mm-wave
array. The proposed antenna system is planar and is designed for smartphone devices. Similarly, in [81], a MIMO antenna structure operating at microwave frequencies and an mm-wave tapered slot antenna array, as shown in Figure 20, are suggested as an integrated antenna solution for handheld devices. The tapered slots array is also used as a decoupling structure at microwave frequency. In another work [82], a two-element MIMO antenna for LTE and four-element MIMO antenna structure for mm-wave 5G is reported to be co-existing on the same board, as illustrated in Figure 21. The proposed design incorporates rectangular and circular slots as DGS to improve the antenna performance. The SAR and PD analysis are also carried out to verify if the proposed antenna system satisfies the international human safety standards.

6. Towards’s 6G communication

The rapid advancement of emerging technologies such as artificial intelligence, three-dimensional (3D) media, virtual reality, and the Internet of Things (IoT) has increased the volume of data traffic. This demand for substantial data rates led to the transition and up-gradation of 5G technology to 6G communication. As it is an early stage of development, therefore, 6G wireless communication system is not completely defined yet. However, the main focus of 6G will be on higher capacity, ultra-low latency, broader coverage, and high security [83, 84]. The critical candidate technologies for 6G communication are shown in Figure 22 [85]. The terahertz (THz) frequency band (0.1–10 THz) will primarily be used for 6G communication systems. 6G wireless communication will be involved in all areas of society, including health, industry, land, oceans, and space [15].
6.1 6G antenna specifications

Design specifications for the 6G antenna depend on the type of application. However, general antenna specifications for 6G communication systems are:

1. Ultra-wideband and multi-band antenna [14].

2. Omnidirectional antennas will be required for some applications, whereas for some other applications highly directional antennas will be preferred [14]. Considering the application, a high gain omnidirectional antenna with a gain between 18 and 34 dBi or even up to 60 dBi, or a highly directional antenna of 25 dBi will be required [86, 87].

3. The 6G communication band is the THz band (0.1–10 THz).

4. 6G antenna should be compact in size [14] and have a low cost.

5. Circular polarization is preferred for communication at 6G frequencies [88].

Multiband antennas can be used to increase the bandwidth, data rate, and capacity of the THz communication system [89]. Also, multi-band antennas offer multi-functionality and thus can be used for multiple purposes. As the THz frequency band suffers from high atmospheric absorption and path losses, therefore, high gain antennas are necessary to overcome these losses for 6G communication systems [15]. Highly directional antennas are required for ultra-broadband THz wireless communication in 6G systems. Furthermore, as the circularly polarized antenna receives signals both in the horizontal and vertical planes as compared to the linear polarized antenna, therefore, circular polarized antennas are preferred for 6G indoor and outdoor applications as multipath fading will have negligible effects in this case as compared to...
linear polarization [88]. In addition, lens-coupled photoconductive antennas are also envisioned to be used in THz 6G communications and have been widely studied in the literature [90–94]. These antennas offer the high gain characteristics to cope with the high propagation losses in the THz regime.

7. Conclusion

This chapter describes the specifications and requirements for 5G and 6G THz wireless communication. Spectrum allocation for 5G mobile communication is also discussed briefly. Moreover, essential design considerations for 5G and 6G antennas are explained in detail. The state-of-the-art works related to 5G sub-6 GHz and 5G mm-wave antenna designing are also demonstrated. It is described in detail how these antennas are utilizing key enabling technologies such as arrays and MIMO to improve the radiation characteristics of the 5G and 6G antennas. In addition, recently reported integrated 4G/LTE and 5G antenna systems for handheld devices are also discussed.

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