Study of techniques to improve performance of patch antennas for 5G applications at millimeter wave (mmW) frequencies

Sagar Juneja and Rajnish Sharma*

VLSI Centre of Excellence, Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India
Email: rajnish.sharma@chitkarauniversity.edu.in

Abstract. Millimeter wave (mmW) frequency signals of 28 GHz and 38 GHz that are being explored for implementing next generation cellular communication network (i.e. 5G) suffer from severe attenuation in the outdoor environment. Therefore, efficient and intelligent antenna design techniques are needed for proper transmission and reception of signals at mmW frequencies. Beamforming, multiple input multiple output (MIMO) and space division multiple access (SDMA) are important requirements of mmW 5G network, and these technologies are heavily dependent upon antenna design and implementation. This paper presents various contemporary techniques for improving performance parameters of patch antennas for 5G implementation at mmW frequencies. These performance parameters include gain, bandwidth, directivity, suppression of surface waves, ease of design, compactness, and mutual coupling between antenna elements for MIMO system. This study also highlights the benefits and drawbacks of each of these techniques discussed in the paper.

Keywords. Millimeter wave frequencies for 5G, mmW for 5G, antenna design for 5G, antenna design for mmW applications, beamforming antenna, directional antenna, DGS, FSS, EBG

1. Introduction

In the year 2017 mobile data traffic was 11.5 billion gigabytes per month and it was almost double in comparison to mobile data traffic of the year 2016 [1]. This data deluge is due to the dramatic surge in number of smartphones users and growing mobile internet applications like cloud computing, internet of things, streaming HD videos, massive machine to machine communication etc. All these applications have been putting an enormous pressure on exiting wireless technologies for providing more bandwidth and higher data rates to support huge volume of data, exponentially growing number of wireless connections and high-speed data transmission. Latest cellular technology that is in use today is Long Term Evolution Advanced, commonly referred to as 4G. 4G operates in the frequency range of 750 MHz – 2.6 GHz and supports data rate of upto 100 Mbps with mobility, over a channel bandwidth of 20-40 MHz [2]. It has been agreed by the research community that existing 4G technology will not be able to support the future demand of greater network speed and capacity, and therefore a new paradigm needs to be explored [3]. In order to meet the bandwidth and speed requirements of future cellular applications, a lot of work is being done today for the implementation of the next generation cellular communication standard i.e. 5G. The standardization process of the global specifications for 5G began in 2012 by the International Telecommunication Union Radiocommunication Sector (ITU-R). Official term coined by ITU-R for 5G is IMT2020, and the global specifications for IMT2020 are to be finalized by 2020 [4]. As per these specifications, key
service requirements of 5G include data rates of up to 10 Gbps per connection, latency in the range of 1 ms to 4 ms and connection density of 1 million connections in one square kilometers area [5]. These service requirements cannot be achieved while operating in existing sub 3 GHz radio frequency bands only, and therefore ITU-R has recommended the use of millimeter wave (mmW) frequency bands between 24 and 71 GHz for 5G implementation. A total bandwidth of 17.25 GHz has been allocated by ITU-R in this mmW band for 5G [6]. Federal Communication Commission (FCC) of the United States of America was among the first ones to allocate mmW bands of 28 GHz and 38 GHz for 5G implementation [7].

Millimeter wave frequencies owing to their short wavelengths have crucial limitation that they suffer from atmospheric attenuation and severe losses in the outdoor environment. This limitation restricts long distance propagation of mmW signals beyond few hundred meters in outdoor environment and also restricts non line of sight (NLOS) communication [3]. This has put forward a need for intelligent antenna design in order to provide sufficiently high directive gain over a wide bandwidth to overcome the propagation related limitation of mmW frequencies [8]. In addition, due to the short wavelengths of mmW frequencies it is possible to put a large number of antenna elements in a form of an array to achieve adaptive beamforming and high directivity in small cell heterogeneous networks [9]. Both beamforming and directivity are mandatory requirements for antenna implementation at mmW frequencies for 5G applications. However, such antenna array architectures result in mutual coupling between antenna elements, and therefore mutual coupling issue must be addressed while designing antenna array systems at mmW frequencies. Mutual coupling in antenna arrays occurs because of electromagnetic interaction between antenna elements of the array, and it adversely affects impedance, gain, radiation pattern, side lobe levels of antenna arrays [10].

Planar antenna is a preferred choice today for most wireless communication applications including cellular communication applications because of its simple design, easy construction, low cost, small size, and easy integration possibilities [11]. However, planar antenna also suffers from drawbacks like narrow bandwidth, high dielectric losses, and small gain values [11]. Today research community is extensively working on proposing different planar antenna element and array topologies that can offer higher gain, higher bandwidth, better efficiency while maintaining small physical dimensions [12]. There are different planar antenna topologies discussed in contemporary literature like patch antenna, slot antenna, dipole antenna, dielectric resonator antenna etc. Among all these planar topologies, patch antenna is one of the most popular choice since it is comparatively low cost and simple to construct [13]. Therefore, in this paper, patch antenna design for mmW frequencies operation has been discussed. Some of the key design issues of patch antenna at mmW frequencies have been presented in section 2 of the paper. Contemporary techniques used by researchers to improve the performance of patch antenna operating at mmW frequencies have been discussed in section 3, as well as feeding issues of planar antennas have also been presented in this section and the whole study has been concluded in section 4.

2. **Patch antennas at mmW frequencies**

Patch antennas have several benefits as well as drawbacks while operating at mmW frequencies and some of these benefits and drawbacks are presented in Table 1 [14, 15].

**Table 1.** Benefit and drawbacks of patch antennas [14, 15].

| Benefits       | Drawbacks          |
|----------------|--------------------|
| Planar         | Low gain           |
| Compact        | Narrow bandwidth   |
| Robust geometry| Poor directivity   |
| Easy to design | Single frequency   |
| Low cost       | Polarization issues|


For low radio frequency operations some of these drawbacks may be overlooked, but at mmW frequencies for 5G applications these drawbacks have severe negative effects because of the following reasons and therefore these effects need to be addressed while designing mmW antenna systems –

- Millimeter wave signals cannot propagate more than a few hundred meters in the outdoor environment and therefore antenna with high gain is needed [3].
- Wide bandwidth is required to meet the high throughput requirements of 5G applications at mmW frequencies [16].
- Multiband operation is required to support functioning of different services simultaneously [14].
- High directivity is required so that advanced spatial multiplexing can be achieved in small cell network to improve network capacity [17].

Figure 1 is an example of a single microstrip patch antenna of rectangular configuration designed for operation at 28 GHz frequency. The antenna has been fabricated on RT Duroid substrate [18]. In this work, different design issues of single patch antenna element operating at mmW frequencies have been discussed. The proposed antenna has been fed by a coplanar waveguide in order to achieve a right balance between desired performance and simplicity of the design.

![Figure 1. Rectangular patch antenna [14].](image)

It is evident that antenna system for mmW 5G applications will feature antenna array implementation that contains multiple antenna elements in order to meet the gain and bandwidth requirements. Jang et al. [19] have proposed a four-element antenna array implemented using E-shaped microstrip patch antenna element for operation at 60 GHz frequency. Series feeding using microstrip line has been implemented in the design, and antenna array has been designed in a single layer thereby making it low profile and simple in construction. As shown in figure 2, the authors have introduced co-polarized parasitic patches in the design in order to achieve high gain. In the proposed antenna implementation, current flows in the same direction in E shaped patches as well as in parasitic patches thereby achieving current coupling that led to gain enhancement. The antenna array has been operating at 60 GHz frequency with impedance bandwidth of 25.4% (50 GHz – 64.6 GHz). Reported value of peak directional gain of antenna array is 14.5 dBi and beam width is 20° in E-Plane and 44° in H-Plane.
In addition to series fed antenna arrays, multiple input multiple output (MIMO) systems have been extensively explored by researchers today in order to improve capacity, data-rates and directivity of antenna systems in cellular mobile networks. MIMO systems have capability to drive multiple patch antenna elements simultaneously thereby increasing the capacity and bandwidth of existing communication system without any additional operational requirements [20]. Therefore, in order to achieve compatible with existing MIMO systems, 5G antenna array architectures operating at mmW frequencies should be simple, flexible and robust in design. Also, in antenna array implementation, maximum spacing between antenna elements should be half wavelength in order to get the desired performance [10]. This is a big design challenge at mmW operation, as due to short wavelengths of mmW frequencies, antenna elements will be too close to each other and strong mutual coupling would exist between them that will severely affect the antenna array performance [21].

Several techniques have been reported in literature to improve the performance parameters of both individual patch antenna element as well as antenna array system. Some of these performance enhancement techniques have been discussed in the next section of the paper. Feeding network of antenna array and MIMO system should be carefully designed as feeding network significantly affect the performance of antenna system. Some of the curial antenna feeding techniques have also been discussed in the next section.

3. Techniques to improve performance of patch antennas
The prime issue associated with the planar antennas is existence of surface waves that adversely affect the radiation pattern of antenna and leads to gain deterioration [22]. Surface waves occur when electromagnetic energy is radiated into substrate of the antenna. Performance improvement techniques for patch antennas are mainly based on restricting propagation of these surface waves in antennas. In addition, there are certain techniques that restrict the propagation of electromagnetic waves generated from antenna in undesired directions, thereby increasing directivity and gain of antenna. In this section of the paper performance enhancement techniques like Photonic bandgap (PBG) / Electromagnetic bandgap (EBG) structures, Defected ground structures (DGS) and Frequency Selective Superstrate (FSS) structures have been discussed. In addition, antenna feeding techniques using microstrip lines and Surface Integrated Waveguide (SIW) have also been discussed in this section.

3.1. Photonic bandgap (PBG) / Electromagnetic bandgap (EBG) structures
PBG structures were first introduced in 1987 [23] and after their successful implementation in photonics these structures have been widely used in RF and Microwave circuits and are broadly referred to as EBG structures. They are periodic structures - air gaps or air columns that introduce frequency band gaps in order to suppress propagation of certain frequencies, normally surface waves [22]. These same structures are also used for removing coupling between adjacent antenna elements in antenna array system [21]. Figure 3 shows a rectangular patch antenna surrounded by periodic PBG structure [15].
Figure 3. Patch antenna with periodic PBG structure [15].

Propagation properties of electromagnetic waves in these PBG structures are similar to propagation of electrons in semiconductor crystals [15]. Spacing between radiating patch and periodic PBG structure is a very crucial design consideration. If PBG structure is too close to the radiator then tuning of antenna will be difficult, and if PBG structure is too far away then its coupling with radiating patch will not be sufficient to enhance its performance [22]. This patch antenna with proposed PBG structure shows improvement in directivity by a difference of 2 dB when compared with a non PBG antenna [15]. It should be noted that PBG structure can be incorporated in substrate, in ground plane and as cover on top of radiating patch [24]. Zaidi et al. [16] have reported 100% improvement in gain of circular microstrip patch antenna over a bandwidth of 2 GHz by incorporating PBG lattice both in antenna substrate and as two-dimensional PBG cover. Geometry of PBG lattice cover is shown in figure 4.

Figure 4. Geometry of 2D PBG lattice as cover [16].

Mu'ath et al. [21] have used PBG structure in order to remove mutual coupling between two dielectric resonator antennas located half wavelength apart and operating at 60GHz. The proposed PBG structure provides a wide bandgap that isolates the two antennas, and this technique could be used in designing MIMO antenna arrays with reduced mutual coupling between them. Figure 5 shows the PBG lattice and PBG unit cell that is proposed in this design. The central patch in unit PBG cell act as capacitor and protruding arms from the central patch act as lead inductors. When this PBG cell is used in designing a PBG lattice then the air gaps that are introduced also act as capacitors. PBG lattice forms a resonating LC network that presents a wide bandgap with 13 dB reduction in transmission coefficient over a band of 57-64 GHz. The proposed design has also claimed to have achieved more compact sized antenna as compared to conventional PBG antennas.
PBG structures suffer from some limitations that include complex design procedures, costly implementation and large sized antennas because of large periodic structure in the design [24, 25]. Radiation from PBG lattice is another design challenge that needs to be addressed. The other prominent technique that is being used for improving performance parameters of patch antennas is to employ Defected Ground Structure (DGS) in the ground plane to break uniformity of electromagnetic field, and this technique was introduced in the year 2000 [26]. DGS antennas are easier to design, lower in cost, compact in size and have higher precision in comparison to PBG antennas [24].

3.2. Defected ground structure (DGS)

DGS is basically a defect that is introduced in the ground plane of patch antenna to disturb the characteristics of transmission line by introducing additional capacitance and inductance [24]. DGS is actually an extension of Ground Plane Aperture (GPA) technique [27] in which a slot in ground plane is introduced just below the transmission line in order to improve coupling with the feed lines [28]. DGS can be implemented in patch antenna as a unit cell or as a periodic structure in ground plane. Figure 6 shows a dumbbell shaped DGS etched in the ground plane below the transmission line of patch antenna.

Two rectangular patches of dumbbell act as inductors because they increase route length of current thereby disturbing uniformity of current distribution in ground plane. The slot connecting these patches store charge and acts as capacitor. Therefore, DGS acts as LC resonating circuit that has notch frequency response and it works as bandgap to restrict propagation of surface waves. Figure 7 shows RLC equivalent circuit of DGS wherein transmission line is terminated in characteristic impedance \(Z_0\) [24]. R represents resistive losses that include conduction, radiation and dielectric losses in DGS.

Figure 5. PBG lattice and PBG unit cell [21].

Figure 6. Dumbbell shaped DGS structure in ground plane.
Figure 7. RLC equivalent circuit of DGS.

It is possible to tune DGS to any frequency by changing either the dimensions of DGS geometry or by using different geometry altogether. Different DGS geometries that are available in literature include split ring, arrow head, spiral head, H shape etc [24]. It is also possible to design a periodic DGS structure with multiple DGS cells wherein each cell will have a different resonance frequency, and as a combined structure it will have a wide bandgap. This technique is very useful at mmW frequencies where wide bandgap is needed to suppress surface waves and to achieve isolation between adjacent antenna elements.

Jilani et al. [14] have proposed a MIMO antenna for 5G applications at mmW frequency of 28 GHz using periodic DGS structure. The proposed design has 5 symmetrical split rings DGS in the ground plane as shown in figure 8.

Figure 8. (a) T-shaped patch antenna, (b) symmetrical split ring DGS in ground plane [14].

Each of these rings acts as resonant gap with different resonance frequencies, and with this a continuous bandgap of 12.4 GHz has been achieved in the design over a bandwidth of 25.1 to 37.5GHz. The design has also been tested for MIMO system using a four-element linear antenna array and good isolation between these elements has been reported. The maximum value of gain achieved in the proposed design is 10 dBi.

Defected ground structures were first used in the designing of microwave filters, but today frequency selective properties of DGS are prominently used in designing compact wideband and multiband MIMO antenna array systems [14, 24, 28].

3.3. Frequency selective superstrate (FSS) structures

FSS structures are primarily used for gain enhancement in planar antenna and these structures are implemented as top layer in antenna system. It is also possible to achieve circular polarization with FSS layer. FSS layer causes multiple reflections of electromagnetic (EM) waves within the air cavity that lies between the patch antenna layer and the top FSS layer, thereby generating multiple resonant frequencies. EM waves that partially transmit through the FSS layer are highly directive in nature and this is how high directivity (gain) is achieved in the broadside direction of the antenna. Akbari et al. [29] have reported a three-layer antenna structure with bottom layer as feedline, middle layer as radiator and top layer as FSS. The reported value of peak gain with the proposed design is 15.5 dBi, bandwidth is 26.9 – 34.8 GHz (25%), axial ratio of circular polarization is less than 3dB and side lobe level is below -13 dB. The only disadvantage of adding FSS layer is that the size of the antenna gets
increased and moreover, FSS layer needs careful and precise tuning to generate desired resonant frequencies in the air cavity. Asaadi et al. [30] have also reported a use of FSS structure for gain enhancement in planar antenna operating at 28 GHz frequency for 5G applications. Figure 9 shows the fabricated antenna that has been proposed in this work. The antenna is composed of FSS structure with 7 X 7 unit cells, a dielectric resonator and a rectangular aperture for coupling energy from microstrip feedline to the radiator. The reported value of gain from this antenna is 15.4 dBi, impedance bandwidth is 15.54% around 28 GHz frequency, and radiation efficiency is 90%.

![Fabricated DRA with FSS](image)

Figure 9. Fabricated DRA with FSS [30].

### 3.4. Antenna feeding techniques

There are two kinds of antenna feeding techniques used in planar antennas – microstrip feedlines and surface integrated waveguides (SIWs). Microstrip lines based feeding network suffer from both dielectric and radiation losses that are quite appreciable at mmW frequencies, because at such high frequencies, size of radiating element is comparable to the width of feedline [31]. This is a reason that SIW based feeding network is most commonly used in mmW antenna design these days. Series feeding SIW network promises high gain and high radiation efficiency due to shorter path lengths, but at the same time it suffers from narrow bandwidth [32]. Parallel SIW feeding network promises wide bandwidth but it suffers from huge losses which is a big challenge, and it is also more complex to design [33]. Hence, several design trade-offs need to be considered while designing feeding network for mmW antenna system. SIW feeding network with a combination of series and parallel feeding has been reported in literature [34]. Similarly, a combination of microstrip feedline and SIW network for antenna system implementation at mmW frequency has also been reported in one of the contemporary works [35]. In a multi-layer antenna structure, design of SIW feeding network requires implementation of buried vias which also remains a challenging task [33].

### 4. Conclusions

Patch antennas are ideal choice for portable wireless applications because of their small size, planar geometry, low cost, easy design etc. However, they suffer from crucial limitations especially when used at very high RF frequencies like mmW signals of 28 GHz and 38 GHz. These limitations include low gain and low directivity, narrow bandwidth and existence of surface waves. In this paper some of the contemporary and prominent performance enhancement techniques for patch antennas at mmW frequency operations have been discussed. These techniques are Photonic bandgap (PBG)/Electromagnetic bandgap (EBG), Defected ground structure (DGS) and Frequency Selective Superstrate (FSS) structure. The paper has presented operating principle of these techniques, their working and contemporary antenna system designs carried out by researchers using these techniques. The paper has also discussed two prominent antenna feeding techniques namely microstrip feedlines and surface integrated waveguides (SIWs). This study can help RF designers and researchers in wisely selecting the appropriate technique for enhancing performance parameters of patch antenna for desired mmW application.
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