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Chapter 10

Beamformer development challenges for 5G and beyond

M. Ali Babar Abbasi¹ and Vincent F. Fusco¹

Antenna's beamforming technology [1] is vital in the utilization of the microwave and millimeter-wave (mmWave) frequency bands for the fifth-generation (5G) communication technology, and beyond, applications that include the sixth generation (6G), Internet of Things and Industry 4.0 [2,3].

Antenna beamforming can be defined as the ability of an antenna array to steer the maximum radiation toward a prescribed direction, or, conversely, the ability of the antenna array to estimate the direction of arrival (DOA) of an impinging signal.

Beamforming is generally achieved by using multiple antennas, spatially colocated to either function as an independent radiator or as a unit cell in larger array arrangements. Recently, the term multiple-input-multiple-output (MIMO) has been used in conjugation with the beamforming technology since it also involves multiple antenna systems, thus linking it to the beamforming technology [4]. When the number of antennas used in the MIMO operation becomes very large, it is generally termed massive MIMO technology [5]. Different beamforming concepts are used for the two frequency spectrum classifications in cellular technology, i.e., sub-6 GHz and mmWave. The majority of beamformer challenges at sub-6 GHz are already resolved, and prototypes are now available [6]; however, there are still major fundamental challenges that engineers face while developing beamformers for use in the mmWave bands, i.e., >28 GHz. Challenges include, but are not limited to, high path loss, power generation, adaption to account for realistic channel estimation, hardware impairments, energy leakage in circuits, high development cost, spatial-temporal channel variations, signal blockages due to the presence of obstacles such as beamformer casing, user body and hand. Also, multiuser MIMO techniques are not easily implementable in mmWave frequencies. In addition to this, beam coordination at transmitter and receiver antenna systems especially in mmWave spectrum is very challenging. In this chapter, we will first classify the beamformers based on the system architecture, operational frequency

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band and use cases. We will then elaborate the hardware development challenges encountered in realizing beamformers for specialized purpose in 5G and beyond applications.

10.1 Introduction

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The 5G communication technology is now ready to be deployed and efforts are now pushed forward to develop the technology for the 6G and beyond applications. As a first step of 5G deployment, communication base stations have been launched in many cities around the world and 5G-supported communication devices are available in the market since the mid-2019. The story does not end here since the 5G communication infrastructure launched so far has not fully satisfied user experience promises. There is still a long way before society fully harvests the actual benefits of research and development efforts that were pushed by the communication industry in 5G. The sub-6-GHz 5G technology currently available in marketplace performs better than previous communication technologies like the long-term evolution (LTE) and LTE Advanced (LTE-A). For full 5G evolution, we expect data rate of multiple gigabits per second per user and ten times better latency compared to 4G for all users in a cell [7]. It is expected to see this during the launch of mmWave 5G over the coming years.

Antenna array beamforming technology is now an integral part of the 5G infrastructure, as per the popular belief of researchers, communication engineers and major corporate telecom operators. It was envisioned in the early 2010s that the frequency spectrum used for the global system of mobile communication, LTE and LTE-A operating with other wireless technologies would quickly fill in the available sub-6-GHz spectrum. There will be less bandwidth available for further usage and moving to the higher frequencies will be the only option left. This gave rise to an immense research effort in engineering development at the higher frequencies into the millimeter range. This spectrum comprises mainly frequencies having wavelengths of millimeters and is generally referred to as mmWave spectrum. The migration of wireless technology from sub-6 GHz to mmWave has a high cost since the wireless devices operating at high frequencies face several problems that were solved due to technological advancements focused at sub-6-GHz spectrum. First problem is that the free-space path loss at mmWave frequencies is high compared to lower frequencies. The path loss of an electromagnetic wave is governed by the following expression:

$$path\ loss = \left(\frac{4\pi r \times f}{c} \right)^2 \quad (10.1)$$

where f is the frequency of an electromagnetic wave, r is the path length and c is the speed of light (all in SI units). This means that as we move higher along the frequency spectrum, the free-space path loss increases at the squared rate. A wireless link operating at 3 GHz suffering a path loss of around 82 dB will suffer a path loss

of around 102 dB when operated at 30 GHz given all other variables are kept constant in the wireless link. Another way of looking at this is at the same distance and same transmitted power by the antenna in a wireless link, a 3-GHz carrier signal operating over a 1-km range, when replaced by 30-GHz carrier signal, will cover only 100 m and around 30 m at carrier signal of 100 GHz. To deal with this much path loss, we need compensation. This can be achieved by either enhancing the output signal of the power amplifier or directing the antenna energy into a more confined spatial direction. The second way is preferred because of the well-studied concept of antenna array beamforming [1] in which the radiated energy from an antenna array can be directed toward a predefined spatial sector and, if correctly designed, prevented from going in other directions where the radiated signal is not required. A system that performs this function is termed a beamformer.

A beamformer adds spatial “gain” by using antenna radiating elements in ensemble such that the resulting arrangement compensates path loss. Antenna gain is defined as the power radiated by the antenna per unit solid angle in a given direction, divided by the average power radiated per unit solid angle [8]. For example, assume a point source radiating electromagnetic energy equally in all directions, the power flux density can be written as

$$\Phi = \frac{P_T}{4\pi r^2} \quad (10.2)$$

where P_T is the transmitted power and r is the observation distance from the point source. A practical antenna cannot radiate equally in all directions, so its radiation is generally denoted in comparative forms of directivity (D) and gain (G) where directivity is defined as

$$D = \frac{4\pi\Phi(\theta, \phi)}{\int_0^{2\pi} \int_0^\pi \Phi(\theta, \phi) d\theta d\phi}, \quad (10.3)$$

and the gain as defined as

$$G = \eta D. \quad (10.4)$$

where η is the antenna efficiency that always less than 1 (for further details see [8]). Beamformer gain is normally tested in an anechoic environment using setups such as those in [9,10].

Most commonly used beamformers are arrays of antenna in which the gain of a single-antenna radiating element is enhanced by increasing the number of antennas radiating elements placed at approximately one-half wavelength spacing with respect to each other [8]. In this way, the magnitude of the antenna radiated by all the closely spaced antennas adds constructively or destructively in a spatial footprint defined by both the radiation characteristics of the antenna and the element separation. The directions where all the signals radiated by every antenna are added constructively, the array gain is the highest. The direction in which the maximum gain is achieved is generally referred to as boresight of the antenna array and the radiation along this direction is called a beam. A general rule of thumb is that as we

increase the number of antennas in an array, we increase the array gain. If we add phase difference between the antenna elements in an array, we can steer the constructive interference between the signal radiated by each antenna away from the boresight direction. This concept is generally referred to as beam steering. By carefully managing the phases of each antenna element in an array using phase shifters, we can control the beam in multiple ways and achieve beam tilting, beam scanning, multi-beam radiation and interference rejection null formation [11]. An array that uses phase shifters to control the antenna array is called a phased array (Figure 10.1(b)). This is not a new concept and wealth of literature is available for design, synthesis and analysis of phased arrays.

According to the classical Shannon–Hartley theorem [12] that defines the tightest upper bound of the data rate, channel capacity (C) is defined by

$$C = B \times \log_2 \left(1 + \frac{S}{N} \right) \quad (10.5)$$

where C is in bits per second. B is the bandwidth in Hertz and ideally is equal to the frequency passband used in signal transmission. S is the average signal power at the receiver end averaged over the bandwidth B while N is average noise/interference power averaged over B , and both S and N are in Watts. The ratio S/N is generally referred to as signal-to-noise ratio (SNR) and has a direct logarithmic (base 2) relationship with the channel capacity. Beamforming has a direct impact on increasing the signal power in (10.5), so by adding beamformer gain one can increase capacity.

Looking toward the example given previously, a wireless link suffering a path loss of 102 dB can use beamforming technology to reduce the path loss to 82 dB if an antenna array having a gain value of 20 dBi is used as a beamformer.

Figure 10.1 (a) Multiple antennas connected to a single radio-frequency source forming an antenna array capable of beamforming only along boresight direction. (b) Same antenna array with bank of phase shifters capable of beam scanning at an angle θ from the boresight direction

Beamformer gain is generally added to the communication system link budget directly.

As we move from sub-6 GHz toward the mmWave spectrum and beyond, the design of a standard phased array gets difficult because of the two main reasons. The first reason is that compensation of the path loss at mmWave requires high array gain, and in order to achieve this, increased numbers of antenna elements are required in an array. This requires additional hardware per antenna element (power amplifier, filter, mixer, etc.) and increases the overall system cost compared to a sub-6-GHz phased array where individual components are cheaper to realize at the present time due to volumes currently in use. The second difficulty lies with the technological limitations of mmWave electronics. Principally a phase shift is required for every radiating element in a phased array. At mmWave, this demands high-precision low-loss electronics. This trend of elevating cost and complexity generally increases as we move higher up in the frequency spectrum. Regardless of these problems, beamforming is inevitable if we want to use a high-frequency spectrum for communication technology, and innovative mmWave beamforming approaches are required now than ever before.

In this chapter, we will discuss the current state-of-the-art in beamforming technology. Our focus will be especially toward the frequencies higher than the sub-6-GHz bands. We will look at the beamformers in frequency spectrum bands centered at 26–32, 36–39, 50 and 60 GHz as these are frequencies currently allocated for 5G wireless [13]. The pressing need is to find beamforming architectures at these frequencies that are capable of meeting the high data rate and latency demands of the communication industry. The launch of mmWave 5G is expected soon and further technological migration from 5G to 6G will increase the requirement of high-efficiency beamforming system even more than at present [14].

Beamformer requirements and development challenges vary as we move from one communication system to another one. Due to this reason we will classify the types of beamformer based on system, operation and use cases in the following sections of the chapter. We will then discuss some state-of-the-art beamformer solutions as well as technical challenges that are yet to be solved.

10.2 Beamformer type classification

10.2.1 Classification based on architecture

10.2.1.1 Analog beamformer

Analog beamformer architectures generally consist of a matrix of fixed phase shifters. Conceptually, just by controlling phase of each transmitted signal from each antenna, we can form a beam in a particular direction. Analog beamformers normally contain radio-frequency (RF) switching matrices after the bank of phase shifters in order to facilitate the beam steering and to connect the required beams to a specific signal path. Some analog beamformers show capability of continuously scanning a radiated beam within a given sector (e.g., [15]). Analog beamformers can place nulls along interferences direction in order to cancel unwanted user

Figure 10.2 Analog beamformer when high beamforming gain is directed toward the desired signal and nulls are placed toward the direction of interfering or undesired signals. LNA, low-noise amplifier; PA, power amplifier

interference in real time. This concept is illustrated in Figure 10.2. Such a capability is required in almost every future multiuser communication standard where simultaneous signal is received by an antenna array from multiple users located along multiple directions.

10.2.1.2 Digital beamformer

In a digital beamformer, the radiated beam patterns of an array are constructed by processing the signal in the desired direction and cancelling the beams from interfering directions, all within the digital domain. This is generally accompanied using finite impulse response filters [1] that have the benefit of managing the weights of each antenna element adaptively. By optimizing the weights, theoretically perfect beamforming can be achieved with perfect nulls placed in the direction of interfering signal. There are several advantages of digital beamforming in large antenna array systems. These include high-resolution DOA estimation, high spectral efficiency, high system security and enhanced energy efficiency [16].

Beamforming is directly linked with the improvement of signal quality at the receiver end. When this attribute is coupled with high energy efficiency, the digital beamforming method can use the standards of massive MIMO technology to enhance spectral efficiency [17]. To elaborate on this, in a standard beamforming synthesis for massive MIMO, the power radiated by a single-antenna element is limited, which leads to energy efficiency [18,19]. Since massive MIMO technology can use digital beamforming, optimization of power consumption is possible through manipulation of the usage of number of antennas based on a specific criterion. For example, in a base station, the overall throughput of a MIMO system is optimized by utilizing the minimum number of radiating antennas and this is only possible by using the principles of weight management of antennas in digital domain [20]. The optimization goals are selected as per the required power control

for a particular use case for example, at the mmWave base station in [21], analog phase shifters do not have a high resolution, so digital beamforming (pre-coding) is added. Digital beamforming works well at sub-6-GHz frequency spectrum and fully functional prototypes are already available, for example, see [22].

10.2.1.3 Hybrid or analog/digital beamformers

As discussed previously, analog beamforming is easy to implement using advancements in well-known phased array topology; however, the quality of interference cancellation is not as good as with a digital beamformer. However, to connect each antenna element to a digital domain requires complex hardware set-ups. These motivations lead to the introduction of a topology of a beamformer that attempts to yield the benefits of both digital and analog beamforming. Such a beamformer is classified as an analog/digital or hybrid beamformer [23,24]. The benefit of this topology is that digital beamforming methods generate digital signals that are good enough to allow good-quality DOA estimation, while the analog beamforming method enables a lower number of RF chains required to beamform. This eventually makes it possible, in principle, to develop a cost-effective hardware of the overall system. The analog parts of the beamformer include digital-to-analog conversion and power amplification on transmit and low-noise amplification on receive. Hybrid beamforming is usable not only at sub-6 GHz but also in the mmWave spectrum. It has been shown that in mmWave hybrid systems, with a given number of RF chains and analog-to-digital-converters (ADCs), the performance of a hybrid beamformer can bring closer to a purely digital beamformer with large number of RF chains [20]. This is done by inducing symbol multiplexing and comparatively smaller number of RF chains. In contrast to this, an increase in the number of RF chains and ADCs can improve the obtainable spectral efficiency [25,26]. This provides an attractive trade-off for communication hardware design engineers such that they can select the number of RF chains and radiating antennas as per cost cap and spectral efficiency requirements. Figure 10.3 shows a beamformer that can be purely analog or hybrid depending upon the number of antennas (N_{ant}) and the number of RF chains (L).

Figure 10.3 Phase-shifter-based analog or hybrid beamformer architecture. Hybrid beamforming when $N_{ant} > L$

A standard digital or hybrid beamformer relies on a weighting technique in which every antenna element's signal is independently multiplied by a weighting factor. This is done because when signal from one antenna is scaled compared to other antennas in an array, it can create a beamforming gain. Antenna weighting is difficult to manage accurately at mmWave and is generally done by programmable amplifier blocks that are located before the down conversion chain in the uplink. One such amplifier example is presented in [27] operating from 25 to 30 GHz and implemented on 64-nm CMOS (see Figure 10.4).

At the RF side, hybrid beamformers utilize analog beamforming hardware; however, it is a challenging task to select the optimum number of RF chains, switches, etc. for a given application scenario. In the current literature, this is decided by first analyzing hybrid beamforming as an optimization problem with a realistic formulation solvable in digital domain, e.g., as a minimum mean square problem. Techniques like [29] are then used to solve this problem, and as a result beam selection is assigned on the basis of the ratio between the number of users and the number of antenna elements required to serve the maximum number of users prescribed for a given scenario. Spectral efficiency in this case is reliant on the number of antennas, number of active RF chains, energy consumption and cell coverage area. The formulation of this kind is solved to find a “green point” that can be described as the maxima in the energy efficiency versus spectral efficiency

Figure 10.4 Die photograph of 25–30 GHz fully connected hybrid beamforming receiver [27]

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graph. This approach is applicable for almost all hybrid beamformers and theoretically for any frequency [30]. Although accurate trade-offs between efficiency and energy consumption can be obtained, the solution does not consider the hardware-related challenges especially at mmWave spectrum where hardware impairments can be significant and should not be ignored [31,32].

Channel estimation using hybrid beamforming is also a challenging task, thanks to the amalgamation of digital and analog beamforming that delivers mixed signals to the DSP unit. Especially in mmWave systems, link availability and reliability are normally impaired due unfavorable propagation characteristics that can have a bad impact on the network service continuity. There is a requirement to identify the best beam pairs, and to do so, reference signal transmission schemes are required. Reference signals can serve several purposes, including beam alignment, channel state information exchange and initial access. Note that the purpose of reference signaling in mmWave channels is same as that of a cell-specific reference signal in Third-Generation Partnership Project (3GPP) LTE systems [33].

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At sub-6-GHz spectrum, there is literature that shows that the reference signaling method can be used with hybrid beamformers for channel estimation, e.g., [35]. This method utilizes stochastic geometry; however, it is still not fully mature for use with mmWave hybrid beamformers. However, measurement campaigns in recent years are moving this line of research forward. One example is given in [36] where a reference signal is transmitted using highly directional antenna beamformers. The technique claimed to enable efficiency referencing in terms of angular coverage and yield the trade-off between channel information overheads and measurement accuracy. In a real-application scenario, this technique was used with a 28-GHz prototype depicting a high data rate in the downlink [37]. As per the description in [36], beam handover and switching at the base station end is simplified due to the directional nature of mmWave signals. Also, in addition to mitigating path loss, high-directivity reference signaling in mmWave beamforming can provide an assist with scattered signals such that the non-line-of-sight links can also be leveraged. An example of a high-directivity practical beamformer at 28 GHz, which provides high accuracy and precise phase shifting is given in [28] (see Figure 10.5(a)). While an evaluation study on a beamforming (receiver) array is shown in Figure 10.5(b) with digital baseband processing given in [34] wherein accurate phase shifting in a large-scale array is evaluated (Figure 10.6). Both systems in [28,34] are implementable with reference signaling [36] for mmWave channel estimation.

10.2.1.4 Lens-based hybrid beamformers

Most hybrid and analog beamforming strategies require a bank of phase shifters, power dividers and switches that are challenging to manufacture, especially in the mmWave spectrum. Lens structures are a plausible alternative since they inherently and simultaneously perform similar functions of power dividing, combining, phase shifting and even beam selection inside the lens structure.

A general architecture of lens-based beamformer is shown in Figure 10.7. There are a number of lens-based beamforming topologies and a comparative

Figure 10.5 (a) Photograph of sub-array phase-shifting network and (b) Photograph of front-end circuits in one phased sub-array hybrid analog and digital beamforming transceiver system [28]

analysis is given in [38]. Lens-based beamformers rely on the lens-focusing property that is analogous to that of optical lenses. In spherical or semispherical optical lenses, an incoming beam of rays parallel to the lens's principal axis focuses at the so-called focal point [39]. In microwave and mmWave lens structures, a radiator placed at the focal point can create an outgoing electromagnetic signal traveling parallel to the principal axis. Theoretically, all sets of rays coming from infinity have an image at the focal point; however, practical lens structures have physical limitations. These limitations cause lens imperfections that end up creating spherical aberration, coma, chromatic aberration and astigmatism [40]. Regardless of the type of lens and the synthesis approach used in development, lens-based

Figure 10.6 Left-side hardware is a full field-of-view autonomous hybrid beamformer array chip and its scalability for phased array. The results in the right side demonstrate the blocker rejection and desired signal beamforming when both signals are broadband modulated at the same speed and scheme. Further information can be found in [34]

Figure 10.7 Lens-based beamformer architecture when power dividing/combining, and phase shifting happens at the lens structure

beamformers are found to work well in the mmWave spectrum range when deployed for massive antenna array operation at the radio front end [39]. According to the study and conclusion in [41], a lens-based beamformer simplifies the signal processing effectively by exploiting the mmWave channel's angular sparsity [42].

This is extremely important in order to achieve high data rates with low latency required in “mmWave 5G and beyond” communication standards.

The most well-known lens-based beamformer operating in the microwave range was reported in 1964 and is known as Luneburg lens [43]. Since then, researchers worked on many lens variations, but the principle is the same as that of an antenna array beamformer, i.e., focus the radiated electromagnetic energy in one direction and reduce its leakage in directions where the signal is not required. Recently using transformation optics [43], researchers have formulated the lens refractive index grading in such a way that the grading principle enables the focusing of energy at the focal point. An example is a slab-based lens having properties of beamforming in azimuth direction given in [44]. A similar principle is shown in [45] where parallel plate spacing is varied along lens radius to achieve focusing. Another example is the conversion of 3D lens to 2D plane and achieving beamforming along azimuthal plane [46]. Transformation optics theory has been used to first test the lens focusing capabilities and then for its utility for sub-6 GHz and also for mmWave beamforming [38]. Antenna theory suggests that lens-based beamformers need to be electrically large to be able to ensure high-directivity beamforming so they are not preferred at low frequencies where wavelength is long.

However, since the lens size shrinks as we move higher along the frequency range, thanks to shorter wavelengths, lens-based beamformers work very well at mmWaves where size is no longer a core limitation. For example, a multilayer planar lens using metamaterial principles that use a planar substrate integrated waveguide (SIW) for specialized beamforming [47] has a practical size. Focusing capacity can also be achieved by arranging small-sized single unit cells in a lattice and replicating it along a body of lens. 3D monolithic periodic structures having low loss and uniform dielectric constant are shown to work well [48]. Nonperiodic drilling of holes changes the dielectric property of lens, and if controlled properly, this method has also been shown to work for lens-based beamformers [49]. Also, some classes of metasurface use subwavelength resonators (examples are given in Figure 10.8), and deployment of them over the lens profile can result in focused energy [50].

A special lens-based beamformer replicates the principle of phase shifters by using easy-to-develop Rotman lenses. The manufacturing cost of this type of lens-based beamformers is low, thanks to advancements in PCB development techniques and photolithography. For example, an SIW-based Rotman lens beamformer showing seven-beam selection capability was described in [51]. A more detailed investigation of a Rotman lens beamformer and its applicability in beamforming systems was given in [52], which showed that optimal beam selection can be done using this class of beamformer. Also, digital beamforming can further enhance interference reduction when deployed in conjunction with Rotman-lens-based beamformers [51]. A recent study has shown that a Rotman-lens-based beamformer with digital processing principles can work together to scan not only azimuth but also the elevation plane beamforming [42]. One example of Rotman-lens-based beamformer at higher frequencies is given in [53] where a 60-GHz module with

Figure 10.8 Multiple metasurfaces, sub-wavelength periodic and spiral structure modulating the required surface impedance to assist in beamforming [50]

Figure 10.9 Photographs of the beam switching Rotman-lens-based beamformer with front and back view when back view has 4×8 antenna array [53]

integrated amplifier is shown to perform beamforming along the elevation and azimuth plane (see Figure 10.9).

Polarization control in lens-based beamformers is a challenging task since lens-based beamformers rely on geometrical positioning of feed antenna that

normally supports only single polarization. Also, the frequency agility, multiband and multi-beam operation and signal amplification due to lens losses are some of the development challenges that need new innovative solutions. High complexity and sophisticated design approaches like the one in [54] have attempted to solve some of these challenges. The problem is that as we move from simple to complex development methods to achieve reliable beamforming, cost increases and may become even higher than those incurred when using standard antenna array analog beamforming methods.

10.2.2 *Classification based on frequency*

The second beamformer classification from an application point of view is based on the frequency of operation. In the previous section, we briefly touched on this classification also, but since the widely used MIMO and massive MIMO deployed systems are associated with both the sub-6-GHz and mmWave frequencies, it is important to highlight their differentiating characteristics with respect to beamformer development challenges. Sub-6-GHz frequencies are used for good network coverage since path loss is comparatively low. Also, the network coherence time is favorable at sub-6-GHz frequencies. The coherence time of the network is defined by an approximate time where the channel response is invariant [55]. It is defined by

$$T_0 \approx \frac{1}{f_d} \quad (10.6)$$

where f_d is the maximum Doppler frequency so we can say that there is an inverse relationship between the carrier frequency and the coherence time. In dense radio environments where the number of users is high, massive antenna arrays can, in principle, increase overall system efficiency by increasing the number of antennas [56]. Hence, already deployed base station infrastructure can often be uprated to implement sub-6-GHz massive antenna arrays. On the other hand, the efficiency of system at mmWave frequencies is increased by large available bandwidth but will only provide a shorter coverage area. The addition of large number of antennas in an array will add the beamformer gain, consequently helping the link budget as we discussed in the previous section. The major limiting factor for mmWave beamforming is noise power that is directly proportional to bandwidth so there is always a cap on the highest usable bandwidth at mmWave where more percentage bandwidth is available, which is not the case for sub-6-GHz usage. The following subsections will further detail the differences between sub-6-GHz and mmWave beamformers.

10.2.2.1 **Beamformers at sub-6 GHz**

Earlier investigations on massive MIMO were focused primarily sub-6-GHz frequencies and today, researchers associate the term massive MIMO technology largely only with the sub-6-GHz range. It is now well established that to achieve maximum theoretically achievable massive MIMO performance, digital

beamforming is the preferred way forward for sub-6 GHz [57]. As mentioned previously, this requires each antenna element to be independently connected to the digital processing unit. The hardware required to support both digital and analog beamforming has advanced enough to handle such systems at sub-6 GHz. Here is an example in which hardware requirements for sub-6-GHz beamformers change as we move from digital to analog beamforming. Consider a 16-element antenna array performing digital beamforming at the receiver end. This requires each of the 16 element's received signal to have the capability to pass through a dedicated RF transmission line, and an ADC. Sixteen digital signal streams will then go into the DSP unit. Each signal stream will then be digitally added with a defined scaling factor or phase shift to get a resultant signal from the formed beam. In contrast to this, standard analog beamformers will require a scaling and phase shifting in the analog (RF) domain which will be done by 16 weighted phase shifters to get a resultant signal. Hence, the 16-element antenna array will require only a single ADC to convert this signal to digital data stream entering the DSP.

Since the mobility and number of users within a cell are high at sub-6 GHz, digital beamforming supports this operational scenario. Digital beamforming provides the necessary spatial multiplexing that can in turn enhance the spectral efficiency of the communication link. This multiplexing also compensates the low-bandwidth availability while keeping spectral efficiency as high as possible. Sub-6-GHz channels are rich in multipaths [6], which is another reason why multi-beam excitation in digital domain is preferred over the analog beamforming. Data rate in most propagation scenarios within the sub-6-GHz spectrum should be around 100 Mbits/s/user with reasonably uniform quality of service in a band of 40 MHz [6].

10.2.2.2 Beamformers at mmWave

The mobility at mmWave is also considered low and the number of users per cell is generally less compared to the number of users operating in sub-6-GHz cells [6]. It is generally recommended to have beamforming gain particularly for a signal or a small number of users so a portion of complexity of special multiplexing is moved to the analog domain suggesting the applicability of hybrid beamforming in the mmWave spectrum.

In recent years, measurement campaigns involving the mmWave beamforming reveal interesting information, i.e., the number of multipath required to serve users in mmWave cells is few [35]. Also, the multipath components are generally clustered in spatially independent sectors and a few beams radiating from the antenna array should be enough to serve a single user at a given time. Due to these reasons, in addition to large available bandwidth and a low number of users per cell, the spectral efficiency achieved by a mmWave beamformer is generally low [58].

Channel information is always important and becomes more difficult when fewer RF chains are used. Therefore techniques like power iterative adaptation [59] can be deployed, which when added to the benefit of mmWave sparsity allows channel estimation just by a few measurements. The disadvantage of this technique is the codebook burden that requires signaling and reconfiguration in every coherence time. As soon as the channel information is known to a beamformer, the

sectoral mapping of the scatterers and receivers within a cell coverage area can further be optimized. This way, the known information will aid in increasing per user SNR values and interference signal. Load on the codebook is generally reduced by further micromanaging the mmWave channel into smaller clusters. An example of a user selection algorithm that is usable for multiuser cellular systems is reported in [60]. Additional difficulty is that by sub-clustering the channel, signal-to-noise-and-interference ratio will also start playing a role. Studies like [61] have tried to address this issue in which intercluster interferences are shared across all the clusters and algorithms manage the cluster allocation for a particular user dynamically. Further to this, algorithm 4 presented in [61] uses beam channel selection in multi-clusters in an attempt to reduce the complexity of channel estimation, and eventually the load on codebook. Another method of decreasing the codebook complexity of mmWave hybrid beamformer system is by using open-loop channel estimation given in [62] where decomposition of the clusters is defined using low-rank optimization problem. The channel estimation achieved using this method is suboptimal; however, it is stationary and usable for signal processing (refer to [62]). The technique is helpful at low SNR values compared to open-loop estimation techniques.

A summary here is that mmWave beamforming is not suitable for low data rate applications due to high network overheads, and mobility support in mmWave channels is also extremely challenging. Moreover, unlike sub-6-GHz beamforming that enjoys the spatial multiplexing of many users, mmWave beamforming can support high user density only when specialized forms of hybrid beamforming architectures are used.

10.2.3 *Classification based on the use case*

The overall purpose of beamforming is almost the same for all communication-related technologies; however, specific beamformer purpose varies from application to application. For instance, consider future mmWave 5G communication access points that can either be small-cell base stations, indoor wireless nodes or hotspots. The required beamformer in this case should be able to serve a small number of users within a limited area so a high-gain multi-beam operation is desirable [39]. Conversely, an outdoor base station operating at sub-6-GHz 5G should be able to serve multiple users; here, a limited number of beams with high half-power beamwidth should suffice [63]. A beamformer that is a part of handheld mobile device (also referred to as “mobile user,” and “user equipment” or simply “user” in literature) practically has a limited battery power. Since mmWave signal path loss is high, the beamformer gain should be enough to compensate for this path loss so that the transmitted signal from the handheld device is received by the mmWave beamformer with an acceptable SNR.

10.2.3.1 **Fixed beamformers**

A beamformer that is not a subject to mobility in a communication system can be classified as a fixed beamformer. Any classification of architecture described in

Section 10.2.1 can be used as a fixed beamformer to serve either single or multiple users. The type of antenna array to be used at the front end of a fixed beamformer purely depends upon the application and the frequency of operation. For low-frequency (sub-6 GHz) operations, generally a low number of antennas are enough to provide the service, so an easily realizable RF architecture should suffice. As we move higher in the frequencies, fixed beamformer architectures tend to demand an increased number of antennas, which consequently increase the complexity of the RF front end. Depending upon the application, in addition to beamformer gain, sometimes diversity gains like polarization and spatial are also required. There have always been concerns regarding the use of mmWave spectrum for fixed beamformers in a multiuser or a cellular communication system. According to the Friis transmission equation [64]:

$$P_r = P_t + G_t + G_r + 20 \log \left(\frac{c}{4\pi f \times r} \right) \quad (10.7)$$

where P_r is the received power in dB m, P_t is the transmitted power, G_t and G_r are the transmitter and receiver antenna gains and r is the distance between the point of received power P_r and the radiating antenna.

The received power at r is inversely proportional to the frequency of operation squared, when an ideal isotropic radiator is considered, i.e., $G_t = 1$. At mmWave, antennas with G_t and G_r much greater than unity are typically used and the antenna gains are proportional to the square of the frequency of operation when a given aperture is to be used for the radiation. This allows the beamformer to yield gain to the antennas operating at mmWaves. To substantiate this, measurement campaigns are discussed in [65] in which same aperture area is used to host an antenna operating at 3 GHz and an antenna array operating at 30 GHz. In the experiment, a single microstrip patch antenna is used at 3 GHz while an array of patch antennas is designed on the same substrate size that was used to host a 3-GHz patch antenna.

Both antennas were placed in anechoic chamber such that the Friis transmission equation and the aforementioned argument can be verified. The experiment verified same amount of propagation loss regardless of the operating frequency when same physical aperture is used to host 3- and 30-GHz antennas. In addition to this, when a 30-GHz array antenna is used at both ends of the communication link, (consequently increasing the G_t and G_r), the measured received power was 20 dB higher than was achieved at 3 GHz. Other than these controlled measurement campaigns, outdoor measurements like the ones presented in [66,67] verify the applicability of mmWave frequency bands in fixed outdoor and indoor beamformers. The following two challenges still exist when it comes to development and deployment of such beamformers:

1. mmWave radio signals have propagation characteristics such as high penetration loss, foliage losses and losses due to precipitation. Although free-space path loss can be compensated by adding the beamformer gain at the fixed beamformer end, the channel characteristics and losses are uncontrollable.

2. Single-antenna radios are simple to design; however, for multiple antenna beamformers, when the number of antennas should be high enough to cover a comparatively large aperture area, the feed network and associated RF electronics require high precision. This can increase cost.

Consider again the example given in Figure 10.10. Although it has been shown that the beamformer gain is practically viable for a communication system implementation at mmWave spectrum, the beamforming array development all the way from antennas to the digital signal processing unit is again complex. Research efforts are focused on ways to reduce the cost and complexity of entire mmWave beamformer implementation. Classical phased arrays like the ones presented in [68] are one of the most commonly used antenna feed networks in fixed beamformers. A high-gain 16-element beamformer created using stacked patch antenna is given in [69]. This beamformer operates in 24.35–31.23 GHz band with a gain of 18.7 dB i. In addition to this, Butler matrix [70], Rotman-lens-based [42] and SIW-based feed network like the ones presented in [71] are commonly used fixed beamformer feed networks.

A frequency-selective surface (FSS) capable of assisting in beam tilt for a fixed beamformer with the frequency of operation 28–31 GHz is given in [72]. Generally, such FSS structures are scalable and higher frequency operation can also be achieved using the proof-of-concept module given in [72]. A positive–intrinsic–negative (p–i–n) diode-based beam switching system operating at 28 GHz is elaborated in [73] that can be used as a fixed beamformer. The maximum beam tilt achieved is shown to be around 45°. Similar to this, another fixed beamformer for the operation at 28-, 38- and 48-GHz 5G bands is discussed in [74]. An octagonal prism-like configuration of this array has been shown to achieve a radiation

Figure 10.10 Verification of propagation losses using Friis equation and antenna apertures at 3 and 30 GHz [65]

efficiency of around 82%. This antenna array is specifically designed for 5G cellular base station. The antenna array gains in this system are around 7.8, 8.3 and 7.7 dB i at the centers of the three operating frequency bands.

Another subclassification of fixed beamformer is based on the ability of a beamformer to scan along either one or two planes. Fixed beamformers that are only capable of beam scanning along one plane generally use uniform linear arrays with phase shifters connected to each antenna. The illustrations in Figures 10.3 and 10.7 show uniform linear arrays in which beam can only scan along either horizontal or vertical planes. Also, the practical beamformer example given in [53] is capable of beam scanning along one plane. The drawback of single plane beamformer is that in a multipath channel, a significant amount of diversity information is lost since the fixed beamformer is operating along a single plane only. This is mitigated by using a fixed beamformer that utilizes multiple layers of uniform linear arrays forming a rectangular antenna array with a bank of phase-shifting network that can help in scanning two planes. This classification of beamformer is referred to as “full dimensional” in communication and multiple antenna system-related literature. The most important benefit of using full-dimensional fixed beamformers is when advanced beamforming technologies are used to eliminate interference. An example that compares the use of a uniform linear array and uniform rectangular array as a fixed beamformer is given in [42]. The end-of-end spectral efficiency of a fixed beamformer listening along two planes is shown to be better in terms of end-to-end spectral efficiency compared to the fixed beamformer listening to only along a single plane at uplink scenario. This is because by beam scanning along two planes, nonuniformly distributed users can be served using higher resolution. An example of full-dimensional precoding that yields the benefits of multiple antenna system is provided in [75]. This work also shows a two-layer phase shifter feed network architecture for mmWave use.

A significant amount of work is required to develop the mmWave RF hardware design required to facilitate complex fixed systems like full-dimensional beamformers and multilayer phase shifters. A pattern diversity fixed beamformer for cellular base station was discussed in [76] in which an antenna aperture was engineered for operation in the 27–30 GHz band and two fixed beams. The measured gain ranges from 7 to 8 dB i, while the mutual coupling is shown to be better than -18 dB at the center of the band of operation. Dual-polarization capability was added into beamformer by using zero-index metamaterial. By doing so, multiple-beam equalization is achieved. The end-fire antenna gain of polarization orthogonal ports was reported to stay between 9.2 and 9.6 dB i. Another way of beamforming in the fixed antenna array case is by using electromagnetic-bandgap-(EBG) backed structures. One example is provided in [77] where an EBG-backed structure is operating from 26 to 32 GHz. An example of a fixed beamformer that can be mounted onto a ceiling and is designed using tapered slot antennas is given in [78]. The antenna unit cell uses dielectric loading principle with metamaterial and tapered slot operates at the same frequency bands. The aperture and antenna efficiencies are shown to be 73%. This beamformer operates from 27 to 29.8 GHz. The beamformer radiations have pattern integrity and a gain of 9 dB i. The study shows

an addition calibration after computing the path loss and updated version has beam-scanning capability of 45° with a higher gain of 12 dB i. A stacking topology is shown in [77] that uses the principles of artificial magnetic conductor and helps in the pattern diversity and antenna gain of 11.9 dB i. A planar Yagi–Uda antenna uses two parallel T-junctions form parallel antenna feeding resulting in circular polarization.

In recent years, photonic beamforming has also drawn significant attention especially for mmWave 5G transceivers. The main concept behind photonic beamforming is the use optical fiber for beamformer functions like beam scanning and beam switching. A wavelength-division multiplexing system is shown in [40] in which signals corresponding to multiple beams are routed within a multiantenna system. An RF signal of 15 GHz is utilized as a carrier frequency and a high-order modulation scheme is formulated. A similar system is shown in [79] where the wavelength of the operating frequency modifies the coupling coefficient of optical ring resonators and consequently multi-beam operation from 17.6 and 26 GHz is realized. A multicore fiber is used to feed multiple antennas with 128-QAM (quadrature amplitude modulation) signal using around 4 GHz of operational bandwidth and is shown to demonstrate experimentally as an mmWave beam-forming system. Beam steering is controlled by a central computer and fast steering is done by changing the wavelengths of the optical lasers and beam steering is shown to be 11.3° – 23° (at 26 GHz the beam steering is 23°). The experiments are done for 5G NR standards in Europe. The beamformer can provide around 16 GB/s per user. Another study shows the use of phase shifter and Mach–Zehnder interferometer in the antenna array [80] capable of being used in fixed beamformer setups. This work shows that it is possible to successfully translate optical phase shifts to mmWave phase shift (at 28.5 GHz) using an amplitude-modulated optical signal.

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Lens-based architectures as discussed in Section 10.2.1.4 are also viable for fixed beamformers. RF energy focusing structures linking Luneburg, spherical, semispherical, gradient dielectric, constant dielectric and Rotman lenses are gaining a lot of attention as fixed beamformers, especially in mmWave spectrum. Primarily due to their focusing capability and ease in manufacturing, they are sometimes preferred over phased-array-based beamformers [39,81–83]. A simple 3D-printed Luneburg lens [82] has been shown to have a gain value of 21.2 dB i. The lens structure is built using rods that have gradient index and realized the required permittivity distribution as per Luneburg principle. The radiation efficiency of the lens is shown to be 75%. A magnetoelectric dipole antenna is used as a feeder of the lens structure, which can cover around 40% bandwidth at Ka-band. When different feeding points are excited on the same lens structure, measured mutual coupling as low as -17 dB is achievable. The lens is capable of beam scanning along $\pm 61^\circ$ making it a good candidate for fixed beamformer application. Another example shows a different approach in which designing of a single-polarization Fresnel-zone plate lens antenna is discussed [84]. The operational band of the lens feed is 57–64 GHz. Antenna has characteristics, including trans-reflection and twist-reflection. By carefully yielding the benefits of these

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characteristics, the antenna is shown to have a maximum gain of around 32 dB i. Similar circular, semicircular and elliptical lens structures require multiple feeding points to be able to host multiple beams simultaneously. This requires multi-feed excitors like waveguide-based horn antennas [39], groove gap waveguides [85,86] and dipoles [82]. A specialized form of similar feed uses leaky-wave antenna operating at 21.9–23.9 GHz band. The feed structure comprises a metallic strip that has a grating structure and the end of this strip can be placed at the focal point of a lens-based beamformer [87].

In addition to 3D lens structures that require antenna feeds, Rotman and Fourier lenses are classified as 2D lenses in which the lens operation, or RF energy focusing action, happens in transmission-line domain [42]. Such lenses perform same operation of superimposing the radio signal in a transmission as it happens in a Butler matrix [70]. Recent example of a flexible Rotman lens that can be used for mmWave fixed beamformer application is shown in [83]. The passive lens structure can generate multiple beams at 28 GHz and a switching network performs the beam selection. Rotman and Fourier lenses typically have a very wide bandwidth; however, low coupling between multiple beams can be achieved at narrow bands [88]. A Rotman lens beamformer in [81] has a bandwidth from 26 to 40 GHz. The beam-scanning range in this beamformer is $\pm 39.5^\circ$ so it is usable in fixed beamforming scenarios. In [83], the Rotman is shown to have a bandwidth of 18–38 GHz. Another Rotman lens example at high frequencies is in [89] in which the lens operating frequency is from 25 to 31 GHz while generating seven beams.

It is expected that fixed beamformer operation may move to even higher frequencies post the successful implementation and deployment of 28 and 38 GHz 5G bands. Researchers have already pushed forward their efforts to facilitate these advancements. An example of parallel fed slot antenna beamformer is shown in [90], which has inherent mechanism of beam selection and uses low-temperature cofired ceramic technology for the array structure development. The operation band of this 11 beam beamformer is from 57 to 66 GHz, and experiments have verified high-accuracy beam scanning from -39° to $+39^\circ$. Another example of higher frequency beamformer is [84] operating at 60-GHz band. In another work, a novel approach of modeling and measuring channel characteristics using synthetic beamwidth at a fixed transceiver end is given [91]. This work is specific for indoor 60-GHz fixed beamformer.

Other than performing the beamforming to serve users, it is vital for practical fixed beamformers to understand and know the characteristics of the channel it is operating in. For this purpose, state-of-the-art algorithms and protocols are required [92]. As mentioned in previous sections, the classical channel models for sub-6 GHz may not be adequate for mmWave channels, so a new line of research has emerged in which novel methods are used at the fixed beamformer end for channel sounding and user location [92,93]. The channel information and user location are very important for successful beam alignment in order to yield the best data throughout. Localization algorithms designed for mmWave fixed beamformers should have fast initiation, and their runtime phase should be as short as possible [92].

Localization protocols, e.g., in [94], utilize in-band aiding in a standard mmWave geometric channel model. This protocol is shown to work well but imposes extra burden on the system. A new approach of user localization has shown to use the global positioning system (GPS) location data in conjugation to the protocols running purely at mmWaves for localization accuracy [75]. This approach simplifies localization problem by first reducing the size of beam numbers in beam training step by eliminating those beams that are not directly involved in user service. This helps reduce beam training overheads. In the next step, the protocol finds the beam that provides the best coverage, reliability and fastest link to the user. Further details about this protocol can be found in [75]. Another similar work shows an approach of radio-environment mapping of the wireless network, which helps in identifying the location of users, blockers and scatterers [95]. It is argued that even with successful radio-environment mapping, the likelihood of accurate localization is low. This is because of the requirement of processing of a likelihood function designed to find an unknown channel parameter vector can have many local maxima, making it difficult to find an optimum global solution. To achieve the required accuracy, a filter-based estimator at the fixed beamformer is proposed in this study [95].

Some of the channel estimation and user localization schemes that work well in low-density environments may not operate well for practical mmWave fixed beamformers. One way around this problem is increasing the number of fixed beamformers in an environment where the number of obstacles and users is high. In this way, the likelihood of hindrance between fixed beamformer and users can be decreased. There are two challenges associated with this approach:

1. Increasing the density of fixed beamformer or base stations for mmWave 5G cellular will increase network deployment cost.
2. The requirement of additional training overheads may overload the network.

One method as proposed in [96] tried to overcome these by introducing scalability into the high-density environment. It was shown that adaptive capabilities can be added into the localization protocol that can assist in functions like immediate reaction to changes in a channel and finding secondary propagation path for a blocked beam link. Also, the approach suggested the utilization of information of user location from out-of-band frequency applications such as GPS (like the ones presented in [75]) is also possible. This approach is scalable and is user-driven; hence, it scales well as the number of users increases in a dense environment. In addition to this, it is reported that any sensor information from a user mobile device is usable for localization purposes. The useful sensors in mobile device include all sensors that can share data with physical and MAC layers of the communication protocol running within the mobile device [96]. Although this approach is shown to improve the reliability of the mmWave communication standards, it slows down the beamformer functionality and reduces the capacity predictions that a theoretical mmWave antenna array system provides.

In summary, the out-of-band applications for the localization application in mmWave fixed beamformer have following advantages.

1. Network overheads required for operations like beam link training, handovers, load balancing and device tracking can be reduced.
2. Location-aided services can be included into the network without overloading the fixed beamformer hardware.

10.2.3.2 Variable beamwidth fixed beamformer

In an mmWave communication link, beamformer beamwidth has a vital role to play. Consider now a sequence of events that can explain the importance of beamwidth. Imagine a fixed beamformer mounted at the base station of an mmWave communication cell sector. The beamformer can generate high-directivity beams, sharp enough to serve users after mitigating the path loss and after surpassing multiple scatterings. Fixed beamformer theory associated to the large mmWave antenna array systems suggests that the first stage of mmWave network requires a beam training session during which fixed beamformer transmits the information that is received by a mobile terminal. The mobile terminal responses back with the information that contains the index of the best reception beam among all candidate beams. After receiving this information from all mobile users, the base station pairs beams with the corresponding users for the data transmission. During this procedure, mobility within the channel can be a deal breaker and every update in channel will require new beam pairing. This entire process requires a large network training overhead, and since training events require the same bandwidth allocated for signal transmission, these will reduce the achievable spectral efficiency in an mmWave channel. One way is to widen the beamwidth at the fixed beamformer end and serving a set of mobile users with the same beam rather than with individual beams serving individual users. This method can increase the spectral efficiency by reducing the training overhead. It can also add some relaxation in network state in terms of mobility. An example of a non-orthogonal multiple access system that can aid in enabling multiple mobile user service using same beam of a fixed beamformer is given in [97].

The trade-off between the beamwidth and network overheads depends upon the required number of service beams, cell size, number of mobile users, network mobility and coherence time. RF planning and engineering is required for specific use cases, area of coverage as well as the operational mmWave frequency band. One example that illustrates the aforementioned trade-off is given in [98] in which, 28- and 38-GHz fixed beamforming and planning is experimentally performed for an urban environment. It is shown that beamwidth compromise can be more useful when the feasibility study of propagation loss in mmWave 5G communication system is done beforehand. After this quantification, beam number and beamwidth figures can be optimized until the time-targeted spectral efficiency is achieved. In this study, the importance of beam misalignment due to beamwidth reduction and its impact on the power loss is also shown. It is also shown that the signal bandwidth of around 1 GHz is required for fixed beamformer to be able to match the theoretical capacity [99].

The beamwidth of the radiating mmWave beamformer depends upon the coverage area and specific location of mobile users. For instance, consider a fixed

beamformer at base station serving in a dense urban environment. The number of mobile users required to be served on roads, streets, vehicles and shops will be higher as compared to the number of users in high-rise buildings. If the same beamformer with a universal fixed beamwidth is used to serve all mobile users, there will be wastage of spectral resources, which is expensive at mmWaves. Such challenging scenario requires fixed beamformer to be flexible in terms of beamwidth, and research efforts like [75] have shown a possible solution. In this study a variable (nonuniform) beamwidth full-dimensional beamforming system uses narrow beamwidth directive beams to serve high-density mobile user areas like streets and uses wider beamwidth beams to serve multiple mobile users in buildings, etc. Such a scenario is illustrated in Figure 10.11.

The study in [91] reveals interesting information about the beamwidth of a fixed beamformer. The signal delay spread, and the number of multipath components reduces with the reduction in beamwidth of a beamformer. It also experimentally shows that the reduction in beamwidth required to make the beams narrower can provide up to 20-dB improvement in gain, yielding a directionality benefit to the link budget at mmWave. It is importation to note that low beamwidth in a fixed array does not necessarily imply a high number of antenna elements with associated RF electronics. Using array synthesis techniques, including compressive sensing algorithms (like the ones presented in [11,100]), a considerably fewer number of antenna elements with predefined complex weights can be used to achieve a beamwidth in a sparse antenna array format that is comparable to the beamwidth achievable by a fully populated large antenna array.

10.2.3.3 Mobile beamformers

A beamformer that is mounted to a device that is mobile can be classified as a mobile beamformer. This includes all wireless devices that are not a fixed beamformer and require an inbuilt beamformers to establish communication.

Figure 10.11 Illustration of a full-dimensional nonuniform fixed beamformer at mmWave base station array serving users in a dense urban environment

A quasi-omnidirectional single-antenna transmitter/receiver is not considered as a mobile beamformer since it cannot yield a high-directivity beamforming gain. With this description, mmWave devices (like handheld phones, laptops, vehicles and wearable gadgets) that may contain antenna arrays or lens antennas capable of establishing single or multiple-beam-based communication with other beamformers can loosely be classified as mobile beamformers. The 3GPP has identified the spherical coverage area requirements for mmWave mobile beamformers that are based on the cumulative distribution function on the effective isotropic radiated power [101]. At sub-6-GHz frequency bands, antenna radiators with low directivity are enough to provide a complete 360° coverage, while this is not necessarily the case when it comes to mmWave mobile beamformers. The isotropic radiated power from a signal antenna at mmWave frequencies is typically not enough to establish reliable communication with other mobile beamformers or fixed beamformers, so beamformer gain is a requisite. According to [98], the directivity of beams generated by the mmWave beamformer can decrease the capturable number of multipath components, so there is always a trade-off between multipath resolution and free-space penetration when it comes to designing a reliable mobile beamformer.

In the mmWave spectrum, mobile beamformers are generally made reconfigurable in which the beam selection is controlled separately. In doing so, it is possible to select of the best beam covering suitable direction around the mobile beamformer for a reliable communication. In sub-6-GHz bands, a low number of antennas operating at the same frequency band are enough to provide the required coverage around handheld mobile devices. In mmWave frequencies, energy focusing and directive radiation are requirements due to several reasons discussed in previous section; hence, an antenna array is required. Sometimes, a single-antenna array can only cover a portion of 360° coverage area so more than one antenna arrays are required, placed at multiple locations on handheld device (Figure 10.12). An example of reconfigurable beam switching network is given in [102] where 16-element high-directivity antenna array having 1.5-GHz bandwidth is shown. The phase control network in this array is experimentally validated and as a result five beam states are achieved. In addition to this, beam splitting is also shown that can assist in realizing multipath signal reception. Another example of a phased array for 5G handset using 40-nm CMOS technology is shown in [103]. The proof-of-concept module operating from 27 to 30 GHz is developed with standard block-level specifications and the hardware performance is thoroughly investigated. A carrier-aggregated 64-QAM OFDM is tested on a 1P6M bulk CMOS-based prototype to verify the reliability of the communication link. Experiments show a noise figure of around 5.5–6.0 dB and a third-order intercept point of –6 to –8.5 dB.

Some of the recent works on mobile beamformers show applications of multi-stream transmission in which multiple frequencies are used for multiple data streams. This is done by multiband operation that uses cartesian-combining-based complex weighting factors. It is shown in [104] that with the image-rejection scheme, a heterodyne beamformer can be realized. Also, reconfigurability can also

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Figure 10.12 (a) Illustration of a handheld mobile device supporting multiple mmWave mobile beamforming arrays while trying to achieve complete 360° coverage. (b) Comparison of a low-directivity radiation requirement at sub-6 GHz bands with intermediate- and high-directivity requirement at mmWave frequencies

be added by which two bands of 28 and 37 GHz can be used. The technology used in receiver side is 65-nm CMOS. The conversion gains at the receiver end are shown to be 5.7 and 8.5 dB at 28 and 37 GHz.

It is now believed that large antenna array systems in conjugation with the digital beamformers are best suited for the sub-6-GHz frequency bands. This conclusion is yet to be further explored when it comes to mmWave spectrum. A lot of research is going on in finding the best beamformer architecture at mmWave spectrum, e.g., [21] where a fully digital 64-channel radio is shown to work at 28-GHz carrier frequency. Another fully digital beamforming scheme implemented on a software-defined radio is given in [105]. This work uses slot antennas with a bank of low-noise amplifiers connected to eight RF chains. This hardware has been shown to achieve a phase shifter resolution of around 0.72° . The in-band signal that has no utility in communication is utilized to correct the errors in phase and amplitudes, hence calibrating each RF chain. As a result, the amplitude and phase errors are confined to below 0.5 dB and 0.9° , respectively. At higher frequencies, a comparative study between hybrid and fully digital beamforming schemes is given in [20] wherein the 60-GHz band is discussed.

In mobile beamformers, phase errors can easily occur; this can happen because of placement of multiple mobile beamformers on the same handheld platform, tempting

undesirable mutual coupling (Figure 10.12(a)). An innovative beamforming technique is shown in [106] where frequency-modulated diverse array is shown. In such an array, small increments in frequency in a time-dependent signal can generate multiple beams without the necessity of phase shifter network. Handheld mobile devices with mmWave beamformers are likely to face energy leakages due to the presence of human body (hand, head, etc.). Some studies have suggested the confinement of electromagnetic energy within the structures like coplanar waveguides, dielectric slabs and plasmonic structures [107]. These methods are helpful in transmitting the energy from mmWave feeds to the antenna front ends and then to the required mobile direction; however, the signal quality becomes weaker because of the slow-wave propagations and spoof surface plasmon polarization effects. A novel approach is given in [108] by which bounded spoof surface modes are translated to radiation modes in mobile beamformer. A comparison with a horn antenna is shown in this study, which proves the proposed approach. Moreover, it is shown that a radiation efficiency of close to 90% and beamformer gain of 15 dB is achievable. Further to this, the applications of mobile beamformers for beyond 5G are presented in [109].

A detailed comparison of beamformer performance on multiple frequencies is given in [37]. The comparison is focused on 2.9, 29 and 61 GHz and several real-life scenarios are discussed, e.g., shopping center, indoor office and outdoor. The propagation losses because of the materials, buildings and walls are thoroughly investigated for each carrier frequency. This study is very helpful for beamformer gain understanding and about how the channel interacts with the signal radiated from a fixed or mobile beamformer operating at multiple carrier frequencies from 2.9 to 61 GHz.

10.3 Conclusion

In this chapter, we first discussed the definitions that are vital to understand the working of a beamformer. We then classified the beamformer based on the architecture, frequency of operation and a use case. These clarifications are done keeping in mind the future technological advancements in the communication industry. Beamformer architectures are further divided into purely analog, digital and hybrid types, when each one of them has a specific need in specialized communication standards. Frequency bands of operations are divided into the well-known 5G sub-bands that are sub-6-GHz and mmWave bands. We further discussed the ways in which a beamformer function differs when they are operating at different frequency bands. Lastly, we classified beamformers in terms of their utility as a fixed or mobile radio in a communication system. State-of-the-art beamformer examples are comparatively analyzed to better predict the most suitable choice for a given classification of beamformers in the 5G and beyond applications.

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Chapter 10

Beamformer development challenges for 5G and beyond

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