Advanced Antenna Array Engineering for 6G and Beyond Wireless Communications

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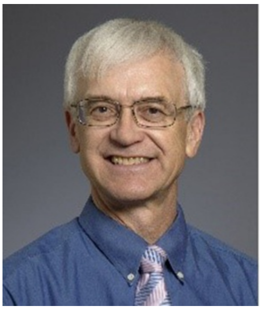
Author Biographies

Y. Jay Guo received a Bachelor Degree and a Master Degree from Xidian University in 1982 and 1984, respectively, and a PhD Degree from Xian Jiaotong University in 1987, all in China. His research interest includes antennas, mm-wave, and THz communications and sensing systems, and beyond 5G mobile communication networks. He has published four books, over 550 research papers including over 280 journal papers, most of which are in IEEE Transactions, and he holds 26 patents.

Prof. Guo is a Fellow of the Australian Academy of Engineering and Technology, a Fellow of IEEE, and a Fellow of IET. He was a member of the College of Experts of Australian Research Council (ARC, 2016–2018). He has won a number of most prestigious Australian Engineering Excellence Awards (2007, 2012) and CSIRO Chairman's Medal (2007, 2012). He was named one of the most influential engineers in Australia in 2014 and 2015, respectively, and one of the top researchers in Australia in 2020.

Prof. Guo has over 30 years of international academic, industrial, and government research experience. Currently, he is a Distinguished Professor and the Director of Global Big Data Technologies Centre (GBDTC) at the University of Technology Sydney (UTS), Australia. Prior to this appointment in 2014, he served as a Director in the Commonwealth Scientific Industrial Research Organization (CSIRO) for over nine years, leading the research on advanced information and wireless communication technologies. Before joining CSIRO in 2005, he held various senior technology leadership positions in Fujitsu, Siemens, and NEC in the UK.



Richard W. Ziolkowski received the B.Sc. (magna cum laude) degree (Hons.) in physics from Brown University, Providence, RI, USA in 1974; the MS and PhD degrees in physics from the University of Illinois at Urbana-Champaign, Urbana, IL, USA in 1975 and 1980, respectively; and an Honorary Doctorate degree from the Technical University of Denmark, Kongens Lyngby, Denmark in 2012.

Prof. Ziolkowski was the recipient of the 2019 IEEE Electromagnetics Award (IEEE Technical Field Award). He is a Life Fellow of the Institute of Electrical and Electronics Engineers (IEEE Fellow, 1994) and a Fellow of the Optical Society of America (OSA, 2006) and the American Physical Society (APS, 2016). He served as the

President of the IEEE Antennas and Propagation Society in 2005. He is also actively involved with the URSI, OSA, and SPIE professional societies. He was the Australian DSTO Fulbright Distinguished Chair in Advanced Science and Technology from 2014 to 2015. He was a 2014 Thomson-Reuters Highly Cited Researcher.

He is currently a Distinguished Professor in the Global Big Data Technologies Centre in the Faculty of Engineering and Information Technologies (FEIT) at the University of Technology Sydney, Ultimo NSW, Australia. He became a Professor Emeritus at the University of Arizona in 2018, where he was a Litton Industries John M. Leonis Distinguished Professor in the Department of Electrical and Computer Engineering in the College of Engineering and was also a Professor in the College of Optical Sciences. He was the Computational Electronics and Electromagnetics Thrust Area Leader with the Engineering Research Division of the Lawrence Livermore National Laboratory before joining The University of Arizona, Tucson, AZ, USA in 1990. His current research interests include the application of new mathematical and numerical methods to linear and nonlinear problems dealing with the interaction of electromagnetic and acoustic waves with complex linear and nonlinear media, as well as metamaterials, metamaterial-inspired structures, nanostructures, and other classical and quantum application-specific configurations.

Acknowledgments

Antennas are a significant, fundamental, and practical research area of electromagnetics. Unfortunately, they have been considered by many academic administrators and government funding agencies simply as being well established, i.e. “old stuff.” However, the wireless communications and sensors community is well aware that antennas are the key enabling technology of all things wireless.

Wireless technologies have become ubiquitous and truly critical in many ways to our everyday lives. These facts have become exceptionally clear now during this 2020 COVID pandemic. Whether you are a homemaker ordering foodstuffs to sustain your family via your cell phone and its network or you are a child learning and doing schoolwork online in your room while your academic parent is lecturing via Zoom from a home office, both being enabled by their computer’s WiFi connection to the family’s MIMO-based router, or you are a new grandparent seeing the newest member of your family remotely for the first time with FaceTime on your mobile platform or you are an antenna engineer interacting with company colleagues through Microsoft Teams on your handheld device to practice proper social-distancing protocols or even if you are two authors writing a book on antenna array technologies and are separated by a 19-hour time difference and a mere 13,000-km, wireless has meant that we can continue to perform tasks that need to be accomplished and can communicate and interact with family, friends, and colleagues on a regular basis.

Consequently, there have been very real and intense industry pushes and market pulls for various modern antenna systems to empower current fifth-generation (5G) and future sixth-generation (6G), and beyond wireless devices, applications, and their associated ecosystems. Scientific and engineering progress in array technologies has particularly benefited from user and stakeholder cravings for higher data rates and lower latencies. Antenna arrays will continue to play a major role in all future wireless generations. Pioneering wireless array research typically stresses advanced features such as steerable beams, multi-beams, multiband antenna coexistence, antenna reconfiguration, low-cost feed networks, and conformity to platforms. The various conundrums associated with the evolving land, air, and space networks associated with them will challenge all of us to develop fundamental and applied electromagnetics breakthroughs to solve them.

Under this backdrop, we have had the great privilege of working with a number of very talented PhD students, postdoctoral fellows, visiting scholars, and international collaborators. Our mutual interest and joint research efforts in antennas and antenna arrays for current 5G (fifth-generation) and future 6G, and beyond wireless ecosystems have deepened our understanding of their fundamentals, as well as their practical considerations necessary to successfully deliver useful systems for commercial applications that actually satisfy most of their generally overambitious, initial performance goals.

Our presentation of antenna and antenna arrays for current 5G and evolving 6G, and beyond systems in this book is organized into eight logical chapters that reflect our thoughts and the findings generated in those endeavors. Consequently, we are deeply indebted to our colleagues for their dedication and great contributions to the state of the art which are highlighted in these chapters. In particular, we would like to acknowledge specific inputs to them as follows:

Chapter 2: Ji-Wei Lian, Visiting Student, University of Technology Sydney (UTS), Australia

Chapter 3: Prof. Ming-Chun Tang, Chongqing University, China

Chapter 4: Dr. Can Ding, Lecturer, UTS, Australia and Dr. Hai-Han Sun, postdoctoral researcher, Nanyang Technology University (NTU), Singapore

Chapter 5: Dr. He Zhu, postdoctoral researcher, UTS, Australia

Chapter 6: Dr. Pei-Yuan Qin, Senior Lecturer, and Ph.D student Li-Zhao Song, UTS, Australia

Chapter 7: Dr. Stanley (Shulin) Chen, postdoctoral researcher, UTS, Australia; Dr. Debabrata K. Karmokar, Lecturer, University of South Australia, Australia; Prof. José Luis Gómez Tornero, Technical University of Cartagena, Spain; and Ji-Wei Lian, visiting student at UTS, Australia; Prof. Zheng Li, Beijing Jiaotong University, China.

Chapter 8: Prof. Yanhui Liu, Research Principal, UTS, Australia, and Ming Li, PhD student, UTS, Australia.

We thank them all for their invaluable time and efforts and wish them even greater successes in their future endeavors and careers.

We would also like to express our gratitude to University of Technology Sydney (UTS) for their whole-hearted support to our antennas research team.

Finally, we happily acknowledge our wives, Clare Guo and Lea Ziolkowski, and thank our lucky stars for their endless understanding, support and patience, particularly when we disappear for uncountable hours on cosmic efforts such as this :-)

1

A Perspective of Antennas for 5G and 6G

The roll-out of the fifth generation (5G) of wireless and mobile communications systems has commenced, and the technology race on the sixth-generation (6G) mobile and wireless communications systems has started in earnest [1, 2]. 5G promises significantly increased capacity, massive connections, low latency, and compelling new applications. For example, device-to-device (D2D) and vehicle-to-vehicle (V2V) communication systems will help facilitate the realization of autonomous transport. The rapid access to and exchange of “Big Data” will increasingly impact real-time economic and political decisions. Similarly, highly integrated, accessible “infotainment” systems will continue to alter our social relationships and communities. Wireless power transfer will replace cumbersome, weighty, short-life batteries enabling widespread health, agriculture, and building monitoring sensor networks with much less waste impact on the environment. 6G networks aim to achieve a number of new features such as full global coverage, much greater data rates and mobility, and higher energy and cost efficiency. These will usher in new services based on virtual reality/augmented reality and artificial intelligence [3].

At the core of wireless devices, systems, networks, and ecosystems are their antennas and antenna arrays. Antennas enable the transmission and reception of electromagnetic energy. Antenna arrays enhance our abilities to direct and localize the desired energy and information transfer. To achieve the many stunning and amazing 5G and 6G promises, significant advances in antenna and antenna array technologies must be accomplished.

1.1 5G Requirements of Antenna Arrays

One of the most important features of 5G is the employment of massive antenna arrays, with the size of the array currently varying from 64 to 128 and 256 elements. Such a large number of antenna elements in an array provide an unprecedented variety of possibilities. These include a means to increase the network capacity; the distance and data rates of individual links between the base station and mobile users; and the reduction of interference between different users and cells.

1.1.1 Array Characteristics

Generally speaking, there are three ways to exploit the benefits of antenna arrays in 5G wireless communication systems [4, 5], namely diversity, spatial multiplexing, and beamforming. These concepts are explained as follows.

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a) Diversity and Diversity Combining

It is a fact that mobile wireless communication channels typically suffer from both temporal fading and frequency fading. As a consequence, the quality of the channel varies with time and across different frequencies. Thus, the specific characteristics of the two propagation channels observed between any two pairs of transmitting and receiving antennas are usually different due to the variation in the scattering along the corresponding propagation paths. The peaks and troughs of the strength of the received signal at one antenna would be different from those at another antenna in a rich scattering environment. If the correlation between those two signals is low, one can combine them through so-called *diversity combining* to obtain a greater signal-to-interference-and-noise ratio (SINR). The latter is also known as diversity gain. A simple viewpoint is that diversity combining techniques aim to improve the quality of the individual links between the base stations and the user terminals by increasing the SINR.

From an antenna point of view, *diversity* can be obtained by exploiting either the distance between adjacent antennas, i.e., their positions, or different polarizations at the receiver and the transmitter. However, a fundamental requirement is that the mutual coupling between these diversity antennas must be low. Most modern base station antennas employ polarization diversity, i.e., each antenna element is dual-polarized typically with two pairs of slanted dipole "arms" in the $\pm 45^\circ$ directions. In 5G millimeter-wave (mm-wave) systems, for example, a popular antenna configuration is to have beamforming antenna arrays with $\pm 45^\circ$ polarizations, respectively.

b) Spatial Multiplexing

Multiplexing is the process of combining multiple digital or analog signals into a data stream for their transmission over a common medium, thus sharing a scarce resource. *Spatial multiplexing* aims to establish separate data streams in parallel using the same time/frequency resources. Thus, the space dimension is reused, i.e., multiplexed.

The simplest spatial multiplexing scheme is to employ sectorized antennas, a conventional technique for frequency reuse. More advanced spatial multiplexing schemes employ spatial–temporal (or frequency) coding by virtue of multiple input and multiple output (MIMO) antennas. A MIMO system requires the use of multiple antennas at least at the base stations. MIMO is implemented with two basic schemes as described below.

The first spatial multiplexing scheme is known as single user MIMO (SU-MIMO). By virtue of multiple antennas at both the base station and the user terminals, SU-MIMO first splits the data stream transmitted toward a specific user into multiple data streams. It then recombines them together at the user terminal to improve the information throughput and system capacity. One major challenge to SU-MIMO is the need for the tightly packed multiple antennas in the terminals to be decoupled.

The second spatial multiplexing scheme is known as multiuser MIMO (MU-MIMO). MU-MIMO aims to maximize the overall data throughput between all of the users and their associated base station. While it employs an antenna array at the base station, only one or a few antenna elements are present at each user terminal. Since user terminals are typically well dispersed within a radio cell and their individual channels are likely to be uncorrelated, the benefits of MU-MIMO are easier to achieve.

Both SU-MIMO and MU-MIMO protocols are intended for implementation in most 5G systems.

c) Beamforming

Spatial filtering can be regarded as a simple version of MU-MIMO. *Beamforming* achieves this spatial filtering by coherently combining the fields radiated by the array elements to direct their radiated energy into particular directions. These multiple beams are created at the base station to communicate with different users simultaneously.

Beamforming offers two benefits to a communication system. The first is capacity. If there is no overlap of the beams, simultaneous communications can take place in the same frequency band and at the same time without causing much interference. The second is the gain of the antenna array. Higher gain translates into information exchange over greater distances or higher data rates due to increased SINR values. Unlike 3G and 4G antenna arrays that provide coverage with fixed beam patterns and directivity, 5G arrays must support on-demand beam coverage according to real-time application scenarios and user distributions. Moreover, they must be able to support beam management in order to deliver precise coverage in target areas while significantly suppressing interference in other areas.

For beamforming to be effective, large antenna arrays are necessary to generate narrow beams and produce scattering from mobile users with small angular spreads. The latter is to ensure that the majority of the signals transmitted and received from a mobile platform is covered by a narrow base station antenna beam. These requirements, in conjunction with wide bandwidths, support the use of millimeter wave (mm-wave) communications for 5G. In particular, mm-waves propagate in a pseudo-light fashion so the scattering of the signals to and from a mobile platform is highly localized. Furthermore, since their wavelengths are small, an electrically large mm-wave array can be fit easily into a physically small space.

1.1.2 Frequency Bands

Another major challenge associated with 5G antenna arrays is the simultaneous support of all allotted frequency bands [6]. As the number of bands being considered to meet current and future 5G needs increases, significant antenna array innovations are required to support all of them. Moreover, existing 4G bands must be supported as well [7].

Owing to the stringent requirements placed on the radiation patterns produced by cellular systems and on the levels of their impedance matching to sources to maximize their realized gains, the mobile communication industry has so far adopted an approach of using different antennas to support different frequency bands. However, because of the limited space at base station antenna sites and in mobile platforms, the coexistence of these different antennas has posed serious challenges already. It is extremely difficult to maintain low coupling levels between antennas operating over the same band and even harder to suppress the scattering interactions between antennas that operate over different bands. The latter can cause significant distortions to the radiation patterns. It is with this background that the decoupling and de-scattering issues will be addressed in Chapters 2 and 3, respectively.

1.1.3 Component Integration and Antennas-in-Package (AiP)

Clearly, the number of antenna ports and radios for 5G systems will grow dramatically with the increasing numbers of massive antenna arrays and operating bands. This growth implies that the number of cables that connect the radios to the antennas would increase accordingly. This increase necessarily leads to increased fabrication complexities, losses in the cables and connectors, and difficulties in the control of passive intermodulation (PIM) and testing. To mitigate these problems, one needs to change antenna system design methodologies to introduce much higher levels of integration. To this end, there has been a high expectation that 5G antennas, the mm-wave band antennas in particular, will become highly integrated systems.

Integrated antenna and radio systems eliminate the need for multiple cables between the radios and antennas, thus increasing their reliability by reducing part counts and handling, and simplifying their testing and installation. As a result, there has been an increasing need for effective antenna-in-package (AiP) solutions. In addition to managing the radiation performance of the

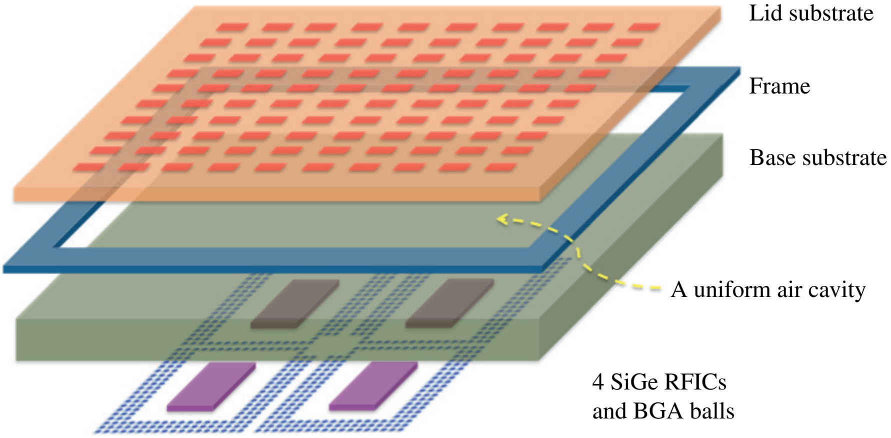

Figure 1.1 An illustration of a 64-element antenna-in-package (AiP) assembly breakout. *Source*: From [8] / with permission of IEEE.

antenna elements and arrays, one must consider several issues for AiP designs. These include, for instance, the materials; process selection and control; power and heat management; and new testing techniques. As an example, Figure 1.1 shows a 64-element AiP system at 28 GHz. It has four flip-chip-mounted transceiver ICs that support its dual-polarized operation [8]. For clarity, the heat sink below the ball-grid-array (BGA) interface is not shown.

One particular new challenge associated with highly integrated 5G antenna arrays is obtaining accurate antenna beam patterns. Depending on their actual implementation, methods for testing active antennas vary. Current examples include the following [4]:

a) Sample Testing

This approach involves the fabrication of a number of fixed analog beamforming circuits that provide the requisite amplitude and phase excitations to the antenna array to produce the desired beams including narrow beams for user traffic and broad beams for user management. Each circuit produces one specific beam. This allows one to sample each of the desired beam types and steering directions. For practical reasons, it is difficult to perform a comprehensive test of all of the possible beams generated by a large array. Therefore, only those beams of greatest interest are likely to be tested.

b) Element-by-Element Testing

The far-field vectorial pattern of each element, i.e., the amplitude and phase distribution in the far-field of the array, can be measured with respect to a common reference. Any beamforming pattern can then be synthesized numerically by adding all the element patterns with the corresponding appropriate complex weights. This approach is the most flexible method since all possible patterns can be tested. Nevertheless, one can argue realistically that the synthesized beam patterns may differ from the real ones to a certain extent because all of the actual interactions are not explicitly included.

c) Employ Beam Testers

Beam testers are effectively flexible beamforming networks. By connecting a beam tester to an antenna array, one can test a variety of the beams defined by the beam tester using a traditional method for antenna pattern testing. The 3rd Generation Partnership Project (3GPP), which unites

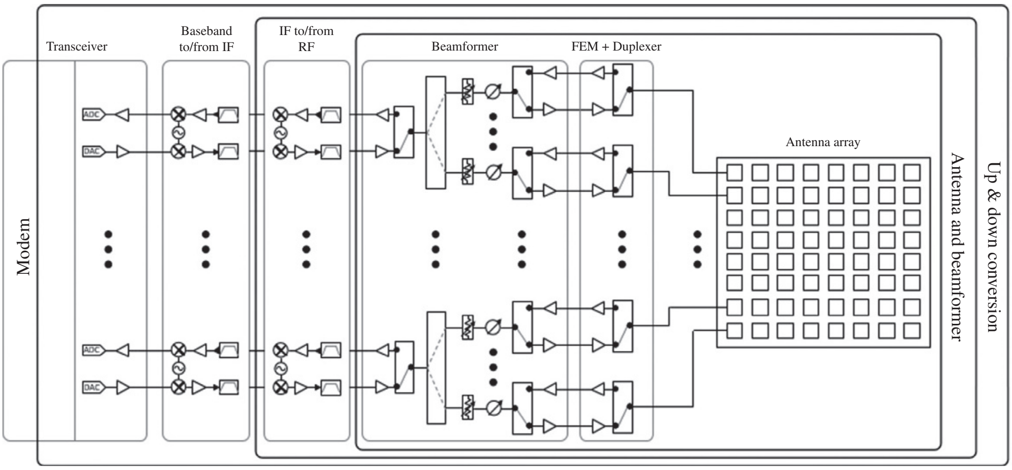

Figure 1.2 Three levels of AiP implementation by TMYTECH. *Source*: From [9] / with permission of TMY Technology Inc.

seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC), has defined three Over-the-Air (OTA) test methods for MIMO antennas: the direct far-field (DFF) method using a far-field chamber, the indirect far-field (IFF) method using a compact range, and the near-field to far-field transform (NFTF) method using a near-field chamber. All three OTA approaches are conventional methods familiar to antenna engineers.

It must be recognized that when active electronics are added to a radiating aperture to form a MIMO antenna, the antenna ports are now embedded in the system. As a result, it becomes much more difficult to measure the true gain and antenna efficiency. Because a massive MIMO antenna has a large number of antenna elements and its radiating aperture can be excited in many ways to create different beams, both narrow and broad, it is truly difficult to fully test and validate beam performance in terms of conventional figures of merit, e.g., pattern characteristics, beam shapes, beam steering, side lobe levels, and null locations. Testing is further complicated because measurements for both the transmit case and the receive case must be performed to understand the operating characteristics of both RF chains.

To facilitate the manufacturing and adoption of large antenna arrays in 5G and beyond systems, the wireless industry is pushing to increase the level of integration of the system frontend modules (FEM). Figure 1.2 shows the AiP roadmap of the TMY Technology (TMYTEK) company for their 5G mm-wave products [9]. Each enclosure block represents one particular level of component integration. The industry trend is to integrate the antenna arrays with all of the radio frequency (RF) and intermediate frequency (IF) modules into one package. Characterization of all of the beams produced by such modules is undoubtedly a new challenge for antenna designers.

1.2 6G and Its Antenna Requirements

5G mobile and wireless systems are ground-based. Consequently, they have coverage requirements similar to earlier generations of terrestrial networks. In contrast, space-communication networks provide vast coverage for people and vehicles at sea and in the air, as well as in remote and rural areas. They are complementary to terrestrial networks. Clearly, future information networks must seamlessly integrate space networks with terrestrial networks to achieve significant advances beyond 5G. This integrated wireless ecosystem may become one of the most ambitious targets of 6G systems [10]. It is currently envisaged that 6G wireless systems will support truly global wireless communications, anywhere and anytime. An integrated space and terrestrial network (ISTN) is expected to be at the core of beyond 5G communication systems. As a consequence, the development of the technologies to achieve a high-capacity, yet low-cost, ISTN is of significant importance to all of the emerging 6G wireless communication systems.

Currently, there are a number of commercial and government spaceborne and airborne platforms that support various applications in communications and sensing. These include geostationary Earth orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) satellites. As their names indicate, they operate at different altitudes relative to the Earth's center. Various airborne platforms also operate at different altitudes such as high-altitude platforms (HAPs), airplanes, and unmanned aerial vehicles (UAVs, otherwise known as drones). It is anticipated that any eventual 6G and beyond mobile wireless communication networks will thus consist of three network layers, namely the space network layer, the airborne network layer, and the terrestrial network layer. An illustration of a potential ISTN architecture is shown in Figure 1.3. Figure 1.3 clearly suggests that there will be a huge number of dynamic nodes constituting the mobile airborne networks, in addition to the dynamic nodes of the ground and space (satellite) networks [10].

Airborne networks have a number of unique characteristics. First, most of their nodes would have multiple links to achieve network reliability, high capacity, and low latency. Second, most of them will be mobile. Therefore, both their network links and topologies will vary with time, some faster than others. Third, the distances between any two adjacent nodes will vary significantly, from hundreds of meters to tens of kilometers. Fourth, the power supplied to any node would be limited. Consequently, as in the case for terrestrial networks, the energy efficiency of each node not only impacts the operation costs, but also the commercial viability of the entire network. Fifth, it is highly desirable for antennas on most airborne platforms to be conformal in order to meet their aerodynamic requirements and to maintain their mechanical integrity.

All of the noted, desirable ISTN features pose a number of significant and interesting challenges for future 6G antennas and antenna arrays. The antennas, for example, must be compact, conformal, and high-gain. They must be reliable, lightweight, and low-cost. The corresponding arrays must provide individually steerable multiple beams; dynamic reconfiguration of their patterns, polarizations, and frequencies to cope with the movement of the platforms; and overall high energy efficiency. The biggest challenge among all of them is arguably the reduction of the overall energy consumption. One promising solution is to employ analog steerable multi-beam antennas. Hybrid beamforming is another. Since beamforming and beam scanning can be done by antenna reconfiguration through electronic switching or tuning, the energy required is negligible in comparison to employing a full digital beamforming approach.

1.3 From Digital to Hybrid Multiple Beamforming

There are several ways to form multiple beams from an array. Major schemes can be categorized into digital, analog, and crossover strategies. We begin by describing digital beamforming and a major crossover of much recent excitement, hybrid beamforming.

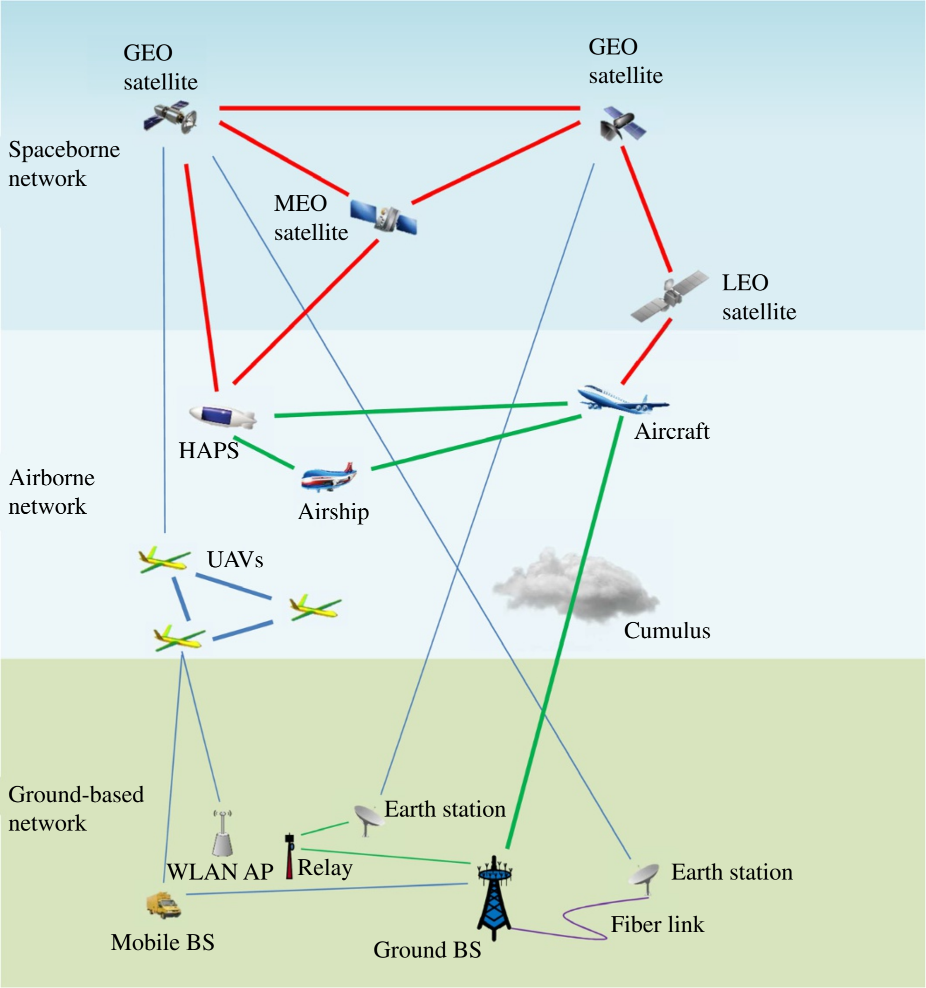

Figure 1.3 An illustration of a potential ISTN architecture for 6G and beyond. *Source*: From [10] / with permission of IEEE.

1.3.1 Digital Beamforming

Given an antenna array, digital beamforming is the ultimate way to achieve optimal performance. It is the most flexible approach to generating individually steerable and high-quality multiple beams. With a single antenna array of large enough size and the same set of RF circuits, one can effectively create as many beams as desired by applying different complex weights (amplitude and phase) to each element of the array in the digital domain. More advanced digital beamforming schemes employ algorithms such as eigen-beamforming to obtain the maximum SINR values [11]. Fully digital beamforming with massive antenna arrays serves as a powerful technology to meet some of the most challenging desired features of future wireless communication networks including capacity, latency, data rates, and security.

A high-level digital beamformer for reception is shown in Figure 1.4. It consists of an array of antennas, each antenna element being connected with an RF receiver. The RF receiver includes

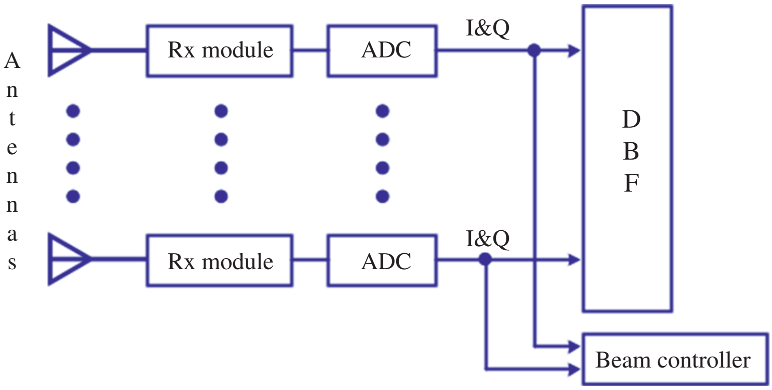

Figure 1.4 High-level architecture of a digital beamformer (DBP) for reception.

a filter, a low noise amplifier, a down converter, and an analog-to-digital converter (ADC). Thus, a signal chain is formed for each antenna.

The signals from all of the signal chains are fed into a digital beamformer (DBF). The DBF can form, in principle, as many beams as required. Theoretically it can realize real-time beamforming via real-time signal processing. However, in practice, this approach will generally incur prohibitive costs, including computing resources and hardware expenditures in both the RF circuits and digital devices such as ADCs and field-programmable gate arrays (FPGAs). In fact, the cost of the RF components is almost independent of the desired bandwidth whereas the cost of digital signal processing is approximately proportional to it in terms of both hardware and computing requirements. While those system costs are extensive, the necessary amount of energy to run the system may be even a higher outlay. The energy consumption of a large scale digital beamformer can easily amount to hundreds and even thousands of watts.

These significant practical issues mean that to achieve all of the desired functionalities of future ultra-high data rate communication systems, fully digital beamforming using massive antenna arrays is simply unaffordable for most application scenarios. Moreover, it is actually not even acceptable for many base station antennas for 5G with the current state of the art of device technologies [9]. These factors lead to the conclusion that some kind of hybrid system based on both digital and analog beamforming might serve as a good solution to large scale antenna arrays with multiple steerable beams in the foreseeable future.

1.3.2 Hybrid Beamforming

Hybrid beamforming is a strategy that combines the advantages of both analog and digital beamforming techniques. The motivation for employing hybrid beamformers is now clear. One wants to reduce hardware costs and processing complexities while retaining nearly the optimal performance that is achievable with optimized digital designs.

The hybrid beamforming approach does not treat every antenna element as a completely independent one. The key concept is to partition a large antenna array into smaller subarrays. This type of array is also known in the 5G literature as an array of subarrays (AOSA) [4]. Each subarray consists of a conventional analog antenna array that forms its beam in the analog domain [12, 13]. The number of sub-arrays into which the whole array is partitioned determines its degrees of freedom.

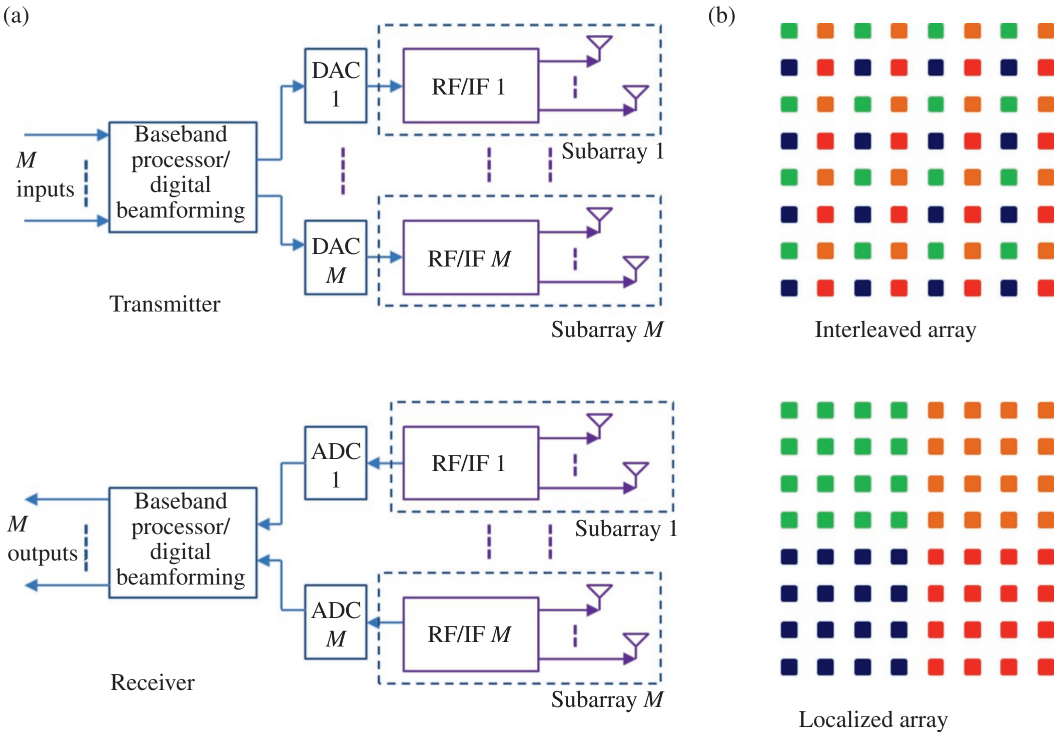

Figure 1.5 Hybrid antenna arrays. (a) The basic architectures of transmitter and receiver systems. (b) Two types of array configurations for uniform square hybrid arrays: interleaved (upper) and localized (bottom). Each square represents an antenna element and squares with the same color represent antenna elements in the same analog subarray. *Source*: From [12] / with permission of IEEE.

When analog beamforming is performed using analog phase shifters and other equivalent devices, significant cost reductions can be achieved immediately due to the decrease in the number of complete RF chains required to form the beams. However, the number of simultaneously supported data streams or beams in a hybrid array is lower in comparison to a full-blown digital array. In practice, the actual antenna array design depends on the beamforming capabilities required along with the system's total complexity and budget considerations, both issues being influenced directly by factors such as the number of steerable beams and costs. Although reducing the number of RF chains also limits the number of data streams, per-user performance can be designed to come close to that attained with a fully digital beamformer. Owing to the nature of line of sight radio propagation and smaller numbers of users per cell, the hybrid beamforming strategy is definitely the more practical beamforming approach for mm-wave systems in the near future [4, 11].

Figure 1.5a shows the basic architectures of both transmitting and receiving hybrid arrays. Their schematics illustrate the whole array being divided into many analog subarrays [12]. Each subarray includes N antennas and an RF/IF (intermediate frequency) unit. These components can be shared by different antenna elements in different ways, depending on their actual implementations. For convenience, we have simply denoted an array with M subarrays with N antenna elements in each subarray as an $N \times M$ hybrid array. Typically, given the dimension of the whole array, the decision on the size of the subarray, or the selection of N and M, is a trade-off between the system cost and performance. If N is large, a high antenna gain can be achieved at a lower cost. If N is too large, however, the number of users the array can support would be limited. The distance between corresponding elements in adjacent subarrays is called the *subarray spacing*. It is determined by the desired multiple beam performance and the allowed physical area of the array. Each subarray is connected to a baseband processor via a digital-to-analog convertor (DAC) in the transmitter and an analog-to-digital convertor (ADC) in the receiver. The signals from all of the subarrays are interconnected and processed centrally in the baseband processor.

Signals in the analog subarray and in the digital processor can be processed in different domains and in different ways. A signal in each subarray can be simply weighted in the analog domain mainly for the purpose of achieving array gain and beam steering. The signal for each antenna element in a subarray can be varied in both its magnitude and phase, typically with limited resolution. In the simplest case, only a phase shifter is applied and the signal is weighted by a discrete phase shift value from a quantized set of values. The size of the set is typically represented by the number of quantized bits. For example, a 3-bit quantization means eight discrete values are uniformly distributed over the angular interval $[-\pi, \pi]$. In the digital processor, signals from/to all of the subarrays are jointly processed. Advanced techniques which are similar to those utilized in conventional MIMO systems, such as spatial precoding/decoding, can be implemented.

Antenna elements in a hybrid array can be configured in various ways to form different topologies. Each of them has respective advantages and disadvantages. A configuration is typically fixed at the fabrication stage. The typical two types of regular configurations are interleaved and localized arrays. They are illustrated in Figure 1.5b for a 16×4 uniform square hybrid array. The antenna elements in each subarray in an interleaved array are distributed uniformly over the whole array. On the other hand, they are adjacent to each other in a localized array.

The analog subarrays in Figure 1.5 can be implemented in four different configurations depending on where the phase shifters are placed for beamforming. They are illustrated in Figure 1.6. Figure 1.6a shows the conventional phased array architecture for a receive analog array. Only the phase shifters and antennas are independent; all of the rest of its components are shared by all elements in each analog subarray. This passive power combining architecture incurs losses in the phase shifters and power combiners which increase with the number of antenna elements and operating frequency. These power losses could make large passive arrays impractical. A modification of this architecture is shown in Figure 1.6b. An individual LNA is applied to each antenna element before the phase shifter. This modification reduces the noise significantly and provides increased receiver sensitivity. This architecture can be implemented using either a shared frequency converter (with individual RF chains combined at the input to the mixer) or individual frequency conversion and combining in the IF unit. Figures 1.6c and 1.6d depict more advanced configurations in which the phase shift is implemented in the IF unit and local oscillator (LO) circuits, respectively.

It must be noted that commercial 6-bit digital phase shifter mm-wave integrated circuits (MMICs) are available for a range of LO and IF frequencies suitable for mm-wave arrays. These devices provide 360° of phase change with a least significant bit (LSB) of 5.625°. This resolution allows analog beamforming with a scan angle accuracy to a fraction of a degree. The system configuration in Figure 1.5d is particularly attractive since the devices in the LO path are typically operated in saturation. Consequently, variable losses that usually change with any phase shift are avoided in this scheme.

It is should be pointed out that a more elegant and highly desirable solution to forming multiple beams in a hybrid fashion is to employ analog multi-beam antennas rather than using subarrays of antenna elements. In principle, the entire antenna aperture can be shared by all the users. However, the generation of multiple individually steerable analog beams is in itself a huge challenge. Unfortunately, there exist only a very limited number of solutions that can be incorporated into the hybrid beamforming configurations discussed above. A number of the remaining chapters in this book will explore various ideas to fill such current technology gaps.

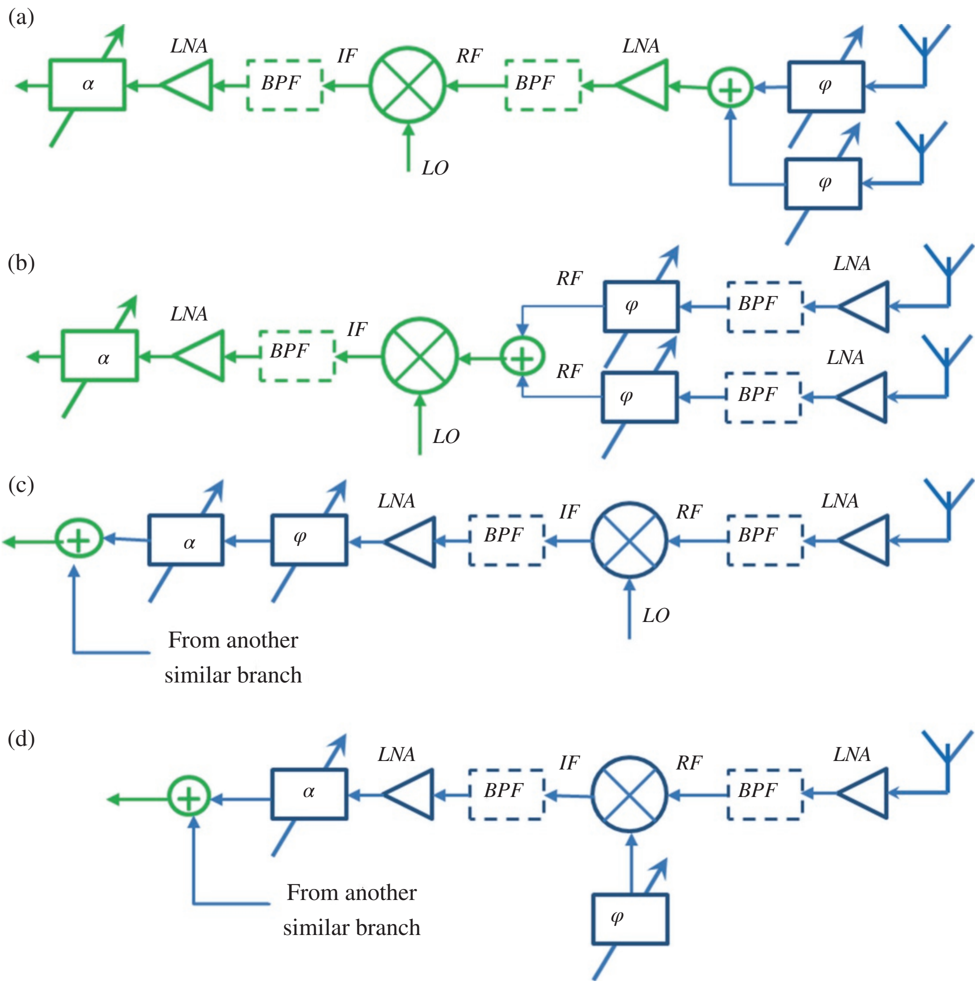

Figure 1.6 Options for implementing analog subarrays. The blocks φ and α denote a variable phase shifter and magnitude attenuator, respectively. Blocks in green represent those able to be shared by the antenna elements in a subarray. The circle with a cross in it denotes where signals from individual antenna elements are combined to be delivered to the shared components. The subfigures show the four main options. (a) Phase shifter at the RF element before an LNA. (b) Phase shifter at the RF element after an LNA. (c) Phase shifter at the IF unit. (d) Phase shifter at the LO unit.

Notice that it is expected that both fully digital beamformers and hybrid beamformers will be employed for 5G deployments. Some of the anticipated use cases envisaged by industry are listed in Table 1.1 [4].

1.4 Analog Multiple Beamforming

There are a number of ways to create steerable antenna beams in an analog manner. These include the use of circuit-type beamformers, reflectors, lenses, and phased arrays. These and other more advanced methods will be presented in later chapters. We review some of the basic concepts here.

Table 1.1 Use cases for digital and hybrid beamforming.

Beamforming type	**Use cases**
Digital beamforming	• Sub-6 GHz massive MIMO: MU-MIMO • Sub-6 GHz macro cell • 2D beamforming • Fixed wireless access
Hybrid beamforming	• mm-wave based systems • Sub-6 GHz small cells/hot spot coverage • Fixed wireless access • Massive MIMO macro cells

Source: From [4] / with permission of 5G Americas.

The most common analog beamforming antennas are phased arrays. The original technology dates back to the mid-twentieth century. It remained primarily as a military technology until the 5G era. In a phased array, the same signal is fed to each antenna element. The amplitudes of the elements are weighted according to the desired shape of the beam, i.e., the shape of the radiated pattern, and then phase-shifters are used to steer the beam emitted by the array into the desired direction. In order to save cost, the current commercial 5G mm-wave systems employ phased arrays to conduct analog beamforming. Both the base station and the user equipment (UE) use a number of fixed weight settings, or sets of phase-shifting values, to produce different beams pointed in specific directions. There are only two beams pointed in the same direction at any given point of time, each for the horizontal and vertical polarizations, respectively. Consequently, current base stations steer their beams sequentially in different directions to provide the desired coverage. The system capacity could be significantly improved by introducing multiple beams. However, it remains a major technological challenge to provide sufficient flexibility to achieve multiple beam directions with an analog beamforming system.

Phased arrays are inherently suited for producing single beams. Because one signal is fed to all of its elements, a phased array constitutes only one antenna port per beam. The beam is steered to follow the intended user by controlling the values of its phase shifters. Some sacrifices have to be made to produce individually steerable multiple beams with a phased array. They include partitioning the array aperture for different beams; and, hence, this limits the overall performance of each generated beam. In the following subsections, we present two multiple analog beamforming techniques that are currently popular for cellular systems: Butler matrices, and Luneburg lenses.

1.4.1 Butler Matrix

One traditional method of producing multiple beams is to utilize Butler matrices [14]. These multiple beams can be steered together in principle, but not independently. Therefore, Butler matrices are almost exclusively used for fixed beams. A Butler matrix is an RF circuit consisting of couplers, delay lines, crossovers, and transition parts. An n-way Butler matrix has n inputs and n outputs. A signal applied to a given input will lead to outputs of equal amplitude but with a uniform phase gradient, thus leading to a single steered beam. The phase increment between adjacent outputs is a multiple of $\frac{360^\circ}{n}$ depending on which input is fed. The phase increment across the outputs, that occurs if input i is fed, is $\frac{360^\circ}{n}i$, where i can take on integer values from 0 to $n-1$. If the n outputs of the Butler matrix are connected to a linear array of n equally spaced radiating elements, a set of n

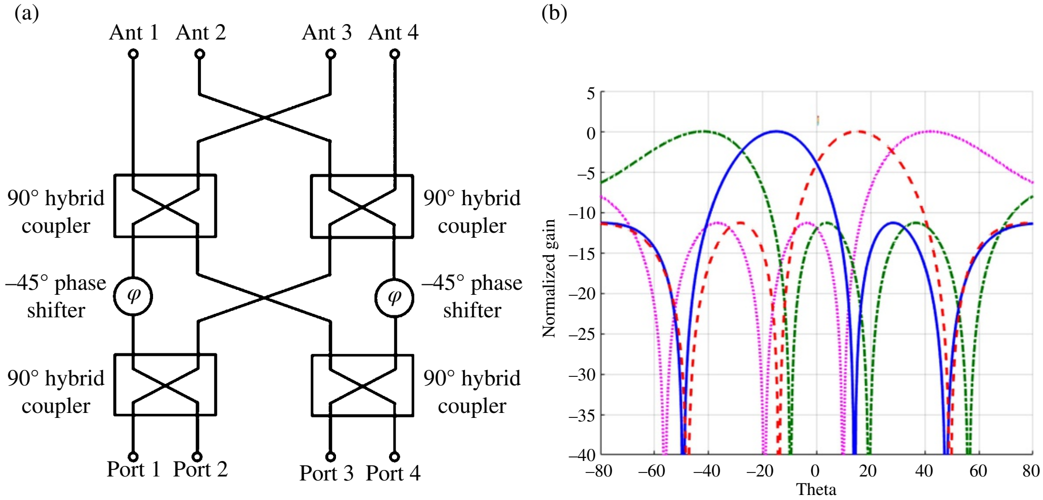

Figure 1.7 Typical implementation of a 4 × 4 Butler matrix (BM) connected to 4 radiating elements and the 4 beams it produces.

beams equally spaced in angle will be generated if all of the inputs are fed. Figure 1.7 shows the configuration of a 4×4 Butler matrix and the 4 beams it produces with 4 radiating elements.

Unfortunately, multiple beamforming employing a Butler matrix has a number of disadvantages. First, the beams are fixed. Consequently, it is only a switched beam solution for tracking mobile users. Second, owing to the losses in the Butler matrix's circuits, a major challenge for large antenna arrays is keeping the overall losses small, especially at millimeter-wave frequencies. Third, a 2D Butler matrix would be required for two-dimensional (2D) beamforming. However, the conventional structure is generally too bulky and too lossy owing to the complicated requisite crossovers. Fourth, a complete system engineering approach is required to achieve wideband operation with a Bulter matrix. These issues are only some of the challenges facing the antenna research community. They and some recently developed solutions will be addressed in several later chapters.

1.4.2 Luneburg Lenses

A simple, yet powerful, analog method to create steerable and multiple beams is to employ a spherical Luneburg lens. A Luneburg lens in its simplest form consists of a radially inhomogeneous sphere with a well-defined graded dielectric constant that varies from 2.0 at the center of the sphere to 1.0 at its outer surface. The gradation is given by the equation: $\varepsilon_{\mathrm{r}} = 2 - \left({}^{r}\!/_{a}\right)^2$, where ε_{r} is the relative dielectric constant at radius r and a is the outer radius of the sphere. The resulting structure serves to transform rays incident on one side to parallel rays on the opposite side. An antenna feed located on the surface of the lens produces a steered beam if the element moves around the surface as illustrated in Figure 1.8a. The low dielectric constant near the lens surface ensures that no energy is reflected back to the feed. In order to accommodate feeds whose phase centers cannot be placed at the surface of the Luneburg lens, such as a horn antenna, one can modify the distribution of the dielectric constant within the lens [15]. Figure 1.8b shows the corresponding cylindrical version, which is known as a *cylindrical Luneburg lens*.

The beamwidth of a Luneburg lens is approximately the same as that of a linear array whose length equals the diameter of the lens. Nevertheless, the nulls are considerably deeper. If one places

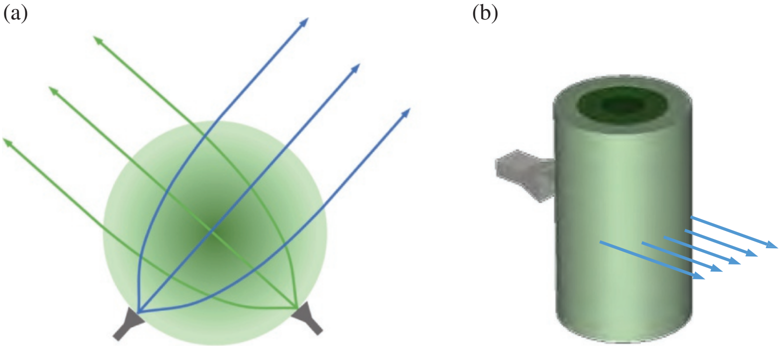

Figure 1.8 Illustration of Luneburg lenses. (a) Spherical. (b) Cylindrical.

a number of feeds along the surface of a Luneburg lens, one can produce a multiple beam antenna, one beam per feed. These multi-beam antennas can be employed for data distribution or broadcasting in 5G networks.

It is very difficult and very costly to produce an ideal Luneburg lens. As a practical alternative, one can employ several separate shells to replace the theoretical continuous gradation of the dielectric constant with a discrete approximation to it. Many such versions have been deployed in a variety of current systems.

The main advantages of Luneburg lenses over antenna arrays based on beamforming networks can be summarized as follows [14]:

- A great simplification in component count and inherent low passive intermodulation (PIM).
- Reduction of network losses.
- Beam crossover levels can be selected arbitrarily by choosing the spacing of the source elements.
- Isolation between elements is generally superior to that obtained with beamforming networks.

The relative disadvantage of a Luneburg lens antenna is its three-dimensional bulk compared with planar forms of the array antennas. Nevertheless, some mobile operators are currently showing strong interest in Luneburg lenses due to their low cost in hardware and low energy consumption.

1.5 Millimeter-Wave Antennas

To date, every new generation of mobile wireless communication has been allocated its own dedicated spectrum. This is again true for 5G networks. Given the fact that the radio spectrum is a worldwide limited resource, the mobile wireless communication industry has been "forced" to start using the mm-wave spectrum to accommodate some portion of its 5G networks, known as 5G mm-wave. Application examples include small cells for data-hungry hot spots and fixed wireless access services where line of sight (LoS) propagation is easier to be guaranteed. Moving forward to 6G, it is expected that some airborne and satellite systems will also embrace the mm-wave spectrum. Compared with the microwave frequency bands, the propagation of mm-waves is negatively impacted by higher attenuation rates and severe weather.

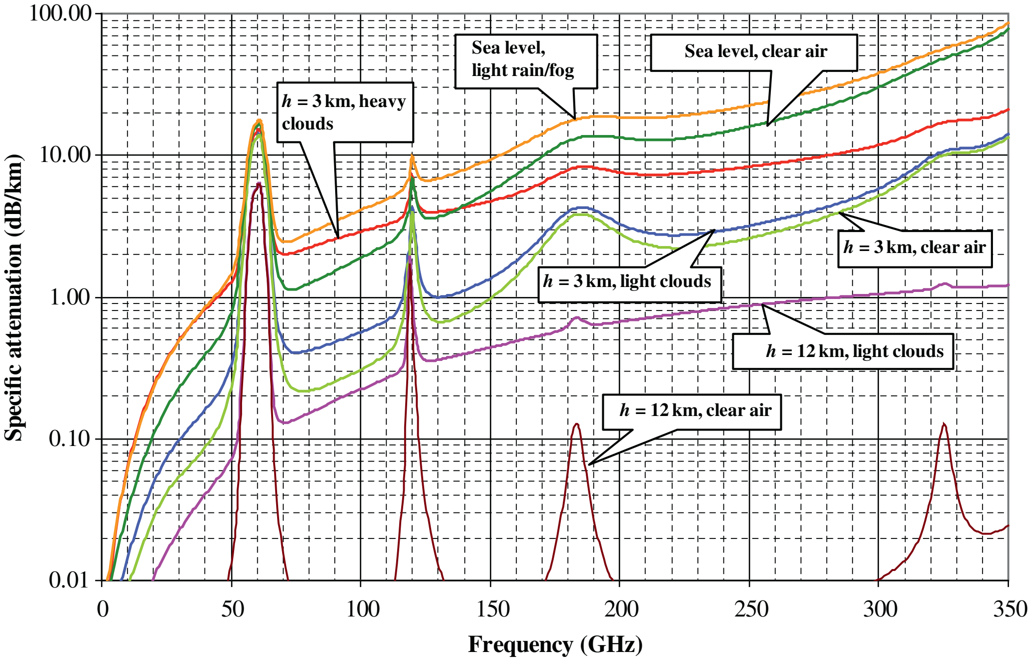

Figure 1.9 Specific atmospheric attenuation (dB/km) at the indicated altitude *h* and for several exemplary weather and air conditions. *Source*: Based on [16] / IEEE.

To emphasize this issue, Figure 1.9 shows the attenuation of electromagnetic waves from DC into the low terahertz (THz) range as functions of the propagation distance, altitude, and weather conditions. Notice that there are some windows in these spectra where the atmospheric attenuation is high, such as around 60 GHz, and, conversely, much lower. The former are clearly not suitable for long-distance communication. The latter are targeted for many applications. Also notice that the propagation losses are reduced at higher altitudes where the air is thinner. Examining Figure 1.9 more closely, it is little wonder that the current “first choice” for commercial 5G rollouts of mm-wave systems is at the lower end of the mm-wave range, i.e., around 28 GHz.

Certain important advantages for 5G operations are offered by mm-wave systems. One is that high-gain mm-wave antenna arrays can be realized over physically small areas because the associated wavelengths are small (recall that the gain of an aperture antenna – Gain = 4π Area/λ^2). In fact, given the inherent high propagation losses of their radiated fields, high-gain antennas are needed for virtually all mm-wave communication systems. As a result, it has become imperative to develop mm-wave beamforming networks to support multi-beam mm-wave antennas. In the current 3GPP standards for 5G mm-wave, for example, user equipment (UE) or terminals are required to have an array antenna with between 8 and 64 elements [17].

1.6 THz Antennas

With 6G data rates promised to be even higher than those of 5G [1–3], a much wider spectrum is needed to accommodate 6G expectations. Unfortunately, a large currently unoccupied spectrum does not exist below 100 GHz. Consequently, it is widely expected that 6G will occupy a significant part of the THz spectrum [2]. Along with terrestrial-based communication systems, it is anticipated that THz systems will also play a major role in space-based communications [18, 19].

Currently, the most common definition of the THz band is that it consists of frequencies from 0.3 to 3.0 THz. Recall that the wavelength at 0.3 THz (300 GHz) is just 1.0 mm. Owing to the fact that THz wavelengths are even smaller than the mm-wave ones, very narrow multiple beams with low probability of intercept (LPI) can be generated from very physically small areas. Beam steering and target tracking again will be indispensable features for THz antennas.

Referring to Figure 1.9, signal attenuation in the lower portion of the THz range is even more severe than in the mm-wave band. Thus, high-gain antenna arrays are even more necessary for anticipated 6G operations. Other important related THz technologies that must also be developed to address 6G expectations are high power sources and highly sensitive receivers [20]. Feeding a large array of THz antenna elements of 0.5λ in size using a corporate network is a daunting engineering task. Therefore, it has not been favoured to date. Instead, a more promising approach is to employ an electrically large lens fed by a simple radiating element such as a dipole or a slot or even a small array. To ease the problem of the precise alignment of the antenna and lens, one could integrate the antenna feed with the lens. Antennas with this characteristic are known as integrated lens antennas [20–22].

1.7 Lens Antennas

A number of different types of lens antennas operating in the mm-wave and THz bands have been reported [21–25]. These include the elliptical lens, extended hemispherical lens, and Fresnel zone lens. Each has its own unique physical and performance characteristics.

A homogeneous elliptical lens has two focal points. It can transform the radiation pattern of a feed placed at one focal point into a plane wave exterior to it propagating in the direction of the second focal point. Assuming a represents the major semiaxis, b represents the minor semiaxis, L represents the distance between the focal point of the feed to the centre of the ellipsoid, and n is the index of refraction of the dielectric from which the lens is fabricated, one has the following relationships:

$$a = b/\sqrt{\left(1-\frac{1}{n^2}\right)} \tag{1.1}$$

$$L = a/n \tag{1.2}$$

An integrated elliptical lens antenna is obtained by cutting off the part of the dielectric below the bottom focal point and placing the feeding antenna beneath it. As depicted in Figure 1.10, only rays that hit the surface of the elliptical lens above the plane of its maximum diameter, denoted herein as its waist, are collimated. The portion of the radiated fields intersecting the lens below its waist is not collimated, but rather propagates along undesired directions or excites surface wave modes, thus giving rise to side lobes or other perturbations in the lens' radiation pattern [20]. One solution to solve this problem is to control the beamwidth of the feed in order that the majority of its radiated energy falls within the angular range above the waist of the lens.

Another issue arising from the internal reflections at the surface of an elliptical lens is the matching of the feed. One inherent characteristic of elliptical lenses is that all of the reflected rays that pass through the second focal point are reflected back to the first focal point. This reflected power causes a substantial mismatch to the feed impedance. A classical method to address this issue is to