Chapter 10
5G Mobile Communication Systems: Fundamentals, Challenges, and Key Technologies

Yasin Kabalci

Abstract Wireless and mobile communication technologies exhibit remarkable changes in every decade. The necessity of these changes is based on the changing user demands and innovations offered by the emerging technologies. This chapter provides information on the current situation of fifth generation (5G) mobile communication systems. Before discussing the details of the 5G networks, the evolution of mobile communication systems is considered from first generation to fourth generation systems. The advantages and weaknesses of each generation are explained comparatively. Later, technical infrastructure developments of the 5G communication systems have been evaluated in the context of system requirements and new experiences of users such as 4K video streaming, tactile Internet, and augmented reality. After the main goals and requirements of the 5G networks are described, the planned targets to be provided in real applications by this new generation systems are clarified. In addition, different usage scenarios and minimum requirements for the ITU-2020 are evaluated. On the other hand, there are several challenges to be overcome for achieving the intended purpose of 5G communication systems. These challenges and potential solutions for them are described in the proceeding subsections of the chapter. Furthermore, massive multiple-input multiple-output (MIMO), millimeter wave (mmWave), mmWave massive MIMO, and beamforming techniques are clarified in a detail which are taken into account as promising key technologies for the 5G networks. Besides, potential application areas and application examples of the 5G communication systems are covered at the end of this chapter.

Keywords Mobile communication systems · Multiple-input multiple-output (MIMO) systems · Massive MIMO systems · Millimeter wave (mmWave) systems · mmWave massive MIMO systems · Beamforming techniques

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Y. Kabalci (✉)
Department of Electrical and Electronics Engineering, Faculty of Engineering, Nigde Omer Halisdemir University, Nigde 51240, Turkey
e-mail: yasinkabalci@ohu.edu.tr; yasinkabalci@mail.usf.edu

Y. Kabalci
Department of Electrical Engineering, College of Engineering, University of South Florida, Tampa, FL 33620, USA

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10.1 Introduction

Active use of emerging information and communication technologies (ICT) has become an important key element for enhancing world economy. The one of the most crucial elements for the global ICT is wireless and mobile communication systems that have effective roles to support the development of other many sectors. In addition, it is informed by European Mobile Observatory (EMO) that the mobile communication sector has reached enormous revenue levels by passing other main sectors such as aerospace and pharmaceutical [1, 2]. It is obvious that these technologies are globally growing and developing to meet user demands day by day. Nowadays, demand of time and place-free communication has become one of the essential requirements for everyone, even for every objects called smart things. The use of mobile communication technologies to meet these demands is greatly preferred due to offered advantages and developing technologies. In addition, remarkable achievements of the mobile communication systems reflect the development rate of innovative technologies at the same time.

When the evolution of mobile communication systems are considered from first generation (1G) to fourth generation (4G), it is clear that the main motivation between each generation of mobile communication systems is to eliminate the weaknesses of the previous generation and to present more robust systems. These are closely correlated with spectral efficiency, mobility, data rate, and coverage [3, 4]. Table 10.1 summarizes the development of mobile communication generations in terms of service and performance. The 1G cellular systems that were based on using narrowband and analog systems were launched at the beginning of the 1980s. The widely used standards in 1G systems were Advanced Mobile Phone System (AMPS), Total Access Communication System (TACS) and Nordic Mobile Telephone (NMT). The data rate of these standards are typically 2.4 Kbps, and they use frequency-division multiple access (FDMA) method. As can be seen from the table, the main problems of the 1G communication systems were poor spectral efficiency and security problems. After the 1G systems which could only support voice service, second generation (2G) cellular systems were announced in the initial of 1990s. The main idea behind changeover from 1G to 2G cellular systems is the moving from analog systems to digital systems. In other words, it can be considered as a requirement to present more capacity and better coverage areas. This new generation not only improved voice communication but also provided the possibility of messaging to the users. Either time division multiple access (TDMA) or code division multiple access (CDMA) technology is utilized by the 2G cellular systems to reach up 64 Kbps data rates. The most popular standards for this generation are Global System for Mobile communication (GSM), digital AMPS (D-AMPS), Personal Digital Cellular (PDC), and CDMA One or with its other name IS-95. Although main weaknesses of the 1G systems were eliminated by the 2G mobile systems, this generation had still limited data rates that were not able to support enough Internet access speed for users.

Unlike previously suggested generations, first international standard proposed by International Telecommunication Union (ITU) was third generation (3G) mobile

Table 10.1 Evolution of mobile communication generations in terms of service, performance, and problems

Generation	Rollout year	Max. speed	Primary services	Features	Problems
1G	1981	2 kbps	Analog phone calls (Only voice)	Mobility	Low spectral efficiency, important security problems
2G	1992	64 kbps	Digital voice, messaging, and packet	More secure, mass adoption	Low data rates—difficult to support demand for Internet/e-mail
3G	2001	2 Mbps	Audio and video calls with high quality, messaging and data	Better Internet experience and multimedia services	Real performance failed to match hype, failure of WAP for Internet access
3.5G	2006	14 Mbps	Audio and video calls with higher quality, messaging, and broadband data	Broadband Internet and new applications	Tied to legacy, mobile-specific architecture, and protocols
4G	2011	1 Gbps	All IP services (including voice, messaging, and wearable devices)	Faster broadband Internet, lower latency	**?**

communication system that came along with an important innovation such as data capability. The main difference between 2G and 3G cellular systems was migrating from voice-based systems to data-based systems. In addition, it was possible to access services up to 2 Mbps data rates in this new generation through Internet Protocol (IP). The 3G systems enabled new experiences for users such as video calling, multimedia messaging, online TV, and better Internet access. The 3G networks that could operate in both frequency-division duplex (FDD) and time division duplex (TDD) modes utilized wideband CDMA (W-CDMA) technology. The most popular 3G standards are International Mobile Telecommunications-2000 (IMT-2000), Universal Mobile

Telecommunications Systems (UMTS), and CDMA 2000. By the following these standards, some evolved technologies such as High-Speed Uplink/Downlink Packet Access (HSUPA/HSDPA) and Evolution-Data Optimized (EVDO) are proposed as an 3.5G cellular technologies that can reach up to 30 Mbps data rates [4–6].

In 2008, the ITU has stated key requirements of 4G systems that are 100 Mbps data service speeds for high-mobility users and 1 Gbps data rates for low-mobility users. The 4G cellular systems ensure high-speed data rates with 20 MHz bandwidth according to previous generations. There are two technologies for this generation. One of them is Long-Term Evolution (LTE) proposed as part of the 3rd Generation Partnership Project (3GPP), and the other is Worldwide Interoperability for Microwave Access (WiMAX) developed as part of the IEEE. While LTE exploits orthogonal frequency-division multiple access (OFDMA) in the downlink and single carrier frequency-division multiple access (SC-FDMA) in the uplink, WiMAX utilizes the OFDMA in both uplink and downlink [6].

Users can access to Internet with faster data transmission rates and lower latency in these days since 4G services are adopted in certain regions of the world. With the increasing Internet speeds thanks to the 4G mobile communication systems, growing popularity of smart phones and other smart devices such as netbooks, tablets, and e-book readers have led to changes in users' habits (i.e., downloading and/or watching more video streaming in high definition, more using of third-party applications especially in social platforms, and so on). Service providers have faced with the more bandwidth requirements owing to increasing use of the Internet. Fortunately, beyond 4G and first fifth generation (5G) mobile communication systems are indicated that millimeter wave (mmWave) frequencies will be promising for future wireless networks since there is an important potential to reach more gigabit (Gbps) data rates by utilizing available free bandwidths in these frequencies [7–9]. On the other hand, there are several challenges to be solved by the emerging mobile communication standards. One of the most important problems is scarcity of physically allocated RF spectrum for cellular communication systems. The ultra-high frequency (UHF) bands covered from several hundreds of MHz to a few GHz bands are intensively exploited. Another challenge is that advanced wireless technologies lead to high energy consumption costs. For instance, nearly 40–50 MW power is typically required to feed only for a mobile phone network [10]. In addition to these, it is informed by service providers that energy consumption levels of the base stations are 70% of the total energy consumption of operators. Increasing of energy consumption in wireless communication systems directly affects the rise of CO_2 emissions that is currently considered as a major threat to the environment. It is important to note that the energy-efficient communication is not one of the essential requirements for mobile communication systems; it is raised as an issue in later stages, especially in 4G systems. The other challenges need to be addressed in the next generations of mobile communication systems can be classified as better spectral efficiency, higher data rate and mobility, unlimited coverage, different quality of service (QoS) requirements, and incompatibility of different wireless devices/interfaces and heterogeneous networks.

10.2 5G Mobile Communication Systems: Fundamentals and State of the Art

After 4G systems were rolled out in 2011, research comities have changed their interests to investigate innovations for wireless communication technologies, namely for 5G systems. When the revolutionary change of mobile technologies in every decade is considered, the standardization of 5G cellular systems is expected to be completed around 2020s. Nowadays, ITU-R has issued a recommendation for framework and overall objectives of the future development of cellular systems for 2020 and beyond [11]. The recommendation emphasizes the developing consensus on the usage states and needs. It is also highlighted requirements of other recent services such as e-health, augmented reality (AR), remote tactile control, traffic safety and efficiency, wireless industry automation, smart grids [6, 11]. The usage scenarios and use cases will be explained after the main motivations, and objectives of 5G mobile communication systems are presented. When 5G mobile systems are compared with 4G systems, it is expected that this new generation systems aim to come up with remarkable improvements. These features are 25-fold average cell throughput, 10 times energy efficiency, tenfold spectral efficiency and data rates (i.e., 10 Gbps peak data rate for low-speed mobile systems and 1 Gbps for high-speed mobile systems), and 1000-fold system capacity per km^2. Moreover, the 5G mobile systems intend to support some specific scenarios such as communication in high-speed vehicles, 4K video streaming without any disconnection, which could not achieve by 4G mobile systems [2]. Several market and services expected to be supported by 5G mobile systems are shown in Fig. 10.1 [12]. This expectation scenario is composed of two main trends. One of them is that wireless connection will collect everything under the same umbrella in order to make possible data acquisition, monitoring, and controlling of devices. For instance, smart grids will be more effective and robust due to the fact that all sensors, smart meters, and entire system are connected each other and to the management system thanks to high-speed wireless connection. On the other hand, machine-to-machine (M2M) services and Internet of Things (IoT) will be monitored and be controlled more efficiently. The other expectation is big data as a result of increasing connected devices, sensors, and new services such as 4K video streaming, AR, remote health check. Eight main requirements to be met by the 5G technology are defined by many of the industry initiatives, and these requirements can be summarized as follows [3].

- 99.999% availability
- Full coverage (100%)
- 90% less energy consumption
- 1000 times more bandwidth per unit area
- 1–10 Gbps data rate for all nodes of the network
- Up to ten years battery life for low-power mode
- Supporting 10–100 times more connected devices
- 1 ms end-to-end (E2E) loop delay in the network (latency).

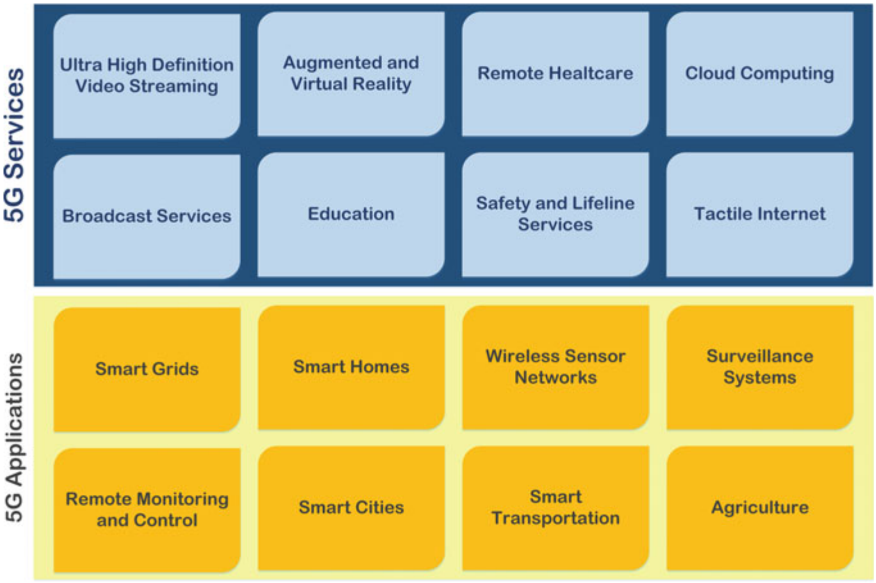

Fig. 10.1 Market and services to be supported 5G mobile systems

Figure 10.2 illustrates the key requirements of 5G mobile technology briefly. The 5G mobile systems must be able to cope future user traffics that will be larger and more complicated than that of the current networks. This issue is regarded as one of the major challenges of the future dense networks. As mentioned before, the one of the aims is to obtain a 1000× system capacity per km^2 when it is compared with LTE systems. The other important requirement is to present higher data rates than current LTE networks. When the developing of cloud systems and dense contents such as high definition data streams and AR are taken into account, new generation mobile systems not only should provide a better quality of the user experience (QoE) but also should aim to offer faster data rate services. The 5G systems need to permit many devices to be joined to the network at the same time so as to provide better assistance to devices that should be always on the network. The main aim of the 5G networks in terms of the user perspective is to accomplish 100 times more simultaneously user supporting according to the LTE systems. In addition to providing higher data rates, 5G systems have to offer a user latency period of less than 1 ms over radio access networks (RAN) [3, 12].

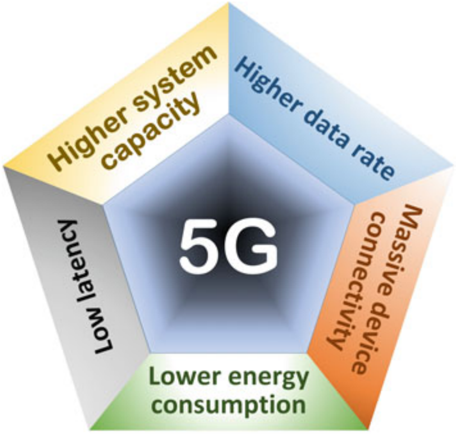

Fig. 10.2 Main targets of 5G mobile communication systems

10.2.1 Different Usage Scenarios and Minimum Requirements of IMT 2020

ITU-R has specified International Mobile Telecommunications-2020 (IMT-2020) as mobile systems in Resolution ITU-R 56-2 [13]. The IMT-2020 will have novel radio interfaces that will be supported new developing systems as well as the IMT-2000 and IMT-Advanced. The capabilities of the IMT-2020 are specified in Recommendation ITU-R M.2083 [11]. According to the ITU-R, the IMT-2020 will be more advanced than that of the IMT-2000 and IMT-Advanced. It will also present new several usage scenarios that are called as enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine-type communications (mMTC) [11, 14–17].

- *Enhanced mobile broadband (eMBB)*: According to this usage concept, users will experience much better performance and uninterrupted service in future mobile networks compared with current systems. The eMBB usage scenario is composed of various cases that contain wide area coverage and hotspot cases. Full coverage, higher mobility, and higher data rates are expected when the wide area case is considered. The planned data rates will be on the level of Gbps. On the other hand, in the event of the hotspot case is taken into account, high user density and traffic capacity are desired. However, mobility requirements for this case are only at speeds of pedestrian. It is also important to note that requirement of user data rate is much higher in the hotspot case compared with other one.
- *Ultra-reliable and low-latency communications (URLLC)*: There are several important needs in terms of reliability, availability, and latency for this usage scenario. Especially, E2E latency should be less than 5 ms for this scenario [15]. The most popular application areas for the URLLC are smart grids, remote monitoring and control, vehicle-to-everything (V2X), intelligent transport systems, tactile Internet applications, and so on.

Table 10.2 Minimum technical performance requirements defined by ITU-R for the 5G networks

KPI	Usage scenarios	Values
Peak data rate	eMBB	DL: 20 Gbps, UL: 10 Gbps
Peak spectral efficiency	eMBB	DL: 30 bps/Hz, UL: 15 bps/Hz
User experienced data rate	eMBB	DL: 100 Mbps, UL: 50 Mbps (for Dense Urban case)
5% user spectral efficiency	eMBB	DL: 0.3 bps/Hz, UL: 0.21 bps/Hz (for Indoor Hotspot) DL: 0.225 bps/Hz, UL: 0.15 bps/Hz (for Dense Urban) DL: 0.12 bps/Hz, UL: 0.045 bps/Hz (for Rural)
Average spectral efficiency	eMBB	DL: 9 bps/Hz/TRxP, UL: 6.75 bps/Hz/TRxP (for Indoor Hotspot) DL: 7.8 bps/Hz/TRxP, UL: 5.4 bps/Hz/TRxP (for Dense Urban) DL: 3.3 bps/Hz/TRxP, UL: 1.6 bps/Hz/TRxP (for Rural)
Area traffic capacity	eMBB	DL: 10 Mbps/m^2 (for Indoor Hotspot)
User plane latency	eMBB, URLLC	4 ms for eMBB and 1 ms for URLLC
Control plane latency	eMBB, URLLC	20 ms
Connection density	mMTC	1,000,000 devices per km^2
Energy efficiency	eMBB	Supporting low energy consumption capability when there is no data
Reliability	URLLC	1–10^{-5} success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge
Mobility	eMBB	Up to 500 km/h for high-speed vehicular
Mobility interruption time	eMBB, URLLC	0 ms
Bandwidth	eMBB	Minimum 100 MHz, up to 1 GHz for higher frequency band operation

- *Massive machine-type communications* (mMTC): In light of the information available now, mMTC structure is able to comprise a plenty number of devices that have latency insensitive structure, low cost, and long battery life. For instance, millions of sensors and actuators with limited power will be utilized in the mMTC.

Furthermore, the minimum performance needs of 5G mobile communication networks are approved and released by ITU-R in [14]. Several key performance indicator (KPI) parameters are included in this released report and these KPIs for different usage cases are listed in Table 10.2.

10.2.2 Challenges of 5G Networks and Some Potential Solutions

In order to achieve targets of the 5G networks, there are several challenges to be overcome. For instance, capacity, data rate, E2E latency, massive device connectivity, and the QoE issues are some examples for these challenges that will be explained and some potential solution proposals are given below. Figure 10.3 illustrates the challenges of 5G networks and some potential solutions for these challenges. In future, mobile networks will require supporting more network traffic than current levels and higher data rates for everywhere and every conditions. In order to accomplish this, there is clearly more capacity requirement both in the RAN and all network components such as backbone, backhaul, and fronthaul. It is important to note that wider spectrum, efficiency, and network densification are necessary for achieving more data rates and more capacity in the RAN [18, 19]. Moreover, new frequency bands at millimeter wavelength are being considered to provide wider spectrum for future networks. In addition to the using mmWave frequency bands for the 5G networks, massive multiple-input multiple-output (MIMO) is a good candidate to expand coverage area of higher frequency bands thanks to beamforming techniques. At this point, it is noteworthy that energy consumption and cost parameters must be kept in balance while increasing the capacity and data rate. One of the proposed methods is network densification that is composed of spatial densification and spectral aggregation [20, 21]. Spatial densification is a densification technique for base stations, which is based on increasing antenna numbers per user equipment and macrocell base station (MBS). Spectral aggregation is a technique to enable using multiple spectrum bands for a user and exploits higher frequencies than 3 GHz band. Another method is to use cognitive radio network (CRN) which includes cognitive radio processors.

This scheme is also called as secondary users (SUs) which utilize the available spectrum if there are no licensed users, in other words primary users (PUs). Spectrum gaps can be used more efficiently to enable higher data rate by this method [20]. Furthermore, spectral efficiency might be improved by exploiting novel techniques such as nonorthogonal multiple access (NOMA), sparse coded multiple access (SCMA) and filter bank multicarrier (FBMC). On the other hand, trade-off issues between spectral efficiency and energy efficiency are taken into account [20, 22–25].

Latency and reliability are crucial parameters for 5G networks to support new real-time applications. For instance, remote health check systems, industrial applications, cloud systems, smart grids, and so on need high-speed communication infrastructure to operate properly and safely. Furthermore, latency is a big problem for safety crucial applications of transportation systems in future networks because of the fact that the vehicles, especially high-speed trains, will be very fast such as up to 500 km/h and they will need quick response of request with high reliability and availability. Therefore, the 5G networks have to support 1 ms E2E latency to carry out these and new applications in the future. The latency issue, which depends on many effects, is a very challenging problem since it cannot be obtained by varying a single parameter or method. Developments of air interface, protocol stacks, and novel network structures

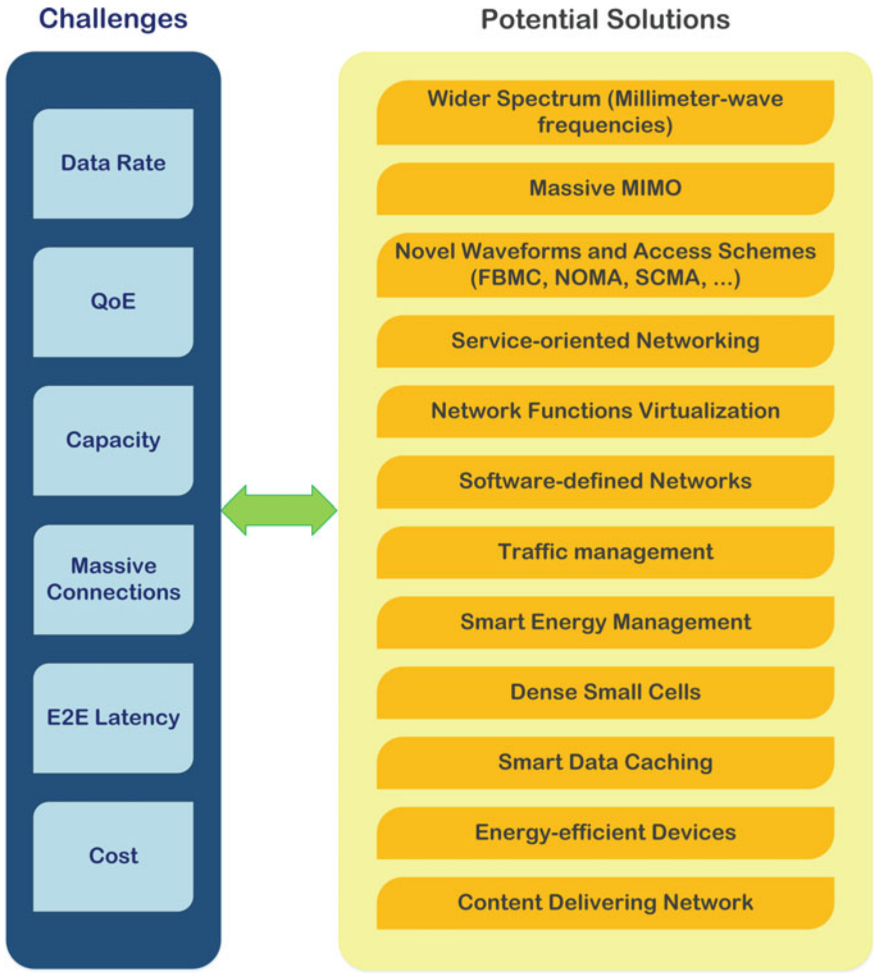

Fig. 10.3 Important challenges of 5G networks and some potential solutions

can be combined overcome this difficulty [19]. In addition, fast handover techniques and novel caching methods may help to reduce E2E latency of 5G networks [20].

The expectation of the increase of connected devices in the future networks is inevitable as mentioned before. Besides, supporting of the service requirements and device diversity is another difficulty for this concept. The devices connected to the network will be composed of two main categories. One of them is devices such as sensors, tags, and smart meters connected to the network only for conveying data at certain times, and the other is continuously connected devices to monitor something such as security cameras, health monitoring systems, and transportation tracking systems. While new methods are presented for decreasing latency, whole of the devices does not have to be with high resolution to overcome perfect synchronization for protecting orthogonality in multiple access mediums [19]. New waveforms and flexible radio accessing schemes can be also considered as potential candidates [26].

Generally, the QoS has been considered to evaluate service performance of mobile networks in 3G and 4G systems [19, 27]. Concept of user satisfaction will be important in the 5G mobile networks, which is called the QoE. This new concept characterizes how a service or application is perceived by the users in terms of all system performance, service prices, quality of contents, and so on. Therefore, this very specific metric may depend on both applications and users. On the other hand, future networks have to ensure services and applications with optimum QoE level for users. The cost issue is another and very important challenge for the future mobile communication techniques. In order to cope with explained challenges, there is a requirement to ensure for major developments that directly affect cost of the 5G networks. Since the customers will not meet the cost, the new network has to be at an affordable cost that will ensure the sustainable service quality.

10.3 Promising Key Technologies for 5G Networks

The development of cellular network generations is mainly affected by progress on wireless devices, higher data rate demand, and better system performance expectations. In recent years, a remarkable expansion in cellular traffic has been also obtained depending on increasing number of mobile user and new technologies in the market such as smart phones, tablets, e-book readers. The joint property of these new devices is able to support applications and services requiring high data usage. There is an expectation that new generation networks will have to service more than 50 billion connected devices by the end of the year 2020. This increase in the number of devices connected the network will lead to enormous data traffic when compared to the present networks [2, 20, 28]. Nevertheless, existing solutions are not adequate to overcome the mentioned challenges. Therefore, the aim of the improving technologies is to provide an increment in capacity of 5G networks by using all resources effectively. Total capacity of a system can be defined in accordance with the Shannon theory as follows [2].

$$C_{\text{total}} \approx \sum_{\text{Hetnets}} \sum_{\text{Channels}} B_k \log_2\left(1 + \frac{P_k}{P_N}\right) \tag{10.1}$$

where B_k denotes bandwidth of kth channel, P_k shows the signal power of kth channel, and P_N shows the power of noise. As can be obviously seen from the equation, total capacity of the system is composed of the combination of sub-channels and heterogeneous networks. There are several potential ways to improve total capacity of the systems [2, 20]. For instance, coverage area may be improved through heterogeneous networks including macro-/micro-/small cells, mobile femtocell, relays. Methods such as cooperative MIMO, massive MIMO, distributed antenna system

(DAS), spatial modulation, and interference management can be exploited to rise number of sub-channels. In order to increase bandwidth, new systems such as cognitive radio (CR) networks, mmWave communications, visible light communication (VLC), and multi-standard systems can be considered. Energy-efficient or green communications techniques may be also regarded to increase total capacity of systems. Some of these methods will be explained in the following subsections.

10.3.1 Massive Multiple-Input Multiple-Output (Massive MIMO) Technology

The developments in capacity and stability of the wireless communication systems with the use of multiple antennas opportunity have led to the creation of the active research area for last two decades. MIMO systems are important part of existing standards and have being used throughout the world. For instance, MIMO systems are widely exploited in the LTE and other similar technologies. The use of more antennas theoretically means more spectral efficiency and more transmission stability. However, channel capacity of the MIMO systems approximately increases linearly with the number of antennas especially when the number of transmit and receive antennas is large. Therefore, the use of multiple antennas will provide a largely effective way to increase system capacity. Practical MIMO systems utilize access points or base stations with relatively small number of antennas, and the corresponding improvement in spectral efficiency has been at modest rates. The number of multi-side antenna receiver configurations in existing wireless communication systems is not very high due to the limitations of the area covered by the multi-antenna. For instance, while the LTE systems exploit four antennas, the LTE-A systems may use up to eight antennas [29, 30]. In addition, technological studies on the MIMO systems with multiple antennas have attracted the attention of researchers because of the large capacity and reliability gains [31]. In order to achieve greater gains, it is envisaged the use of massive MIMO system that is a different application of the MIMO concept recommending the use of larger and more antennas in each base station (e.g., 100 or more) [32, 33]. The main idea of the massive MIMO is to extend MIMO concept for much larger scales. The massive MIMO is an improving technology that intends to provide more stability, more security, and more efficiency in terms of energy and spectrum for 5G mobile networks [4, 34]. First application foreseen for the massive MIMO systems is a cellular network infrastructure which has a base station with a large number of antennas (N_t) serving the community of single-antenna common channel users [32]. Traditional MIMO systems cannot realize high multiplexing gain, which is a performance indicator for the 5G mobile networks, since they contain a limited number of antennas. On the other hand, massive MIMO systems with multiple antenna arrays have the ability to serve a large number of single-antenna users at the same time and frequency range [35, 36]. The interaction of massive MIMO systems

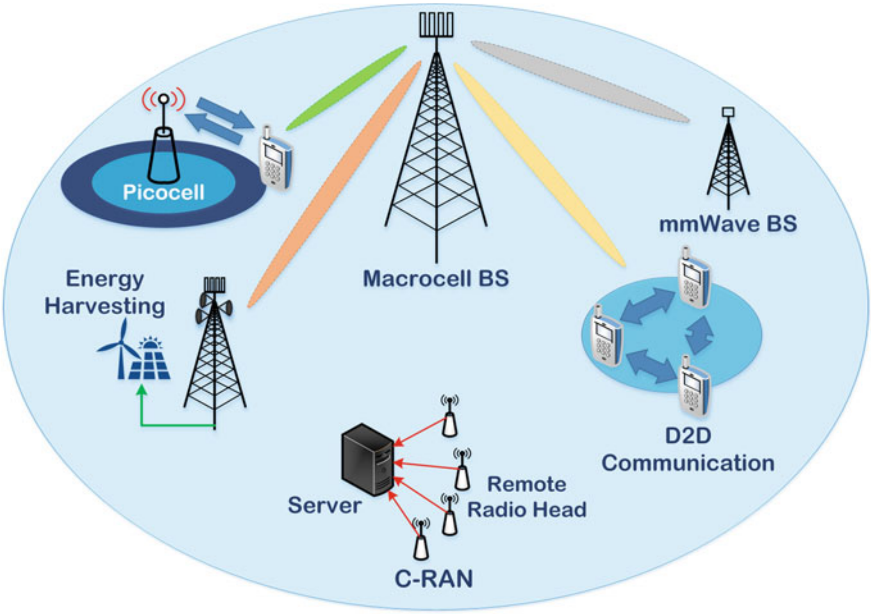

Fig. 10.4 Use of massive MIMO system in 5G communication technology

with 5G technology is shown in Fig. 10.4. The main features of massive MIMO systems are listed as follows [35].

- Massive MIMO systems provide higher power gain compared to conventional MIMO systems. Thus, the power of received signal increases considerably. For this reason, lower transmission power is required to achieve a specific QoS value [37]. The most important result of the low-power requirement advantage of the massive MIMO is no requirement for expensive equipment [4].
- Massive MIMO systems present higher spectral efficiency that remarkably advances the system throughput. This is the result of the ability of base stations with large antenna arrays to serve more users [34].
- The averaged effects of channel estimation errors, hardware failures, and small-scale fading are taken into account when the number of base station antennas is sufficiently high. Nevertheless, there is a main performance limiter called pilot pollution that occurs owing to improper use of the same pilot signals [38].

Simple signal processing methods such as maximal ratio combining (MRC) and maximal ratio transmission (MRT) can be exploited to achieve the superiorities of massive MIMO systems. It is assumed that these outcomes are generally obtained for ideal propagation environments including independent Rayleigh fading conditions. These wireless channels are inherently uncorrelated, and they are even asymptotic orthogonal structure. However, very high spectral efficiency can still be achieved in reality using a multitude of N_t antennas in non-ideal environments. Channel correla-

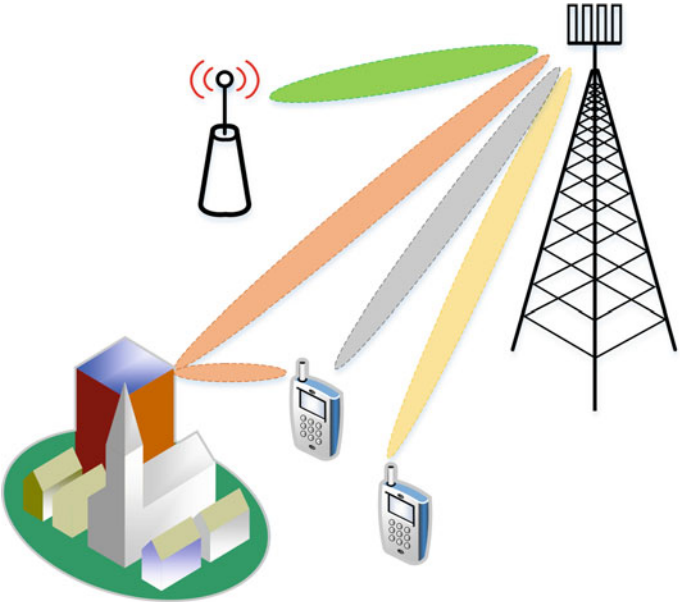

Fig. 10.5 Three-dimensional MIMO structure

tion problem may be particularly crucial for the realization of mmWave applications including line-of-sight (LOS) or near-LOS cases. This problem will probably prevent the use of MRC and MRP to suppress the interference. Therefore, zero-forcing (ZF) or minimum mean squared error (MMSE)-based beamforming methods can be exploited to decrease interference effects. One another advantage of the massive MIMO systems is the providing important gains in terms of energy efficiency. The presented gains by massive MIMO systems in energy efficiency may be used to handle path losses shown in mmWave frequencies [35]. In addition, massive MIMO systems can be obtained with low-cost and low-power components and they provide a great opportunity for the realization of mobile systems operating at high frequencies. Furthermore, this concept offers several additional advantages such as improving spectrum efficiency and coverage of network, enhancing system capacity, and providing the possibility to make better use of the available system structure [39]. Moreover, as can be seen from Fig. 10.5, 3D-MIMO includes a new dimension to the MIMO system, which enables three-dimensional beamforming and the possibility of mutual interference prevention [40]. Therefore, massive MIMO systems offer the advantage of multi-directional beamforming [29].

One of the important issues for the 5G networks is latency as mentioned before. The latency is mainly originated from fading which emerges between base station and user terminal. After the signal is conveyed from the base station, it is exposed to several disruptive effects such as reflection, diffraction, and scattering that cause to occur multi-paths. When the signal arrives to the terminal unit by passing over these multi-paths, it will induce interference that may affect the terminal unit positively or negatively. If a negative effect occurs on the terminal unit, strength of received signal decreases a significant low-value level. In the event of the terminal unit experiences a fading case, it needs to look forward to the transmission medium to vary until any data can be taken. The use of multiple antennas and beamforming techniques will prevent exposure to fading cases in the massive MIMO technology [4, 34].

Jamming is another important problem for wireless communication systems, which causes a critical threat for security. Fortunately, one of the important advantages of the massive MIMO systems is superiority in the security. It provides several methods for developing robustness of communication systems by employing multiple antennas. Also, it enables the possibility of creating excessive degrees of freedom that may be beneficial for removing jammer signals. It is possible to diminish jamming problem substantially in massive MIMO systems by exploiting mutual channel estimation and decoding in lieu of uplink pilots [4, 34].

10.3.2 Millimeter Wave (mmWave) Systems and mmWave Massive MIMO

The present allocated spectrum will not ensure the sufficient bandwidth that have to support increasing demand of users. The use of several methods such as utilizing of smaller cell structures, heterogeneous networks, more complicated modulation schemes, and MIMO systems will not be sufficient to compensate for required capacity of next generation networks. The mmWave communication systems have recently gained a great attention as a potential candidate technology for 5G networks since they are able to present gigabit-per-second data rates. The mmWave band, also known as extremely high frequency (EHF) band, covers the frequency band between 30 and 300 GHz. The highest electromagnetic radiation is shown in this band. The frequency range from 3 to 30 GHz is usually defined as super high frequency (SHF) band. The frequency band between 3 and 300 GHz is jointly called as mmWave bands with 1 to 100 mm wavelengths since the radio waves in these bands are subject of same propagation properties [7, 28].

The use of mmWave bands in the next generation networks presents several advantages [41]. The first advantage of mmWave frequencies is providing a very wide spectrum. When the current situation is considered, it is obvious the cellular systems below 3 GHz have very full and limited spectrum. The second one is able to reuse same frequency more often at mmWave communications because of the high attenuation effect of the free space. Third advantage is that the physical dimensions of the antennas in the mmWave frequencies are very small. Therefore, practical implementation of complex antennas and/or antenna arrays on printed circuit boards (PCBs) will be easier and feasible. The fourth, the mmWave band provides more secure and private transmission medium owing to narrow transmission space and beam widths. When the wire-line communication mediums are considered, traditional optical fibers offer more bandwidth and security. However, it is not an economic option to utilize fiber as a backhaul of ultra-dense networks for service providers since there are several limitations in terms of installation and distribution. Therefore, the use of wireless backhaul techniques (particularly using of mmWave backhaul) will be more appealing to handle these constraints [41, 42].

There are some proposed standards for the mmWave communications. IEEE 802.15 Task Group 3c (TG3c) developed an alternative physical layer (PHY) for wireless personal area network (WPAN) which is called IEEE 802.15.3c and operates the frequency range from 57 GHz to 64 GHz. Another important standard is IEEE 802.11ad that is developed as a PHY alternative in 60 GHz band to support short-range applications such as wireless docking, displaying, instant wireless synchronization, cordless computing [28, 43]. On the other hand, there are still challenges to be solved in order to make possible the use of mmWave communications in next generation networks. The most important six main challenges have to be firstly solved for achieving this task. The first three of these challenges are associated with mmWave transmission features that are channel characteristics, block effects, and beamforming methods. The other three challenges are related to application of mmWave into the device-to-device (D2D) communication, heterogeneous networks, and small cell backhaul issues.

Multi-path interference in the mmWave communications that is originated from multi-paths shown in the mmWave propagation channel is an important issue as in the other wireless communication technologies [44, 45]. In addition, if the signal attenuation is joined with the multi-path interference, paths in different lengths will clearly occur owing to scattering, reflections, and heterogeneous propagations. The reflections and scattering can be significantly decreased if the wavelength is close enough to the size of object, and the other one is related to penetration features of solid substances [45]. Doppler frequency should be also taken into account that changes with frequency of transmitted signal proportionally and denotes the maximum frequency difference between received and transmitted signals because of object mobility [46]. It is evident that rising carrier frequency will induce amplified Doppler effects. In order to prevent Doppler effect in the mmWave communication systems, they should be comprehensively analyzed for different conditions. The conducted experiments for explaining the relation between Doppler effect and varying channel conditions are shown that the Doppler effect is approximately 10 times higher in the mmWave communication systems [47]. Therefore, it is obvious that the Doppler effect will be very important issue in the mmWave communications, especially for high mobile systems.

Recently, a new concept called "mmWave massive MIMO" has been presented that combines the massive MIMO techniques with the mmWave communications. This novel approach aims to offer wireless networks including sub-networks of small cells and ensuring high-speed communication for 5G mobile networks than actual data rates [48]. It presents several advantages in terms of beamforming, diversity, and spatial multiplexing due to the nature of traditional massive MIMO architecture. While one significant advantage provided by the mmWave massive MIMO is the presenting more reliable backhaul connection, the other one is more flexible backhaul network scheme. Nevertheless, if this new concept is compared with the traditional massive MIMO systems employed for RANs, it is clearly seen that realization of this new scheme has several challenges to be overcome. The first challenge is about feasibility of transceivers and cost. There is a requirement to utilize more essential components such as ADCs, DACs, and mixers than that of the traditional wireless communication systems and this increases both cost and complexity of the system. Even though there is an opportunity to exploit many low-cost antennas and a few number of baseband chains to form transceiver structure for this new concept, disadvantage of this design idea is the causing new challenges for traditional precoding and/or combining schemes and requiring new design approaches in these units [42, 48]. The second challenge is about number of antennas in the mmWave systems, especially at both macro- and small cell base stations, which may be much larger because of smaller wavelength of mmWave. This challenge essentially means that channel estimation process will be harder in the mmWave massive MIMO systems [42, 48]. The other challenge is concerning channel state information (CSI) requirement at the receiver side. When single-antenna users in conventional massive MIMO systems are taken into account, the CSI is merely required for precoding process. On the other hand, when the mmWave massive MIMO systems are considered, the CSI is also necessary for the combining process at the receiver unit as well as the precoding process. Moreover, the obtained CSI via channel estimation at the receiver unit have to feedback to the small cell base stations in the uplink [42, 48].

10.3.3 Beamforming Techniques for 5G Mobile Communication Systems

Beamforming is an important method in order to decrease interference and to make up for heavy channel attenuation in the mmWave networks. An example of a cellular network structure in which units are able to support directional operation of multi-beam is illustrated in Fig. 10.6. By employing beamforming techniques, the base stations are authorized to utilize multiplexing for increasing data rate and/or to exploit spatial diversity for improving durability according to blockage cases. There are several communication modes like fully directional, omnidirectional, and semi-directional to set up a wireless connection. In fully directional way, base station and user equipment have directional structure all together. While both base station and user equipment have omnidirectional structure in omnidirectional mode, one of base station or user equipment has omnidirectional and other has directional mode in the semi-directional mode. As can be seen from Fig. 10.6, the use of fully directional pencil-beam communication can considerably decrease the inter-cell interference for both uplink and downlink. The beamforming techniques can be classified into three categories as analog, digital, and hybrid beamforming [49].

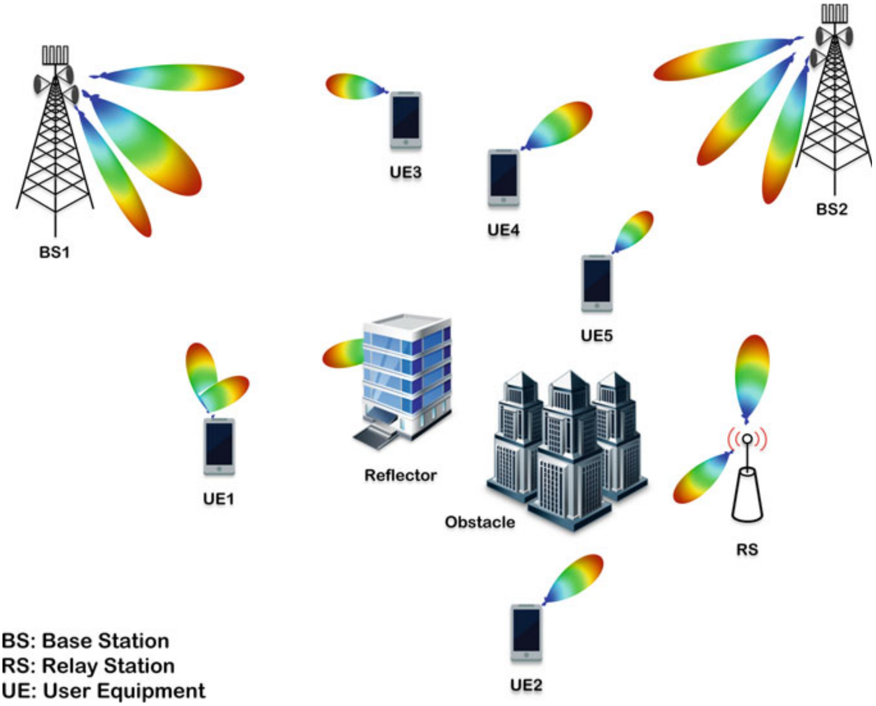

Fig. 10.6 An example of network structure utilizing directional communication via the beamforming

10.3.3.1 Analog Beamforming Technique

The beam is merely formed by employing an RF chain and one DAC in the analog beamforming method [50, 51]. The analog beamforming structure that is exploited at the transmitter side is depicted in Fig. 10.7a. This type of the beamforming process is realized in the RF domain by means of N phase shifters where each phase shifter is connected to an antenna. The transmitter can create a broadband beam by using this beamforming technique, which concentrates the power to a particular direction to be able to rise performance of the receiver unit. The most important advantage provided by this method is that beam-searching procedure that is a simple searching algorithm to determine optimum beams can be simply utilized. Analog beamforming technique has been already exploited in current mmWave wireless personal area networks (mmWave WPAN) , and wireless local area networks (WLAN) because of this simple searching advantage [43]. Comprehensive searching processes are also performed over codebooks that are composed of vector combinations having a finite knowledge about particular directions. The combination of these vectors that will enhance the signal-to-noise rate is chosen for the beamforming process. While this method reduces instantaneous CSI requirement, a trade-off between alignment and throughput should be considered [52]. Disadvantage of this method is that an RF chain only shapes one beam in a cycle due to the fact that spatial multiplexing of the beams is not possible. Therefore, this beamforming method can only ensure directional gain. In a special case such as narrow beam process, this method needs various RF chains to manage users located far away from each other. This reduces superiorities of the analog beamforming in terms of power consumption and complexity.

10.3.3.2 Digital Beamforming Technique

The block diagram of digital beamforming structure is depicted in Fig. 10.7b. The realization of the precoder in the digital baseband domain provides two significant advantages. One of them is availability to carry out precoders on several sub-bands that allow making up frequency selectivity of the channel. The other one is the carrying out multi-stream transmission that permits to support LOS users at the same time. In spite of the fact that digital beamforming architecture has the ability of ensuring flexibility in shaping of transmitted beams, this architecture needs an RF chain for each antenna. When this requirement is considered for the mmWave bands where a large number of antennas will be utilized as explained before, there will be an enormous increase in terms of cost and design complexity. In addition, if exploiting high-resolution ADCs for the RF chains are taken into account; this method will cause both very high-cost and very high-power consumption. Unfortunately, this situation is inversely proportional to the design targets of the 5G mobile networks [49, 53]. What is more, channel estimation process should be performed for all antenna couples of the transmitter and the receiver in this beamforming technique. The number of the transmitter antennas proportionally affects the complexity of the estimation process in addition to complicating the precoding process [33]. To exploit digital beamforming method in communication systems operating over very wide spectrum (in the level of several MHz and more), there is no possible and economical solution by satisfying the existing conditions [50, 54]. On the other hand, there are several approaches originated from employing sparse channel estimation techniques and low-resolution ADCs to enable digital beamforming in mmWave communication systems [55, 56].

10.3.3.3 Hybrid Beamforming Technique

Hybrid beamforming that contains a combination of analog and digital beamforming techniques is a special form of beamforming techniques. The architecture of hybrid beamforming is shown in Fig. 10.7c, and it is a promising technique for mmWave communication systems. Even though there is possibility to create hybrid precoders in several types, the main concept is the forming hybrid precoder by employing a small number of RF chains (M) compared with the number of antennas (N). In other words, this method authorizes the use of multiple antennas with limited RF chains [54, 57, 58]. It is also known via the performed researches that hybrid beamforming

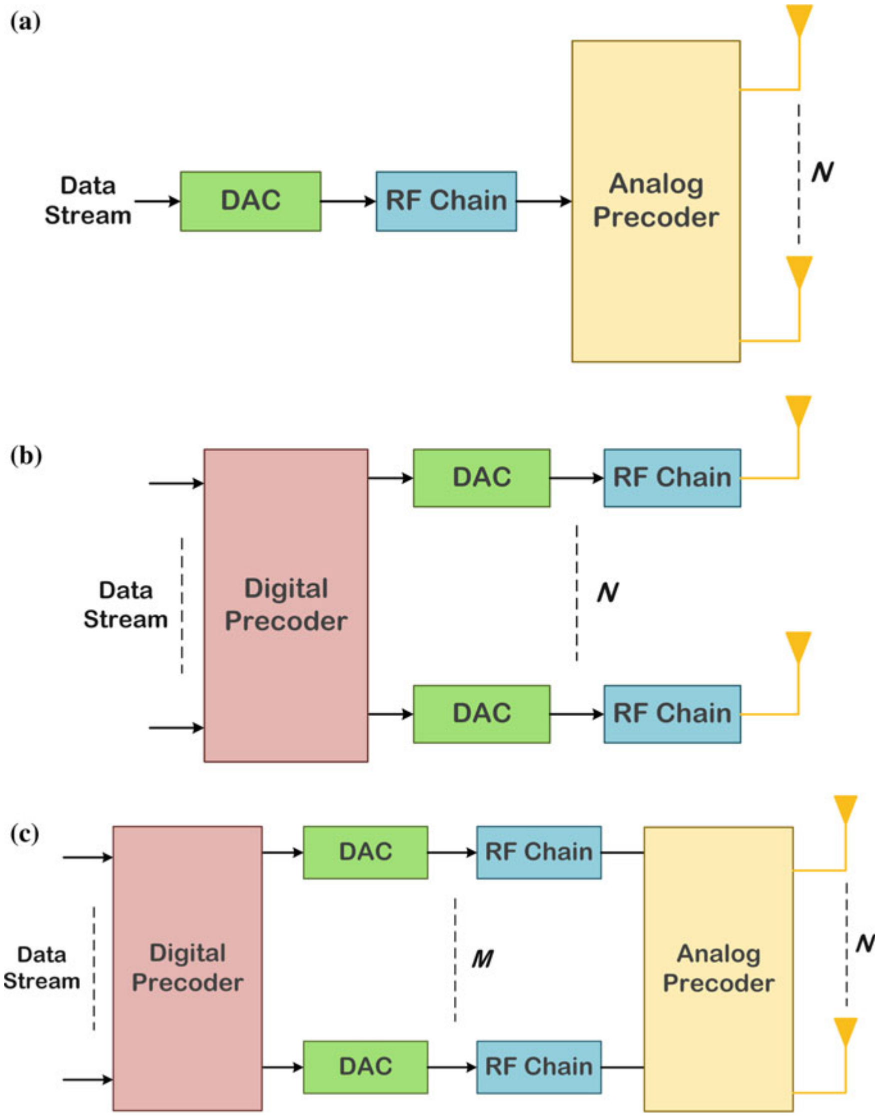

Fig. 10.7 Block diagrams of beamforming techniques employed at the transmitter: **a** Analog beamforming architecture, **b** digital beamforming architecture, **c** hybrid beamforming architecture

technique can reach up to the performance of digital beamforming method in the event of considering one base station serving one or more user. Nevertheless, difference in the performance between digital and hybrid beamforming techniques is inclined to rise if the RF disorders are comprised. Moreover, topological differences in the structure can remarkably affect the performance of the hybrid beamformers.

While the spatial division and directivity gains are performed by analog part of the hybrid beamformer, digital part is exploited to decrease intersector interference and to achieve multiplexing gain by employing the CSI. The complexity of the hybrid beamforming technique can be diminished thanks to sparse scattering feature inherent of the mmWave channels [55, 59, 60]. The results reported in [59] presents that hybrid beamforming technique can practically reach the pure digital beamforming performance by employing 8–16-fold fewer RF chains. At the same time, this result clearly showed that energy consumption could be remarkably decreased at the expense of very little performance degradation. Therefore, it can be clearly highlighted that hybrid beamforming technique offers the advantage of trade-off in terms of performance, cost, and energy consumption for the mmWave communications.

10.4 Channel Characteristics for 5G Mobile Communication Networks

The propagation channels directly affect performance of communication systems. Hence, investigation of the channel characteristics for 5G mobile communication systems is a significant need to design reliable communication systems in near future. The first step to fulfill this process is the obtaining correct CSI for the mmWave massive MIMO systems. If the CSI is obtained in a reliable and accurate way, maximum benefit can be provided from the superiorities of the mmWave massive MIMO systems in the 5G communication networks. Unfortunately, the channel estimation process of mmWave massive MIMO systems is more difficult task than that of the current communication systems since there are several reasons inherent of these systems as follows [16, 48].

- *Excessive number of antennas*: The antenna number of mmWave massive MIMO communication systems can be much more than that of the current communication systems operating between 3 and 6 GHz frequency band since the smaller wavelength of the mmWave signals will require using more antenna equipment. The decreasing wavelength of the communication signals offers several advantages as well as challenges. The advantage of this situation is that the same frequency values are more frequently reusable. The difficulty emerged in this case is challenging channel estimation process.
- *Constraints for practical implementation*: In the mmWave massive MIMO systems, the cost and energy consumption of communication units will be much more important than present cellular systems since there is a requirement to employ more ADCs, DACs, RF chains, mixers, and so on. The approaches to reduce cost and energy consumption will further complicate the channel estimation process. Therefore, the system designers need to provide a good trade-off between these parameters in order to present a reliable and appropriate communication system operating in the mmWave frequency band.

- *Low performance before beamforming process*: Thermal noise case will be more important problem due to using wider band in the mmWave communication systems. In addition, low performance occurring prior to beamforming process, which is originated from powerful directed signal, will complicate the channel estimation operation in the mmWave band. Moreover, Doppler effect and blockage effect have to take into account owing to wider bandwidth utilized.
- *Channel feedback requirement*: In order to increase connection reliability in mmWave massive MIMO communication systems in which both transmitters and receivers will have many antennas, precoding and combining processes are required to perform at user equipment for uplink and downlink, respectively. Hence, the CSI not only should be known both transmitter and receiver side, but also obtained CSI at the uplink side should be sent to the user equipment. This causes a channel feedback requirement in the mmWave massive MIMO communication systems.

10.4.1 Millimeter Wave Channel Characteristics

To date, performed researches have clearly indicated that mmWave massive MIMO channels have sparsity in the spatial or angular domain since they show high path loss for non-line-of-sight (NLOS) signals in which just a few number of entire paths include remarkable multi-path components. For practical cases, the number of paths is nearly 3–5. When the uniform linear array (ULA) antenna structure is considered, the mmWave massive MIMO channel can be defined as follows [48].

$$\mathbf{H} = \sqrt{\frac{N_T N_R}{\rho}} \sum_{l=1}^{L} \alpha_l \mathbf{a}_R(\theta_l) \mathbf{a}_T^*(\varphi_l) = \sqrt{\frac{N_T N_R}{\rho}} \mathbf{A}_R \mathbf{H}_a \mathbf{A}_T^* \tag{10.2}$$

where $(\cdot)^*$ represents Hermitian process (conjugate transpose), N_T and N_R denote the antenna numbers of transmitter and receiver units, respectively. ρ shows the average path loss, L shows multi-path number, α_l stands for the complex gain of the lth path, θ_l or $\varphi_l \in [0, 2\pi]$ denote azimuth angles of arrival or departure (AoA/AoD), respectively. The antenna array vectors $\mathbf{a}_R(\theta_l)$ and $\mathbf{a}_T(\varphi_l)$ given in Eq. (10.2) can be expressed as

$$\mathbf{a}_R(\theta_l) = \frac{1}{\sqrt{N_R}} \left[1,\ e^{j2\pi d \sin(\theta_l)/\lambda},\ \ldots,\ e^{j2\pi (N_R-1) d \sin(\theta_l)/\lambda}\right]^{\mathrm{T}} \tag{10.3}$$

$$\mathbf{a}_T(\varphi_l) = \frac{1}{\sqrt{N_T}} \left[1,\ e^{j2\pi d \sin(\varphi_l)/\lambda},\ \ldots,\ e^{j2\pi (N_T-1) d \sin(\varphi_l)/\lambda}\right]^{\mathrm{T}} \tag{10.4}$$

The antenna array vectors $\mathbf{A}_R$, $\mathbf{A}_T$ and diagonal matrix H_a can be also expressed as

$$\mathbf{A}_R = [\mathbf{a}_R(\theta_1),\ \mathbf{a}_R(\theta_2),\ \ldots,\ \mathbf{a}_R(\theta_L)] \tag{10.5}$$

$$\mathbf{A}_T = [\mathbf{a}_T(\varphi_1),\ \mathbf{a}_T(\varphi_2),\ \ldots,\ \mathbf{a}_T(\varphi_L)] \tag{10.6}$$

$$\mathbf{H}_a = \mathrm{diag}\{\alpha_1,\ \alpha_2,\ \ldots,\ \alpha_L\} \tag{10.7}$$

where λ and d denote wavelength and distance between antennas, respectively. The channel matrix of the mmWave massive MIMO possesses low-rank feature due to the sparsity of the mmWave channels. Therefore, effective communication systems operating in the mmWave frequency band can be created by using either the sparsity feature of these channels in the spatial/angular domain or the low-rank feature of the channel matrices. However, the mmWave channels are exposed various propagation effects different from the other communication channels such as atmospheric absorption and reflection in remarkable levels, and poor diffraction. In addition, it is expected that attenuation and dispersion characteristics of mmWave channels will be extremely distinctive [7, 16, 48]. These characteristics of the mmWave channels can be explained as follows.

Atmospheric and vegetation attenuations: The atmosphere may behave as an absorbent environment at mmWave frequency band, which will cause attenuation at significant level in the received signal. This attenuation can be expressed as

$$\text{Attenuation} = \exp(\phi_{\text{atm}} d_{TR}) \tag{10.8}$$

where d_{TR} denotes the distance between transmitter and receiver unit, ϕ_{atm} is the attenuation coefficient that is sensitive against to frequency and atmospheric situations (e.g., rain, storm, fog, and so on). It is assumed that this type of attenuation will not affect the next generation communication systems apart from the most violent conditions (such as rainstorms, hurricanes) since the foreseen cell size of the 5G systems at mmWave frequencies is no more than 200 m. However, there are special frequency ranges to be considered before designing of the mmWave communication systems. Attenuation level variations originated from the atmospheric gases are illustrated for millimeter waves in Fig. 10.8. Millimeter waves in the range of 3–300 GHz suffer from oxygen (O_2) and water vapor (H_2O) in these conditions. The frequencies from 57 to 64 GHz are called oxygen absorption band where millimeter waves can be exposed up to 15 dB/km attenuation values at around 60 GHz. The absorption effect of the water vapor is intensively shown between 164 and 200 GHz, and attenuation levels can reach up to tens of dBs in these frequencies. The more important attenuation type is vegetation attenuation case that may affect signals in mmWave more than atmospheric attenuation type. In this case, the level of attenuation generally rises depend on the increased path length over the vegetation. However, researches about this type of the attenuation are still in progress [7, 16].

Shadowing problem: The mmWave signals cannot pass through or diffract around humans and objects due to having very low wavelengths. Additionally, the shadowing effect directly leads to changes in the channel environment. Therefore, the shadowing is very important for communication systems that will operate in the mmWave frequencies. It is important to note that there exist different effects originated from

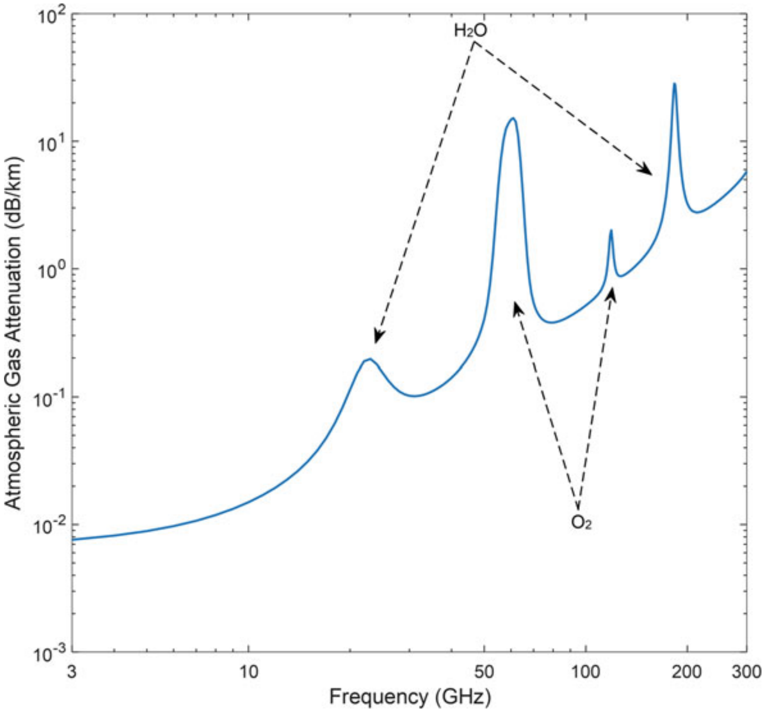

Fig. 10.8 Atmospheric absorption levels affecting the millimeter waves

the shadowing issue. In other words, the outcomes of the shadowing case may cause to influence communication systems both positively and negatively. One of them is that when the LOS is blocked there will be approximately 20 dB attenuation between transmitter and receiver unit, and this value is also valid for vehicles. Secondly, people moving around the receiver unit can lead to improve signal level of received power because of scattering effect.

Free space propagation: The loss of mmWave transmission is generally assumed to be due to free space propagation loss. The assumption where mmWave channels are affected more free space path loss originated from higher frequency values may lead to misunderstanding. This case is merely valid when antenna gain is frequency independent. If the effective aperture area of the antenna is constant, the path loss will not depend on the frequency. It is because that higher antenna gain can be obtained at higher values of frequencies for a fixed region. Therefore, when mmWave antenna arrays are compared with centimeter wave antenna arrays, the mmWave antenna array can provide to establish more antenna elements opportunity for the same area. Consequently, the advantage of the mmWave antenna array is to allow obtaining higher beamforming gains in both transmitter and receiver units [7, 16].

10.5 Potential Application Areas of the 5G Networks

Diversity of potential evolving applications encourages the release of the 5G network in the near future. It is expected that the 5G communication systems will offer new solutions for several sectors such as energy, health care, transportation, smart environments since this new generation communication system will come up with various outstanding characteristics that are higher data rate, higher energy efficiency, zero latency, and continuous connection for everything. The 5G networks need to ensure variety of devices and services in order to achieve these goals. Even though 4G networks are trying to support some application types in these sectors, there are obvious technical infrastructure deficiencies. The most important one of these deficiencies is the lack of sufficient bandwidth for these applications that will be solved via mmWave frequency band as explained before. A general classification diagram for the potential application areas and application types is illustrated in Fig. 10.9. As can be seen from the figure, the 5G networks can support wide range applications in several sectors. These sectors and specific application examples in these sectors will be explained by the following subsections in a detail [20, 61, 62].

Device-to-device (D2D) communication: The D2D communication method permits close user devices to communicate with each other through a licensed bandwidth by passing the base station. The D2D provides the advantage of more efficient employing energy and spectrum resources thanks to direct communications. The main application researches performed in the D2D communication are related with pricing schemes, social networks, emergency communications, video distribution, and smart grids. In addition, the coverage area of a base station and/or access point can be expanded by employing multi-hop communications in the D2D. In other words, user devices in the network can extend coverage range by behaving as relay stations. On the other hand, there are several challenges and open issues to be solved in the D2D communications. While the main challenges are interference management, resource allocation, delay-sensitive processing and pricing, the open issues are security and privacy, multi-mode selection and network coding schemes [6, 20, 62].

Machine-to-Machine (M2M) communication: A special communication type realized between only machines is referred as M2M communication system. Generally, data generation, measurement, acquisition, processing, and monitoring systems such as health measurement, remote monitoring of buildings and energy systems, security systems can be considered as examples of the M2M communications. It is expected that consumer electronics and building automation systems will form a large part of the M2M communication systems in the near future. The main idea behind the M2M communications is the performing these processes with minimum human intervention. Unfortunately, in order to progress development of existing M2M communication systems, there are various challenges to be overcome such as latency, security, capacity, and big data issues. Moreover, there are requirements to improve efficient algorithms for M2M communication systems. Similar to the D2D communication systems, the M2M communication systems will be supported by the 5G networks. Therefore, it is foreseen that these challenges can be eliminated by

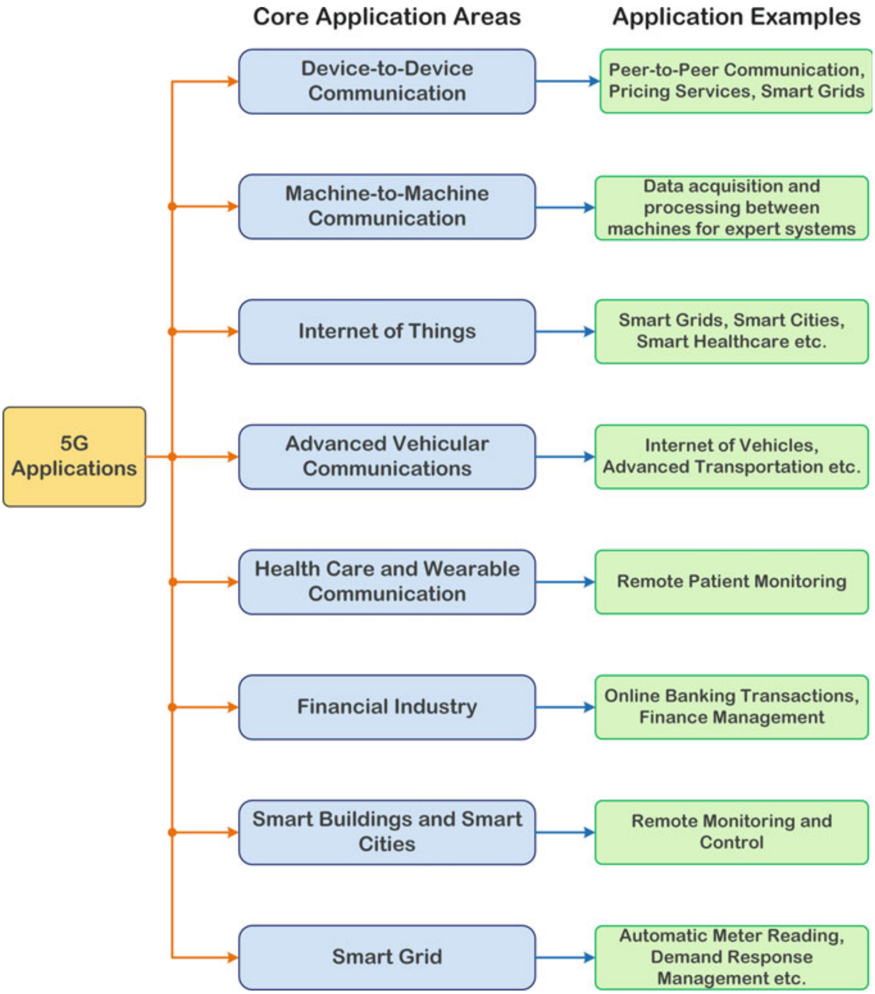

Fig. 10.9 Potential application areas of the 5G networks

superiorities of the 5G networks. The M2M communications in the 5G networks will serve wider coverage range and much more devices including sensors, smart meters, and smart grid instruments than that of the D2D communication systems [6, 20, 62].

Internet of Things (IoT): IoT aims to enable continuous Internet connection facility to all smart things, devices, and applications. Hence, the IoT concept considers a massive network structure where different type devices, smart environments such as smart grids, smart vehicles, smart cities, and smart logistics will be connected to the network. In order to accomplish this concept, there is high bandwidth requirement to be handled, which will be provided by developing of 5G wireless networks. There some issues need to be overcome in the current situation of IoT systems. These problems can be classified as automatic sensor configuration, system management modeling, context sharing, and security issues. Since the IoT system covers massive, distributed, and heterogeneous elements, realization of this platform is very complicated. In addition, cloud systems that provide storage, networking, and computing facilities can be combined with the IoT devices. It is also foreseen that the IoT concept will progressively convert the present Internet platform into the M2M communication concept enabled with 5G communication networks [6, 62].

Advanced vehicular communications: Internet of Vehicles (IoV) concept that is vehicles network structure targeting robust traffic management will appear depend on the development of IoT systems. Vehicular communication applications have gained a great attention recently where vehicles and roads have sensor and tag equipment for receiving and conveying information. For instance, driving assistance is a good application example for the advanced vehicular communication. In this application, each terminal unit utilizes the identical services such as traffic management and/or some special groups in particular area can be created to prevent extraordinary circumstances such as informing vehicles about accident situation occurred in the same area. In addition, developing of the 5G networks will ensure advancement in the vehicular communication systems. Similar to the IoT systems, the IoV will have a big data background that requires be handling and transmitting in a secure way. In addition, the use of cloud networks in the IoV systems will help to overcome the big data problem and to manage network efficiently [6, 20, 61, 62].

Health care and wearable communication: Health monitoring and wearable systems have gained a great attention recently due to developments shown in sensing and communication technologies. The wearable technologies aim to offer new solutions for health care. New devices that can measure multiple physiological signals are built up in recent years. The recording and processing multiple health signals are very crucial to diagnose diseases early. Similar to areas explained before, high bandwidth requirement is also appeared in the healthcare applications to manage the big data. In addition, there is a new application concept called remote health monitoring thanks to 5G wireless networks and body area networks (BANs). This real-time application also requires higher bandwidth. It is expected that the 5G networks will assist to improve healthcare applications by ensuring higher data rates and higher bandwidth opportunities [62].

Other applications: In addition to the above-explained application areas, the 5G networks will have application areas in financial industry, smart cities, smart building, and smart grids. Smart grids exploit wireless communication techniques for data collecting and monitoring, demand management, response management, and fault protection processes. The smart grid concept is composed of information and communication systems. Smart grid creates an excellent connection between physical equipment, sensing devices, and communication systems. The superiorities of 5G networks in terms of bandwidth, latency, and data rate will eliminate several present challenges of the smart grid systems. In addition, the 5G networks permit advanced observation, analysis, and management facilities for demand response process of smart grids [20, 62, 63].

10.6 Conclusions

This chapter deals with fundamentals, challenges, and key technologies of the 5G communication systems and recent trends of the mobile communication systems. There are several challenges to be handled such as higher capacity and data rate requirement, less E2E latency, supporting massive device connectivity, and higher QoEs in order to achieve aims of the 5G networks. On the other hand, there are some potential solutions to overcome these challenges. The most important key technologies for the 5G networks are massive MIMO, mmWave systems, mmWave massive MIMO systems, and beamforming techniques. The massive MIMO technology intends to extend traditional MIMO concept for much larger scales in the 5G mobile communication systems. In addition, the enabling of the millimeter wave frequencies via mmWave communication systems will be promising for the bandwidth problem of existing communication system infrastructure. Furthermore, combining the massive MIMO systems with mmWave communications will provide several advantages for 5G mobile communication systems in terms of beamforming, diversity, and spatial multiplexing. One of the most important issues for the 5G networks is the beamforming process. The use of pure beamforming techniques in the 5G networks such as full-digital or full-analog beamforming methods is not appropriate due to the cost, consumption, and design complexity. Therefore, the hybrid beamforming technique that offers the advantage of trade-off in terms of performance, cost, and energy consumption is a potential candidate for the 5G mobile communication systems. Another important open issue is the channel models for the 5G networks. Even though several measurement and modeling researches have been performed to characterize the mmWave massive MIMO channels, there is no standardized channel model for the 5G networks. As a final remark, it is obvious that the 5G networks, which will be standardized around 2020s, will come up with various outstanding characteristics for supporting several sectors such as energy, health care, transportation, smart environments.

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