CHAPTER

5G WIRELESS ACCESS

23

23.1 WHAT IS 5G?

As described already in Chapter 1, the world has witnessed four generations of mobile communication, with each new generation emerging roughly 10 years after the emergence of the previous generation.

The first generation consisted of the analog systems introduced in the early 1980s. They were only supporting voice services and, for the first time, made mobile telephony available to ordinary people.

The second generation (2G), emerging in the early 1990s, took mobile telephony from being used by some people to being available to essentially everyone and everywhere. Technology-wise, the key feature of 2G was the transition from analog-to-digital transmission. Although the main service was still voice, the introduction of digital transmission also enabled the first support of mobile data.

Third-generation (3G) WCDMA, later evolved into HSPA, was introduced in 2001. 3G lay the foundation for mobile broadband and, especially with HSPA, made true mobile internet access available to ordinary people.

We are now well into the fourth-generation (4G) era of mobile communication with the first LTE systems being introduced in 2009. Compared to HSPA, LTE provides even better mobile broadband including higher achievable data rates and higher efficiency in terms of, for example, spectrum utilization.

It is important to note that the introduction of a new generation of mobile communication has, in no way, implied the end of the previous generation. The situation has rather been the opposite. The deployment of 2G systems actually accelerated after the introduction of 3G. Likewise, there is still a massive deployment of 3G systems despite the introduction of LTE more than 6 years ago. Thus it is not surprising that, although LTE is still at relatively early stage of deployment, the industry is already well on the path toward the next step of mobile communication—that is, the *fifth generation* or 5G.

5G will continue on the path of LTE, enabling even higher data rates and even higher efficiency for mobile broadband. However, the scope of 5G is much wider than just further enhanced mobile broadband. Rather, as already mentioned in Chapter 1, 5G is often described as a platform that should enable wireless connectivity for essentially any kind of device or any

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00023-6

kind of application that may benefit from being connected. The concept of *machine-type communication* (MTC) is one part of this extended set of use cases expected in the 5G era. As described in Chapter 20, major steps to further enhance the support for certain types of MTC applications have already been taken as part of the evolution of LTE. More specifically, these steps have focused on *massive-MTC* applications associated with very low-cost devices with very long battery life but with relatively modest data rate and latency requirements.

However, 5G is assumed to enable connectivity for a much wider range of new use cases. Examples of additional use cases explicitly mentioned in the context of 5G includes wireless connectivity for remote control of machinery, wireless connectivity for traffic safety and control, and monitor/control of infrastructure, to just name a few. Furthermore, 5G should not only be a platform for providing connectivity for already identified applications and use cases. Rather 5G should be flexible enough to enable connectivity also for future applications and use cases that may not yet even be anticipated.

The very wide range of use cases to be covered by 5G implies that the capabilities of 5G wireless access have to extend far beyond that of previous generations. For the first and second generation networks the use case in focus was mobile telephony with the main target to provide good speech quality for as many users as possible. For 3G and 4G, the change of focus toward mobile broadband implied that the quality measure changed from speech quality to achievable end-user data rate. In line with this, the main target for 3G and 4G has been to enable as high data rates as possible for as many users as possible. However, for 5G there will be a much wider set of capabilities and requirements, some of which may even be partly contradicting each other.

23.1.1 DATA RATES

Providing the possibility for even higher end-user data rates will be an important requirement also in the 5G era, primarily as part of a quest for further enhanced mobile-broadband experience. Although support for extremely high peak data rates of 10 Gbit/s and higher is often mentioned in the context of 5G, this is just one aspect of a more general aim for higher data rates in all types of environments. Providing higher data rates may, for example, also include making several 100 Mbit/s generally available in urban and suburban environments. This would imply an increase in achievable data rates roughly a factor 10 compared to what can be provided with current technologies.

Furthermore, if one agrees with the vision of wireless connectivity being available "everywhere and for everyone," higher data rates may, for example, also include a few Mbit/s essentially everywhere in the world including rural areas in developing countries where there may currently be no broadband access what-so-ever.

23.1.2 LATENCY

In terms of latency requirements, the possibility to provide an end-to-end latency in the order of 1 ms is often mentioned in the context of 5G.

Low latency has since the emergence of HSPA been recognized as an important component to enable a good mobile-broadband experience. However, for 5G the possibility to provide connectivity with very low latency will also be an enabler for new latency-critical wireless applications such as remote control with haptic feedback and wireless connectivity for traffic safety.[1] It should be pointed out though that very few wireless applications that actually require an end-to-end latency as low as 1 ms have been identified. Providing the possibility for such low latency should thus more be seen as an enabler of future yet unknown applications, rather than something that has been concluded to be needed for currently envisioned applications. It should also be noted that end-to-end latency depends on much more than just the radio-access solution. Depending on the physical distance between the end points, an end-to-end latency of 1 ms may even be physically impossible. Nevertheless, a requirement of a 1 ms end-to-end latency implies that the radio-access network, including the network-to-device link, should be able to provide a latency significantly less than 1 ms.

23.1.3 EXTREME RELIABILITY

Another characteristic often mentioned in the context of 5G is the possibility to enable connectivity with extremely high reliability.

It should be noted that high reliability, in this context, could mean very different things. In some cases high reliability has been associated with the ability of the wireless-access solution to provide connectivity with extremely low error rate, for example, an error rate below 10^{-9}. In other contexts extreme reliability has, for example, been associated with the ability to retain connectivity even in case of unexpected events including natural disasters. This is obviously a very different requirement, requiring very different solutions, compared to a requirement to provide connectivity with extremely low error rate under more normal conditions.

23.1.4 LOW-COST DEVICES WITH VERY LONG BATTERY LIFE

Some applications, such as the collection of data from a very large number of sensors, require the possibility for devices of much lower cost compared to the devices of today. In many cases, such applications also require the possibility for devices with extremely low device energy consumption enabling battery life of several years. At the same time, these applications typically require only very modest data rates and can accept long latency. As described in Chapter 20, the evolution of LTE has already taken some substantial steps in this direction, fulfilling many of the 5G requirements in this area.

23.1.5 NETWORK ENERGY EFFICIENCY

Another important requirement emerging during the last few years has been the aim for significantly higher network energy efficiency. Although partly driven by the general quest

[1] The term haptic feedback is used to indicate remote control where feedback from the controlled device is used to provide a "real-life" sensation to the controlling device.

for a more sustainable society, enhanced network energy efficiency also has some very real and concrete drivers.

First, the cost of the energy needed to operate the network is actually a significant part of the overall operational expense of many operators. Increased network energy efficiency is therefore one important tool to reduce the operational cost of a network.

Secondly, there are many places, especially in developing countries, where there is a need to provide mobile connectivity but where there is no easy access to the electrical grid. The typical way of providing power to infrastructure in such locations is by means of diesel generators, an inherently costly and complex approach. By improving the energy efficiency of infrastructure, primarily base stations, providing power by means of decently sized solar panels becomes a much more viable option.

It should be noted that high network energy efficiency is not just an issue for future 5G networks. Enhancing the network energy efficiency of currently available technologies and networks is at least as important, especially taking into account that, in terms of deployed infrastructure, currently available technologies will dominate for many years to come. However, the introduction of a new generation not constrained by backward compatibility opens up for new opportunities in terms of energy efficiency. On the other hand, the potential to enhance energy efficiency of existing technologies is partly constrained by the requirement to retain backward compatibility and support legacy devices.

23.2 5G AND IMT-2020

As described in Chapter 2, since the emergence of 3G the different generations of mobile communication have been tightly associated with so-called *IMT* technologies defined by ITU-R. ITU-R does not, by itself, develop any detailed technical specifications related to IMT. Rather, what ITU-R does is to specify the capabilities needed from a certain IMT technology and the requirements that the technology needs to fulfill. Actual technology is developed elsewhere, for example, within 3GPP, and then submitted to ITU-R as a *candidate IMT technology*. After evaluation against the specified requirements, the submitted candidate technology may be approved as an IMT technology.

Around year 2000 ITU-R defined the concept of *IMT-2000*. The 3G technologies WCDMA/HSPA, cdma2000, and TD-SCDMA were all submitted to ITU-R and subsequently approved as IMT-2000 technologies. Ten years later ITU-R defined the concept of *IMT-Advanced*. Two technologies, LTE and WiMax [67], were submitted to ITU-R and both were approved as IMT-Advanced technologies.[2] Among these, LTE is by far the most dominating.

In 2013 ITU-R initiated activities to define the next step of IMT, referred to as *IMT-2020*. In-line with IMT-2000 being associated with 3G and IMT-Advanced being associated with

[2]Strictly speaking, only LTE release 10 and beyond are approved as IMT-advanced technology although all releases of LTE are seen as 4G.

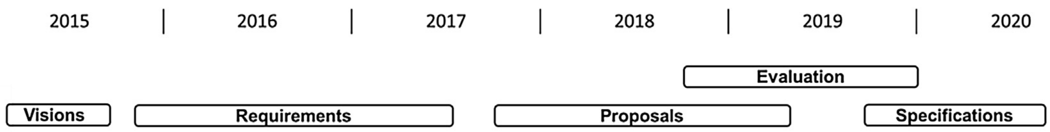

FIGURE 23.1

ITU-R time plan for IMT-2020.

4G, IMT-2020 can be seen as being associated with 5G wireless access. The detailed ITU-R time plan for IMT-2020 was presented in Chapter 2 with the most important steps summarized in Figure 23.1.

The ITU-R activities on IMT-2020 started with the development of a "vision" document [63], outlining the expected use scenarios and corresponding required capabilities of IMT-2020. ITU-R is now in the process of defining more detailed requirements for IMT-2020, requirements that candidate technologies are then to be evaluated against. These requirements are targeted to be finalized mid-2017.

Once the requirements are finalized, candidate technologies can be submitted to ITU-R. The proposed candidate technology/technologies will then be evaluated against the IMT-2020 requirements and the technology/technologies that fulfill the requirements will be approved and published as part of the IMT-2020 specifications in the second half of 2020. Further details on the ITU-R process can be found in Section 2.3 of Chapter 2.

23.2.1 USAGE SCENARIOS FOR IMT-2020

With a wide range of new use cases being one principal driver for 5G, ITU-R has defined three usage scenarios that form a part of IMT vision recommendation [63]. Inputs from the mobile industry and different regional and operator organizations were taken into the IMT-2020 process in ITU-R WP5D, and were synthesized into the three scenarios:

- *Enhanced mobile broadband (EMBB)*: With mobile broadband today being the main driver for use of 3G and 4G mobile systems, this scenario points at its continued role as the most important usage scenario. The demand is continuously increasing and new application areas are emerging, setting new requirements for what ITU-R calls *enhanced mobile broadband.* Because of its broad and ubiquitous use, it covers a range of use cases with different challenges, including both hot spots and wide-area coverage, with the first one enabling high data rates, high user density and a need for very high capacity, while the second one stresses mobility and a seamless user experience, with lower requirements on data rate and user density. The enhanced mobile broadband scenario is in general seen as addressing human-centric communication.
- *Ultra-reliable and low-latency communications (URLLC)*: This scenario is intended to cover both human and machine-centric communication, where the latter is often referred to as critical machine-type communication (C-MTC). It is characterized by use cases

with stringent requirements for latency, reliability and high availability. Examples include vehicle-to-vehicle communication involving safety, wireless control of industrial equipment, remote medical surgery, and distribution automation in a smart grid. An example of a human-centric use case is 3D gaming and "tactile internet," where the low-latency requirement is also combined with very high data rates.

- *Massive machine-type communications (M-MTC)*: This is a pure machine-centric use case, where the main characteristic is a very large number of connected devices that typically have very sparse transmissions of small data volumes that are not delay sensitive. The large number of devices can give a very high connection density locally, but it is the total number of devices in a system that can be the real challenge and stresses the need for low cost. Due to the possibility of remote deployment of M-MTC devices, they are also required to have a very long battery life time.

The usage scenarios are illustrated in Figure 23.2, together with some example use cases. The three scenarios described in the preceding list are not claimed to cover all possible use cases, but they provide a relevant grouping of a majority of the presently foreseen use cases and can thus be used to identify the key capabilities needed for the next-generation radio-interface technology for IMT-2020. There will most certainly be new use cases emerging,

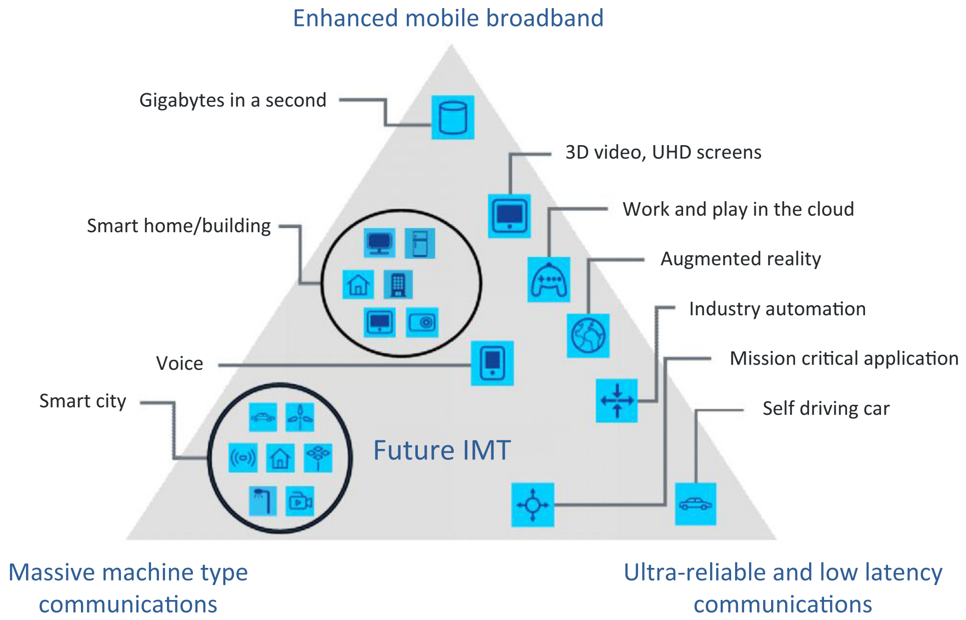

FIGURE 23.2

IMT-2020 use cases and mapping to usage scenarios.

From Ref. [63], used with permission from the ITU.

which we cannot foresee today or describe in any detail. This also means that the new radio interface must have a high flexibility to adapt to new use cases, and the "space" spanned by the range of the key capabilities supported should support the related requirements emerging from evolving use cases.

23.2.2 CAPABILITIES OF IMT-2020

As part of the development the framework for the IMT-2020 as documented in the IMT vision recommendation [63], ITU-R defined a set of capabilities needed for an IMT-2020 technology to support the 5G use cases and usage scenarios identified through the inputs from regional bodies, research projects, operators, administrations, and other organizations. There are a total of 13 capabilities defined in [63], where eight were selected as *key capabilities*. Those eight key capabilities are illustrated through two "spider web" diagrams, see Figures 23.3 and 23.4.

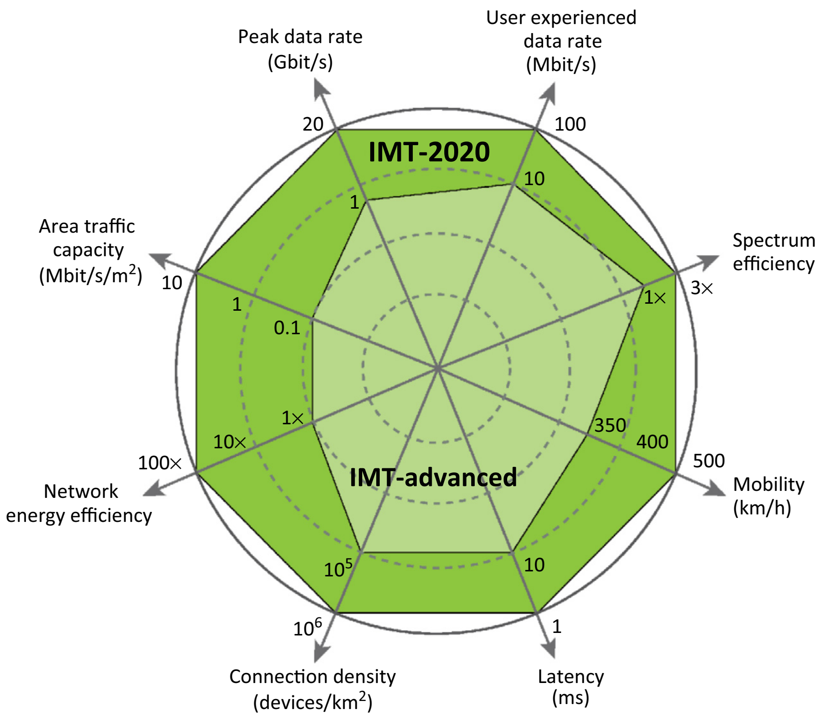

FIGURE 23.3

Key capabilities of IMT-2020.

From Ref. [63], used with permission from the ITU.

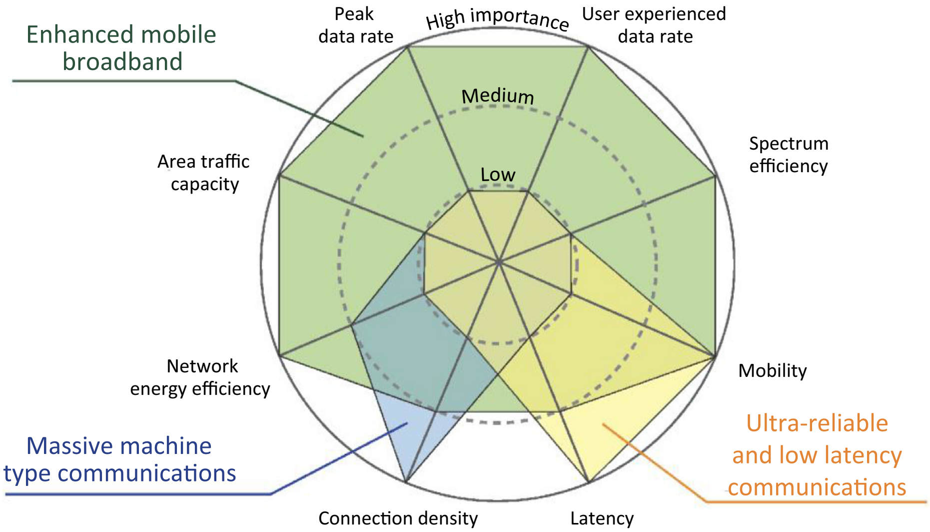

FIGURE 23.4

Relation between key capabilities and the three usage scenarios of ITU-R.

From Ref. [63], used with permission from the ITU.

Figure 23.3 illustrates the key capabilities together with indicative target numbers intended to give a first high-level guidance for the more detailed IMT-2020 requirements that are now under development. As can be seen the target values are partly absolute and partly relative to the corresponding capabilities of IMT-advanced. The target values for the different key capabilities do not have to be reached simultaneously, and some targets are to a certain extent even mutually exclusive. For this reason there is a second diagram shown in Figure 23.4 which illustrates the "importance" of each key capability for realizing the three high-level usage scenarios envisioned by ITU-R.

Peak data rate is a number which always has a lot of focus, but it is in fact quite an academic exercise. ITU-R defines peak data rates as the maximum achievable data rate under ideal conditions, which means that the impairments in an implementation or the actual impact from a deployment in terms of propagation, and so on does not come into play. It is a dependent *key performance indicator* (KPI) in that it is heavily depending on the amount of spectrum available for an operator deployment. Apart from that, the peak data rate depends on the peak spectral efficiency, which is the peak data rate normalized by the bandwidth:

$$\text{Peak data rate} = \text{System bandwidth} \times \text{Peak spectral efficiency}$$

Since large bandwidths are really not available in any of the existing IMT bands below 6 GHz, it is expected that really high data rates will be more easily achieved at higher frequencies. This leads to the conclusion that the highest data rates can be achieved in indoor and hot-spot environments, where the less favorable propagation properties at higher frequencies are of less importance.

The *user-experienced data rate* is the data rate that can be achieved over a large coverage area for a majority of the users. This can be evaluated as the 95th percentile from the distribution of data rates between users. It is also a dependent capability, not only on the available spectrum but also on how the system is deployed. While a target of 100 Mbit/s is set for wide area coverage in urban and suburban areas, it is expected that 5G systems could give 1 Gbit/s data rate ubiquitously in indoor and hot-spot environments.

Spectrum efficiency gives the average data throughput per Hz of spectrum and per "cell," or rather per unit of radio equipment (also referred to as *transmission reception point*, TRP). It is an essential parameter for dimensioning networks, but the levels achieved with 4G systems are already very high. The target was set to three times the spectrum efficiency target of 4G, but the achievable increase strongly depends on the deployment scenario.

Area traffic capacity is another dependent capability, which depends not only on the spectrum efficiency and the bandwidth available, but also on how dense the network is deployed:

$$\text{Area Traffic Capacity} = \text{Spectrum efficiency} \cdot \text{BW} \cdot \text{TRP density}$$

By assuming the availability of more spectrum at higher frequencies and that very dense deployments can be used, a target of a 100-fold increase over 4G was set for IMT-2020.

Network energy efficiency is, as already described, becoming an increasingly important capability. The overall target stated by ITU-R is that the energy consumption of the radio access network of IMT-2020 should not be greater than IMT networks deployed today, while still delivering the enhanced capabilities. The target means that the network energy efficiency in terms of energy consumed per bit of data therefore needs to be reduced with a factor at least as great as the envisaged traffic increase of IMT-2020 relative to IMT-advanced.

These first five key capabilities are of highest importance for the enhanced mobile broadband usage scenario, although mobility and the data rate capabilities would not have equal importance simultaneously. For example, in hot spots, a very high user-experienced and peak data rate, but a lower mobility, would be required than in wide-area coverage case.

Latency is defined as the contribution by the radio network to the time from when the source sends a packet to when the destination receives. It will be an essential capability for the URLLC usage scenario and ITU-R envisions that a 10-fold reduction in latency from IMT-advanced is required.

Mobility is in the context of key capabilities only defined as mobile speed, and the target of 500 km/h is envisioned in particular for high-speed trains and is only a moderate increase from IMT-advanced. As a key capability, it will however also be essential for the URLLC usage scenario in case of critical vehicle communication at high speed and will then be of high importance simultaneously with low latency. Note that mobility and high user-experienced data rates are not targeted simultaneously in the usage scenarios.

Connection density is defined as the total number of connected and/or accessible devices per unit area. The target is relevant for the M-MTC usage scenario with a high density of connected devices, but an EMBB dense indoor office can also give a high connection density.

In addition to the eight capabilities given in Figure 23.3 there are five additional capabilities defined in [63]:

- *Spectrum and bandwidth flexibility*
  Spectrum and bandwidth flexibility refers to the flexibility of the system design to handle different scenarios, and in particular to the capability to operate at different frequency ranges, including higher frequencies and wider channel bandwidths than today.
- *Reliability*
  Reliability relates to the capability to provide a given service with a very high level of availability.
- *Resilience*
  Resilience is the ability of the network to continue operating correctly during and after a natural or man-made disturbance, such as the loss of mains power.
- *Security and privacy*
  Security and privacy refers to several areas such as encryption and integrity protection of user data and signaling, as well as end-user privacy preventing unauthorized user tracking, and protection of network against hacking, fraud, denial of service, man in the middle attacks, and so on.
- *Operational lifetime*
  Operational life time refers to operation time per stored energy capacity. This is particularly important for machine-type devices requiring a very long battery life (e.g., more than 10 years) whose regular maintenance is difficult due to physical or economic reasons.

Note that these capabilities are not necessarily less important than the capabilities of Figure 23.3 despite that the later are referred to as “key capabilities.” The main difference is that the key capabilities are more easily be quantifiable while the remaining five capabilities are more of qualitative capabilities that cannot easily be quantified.

23.2.3 STUDIES OF 5G IN REGIONAL AND OPERATOR GROUPS

As shown earlier, the driver for a new generation of mobile systems is this time not only an envisioned evolution of mobile-broadband services that would require higher data rates, lower delays, and a demand for higher capacity, but also new usage scenarios that could be of a more revolutionary nature. Such a development is forecasted in early research projects for the next generation, such as the European METIS project. Requirements from the mobile operators, as put forward by the *next-generation mobile network* (NGMN) alliance [77], also draws on similar new use cases and interaction with new industries as a basis for their requirements on the next generation. The studies have been input to the ITU-R as part of the work on IMT-2020.

The METIS project in Europe did early work on identifying what solutions were necessary for the next-generation radio access in [78]. While a further evolution of present networks can meet many new demands through an evolutionary approach, METIS identified challenges that would also require a disruptive approach for handling a "traffic explosion" in terms of increased use of mobile communication and in addition an extension to new application fields. Five main challenges were identified that each corresponded to specific scenarios:

- "*Amazingly fast*" is a scenario where instantaneous connectivity gives the user a "flash" behavior when using the mobile network for work or infotainment. The challenge is the very high data rates required, which also implies that very large data volumes will be exchanged.
- "*Great service in a crowd*" implies a scenario with wireless internet access in places with a high density of users in large crowds such as in a stadium. The challenge in such scenarios will be the high density of communicating devices, in addition to high data rates and data volumes.
- "*Ubiquitous things communicating*" is a scenario looking beyond human-centric communication, focusing on MTC, sometimes also called the internet of things (IoT). Such connected devices will often be simple, such as temperature sensors, but there may be many of them in massive deployments. The challenge will then be battery life time, cost, and just the large number of devices itself.
- "*Best experience follows you*" is a scenario envisioning a consistent and reliable high-quality user experience for the fully mobile user, whether you are at home, walking down the street, or traveling on a train. This could also apply to machine communication in, for example, vehicles. The challenge here is the mobility, in combination with the high-quality experience.
- "*Super real-time and reliable connections*" is a scenario targeting machine-to-machine communication, where a very low end-to-end latency must be guaranteed with a very high reliability. Examples are industrial applications and vehicle-to-vehicle communication involving safety. The challenge will be providing the low latency with very high probability.

These five scenario scenarios are not mutually exclusive, but give a broad coverage of possible applications for 5G.

The mobile operators group NGMN Alliance published a 5G white paper [77] where requirements on the next-generation mobile systems are analyzed for a total of 24 different use cases, divided into 14 categories and 8 families. The use cases map in general to scenarios similar to the ones put forward by the METIS project. One notable difference is that "broadcast" is put forward by NGMN as a separate use-case category. For each use-case category, a set of requirements are stated by NGMN.

Another operator group that also produced a 5G white paper is 5G Americas[3] [79], where five market drivers and use cases are identified for 5G. In addition to the already identified scenarios for internet of things and extreme mobile broadband, including gaming and extreme video, 5G Americas also stress the needs of public safety operations for mission-critical voice

[3]The organization was earlier known as *4G Americas*.

and data communications and the task for the 5G ecosystem to also replace the landline (PSTN) network with wireless broadband. One additional use case identified by 5G Americas is context-aware devices, as a new service model addressing the end user's need to find relevant information in the ever-increasing amount of available information.

There are also several regional groups that have provided input to the requirements for the next-generation mobile system, such as the *5G Forum* in Korea and the *ARIB 2020 Beyond AdHoc* in Japan, and the *IMT-2020(5G) Promotion Group* in China. The latter published a white paper [80] with a very similar overall vision as the one provided by operator and regional groups. It identifies a broader use of 5G that will penetrate every element of the future society, not only through an extended use of mobile broadband, but also by "connecting everything" and providing interconnection between people and things. One aspect that is stressed in particular is the sustainability of future networks, where the energy efficiency will be an essential parameter.

23.3 ONE VERSUS MULTIPLE TECHNOLOGIES: "NETWORK SLICING"

The very wide range of applications and use cases to be addressed by 5G wireless access has raised the question whether this should be achieved with a single 5G radio-access solution or if one should rather develop a set of radio-access solutions addressing different groups of applications.

Optimizing the radio-access solution toward a specific group of applications with a more limited requirement space may obviously lead to a more efficient solution for those specific applications. At the same time, there are clear benefits of being able to support an as wide range of applications as possible with the same basic technology and within a common pool of spectrum. Most importantly, there is still a high degree of uncertainty about what will really be the most important and economically most feasible new wireless applications in the 5G era. Developing a technology and deploying a system specifically targeting a limited group of applications thus implies a big risk from an operator point of view. By developing and deploying a technology that can be used for a wide range of different applications this risk will be significantly reduced.

One can make a parallel to the introduction of 3G roughly 15 years ago. At that time there was still a high degree of uncertainty about the actual potential of mobile broadband. However, the 3G technologies were also able to support voice service with high efficiency, something which in itself motivated the deployment of 3G networks. Mobile broadband could then be gradually introduced with limited extra investment.

Thus, there is relatively large consensus within the industry and especially among operators that the aim should be to develop a single flexible 5G radio-access solution that can address as many applications and use cases as possible.

In relation to this, the concept of *network slicing* has been introduced. As outlined in Figure 23.5, network slicing implies that virtualization techniques are used to create multiple

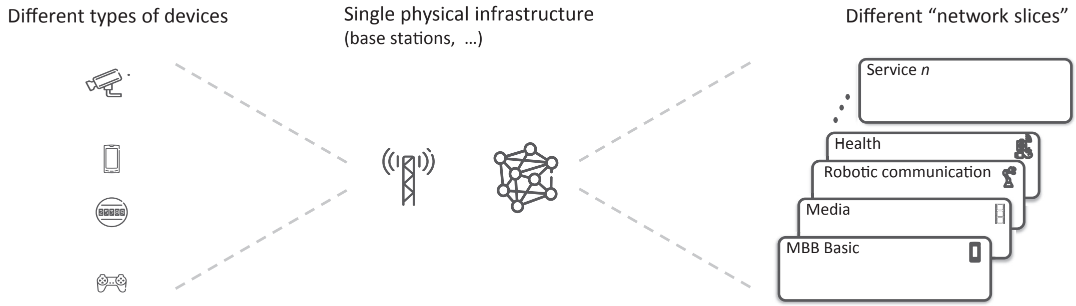

FIGURE 23.5

Network slicing creating multiple virtual networks for different applications and use cases on top of a common physical infrastructure and a common spectrum pool.

virtual networks, or *network slices*, on top of the same physical infrastructure and a common spectrum pool. As an example, one can create one network slice for mobile broadband, another network slice targeting massive-MTC applications, yet another network slice optimized for industry automation, and so on. Each network slice will, from the outside, appear as an independent network with its own resources and its own capabilities optimized for the set of applications targeted by the slice.

23.4 5G SPECTRUM

Spectrum is one the fundamental pillars of wireless communication, and the history of mobile communication has to a large extent been about extending the amount of available spectrum and introducing new technology allowing for more efficient utilization of the available spectrum.

23.4.1 EXPANSION INTO HIGHER-FREQUENCY BANDS

As illustrated in Figure 23.6, every generation of mobile communication has expanded the range of spectrum in which the wireless-access technology can operate into higher-frequency bands:

- The first-generation systems were limited to operation below 1 GHz.
- The second-generation systems were initially deployed below 1 GHz but later expanded into the 1.8/1.9 GHz bands.
- The initial deployment of 3G systems for the first time expanded mobile communication above 2 GHz, more specifically into the so-called *IMT core bands* around 2.1 GHz.
- LTE was first deployed in the 2.5 GHz band and has recently expanded to frequency bands as high as around 3.5 GHz.

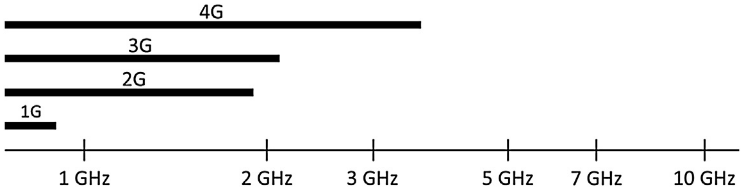

FIGURE 23.6

Expanded spectrum range from 1G to 4G.

It should be noted that the expansion to higher-frequency bands does in no way imply that the later generations cannot be deployed in lower-frequency bands. As an example, although LTE has expanded into higher-frequency bands above 3 GHz, there are LTE-based networks operating at as low frequencies as 450 MHz. The main benefit with operation in lower-frequency bands is better coverage allowing for a given area to be covered by less infrastructure (base stations). The expansion to higher-frequency bands, on the other hand, is mainly driven by a need for more spectrum providing higher system capacity to handle the continuously increasing traffic volumes.

The trend toward utilizing higher-frequency bands will continue and be even more pronounced in the 5G era. Already the first phase of 5G wireless access is expected to support operation in spectrum up to in the order of 30 GHz—that is, well into the millimeter wave range.[4] Later phases may expand this even further, up to 60–70 GHz and perhaps even further. Note that this implies a much larger step in terms of addressing new spectrum ranges, compared to earlier generational steps. From the first generation to the fourth generation, the upper limit on the frequency-band-of-operation expanded from just below 1 GHz to just above 3.5 GHz—that is, roughly a factor of 4. In comparison, already the first phase of 5G is expected to increase the upper limit on the frequency-band-of-operation close to a factor of 10 compared to the frequency range currently supported by LTE. A direct consequence of this is that, compared to earlier generational shifts, there is much more uncertainty in terms of spectrum characteristics when entering the 5G era.

Higher-frequency bands, especially beyond 10 GHz, has for long been assumed to be unsuitable for mobile communication due to very high-propagation loss and corresponding limited range. One reason for this has been an implicit assumption that the dimensions of the antenna configuration scale with the wave length, implying that operation in higher-frequency bands leads to much smaller effective antenna area and thus less captured received energy. At the same time, the smaller size of the antenna elements also enables the use of more antenna elements for a given size of the overall antenna configuration. By applying many small antenna elements at the receiver side, the overall effective receive antenna area can be kept constant avoiding the loss in captured energy. Another way to describe this is to say that the

[4]Strictly speaking, the mm-wave band starts at 30 GHz (10 mm wave length). However, already frequencies above 10 GHz, or in some cases already above 6 GHz, are in daily discussions often referred to as “mmw frequencies.”

larger antenna area relative to the wavelength enables more extensive receiver-side beam-forming or, equivalently, higher effective antenna gain at the receiver side.

By assuming multi-antenna configurations and an associated possibility for beam-forming also at the transmitter side, one could even argue that, for a given physical size of the overall antenna configurations, operation in higher-frequency bands may actually allow for extended range, assuming line-of-sight propagation conditions. This is a main reason for the use of higher-frequency bands in the 10 GHz to 100 GHz range for point-to-point radio links. However, this is only valid for line-of-sight conditions. In real-life scenarios, with non-line-of-sight conditions, need for outdoor-to-indoor propagation, and so on, radio propagation is undoubtedly more challenging at higher-frequency bands above 10 GHz compared to, for example, operation in the 2 GHz band.

As an example, mobile communication relies heavily on diffraction—that is, the property that a radio wave "bends" around corners—to enable connectivity in non-line-of-sight locations. The amount of diffraction is reduced as the frequency-of-operation increases, making it more difficult to provide coverage in shadowed locations. Nevertheless, recent investigations [68] have shown that coverage up to a few 100 m is possible also in non-line-of-sight conditions at least up to roughly 30 GHz, assuming proper use of beam-forming. One reason is that the degraded diffraction at higher frequencies is at least partly compensated for by stronger reflections.

However, there are also other factors that impact the propagation and restrict the use of higher frequencies for mobile communication. One such factor is building penetration loss. Most base stations, including low-power base stations in dense deployments, are located outdoors. At the same time, most of the users are located indoors making good outdoor-to-indoor coverage essential for many deployments. However, the building penetration loss is typically frequency dependent with, in general, increasing penetration loss and, as a consequence, degraded outdoor-to-indoor coverage as the carrier frequency increases, see for example [81].

It should be noted that the building penetration loss depends on the type of building material. It may also be heavily impacted by the type of windows being used. Modern buildings, especially office buildings, are often equipped with so-called infrared reflective (IRR) glass windows for energy-saving reasons. However, such windows also have higher penetration loss, leading to further degraded outdoor-to-indoor coverage. Note that this is a general effect not just related to high-frequency operation.

Additional factors impacting propagation at higher frequencies include atmospheric attenuation, rain fade, foliage attenuation, and body loss. Although being very important, for example, for radio links, the first two are less relevant for the relatively short link distances envisioned for mobile communication on high frequencies. On the other hand, both the foliage attenuation and body loss are highly relevant in the mobile-communication scenario.

Another factor limiting the coverage at higher frequencies is regulations on allowed transmission power for frequencies above 6 GHz. As mentioned in Chapter 2, due to the present international regulations, the maximum transmit power at higher frequencies may be up to 10 dB lower than the maximum power levels for current cellular technologies. This may however change with future updates of regulation.

Altogether, this means that lower-frequency bands will remain the backbone of mobile communication also in the 5G era, providing 5G services with wide-area coverage. However, the lower-frequency bands will be complemented by higher frequencies, including frequency bands above 10 GHz, for very high traffic capacity and very high data rates but mostly in dense outdoor and indoor deployments.

23.4.2 LICENSED VERSUS UNLICENSED SPECTRUM

Mobile communication has since its inception relied solely on licensed spectrum exclusively assigned on a regional basis to a certain operator. However, this has partly begun to change already with LTE with the introduction of LAA (Chapter 17) providing the possibility for complementary use of unlicensed spectrum for enhanced service provisioning when the conditions so allow.

There is no reason to expect that this trend will not continue in the 5G era. Rather, everything speaks in favor of both licensed and unlicensed spectrum being key components for 5G wireless access. Licensed spectrum will remain the backbone, giving network operators the possibility to provide high-quality services with a high degree of guarantee. At the same time, unlicensed spectrum will be an important complement providing additional capacity and enabling even higher data rates when the interference conditions so allow. Consequently, the new 5G radio-access technology should already from the start support operation in both licensed and unlicensed spectrum. Operation in unlicensed spectrum should be possible in combination with and under assistance from licensed spectrum, similar to LAA, as well as standalone with no support from a licensed carrier.

From a technical perspective, this requires support for a listen-before-talk mechanism as discussed in Chapter 17. Most likely, the design will be similar to the LAA listen-before-talk to simplify coexistence with LAA and Wi-Fi deployed in the same band. However, the possibility for extensive use of multi-antenna techniques and beam-forming may impact the design, at least in scenarios with no Wi-Fi or LAA transmissions being present.

23.5 LTE EVOLUTION VERSUS NEW 5G TECHNOLOGY

The different generations of mobile communication have very much been defined based on some specific technical characteristics. For example, 3G was very much associated with the use of CDMA technology. Likewise, 4G is very much associated with OFDM transmission in combination with MIMO. At the same time, there is not a fundamental difference between the applications and use cases being supported by 3G, especially HSPA, and 4G.

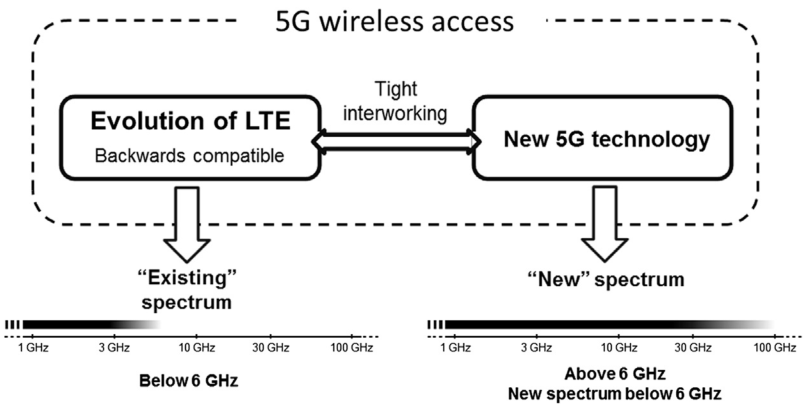

FIGURE 23.7

Overall 5G wireless-access solution consisting of the evolution of LTE in combination with a new 5G radio-access technology.

In contrast, the concept of 5G is much more associated with the kind of applications and use cases being envisioned, rather than a specific technology. More specifically, the term 5G is very much associated with the envisioned new use cases to be provided in the 5G era.

Nevertheless, it is clear that that many of the applications and use cases envisioned for the 5G era can be well supported by the evolution of LTE. Thus, there is a relatively well accepted view that the evolution of LTE should actually be seen as a part of the overall 5G wireless access solution, see Figure 23.7. The benefit of being able to provide a substantial part of the 5G applications and use cases by the evolution of LTE is that these applications and use cases can then be provided within existing spectrum while still supporting legacy devices in that spectrum (backward compatibility).

However, in parallel to the evolution of LTE there will also be development of new 5G radio-access technology not constrained by backward compatibility. This technology will at least initially target new spectrum both above and below 6 GHz. In a longer-term perspective, the new 5G radio-access technology may also migrate into spectrum currently used by other technologies including LTE.

The possibility for tight interworking between the evolution of LTE and the new 5G radio-access technology will in many cases be critical for introduction of the new radio-access technology. As an example, the new 5G radio-access technology may be deployed in a very dense layer operating on higher frequencies. Such a layer can support very large traffic volumes and very high end-user data rate. However, it will be inherently more unreliable as devices may easily fall out of coverage of such layer. By providing the possibility for simultaneous connectivity to an LTE-based macro-layer operating on lower frequencies, the reliability of the overall connectivity can be dramatically improved.

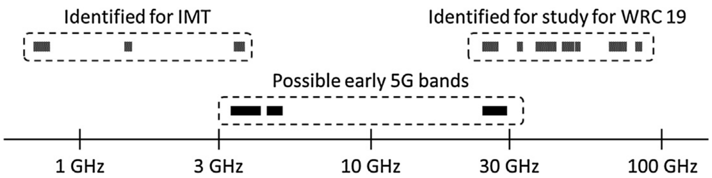

FIGURE 23.8

Spectrum identified by WRC 15 and spectrum considered for early 5G deployments.

23.6 FREQUENCY BANDS FOR 5G INITIAL DEPLOYMENTS

It is not yet decided exactly what frequency bands will be used for the new 5G radio-access technology.

As described already in Chapter 2, WRC-15 identified a set of frequency bands below 6 GHz as new frequency bands for IMT, see Figure 23.8. WRC-15 also identified a set of frequency bands above 10 GHz to be studied as potential new IMT spectrum for WRC-19. These bands are clearly candidates for the new 5G radio-access technology. However, initial deployment of the new 5G radio-access technology may also take place in other bands depending on decisions by regional/national regulators. As of today, there are primarily two frequency ranges being discussed in the context of early deployment of the new 5G radio-access technology, see Figure 23.8. They are:

- frequencies in the 3.3–4.2 GHz and 4.4–4.99 GHz range;
- frequencies in the 24.25–29.5 GHz range.

It should be noted that these frequency ranges only partly coincide with the spectrum bands identified at WRC'15 or being studied for WRC'19.

23.7 5G TECHNICAL SPECIFICATION

As mentioned already in Section 23.2 when discussing ITU-R and IMT-2020, the actual technical specification of the new 5G radio-access technology will be carried out by 3GPP, in parallel to the evolution of LTE.

Although fundamentally the new radio-access technology is developed in order to satisfy a need for new capabilities, the 3GPP 5G development also needs to take into account the ITU-R time schedule for IMT-2020 as outlined in Section 23.2. Initially, a study item in 3GPP will develop requirements for the new 5G radio-access technology and a parallel study item will develop the technology aspects. This goes on in parallel with the requirements phase in ITU-R, as shown in Figure 23.9.

To align with the ITU-R time plan (Figure 23.1) 3GPP needs to have a high-level technology description of the new 5G radio-access technology available in the second half of 2018 for submission to ITU-R as a candidate for IMT-2020. Detailed technical specifications

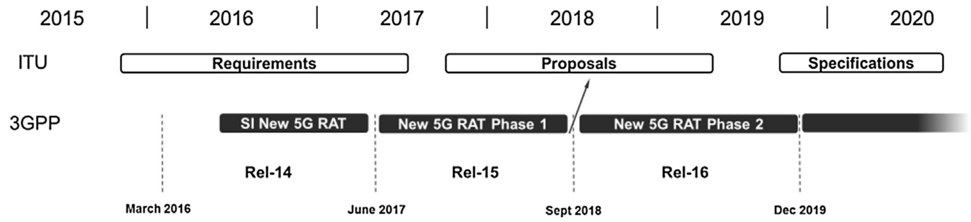

FIGURE 23.9

ITU-R time schedule and 3GPP phased approach to 5G.

must then be ready late 2019 to allow for inclusion in the IMT-2020 specifications to be published by ITU-R in the fall of 2020.

However, the 3GPP development of a new 5G radio-access technology is not only driven by the ITU-R time plane. Actually, it has become more and more evident that, in some countries/regions, there is a desire for the new 5G technology to be available even earlier than what is given by the ITU-R time plan. More specifically, some countries and regions have expressed a strong desire to have a new 5G technology in *commercial operation* in 2020. To allow for sufficient time for actual product development, this requires detailed technical specifications to be available already during 2018.

To satisfy these demands 3GPP has decided on a phased approach to 5G specification as outlined in Figure 23.9.

- A first phase with limited functionality but satisfying the desire for technical specifications available in 2018 thereby enabling commercial operation in 2020.
- A second phase fulfilling all the IMT-2020 requirements and being available in time for the ITU-R specification in 2020.

Although there have been extensive discussions about the two-phase 3GPP approach, it should be understood that the development of the new 5G radio-access technology will not end with phase 2. In the same way as any 3GPP technology there will be a sequence of releases, each adding additional features to the technology.

It can be noticed that the 3GPP technical work will start even before the ITU-R requirements for IMT-2020 have been finalized. However, already at the start of the 3GPP technical activities there is a relatively good understanding of where these requirements will end up. Furthermore, 3GPP does not rely solely on ITU-R to develop the requirements for the new 5G radio-access technology. Rather, 3GPP develops its own 5G requirements based on inputs from all the 3GPP members including operators, device and network vendors, and other organizations, for example, NGMN.

In order to ensure that that 5G radio-access technology will fulfill all the requirements on IMT-2020, the 3GPP requirements must include, but may be a superset of, the ITU-R requirements. Another way to express this is to say that one important requirement for the new 5G technology to be developed by 3GPP is that it has to fulfill all the requirements of IMT-2020 as defined by ITU-R.