CHAPTER

5G Standardization

2

The research, development, implementation, and deployment of mobile-communication systems is performed by the wireless industry in a coordinated international effort by which common industry specifications that define the complete mobile-communication system are agreed. The work depends heavily on global and regional regulation, in particular for the spectrum use that is an essential component for all radio technologies. This chapter describes the regulatory and standardization environment that has been, and continues to be, essential for defining the mobile-communication systems.

2.1 OVERVIEW OF STANDARDIZATION AND REGULATION

There are a number of organizations involved in creating technical specifications and standards as well as regulation in the mobile-communications area. These can loosely be divided into three groups: Standards Developing Organizations, regulatory bodies and administrations, and industry forums.

Standards Developing Organizations (SDOs) develop and agree on technical standards for mobile communications systems, in order to make it possible for the industry to produce and deploy standardized products and provide interoperability between those products. Most components of mobile-communication systems, including base stations and mobile devices, are standardized to some extent. There is also a certain degree of freedom to provide proprietary solutions in products, but the communications protocols rely on detailed standards for obvious reasons. SDOs are usually nonprofit industry organizations and not government controlled. They often write standards within a certain area under mandate from governments(s) however, giving the standards a higher status.

There are nationals SDOs, but due to the global spread of communications products, most SDOs are regional and also cooperate on a global level. As an example, the technical specifications of GSM, WCDMA/HSPA, LTE, and NR are all created by 3GPP (Third Generation Partnership Project) which is a global organization from seven regional and national SDOs in Europe (ETSI), Japan (ARIB and TTC), the United States (ATIS), China (CCSA), Korea (TTA), and India (TSDSI). SDOs tend to have a varying degree of transparency, but 3GPP is

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fully transparent with all technical specifications, meeting documents, reports, and e-mail reflectors publicly available without charge even for nonmembers.

Regulatory bodies and administrations are government-led organizations that set regulatory and legal requirements for selling, deploying, and operating mobile systems and other telecommunication products. One of their most important tasks is to control spectrum use and to set licensing conditions for the mobile operators that are awarded licenses to use parts of the *Radio Frequency* (RF) spectrum for mobile operations. Another task is to regulate "placing on the market" of products through regulatory certification, by ensuring that devices, base stations, and other equipment is type-approved and shown to meet the relevant regulation.

Spectrum regulation is handled both on a national level by national administrations, but also through regional bodies in Europe (CEPT/ECC), the Americas (CITEL), and Asia (APT). On a global level, the spectrum regulation is handled by the *International Telecommunications Union* (ITU). The regulatory bodies regulate what services the spectrum is to be used for and in addition set more detailed requirements such as limits on unwanted emissions from transmitters. They are also indirectly involved in setting requirements on the product standards through regulation. The involvement of ITU in setting requirements on the technologies for mobile communication is explained further in Section 2.2.

Industry forums are industry-led groups promoting and lobbying for specific technologies or other interests. In the mobile industry, these are often led by operators, but there are also vendors creating industry forums. An example of such a group is GSMA (GSM Association) which is promoting mobile-communication technologies based on GSM, WCDMA, LTE, and NR. Other examples of industry forums are *Next Generation Mobile Networks* (NGMN), which is an operator group defining requirements on the evolution of mobile systems, and *5G Americas*, which is a regional industry forum that has evolved from its predecessor 4G Americas.

Fig. 2.1 illustrates the relationship between different organizations involved in setting regulatory and technical conditions for mobile systems. The figure also shows the mobile industry view, where vendors develop products, place them on the market and negotiate with operators who procure and deploy mobile systems. This process relies heavily on the technical standards published by the SDOs, while placing products on the market relies on certification of products on a regional or national level. Note that, in Europe, the regional SDO (ETSI) is producing the so-called *harmonized standards* used for product certification (through the "CE"-mark), based on a mandate from the regulators, in this case the European Commission. These standards are also used for certification in many countries outside of Europe. In Fig. 2.1, full arrows indicate formal documentation such as technical standards, recommendations, and regulatory mandates that define the technologies and regulation. Dashed arrows show more indirect involvement through, for example, liaison statements and white papers.

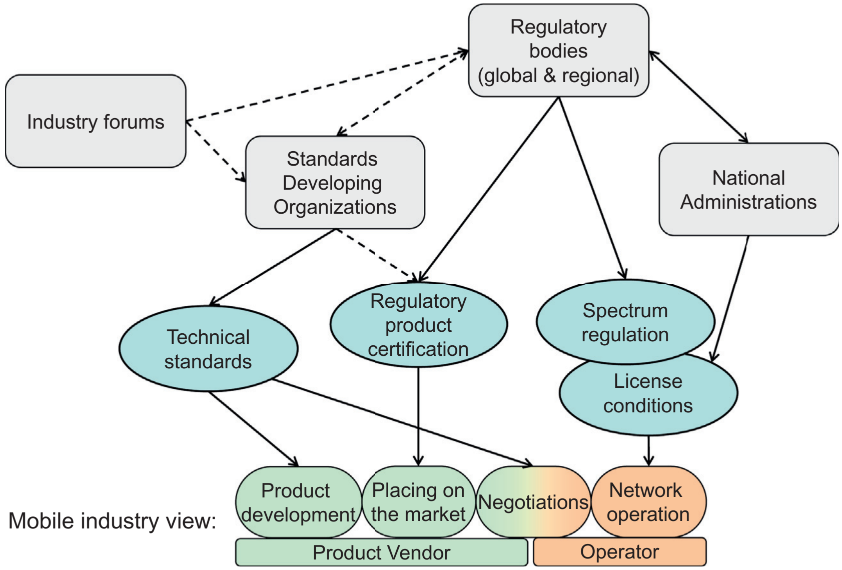

FIGURE 2.1

Simplified view of the relationship between regulatory bodies, standards developing organizations, industry forums, and the mobile industry.

2.2 ITU-R ACTIVITIES FROM 3G TO 5G

2.2.1 THE ROLE OF ITU-R

ITU-R is the radio communications sector of the International Telecommunications Union. ITU-R is responsible for ensuring efficient and economical use of the RF spectrum by all radio communication services. The different subgroups and working parties produce reports and recommendations that analyze and define the conditions for using the RF spectrum. The quite ambitious goal of ITU-R is to "ensure interference-free operations of radio communication systems," by implementing the *Radio Regulations* and regional agreements. The Radio Regulations is an international binding treaty for how RF spectrum is used. A *World Radio-communication Conference* (WRC) is held every 3–4 years. At WRC the Radio Regulations are revised and updated, resulting in revised and updated use of the RF spectrum across the world.

While the technical specification of mobile-communication technologies, such as NR, LTE, and WCDMA/HSPA is done within 3GPP, there is a responsibility for ITU-R in the process of turning the technologies into global standards, in particular for countries that are not covered by the SDOs that are partners in 3GPP. ITU-R defines the spectrum for different services in the RF spectrum, including mobile services, and some of that spectrum is particularly identified for so-called International Mobile Telecommunications (IMT) systems. Within ITU-R, it is *Working Party 5D* (WP5D) that has the responsibility for the overall radio system aspects of IMT systems, which, in practice, corresponds to the different generations of mobile-communication systems from 3G onwards. WP5D has the prime responsibility within ITU-R for issues related to the terrestrial component of IMT, including technical, operational, and spectrum-related issues.

WP5D does not create the actual technical specifications for IMT, but has kept the roles of defining IMT in cooperation with the regional standardization bodies and maintaining a set of recommendations and reports for IMT, including a set of *Radio Interface Specifications* (RSPCs). These recommendations contain "families" of *Radio Interface Technologies* (RITs) for each IMT generation, all included on an equal basis. For each radio interface, the RSPC contains an overview of that radio interface, followed by a list of references to the detailed specifications. The actual specifications are maintained by the individual SDO and the RSPC provides references to the specifications transposed and maintained by each SDO. The following RSPC recommendations are in existence or planned:

- For IMT-2000: ITU-R Recommendation M.1457 [49] containing six different RITs including the 3G technologies such as WCDMA/HSPA.
- For IMT-Advanced: ITU-R Recommendation M.2012 [45] containing two different RITs where the most important is 4G/LTE.
- For IMT-2020: A new ITU-R Recommendation, containing the RITs for 5G technologies, planned to be developed in 2019–20.

Each RSPC is continuously updated to reflect new developments in the referenced detailed specifications, such as the 3GPP specifications for WCDMA and LTE. Input to the updates is provided by the SDOs and the Partnership Projects, nowadays primarily 3GPP.

2.2.2 IMT-2000 AND IMT-ADVANCED

Work on what corresponds to third generation of mobile communication started in the ITU-R in the 1980s. First referred to as *Future Public Land Mobile Systems* (FPLMTS) it was later renamed IMT-2000. In the late 1990s, the work in ITU-R coincided with the work in different SDOs across the world to develop a new generation of mobile systems. An RSPC for IMT-2000 was first published in 2000 and included WCDMA from 3GPP as one of the RITs.

The next step for ITU-R was to initiate work on IMT-Advanced, the term used for systems that include new radio interfaces supporting new capabilities of systems beyond IMT-2000. The new capabilities were defined in a framework recommendation published by the ITU-R [41] and were demonstrated with the "van diagram" shown in Fig. 2.2. The step into IMT-Advanced capabilities by ITU-R coincided with the step into 4G, the next generation of mobile technologies after 3G.

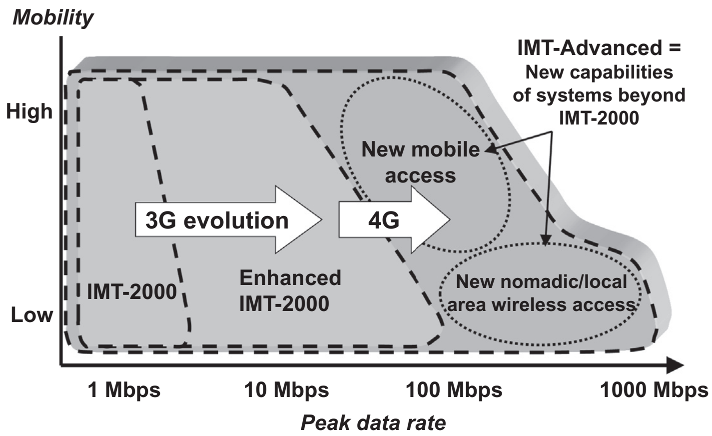

FIGURE 2.2

Illustration of capabilities of IMT-2000 and IMT-Advanced, based on the framework described in ITU-R Recommendation M.1645 [41].

An evolution of LTE as developed by 3GPP was submitted as one candidate technology for IMT-Advanced. While actually being a new release (Release 10) of the LTE specifications and thus an integral part of the continuous evolution of LTE, the candidate was named LTE-Advanced for the purpose of ITU-R submission and this name is also used in the LTE specifications from Release 10. In parallel with the ITU-R work, 3GPP set up its own set of technical requirements for LTE-Advanced, with the ITU-R requirements as a basis [10].

The target of the ITU-R process is always harmonization of the candidates through consensus building. ITU-R determined that two technologies would be included in the first release of IMT-Advanced, those two being LTE-Advanced and WirelessMAN-Advanced [37] based on the IEEE 802.16m specification. The two can be viewed as the "family" of IMT-Advanced technologies as shown in Fig. 2.3. Note that, of these two technologies, LTE has emerged as the dominating 4G technology by far.

2.2.3 IMT-2020 PROCESS IN ITU-R WP5D

Starting in 2012, ITU-R WP5D set the stage for the next generation of IMT systems, named IMT-2020. It is a further development of the terrestrial component of IMT beyond the year 2020 and, in practice, corresponds to what is more commonly referred to as "5G," the fifth generation of mobile systems. The framework and objective for IMT-2020 is outlined in ITU-R Recommendation M.2083 [47], often referred to as the "Vision" recommendation. The recommendation provides the first step for defining the new developments of IMT, looking at the future roles of IMT and how it can serve society, looking at market, user and technology trends,

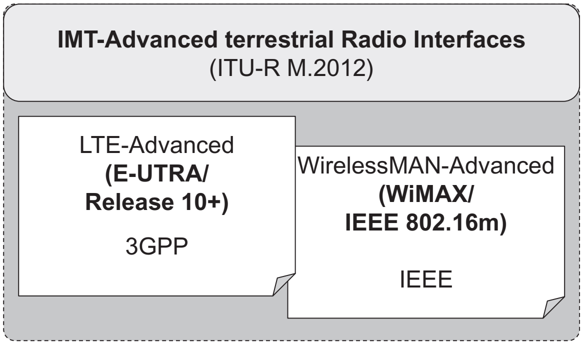

FIGURE 2.3

Radio Interface Technologies IMT-Advanced.

and spectrum implications. The user trends for IMT together with the future role and market lead to a set of *usage scenarios* envisioned for both human-centric and machine-centric communication. The usage scenarios identified are *Enhanced Mobile Broadband* (eMBB), *Ultra-Reliable and Low Latency Communications* (URLLC), and *Massive Machine-Type Communications* (mMTC).

The need for an enhanced mobile broadband experience, together with the new and broadened usage scenarios, leads to an extended set of capabilities for IMT-2020. The Vision recommendation [47] gives a first high-level guidance for IMT-2020 requirements by introducing a set of key capabilities, with indicative target numbers. The key capabilities and the related usage scenarios are discussed further in Section 2.3.

As a parallel activity, ITU-R WP5D produced a report on "Future technology trends of terrestrial IMT systems" [43], with a focus on the time period 2015–20. It covers trends of future IMT technology aspects by looking at the technical and operational characteristics of IMT systems and how they are improved with the evolution of IMT technologies. In this way, the report on technology trends relates to LTE in 3GPP Release 13 and beyond, while the Vision recommendation looks further ahead and beyond 2020. A new aspect on IMT-2020 is that it will be capable of operating in potential new IMT bands above 6 GHz, including mm-wave bands. With this in mind, WP5D produced a separate report studying radio wave propagation, IMT characteristics, enabling technologies, and deployment in frequencies above 6 GHz [44].

At WRC-15, potential new bands for IMT were discussed and an agenda item 1.13 was set up for WRC-19, covering possible additional allocations to the mobile services and for future IMT development. These allocations are identified in a number of frequency bands in the range between 24.25 and 86 GHz. The specific bands and their possible use globally are further discussed in Chapter 3.

After WRC-15, ITU-R WP5D continued the process of setting requirements and defining evaluation methodologies for IMT-2020 systems, based in the

Vision recommendation [47] and the other previous study outcomes. This step of the process was completed in mid-2017, as shown in the IMT-2020 work plan in Fig. 2.4. The result was three documents published late in 2017 that further define the performance and characteristics that are expected from IMT-2020 and that will be applied in the evaluation phase:

- *Technical requirements:* Report ITU-R M.2410 [51] defines 13 minimum requirements related to the technical performance of the IMT-2020 radio interface(s). The requirements are to a large extent based on the key capabilities set out in the Vision recommendation (ITU-R, 2015c). This is further described in Section 2.3.
- *Evaluation guideline:* Report ITU-R M.2412 [50] defines the detailed methodology to use for evaluating the minimum requirements, including test environments, evaluation configurations, and channel models. More details are given in Section 2.3.
- *Submission template:* Report ITU-R M.2411 [52] provides a detailed template to use for submitting a candidate technology for evaluation. It also details the evaluation criteria and requirements on service, spectrum, and technical performance, based on the two previously mentioned ITU-R reports M.2410 and M.2412.

External organizations are being informed of the IMT-2020 process through a circular letter. After a workshop on IMT-2020 was held in October 2017, the IMT-2020 process is open for receiving candidate proposals.

The plan, as shown in Fig. 2.4, is to start the evaluation of proposals in 2018, aiming at an outcome with the RSPC for IMT-2020 being published early in 2020.

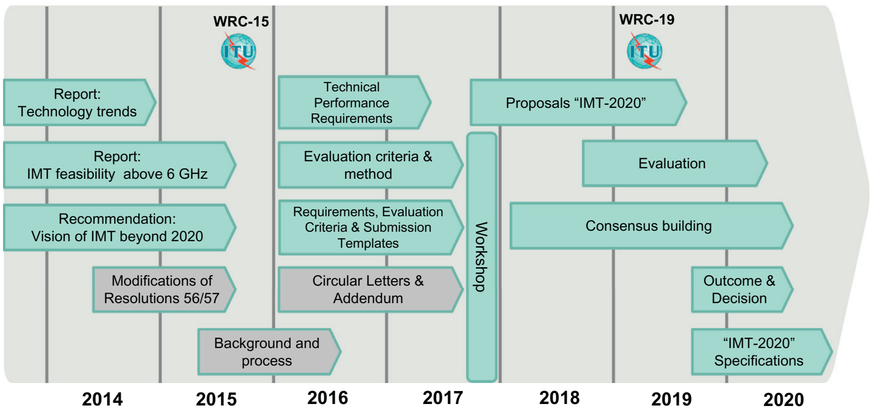

FIGURE 2.4

Work plan for IMT-2020 in ITU-R WP5D [40].

2.3 5G AND IMT-2020

The detailed ITU-R time plan for IMT-2020 was presented above with the most important steps summarized in Fig. 2.4. The ITU-R activities on IMT-2020 started with development of the "vision" recommendation ITU-R M.2083 [47], outlining the expected use scenarios and corresponding required capabilities of IMT-2020. This was followed by definition of more detailed requirements for IMT-2020, requirements that candidate technologies are then to be evaluated against, as documented in the evaluation guidelines. The requirements and evaluation guidelines were finalized mid-2017.

With the requirements finalized, candidate technologies can be submitted to ITU-R. The proposed candidate technology/technologies will 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 2.2.3.

2.3.1 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 the IMT Vision recommendation [47]. 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 hotspots 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 (mMTC):* 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 mMTC devices, they are also required to have a very long battery life time.

The usage scenarios are illustrated in Fig. 2.5, together with some example use cases. The three scenarios above 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, 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.

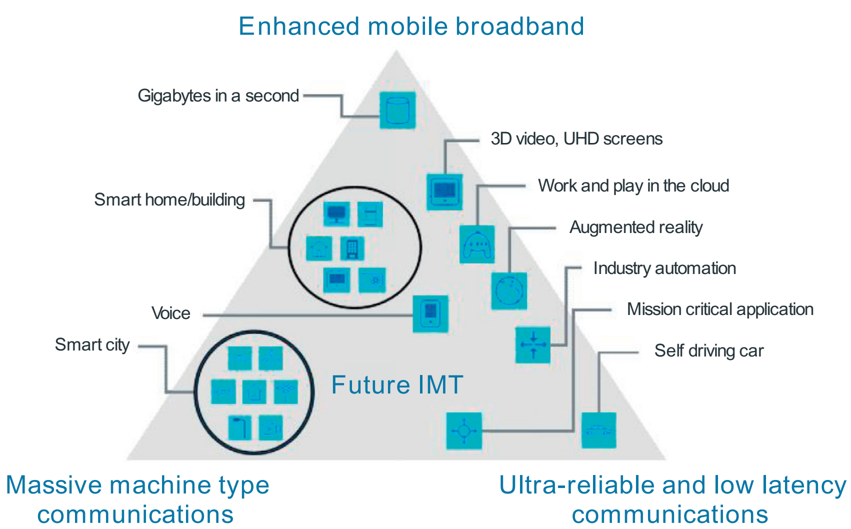

FIGURE 2.5

IMT-2020 use cases and mapping to usage scenarios.

From ITU-R, Recommendation ITU-R M.2083 [47], used with permission from the ITU.

2.3.2 CAPABILITIES OF IMT-2020

As part of developing the framework for the IMT-2020 as documented in the IMT Vision recommendation [47], 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 ITU-R [47], where eight were selected as *key capabilities*. Those eight key capabilities are illustrated through two "spider web" diagrams (see Figs. 2.6 and 2.7).

Fig. 2.6 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 Fig. 2.7 which illustrates the "importance" of each key capability for realizing the three high-level usage scenarios envisioned by ITU-R.

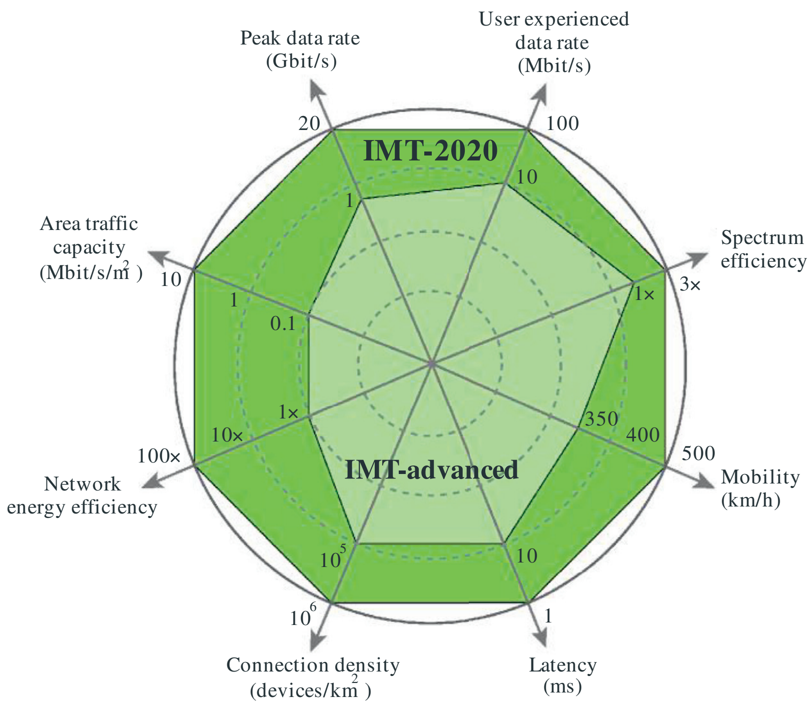

FIGURE 2.6

Key capabilities of IMT-2020.

From ITU-R, Recommendation ITU-R M.2083 [47], used with permission from the ITU.

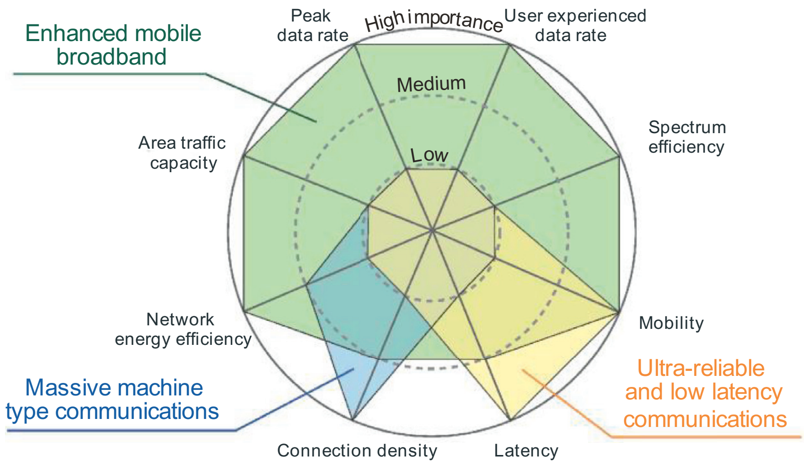

FIGURE 2.7

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

From ITU-R, Recommendation ITU-R M.2083 [47], used with permission from the ITU.

Peak data rate is a number on which there is always 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, etc. does not come into play. It is a dependent *key performance indicator* (KPI) in that it is heavily dependent 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 hotspot 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 hotspot 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 hotspots, 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 the 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 mMTC 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 Fig. 2.6 there are five additional capabilities defined in [47]:

- *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, etc.
- *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 (for example 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 Fig. 2.6, despite the fact that the latter are referred to as "key capabilities." The main difference is that the "key capabilities" are more easily quantifiable, while the remaining five capabilities are more of qualitative capabilities that cannot easily be quantified.

2.3.3 IMT-2020 PERFORMANCE REQUIREMENTS AND EVALUATION

Based on the usage scenarios and capabilities described in the Vision recommendation (ITU-R, 2015c), ITU-R developed a set of minimum technical performance requirements for IMT-2020. These are documented in ITU-R report M.2410 [51] and will serve as the baseline for the evaluation of IMT-2020 candidate technologies (see Fig. 2.4). The report describes 14 technical parameters and the corresponding minimum requirements. These are summarized in Table 2.1.

The evaluation guideline of candidate radio interface technologies for IMT-2020 is documented in ITU-R report M.2412 [50] and follows the same structure as the previous evaluation done for IMT-Advanced. It describes the evaluation methodology for the 14 minimum technical performance requirements, plus two additional requirements: support of a wide range of services and support of spectrum bands.

The evaluation is done with reference to five *test environments* that are based on the usage scenarios from the Vision recommendation [47]. Each test environment has a number of *evaluation configurations* that describe the detailed

Table 2.1 Overview of Minimum Technical Performance Requirements for IMT-2020

Parameter	Minimum Technical Performance Requirement
Peak data rate	Downlink: 20 Gbit/s Uplink: 10 Gbit/s
Peak spectral efficiency	Downlink: 30 bit/s/Hz Uplink: 10 bit/s/Hz
User-experienced data rate	Downlink: 100 Mbit/s Uplink: 50 Mbit/s
Fifth percentile user spectral efficiency	3 × IMT-Advanced
Average spectral efficiency	3 × IMT-Advanced
Area traffic capacity	10 Mbit/s/m^2 (indoor hotspot for eMBB)
User plane latency	4 ms for eMBB 1 ms for URLLC
Control plane latency	20 ms
Connection density	1,000,000 devices per km^2
Energy efficiency	Related to two aspects for eMBB: a. Efficient data transmission in a loaded case b. Low energy consumption when there is no data The technology shall have the capability to support a high sleep ratio and long sleep duration
Reliability	$1-10^{-5}$ success probability of transmitting a layer 2 PDU (Protocol Data Unit) of 32 bytes within 1 ms, at coverage edge in Urban Macro for URLLC
Mobility	Normalized traffic channel data rates defined for 10, 30, and 120 km/h at ~1.5 × IMT-Advanced numbers Requirement for high-speed vehicular defined for 500 km/h (compared to 350 km/h for IMT-Advanced)
Mobility interruption time	0 ms
Bandwidth	At least 100 MHz and up to 1 GHz in higher-frequency bands. Scalable bandwidth shall be supported

parameters that are to be used in simulations and analysis for the evaluation. The five test environments are:

- *Indoor Hotspot-eMBB:* An indoor isolated environment at offices and/or in shopping malls based on stationary and pedestrian users with very high user density.
- *Dense Urban-eMBB:* An urban environment with high user density and traffic loads focusing on pedestrian and vehicular users.
- *Rural-eMBB:* A rural environment with larger and continuous wide area coverage, supporting pedestrian, vehicular, and high-speed vehicular users.
- *Urban Macro-mMTC:* An urban macro-environment targeting continuous coverage focusing on a high number of connected machine type devices.

- *Urban Macro-URLLC:* An urban macro-environment targeting ultra-reliable and low-latency communications.

There are three fundamental ways that requirements will be evaluated for a candidate technology:

- *Simulation:* This is the most elaborate way to evaluate a requirement and it involves system- or link-level simulations, or both, of the radio interface technology. For system-level simulations, deployment scenarios are defined that correspond to a set of test environments, such as indoor, dense urban, etc. Requirements that will be evaluated through simulation are average and fifth percentile spectrum efficiency, connection density, mobility and reliability.
- *Analysis:* Some requirements can be evaluated through a calculation based on radio interface parameters or be derived from other performance values. Requirements that will be evaluated through analysis are peak spectral efficiency, peak data rate, user-experienced data rate, area traffic capacity, control and user plane latency, and mobility interruption time.
- *Inspection:* Some requirements can be evaluated by reviewing and assessing the functionality of the radio interface technology. Requirements that will be evaluated through simulation are bandwidth, energy efficiency, support of a wide range of services, and support of spectrum bands.

Once candidate technologies are submitted to ITU-R and have entered the process, the evaluation phase will start. Evaluation can be done by the proponent ("self-evaluation") or by an external evaluation group, doing partial or complete evaluation of one or more candidate proposals.

2.4 3GPP STANDARDIZATION

With a framework for IMT systems set up by the ITU-R, with spectrum made available by the WRC and with an ever-increasing demand for better performance, the task of specifying the actual mobile-communication technologies falls on organizations like 3GPP. More specifically, 3GPP writes the technical specifications for 2G GSM, 3G WCDMA/HSPA, 4G LTE, and 5G NR. 3GPP technologies are the most widely deployed in the world, with more than 95% of the world's 7.8 billion mobile subscriptions in Q4 2017 [30]. In order to understand how 3GPP works, it is important to also understand the process of writing specifications.

2.4.1 THE 3GPP PROCESS

Developing technical specifications for mobile communication is not a one-time job; it is an ongoing process. The specifications are constantly evolving, trying to meet new demands for services and features. The process is different in the different fora, but typically includes the four phases illustrated in Fig. 2.8:

1. *Requirements*, where it is decided what is to be achieved by the specification.
2. *Architecture*, where the main building blocks and interfaces are decided.
3. *Detailed specifications*, where every interface is specified in detail.
4. *Testing and verification*, where the interface specifications are proven to work with real-life equipment.

These phases are overlapping and iterative. As an example, requirements can be added, changed, or dropped during the later phases if the technical solutions call for it. Likewise, the technical solution in the detailed specifications can change due to problems found in the testing and verification phase.

The specification starts with the *requirements* phase, where it is decided what should be achieved with the specification. This phase is usually relatively short.

In the *architecture* phase, the architecture is decided—that is, the principles of how to meet the requirements. The architecture phase includes decisions about reference points and interfaces to be standardized. This phase is usually quite long and may change the requirements.

After the architecture phase, the *detailed specification* phase starts. It is in this phase that the details for each of the identified interfaces are specified. During the detailed specification of the interfaces, the standards body may find that previous decisions in the architecture or even in the requirements phases need to be revisited.

Finally, the *testing and verification* phase starts. It is usually not a part of the actual specification, but takes place in parallel through testing by vendors and interoperability testing between vendors. This phase is the final proof of the specification. During the testing and verification phase, errors in the specification may still be found and those errors may change decisions in the detailed specification. Albeit not common, changes may also need to be made to the architecture or the requirements. To verify the specification, products are needed. Hence, the implementation of the products starts after (or during) the detailed specification phase. The testing and verification phase ends when there are stable test specifications that can be used to verify that the equipment is fulfilling the technical specification.

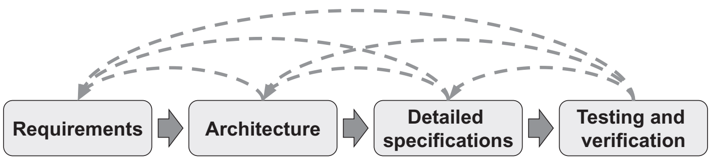

FIGURE 2.8

The standardization phases and iterative process.

Normally, it takes approximately one year from the time when the specification is completed until commercial products are out on the market.

3GPP consists of three *Technical Specifications Groups* (TSGs) (see Fig. 2.9) where TSG RAN (*Radio Access Network*) is responsible for the definition of functions, requirements, and interfaces of the Radio Access. TSG RAN consists of six working groups (WGs):

1. RAN WG1, dealing with the physical layer specifications.
2. RAN WG2, dealing with the layer 2 and layer 3 radio interface specifications.
3. RAN WG3, dealing with the fixed RAN interfaces—for example, interfaces between nodes in the RAN—but also the interface between the RAN and the core network.

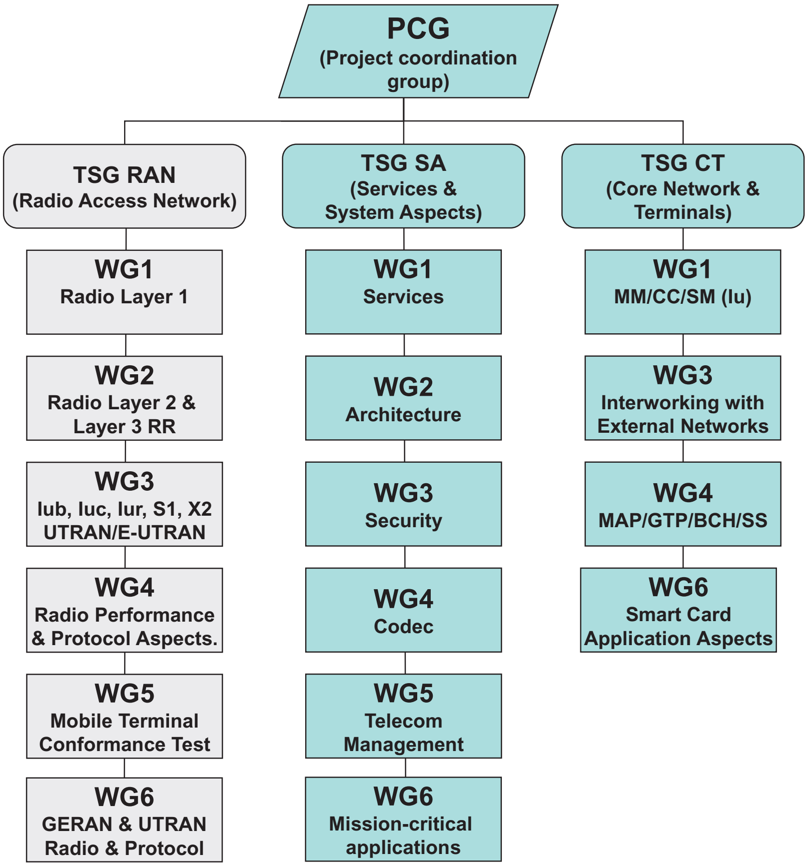

FIGURE 2.9

3GPP organization.

4. RAN WG4, dealing with the *radio frequency* (RF) and *radio resource management* (RRM) performance requirements.
5. RAN WG 5, dealing with the device conformance testing.
6. RAN WG6, dealing with standardization of GSM/EDGE (previously in a separate TSG called GERAN) and HSPA (UTRAN).

The work in 3GPP is carried out with relevant ITU-R recommendations in mind and the result of the work is also submitted to ITU-R as being part of IMT-2000, IMT-Advanced, and now also as a candidate for IMT-2020 in the form of NR. The organizational partners are obliged to identify regional requirements that may lead to options in the standard. Examples are regional frequency bands and special protection requirements local to a region. The specifications are developed with global roaming and circulation of devices in mind. This implies that many regional requirements in essence will be global requirements for all devices, since a roaming device has to meet the strictest of all regional requirements. Regional options in the specifications are thus more common for base stations than for devices.

The specifications of all releases can be updated after each set of TSG meetings, which occur four times a year. The 3GPP documents are divided into releases, where each release has a set of features added compared to the previous release. The features are defined in Work Items agreed and undertaken by the TSGs. LTE is defined from Release 8 and onwards, where Release 10 of LTE is the first version approved by ITU-R as an IMT-Advanced technology and is therefore also the first release named *LTE-Advanced*. From Release 13, the marketing name for LTE is changed to *LTE-Advanced Pro*. An overview of LTE is given in Chapter 4. Further details on the LTE radio interface can be found in [28].

The first release for NR is in 3GPP Release 15. An overview of NR is given in Chapter 5 with further details throughout this book.

The 3GPP Technical Specifications (TS) are organized in multiple series and are numbered TS XX.YYY, where XX denotes the number of the specification series and YYY is the number of the specification within the series. The following series of specifications define the radio access technologies in 3GPP:

- 25-series: Radio aspects for UTRA (WCDMA/HSPA);
- 45-series: Radio aspects for GSM/EDGE;
- 36-series: Radio aspects for LTE, LTE-Advanced and LTE-Advanced Pro;
- 37-series: Aspects relating to multiple radio access technologies;
- 38-series: Radio aspects for NR.

2.4.2 SPECIFICATION OF 5G IN 3GPP AS AN IMT-2020 CANDIDATE

In parallel with the definition and evaluation of the next-generation access initiated in ITU-R, 3GPP started to define the next-generation 3GPP radio access. A workshop on 5G radio access was held in 2014 and a process to define the evaluation criteria for 5G was initiated with a second workshop in early 2015. The evaluation will follow the same process that was used when LTE-Advanced was evaluated and submitted to ITU-R and approved as a 4G technology as part of IMT-advanced. The evaluation and submission of NR follows the ITU-R timeline described in Section 2.2.3.

3GPP TSG RAN documented scenarios, requirements, and evaluation criteria for the new 5G radio access in report TR 38.913 [10] which is in general aligned with the corresponding ITU-R reports [50, 51]. As for the case of the IMT-Advanced evaluation, the corresponding 3GPP evaluation of the next-generation radio access could have a larger scope and may have stricter requirements than the ITU-R evaluation of candidate IMT-2020 radio interface technologies that is defined by ITU-R WP5D.

The standardization work for NR started with a study item phase in Release 14 and continued with development of a first set of specifications through a work item in Release 15. A first set of the Release 15 NR specifications was published in December 2017 and the full specifications are due to be available in mid-2018. Further details on the time plan and the content of the NR releases is given in Chapter 5.

3GPP made a first submission of NR as an IMT-2020 candidate to the ITU-R WP5D meeting in February 2018. NR was submitted both as an RIT by itself and as an SRIT (set of component RITs) together with LTE. The following three candidates were submitted, all including NR as developed by 3GPP:

- 3GPP submitted a candidate named "5G," containing two submissions: the first submission was an SRIT containing two component RITs, these being NR and LTE. The second submission was a separate RIT being NR.
- Korea submitted NR as a RIT, with reference to 3GPP.
- China submitted NR as a RIT, with reference to 3GPP.

Further submissions to ITU-R will be made by 3GPP, giving more details of NR as an IMT-2020 candidate, according to the process described in Fig. 2.4. Simulations for the self-evaluations have also started in 3GPP, targeting the evaluation phase in 2019.