CHAPTER

SPECTRUM REGULATION AND STANDARDIZATION FROM 3G TO 5G

2

The research, development, implementation, and deployment of mobile-communication systems are 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 also 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, and LTE 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), United States (ATIS), China (CCSA), Korea (TTA), and India (TSDSI). SDOs tend to have a varying degree of transparency, but 3GPP is fully transparent with all technical specifications, meeting documents, reports, and email reflectors publically available without charge even for nonmembers.

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00002-9

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), 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 also 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 lead 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, and LTE. 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.

Figure 2.1 illustrates the relation 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 also 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. These standards are used for certification in many countries also outside of Europe.

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 ITU. 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 goal of ITU-R is to "ensure interference-free operations of radio communication systems," by implementing the *Radio*

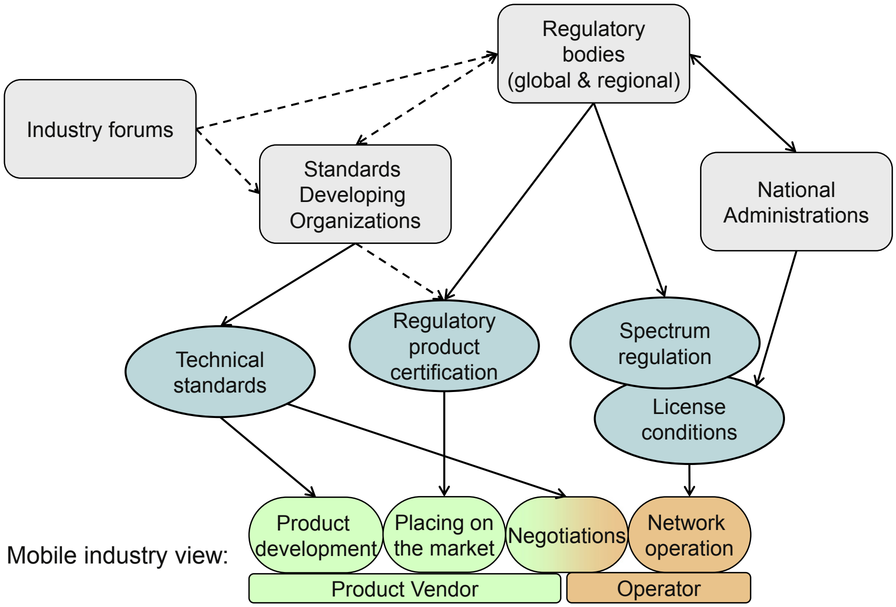

FIGURE 2.1

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

Regulations and regional agreements. The Radio Regulations is an international binding treaty for how RF spectrum is used. A *World Radiocommunication Conference* (WRC) is held every 3—4 years. At WRC the Radio Regulations are revised and updated and in that way provide revised and updated use of RF spectrum across the world.

While the technical specification of mobile-communication technologies, such as 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 are partners in 3GPP. ITU-R defines spectrum for different services in the RF spectrum, including mobile services and some of that spectrum is particularly identified for the 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 and onward. 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* (RSPC). These recommendations contain “families” of *radio interface technologies*

(RITs)—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 [1] containing six different RITs including the 3G technologies.
- For IMT-Advanced: ITU-R Recommendation M.2012 [4] containing two different RITs where the most important is 4G/LTE.
- For IMT-2020 (5G): A new ITU-R Recommendation, planned to be developed in 2019–2020.

Each RSPC is continuously updated to reflect new development 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 already 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 [2] and were demonstrated with the "van diagram" shown in Figure 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.

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. 3GPP also set up its own set of technical requirements for LTE-Advanced, with the ITU-R requirements as a basis.

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 and WirelessMAN-Advanced [3] based on the IEEE 802.16m specification. The two can be viewed as the "family" of IMT-Advanced technologies as shown in Figure 2.3. Note that, among these two technologies, LTE has emerged as the dominating 4G technology.

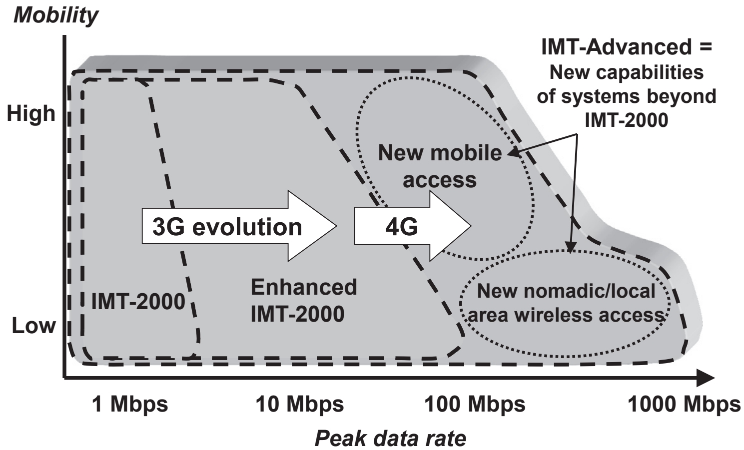

FIGURE 2.2

Illustration of capabilities of IMT-2000 and IMT-Advanced, based on the framework described in ITU-R Recommendation M.1645 [2].

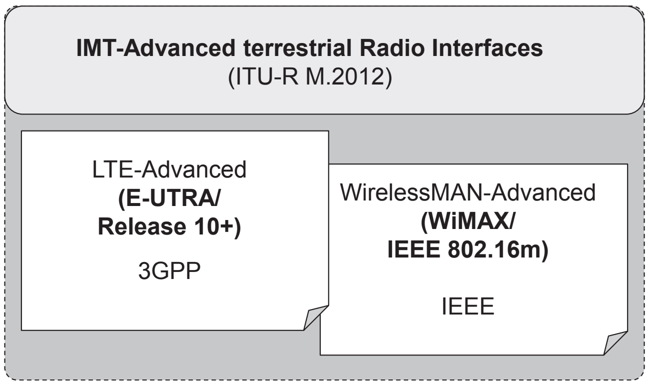

FIGURE 2.3

Radio interface technologies in IMT-Advanced.

2.2.3 IMT-2020

During 2012 to 2015, ITU-R WP5D set the stage for the next generation of IMT systems, named IMT-2020. It is to be 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 [63], 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, and spectrum implications. The user trends for IMT together with the future role and market leads 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* (MTC).

The need for an enhanced MBB experience, together with the new and broadened usage scenarios, leads to an extended set of capabilities for IMT-2020. The Vision recommendation [63] 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 further discussed in Chapter 23.

As a parallel activity, ITU-R WP5D produced a report on “Future technology trends of terrestrial IMT systems” [64], with focus on the time period 2015–2020. 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 relate to LTE release 13 and beyond, while the vision recommendation looks further ahead and beyond 2020. A report studying operation in frequencies above 6 GHz was also produced. Chapter 24 discusses some of the technology components considered for the new 5G radio access.

After WRC-15, ITU-R WP5D is in 2016 initiating the process of setting requirements and defining evaluation methodologies for IMT-2020 systems. The process will continue until mid-2017, as shown in Figure 2.4. In a parallel effort, a template for submitting an evaluation

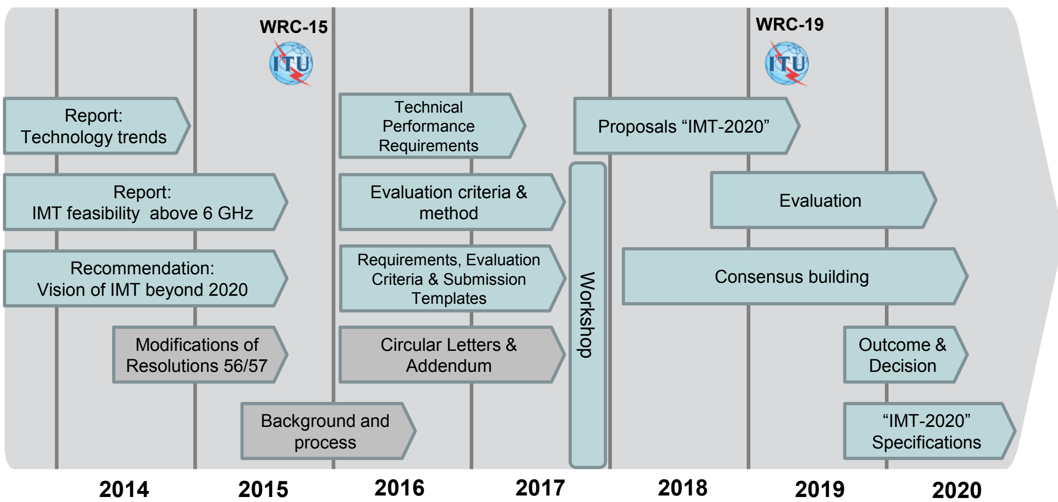

FIGURE 2.4

Work plan for IMT-2020 in ITU-R WP5D [4].

of candidate RITs will be created. External organizations are being informed of the process through a circular letter. After a workshop on IMT-2020 is held in 2017, the plan is to start the evaluation of proposals, aiming at an outcome with the RSPC for IMT-2020 being published early in 2020.

The coming evaluation of candidate RITs for IMT-2020 in ITU-R is expected to be conducted in a way similar to the evaluation done for IMT-Advanced, where the requirements were documented in Recommendation ITU-R M.2134 [28] and the detailed evaluation methodology in Recommendation ITU-R M.2135 [52]. The evaluation will be focused on the key capabilities identified in the VISION recommendation [63], but will also include other technical performance requirements. There are three fundamental ways that requirements are 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 RIT. For system-level simulations, deployment scenarios are defined that correspond to a set of test environments, such as Indoor and Dense Urban. Requirements that are candidates for evaluation through simulation are for example spectrum efficiency and user-experienced data rate (for details on the key capabilities, see Chapter 23).
- **Analysis**: Some requirements can be evaluated through a calculation based on radio interface parameters. This applies for example in case of requirements on peak data rate and latency.
- **Inspection**: Some requirements can be evaluated by reviewing and assessing the functionality of the RIT. Examples of parameters that may be subject to inspection are bandwidth, handover functionality, and support of services.

Once the technical performance requirements and evaluation methodology are set up, the evaluation phase starts. 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.

2.3 SPECTRUM FOR MOBILE SYSTEMS

There are a number of frequency bands identified for mobile use and specifically for IMT today. Many of these bands were first defined for operation with WCDMA/HSPA, but are now shared also with LTE deployments. Note that in the 3GPP specifications WCDMA/HSPA is referred to as *Universal Terrestrial Radio Access* (UTRA), while LTE is referred to as *Enhanced UTRA* (E-UTRA).

New bands are today often defined only for LTE. Both paired bands, where separated frequency ranges are assigned for uplink and downlink, and unpaired bands with a single shared frequency range for uplink and downlink, are included in the LTE specifications. Paired bands are used for Frequency Division Duplex (FDD) operation, while unpaired bands are used for Time Division Duplex (TDD) operation. The duplex modes of LTE are described further in Section 3.1.5. Note that some unpaired bands do not have any uplink specified. These "downlink only" bands are paired with the uplink of other bands through *carrier aggregation*, as described in Chapter 12.

An additional challenge with LTE operation in some bands is the possibility of using channel bandwidths up to 20 MHz with a single carrier and even beyond that with aggregated carriers.

Historically, the bands for the first and second generation of mobile services were assigned at frequencies around 800−900 MHz, but also in a few lower and higher bands. When 3G (IMT-2000) was rolled out, focus was on the 2 GHz band and with the continued expansion of IMT services with 3G and 4G, new bands were used at both lower and higher frequencies. All bands considered are up to this point below 6 GHz.

Bands at different frequencies have different characteristics. Due to the propagation properties, bands at lower frequencies are good for wide-area coverage deployments, both in urban, suburban, and rural environments. Propagation properties of higher frequencies make them more difficult to use for wide-area coverage, and higher-frequency bands have therefore to a larger extent been used for boosting capacity in dense deployments.

With new services requiring even higher data rates and high capacity in dense deployments, frequency bands above 6 GHz are being looked at as a complement to the frequency bands below 6 GHz. With the 5G requirements for extreme data rates and localized areas with very high area traffic capacity demands, deployment using much higher frequencies, even above 60 GHz, is considered. Referring to the wavelength, these bands are often called mm-wave bands.

2.3.1 SPECTRUM DEFINED FOR IMT SYSTEMS BY THE ITU-R

The global designations of spectrum for different services and applications are done within the ITU-R and are documented in the *ITU Radio Regulations* [65]. The *World Administrative Radio Congress* WARC-92 identified the bands 1885−2025 and 2110−2200 MHz as intended for implementation of IMT-2000. Of these 230 MHz of 3G spectrum, 2 × 30 MHz were intended for the satellite component of IMT-2000 and the rest for the terrestrial component. Parts of the bands were used during the 1990s for deployment of 2G cellular systems, especially in the Americas. The first deployments of 3G in 2001−2002 by Japan and Europe were done in this band allocation, and for that reason it is often referred to as the IMT-2000 "core band."

Additional spectrum for IMT-2000 was identified at the World Radiocommunication Conference[1] WRC-2000, where it was considered that an additional need for 160 MHz of spectrum for IMT-2000 was forecasted by the ITU-R. The identification includes the bands

[1]The World Administrative Radio Conference (WARC) was reorganized in 1992 and became the World Radiocommunication Conference (WRC).

used for 2G mobile systems at 806–960 and 1710–1885 MHz, and "new" 3G spectrum in the bands at 2500–2690 MHz. The identification of bands previously assigned for 2G was also recognition of the evolution of existing 2G mobile systems into 3G. Additional spectrum was identified at WRC'07 for IMT, encompassing both IMT-2000 and IMT-Advanced. The bands added were 450–470, 698–806, 2300–2400, and 3400–3600 MHz, but the applicability of the bands varies on a regional and national basis. At WRC'12 there were no additional spectrum allocations identified for IMT, but the issue was put on the agenda for WRC'15. It was also determined to study the use of the band 694–790 MHz for mobile services in Region 1 (Europe, Middle East, and Africa).

The somewhat diverging arrangement between regions of the frequency bands assigned to IMT means that there is not one single band that can be used for 3G and 4G roaming worldwide. Large efforts have, however, been put into defining a minimum set of bands that can be used to provide truly global roaming. In this way, multiband devices can provide efficient worldwide roaming for 3G and 4G devices.

2.3.2 FREQUENCY BANDS FOR LTE

LTE can be deployed both in existing IMT bands and in future bands that may be identified. The possibility of operating a radio access technology in different frequency bands is, in itself, nothing new. For example, 2G and 3G devices are multiband capable, covering bands used in the different regions of the world to provide global roaming. From a radio access functionality perspective, this has no or limited impact and the physical layer specifications such as the ones for LTE [24–27] do not assume any specific frequency band. What may differ, in terms of specification, between different bands are mainly the more specific RF requirements, such as the allowed maximum transmit power, requirements/limits on out-of-band (OOB) emission, and so on. One reason for this is that external constraints, imposed by regulatory bodies, may differ between different frequency bands.

The frequency bands where LTE will operate are in both paired and unpaired spectrum, requiring flexibility in the duplex arrangement. For this reason, LTE supports both FDD and TDD operation, will be discussed later.

Release 13 of the 3GPP specifications for LTE includes 32 frequency bands for FDD and 12 for TDD. The number of bands is very large and for this reason, the numbering scheme recently had to be revised to become future proof and accommodate more bands. The paired bands for FDD operation are numbered from 1 to 32 and 65 to 66 [38], as shown in Table 2.1, while the unpaired bands for TDD operation are numbered from 33 to 46, as shown in Table 2.2. Note that the frequency bands defined for UTRA FDD use the same numbers as the paired LTE bands, but are labeled with Roman numerals. Bands 15 and 16 are reserved for definition in Europe, but are presently not used. All bands for LTE are summarized in Figures 2.5 and 2.6, which also show the corresponding frequency allocation defined by the ITU-R.

Some of the frequency bands are partly or fully overlapping. In most cases this is explained by regional differences in how the bands defined by the ITU-R are implemented. At

Table 2.1 Paired Frequency Bands Defined by 3GPP for LTE

Band	Uplink Range (MHz)	Downlink Range (MHz)	Main Region(s)
1	1920–1980	2110–2170	Europe, Asia
2	1850–1910	1930–1990	Americas, Asia
3	1710–1785	1805–1880	Europe, Asia, Americas
4	1710–1755	2110–2155	Americas
5	824–849	869–894	Americas, Asia
6	830–840	875–885	Japan (only for UTRA)
7	2500–2570	2620–2690	Europe, Asia
8	880–915	925–960	Europe, Asia
9	1749.9–1784.9	1844.9–1879.9	Japan
10	1710–1770	2110–2170	Americas
11	1427.9–1447.9	1475.9–1495.9	Japan
12	698–716	728–746	United States
13	777–787	746–756	United States
14	788–798	758–768	United States
17	704–716	734–746	United States
18	815–830	860–875	Japan
19	830–845	875–890	Japan
20	832–862	791–821	Europe
21	1447.9–1462.9	1495.9–1510.9	Japan
22	3410–3490	3510–3590	Europe
23	2000–2020	2180–2200	Americas
24	1626.5–1660.5	1525–1559	Americas
25	1850–1915	1930–1995	Americas
26	814–849	859–894	Americas
27	807–824	852–869	Americas
28	703–748	758–803	Asia/Pacific
29	N/A	717–728	Americas
30	2305–2315	2350–2360	Americas
31	452.5–457.5	462.5–467.5	Americas
32	N/A	1452–1496	Europe
65	1920–2010	2110–2200	Europe
66	1710–1780	2110–2200	Americas
67	N/A	738–758	Europe

the same time, a high degree of commonality between the bands is desired to enable global roaming. A set of bands was first specified as bands for UTRA, with each band originating in global, regional, and local spectrum developments. The complete set of UTRA bands was then transferred to the LTE specifications in release 8 and additional ones have been added since then in later releases.

Table 2.2 Unpaired Frequency Bands Defined by 3GPP for LTE

Band	Frequency Range (MHz)	Main Region(s)
33	1900–1920	Europe, Asia (not Japan)
34	2010–2025	Europe, Asia
35	1850–1910	(Americas)
36	1930–1990	(Americas)
37	1910–1930	–
38	2570–2620	Europe
39	1880–1920	China
40	2300–2400	Europe, Asia
41	2496–2690	United States
42	3400–3600	Europe
43	3600–3800	Europe
44	703–803	Asia/Pacific
45	1447–1467	Asia (China)
46	5150–5925	Global

Bands 1, 33, and 34 are the same paired and unpaired bands that were defined first for UTRA in release 99 of the 3GPPP specifications, also called the 2 GHz "core band." *Band 2* was added later for operation in the US PCS1900 band and *Band 3* for 3G operation in the GSM1800 band. The unpaired *Bands 35, 36, and 37* are also defined for the PCS1900 frequency ranges, but are not deployed anywhere today. *Band 39* is an extension of the unpaired Band 33 from 20 to 40 MHz for use in China. Band 45 is another unpaired band for LTE use in China.

Band 65 is an extension of Band 1 to 2 × 90 MHz for Europe. This means that in the upper part, which previously has been harmonized in Europe for *Mobile Satellite Services* (MSS), it will be for satellite operators to deploy a *Complementary Ground Component* (CGC) as a terrestrial LTE system integrated with a satellite network.

Band 4 was introduced as a new band for the Americas following the addition of the 3G bands at WRC-2000. Its downlink overlaps completely with the downlink of Band 1, which facilitates roaming and eases the design of dual Band 1 + 4 devices. *Band 10* is an extension of Band 4 from 2 × 45 to 2 × 60 MHz. *Band 66* is a further extension of the paired band to 2 × 70 MHz, with an additional 20 MHz at the top of the downlink band (2180–2200 MHz) intended as a supplemental downlink for LTE carrier aggregation with the downlink of another band.

Band 9 overlaps with Band 3, but is intended only for Japan. The specifications are drafted in such a way that implementation of roaming dual Band 3 + 9 devices is possible. The 1500-MHz frequency band is also identified in 3GPP for Japan as *Bands 11 and 21*. It is allocated globally to mobile service on a co-primary basis and was previously used for 2G in Japan.

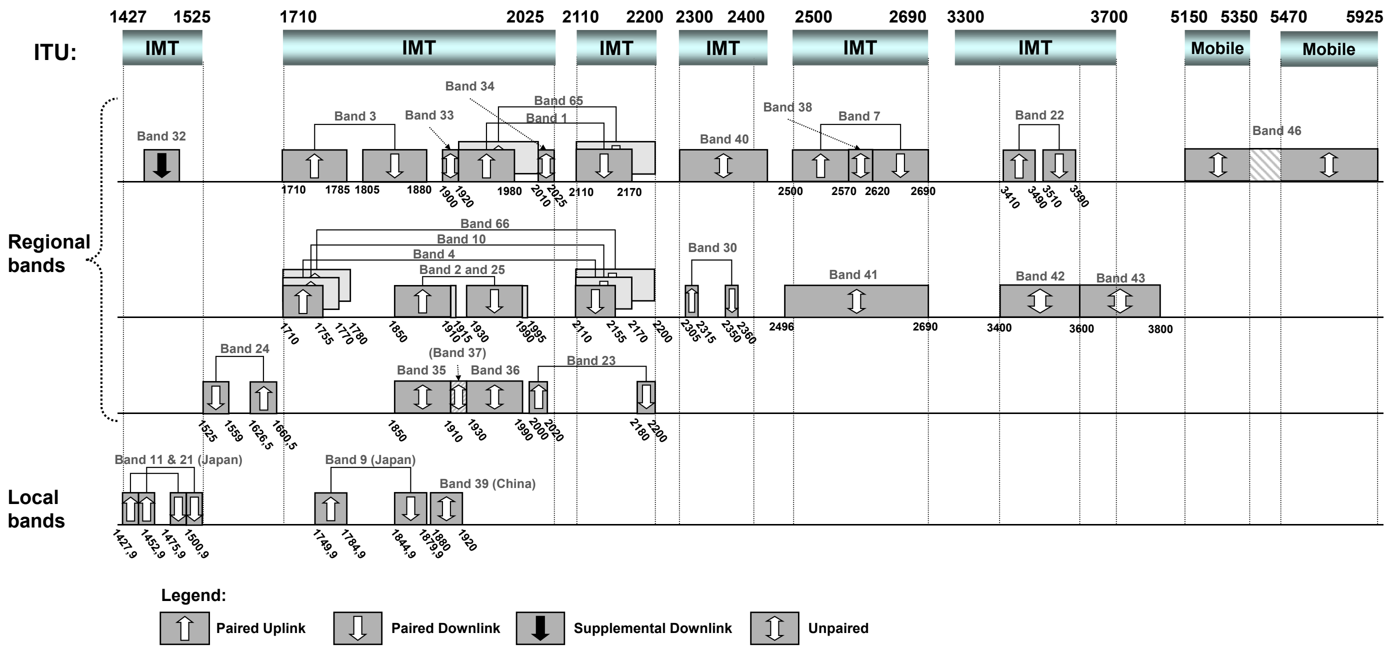

FIGURE 2.5

Operating bands specified for LTE in 3GPP above 1 GHz and the corresponding ITU-R allocation (regional or global).

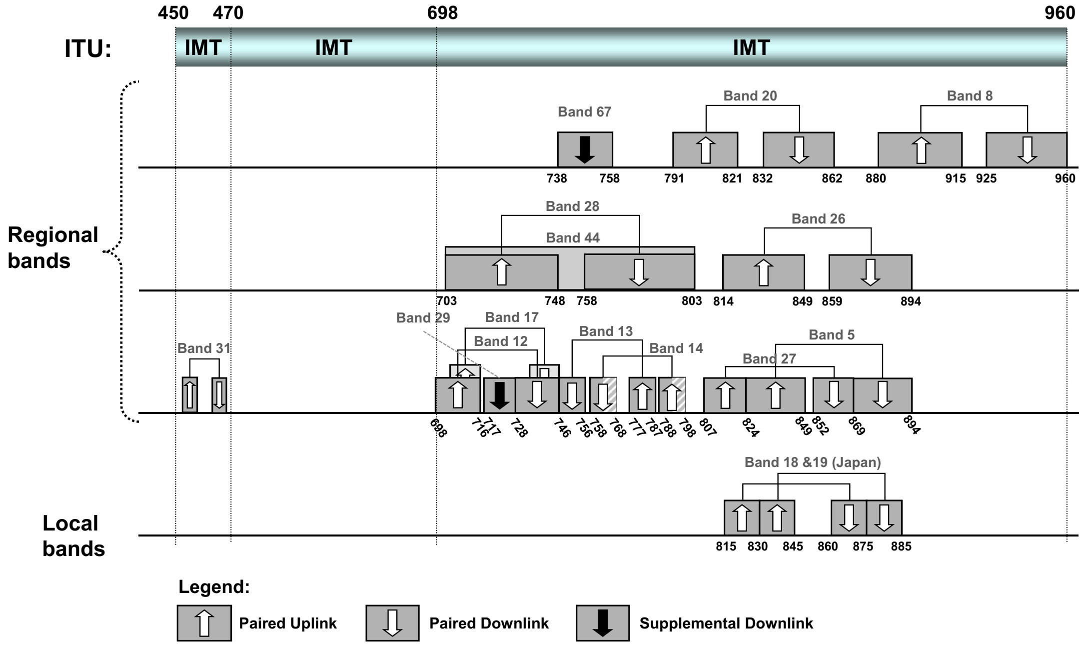

FIGURE 2.6

Operating bands specified for LTE in 3GPP below 1 GHz and the corresponding ITU-R allocation (regional or global).

With WRC-2000, the band 2500−2690 MHz was identified for IMT-2000, and it is identified as *Band 7* in 3GPP for FDD and *Band 38* for TDD operation in the "center gap" of the FDD allocation. The band has a slightly different arrangement in North America, where a US-specific *Band 41* is defined. *Band 40* is an unpaired band specified for the new frequency range 2300−2400 MHz identified for IMT and has a widespread allocation globally.

WRC-2000 also identified the frequency range 806−960 MHz for IMT-2000, complemented by the frequency range 698−806 MHz in WRC'07. As shown in Figure 2.6, several bands are defined for FDD operation in this range. Band 8 uses the same band plan as GSM900. *Bands 5, 18, 19, 26, and 27* overlap, but are intended for different regions. Band 5 is based on the US cellular band, while Bands 18 and 19 are restricted to Japan in the specifications. 2G systems in Japan had a very specific band plan and Bands 18 and 19 are a way of partly aligning the Japanese spectrum plan in the 810−960-MHz range to that in other parts of the world. Note that Band 6 was originally defined in this frequency range for Japan, but it is not used for LTE.

An extensive study was performed in 3GPP to create an extension of Band 5 (850 MHz), which is one of the bands with the most widespread deployment globally. The extension adds additional frequency ranges below the present Band 5 and is done with two new operating bands. Band 26 is the "Upper Extending 850-MHz" band, which encompasses the band 5 range, adding 2 × 10 MHz to create an extended 2 × 35-MHz band. Band 27 is the "Lower Extending 850-MHz" band which consists of the 2 × 17-MHz frequency range right below and adjacent to Band 5.

Bands 12, 13, 14, and 17 make up the first set of bands defined for what is called the *digital dividend*—that is, for spectrum previously used for broadcasting. This spectrum is partly migrated to be used by other wireless technologies, since TV broadcasting is migrating from analog to more spectrum-efficient digital technologies. Other regional band for the digital dividend is *Band 20* that is defined in Europe and *Band 28* for the Asia/Pacific region. An alternative unpaired arrangement in the Asia/Pacific region is the unpaired Band 44.

Band 29, 32, and 67 are "paired" bands that consist of a downlink without an identified uplink. The bands are intended for carrier aggregation with downlink carriers in other bands. Primarily, Band 29 can be paired with Band 2, 4, and 5 in the Americas and Band 32 and 67 can be paired with for example Band 20 in Europe.

The paired *Band 22* and unpaired *Band 42 and 43* are specified for the frequency range 3.4–3.8 GHz [39]. In Europe, a majority of countries already license the band at 3.4–3.6 GHz for both Fixed Wireless Access and mobile use, and there is a European spectrum decision for 3.4–3.8 GHz with "flexible usage modes" for deployment of fixed, nomadic, and mobile networks. In Japan, not only 3.4–3.6 GHz but also 3.6–4.2 GHz will be available to terrestrial mobile services in the future. The band 3.4–3.6 GHz has also been licensed for wireless access in Latin America.

The paired *Band 31* is the first 3GPP band defined in the 450-MHz range. Band 31 is specified for use of LTE in Brazil. Band 32 is an LTE band for the United States, also called the *Wireless Communication Service* (WCS) band.

Several Mobile Satellite Service operators in the United States are planning to deploy an *Ancillary Terrestrial Component* (ATC) using LTE. For this purpose two new frequency bands are defined, *Band 23* with 2 × 20-MHz band for the S-band MSS operators at 2 GHz and *Band 24* with 2 × 34-MHz band for the L-band MSS operators at 1.5 GHz.

Band 46 is a band in a frequency range at 5 GHz that is globally assigned for *Wireless Access Systems* (WAS) including Radio Local Area Networks (RLAN). The band is not fully assigned in any region, but parts are under study, see Section 17.1 for more details on the spectrum for LAA. Operation in the band is unlicensed. For LTE, the band is in Release 13 defined for what is called License-Assisted Access, where downlink operation in Band 46 is combined with licensed operation in other bands through downlink carrier aggregation.

2.3.3 NEW FREQUENCY BANDS

Additional frequency bands are continuously specified for UTRA and LTE. WRC'07 identified additional frequency bands for IMT, which encompasses both IMT-2000 and

IMT-Advanced. Several of the bands defined by WRC'07 are already available for LTE as described earlier, or will become available partly or fully for deployment on a global basis:

- *450–470 MHz* was identified for IMT globally. It is already allocated to mobile service globally, but it is only 20-MHz wide and has a number of different arrangements. LTE Band 31 is defined in this range.
- *698–806 MHz* was allocated to mobile service and identified IMT to some extent in all regions. Together with the band at 806–960 MHz identified at WRC-2000, it forms a wide frequency range from 698 to 960 MHz that is partly identified to IMT in all regions, with some variations. A number of LTE bands are defined in this frequency range.
- *2300–2400 MHz* was identified for IMT on a worldwide basis in all three regions. It is defined as LTE Bands 30 and 40.
- *3400–3600 MHz* was allocated to the mobile service on a primary basis in Europe and Asia and partly in some countries in the Americas. There is also satellite use in the bands today. It is defined as LTE Bands 22, 42, and 43.

For the frequency ranges below 1 GHz identified at WRC-07, 3GPP has already specified several operating bands, as shown in Figure 2.6. The bands with the widest use are Bands 5 and 8, while most of the other bands have regional or more limited use. With the identification of bands down to 698 MHz for IMT use and the switchover from analog to digital TV broadcasting, Bands 12, 13, 14, and 17 are defined in the United States, Band 20 in Europe, and Bands 28 and 44 in Asia/Pacific for the digital dividend.

Additional bands for IMT were identified at WRC'15, some of which are already bands defined for LTE:

- *470–698 MHz* was identified for IMT in some countries in the Americas, including the United States and Canada. Also some countries in the Asia–Pacific identified the bands fully or partly for IMT. In Europe and Africa, the use of this frequency range will be reviewed until WRC'23.
- *1427–1518 MHz*, also called the L-band, was identified for IMT globally. The band has been used for a long time in Japan and the LTE Bands 11, 21, and 32 are already defined for 3GPP in this frequency range.
- *3300–3700 MHz* is now identified for IMT at least in some regions or countries. The frequency range 3400–3600 MHz, which was identified already at WRC-07, is now identified globally for IMT. LTE Bands 22, 42, and 43 are in this range.
- *4800– 4990 MHz* was identified for IMT for a few countries in the Americas and Asia-Pacific.

2.4 SPECTRUM FOR 5G

2.4.1 NEW FREQUENCY BANDS TO BE STUDIED BY WRC

The frequency listings in the ITU Radio Regulations [65] do not directly list a band for IMT, but rather allocates a band for the mobile service with a footnote stating that the band is identified for use by administrations wishing to implement IMT. The identification is mostly by region, but is in some cases also specified on a per-country level. All footnotes mention "IMT" only, so there is no specific mentioning of the different generations of IMT. Once a band is assigned, it is therefore up to the regional and local administrations to define a band for IMT use in general or for specific generations. In many cases, regional and local assignments are "technology neutral" and allow for any kind of IMT technology.

This means that all existing IMT bands are potential bands for IMT-2020 (5G) deployment in the same way as they have been used for previous IMT generations. In addition, it is also expected that bands above 6 GHz will be used for IMT-2020. An agenda item has been set up for WRC'19 where additional spectrum will be considered, and studies will be conducted until WRC'19 to determine the spectrum needs for terrestrial IMT. Sharing and compatibility studies of IMT will also be performed for a set of specific bands in the range from 24.25 to 86 GHz as illustrated in Figure 2.7. A majority of the bands to be studied are already assigned to the mobile service on a primary basis, in most bands together with fixed and satellite services. These are:

- 24.25–27.5 GHz
- 37–40.5 GHz
- 42.5–43.5 GHz
- 45.5–47 GHz
- 47.2–50.2 GHz
- 50.4–52.6 GHz
- 66–76 GHz
- 81–86 GHz

There are also bands to be studied for IMT that are presently not allocated to the mobile service on a primary basis and where it will be investigated whether the allocation can be changed to include mobile:

- 31.8–33.4 GHz
- 40.5–42.5 GHz
- 47–47.2 GHz

Sharing studies between IMT as a mobile service and the other primary services in those bands will be a task for regional and national administrations together with the industry in

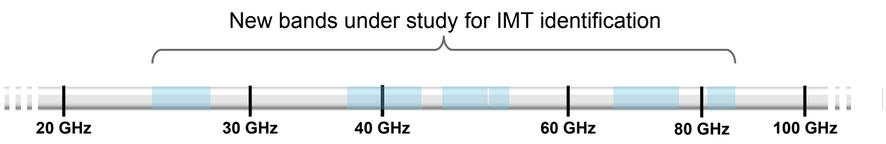

FIGURE 2.7

New IMT bands under study in ITU-R.

preparation for WRC'19. In some cases studies of adjacent services may be performed too. As an input to the studies, technical and operational characteristics of IMT are needed, which in this case implies the characteristics of IMT-2020.

2.4.2 RF EXPOSURE ABOVE 6 GHZ

With the expansion of the frequency ranges for 5G mobile communications to bands above 6 GHz, existing regulations on human exposure to RF *electromagnetic fields* (EMF) may restrict the maximum output power of user devices to levels significantly lower than what are allowed for lower frequencies.

International RF EMF exposure limits, for example, those recommended by the *International Commission on Non-Ionizing Radiation Protection* (ICNIRP) and those specified by the *Federal Communications Commission* (FCC) in the United States, have been set with wide safety margins to protect against excessive heating of tissue due to energy absorption. In the frequency range of 6 to 10 GHz, the basic limits change from being specified as specific absorption rate (W/kg) to incident power density (W/m^2). This is mainly because the energy absorption in tissue becomes increasingly superficial with increasing frequency, and thereby more difficult to measure.

It has been shown that for products intended to be used in close proximity of the body, there will be a discontinuity in maximum allowed output power as the transition is made from specific absorption rate to power-density-based limits [62]. To be compliant with ICNIRP exposure limits at the higher frequencies, the transmit power might have to be up to 10 dB below the power levels used for current cellular technologies. The exposure limits above 6 GHz appear to have been set with safety margins even larger than those used at lower frequencies, and without any obvious scientific justification.

For the lower-frequency bands, large efforts have been spent over the years to characterize the exposure and to set relevant limits. With a growing interest for utilizing frequency bands above 6 GHz for mobile communications, research efforts are likely to increase which eventually may lead to revised exposure limits. In the most recent RF exposure standards published by IEEE (C95.1-2005, C95.1-2010a), the inconsistency at the transition frequency is less evident. However, these limits have not yet been adopted in any national regulation, and it is important that also other standardization organizations and regulators work to address this issue. If not, this might have a large negative impact on coverage at higher frequencies, in particular for user equipment intended to be used near the body, such as wearables, tablets, and mobile phones, for which the maximum transmit power might be heavily limited by the current RF exposure regulations.

2.5 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, and 4G LTE. 3GPP technologies are the most widely deployed in the world, with more than 90% of the world's 7.4 billion mobile subscriptions in Q4 2015 [54]. In order to understand how 3GPP works, it is important to also understand the process of writing specifications.

2.5.1 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 Figure 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 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.

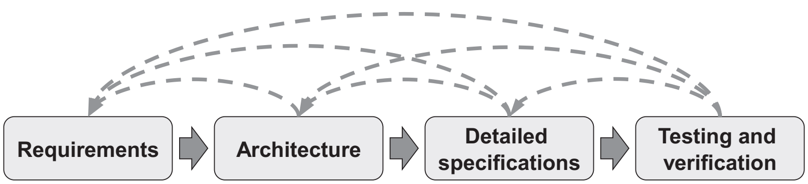

FIGURE 2.8

The standardization phases and iterative process.

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.

Normally, it takes about 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 Figure 2.9—where TSG RAN (*Radio Access Network*) is responsible for the definition of functions, requirements, and interfaces of the Radio Access. It 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.
4. RAN WG4, dealing with the RF and *radio resource management* (RRM) performance requirements.
5. RAN WG5, dealing with the device conformance testing.
6. RAN WG6, dealing with standardization of GSM/EDGE (previously in a separate TSG called GERAN).

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 and IMT-Advanced. 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. The releases from release 8 and onward, with some main features listed for LTE, are shown in Figure 2.10. The date shown for each release is the day the content of the release was frozen. 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-*

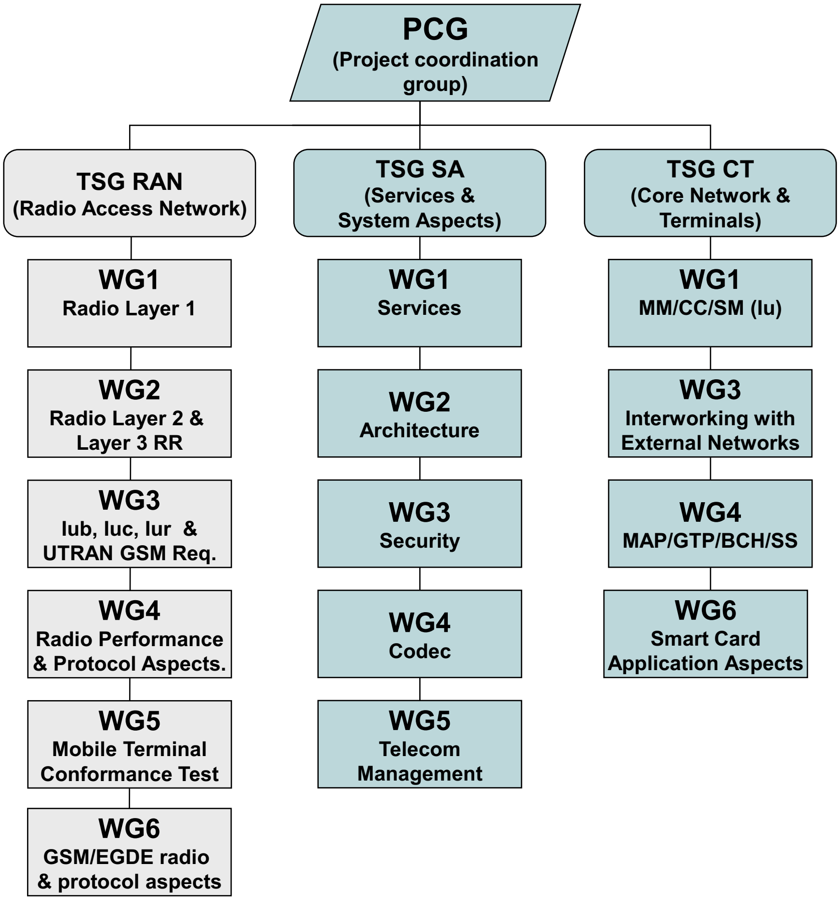

FIGURE 2.9

3GPP organization.

Advanced. From Release 13, the marketing name for LTE is changed to *LTE-Advanced Pro*. The content of the 3GPP releases for LTE is described with further details in Chapter 3.

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).
- 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 the next generation (5G).

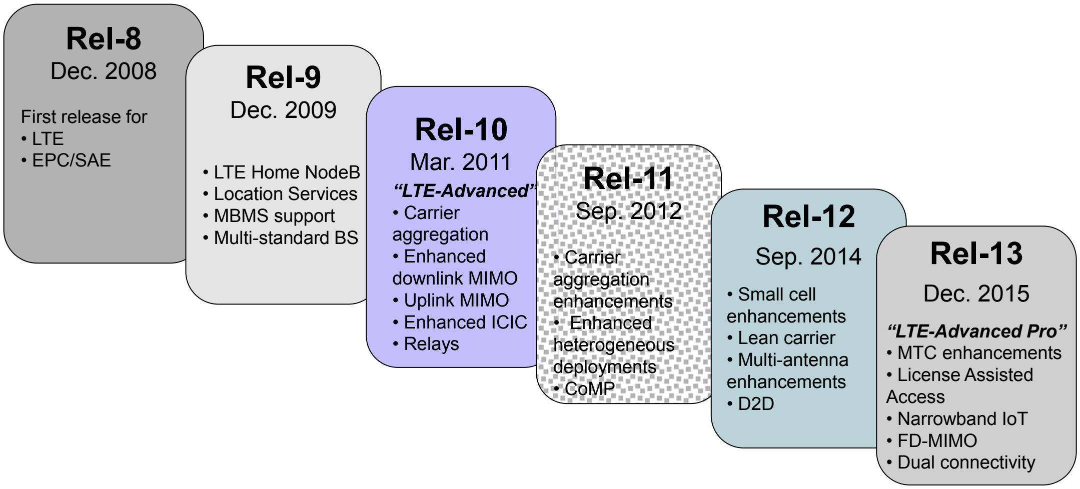

FIGURE 2.10

Releases of 3GPP specifications for LTE.

2.5.2 SPECIFYING 5G IN 3GPP

In parallel with the definition and evaluation of the next-generation access initiated in ITU-R, 3GPP has started to define the next-generation 3GPP radio access. A workshop on 5G radio access was held in 2014 and a process to define evaluation criteria for 5G was initiated with a second workshop in early 2015. The evaluation is planned to 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 will follow the ITU-R time line described in Section 2.2.3. With reference to the four phases described in Figure 2.8, the 5G work in 3GPP is presently in the first phase of defining requirements. The 3GPP process is further described in Chapter 23.

3GPP TSG RAN is documenting scenarios, requirements, and evaluation criteria for the new 5G radio access in a new report TR 38.913 [66], which corresponds largely to the report TR 36.913 [29] that was developed for defining requirements on LTE-Advanced. 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 RITs that is defined by ITU-R WP5D. It is essential that the ITU-R evaluation is kept at a reasonable complexity, in order to complete the work on time and for also external evaluation groups to be able to participate in the evaluation.

Further details on the 5G radio access and its possible components are given in Chapters 23 and 24.