Spectrum Analysis and Regulations for 5G

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Abstract In 5G vision, the spectrum issue is one of the most important parts. Governments, agencies, standardization organizations and research institutions from many countries pay high attention to the 5G spectrum strategies. The appeals for international harmonized spectrum and full band spectrum access are intense, the range of which are possibly from 0-100GHz. This chapter addresses the current spectrum for mobile communications, the future spectrum demand, possible candidate frequency bands and spectrum management considerations. Information from international and regional telecommunications such as ITU, CEPT, APT, and also from different countries are collected and analyzed. Some academic views are also provided for future work.

1 Introduction

Mobile communication has gone deep into people's lives. For the year 2020 and beyond, all kinds of new services will continue to emerge, mobile data traffic will show explosive growth, and connections from terminals will increase exponentially. With the rapid development of Mobile Internet and Internet of Things, the 5G will be integrated into each field of the society in the future, and construct a full range of information ecosystem, providing a broad prospect.

Spectrum is the one of the most valuable resource for mobile communications. Among the 5G studies and pre-standardization works, the spectrum issue is one of the most important parts. In this context, the global 5G research institutions pay high attention to the research on spectrum, such as EU FP7 METIS project [1] and China's IMT-2020 Promotion Group [http://www.imt-2020.org.cn/zh]. In addition, some countries put the spectrum for next generation of mobile communication in

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Fig. 1 General consideration of spectrum for 5G

a prominent position [2, 3]. Furthermore, in the framework of ITU, the ITU-R study groups (e.g., WP 5D) and related regional telecommunication organizations (including ASMG, APT, CEPT, CITEL, RCC, ATU and so on) are actively conducting studies for 5G spectrum.

According to current research, generally, spectrum below 6 GHz is the best resource in the near future [4]. These bands mainly include re-farmed 2G/3G spectrum, identified frequency band for IMT in Radio Regulations and also WRC-15 candidate bands. However, due to its scarcity and increasingly difficulty to realize international harmonization after WRC-15, it is the time to seek spectrum above 6 GHz, as shown in Fig. 1. The 5G spectrum solution will be a comprehensive outcome, indicating combinations of different frequency ranges for different scenarios. It is expected that 5G requires more in the total amount, wider with respect to individual bandwidths, greater in the range and more flexible in the usage and management pattern.

In this chapter, 5G spectrum related issues are investigated, discussed and summarized, taking typical regions and countries as examples around the world including Asia-Pacific, Europe and Americas. In Sect. 2, the current used spectrum for mobile communication is described. Section 3 focuses on the 5G spectrum demand, followed by the 5G potential candidate frequency bands in Sect. 4. Some new ideas in 5G spectrum management are investigated in Sect. 5 to give some food for thought. We conclude this chapter in Sect. 6.

2 Current Spectrum for Mobile Communications

The sharing of information on frequency allocation and spectrum usages will be beneficial to reach harmonization on spectrum usages among all countries around the world, especially for mobile communications. Moreover, as described in Sect. 4, the current allocated spectrum for International Mobile Telecommunication (IMT) is an important part of 5G candidate spectrum. In this regard, this chapter starts with the usage status of mobile communication spectrum. In different countries, due to the different development stages of mobile communication industry, the total amount of spectrum, different frequency ranges for 2G/3G/4G vary widely, but also reflects a certain degree of consistency.

Take the situation of Asia as the first step. In Asia, it was agreed to develop an APT Report on information of mobile operators' frequencies, technologies and license durations in Asia Pacific countries [5]. The APT report is a compilation

Table 1 Operators, frequency bands, used technology and license duration of Japan

Japan				
	Frequency band (MHz)			
Operator	Uplink	Downlink	Technology	License duration
NTT DoCoMo, Inc.	728–738	783–793	LTE	Period: 5 years (Note)
	830–845	875–890	WCDMA/LTE	
	1447.9–1462.9	1495.9–1510.9	LTE	
	1764.9–1784.9	1859.9–1879.9	WCDMA/LTE	
	1940–1960	2130–2150	WCDMA/LTE	
	3480–3520 (TDD)		LTE	
KDDI Corporation	718–728	773–783	LTE	
	815–830	860–875	CDMA2000/LTE	
	1437.9–1447.9	1485.9–1495.9	LTE	
	1920–1940	2110–2130	CDMA2000/LTE	
	3520–3560 (TDD)		LTE	
Softbank Mobile Corp.	900–915	945–960	WCDMA/LTE	
	1427.9–1437.9	1475.9–1485.9	WCDMA	
	1960–1980	2150–2170	WCDMA/LTE	
	3560–3600 (TDD)		LTE	
Ymobile Corp.	738–748	793–803	LTE	
	1749.9–1764.9	1844.9–1859.9	WCDMA/LTE	
Ymobile Corp.	1884.5–1915.7 (TDD)		PHS	
Wireless City Planning Inc.	2545–2575 (TDD)		AXGP (Advanced eXtended Global Platform)	
UQ Communications Inc.	2595–2645 (TDD)		WiMAX/WiMAX2+	

Note: License is granted to Base Station each. Expiration date of license for each station is different

of responses to the Questionnaire and up to now includes information from 26 members such as Australia, China, India, Iran, Japan, Korea, and Thailand, etc. One example with relatively new information is shown in Table 1.

For US, the public mobile communications spectrum is mainly reflected in Title 47 Telecommunication [http://reboot.fcc.gov/reform/systems/spectrum-dashboard]. As for Europe, the ECC is in response of developing European common positions and proposals for efficient use of radio spectrum in the framework of international and regional bodies. A European Table of Frequency Allocations and Applications (ECA Table) [6] is provided by CEPT.

In general, the frequency table for mobile communication in countries can be found in national official publications or output documents in regional organizations. It is shown that almost all the frequency ranges are focus on the spectrum below 3 GHz. Another observation from these data is that generally the amount of spectrum currently used for mobile communications is several hundred megahertz.

3 5G Spectrum Demand

Every few years, ITU-R sets up agenda items in advance to study the future spectrum demand for IMT, and to support the consideration of additional spectrum allocations. Currently, ITU-R has already finished the study on IMT spectrum demand towards the year 2020. Some countries have also started the study on spectrum demand beyond 2020.

3.1 Demand in the Year 2020

How to calculate IMT spectrum demands? Generally, a methodology starts with an analysis of future market and traffic volume, moves on to calculate and distribute the traffic on different RATs, and then calculates the required capacity, before concluding the estimation. The actual calculation process can be very complicated, when there are a variety of traffic types, different environments and multiple cell types of different RATs. For example, imagine how to estimate the data rates of a high quality video streaming user located in indoor offices, connecting with future 5G small cells, in the year 2025.

Many countries have made contributions to the calculation methodology and output results. Table 2 summarizes national spectrum requirements as provided by some countries and organizations during the study of ITU-R, in the form of total amount for all the operators in one country [7]. It should be noted that these national spectrum requirements have differences in the methodology used and assumptions made (e.g., differences in traffic/radio-aspects related parameters, differences in estimation year, differences in estimates based on whether the spectrum requirements are total or additional, etc.).

Some of them, such as GSMA (GSM Association) and UK, focused on the improvements of existing ITU-R method specified in Recommendation M.1768-1.

The methodology of Recommendation ITU-R M.1768-1 is developed by ITU-R Study Group, which is used in WRC-07 to calculate the spectrum demand in the future. The methodology provides the spectrum requirements of IMT as a whole, and divided between two radio access technique groups (RATGs):

- RATG 1: Pre-IMT systems, IMT-2000 and its enhancements;
- RATG 2: IMT-Advanced.

The methodology reflects certain recent advances in IMT technologies and the deployment of IMT networks such as the introduction of spectrum sharing between the macro and micro cell layers in IMT Advanced, and the introduction of a new spectrum granularity parameter for IMT systems.

Figure 2 summarizes the steps of the calculation algorithm employed in Recommendation ITU-R M.1768-1 in conjunction with relevant input parameters (detailed descriptions of these parameters are provided in Sect. 4) [7]. The methodology starts

Table 2 Summary of national spectrum requirements in some countries [7]

Source	US	Australia	Russia	China	GSMA	India	UK
Estimation year	Until 2014	Until 2020	2020	2015, 2020	2020	2017, 2020	2020
Spectrum requirements	Additional 275 MHz by 2014	1081 MHz in total	1065 MHz in total	570–690 MHz in total by 20151490–1810 MHz in total by 2020	1600–1800 MHz in total for some countries	Additional 300 MHz by 2017Additional another 200 MHz by 2020	775–1080 MHz in total for low2230–2770 in total MHz for high
Methodology	Original	Original	Original	Rec. ITU-R M.1768-1	Complementary to Rec. ITU-R M.1768-1	Original	Rec. ITU-R M.1768-1

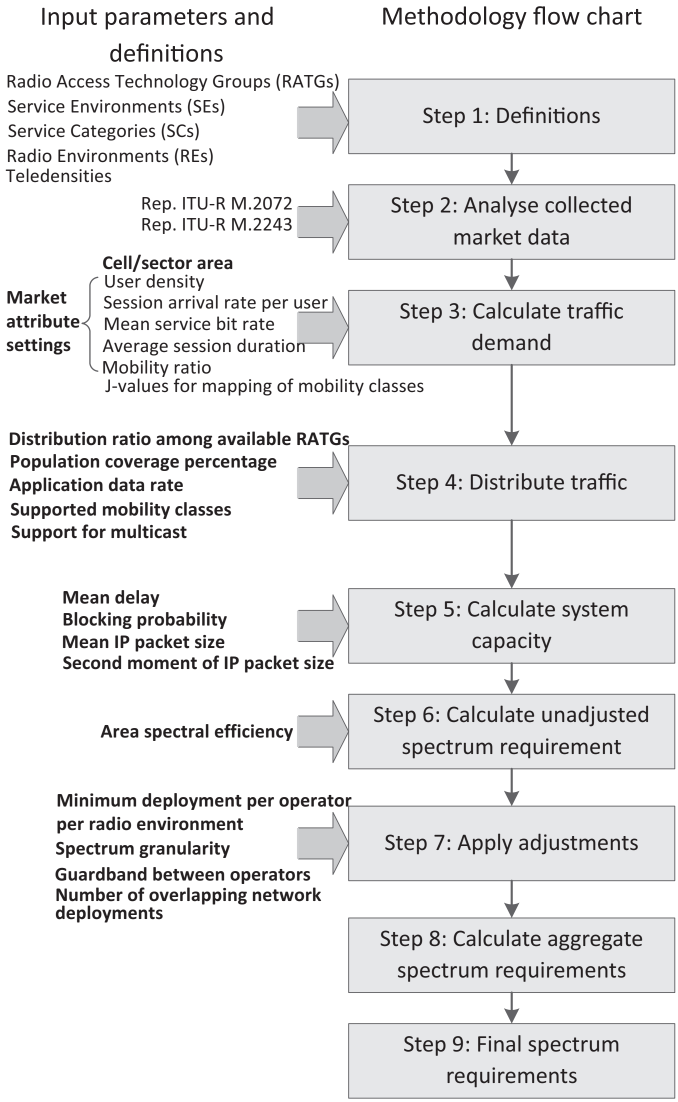

Fig. 2 Steps of calculation algorithm and relevant input parameters [3]

from market studies that characterize all of the traffic carried by IMT and other mobile systems, corresponding to Steps 2–3. In Step 4, the total traffic obtained from the market studies is distributed among different radio environments (cell layers) and RATGs according to factors such as traffic characteristics (required data rates and user mobility), RATG capabilities (supported data rates, available cell types and their coverages), etc. The system capacity required to carry the offered traffic is then calculated in Step 5 using separate capacity calculation algorithms

Table 3 Total spectrum requirements for both RATG 1 and RATG 2 in the year 2020 [7]

Total spectrum requirements	RATG 1	RATG 2	RATGs 1 and 2
Lower user density settings	440 MHz	900 MHz	1340 MHz
Higher user density settings	540 MHz	1420 MHz	1960 MHz

for reservation-based traffic and packet-based traffic respectively. Initial spectrum estimates are obtained from the capacity requirements by dividing the latter by the spectral efficiencies (Step 6). Then, adjustments are made to take into account network deployments with the spectrum requirements being aggregated over the relevant deployments (Steps 7–8). Finally, the methodology outputs the overall spectrum requirements of RATG 1 and RATG 2, which collectively denote IMT systems (Step 9).

There are differences in the markets and deployments and timings of the mobile data growth in different countries. Therefore, two settings are developed to characterize lower and higher user density settings. These two sets of market study input parameter values are considered in the calculations to characterize differences in the user densities in different countries. Table 3 shows the calculated spectrum requirements for both RATGs 1 and 2.

In some countries, national spectrum requirement can be lower than the estimate derived by lower user density settings and in some other countries, national spectrum requirement can be higher than the estimate derived by higher user density settings.

Besides using existing methodologies, there are also original methodologies proposed by US [8], Australia [9], Russia [10] and so on. These methodologies are reflected as case studies based on national considerations. In the following, a brief example is shown from China, which is conducted from the IMT-2020 Promotion Group.

The main point of the new method is to estimate the upper bound of demand. In fact, it is proved by the operational data that the area which has the largest spectrum demand is always in metropolises. When requirements of such a scenario are satisfied, the solution might be applicable for others as well. In the calculation, a typical hotspot zone in Beijing is selected as the research area. To gather the historical data within, the government issued an investigation letter to all network operators. The data survey is based on the operator's network management system in China, which is a major difference between the proposed method and other international methods. Supported by these first-hand data, analyses are made to estimate the traffic increase, traffic distribution and Base Station (BS) deployments in the future. The general flow chart of the methodology is shown in Fig. 3. According to the calculation, the total IMT spectrum demand in China is 1350–1810 MHz in 2020 [11], which are a little different from but similar with the result from the calculation by M.1768-1 (1490–1810 MHz).

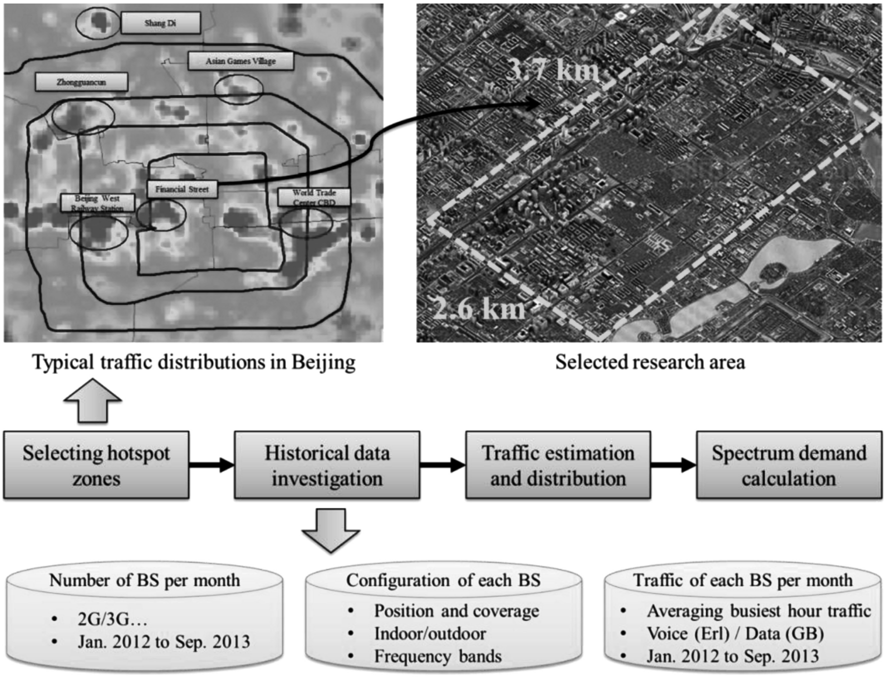

Fig. 3 Flow chart of the spectrum demand methodology proposed by China, where a 3.7 km × 2.6 km square area around Beijing Financial Street is selected as the typical dense traffic area [4]

The obtained estimation results regardless from different methods are huge. Compared with current identified spectrum for IMT in different countries, there are still several hundred to even 1000 MHz deficit. Moreover, in the period of 5G commercialization after 2020, the total spectrum demand may continue to increase.

3.2 Demand Beyond the Year 2020

The above result is, to some extent, a total amount of spectrum and the range depends on the assumptions made in the estimation process. However, in view of 5G beyond 2020, it is probably difficult to measure the new demand only in a total number. For example, in 5G indoor high traffic scenarios, in order to achieve high peak data rates, the demand for frequency bandwidth may be up to several GHz. This can be solved by using higher frequencies and denser deployments [12]. But these solutions may not be the best choice for outdoor wide area scenarios. Therefore, it will be useful to separately estimate how much spectrum is required for coverage, capacity, performance and connections for each 5G scenario as Fig. 4 shows, to

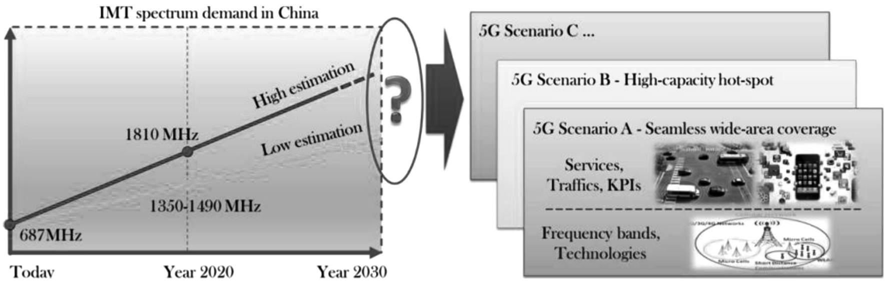

Fig. 4 A scenario-based solution for spectrum demand in 2030 [http://www.imt-2020.org.cn/zh]

perform a mapping onto different frequency bands, such as bands below 1 GHz, between 1 and 6 GHz and above 6 GHz. It may be believed that the results from different scenarios will vary a lot.

Generally, the 5G spectrum demand estimation will be a comprehensive outcome, indicating spectrum solutions for different scenarios. It is expected that 5G requires more in the total amount, wider with respect to individual bandwidths, greater in the range and more flexible in the usage pattern.

4 5G Candidate Frequency Bands

Is the world ready to provide sufficient frequency bands for 5G? From the study point of view, the potential bands can be divided into two parts: bands below 6 GHz and above [4].

4.1 Spectrum Below 6 GHz

For wireless communications, lower frequencies provide better coverage. Currently, almost all countries are using spectrum below 6 GHz for IMT systems. Besides achieving high data rates, it is also necessary to guarantee wide-area coverage and outdoor-to-indoor coverage in 5G. Therefore, spectrum below 6 GHz forms a very important part for the 5G spectrum solution. Potential 5G spectrum below 6 GHz includes the following aspects:

- Spectrum re-farming

In order to realize the benefits of new generation of mobile communication systems, regulators need to deliver efforts to enable re-farming of spectrum in the frequency band occupied by the old ones.

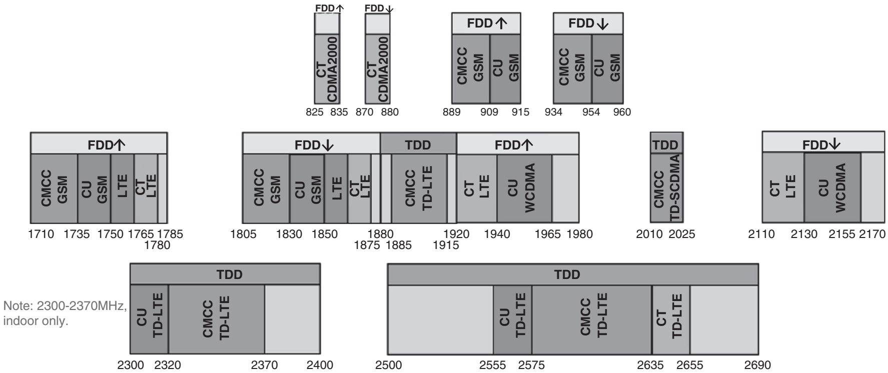

Fig. 5 Frequency bands used for mobile technology in China (CT: China Telecom, CM: China Mobile, CU: China Unicom)

Taking China as an example, up to Feb. 2016, 517 MHz been allotted to three operators for eight networks, as shown in Fig. 5. For the two operators authorized for LTE hybrid network, China Telecom has 2×15 MHz spectrum for LTE FDD, while China Unicom only has 2×10 MHz in the beginning. Market competition has prompted Chinese Unicom to accelerate the pace of 2G spectrum re-farming for 3G and 4G networks. On the other hand, owing the world largest TD-LTE network, China Mobile has also expressed willingness to re-farm 2G spectrum for LTE FDD.

When 5G is put into use, it is expected that some spectrum from the old generation could be re-farmed for it as well. However, re-farming does not increase the total spectrum amount.

- Identified spectrum

In the past ITU-R studies, sometimes it is difficult to reach global or even regional agreement for the usage of some frequency bands. Therefore some Resolutions from WRC will not modify the Table of Frequency Allocations uniformly, but usually take effect in the form of adding footnotes for some countries. There are many cases for IMT frequency bands planning in this way.

For example, footnote **5.432A** specifies that "In Korea (Rep. of), Japan and Pakistan, the band 3400–3500 MHz is identified for International Mobile Telecommunications (IMT). This identification does not preclude the use of this band by any application of the services to which it is allocated and does not establish priority in the Radio Regulations ..."

However, some identified IMT spectrum is not for immediate use. For example, in Regulations of Radio Frequency Division of China, there are several frequency bands identified for IMT specified in footnote CHN28 such as 2300–2400 MHz and 3400–3600 MHz [13], but only when the compatibility studies are finished. Currently in China, LTE-Hi (LTE Hotspot/indoor) is proposed to meet the coverage requirement of hotspot and indoor scenarios. Compared with current IMT, LTE-Hi is targeting higher frequency, including 3400–3600 MHz.

For 2300–2400 MHz, after careful studies, IMT systems have proven the capability of coexisting with radio location services, but only limited to indoor use. This band has been assigned in Dec. 2013, for deploying TD-LTE systems.

Nevertheless, other frequency bands are still to be studied with respect to compatibility before official use. For example, 3400–3600 MHz is already used as extended C band for satellite services in China, since it can provide better propagation characteristics against the rain attenuation than higher frequency bands. Therefore, up to now, allowing this band for IMT systems needs further demonstration and coordination.

- New frequency bands after WRC-15

In accordance with resolves to invite ITU-R 2 of Resolution 233 (WRC-12), there are 19 candidate frequency bands proposed for IMT from different administrations, in the framework of WRC-15 Agenda Item (AI) 1.1 [14], as shown in Fig. 6.

These frequency bands are considered as potential candidate frequency bands from among the suitable frequency ranges provided by the ITU-R. These frequency bands were proposed by one or more administrations and were studied by the ITU-R. For a frequency band to be included, the ITU-R JTG 4-5-6-7 developed the following criteria: it must have been proposed by an administration and have been studied.

In studying AI 1.1, inputs were received reflecting views on certain frequency ranges/bands. Some of the views are listed in Table 4. Studies related to various frequency bands (studies initiated, carried out, not completed, completed), as well as an overview of which services were and were not studied for each band, are addressed in [14].

Different administrations or regions may have different considerations in supporting these frequency bands. The final results could be found in Provisional Final Acts of WRC-15 [15]. It shows that, to realize global harmonization, it is necessary to achieve further regional convergence.

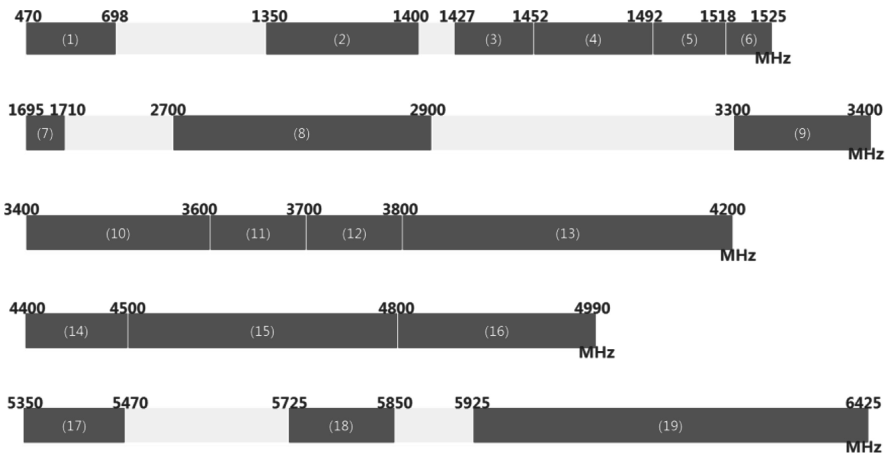

Fig. 6 Possible candidate bands in WRC-15 Agenda Item 1.1 before the conference

Table 4 Views on suitable frequency ranges/bands

Frequency ranges (MHz)		Views[a]					
		EU	US	Russia	Japan	Korea	China
1	470–694/698	s	√	×	×	√	
2	1350–1400	×		×			
3	1427–1452	√	×	×	√		
4	1452–1492	√	×	×	√	√	
5	1492–1518	√	×	×	√		
6	1518–1525	×	×	×	√		
7	1695–1710	×	√				×
8	2700–2900	×	s				×
9	3300–3400	×					√
10	3400–3600	√	s	×	√	√	×
11	3600–3700	√	s	×	√	√	×
12	3700–3800	√	s	×	√	√	×
13	3800–4200	×	s	×	√	√	×
14	4400–4500	×			√		√
15	4500–4800	×			√		×
16	4800–4990	×			√	√	√
17	5350–5470	×	√				
18	5725–5850	s					
19	5925–6425	s		√			×

[a] √: support, ×: oppose, s: study

Spectrum below 6 GHz are the best resources for IMT in the near future. However, due to its scarcity and increasingly difficulty to realize international harmonization, it is the time to seek spectrum above 6 GHz.

4.2 New Spectrum After WRC-15, Especially the Bands Above 6 GHz

Traditionally, spectrum usage above 6 GHz such as millimeter wave (mmWave) often applies for point-to-point communications in large power systems such as satellite systems and microwave systems.

From the perspective of public mobile communication, mmWave communication technology also attracts peoples' attention. Samsung from Korea conducted studies and tests for the above 6 GHz, especially at 13.4–14 GHz, 18.1–18.6 GHz, 27.0–29.5 GHz and 38.0–39.5 GHz. At 28 GHz, deploying 64 antennas, Samsung has done the experiments of the adaptive beam-forming technology to implement 1 Gbps peak rate within 200 m, and its error rate is less than 0.01 % [16]. Moreover, at 11 GHz, NTT DoCoMo implemented prototype for high-speed mobile vehicle communications. In addition, manufacturers such as Ericsson, Huawei, and

NSN show their vision for mmWave communications on various bands such as 14 GHz, E-band (71–76 GHz/81–86 GHz) and so on. It is obvious that mmWave communication is drawing attentions all over the world as one of the potentially essential technologies of the next generation of mobile communication systems.

The 60 GHz International Broadband Wireless Access Systems (BWAS) are drawing peoples' attention. It mainly focuses on short-distance, high-rate communications. The transmission distance is usually within 10 m, and TDD mode is applied. The specific operating frequency is 56–66 GHz (59–64 GHz in China). The three related international standards are ECMA 387, IEEE 802.15.3c and IEEE 802.11ad. In addition, IEEE establishes IEEE 802.11aj to formulate the specific criteria of 60 and 45 GHz usage in China.

In 2001, FCC allotted a continuous section of spectrum (57–64 GHz) for wireless communication in unlicensed mode [17]. In Europe, ECC also allotted 57–66 GHz unlicensed spectrum. Specifically, 62–63 GHz and 65–66 GHz were for Mobile Broadband System, and 59–62 GHz were for Wireless Local Area Network (WLAN) [18]. In 2006, 59–64 GHz was planned in China for wireless short-distance technologies. Similarly, Japan and Australia conducted the related spectrum planning in this frequency band. The detail procedure is shown in Fig. 7. In 2013, China allotted 40.5–42.3 GHz band and 48.4–50.2 GHz band for fixed point-to-point wireless access system (light license management), 42.3–47 GHz band and 47.2–48.4 GHz band for mobile point-to-point wireless access system (unlicensed management).

However, due to the characteristics of high frequency, the key technologies applied for low frequency are hard to directly put into use. How to utilize the advantage and overcome the disadvantage are both opportunities and challenges [19].

- Principles for candidate bands selection [20]

In the Table of Frequency Allocations, spectrum above 6 GHz are mainly allocated to fixed service, mobile services, radio location service, radio navigation service, fixed satellite service, inter-satellite services and broadcasting satellite service, etc. In practical use, for example, there are digital microwave relay systems, navigation

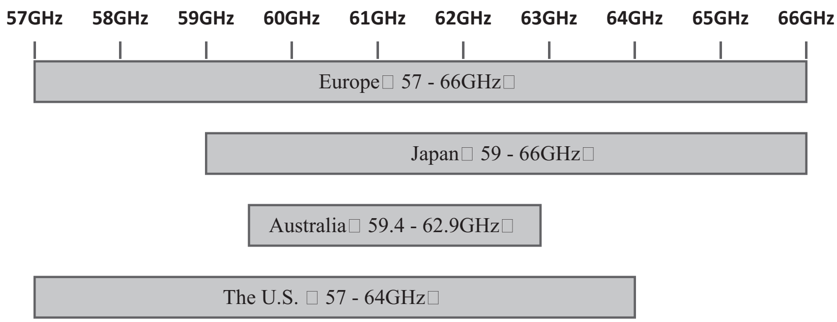

Fig. 7 International spectrum allocation of 60 GHz

and air traffic control radar system and satellite communication systems. High frequency radio communication has different characteristics in radio propagation antenna and RF, compared with lower frequency communication. For candidate bands selection for mobile communications, the following principle could be considered.

Compliance Bands allocated to Mobile Services (or in footnotes identified) are preferred.

Consistency To select potential candidates for international harmonization, to take into account the future promotion in WRC.

Security Fully consideration on the electromagnetic compatibility between systems, to ensure the protection of mobile systems as well as other systems.

Continuous To take the advantage of broadband (e.g., >500 MHz) from high frequency to guarantee that the system can obtain a higher efficiency.

Effective Taking into account the propagation characteristics of high frequency and industrial hardware manufacturing capability, to select the appropriate frequency to ensure the effective design and realization of the system, terminal, instrument, etc.

- Some potential frequency ranges for 5G above 6–100 GHz

Preliminary studies from different administrations or organizations show that a lot of potential suitable frequency ranges could be found from 6 to 100 GHz. This sub-section summaries some considerations from research institutes, countries and regional organizations.

4.2.1 METIS

The METIS project has delivered study results on potential suitable frequency ranges [21] in terms of a prioritization of the bands as shown in Figs. 8 and 9,

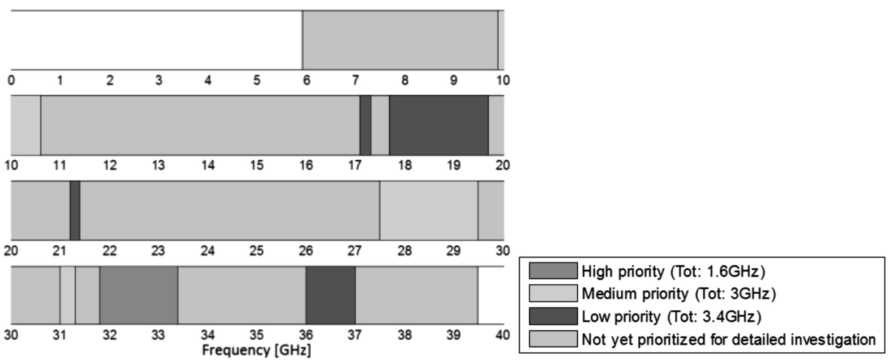

Fig. 8 Opportunities of potential sharing with current incumbent within 5.925–40.5 GHz [21]

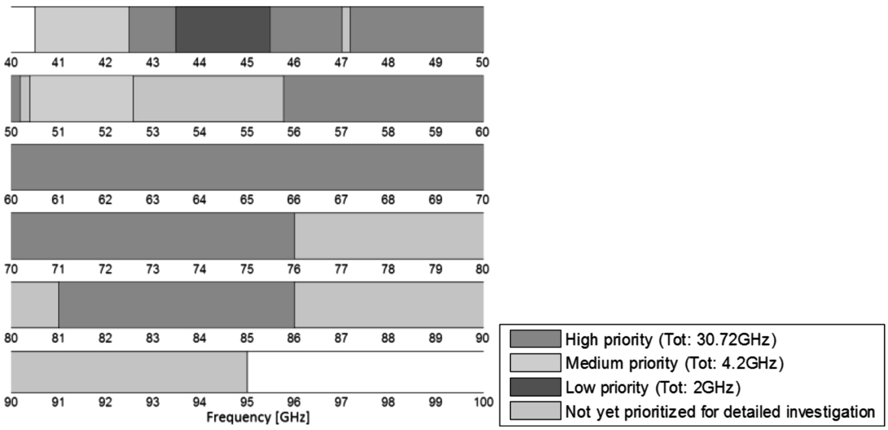

Fig. 9 Opportunities of potential sharing with current incumbent within 40.5–100 GHz [21]

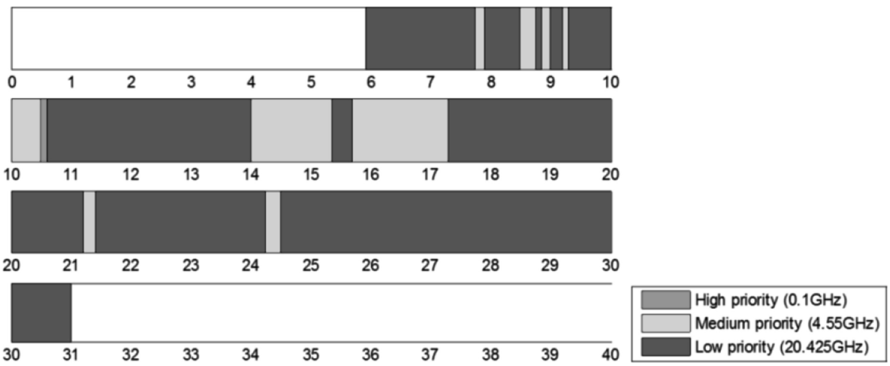

Fig. 10 Opportunities of potential sharing with current incumbent for outdoor scenario [21]

indicating the most relevant bands for initial consideration in regulation when starting the procedure to find additional bands for 5G systems considering only current allocations.

To further shed light on the opportunities in the 5.925–31 GHz range, an additional band assessment with modified assessment criteria has been performed, as shown in Fig. 10. In this assessment, a reduced target minimal contiguous bandwidth of 60 MHz was used, and a larger focus was given to outdoor deployments.

4.2.2 Ofcom [22, 23]

For spectrum above 6 GHz, the Ofcom started with a national Call For Input (CFI) for the potential candidate bands and summarized the response as shown in Table 5.

Table 5 Ofcom 5G candidate frequency bands above 6 GHz

Frequency ranges	6–20 GHz	20–40 GHz	40–60 GHz		60–100 GHz
Candidate bands	10.125–10.22510.475–10.575	31.8–33.4	40.5–43.5	45.5–48.9	66–71

Table 6 FCC 5G candidate frequency bands above 6 GHz

Frequency ranges	Candidate bands (GHz)
24 GHz	24.25–24.45, and 25.05–25.25
LMDS	27.5–28.35, 29.1–29.25 and 31–31.3
39 GHz	38.6–40
37/42 GHz	37–38.6 and 42–42.5
60 GHz	57–64 and 64–71
70/80 GHz	71–76 and 81–86

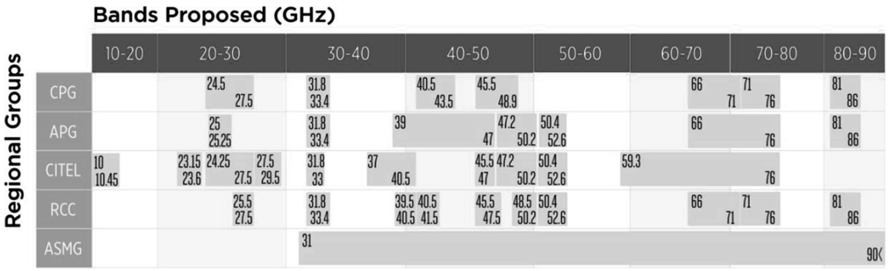

Fig. 11 Views from different regional organizations on identification of frequency bands for IMT in portion(s) of the frequency range between 6 and 100 GHz

4.2.3 FCC [24]

Similarly, FCC started with a Notice Of Inquiry (NOI) the potential candidate bands and only consider bands above 24 GHz as shown in Table 6.

4.2.4 Regional Organizations

Up to Oct. 2015, several regional organizations have made preliminary views for WRC-15 Agenda Item 10. Almost all the organizations have agreed to establish a new agenda item for WRC-19, to consider identification of frequency bands for IMT in portion(s) of the frequency range between 6 and 100 GHz. These views are shown in Fig. 11.

From the regulatory perspective, it is vital to perform solid research of these bands, including channel measurements, system modeling and detailed compatibility studies with currently used services [25].

4.2.5 Provisional Final Acts of WRC-15

After WRC-15, a new Agenda Item 1.13 is established in WRC-19, to consider identification of frequency bands for the future development of IMT, including possible additional allocations to the mobile service on a primary basis [15]. The related frequency bands are:

- 24.25–27.5 GHz2, 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 and 81–86 GHz, which have allocations to the mobile service on a primary basis; and
- 31.8–33.4 GHz, 40.5–42.5 GHz and 47–47.2 GHz, which may require additional allocations to the mobile service on a primary basis.

4.3 Spectrum for IoT

Compared with previous generations of mobile communications, 5G needs to meet extremely high performance requirements in more diverse scenarios. Besides scenarios such as seamless wide-area coverage and high-capacity hot-spot, there is also a need of low-power massive-connections including machine-to-machine and man-to-machine, driven by internet of things (IoT).

Low-power massive-connection scenario mainly targets sensing and data collecting use cases, such as environmental monitoring and intelligent agriculture. This scenario is characterized by small data packets, low power consumption, low cost, and massive connections. Specifically, probably at least one million connections per squared kilometer need to be supported [26].

The suitable frequency ranges of such 5G usage scenarios will be wide and rather different with those for communication between people. An example is shown in Table 7, which is the list the frequency bands used for smart metering application in Power Grid Management Systems in some parts of the world [27].

When considering certain spectrum for Short Range Devices (SRDs) as one part of 5G, e.g., RFID, the 5G potential frequency ranges will be much wider.

5 Spectrum Management Considerations

New scenarios, service types, spectrum demand and usage methods of 5G will definitely bring new challenges to current spectrum management. In this section, some new policies and policy related studies on spectrum management for mobile communications from a number of countries are introduced, reflecting the future 5G spectrum management development trends.

Table 7 Example of frequency bands in wireless metering in Power Grid Management Systems [27]

Frequency (MHz)	Area/region
40–230 (part of), 470–694/698	North America, UK, Europe, Africa, and Japan
169.4–169.8125	Europe
220–222	Some parts of ITU Region 2
223–235	China
410–430	Parts of Europe
450–470	North America, parts of Europe
470–510	China
470–698	North America and Europe
779–787	China
868–870	Europe
870–876	Parts of Europe
896–901	North America
901–902	North America
902–928	North America, South America, Australia
915–921	Parts of Europe
917–923.5	Korea
920–928	Japan
928–960	North America
950–958	Japan

To be clear, some new ideas mentioned in this chapter do not represent the current policy and are considered as research work aiming to give some food for thought. But from various aspects of the related work, they could be a possible trend.

5.1 US

Foreseeing the rapid development of mobile communications, US pay high attention to the related spectrum resources management, with carefully planned steps to carry out a series of related work.

In June 2010, the Presidential Memorandum entitled of Unleashing the Wireless Broadband Revolution was released. Accordingly, the National Telecommunications and Information Administration (NTIA) collaborating with the Federal Communications Commission (FCC) are planned to make 500 MHz of Federal and nonfederal spectrum available for wireless broadband use within 10 years.

Furthermore, in July 2012, the report from PCAST (President of the Science and Technology Advisory Committee) to the US President propose to released 1000 MHz band to “create of spectrum super-highway” [2].

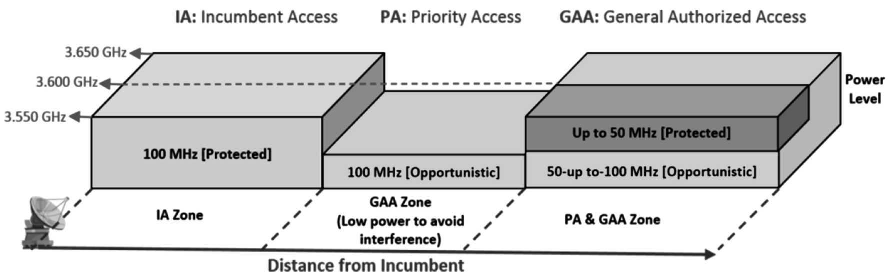

Fig. 12 Proposed Licensing Model for 3.5 GHz (source: http://www.ischool.pitt.edu/)

In June 2013, based on the above report, the Presidential Memorandum entitled of Expanding America's Leadership in Wireless Innovation was released. A Spectrum Policy Team was set up to seek how to bring spectrum sharing measures into current spectrum management of NTIA and FCC for a study period of 1 year.

July 11, 2014, NTIA and the FCC issued a joint notice for comments on Model City for demonstrating and evaluating advanced spectrum sharing technologies recommended by PCAST. More than a dozen replies are received from AT&T, Wireless Innovation Forum, Dynamic Spectrum Alliance, Telecommunications Industry Association, etc.

When seeking the candidate bands to release 1000 MHz, the 3550–3700 MHz band are selected as a possible one. On April 2014, FCC proposed Rules to make up this 150 MHz of spectrum available for new citizens broadband radio service. This innovative rule significantly promotes the intensive shared use of spectrum in the 3.5 GHz Band.

On April 2015, the FCC finally adopted rules for the Citizens Broadband Radio Service, creating a new spectrum band and taking a major step forward in spectrum policy by authorizing advanced spectrum sharing among commercial and federal operators, as shown in Fig. 12.

5.2 EU

Recently, ECC states that License Shared Access (LSA) is a complementary spectrum management tool that fits under an "individual licensing regime" [28] and the national legislation framework is shown in Fig. 13. National Tables of Frequency Allocations (NTFAs) primarily specify the radio services authorized by an individual administration in frequency bands and the entities which have access to them. National frequency assignments, as derived from the ITU concept, allows the fine management of frequency bands in accordance with the rules set in NTFAs, particularly in bands shared by different type of users and also in respect of coexistence issues in adjacent bands. They may contain sensible data and their management requires confidentiality procedures. Under this, two different ways

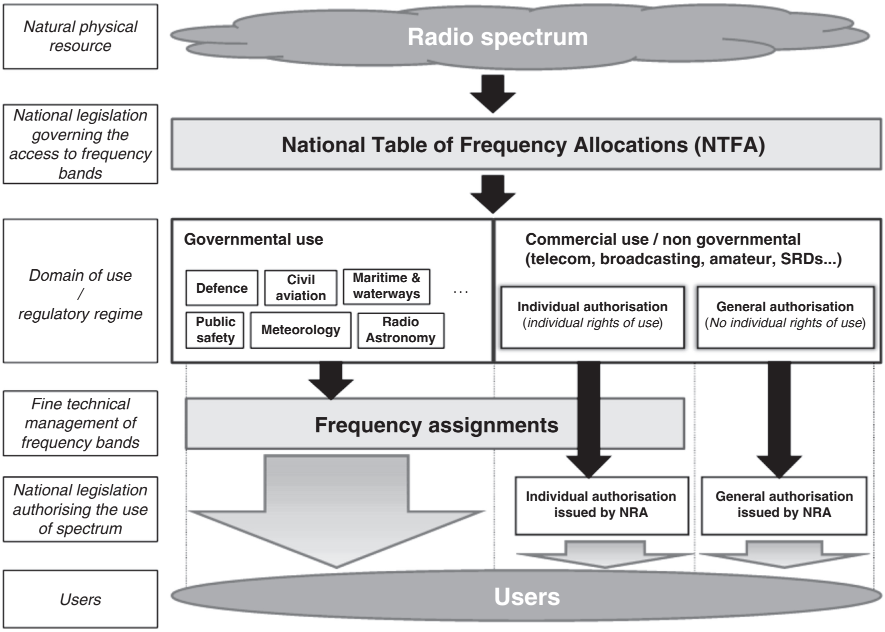

Fig. 13 National legislation from the radio spectrum to users [28]

of using spectrum are introduced: Government use covering various domains (e.g. defense, civil aviation, maritime & waterways, public safety, meteorology, science), and commercial use understood as the public legal act issued by NRAs for the purpose of delivering spectrum usage rights to private entities or citizens. The following two terminologies should also be distinguished for commercial use:

- Individual authorization (Individual rights of use);
- General authorization (No individual rights of use).

Individual rights of use are given for limited duration and do not constitute property act of the frequencies by the operator as frequencies are part of the national domain.

5.3 *China*

At present, the spectrum license pattern in China mainly includes both licensed and unlicensed use. In addition, there is a light license mode, in which the user only needs to report but not apply for setting up a new radio station to the government for recording.

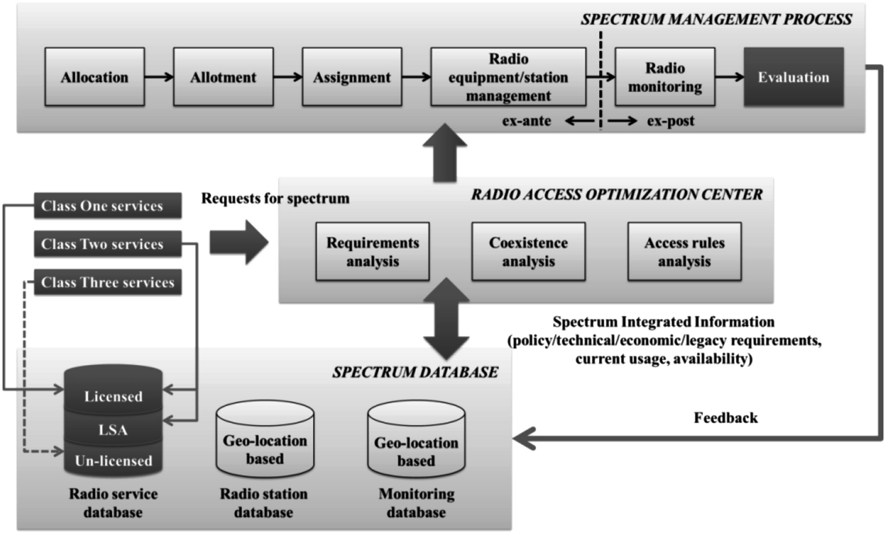

Fig. 14 New elements studied in current spectrum management framework in China [4]

In such a management framework, spectrum sharing is not well supported. As 5G brings much more challenges in spectrum demand and also new spectrum usage methods, the spectrum management has to keep pace with such innovation. Currently based on the current framework of spectrum management in China shown in Fig. 14, two new elements are being studied, namely services classification and spectrum assessment.

The *basic spectrum management process* is shown at the top of Fig. 14. The spectrum allocation (to radio services), allotment (to users or systems) and assignment (to specific radio stations) as well as the radio equipment and station management belong to ex-ante management. The radio monitoring belongs to ex-post management, including radio occupancy measurements, signal parameter and transmitter inspection, illegal transmitter detection and finding and so on [http://www.srrc.org.cn/english/]. The *radio access optimization center*, composed of relevant organizations and institutions, is in charge of spectrum demand calculation, coexistence and access analysis. The *spectrum database*, established in State Radio Monitoring Center and State Radio Spectrum Management Center (SRMC/SRSMC), stores all the information of radio services, stations and monitoring reports, which indicate the current spectrum usage and availability. When a new service access request arrives, the *center* checks the *database*, performs integrated analysis and outputs the solution to support the *process*, which conversely inputs the information to the *database* for further use, establishing a closed-loop management.

- Services classification

Intuitively, not every radio service can be shared with IMT systems. Therefore, it is vital to make clear which types of service can be put forward for sharing. Here, it is proposed to divide them into three classes.

Class One services are those involving government affairs, national security and people's safety. They usually occupy specified licensed spectrum for free and need strict protection. Their spectrum cannot be shared with others.

Class Two services include commercial radio services, and also general public and dedicated services. The spectrum for public mobile communication in 5G is included. Licensed or LSA mode could be used here. The government would flexibly charge the Class Two services.

Class Three services are dedicated for public free use. The access process might also need spectrum sensing, such as WiFi.

- Spectrum assessment

Spectrum assessment belongs to ex-post management. It is not only the basis for whether a frequency band can be allotted to a new service, but also a way of supervising its utilization efficiency. In [4], the assessment of the current spectrum usage is proposed in China for the first time. Based on assessment results, the government can adjust or even retrieve the spectrum allotment.

To make fair assessment, a scientific and effective Key Performance Indicator (KPI) system is required to be established. The KPI currently under studied mainly includes three aspects.

– Radio monitoring related information, such as noise and radio occupancy measurement results in different scenarios and locations.
– Radio stations related information, such as location, RF parameters and also the related statistics.
– Service related information, e.g., different Quality of Service (QoS) and protection requirements.

The KPI system is necessary for making reasonable conclusions in spectrum management. It is important to study the feasibility of providing such information in a technology- and service-neutral way, and whether it allows for a practical and efficient spectrum evaluation process.

6 Summary

Different aspects of 5G spectrum issues are discussed in this chapter. Generally, it is expected that 5G requires more in the total amount, wider with respect to individual bandwidths, greater in the range and more flexible in the usage and management pattern.

The suitable frequency ranges of 5G will include those bands below 6 GHz such as re-farmed 2G/3G spectrum, identified frequency bands for IMT and also WRC-15 candidate bands. However, due to the scarcity of spectrum below 6 GHz, which has almost been fully utilized and it will be even more difficult to find internationally harmonized spectrum after WRC-15, it is necessary to seek potential frequency ranges above 6 GHz.

The controlled spectrum sharing is an important way of re-using spectrum to complement current licensed dedicated spectrum, which is still the basis for operation of 5G systems.

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