

# 1

## Introduction

**Bernhard H. Walke and Hitoshi Yoshino**

This chapter reviews trends in mobile communications and spectrum usage and explains why and how we need spectrum allocation to IMT systems.

### 1.1 Trends in Mobile Communication

This section describes trends in mobile communications on three fronts; applications and services, radio interface technologies and standardization.

#### 1.1.1 Mobile applications and services

User expectations are increasing to support a wide variety of applications and services in mobile communications after the advent of broadband Internet access in wired communication. In the near future, wireless and mobile technology will play a vital role in providing ‘continuous connectivity’ between (end user) terminals and a variety of services. Note that *mobile* systems support an application running on the user terminal without interruption, even when moving with high mobility. *Wireless* systems connect slow-moving terminals to the Internet, interrupting service when switching between network access points. In a scenario where ‘everybody and everything is always connected to access personalized services’, several types of ‘human to human’, ‘human to machine’ and ‘machine to machine’ communication link can exist (Walke and Kumar 2003). See Figure 1.1.

The majority of presently used ‘human to human’ information exchange is voice based. A clear shift towards data services is observed. In ‘human to machine’ and ‘machine to machine’ interaction, the volume of information exchanged is small and a short duration ‘session’ at a low data rate is sufficient in most cases. For ‘human to human’ and ‘machine to human’ interaction for work or leisure, the opposite applies with long session duration and a high data rate required.

		Source	
		Human	Machine
Destination	Human	Voice communications (VoIP) Video phone/conference Interactive game  Chat, Blog  Visual mail Audio mail Text mail	Video relay broadcasting Video surveillance Human navigation Internet browsing Information service Music download Push service
	Machine	Remote control  Recording to storage device (voice, video, etc.)	Location information service Distribution system, etc.  Data transfer  Consumer electronic device maintenance

↑ Real time required

↓ Delay permitted

Figure 1.1 Wireless communication applications to support real-time and nonreal-time future wireless services.

Intelligent spaces in the future wireless world shall contain myriads of ‘intelligent’ wireless devices such as sensors and actuators embedded in appliances and/or carried by humans and interacting with each other as well as with their physical environment. There, the spontaneous information exchange may be based on dynamically configurable ad hoc networks of very low-power transceivers located in devices with varying information-processing capabilities. The transceivers might be connected to sensors and/or actuators, such as microphones and speakers. The very high concentration of such transceivers and the need to communicate not only in short range but also over medium to large distances would need a large spectrum bandwidth. Also, some of the envisaged future wireless and mobile applications and services will be ‘location aware’. This requires suitable new air interface technology capable of combining the functions of data transmission with those of precise localization and position tracking.

The traffic resulting from data communication-based applications and services is similar to that known from the Internet. Accordingly, a packet-based delivery over radio is appropriate. The traffic flow may be unidirectional from transmitter to receiver terminal or bi-directional. The flow may be either symmetrical or asymmetrical, and the service required by an application may be real-time or nonreal-time oriented. The digitized and packetized information transmission permits an integration and convergence of technologies known from information science, telecommunications and contents provisioning. The wireless traffic amount resulting from all the three domains is increasing and consequently consumes ever increasing spectrum bandwidth.

*Moore's law*<sup>1</sup> appears also to apply for the bandwidth consumption. The end users tend to embrace applications and services utilizing an ever faster data rate. The service data rate (offered/required) is doubling every 12 months or so. The constant increase in 'users' injects further positive feedback into the system, thus sending the frequency bandwidth demand to an exponential increase.

This potential growth scenario requiring more and more bandwidth to allow a steady further development of wireless and mobile systems can be sketched in the light of the following:

- The extent of good quality radio coverage is inversely proportional to the transmitted data rate. The cost of 'continuous' and 'all time everywhere' radio coverage increases very sharply with the transmitted data rate.
- The higher the service data rate, the larger is the required bandwidth and the higher is the frequency range where some additional spectrum might be available.
- Deregulation policies of regulators, aiming at competition between operators, result in fragmentation of frequency spectrum licensed to mobile operators, inversely affecting spectrum-efficient use of a radio band allocated for mobile services.
- The present users (systems and service providers) of the already allocated frequency bands would like to make the most out of their allocation. The introduction of sophisticated mechanisms in the standardized air interfaces, e.g. space-time coding, smart antenna systems and multihop links to improve the radio coverage, appear to be a direct consequence of frequency spectrum shortage for mobile radio use.
- Although the spectrum efficiency of radio systems is continuously increasing, much more spectrum is required, in general. Moreover, additional frequency spectrum will be necessary in the low frequency range in order to provide the required coverage in wide areas.
- The variety of networks for provision of seamless services in private to public and short range localized coverage to wide area coverage will find its limits by the demand for cost effectiveness of the corresponding business cases.

The globalization of markets requires a very wide consensus going beyond technology standardization. Especially, the interworking of permanently established and spontaneously created networks shall be fostered to improve user acceptance on mobile/wireless services.

## 1.1.2 Radio interface technologies

### History of mobile radio systems before IMT-2000

The first generation (1G) of wireless technology, dedicated to telephony, started in the 1980s with the analog cellular phone standards. There, mobile terminals and base stations use analog signal processing to transmit and receive the radio signals that propagate in any

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<sup>1</sup>Moore's law generally refers to a trend that the capability of electronic devices grows at an exponential rate. The observation was first made by Intel co-founder Gordon E. Moore in his paper published in 1965 with respect to the number of transistors on an integrated circuit chip.

generation of mobile systems as analog signals through the atmosphere. Examples are the Advanced Mobile Phone Service (AMPS) deployed in the United States, the Nordic Mobile Telephone (NMT) in Scandinavian countries, the Netherlands and Switzerland, RC2000 in France, Total Access Communication System (TACS) in the United Kingdom, and C450 in Germany and Portugal. These continued until being replaced in the mid-1990s by the second generation (2G) technology that is based on digital signal processing applied in base stations and mobile terminals. The 2G services, called Personal Communications Service (PCS) in the United States, comprise mobile voice and narrowband data communication. The systems use combinations of multiplexing techniques at the air (radio) interface such as frequency division multiplex (FDM), time division multiplex (TDM) and code division multiplex (CDM) combined with the respective access protocols, namely frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA). The 2G systems worth mentioning are Global System for Mobile communications (GSM) standardized by the European Telecommunication Standards Institute (ETSI) that reached a 75% market share worldwide, IS (Interim Standard)-95/cdmaOne according to the Telecommunications Industry Association (TIA) in the United States, and Personal Digital Cellular (PDC) specified by the Research Center for Radio (RCR) in Japan. An evolutionary technology called 2.5G introduced multiplexing of data packets to a common radio channel for mobile Internet access at 128 kbit/s mean transmission rate. Worth mentioning are GSM/EGPRS (Enhanced General Packet Radio Service) and the evolution technology of the cdmaOne system that increased the peak user data rate to 256 kbit/s.

### **Capability of future mobile and wireless systems**

The framework and overall objectives of the future development of IMT-2000 and IMT-Advanced are described in Recommendation ITU-R M.1645, which was approved by ITU-R in June 2003. Figure 1.2 shows the capabilities of mobile and wireless systems, which are envisaged in Recommendation ITU-R M.1645.

Due to the wide spread of mobile Internet access supporting a wide variety of data rates and a wide range of mobility, current mobile systems such as IMT-2000 have evolved by the addition of more and more capabilities. Future broadband mobile Internet access will require a new mobile access and new nomadic/local area wireless access technologies. It is envisaged that those new technologies will need to support data rates of up to approximately 100 Mbit/s for high mobility and up to approximately 1 Gbit/s for low mobility, judging from broadband applications currently available in wired networks. To meet the high aggregate data rate requirements, IMT-Advanced systems will require considerably wider bandwidths than current mobile communications systems. Even if the spectral efficiency of the IMT-Advanced system will be considerably higher than in current systems, IMT-Advanced systems will require bandwidths of up to 100 MHz to support aggregate data rates of up to 1 Gbit/s. Currently existing bands for IMT-2000 are too narrow and fragmented, and this does not allow the implementation of 100 MHz carriers. Therefore, the deployment of IMT-Advanced systems with its fully envisioned capabilities is not possible on existing bands.

A similarity of applications and services across different wireless systems stimulates the convergence and interwork of the wireless systems. The prevalence of IP-based applications accelerates this convergence and interwork of the telecommunication systems.

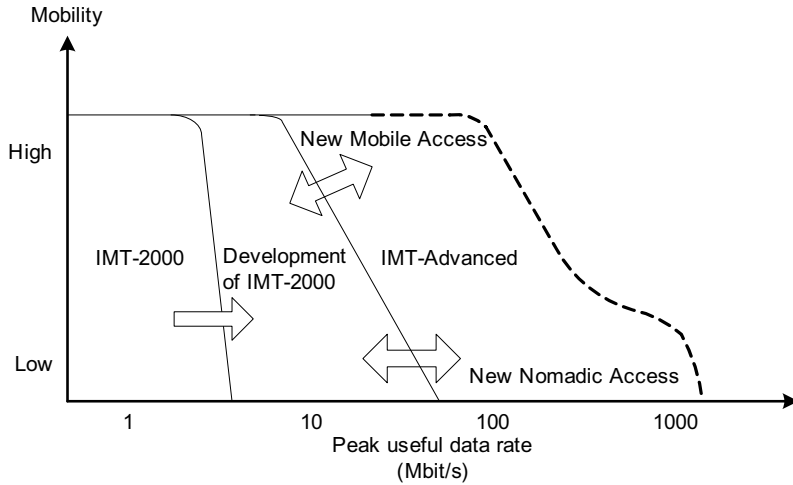


Figure 1.2 Capabilities of mobile systems ('Van Diagram').

Experience from the past has shown that the idea of a universal system able to cover all the needs of wireless and mobile applications cannot be realized. Instead, a multitude of air interfaces has been standardized and will continue to grow in the future to cover the specifically different needs of mobile and wireless communicating users in the various usage scenarios.

Mobile systems such as GSM, shown in Figure 1.3, together with its General Packet Radio Service (GPRS) and its evolution called Enhanced Data Rate for Global Evolution (EDGE), are covering the full range of mobility from fixed to high speed train mobility. The GSM/GPRS/EDGE is supporting low mobile data rates only and is, currently, dominating the world in 2G systems. The CDMA 1x, another 2G system with similar throughput capacity and mobility support, is also shown in the figure. Third generation (3G) systems such as Universal Mobile Telecommunications System (UMTS) and its evolutions called High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA), in short, High Speed Packet Access (HSPA), and a technology called CDMA EV-DO (Evolution Data Only), offer a substantially increased throughput for the full range of terminal mobility. These systems are being planned to evolve further towards mobile broadband supporting systems, shown in Figure 1.3 as UMTS-LTE (Long Term Evolution) and Ultra Mobile Broadband (UMB). The respective standardization processes have started already. As can be seen in Figures 1.2 and 1.3, the right-hand upper corner is difficult to cover, limiting mobile broadband use to moderate speed of terminal movement.

Cordless technology such as Digital Enhanced Cordless Telecommunications (DECT) and Personal Handy-phone System (PHS) covers wireless telephony and low rate data, supporting only slow-moving terminals that are close (approximately 50 m) to the serving base station. Bluetooth is specialized to cover voice and data in the personal area of a human, bridging typically up to 10 m only. Wireless systems have been standardized by Project 802 of the Institute of Electrical and Electronics Engineers (IEEE). According to the standard IEEE 802.11, the wireless local area network (WLAN) is intended to serve nomadic terminals

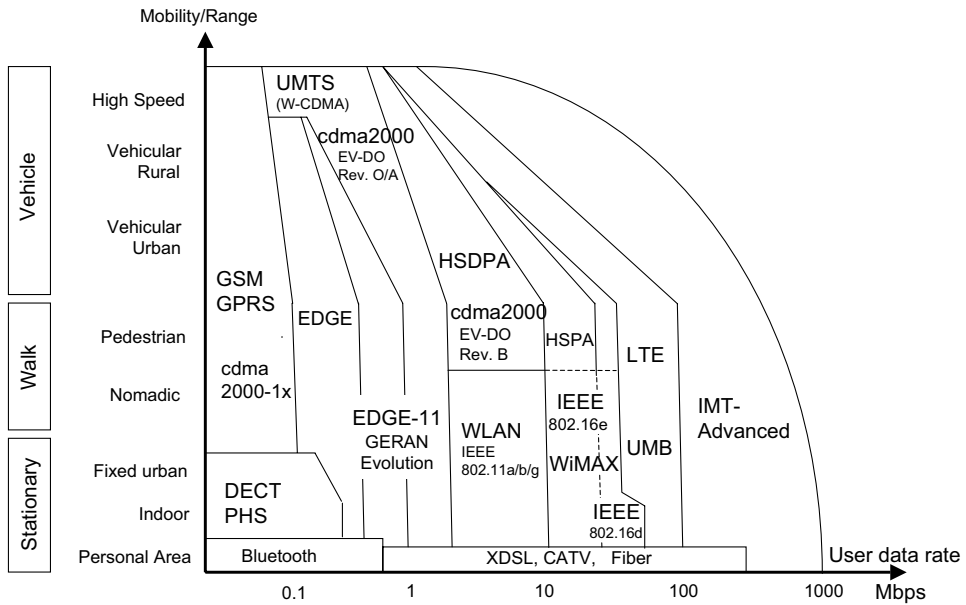


Figure 1.3 Terminal mobility versus peak data rate supported by wireless/mobile systems. (Reproduced by permission of © 2006 John Wiley & Sons, Ltd.)

with connectivity over radio to the Internet. The metropolitan area network (MAN) standard IEEE 802.16, called the Worldwide Interoperability for Microwave Access (WiMAX), was originally aimed to connect fixed subscriber stations via radio to a base station, but evolved to support terminals moving at vehicular speed. The system is expected to evolve further towards a mobile broadband system supporting the full range of terminal mobility in the future according to the Task Group IEEE 802.16m.

For comparison purposes, cable-based transmission systems connecting fixed subscribers in the local loop to telecommunication networks are also shown in Figure 1.3. It is clear that future wireless and mobile broadband systems are planned to reach the throughput rate of wireline systems.

### Peak data rate and spectrum efficiency

There is often a confusion when comparing performance parameters of standardized air interfaces that results from not differentiating between mean values such as capacity (the maximum throughput available in a cell), throughput (the data rate perceived by a user terminal at its current location in the cell) and peak data rate (the maximum data rate available to serve a user terminal under best radio conditions).

According to its technological state-of-the-art, air interfaces are also being characterized by its spectral efficiency measured by the number of bits that can be transmitted in one Hertz bandwidth unit (bit/s/Hz). Figure 1.4 shows the performance characteristics of existing and forthcoming ‘beyond the third generation’ (B3G) and fourth generation (4G) mobile

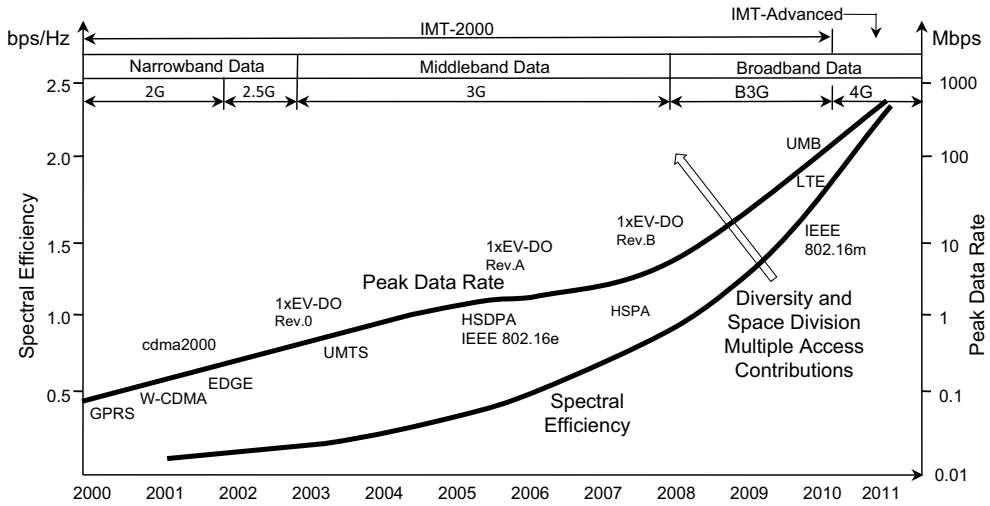


Figure 1.4 Spectral efficiency and peak data rate development over time.

system standards in terms of their peak data rate and spectral efficiency at the time of introduction.

It can be derived from Figure 1.4 that spectral efficiency almost doubles every two years, while peak data rate doubles every year. The increase of spectral efficiency over time clearly points to the fact that more data will be possible to transmit in the future in a given channel bandwidth, compared to what is possible today. This is one reason why the estimation of future spectrum bandwidth needs of mobile systems is difficult to assess. The possible contribution by multiple antenna systems to increase spectral efficiency in future (that would reduce the need for more spectrum allocation to be able to carry a predicted user traffic load) is uncertain and depends, partly, on implementation cost considerations and therefore is difficult to predict.

**Roadmap of radio systems development**

It is worth considering the time plans of various standardization organizations involved in the specification and further development of wireless and mobile systems and the pace of the worldwide spectrum regulation to which these activities are aligned. See Figure 1.5 for the roadmap of 3G and 4G wireless/mobile systems spanning the time interval from 2003 to 2011.

There are two standardization organizations, namely the Third Generation Partnership Project (3GPP) and Third Generation Partnership Project 2 (3GPP2) that both focus exclusively on mobile telecommunication systems. 3GPP represents the European and Asian regional standardization groups as far as they are concerned with the development of Wideband CDMA (W-CDMA). 3GPP2 is supported substantially by the TIA, an American standardization body.

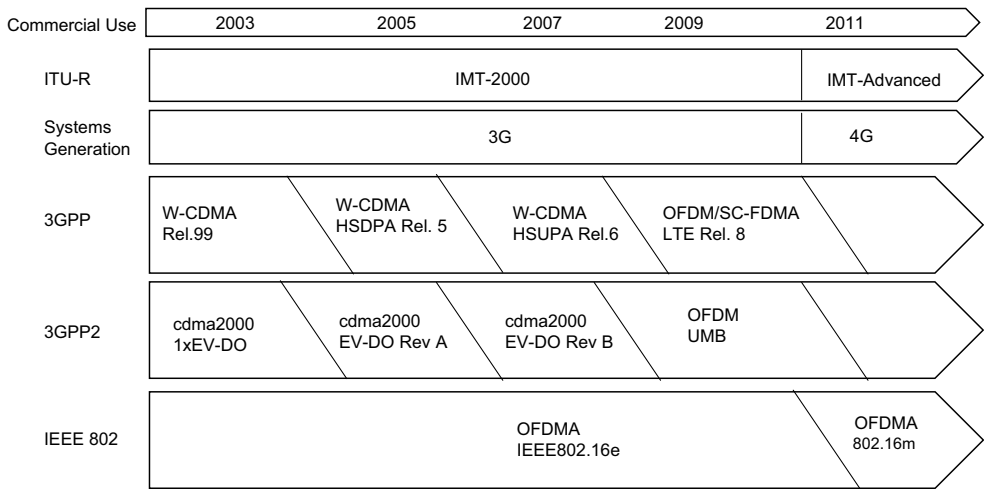


Figure 1.5 Roadmap of the evolution of wireless/mobile systems.

Both 3GPP and 3GPP2 focus in their first 3G system designs on voice and narrowband data transmission using CDMA to carry multiple connections over the same frequency channel at the same time. The main difference is the channel bandwidth applied: W-CDMA (of 3GPP) requires four times the bandwidth per channel of about 5 MHz than CDMA does, making placement of CDMA systems in the spectrum easier, if wideband (5 MHz) channels are not available. The fixed network of the radio access network is similar or even identical in architecture to both systems. With their evolution in time, both have developed towards mobile data networks for Internet access, providing application throughput rates of up to 256 bit/s as long as the serving radio cell is moderately loaded. 3GPP systems have introduced HSDPA first and have extended that technology later also to the uplink, then called HSUPA. Evolved 3GPP2 systems underline by the suffix DO (Data Only) that the respective revisions have their focus on improved data rate. It is worth noting that the CDMA component of both standards has been substantially weakened with the increased data rate, making the systems more sensitive to interference.

What can also be observed from Figure 1.5 is that the future technology for all kinds of mobile systems is Orthogonal Frequency Division Multiplexing (OFDM), a multicarrier-based transmission scheme, where multiple access to some group of carriers of the OFDM system is performed, named OFDMA.

The IEEE Working Group 802.16 originally started with an OFDM-based wireless system that soon was extended to become a mobile system in 2004, named Mobile WiMAX based on the specifications of the Task Group 16e. All three system families, specified by 3GPP, 3GPP2 and IEEE 802, apply Frequency Division Duplex (FDD) for separating downlink and uplink transmissions in the spectrum, requiring paired channels with a substantial duplex distance. 3GPP and IEEE 802 also have specified Time Division Duplex (TDD) variants that fit better into the spectrum. Both downlink and uplink transmissions under TDD are performed on the same radio channel, separated in the time domain.



Table 1.1 Wireless/mobile systems operations philosophies.

IT community	Telecommunications community
Sell terminals (laptop, PDA, etc.), subsidize services	Sell services, subsidize mobile terminals
Certification done by WiFi/WiMAX Forum per device	Certification done per device per operator
Web 2.0 model of operator business revenue: operators rely on service providers to provide applications and get a share of the revenue. Operator revenues are limited to access	Controlled market of services and contents (see Figure 1.6). Walled garden concept. Complete control. Limited applications due to limited and closed devices
Broadband pipe	Value added service
Best efforts service	Reliable and secure service
Internet architecture. Open mobile platform	Complex and expensive infrastructure, e.g. IMS interworking
Flat-rate contract to Internet service provider with unlimited volume. Pay per use	Contract with mobile operator with volume tariffs with a trend towards flat rate component

In particular, the WiMAX WAVE releases go with TDD while 3GPP systems based on TDD have not found acceptance in the market so far.

Wireless and mobile radio systems, respectively, originate from different cultures, namely information technology (IT) and telecommunications communities. They are based on different philosophies as shown in Table 1.1.

There is a trend towards an increased fragmentation of the mobile market in terms of technologies deployed, resulting from the different economical development status of regions in the world, having different needs of mobile services that they can afford. Although it would be most efficient in terms of development costs to have one standard for all mobile systems deployed worldwide, the size of the market counted in the number of potential subscribers is so large that it can bear multiple standard systems competing. Around a hundred million terminals are being sold every year in the world, duplicating every three years. Consequently, the number of radio access technology standards will further grow.

### Interworking of radio systems

Since the number of wireless and mobile systems competing in offering a service at a given location tends to ever increase, multimode terminals will be a must in the future. Such terminals should be able to hook on to the best suited air interface from a number of alternate interfaces available in a given environment. Both the traffic performance and cost shall be considered. The implementation of multimode terminals requires reconfigurability of both the transceiver hardware and protocol stack, resulting in software-defined radio terminals. Currently, terminals provide access to a number of air interfaces, each based on a dedicated transceiver and protocol suite, implemented in the mobile terminal. In future, reconfigurable mobile terminals will rely on adaptive transceivers and protocol suites, controlled by software to operate with the most suitable air interface available at a given location.

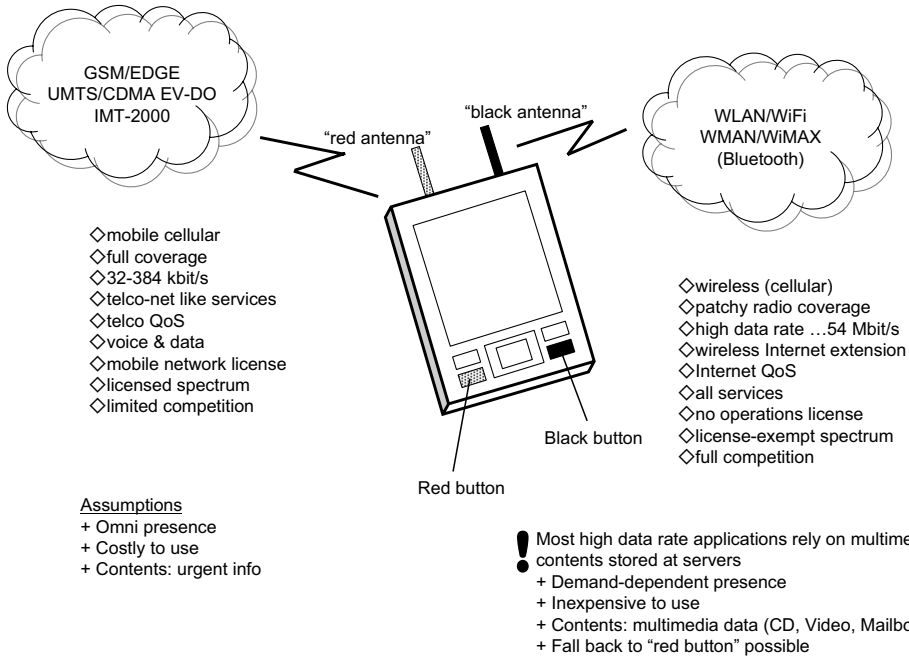


Figure 1.6 Multimode (reconfigurable) terminal able to connect to the best suited network. This figure is a slight update of Figure 18.11 of Walke (2002, p. 1037). (Reproduced by permission of © 2002 John Wiley & Sons, Ltd.)

For an understanding of the issue, Figure 1.6 shows some of the criteria to be considered when applying a multimode terminal to serve a mobile user in an optimal way (Walke 2002, Ch. 18). The characteristics of service provisioning, the class of service and the cost will be the main decision criteria for the use of one of the multiple air interfaces available from the same or a number of competing operators. Further details include:

- availability under the current conditions of terminal movement, e.g. radio coverage;
- real-time constraints of the service to be performed, for example, instantaneous when demanded and semi-instantaneous by provisioning within a given time window at a given location only;
- cost of service per time or per information unit;
- quality of service (QoS), e.g. support of real-time requirements in terms of delay and delay jitter for an interactive service, and/or application throughput rate required;
- service management, i.e. ease of use of services across different radio networks, supported by the terminal and the operators.

The two buttons (red/black) at the terminal represent internal functions used to decide which radio network to use for a given service under the current environmental conditions and costs of service.

The multitude of existing air interfaces and the increased fragmentation of radio spectrum, where a specific service is being offered, provide sufficient motivation for engaging in research towards reconfigurable terminals.

The terminals should be able to cover multiple air interfaces in a cost-efficient way. Besides this goal a demand for an increased data rate of up to 100 Mbit/s for terminals moving at high speed and that of up to 1 Gbit/s for slow-moving terminals has been identified for the future.

### 1.1.3 Standardization

#### Standardization at ITU-R

The International Telecommunication Union (ITU) is an international organization within the United Nations (UN) where governments and the private sector coordinate global telecommunication networks and services. ITU is the only body which is responsible for defining and recommending standards for international mobile telecommunication (IMT) systems. IMT-2000 encompasses all 3G mobile communication standards and their enhancements, while IMT-Advanced is the ITU name for systems beyond IMT-2000, i.e. 4G systems. ITU is responsible for the standardization of IMT systems, but the detailed standardization activities are undertaken by recognized External Organizations (EOs).

IMT-2000 is the term defined by ITU to characterize 3G mobile communication standards. Future Public Land Mobile Telecommunication System (FPLMTS) is the former name of IMT-2000. The meaning of 3G has been standardized in the IMT-2000 standardization process. A remarkable point is that the process did not standardize a technology, but it developed a set of requirements, for example, for the data rate. The Recommendation ITU-R M.1455 defines the original key characteristics of IMT-2000 radio interfaces, and represents the results of the evaluation process by the ITU Radiocommunication sector (ITU-R).

The key features of IMT-2000 are the following:

- high degree of commonality of design worldwide;
- compatibility of services within IMT-2000 and with the fixed networks;
- high service quality;
- small terminals for worldwide use;
- worldwide roaming capability;
- capability for multimedia applications, and a wide range of services and terminals.

IMT-2000 is a system with global development activity. Recommendation ITU-R M.1457 gives the detailed specifications for the radio interfaces of IMT-2000. The IMT-2000 radio interface specifications identified in Recommendation ITU-R M.1457 have been developed by the ITU in collaboration with the radio interface technology proponent organizations, global partnership projects and regional standards development organizations (SDOs).

The ITU has provided the global and overall framework and requirements, and has developed the core global specifications jointly with these organizations. The detailed standardization has been undertaken within the recognized EOs including the 3GPP and 3GPP2.

IMT-2000 comprises a single terrestrial standard which consists of two high-level groupings: CDMA, TDMA or a combination thereof. The CDMA grouping accommodates FDD direct spread, FDD multi-carrier and TDD. The TDMA grouping accommodates FDD and TDD, single carrier and multi-carrier. Recommendation ITU-R M.1457 forms the final part of the process of specifying the radio interfaces of IMT-2000 as it identifies the detailed specifications for the IMT-2000 radio interfaces. The terrestrial radio interfaces are identified as follows:

- IMT-DS (Direct Spread): W-CDMA, UTRA-FDD
- IMT-MC (Multi Carrier): CDMA2000
- IMT-TC (Time Code): UTRA-TDD, TD-SCDMA, TD-CDMA
- IMT-SC (Single Carrier): UWC-136, EDGE, GSM384
- IMT-FT (Frequency Time): DECT

See Appendix C.1 for acronyms.

Despite the promises of more feature-rich, highly interactive and high bit-rate multimedia services of 3G systems for the end users and increased revenues for the operators, the research community has perceived limitations of these systems in terms of user throughput and cost of operation. Consequently it has started to work towards B3G or 4G systems. These future systems are expected to allow subscribers to access broadband multimedia services transparently via multiple wireless and even mobile networks as if their terminals are connected via broadband cabling to the Internet. To achieve this, both the radio and fixed access network parts need substantial evolution steps to meet the expectations. The currently deployed infrastructure representing 2G and 3G technologies will need substantial evolution of existent air interfaces and the architecture of the related fixed networks that together represent a mobile radio network. Excessive investments in infrastructure and technology development are expected to make this happen, requiring time for implementation and a sufficient amount of new spectrum allocated for the operation of mobile broadband as prerequisites.

The name 'IMT-2000' denotes 3G systems, but it also encompasses the enhancements and future developments of 3G systems. ITU-R has decided on the new name for systems beyond IMT-2000 or 4G systems. Systems beyond IMT-2000 are now denoted as 'IMT-Advanced'. In the family of IMT systems, 'IMT' is the ITU accepted root name which encompasses both IMT-2000 and IMT-Advanced systems collectively. The reader is referred to Resolution ITU-R 56 for the naming of IMT systems. ITU-R has started its standardization activities by sending out a Circular Letter on an invitation to propose candidate radio interface technologies for IMT-Advanced in 2008.

The following research and development activities have been observed towards the standardization of IMT-Advanced radio interface technologies in several countries.

## **Japan**

The mobile IT Forum (mITF) was established in 2001 for early implementation of future mobile communications systems and services such as 4G systems and mobile commerce services. It developed visions for future mobile communication systems and published several reports on 4G mobile communication systems. In 2006, the Advanced Wireless Communications Study Committee (AWCSC) was established, and replaced mITF for technical studies on 4G mobile systems. The AWCSC is responsible for:

- conducting technical studies on advanced wireless communication systems in cooperation and coordination with other related institutions in Japan and abroad;
- contributing to international standardization activities.

## **Korea**

The Next Generation Mobile Communications (NGMC) Forum was established in 2003 to realize future mobile communications. The objectives of the NGMC Forum are to analyze technical and social trends, to establish visions on B3G, to steer advanced research and development strategies, to study spectrum use and to cooperate international organizations. The forum is developing guidelines of 4G services, 4G spectrum technologies, and it is coordinating 4G technology-related activities in Korea. The forum published vision document, white papers on system, air interface and terminals, and a document about the frequency bands for B3G with consideration on related research activities within Korea.

## **China**

The Chinese government launched the national research project called Future Technologies for Universal Radio Environment (FuTURE) in the framework program 863 in the area of mobile communications for the time frame of the tenth 5-years-plan 2001–2005, continued in project phase 2 running until the year 2010 and aiming to achieve international leadership in mobile communications.

China-Japan-Korea B3G (CJK-B3G) is a collaboration group of China, Japan and Korea under the framework of cooperation among four Standard Development Organizations (SDOs): the Association of Radio Industries and Businesses (ARIB) and Telecommunication Technology Committee (TTC) of Japan, China Communications Standards Association (CCSA), and Telecommunications Technology Association (TTA) of Korea. In phase 1 of its activity, the CJK-B3G group discussed service requirements, service scenarios and spectrum issues, and identified technical areas and issues for B3G systems in order to form a common understanding of the B3G system. In phase 2, CJK-B3G group members exchanged information on their activities with mITF, NGMC Forum and FuTURE. They produced white papers on system requirements and enabling technologies in 2007.

## **Europe**

In Europe, the standardization of mobile systems according to 3GPP Long Term Evolution (LTE) is supported by the Information Society Technologies (IST) research program

established by the European Commission to achieve the ‘Broadband for All’ throughout Europe. Since the Fifth Framework Programme (FP5) (1998–2002) of the European Union (EU) Commission, research activities have been launched on systems beyond 3G. The Wireless World Initiative New Radio (WINNER) project is one example of the Sixth Framework Programme (FP6) (2002–2006) that is working towards the new radio interface for systems beyond 3G. The ETSI is taking part in the specification of 3G systems evolution.

## United States

The IEEE, a globally operating organization with its headquarters in the USA, has developed standards for WLANs and has expanded that work to drive the development of future systems with enhanced capabilities such as interworking, meshing of base stations and support of mobility management that will have substantial impact on 3G and 4G systems development. Another major player in North America is the Defense Advanced Research Projects Agency (DARPA). The DARPA neXt Generation (XG) communications program is developing a technology to allow multiple users to share the spectrum through adaptive mechanisms.

## 1.2 Trends in Spectrum Usage

This section gives a background to those who are not familiar with radio spectrum and the concept of spectrum allocation currently used for spectrum management. It also mentions a flexible spectrum use for the future.

### 1.2.1 Physical properties of radio spectra

Radio spectrum is the radio frequency portion of the electromagnetic spectrum. The radio spectrum is a valuable and limited natural resource as it is generally available within a range of between 3 kHz and 3000 GHz for communications purposes. This range has been split into radio spectrum bands, e.g. high frequency (HF), very high frequency (VHF) and ultra high frequency (UHF) bands. Only frequency bands between 9 kHz and 275 GHz are currently allocated to radio communication applications by ITU-R on a global basis.

Figure 1.7 shows radio spectrum bands, their corresponding wavelengths/frequencies and example radio applications. Different portions of the radio spectrum have different physical properties due to the different wavelength of the radio waves. These physical properties include, among others, path loss, propagation mechanisms and absorption.

#### Path loss

Line-of-sight (LOS) is the direct propagation of radio waves between transmitter and receiver antennas. The radio waves travel in straight lines just like light waves travel. In the free space, all radio waves obey the inverse square law where the power density of a radio wave is proportional to the inverse of the square of the distance  $d$  between transmitter and receiver antennas:  $d^{-2}$  propagation. Mobile cellular systems use frequencies at which radio waves primarily propagate in the non-LOS mode. Then the  $d^{-4}$  propagation is observed.

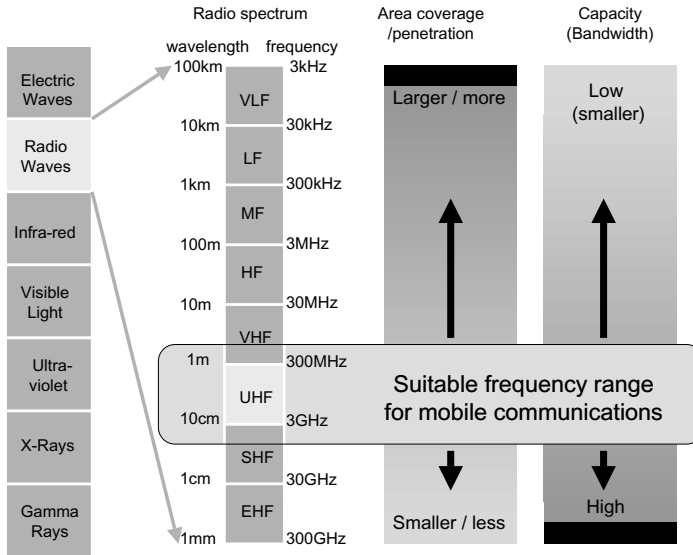


Figure 1.7 Frequency range suitable for mobile communication.

An empirical formula for the dependency of path loss  $L_p$  on the frequency  $f$  can be generally expressed as (COST 231 1991; Hata 1980; Walfisch and Bertoni 1988)

$$L_p = A_d \log(d) + A_f \log(f) + \text{constant}, \tag{1.1}$$

where  $d$  and  $f$  are the distance between mobile and base stations, and carrier frequency, respectively.  $A_d$  and  $A_f$  are coefficients which have distance and frequency dependencies, respectively. As the name says, the path loss describes the deterioration of the radio signal power on its way from a transmitter to the receiver terminal. In urban areas,  $A_d = 38$  and  $A_f = 20$  could be obtained from measuring campaign (Okumura *et al.* 1968). It can be concluded that the path loss increases proportionally to around the second power of the carrier frequency in urban areas.

### Propagation mechanisms

Radio propagation has the following three key elements: diffraction, reflection and scattering. When a radio wave is obstructed by an irregular surface, secondary waves are generated. They bend around and reach behind the obstacles. Reflection occurs when a radio wave encounters obstacles larger than its wavelength. Scattering happens when a radio wave travels through a medium that contains many small objects compared to its wavelength.

Diffraction depends on the wavelength of the radio wave and the size of the obstacles. Due to the nature of the waves, radio waves at a lower frequency diffract more easily around large obstacles such as hills and smooth mountains. Diffraction is very important for the mobile systems to cover the service area with sufficiently strong signal energy. Radio waves diffracted by small obstacles such as buildings at high frequency around UHF and SHF (see Figure 1.7) can travel over roof edges of the buildings into the streets.

The diffracted waves and their reflected waves overlay each other resulting in multi-path propagation. They are finally received by the antenna of a mobile radio terminal. Non-LOS propagation is more easily obtained at a lower frequency range, say VHF.

### **Absorption**

The radio wave at a low frequency travels easily through walls, bricks and stones. Easy penetration into houses or buildings in the UHF mobile cellular system improves the indoor coverage of the mobile system. As the frequency of the radio wave becomes higher, absorption becomes more dominating. In SHF or at higher frequencies, absorption by molecular resonance in the atmosphere, such as gas, water, vapor and oxygen, is a major factor in attenuating the radio wave energy. The attenuation by heavy rain and snow sometimes results in outage of the radio communications at the SHF frequency band and above. This is particularly important for satellite communications in a higher portion of SHF bands, e.g. around 12 GHz.

Taking the above properties into account, different portions of the radio spectrum are better suited to different purposes.

A radio spectrum channel has a bandwidth giving the width of the range of frequencies on which an information signal travels. A broader bandwidth is required in order to convey higher data rate information. This suggests that the higher frequency bands in the spectrum are more suitable for broadband communications.

However, terrestrial mobile radio systems depend mainly on non-LOS radio communications exploiting radio propagation mechanisms such as diffraction, reflection and scattering. Diffracted radio waves at frequencies above 5 GHz are significantly attenuated, resulting in a high path loss making non-LOS communications difficult to realize. It is therefore concluded that the suitable frequency range for mobile systems is below 5 GHz.

## **1.2.2 Spectrum allocation and identification**

### **Allocation**

Each country has an administration that sovereignly regulates and manages spectrum use within its territory. In order to manage radio spectrum appropriately, various kinds of radio stations are categorized into radio services such as mobile service, fixed service, broadcasting service and satellite service. The categorization is based on operational and administrative differences rather than those in technical characteristics. The radio spectrum is also divided into many portions of the frequency bands. Administrations allocate one or more of the services to these discrete portions of the bands in order to achieve an efficient use of spectrum and to avoid harmful interferences among different radio services. Each administration develops its own national table of frequency allocations (see Section 2.2) defining which portion of the spectrum shall be used for what kind of a particular radio service. According to this national allocation table, the administration manages spectrum in its territory as a basis for an orderly and efficient use of the radio spectrum.

Since radio waves propagate across national borders, the administrations cannot manage the radio spectrum separately and independently. International cooperation in spectrum management is required. The international cooperation can be achieved on a bilateral or multi-lateral basis. Regional organizations such as the European Conference of Postal and



Telecommunications Administrations (CEPT), the Asia-Pacific Telecommunity (APT), and the Inter-American Telecommunication Commission (CITEL) have been set up for this purpose. ITU is a global organization that deals with the international cooperation of the spectrum management. The administrations cooperate in spectrum management through the ITU. ITU member countries must obey the agreements that are reached at ITU, giving them a treaty status. Among the agreements, the Radio Regulations (RR) provide basic principles and terminologies which are commonly used by the administrations. The RR also provides an international frequency allocation table which has been agreed at the World Radiocommunication Conferences (WRCs). The RR has been updated at WRCs. National frequency allocation tables are harmonized with the international allocation table in the RR. It should be noted that a discrete portion of the spectrum is 'allocated' to one or more of the 'services' without referring to specific radio systems. The administrations can assign a portion of the spectrum to any kind of radio system that belongs to the service to which the portion of the spectrum is allocated. Since cellular systems emerged quite recently, the spectrum that has already been allocated to the mobile service is small compared to the spectra of other services such as the broadcasting and satellite services.

ITU-R arranges the WRC every three to four years to review and revise the RR, which forms the international treaty governing the use of the radio frequency spectrum and satellite orbits. WRC is therefore the only authority to decide on frequency allocations. For an issue to be considered at the WRC, it needs to be included on the WRC agenda, which is developed at the preceding conference. Proposals for an item to be included on the WRC agenda need to be discussed before the preceding conference. A conference preparatory meeting (CPM) is organized before each WRC to prepare a consolidated report to support the work of the WRC.

Due to the above procedures, it takes more than 3 to 4 years from the beginning of the discussions until the allocation itself. From the allocation of frequency bands for some service, it usually takes several years until the actual frequency bands can be used for the service. Therefore, frequency-related matters must be considered well in advance before the actual need for the bands.

## **Identification**

In mobile communication systems such as IMT-2000, there was a further need to specify what kind of particular radio system uses which portion of the spectrum band to ensure global roaming of radio terminals that belong to the same radio system and use the same spectrum band worldwide. The concept of 'spectrum identification' was created for this purpose. Since the spectrum identification is further made in addition to the spectrum allocation, in general the portion of the band to be identified should have a primary allocation before the identification. Global identification is particularly important for mobile systems in that it ensures that the same radio systems can deploy in the same frequency band on a global basis. This results in economies of scale (cost reduction by mass production) and global roaming of mobile terminals.

### **1.2.3 Flexible use of spectrum**

Concepts of fixed and dynamic spectrum allocation are discussed in the following.

At present, the interference between radio systems operated by different operators is kept below some margin through a fixed allocation of frequency bands to the operators, with sufficient guard bands in between. Thereby, the mobile radio spectrum is segmented and some bands of the spectrum are exclusively licensed by a regulator to one operator, while other bands are assigned to other operators. This is seen as a precondition for competition between operators in the mobile services market, bringing down the cost of the use of mobile services experienced by subscribers. A radio band licensed to an operator is, typically, subdivided into multiple radio channels, and an operator's radio network is planned in a way such that the same channel is being spatially reused at a distance large enough so that the path loss of co-channel signals is high enough to avoid substantial signal interference. This model of spectrum allocation to mobile operators has been applied successfully over decades.

The spectrum range suitable for mobile radio services, see Figure 1.7, is allocated to only a small percentage to mobile services. Many other services such as radio broadcast, television (TV) broadcast, fixed and mobile satellite, fixed radio links and radio navigation have successfully competed for allocation in earlier days. In addition, public and military services have their exclusive allocations for similar services. It is easy to check by measurement that only very small parts of the range 'suitable for mobile use' are really being used by the respective licensees. Measurement campaigns at most locations, which graphically represent the signal energy received over 24 hours per spectrum unit in the range of 300 MHz to 3 GHz, typically, show a blue carpet (where blue color represents 'no signal received') with some narrow frequency band lines covering all the time, representing local radio stations and active mobile operators. From that it can be concluded that spectrum is not a scarce resource, but that spectrum is allocated mostly to licensees that, typically, rarely operate the respective service or operate the service only limited to some small spatial area, or both. This observation is not new and has generated activities for more efficient use of the radio spectrum by introducing flexibility of use.

TV broadcast channels occupy a large portion of the spectrum best suited for mobile services. Since operators of TV channels are known to operate their channels only in metropolitan areas and to keep many channels elsewhere unused, the IEEE 802.22 Working Group on wireless regional area networks (WRANs) is to develop a standard for a cognitive radio-based PHY/MAC air interface for use by license-exempt devices on a non-interfering basis in the spectrum allocated to the TV Broadcast Service. Besides this, the IEEE 802.19 Coexistence Technical Advisory Group (TAG) will develop and maintain policies defining the responsibilities of 802 standards developers to address issues of coexistence with existing standards and other standards under development. Worth noting is also the activity of IEEE 1900 Working Group developing supporting standards dealing with new technologies and techniques being developed for next generation radio and advanced spectrum management. This activity is known as Dynamic Spectrum Access Networks (DySPAN).

Experiences exist for the dynamic spectrum use of systems following the same or different air interface standards operated in license-exempt bands, known as Industrial, Scientific and Medical (ISM) bands. The operation of IEEE 802.11 WLAN is a predominant example of this. The problem with shared use of a frequency channel by non-coordinated systems is that the information transmission range over radio between a transmitter and a receiver substantially differs from the interference range, within which any other receivers might harmfully be affected. Therefore it can happen that a TV broadcast receiver would

catch much ‘noise’ (degradation of the signal quality) from interference by a terminal operated in the same channel according to the standard IEEE 802.22.

Frequency sharing rules (FSRs) have been suggested to avoid unwanted systems interference (Motorola 1994). FSRs have been evaluated by modeling the statistical interference to predict the probability of non-acceptable mutual interference for systems such as UMTS versus DECT, GSM versus TERrestrial Trunked Radio (TETRA) (Lott and Scheibenbogen 1997). The focus there is on the prediction of the QoS of mobile services operated adjacently in the spectrum, with too small a guard band in between.

Present spectrum allocation has some shortcomings, especially when considering efficient use of a given radio band as follows:

- Almost all radio systems experience time-dependent load characteristics. Most services have a certain, predictable load pattern over the course of a day, with peak times and low-load periods. Currently, spectrum is assigned for serving the peak load. However, most of the spectrum will be unused for long periods of time. Dynamic spectrum allocation might take advantage of this by allowing systems to breath in temporal spectrum occupancy according to its current load under given rules.
- Spectrum efficiency can be increased by choosing the optimal transmission technology for a given service. Digital contents can be transmitted via both a point-to-point UMTS link and a broadcast DAB link. Whenever several mobile terminals are requesting the same contents, e.g. ‘Wireless News’, a broadcast service may be more efficient compared to point-to-point transmission. Thereby, bandwidth to transmit multiple copies of the same data may be saved.
- Intelligent systems capable of detecting or predicting interference may be able to avoid mutual interference. Thus, spectrum reserved for guard bands may be used for data transmission.
- Current mobile systems cannot mutually exchange information on their respective spectrum usage. This might be overcome in favor of more cooperation between systems, resulting in a more efficient use of unused spectrum.

Cognitive radio is the key to more spectrum-efficient use of the radio spectrum. It will allow dynamic spectrum use according to the current needs of a system, either under central control, e.g. by following the information broadcast by a pilot channel, or under noncentral control based on game theoretic considerations or similar (Walke *et al.* 2006).

## 1.3 Spectrum Allocation: Why and How

This section describes why spectrum requirement estimation is required for spectrum allocation and how the estimation is conducted.

### 1.3.1 Requirement estimation for allocation

The users’ demands for broadband mobile and wireless communications are increasing as they can provide a wide variety of attractive applications/services. In order to satisfy the users’ demands, new radio interface technologies for IMT-Advanced will be required after

the year 2010 that support the data rate of 100 Mbit/s in full mobility environments and 1 Gbit/s in nomadic environments. These radio interface technologies require continuous and broader spectra.

Since the current spectrum usage is determined based on an allocation table, the allocation table in the RR should be revised at the ITU-R WRC. In order to revise the allocation table, as a justification for the application for allocation of new spectra, the spectrum required for future services and systems must be predicted as accurately as possible, taking into due consideration future market trends including applications and services as well as future technology trends.

### **1.3.2 Method of estimation**

To conduct estimation of spectra to be used in addition to the spectra allocated already for mobile services during the years 2010 to 2020, ITU-R set the following two principles.

- A spectrum estimation methodology should appropriately handle the traffic arising from a wide variety of future mobile applications and services.
- It should also consider multiple delivery mechanisms to accommodate the traffic.

Based on these principles, ITU-R extensively collected and analyzed the data on applications and services as well as market and technology trends in the year 2010 onwards.

As for applications and services, ITU-R investigated a wide variety of services and their similarities, and finally classified these services into 20 service categories (SCs). Moreover, it defined six service environments (SEs) by using service usage patterns and teledensities (density of terminals using a specific telecommunications service) in order to analyze the users' behavior of service usage. Regarding radio access systems, ITU-R defined four Radio Environments (REs) by considering cell deployment scenarios and four Radio Access Technique Groups (RATGs) by considering their system characteristics and their deployments; see Section 4.2.

In ITU-R, the spectrum requirement has been calculated, focusing on a specific radio system, with radio parameters of the system and services associated with it. ITU-R has taken a new approach in which both all possible wireless applications and all possible mobile radio systems that can accommodate them are first considered, and then has systematically categorized them into a limited number of service categories and RATGs for spectrum requirement calculation.

The new ITU-R methodology employs a system capacity calculation algorithm for packet-switched service categories in addition to that for the conventional circuit-switched service categories. The algorithm attains a traffic multiplexing gain, which avoids an overestimation of the spectrum bandwidth. This new methodology is presented in Chapter 4 of this book.