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Introduction

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1.1 Mobile Voice Subscriber Growth

The number of mobile subscribers increased tremendously from 2000 to 2010. The first billion landmark was passed in 2002, the second billion in 2005, the third billion 2007, the fourth billion by the end of 2008 and the fifth billion in the middle of 2010. More than a million new subscribers per day have been added globally – that is more than ten subscribers on average every second. This growth is illustrated in Figure 1.1. Worldwide mobile phone penetration is 75%[1]. Voice communication has become mobile in a massive way and the mobile is the preferred method of voice communication, with mobile networks covering over 90% of the world's population. This growth has been fueled by low-cost mobile phones and efficient network coverage and capacity, which is enabled by standardized solutions, and by an open ecosystem leading to economies of scale. Mobile voice is not the privilege of the rich; it has become affordable for users with a very low income.

1.2 Mobile Data Usage Growth

Second-generation mobile networks – like the Global System for Mobile Communications (GSM) – were originally designed to carry voice traffic; data capability was added later. Data use has increased but the traffic volume in second-generation networks is clearly dominated by voice traffic. The introduction of third-generation networks with High Speed Downlink Packet Access (HSDPA) boosted data use considerably.

Data traffic volume has in many cases already exceeded voice traffic volume when voice traffic is converted into terabytes by assuming a voice data rate of 12 kbps. As an example, a European country with three operators (Finland) is illustrated in Figure 1.2. The HSDPA service was launched during 2007; data volume exceeded voice volume during 2008 and the data volume was already ten times that of voice by 2009. More than 90% of the bits in the radio network are caused by HSDPA connections and less than 10% by voice calls. High Speed Downlink Packet Access data growth is driven by

[1] The actual user penetration can be different since some users have multiple subscriptions and some subscriptions are shared by multiple users.

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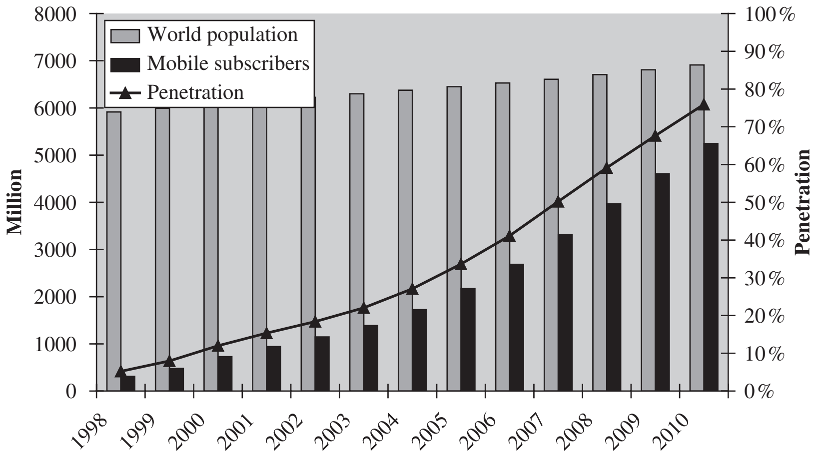

Figure 1.1 Growth of mobile subscribers

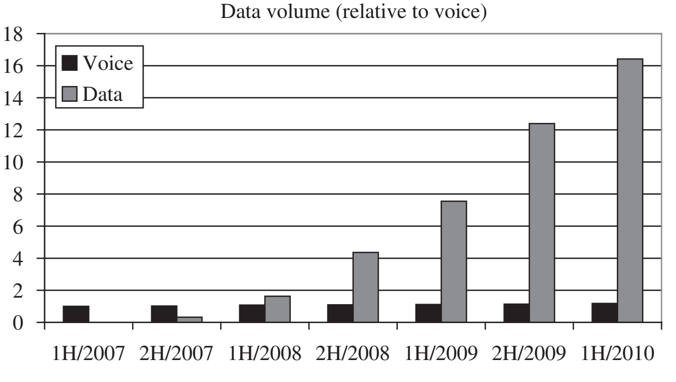

Figure 1.2 HSDPA data volume exceeds voice volume (voice traffic 2007 is scaled to one)

high-speed radio capability, flat-rate pricing schemes and simple device installation. In short, the introduction of HSDPA has turned mobile networks from voice-dominated to packet-data-dominated networks.

Data use is driven by a number of bandwidth-hungry laptop applications, including internet and intranet access, file sharing, streaming services to distribute video content and mobile TV, and interactive gaming. Service bundles of video, data and voice – known also as triple play – are also entering the mobile market, causing traditional fixed-line voice and broadband data services to be replaced by mobile services, both at home and in the office.

A typical voice subscriber uses 300 minutes per month, which is equal to approximately 30 megabytes of data with the voice data rate of 12.2 kbps. A broadband data user can easily consume more than 1000 megabytes (1 gigabyte) of data. The heavy broadband data use takes between ten and 100 times more capacity than voice usage, which sets high requirements for the capacity and efficiency of data networks.

It is expected that by 2015, five billion people will be connected to the internet. Broadband internet connections will be available practically anywhere in the world. Already, existing wireline installations can reach approximately one billion households and mobile networks connect more than three billion subscribers. These installations need to evolve into broadband internet access. Further extensive use of wireless access, as well as new wireline installations with enhanced capabilities, is required to offer true broadband connectivity to the five billion customers.

1.3 Evolution of Wireline Technologies

Wide-area wireless networks have experienced rapid evolution in terms of data rates but wireline networks are still able to provide the highest data rates. Figure 1.3 illustrates the evolution of peak user data rates in wireless and wireline networks. Interestingly, the shape of the evolution curve is similar in both domains with a relative difference of approximately 30 times. Moore's law predicts that the data rates should double every 18 months. Currently, copper-based wireline solutions with Very-High-Data-Rate Digital Subscriber Line (VDSL2) can offer bit rates of tens of Mbps and the passive optical-fiber-based solution provides rates in excess of 100 Mbps. Both copper and fiber based solutions will continue to evolve in the near future, increasing the data rate offerings to the Gbps range.

Wireless networks must push data rates higher to match the user experience that wireline networks provide. Customers are used to wireline performance and they expect the wireless networks to offer comparable performance. Applications designed for wireline networks drive the evolution of the wireless data rates. Wireless solutions also have an important role in providing the transport connections for the wireless base stations.

Wireless technologies, on the other hand, have the huge advantage of being able to offer personal broadband access independent of the user's location – in other words, they provide mobility in nomadic or full mobile use cases. The wireless solution can also

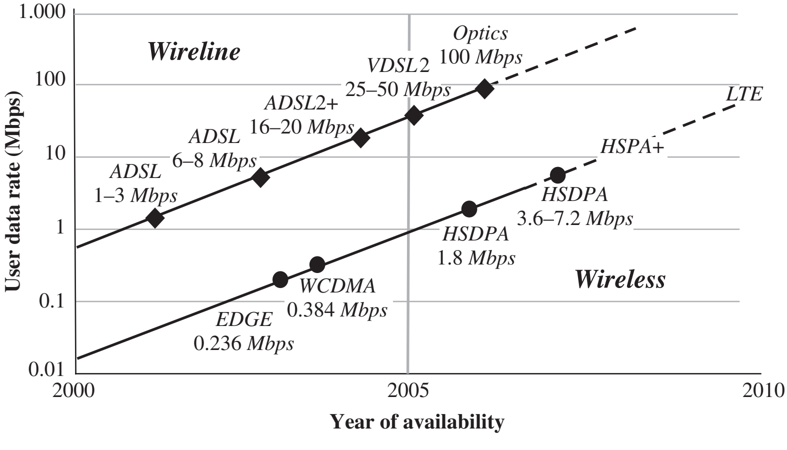

Figure 1.3 Evolution of wireless and wireline user data rates GPON = Gigabit Passive Optical Network. VDSL = Very High Data Rate Subscriber Line. ADSL = Asymmetric Digital Subscriber Line

provide low-cost broadband coverage compared to new wireline installations if there is no existing wireline infrastructure. Wireless broadband access is therefore an attractive option, especially in new growth markets in urban areas as well as in rural areas in other markets.

1.4 Motivation and Targets for LTE

Work towards 3GPP Long Term Evolution (LTE) started in 2004 with the definition of the targets. Even though High-Speed Downlink Packet Access (HSDPA) was not yet deployed, it was evident that work for the next radio system should be started. It takes more than five years from system target settings to commercial deployment using interoperable standards, so system standardization must start early enough to be ready in time. Several factors can be identified driving LTE development: wireline capability evolution, need for more wireless capacity, need for lower cost wireless data delivery and competition from other wireless technologies. As wireline technology improves, similar evolution is required in the wireless domain to ensure that applications work fluently in that domain. There are also other wireless technologies – including IEEE 802.16 – which promised high data capabilities. 3GPP technologies must match and exceed the competition. More capacity is needed to benefit maximally from the available spectrum and base station sites. The driving forces for LTE development are summarized in Figure 1.4.

LTE must be able to deliver performance superior to that of existing 3GPP networks based on HSPA technology. The performance targets in 3GPP are defined relative to HSPA in Release 6. The peak user throughput should be a minimum of 100 Mbps in the downlink and 50 Mbps in the uplink, which is ten times more than HSPA Release 6. Latency must also be reduced to improve performance for the end user. Terminal power consumption must be minimized to enable more use of multimedia applications without recharging the battery. The main performance targets are listed below and are shown in Figure 1.5:

- spectral efficiency two to four times more than with HSPA Release 6;
- peak rates exceed 100 Mbps in the downlink and 50 Mbps in the uplink;
- enables a round trip time of <10 ms;
- packet switched optimized;
- high level of mobility and security;
- optimized terminal power efficiency;
- frequency flexibility with allocations from below 1.5 MHz up to 20 MHz.

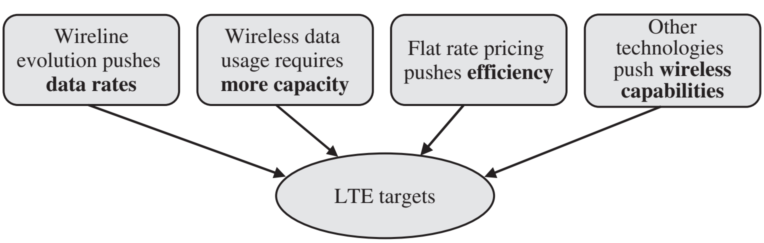

Figure 1.4 Driving forces for LTE development

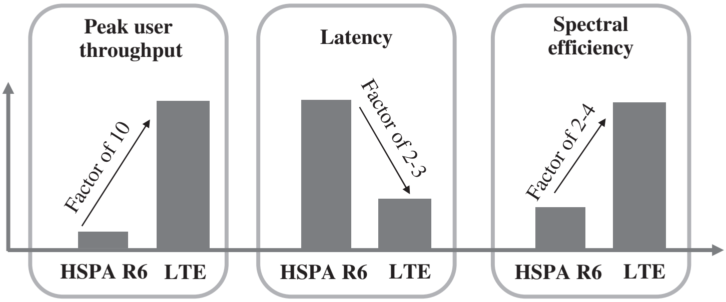

Figure 1.5 Main LTE performance targets compared to HSPA Release 6

1.5 Overview of LTE

The multiple-access scheme in the LTE downlink uses Orthogonal Frequency Division Multiple Access (OFDMA). The uplink uses Single Carrier Frequency Division Multiple Access (SC-FDMA). Those multiple-access solutions provide orthogonality between the users, reducing interference and improving network capacity. Resource allocation in the frequency domain takes place with the resolution of 180 kHz resource blocks both in uplink and in downlink. The frequency dimension in the packet scheduling is one reason for the high LTE capacity. The uplink user specific allocation is continuous to enable single-carrier transmission, whereas the downlink can use resource blocks freely from different parts of the spectrum. The uplink single-carrier solution is also designed to allow efficient terminal power amplifier design, which is relevant for terminal battery life. The LTE solution enables spectrum flexibility. The transmission bandwidth can be selected between 1.4 MHz and 20 MHz depending on the available spectrum. The 20 MHz bandwidth can provide up to 150 Mbps downlink user data rate with 2×2 MIMO and 300 Mbps with 4×4 MIMO. The uplink peak data rate is 75 Mbps. The multiple access schemes are illustrated in Figure 1.6.

High network capacity requires efficient network architecture in addition to advanced radio features. The aim of 3GPP Release 8 is to improve network scalability for increased traffic and to minimize end-to-end latency by reducing the number of network elements. All radio protocols, mobility management, header compression and packet retransmissions are located in the base stations called eNodeB. These stations include all those algorithms that

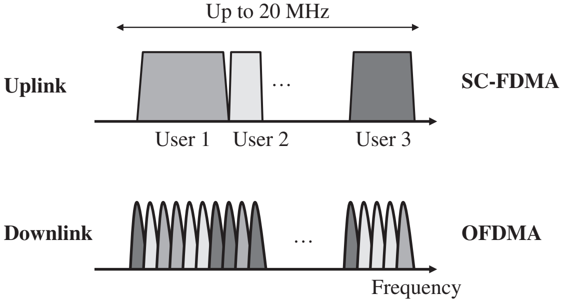

Figure 1.6 LTE multiple access schemes

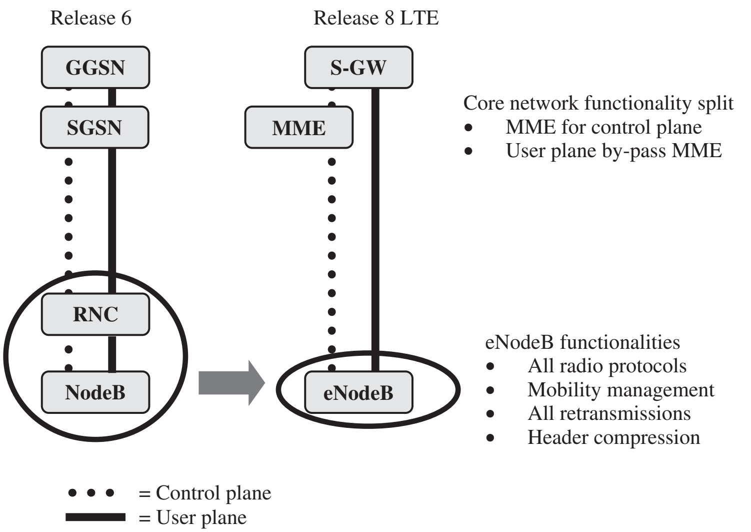

Figure 1.7 LTE network architecture

are located in Radio Network Controller (RNC) in 3GPP Release 6 architecture. The core network is streamlined by separating the user and the control planes. The Mobility Management Entity (MME) is just a control plane element and the user plane bypasses MME directly to Serving Gateway (S-GW). The architecture evolution is illustrated in Figure 1.7.

1.6 3GPP Family of Technologies

3GPP technologies – GSM/EDGE and WCDMA/HSPA – are currently serving 90% of global mobile subscribers. The market share development of 3GPP technologies is illustrated in Figure 1.8. A number of major CDMA operators have already turned to, or

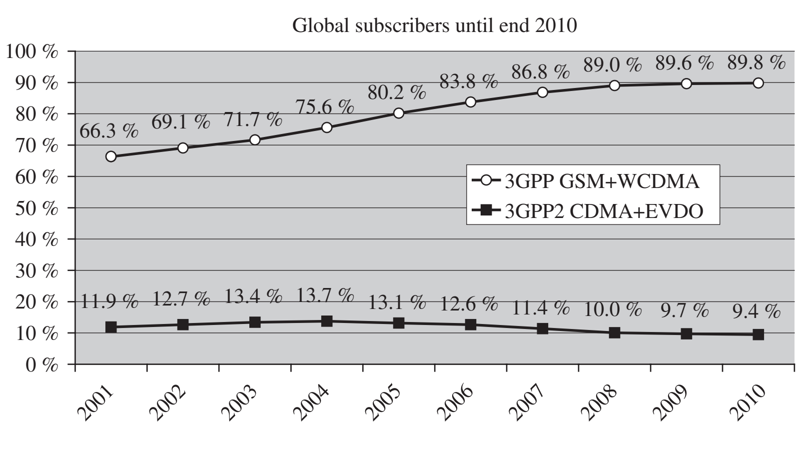

Figure 1.8 Global market share of 3GPP and 3GPP2 technologies

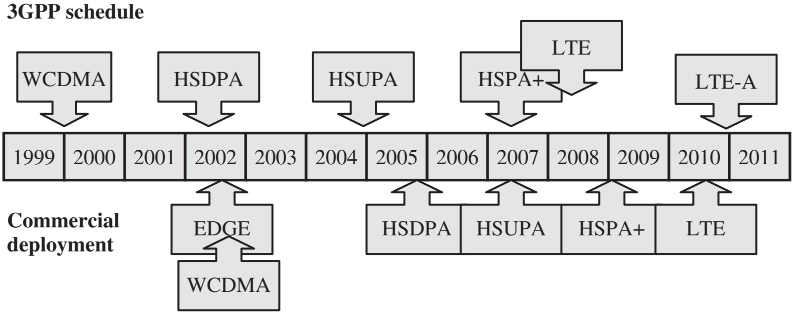

Figure 1.9 Schedule of 3GPP standard and their commercial deployments

will soon be turning to, GSM/WCDMA for voice evolution and to HSPA/LTE for data evolution to access the benefits of the large and open 3GPP ecosystem and for economies of scale for low-cost mobile devices. The number of subscribers using 3GPP-based technologies is currently more than 4.5 billion. The 3GPP Long Term Evolution (LTE) will be built on this large base of 3GPP technologies.

The time schedules of 3GPP specifications and the commercial deployments are illustrated in Figure 1.9. The 3GPP dates refer to the approval of the specifications. WCDMA Release 99 specification work was completed at the end of 1999 and was followed by the first commercial deployments during 2002. The HSDPA and HSUPA standards were completed in March 2002 and December 2004 and the commercial deployments followed in 2005 and 2007. The first phase of HSPA evolution, also known as HSPA+, was completed in June 2007 and the deployments started during 2009. The LTE standard was approved at the end of 2007, backwards compatibility started in March 2009 and the first commercial networks started during 2010. The next step is LTE-Advanced (LTE-A) and the specification was approved in December 2010.

The new generations of technologies push the data rates higher. The evolution of the peak user data rates is illustrated in Figure 1.10. The first WCDMA deployments 2002 offered 384 kbps, first HSDPA networks 3.6–14 Mbps, HSPA evolution 21–168 Mbps, LTE 150–300 Mbps and LTE-Advanced 1 Gbps, which is a more than 2000 times higher data rate over a period of ten years.

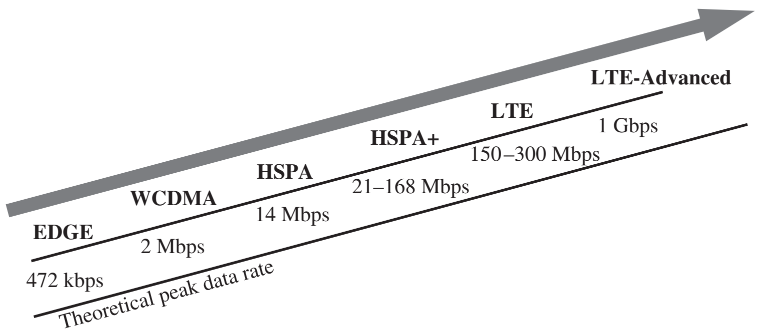

Figure 1.10 Peak data rate evolution of 3GPP technologies

The 3GPP technologies are designed for smooth interworking and coexistence. The LTE will support bi-directional handovers between LTE and GSM and between LTE and UMTS. GSM, UMTS and LTE can share a number of network elements including core network elements. It is also expected that some of the 3G network elements can be upgraded to support LTE and there will be single network platforms supporting both HSPA and LTE. The subscriber management and SIM (Subscriber Identity Module)-based authentication will be used also in LTE.

1.7 Wireless Spectrum

The LTE frequency bands in 3GPP specifications are shown in Figure 1.11 for paired bands and in Figure 1.12 for unpaired bands. Currently 22 paired bands and nine unpaired bands have been defined and more bands will be added during the standardization process. Some of the bands are currently used by other technologies and LTE can coexist with the legacy technologies. In the best case in Europe there is over 600 MHz of spectrum available for the mobile operators when including the 800, 900, 1800, 2100 and 2600 MHz Frequency Division Duplex (FDD) and Time Division Duplex (TDD) bands. In the USA the LTE

Operating band	3GPP name	Total spectrum	Uplink (MHz)	Downlink (MHz)
Band 1	2100	2 × 60 MHz	1920–1980	2110–2170
Band 2	1900	2 × 60 MHz	1850–1910	1930–1990
Band 3	1800	2 × 75 MHz	1710–1785	1805–1880
Band 4	1700/2100	2 × 45 MHz	1710–1755	2110–2155
Band 5	850	2 × 25 MHz	824–849	869–894
Band 6	800	2 × 10 MHz	830–840	875–885
Band 7	2600	2 × 70 MHz	2500–2570	2620–2690
Band 8	900	2 × 35 MHz	880–915	925–960
Band 9	1700	2 × 35 MHz	1750–1785	1845–1880
Band 10	1700/2100	2 × 60 MHz	1710–1770	2110–2170
Band 11	1500	2 × 25 MHz	1427.9–1452.9	1475.9–1500.9
Band 12	US700	2 × 18 MHz	698–716	728–746
Band 13	US700	2 × 10 MHz	777–787	746–756
Band 14	US700	2 × 10 MHz	788–798	758–768
Band 17	US700	2 × 12 MHz	704–716	734–746
Band 18	Japan800	2 × 15 MHz	815–830	860–875
Band 19	Japan800	2 × 15 MHz	830–845	875–890
Band 20	EU800	2 × 30 MHz	832–862	791–821
Band 21	1500	2 × 15 MHz	1447.9–1462.9	1495.9–1510.9
Band 22	3500	2 × 90 MHz	3410–3500	3510–3600
Band 23	S-band	2 × 20 MHz	2000–2020	2180–2200
Band 24	L-band	2 × 34 MHz	1626.5–1660.5	1525–1559

Figure 1.11 Frequency bands for paired bands in 3GPP specifications

Operating band	3GPP name	Total spectrum	Uplink and downlink (MHz)
Band 33	UMTS TDD1	1 × 20 MHz	1900–1920
Band 34	UMTS TDD2	1 × 15 MHz	2010–2025
Band 35	US1900 UL	1 × 60 MHz	1850–1910
Band 36	US1900 DL	1 × 60 MHz	1930–1990
Band 37	US1900	1 × 20 MHz	1910–1930
Band 38	2600	1 × 50 MHz	2570–2620
Band 39	UMTS TDD	1 × 40 MHz	1880–1920
Band 40	2300	1 × 100 MHz	2300–2400
Band 41	2600 US	1 × 194 MHz	2496–2690

Figure 1.12 Frequency bands for unpaired bands in 3GPP specifications

networks will initially be built on 700 and 1700/2100 MHz frequencies. In Japan the LTE deployments start using the 2100 band followed later by 800, 1500 and 1700 bands.

Flexible bandwidth is desirable to take advantage of the diverse spectrum assets: refarming typically requires a narrowband option below 5 MHz while the new spectrum allocations could take advantage of a wideband option of data rates of 20 MHz and higher. It is also evident that both FDD and TDD modes are required to take full advantage of the available paired and unpaired spectrum. These requirements are taken into account in the LTE system specification.

1.8 New Spectrum Identified by WRC-07

The ITU-R World Radiocommunication Conference (WRC-07) worked in October and November 2007 to identify the new spectrum for IMT. The objective was to identify low bands for coverage and high bands for capacity.

The following bands were identified for IMT and are illustrated in Figure 1.13. The main LTE band will be in the 470–806/862 MHz UHF frequencies, which are currently

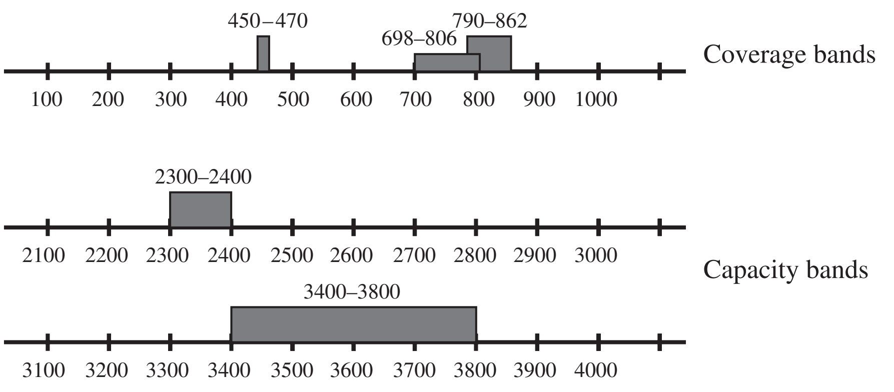

Figure 1.13 Main new frequencies identified for IMT in WRC-07

used for terrestrial TV broadcasting. The 790–862 MHz sub-band was identified in Europe and Asia-Pacific. The availability of the band depends on the national time schedules of the analogue to digital TV switchover. The first auction for that band was conducted in Germany in May 2010 and the corresponding frequency variant is Band 20. The band allows three operators, each running 10 MHz LTE FDD.

The 698–806 MHz sub-band was identified for IMT in Americas. In the US part of the band has already been auctioned. In Asia, the band plan for 698–806 MHz is expected to cover 2 × 45 MHz FDD operation.

The main capacity band will be 3.4–4.2 GHz (C-band). A total of 200 MHz was identified in the 3.4–3.8 GHz sub-band for IMT in Europe and in Asia-Pacific. This spectrum can facilitate the deployment of larger bandwidth of IMT-Advanced to provide the highest bit rates and capacity.

The 2.3–2.4 GHz band was also identified for IMT but this band is not expected to be available in Europe or in the Americas. This band was identified for IMT-2000 in China at the WRC-2000. The 450–470 MHz sub-band was identified for IMT globally, but it is not expected to be widely available in Europe. This spectrum will be narrow with maximum 2 × 5 MHz deployment. Further spectrums for IMT systems are expected to be allocated in the WRC-2016 meeting.

1.9 LTE-Advanced

International Mobile Telecommunications – Advanced (IMT-Advanced) is a concept for mobile systems with capabilities beyond IMT-2000. IMT-Advanced was previously known as ‘Systems beyond IMT-2000’. The candidate proposals for IMT-Advanced were submitted to ITU in 2009. Only two candidates were submitted: LTE-Advanced from 3GPP and IEEE 802.16m.

It is envisaged that the new capabilities of these IMT-Advanced systems will support a wide range of data rates in multi-user environments with target peak data rates of up to approximately 100 Mbps for high mobility requirements and up to 1 Gbps for low mobility requirements such as nomadic/local wireless access. IMT-Advanced work within 3GPP is called LTE-Advanced (LTE-A) and it is part of Release 10. 3GPP submitted an LTE-Advanced proposal to ITU in October 2009 and more detailed work was done during 2010. The content was frozen in December 2010 and the backwards compatibility is expected

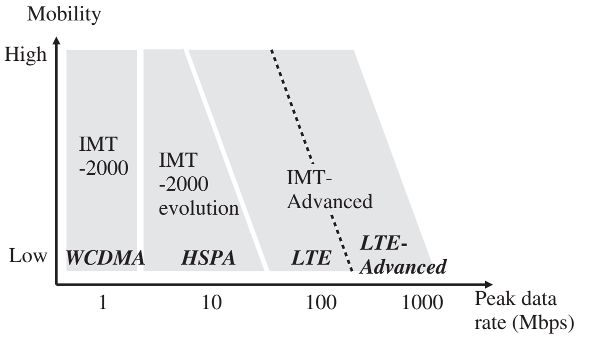

Figure 1.14 Bit rate and mobility evolution to IMT-Advanced

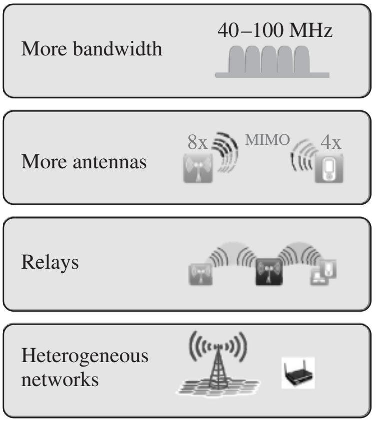

Figure 1.15 LTE-Advanced includes a toolbox of features

in June 2011. The high-level evolution of 3GPP technologies to meet IMT requirements is shown in Figure 1.14.

The main technology components in Release 10 LTE-Advanced include:

- carrier aggregation up to 40 MHz total band, and later potentially up to 100 MHz;
- MIMO evolution up to 8×8 in downlink and 4×4 in uplink;
- relay nodes for providing simple transmission solution;
- heterogeneous networks for optimized interworking between cell layers including macro, micro, pico and femto cells.

LTE-Advanced features are designed in a backwards-compatible way where LTE Release 8 terminals can be used on the same carrier where new LTE-Advanced Release 10 features are activated. LTE-Advanced can be considered as a toolbox of features that can be flexibly implemented on top of LTE Release 8. The main features of LTE-Advanced are summarized in Figure 1.15.