1 Genesis of wireless broadband technology (from 2G to 4.5G)

1.1 Genesis of wireless technology

The digital cellular technology revolution started with the introduction of GSM (Groupe Special Mobile) in the late 1980s. The GSM technology was based on time-division multiple access (TDMA) and was capable of supporting data services of up to 9.6 kbps. In the early 1990s, IS-95, a standard based on code-division multiple-access (CDMA) technology was introduced. This offered data rates of up to 14.4 kbps and improved spectral efficiencies over a GSM system. Subsequently, both these technologies evolved over time, with each phase offering higher peak rates and improved sector/edge spectral efficiencies. Both GSM and IS-95 CDMA evolved in different phases. In 1997, the Generalized Packet Radio System (GPRS) based on packet data instead of circuit data was standardized, followed by Enhanced Data Rates for Global Evolution (EDGE). Also, at the end of 1998, the Third-Generation Partnership Project (3GPP) was started. This was responsible for defining a third-generation (3G) wideband CDMA (WCDMA) standard based on the evolved GSM core network. At the same time the GSM standardization work was moved from ETSI SMG2 to 3GPP, and was called GERAN. Similarly, in the United States the IS-95 standard evolved to cdma2000 under the umbrella of Third-Generation Partnership Project 2 (3GPP2).

The packet-data-based revolution started around 2000 with the introduction of cdma2000 1x Evolved Data Only (1xEV-DO) and 1x Evolved Data Voice (1xEV-DV) in 3GPP2 and High Speed Downlink Packet Access (HSDPA) in 3GPP. These 3.5G technologies had the following common attributes: adaptive modulation and coding, hybrid automatic repeat request, fast scheduling based on smaller frame size, turbo codes, and de-centralized architecture to reduce latency. In the next phase of development of 3.5G technology, improved uplink functionality was added to 3GPP and 1xEV-DO systems. Concurrently, advances were made in cdma2000 1x technology (i.e. cdma 1x-advanced), which included an advanced vocoder, mobile receive diversity, an advanced receiver with interference cancellation, and advanced power control. It may be noted that, although 1xEV-DV was standardized, it never took off as a technology due to the reluctance of the operator community to adopt the technology and the absence of proper eco-systems.

A disruptive technology known as mobile WiMAX based on orthogonal frequency-division multiplexing (OFDM) technology was standardized in 2006, and was dubbed the first 4G multiple access system. This technology was based on the IEEE 802.16e standard and offered scalable bandwidth up to 20 MHz, higher peak rates, and better spectral efficiencies than those provided by 3.5G systems. With the emergence of packet-based wireless broadband systems such as WiMAX, it was evident that a comprehensive evolution of UMTS would be required in order for it to remain competitive in the long term. As a result, work began on Evolved UMTS Terrestrial Radio Access (E-UTRA) based on the OFDM air interface. The Long Term Evolution (LTE Rel-8) system supports high peak data rates and provides low latency, improved system capacity and coverage, reduced operating costs, efficient multi-antenna support, efficient support for packet data transmission, flexible bandwidth of up to 20 MHz, and seamless integration with existing systems. The CDMA-based HSPA technology is also being enhanced to support quad carriers (bandwidth up to 20 MHz), MIMO, and higher-order modulation both on the downlink and on the uplink. A 4G proposal called Ultra Mobile Broadband (UMB) based on OFDM was also adopted by 3GPP2, but it failed to make any impact.

Both WiMAX and LTE are currently being enhanced (LTE-Advanced and 802.16m) so as to support even higher peak rates, higher throughput and coverage, and lower latencies resulting in a better user experience. Further, LTE-Advanced and 802.16m also enable one to meet or exceed IMT-Advanced requirements. Finally, the 4.5G wireless broadband systems will be standardized in 3GPP Rel-12 in the 2013–2017 timeframe. It is clear that 4.5G systems will further enhance the 4G systems in terms of user experience, sector spectral efficiency, and peak rates, but the exact features for 4.5G systems are still being decided.

The Digital Video Broadcasting (DVB) standards, which include Mediaflow and Multimedia Broadcast Multicast Service (MBMS) designed for LTE and HSPA, for global delivery of broadcast services such as digital television are also evolving to provide better spectral efficiencies for broadcast services.

The wireless evolution chart of 2G to 4.5G technology migration is shown in Figure 1.1.

The downlink peak rate improvement on going from 2G to 4.5G technology is shown in Table 1.1.

The improvement in downlink sector spectral efficiencies on going from 2G to 4.5G systems is shown in Figure 1.2.

It may be observed from Figure 1.2 that there has been an improvement by a factor of 30 in sector spectral efficiency with 4G systems compared with 2G, which results in improved cost per bit. Figure 1.3 shows an example of how mobile broadband cost per bit decreases exponentially with technology innovation in wireless technology.

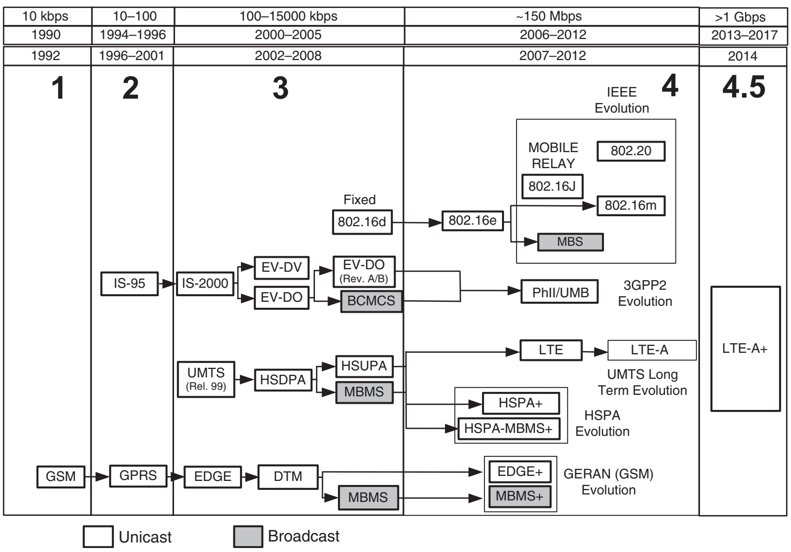

Figure 1.1. Standards evolution of wireless technologies (from 2G to 4.5G).

Table 1.1. *Downlink peak rates for different technologies*

Technology	Theoretical peak rates
GSM (2G)	9.6 kbps
IS-95 (2G)	14.4 kbps
GPRS (2G)	171.2 kbps
EDGE (2.5G)	473 kbps
cdma2000 1x (2G)	628.4 kbps
WCDMA (3G)	1920 kbps
GERAN/EGPRS2 (3G)	947.2 kbps
HSDPA Rel-5 (3.5G)	14 Mbps
cdma2000 1xEV-DO (3G)	3.1 Mbps
HSPA Rel-9 (3.5G)	84 Mbps (2 × 2 MIMO, Dual Carrier)
LTE Rel-8 (4G)	300 Mbps (20 MHz, 4 × 4 MIMO)
WiMAX (4G)	26 Mbps (10 MHz, 2 × 2 MIMO)
WiMAX/802.16m (4.5G)	303 Mbps (20 MHz, 8 × 8 MIMO)
LTE-Advanced Rel-10 (4.5G)	3 Gbps(100 MHz, 8 × 8 MIMO)

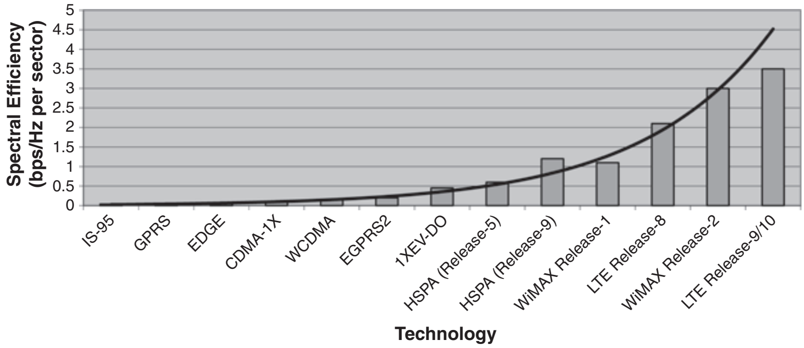

Figure 1.2. Improvement in downlink spectral efficiency going from 2G to 4G systems.

1.2 Key drivers for 4G/4.5G wireless broadband

Technology cycles tend to last on average 10 years. Thus, we have seen mainframe computing (1960s), minicomputing (1970s), personal computing (1980s), desktop internet computing (1990s), and finally mobile internet computing in the 2000s [1]. The need for 4G systems such as LTE

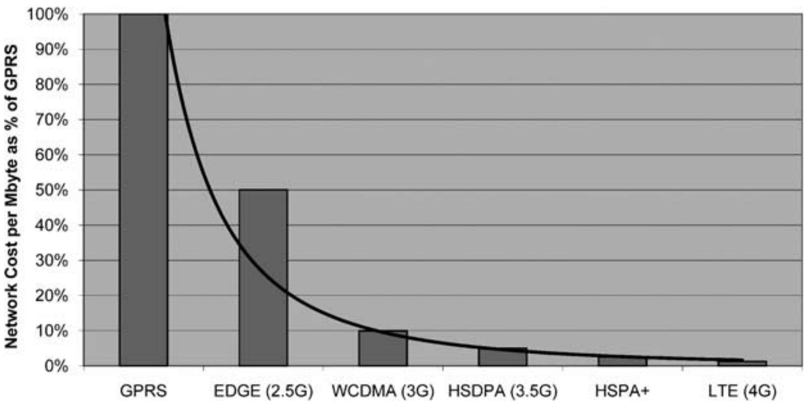

Figure 1.3. Mobile data cost per bit as a function of technology (adapted from [1]).

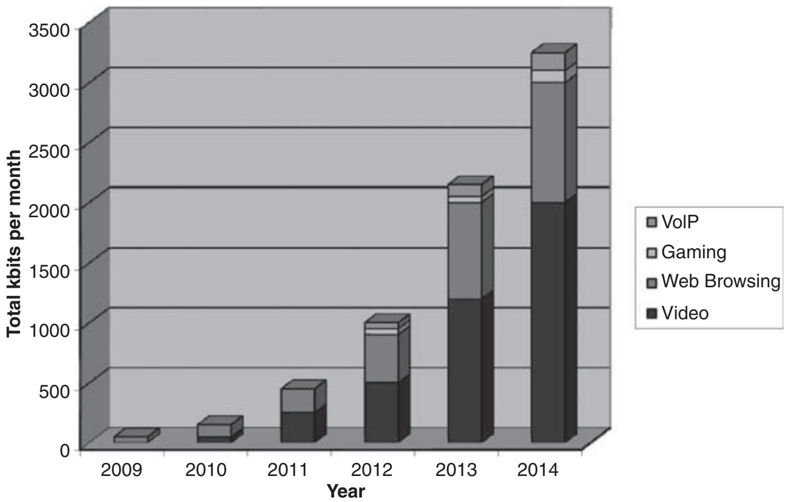

Figure 1.4. An example of the growth of mobile data usage (adapted from [1]).

and WiMAX is driven by the exponential growth in mobile broadband data usage. As shown in Figure 1.4 (adopted from [1]), mobile data usage is expected to increase by a factor of 20–40 by 2014 in total kilobits per month. This has been made possible by the advent of smart phones on the mass market and affordable broadband wireless services using laptops/iPads/USB dongles. Hence today's networks should evolve rapidly to meet the large and rapidly growing data demand.

Table 1.2. *Video requirements for different device types/applications*

Device type	Screen size (inches)	Resolution	Average MPEG4 data rate (kbps)	Mobility	Wireless technology
Smart phones	2.5–3	QVGA (320 × 240)	240	Full	3G/4G
Multimedia phones	3–3.5	HVGA (480 × 320)	600	Full	3G/4G/4.5G
Personal media players	4.7	VGA (640 × 480)	900	Full	4G/4.5G
Standard-definition TV	<32	SD 480i (1280 × 720)	1500	Full	4G
Laptops	12–7	HD 720i (1280 × 720)	3500	Nomadic	4G/4.5G
Low-tier HD TV	<32	HD 720p (1280 × 720)	7000	Fixed	4G/4.5G
High-tier HD TV	>32	HD 1080p (1920 × 1080)	14000	Fixed	4G/4.5G

There seems to have been a paradigm shift in mobile data usage during the past 20 years. There is an increased demand for video data and the cellular network supporting 4G/4.5G systems should be able to cope with this increased demand. The video requirements for different types of applications/devices are shown in Table 1.2.

It may be observed from Table 1.2 that a data rate of 1–4 Mbps is required in order to support video in 4/4.5G wireless systems. Further supporting video with higher quality and low latency over wireless links requires higher bandwidths and the attributes of a 4G system such as LTE-A. The concept of a heterogeneous network (HetNet) has been introduced in LTE-A to address the capacity and coverage challenges resulting from

Table 1.3. *E-UTRA FDD operating bands [2]*

Band number	Operating frequencies (MHz) Downlink	Uplink	Spectrum availability
1	1920–1980	2110–2170	EMEA, Brazil, Japan, India
2	1850–1910	1930–1990	Americas
3	1710–1785	1805–1880	EMEA, Asia–Pacific
4	1710–1755	2110–2155	USA
5	824–849	869–894	Americas, Australia
6	830–840	875–885	Japan
7	2500–2570	2620–2690	EMEA, China, S. America, Canada
8	880–915	925–960	EMEA, Asia–Pacific, S. America
9	1749.9–1784.9	1844.9–1879.9	Japan
10	1710–1770	2110–2170	Americas
11	1427.9–1447.9	1475.9–1495.9	Japan
12	698–716	728–746	USA
13	777–787	746–756	USA
14	788–798	758–768	USA
17	704–716	734–746	USA
18	815–830	860–875	Japan
19	830–845	875–890	Japan
20	832–862	791–821	EMEA
21	1447.9–1462.9	1495.9–1510.9	Japan
22	3410–3500	3510–3600	EMEA, S. America, Asia–Pacific
[23]	2000–2020	2180–2200	USA
[24]	1626.5–1660.5	1525–1559	USA
[25]	1850–1915	1930–1995	Americas

EMEA, Europe, Middle East, and Africa.

the enormous growth of data services. In the HetNet concept, the traditional macro network is deployed to provide umbrella coverage and the augmenting component provides an underlay network that could be either a new type of low-power network nodes (pico-cells, relays, and femtocells) or a complementary technology like Wi-Fi. It will be shown in Section 6.5 how pico-cells can offer an order-of-magnitude improvement

Table 1.4. *E-UTRA TDD operating bands [2]*

Band number	Operating frequencies (MHz)	Spectrum availability
33	1900–1920	Africa, China
34	2010–2025	Africa, China
35	1850–1910	N. America
36	1930–1990	N. America
37	1910–1930	N. America
38	2570–2620	Africa, Europe, S. America
39	1880–1920	China
40	2300–2400	Asia, China, Europe
41	2496–2690	Africa, Americas, Asia, Europe
[42]	3400–3600	EMEA, Americas, Asia–Pacific
[43]	3600–3800	EMEA, S. America, Asia–Pacific

in user experience over a traditional macro-cell network and thus can support the video requirements of different devices as shown in Table 1.2.

1.3 Radio spectrum for wireless broadband

Radio spectrum for wireless broadband is available in different frequency bands and comes as both paired and unpaired bands. The radio-spectrum availability and regulations also vary among geographical areas. The 4G/4.5G wireless broadband technologies are designed to operate in different spectrum allocations using both paired (FDD) and unpaired (TDD) spectrum. The E-UTRA operating bands and spectrum availability for FDD are shown in Table 1.3 [2]. Note that the FDD operating bands 22–25 are currently under discussion in 3GPP and the final details may change.

The corresponding E-UTRA TDD operating bands and spectrum availability are shown in Table 1.4 [2]. Note that the operating TDD bands 42 and 43 are currently under discussion in 3GPP and the final details may change.

Operators and regulators across the world are trying to clear enough spectrum to deploy 4G/4.5G wireless broadband technologies based on LTE/LTE-A or WiMAX Rel-1/Rel-2 to meet the increased demand for mobile data usage which tends to account for approximately 60% of the service revenue. More spectrum is also necessary in order to provide the higher quality of service required for applications such as video, video-conferencing, and gaming.

References

[1] Morgan Stanley, *The Mobile Internet Report Setup*, December 15, 2009.
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Additional reading

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2 LTE overview

2.1 Introduction

Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS) was developed to ensure that the technology remains competitive for the foreseeable future. Requirements for the LTE Rel-8 system include improved system capacity and coverage, improved user experience through higher data rates and reduced latency, reduced deployment and operating costs, and seamless integration with existing systems. The requirements may be broken down into different categories – system performance, latency, coverage, deployment, and complexity. To achieve these goals, new designs for the radio access networks and system architectures are needed.

A representative list of LTE Rel-8 requirements for the radio access networks is given in Table 2.1 while the complete set of requirements may be found in [1]. From a system and user performance perspective, the following requirements have been defined: peak data rate, cell spectral efficiency, cell-edge user throughput, and average user throughput. For the downlink, peak data rates of at least 100 Mbps must be supported for a system bandwidth of 20 MHz, while for the uplink, peak data rates of at least 50 Mbps must be supported. Cell, cell-edge user, and average user performance requirements are defined in terms of spectral efficiency (i.e. supportable throughput in bits per second per MHz) and in relation to Rel-6 UMTS performance. In general, improvement by a factor of 3–4 is expected in the downlink while improvement by a factor of 2–3 is expected in the uplink.

Latency requirements are also defined for the control and user planes. For the user plane (U-plane), a maximum latency of 5 ms is desired. This latency is measured as the one-way delay from when a packet is available at the Internet Protocol (IP) layer to when it arrives at the User Equipment (UE).