Chapter 1

Evolution of Cellular Technologies

1.1 Introduction

All over the world, wireless communications services have enjoyed dramatic growth over the past 25 years. It was only in late 1983 that the first commercial cellular telephone system in the United States was deployed by Ameritech in the Chicago area. That was the analog service called Advanced Mobile Phone Service (AMPS). Today, digital cellular telephone services are available throughout the world, and have well surpassed fixed-line telephone services both in terms of availability and number of users. In fact, as of March 2010 we have over 4.8 billion mobile subscribers in the world, which is more than double the number of fixed line subscribers and amounts to a higher than 60% penetration. The relative adoption of wireless versus fixed line is even more dramatic in the developing world. For example, in India, wireless penetration is more than four times that of fixed line.

It took less then 20 years for mobile subscribers worldwide to grow from zero to over one billion users. This amazing growth demonstrates not only the strong desire of people around the world to connect with one another and have access to information while on the move, but also the tremendous strides that technology has made in fulfilling and further fueling this need. The developments in RF circuit fabrication, advanced digital signal processing, and several miniaturization technologies that made it possible to deploy and deliver wireless communication services at the scale and scope that we see today are indeed quite remarkable.

Today, we are at the threshold of another major revolution in wireless. While mobile voice telephony drove the past growth of wireless systems and still remains the primary application, it is abundantly clear that wireless data applications will drive its future growth. In the past two decades, the Internet transformed from being a curious academic tool to an indispensible global information network providing a vast array of services and applications—from e-mail to social networking and e-commerce to entertainment. As illustrated in Figure 1.1, the global growth in wireless over the past decade was accompanied by a parallel growth in Internet usage. Worldwide, over 1.5 billion people use the Internet today, and there are over 500 million subscribers to Internet access

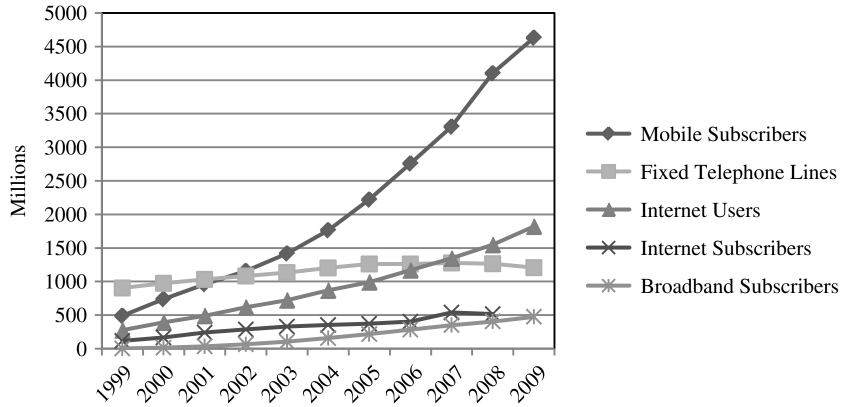

Figure 1.1 Global growth of mobile, Internet, broadband, and fixed telephone line subscribers from 1998–2009 [I].

services; of these over 400 million have broadband or high-speed connections to the Internet. In the United States, more than 60% of households have broadband access to the Internet.

Users worldwide are finding that having broadband access to the Internet dramatically changes how we share information, conduct business, and seek entertainment. Broadband access not only provides faster Web-surfing and quicker downloading but also enables several multimedia applications, such as real-time audio and video streaming, multimedia conferencing, and interactive gaming. Those who have experienced the richness and variety of applications accessible through broadband services in their home or office now clamor for a similar experience wherever they are and while on the move. Providing true broadband experience to mobile users is the next frontier for wireless, and Long-Term Evolution (LTE), the subject of this book, is a key enabling technology for delivering mobile broadband.

In this chapter we provide an overview of the evolution of mobile communication systems. We begin with a brief history of wireless communications and trace the evolution of cellular systems and standards from early developments to the current state of the art. We then cover the market drivers for LTE and the key technical requirements set forth for its development. In the subsequent section, we describe the key ingredient technologies that enable the superior performance of LTE. We then provide a brief overview of the LTE architecture and discuss the spectrum options and migration strategies for operators interested in deploying LTE. We close the chapter with a brief look into the future enhancements being envisioned for LTE.

1.2 Evolution of Mobile Broadband

Before we begin our discussion of modern mobile broadband systems, it is instructive to briefly review the history of mobile wireless communications to gain an appreciation of the remarkable achievements leading to the wireless services that we enjoy today.

The origin of radio communications is often traced back to Guglielmo Marconi, who is commonly credited with its invention and was awarded a patent for the development of a wireless telegraphy system in 1897. Around the same time, Nikola Tesla, Jagadish Bose, and Alexander Popov also demonstrated radio communications and controversy persists about who could claim to be the true inventor of radio. Several scientists and engineers did pioneering experiments with radio in the early years of the twentieth century and achieved remarkable success. The first verifiable transatlantic radio transmission was made in 1902 and voice signals were transmitted across the Atlantic for the first time in 1915. The following decades saw the development of shortwave radio, frequency modulation, and other key technologies that led to the development of the first mobile communication systems.

One of the early uses of mobile communications systems was in the area of public safety. Several U.S. municipalities deployed systems beginning in the 1930s. In 1946, AT&T introduced the first mobile telephone service in St. Louis, Missouri: a manual system with a capacity to support a maximum of three simultaneous calls. By 1948, AT&T expanded the service to 100 cities and had over 5,000 customers—mostly utilities, truck fleet operators, and reporters.

Early mobile telephone systems used base stations with large power amplifiers and tall towers to cover large geographic areas. Each base station was independent of the others, used all the available frequency channels, and was geographically separated from other base stations to avoid interference. Examples of early mobile telephone systems include Mobile Telephone System (MTS) which operated in the 40MHz band, and improved MTS (IMTS), which operated in the 150MHz and 450MHz bands. All these systems were extremely limited in their capacity. For example, in 1976, the IMTS system deployed in New York City had 12 channels and could only support 2,000 subscribers over a thousand square miles. Even those few customers often had to wait 30 minutes to place a call. There was growing demand for mobile services, and a way had to be found to support more users. Governments could not simply allocate spectrum in proportion to the growing demand for mobile service.

The breakthrough solution to the issue of limited capacity was the cellular concept—the idea of replacing a single high-powered transmitter with several lower-power transmitters, each providing coverage to a small portion of the service area and using a fraction of the total available spectrum. Frequencies could then be reused across the service area as long as base stations using the same frequency were sufficiently separated from one another. Although conceived by Bell Labs in 1947, the technology required to implement the cellular concept was not available until the 1970s. In 1971, AT&T submitted a proposal to the Federal Communications Commission (FCC) for a cellular mobile concept, and after more than a decade of deliberations, in 1983 the FCC allocated 40MHz of spectrum in the 800MHz band, which led to the deployment of the first generation of commercial cellular systems (see Table 1.1).

Table 1.1 Important Historical Milestones Toward the Development of Mobile Broadband

Year	Important Milestone
Before 1892	Nikola Tesla found theoretical basis for radio communication and demonstrated radio transmission.
1897	Guglielmo Marconi demonstrated radio communications; awarded patent for it.
1902	First verifiable transatlantic radio transmission (telegraphy) made from an Italian cruiser with Marconi aboard using 272kHz signals.
1906	Reginald Fessendon made first successful two-way transmission over North Atlantic and demonstrated voice transmission using amplitude modulation.
1915	First transatlantic radio transmission of voice from Arlington, Virginia to Paris, France.
1921	Short wave radio (HF radio: 2.3MHz to 25.82MHz) developed.
1934	AM radio systems used in 194 U.S. municipalities for public safety.
1935	Edwin Armstrong demonstrated FM.
1946	First mobile telephone service in St. Louis, Missouri introduced by AT&T.
1948	Claude Shannon published his seminal theory on channel capacity; $C=B\log_2(1+SNR)$.
1956	Ericsson developed first automatic mobile phone called Mobile Telephone A (weighed 40kg).
1960–1970	Bell Labs developed cellular concept.
1971	AT&T submits proposal for a cellular mobile system concept to FCC.
1979	First commercial cellular system deployed by NTT in Japan.
1983	FCC allocated 40MHz of spectrum in 800MHz for AMPS.
1983	Advanced Mobile Phone Service (AMPS) launched in Chicago.
1989	Qualcomm proposes CDMA as a more efficient, wireless voice technology.
1991	First commercial GSM deployment in Europe (Finland).
1995	First commercial launch of CDMA (IS-95) service by Hutchinson Telecom, Hong Kong.
1995	Personal Communication Services (PCS) license in the 1800/1900MHz band auctioned in the United States.
2001	NTT DoCoMo launched first commercial 3G service using UMTS WCDMA.
2002	South Korea Telecom launches first CDMA2000 EV-DO network.
2005	UMTS/HSDPA launched in 16 major markets by AT&T.
2005	IEEE 802.16e standard, the air-interface for Mobile WiMAX, completed and approved.
2006	WiBro (uses the IEEE 802.16e air-interface) commercial services launched in South Korea.
2007	Apple iPhone launched, driving dramatic growth in mobile data consumption.
2009	3GPP Release 8 LTE/SAE specifications completed.

1.2.1 First Generation Cellular Systems

The United States, Japan, and parts of Europe led the development of the first generation of cellular wireless systems. The first generation systems were characterized by their analog modulation schemes and were designed primarily for delivering voice services. They were different from their predecessor mobile communications systems in that they used the cellular concept and provided automatic switching and handover of on-going calls. Japan's Nippon Telephone and Telegraph Company (NTT) implemented the world's first commercial cellular system in 1979. Nordic Mobile Telephone (NMT-400) system, deployed in Europe in 1981, was the first system that supported automatic handover and international roaming. NMT-400 was deployed in Denmark, Finland, Sweden, Norway, Austria, and Spain. Most NMT-400 subscribers used car phones that transmitted up to 15 watts of power.

The more successful first generation systems were AMPS in the United States and its variant Total Access Communication Systems (ETACS and NTACS) in Europe and Japan. These systems were almost identical from a radio standpoint, with the major difference being the channel bandwidth. The AMPS system was built on a 30kHz channel size, whereas ETACS and NTACS used 25kHz and 12.5kHz, respectively. Table 1.2 provides a quick summary of first generation cellular systems.

1.2.1.1 Advanced Mobile Phone Service (AMPS)

AMPS was developed by AT&T Bell Labs in the late 1970s and was first deployed commercially in 1983 in Chicago and its nearby suburbs. The first system used large cell areas and omni-directional base station antennas. The system covered 2,100 square miles

Table 1.2 Major First Generation Cellular Systems

	AMPS	**ETACS**	**NTACS**	**NMT-450/ NMT-900**
Year of Introduction	1983	1985	1988	1981
Frequency Bands	D/L:869-894MHz U/L:824-849MHz	D/L:916-949MHz U/L:871-904MHz	D/L:860-870MHz U/L:915-925MHz	NMT-450:450-470MHz NMT-900:890-960MHz
Channel Bandwidth	30kHz	25kHz	12.5kHz	NMT-450:25kHz NMT-900:12.5kHz
Multiple Access	FDMA	FDMA	FDMA	FDMA
Duplexing	FDD	FDD	FDD	FDD
Voice Modulation	FM	FM	FM	FM
Number of Channels	832	1240	400	NMT-450:200 NMT-900:1999

with only ten base stations, each with antenna tower height between 150 ft. and 550 ft. Most of the early systems were designed for a carrier-to-interference ratio (CIR) of 18dB for satisfactory voice quality, and were deployed in a 7-cell frequency reuse pattern with 3 sectors per cell.

Besides the United States, AMPS was deployed in several countries in South America, Asia, and North America. In the United States, the FCC assigned spectrum to two operators per market—one an incumbent telecommunications carrier and the other a new non-incumbent operator. Each operator was assigned 20MHz of spectrum, supporting a total of 416 AMPS channels in each market. Of the 416 channels, 21 channels were designated for control information and the remaining 395 channels carried voice traffic. AMPS systems used Frequency Modulation (FM) for the transmission of analog voice and Frequency Shift Keying (FSK) for the control channel. Even after the deployment of second generation (2G) systems, AMPS continued to be used by operators in North America as a common fallback service available throughout the geography, as well as in the context of providing roaming between different operator networks that had deployed incompatible 2G systems.

1.2.2 2G Digital Cellular Systems

Improvements in processing abilities of hardware platforms over time enabled the development of 2G wireless systems. 2G systems were also aimed primarily toward the voice market but, unlike the first generation systems, used digital modulation. Shifting from analog to digital enabled several improvements in systems performance. System capacity was improved through (1) the use of spectrally efficient digital speech codecs, (2) multiplexing several users on the same frequency channel via time division or code division multiplexing techniques, and (3) tighter frequency re-use enabled by better error performance of digital modulation, coding, and equalization techniques, which reduced the required carrier-to-interference ratio from 18dB to just a few dB. Voice quality was also improved through the use of good speech codecs and robust link level signal processing. 2G systems also used simple encryption to provide a measure of security against eavesdropping and fraud, which were a source of major concern with first generation analog systems.

Examples of 2G digital cellular systems include the Global System for Mobile Communications (GSM), IS-95 CDMA, and IS-136 TDMA systems. GSM is by far the most widely deployed of these systems; IS-95 is deployed in North America and parts of Asia; IS-54 (later enhanced to IS-136) was initially deployed in North America but was later discontinued and replaced mostly by GSM. IS-136 was a TDMA-based system that was designed as a digital evolution of AMPS using 30kHz channels. The Personal Handyphone System (PHS) deployed in China, Japan, Taiwan, and some other Asian countries is also often considered a 2G system. PHS is a cordless telephone system like the Digital Enhanced Cordless Telephone (DECT) system but with capability to handover from one cell to another, and operated in the 1880–1930MHz frequency band. Table 1.3 provides a summary comparison of the various 2G digital cellular systems.

Besides providing improved voice quality, capacity, and security, 2G systems also enabled new applications. Prime among these was the Short Messaging Service (SMS). SMS was first deployed in Europe in 1991, and quickly became a popular conversational tool

Table 1.3 Major Second Generation Cellular Systems

	GSM	IS-95	IS-54/IS-136
Year of Introduction	1990	1993	1991
Frequency Bands	850/900MHz, 1.8/1.9GHz	850MHz/1.9GHz	850MHz/1.9GHz
Channel Bandwidth	200kHz	1.25MHz	30kHz
Multiple Access	TDMA/FDMA	CDMA	TDMA/FDMA
Duplexing	FDD	FDD	FDD
Voice Modulation	GMSK	DS-SS:BPSK, QPSK	$\pi/4$QPSK
Data Evolution	GPRS, EDGE	IS-95-B	CDPD
Peak Data Rate	GPRS:107kbps; EDGE:384kbps	IS-95-B:115kbps	$\sim$ 12kbps
Typical User Rate	GPRS:20-40kbps; EDGE:80-120kbps	IS-95B: $<$64kbps;	9.6kbps
User Plane Latency	600-700ms	$>$ 600ms	$>$ 600ms

among younger mobile subscribers. Today, over 2.5 billion SMS messages are sent each day in the United States alone, and the service has been used for delivering news updates, business process alerts, mobile payments, voting, and micro-blogging, among other things.

In addition to SMS, 2G systems also supported low data rate wireless data applications. Original 2G systems supported circuit switched data services (similar in concept to dial-up modems), and later evolved to support packet data services as well. Early wireless data services included information services such as the delivery of news, stock quotes, weather, and directions, etc. Limitations in data rate and available space for display in handheld devices meant that specialized technologies, such as the Wireless Access Protocol (WAP), had to be developed to tailor and deliver Internet content to handheld devices.

1.2.2.1 GSM and Its Evolution

In 1982, many European countries came together under the auspices of the Conference of European Posts and Telegraphs (CEPT) to develop and standardize a pan-European system for mobile services. The group was called the Groupe Spécial Mobile (GSM) and their main charter was to develop a system that could deliver inexpensive wireless voice services, and work seamlessly across all of Europe. Prior to GSM, the European cellular market was fragmented with a variety of mutually incompatible systems deployed in different countries: Scandinavian countries had NMT-400 and NMT-900, Germany had C-450, the United Kingdom had TACS, and France had Radiocom.

By 1989, the European Telecommunications Standards Institute (ETSI) took over the development of the GSM standard and the first version, called GSM Phase I, was released in 1990. Shortly thereafter, several operators in Europe deployed GSM. GSM quickly gained acceptance beyond Europe and the standard was appropriately renamed as the Global System for Mobile Communications. According to the Informa Telecoms and Media, an industry analyst, GSM and its successor technologies today boast over 4.2 billion subscribers spread across 220 countries, a 90% global market share. The broad worldwide adoption of GSM has made international roaming a seamless reality.

The GSM air-interface is based on a TDMA scheme where eight users are multiplexed on a single 200kHz wide frequency channel by assigning different time slots to each user. GSM employed a variant of FSK called Gaussian Minimum Shift Keying (GMSK) as its modulation technique. GMSK was chosen due to its constant envelope property providing good power and spectral efficiency characteristics.

Besides voice and SMS, the original GSM standard also supported circuit-switched data at 9.6kbps. By the mid-1990s, ETSI introduced the GSM Packet Radio Systems (GPRS) as an evolutionary step for GSM systems toward higher data rates. GPRS and GSM systems share the same frequency bands, time slots, and signaling links. GPRS defined four different channel coding schemes supporting 8kbps to 20kbps per slot. Under favorable channel conditions, the higher 20kbps rate can be used, and if all eight slots in the GSM TDM frame were used for data transmission, in theory, GPRS could provide a maximum data rate of 160kbps. Typical implementations of GPRS provided a user data rate of 20–40kbps.

Figure 1.2 provides a high-level architecture of a GSM/GPRS network. It is instructive to review this architecture as it formed the basis from which later 3G systems and LTE evolved. The original GSM architecture had two sub-components:

- **Base Station Subsystem**: This is comprised of the base-station transceiver (BTS) units that the mobile stations (MS) connect with over the air-interface and the base station controller (BSC), which manages and aggregates traffic from several BTSs for transport to the switching core, and manages mobility across BTSs connected

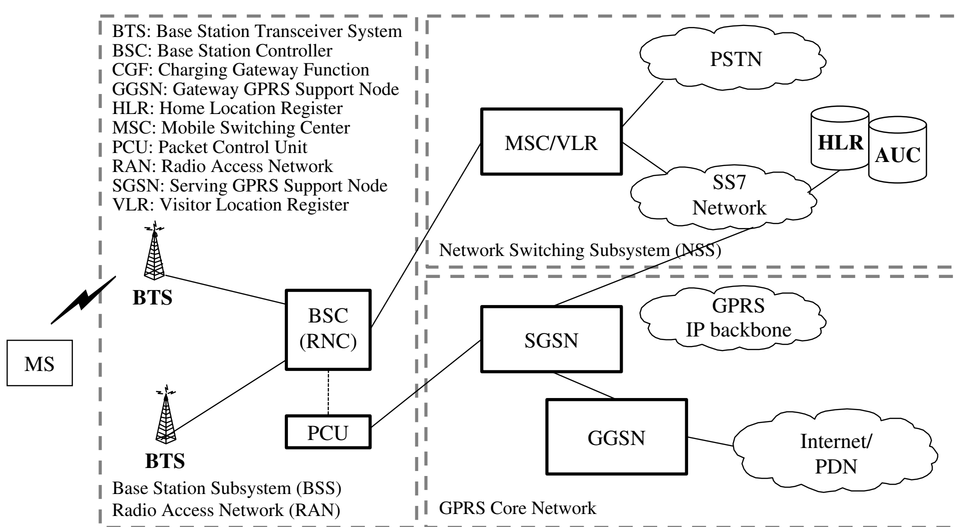

Figure 1.2 GSM network architecture.

directly to them. BSCs evolved to become Radio Network Controllers (RNC) in the 3G evolution of GSM.

- **Network Switching Sub-system**: This is comprised of the Mobile Switching Center (MSC) and subscriber data bases. The MSC provides the required switching to connect the calling party with the called party and is interconnected with the Public Switched Telephone Network (PSTN). The MSC uses the Home Location Register (HLR) and Visitor Location Register (VLR) to determine the location of mobile subscribers for call control purposes.

As shown in Figure 1.2, a GSM system may be upgraded to a GPRS system by introducing new elements, such as the Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN), and upgrading existing network elements such as the BTS with a packet control unit (PCU) for handling data. SGSN provides location and mobility management and may be thought of as the packet data equivalent of MSC. GGSN provides the IP access router functionality and connects the GPRS network to the Internet and other IP networks.

The GSM standard got a further boost in its data handling capabilities with the introduction of Enhanced Data Rate for GSM Evolution, or EDGE, in the early part of 1997. EDGE added support for 8PSK modulation to boost the data rate. This allowed for a maximum per slot data rate of 59.2kbps—a three-fold increase from GPRS speeds. Typical user rates for EDGE varied from 80 to 120kbps.

1.2.2.2 CDMA (IS-95) and Its Evolution

In 1989, Qualcomm, a then obscure start-up company in San Diego, California, proposed Code Division Multiple Access (CDMA) as a more efficient, higher quality wireless technology and demonstrated a system implementation of it. In a remarkable achievement, in 1993, Qualcomm was able to get the Telecommunications Industry Association (TIA) to adopt their proposal as an IS-95 standard providing an alternative to the IS-54 TDMA standard that was adopted earlier as the digital evolution of AMPS. Unlike in other digital wireless systems like GSM, in an IS-95 CDMA system multiple users share the same frequency channel at the same time. Instead of time-slicing multiple users in a given frequency channel, each user is assigned a different orthogonal spreading code that is used to separate their signals at the receiver. Codes are applied by multiplying user data symbols by a much higher rate code sequence, which leads to spreading the occupied bandwidth. IS-95 CDMA uses a 1.25MHz bandwidth to transmit a 9.2kbps or lower voice signal. Spreading signals over a larger bandwidth provides better immunity to multipath fading and interference.

IS-95 CDMA systems claimed a number of advantages over TDMA systems for voice. First, it enabled universal frequency reuse—that is, every cell can use the same frequency channel—which simplified frequency planning and provided increased capacity. Second, it used RAKE receivers that effectively combined multi-path signals to produce a stronger signal thereby reducing the required transmitter power. Third, it improved handoff performance by enabling soft-handoff, where a mobile can make a connection to a new base station before disconnecting from its current base station; this is possible since all base stations use the same frequency. Further, it implemented voice activity detection to turn off transmissions during silent periods, thereby reducing the overall interference level and increasing system capacity. All these features gave CDMA systems a higher voice capacity than GSM. It should be noted, though, that by implementing slow frequency hopping, GSM countered a lot of the frequency reuse advantages of CDMA. To keep the interference in check and improve system capacity, IS-95 implements fast (800Hz on uplink) and effective power control mechanisms, which were a huge challenge at that time.

In the early days of digital cellular, there was a rigorous debate between the proponents of TDMA and CDMA about which technology provided superior capacity and coverage. Practical deployments have tended to prove that IS-95 CDMA technology offered better coverage and capacity. This is further evidenced by the fact that even TDMA proponents adopted a CDMA-based technology as part of their evolution plan for 3G. IS-95 CDMA systems, however, did not succeed in gaining nearly as broad a global adoption as GSM. As of 2009, IS-95 and its evolutionary systems had about 480 million subscribers—most in North America, South Korea, Brazil, and India.

In addition to voice, the original (IS-95A) system supported a single dedicated data channel at 9.6kbps. A later evolution, called IS-95B, introduced a burst or packet mode transmission for improved efficiency. It also defined a new Supplemental Code Channel (SCH) that supported a data rate of 14.4kbps, and allowed for combining up to 7 SCH channels to provide a peak rate of 115.2kbps.

The CDMA community developed 3G evolution plans and aggressively deployed them well ahead of similar systems becoming available for GSM operators. They were able to get 3G rates without changing the 1.25MHz channel bandwidth or giving up on backward compatibility, which made the migration easier on operators. While GSM operators sought more gradual evolution to 3G through GPRS and EDGE, CDMA operators moved more rapidly to deploy their 3G networks: CDMA2000-1X and EV-DO.

1.2.3 3G Broadband Wireless Systems

Clearly, 2G digital cellular systems provided significant increase in voice capacity, improved voice quality, and began support for data applications such as Internet access. The circuit-switched paradigm based on which these systems were built made 2G systems very inefficient for data, and hence provided only low-data rate support—tens of kilobits per second, typically—and limited capacity.

Third generation (3G) systems were a significant leap over 2G, providing much higher data rates, significant increase in voice capacity, and supporting advanced services and applications, including multimedia. Work on 3G began in the early 1990s when the International Telecommunications Union (ITU) began invitation for proposals for 3G systems (known as IMT-2000) and started identifying spectrum for it. The ITU's objective was to create a globally harmonized specification for mobile communication that would facilitate global interoperability and provide the scale to lower cost. The ITU laid out the following data rate requirements as the criterion for IMT-2000:

- 2Mbps in fixed or in building environments
- 384kbps in pedestrian or urban environments
- 144kbps in wide area vehicular environments

Besides high data rate, 3G systems also envisioned providing better Quality of Service (QoS) control tailored for a variety of applications—from voice telephony and interactive games, to Web browsing, e-mail, and streaming multimedia applications.

A number of proposals were submitted to the ITU over the past 10–15 years, and six have been accepted so far. One of the more interesting aspects of the 3G proposals was the choice of CDMA as the preferred access technique for the majority of 3G systems. Not only did the IS-95 camp propose evolution toward a CDMA-based 3G technology called CDMA2000, but the GSM camp offered its own version of CDMA, called wideband CDMA (W-CDMA). So far, the ITU has accepted and approved the following terrestrial radio interfaces for IMT-2000:

- **IMT-2000 CDMA Direct Spread (IMT-DS)**: This standard is more commonly known as W-CDMA and was proposed as the air-interface for the Universal Mobile Telephone Service (UMTS) solution proposed by the Third Generation Partnership Project (3GPP) as the evolution of GSM systems.
- **IMT-2000 CDMA Multi-carrier (IMT-MC)**: This standard was proposed by the 3GPP2 organization and represents an evolution of the IS-95 systems. They are more commonly known as IX-EV-DO.
- **IMT-2000 CDMA TDD (IMT-TC)**: This standard is also proposed by 3GPP for operation in unpaired spectrum using Time Division Duplexing technology. It is also known as UMTS-TDD or TD-SCDMA (Time Division, Synchronous CDMA) and is mostly used in China.
- **IMT-2000 TDMA Single Carrier (IMT-SC)**: This standard was proposed by the Universal Wireless Consortium in the United States as a lower-cost evolution to 3G. Also called UWC-136, this is essentially the EDGE standard developed by 3GPP.
- **IMT-2000 FDMA/TDMA (IMT-FT)**: The Digital European Cordless Telephone (DECT) standard was also accepted as an IMT-2000 air-interface, primarily for indoor and pico-cell applications.
- **IMT-2000 IP-OFDMA**: This standard, more commonly known as WiMAX or IEEE 802.16e, was accepted by the ITU as a sixth air-interface in 2007.

Table 1.4 provides a quick summary of the major 3G system characteristics. A more detailed discussion of the four major 3G technologies is provided in the following subsections.

1.2.3.1 CDMA 2000 and EV-DO

The 3G evolution of IS-95 standards was called CDMA2000 by the CDMA community. Though most of the early work was done by Qualcomm and the CDMA development group, the official standardization process moved to a collaborative standards body called the Third Generation Partnership Project 2 (3GPP2) in 1999. CDMA2000-1X was the first evolution of IS-95 toward 3G accepted as an IMT-2000 interface. The 1X term implies

Table 1.4 Summary of Major 3G Standards

	W-CDMA	**CDMA2000 1X**	**EV-DO**	**HSPA**
Standard	3GPP Release 99	3GPP2	3GPP2	3GPP Release 5/6
Frequency Bands	850/900MHz, 1.8/1.9/2.1GHz	450/850MHz 1.7/1.9/2.1GHz	450/850MHz 1.7/1.9/2.1GHz	850/900MHz, 1.8/1.9/2.1GHz
Channel Bandwidth	5MHz	1.25MHz	1.25MHz	5MHz
Peak Data Rate	384–2048kbps	307kbps	DL:2.4–4.9Mbps UL:800–1800kbps	DL:3.6–14.4Mbps UL:2.3–5Mbps
Typical User Rate	150–300kbps	120–200kbps	400–600kbps	500–700kbps
User-Plane Latency	100–200ms	500–600ms	50–200ms	70–90ms
Multiple Access	CDMA	CDMA	CDMA/TDMA	CDMA/TDMA
Duplexing	FDD	FDD	FDD	FDD
Data Modulation	DS-SS: QPSK	DS-SS: BPSK, QPSK	DS-SS: QPSK, 8PSK and 16QAM	DS-SS: QPSK, 16QAM and 64QAM

that it uses the same bandwidth (1.25MHz) as IS-95. The data capabilities were enhanced by adding separate logical channels termed *supplemental channels*. Each link can support a single fundamental channel (at 9.6kbps) and multiple supplemental channels (up to 307kbps). Strictly speaking, this is less than the 3G requirements, and for this reason, one may refer to CDMA2000-1X as a 2.5G system. The data rate can be increased up to 2Mbps through the use of multiple carriers as in CDMA2000-3X. CDMA2000-1X theoretically doubles the capacity of IS-95 by adding 64 more traffic channels to the forward link, orthogonal to the original set of 64. The uplink was improved through the use of coherent modulation; and the downlink through the addition of fast (800Hz) power control to match the uplink. Advanced antenna capabilities were also integrated into the new standard through options for transmit diversity as well as supplemental pilot options for beam-steering. A key to these upgrades is that they are backward compatible. CDMA2000 and IS-95A/B could be deployed on the same carrier, which allowed for a smooth migration.

In order to achieve higher data rates (up to 2Mbps) as well as improve overall system throughput for packet data scenarios, the CDMA2000-1X standard was also evolved to CDMA2000-1X-EVDO (*EV*olution, *D*ata *O*nly). As the name implies, the standard is applicable to data traffic only and there is no support for voice or other real time services.

Though it uses a 1.25MHz channel bandwidth and shares radio characteristics with IS-95, it cannot be deployed on the same carrier as CDMA2000-1X RTT or IS-95. This required service providers to dedicate a single carrier to data services in order to deploy data.

EV-DO originally was developed as a High-Data Rate (HDR) solution by Qualcomm for use in fixed and nomadic applications meeting the 2Mbps low mobility requirements of IMT-2000. It was, however, later upgraded to meet the full mobility requirements and was indeed the first system to provide real broadband-like speeds to mobile users. In fact, the first deployment of EV-DO occurred in 2002, a full three years ahead of a similar system—HSDPA—being deployed by GSM operators. According to the CDMA Development Group, as of July 2009, EV-DO had over 120 million subscribers.

EV-DO is designed to be an asymmetric system providing downlink rates up to 2.4Mbps and uplink rates up to 153kbps. The downlink is actually a TDMA link where multiple users are time multiplexed. The system supports QPSK and 16QAM modulation and coding rates from 1/5 to 1/3. Depending on the modulation and coding scheme chosen, user rates can vary from 38.4kbps to 2457.6kbps. EV-DO has the capability to adaptively change the modulation and coding based on link conditions.

Enhancements to EV-DO were made in EV-DO Rev. A, which improved the peak user data rates to 3.07Mbps and 1.8Mbps in the downlink and uplink, respectively, while providing a more symmetric link. In commercial deployments, Rev A achieves average throughput of 450–800kbps in the forward link and 300–400kbps in the reverse link.

1.2.3.2 UMTS WCDMA

Universal Mobile Telephone Service (UMTS) was originally developed by ETSI as the 3G system for IMT-2000 based on the evolution of GSM. As GSM went global, in 1998, the 3GPP was formed as a collaboration of six regional telecommunications standards bodies from around the world to continue the development of UMTS and other standards of GSM heritage. 3GPP completed and published the first 3G UMTS standard in 1999, and that standard is often called UMTS Release 99. UMTS Release 99 is widely deployed around the world and enjoys broad success. According to the trade groups 3G Americas and the UMTS Forum, as of May 2010, UMTS networks have been deployed by 346 operators in over 148 countries [2] and has over 450 million users [3].

UMTS includes (1) a core network (CN) that provides switching, routing, and subscriber management; (2) the UMTS Terrestrial Radio Access Network (UTRAN); and (3) the User Equipment (UE). The basic architecture is based on and backward compatible with the GSM/GPRS architecture described in Figure 1.2, with each element enhanced for 3G capabilities. The BTS becomes Node-B, BSC becomes the Radio Network Controller (RNC), the NSS becomes CN, and the MS is called the UE.

While UMTS retains the basic architecture of GSM/GPRS networks, the 3G air-interface called Wide-band CDMA (W-CDMA) is a radical departure from the 2G air-interface. The W-CDMA design was inspired by the success of IS-95 and builds on its basic features. It is a Direct Sequence Spread Spectrum CDMA system where user data is multiplied with pseudo-random codes that provide channelization, synchronization, and scrambling. W-CDMA is specified for both FDD and TDD operations, although FDD is by far the most widely deployed. The system operates on a larger 5MHz bandwidth, capable of supporting over 100 simultaneous voice calls, and providing peak data rates from 384 to 2048kbps. Besides the channel bandwidth, other notable distinguishing features of W-CDMA when compared to CDMA2000 include: (1) support for multi-code use by a single user to increase data rate, (2) wider choice of spreading factors and data rates, and (3) use of Alamouti space-time coding for transmit diversity.

1.2.3.3 HSPA

High-Speed Packet Access, or HSPA, is the term used to refer to the combination of two key enhancements by 3GPP to UMTS-WCDMA: (1) High-Speed Downlink Packet Access (HSDPA) introduced in Release 5 in 2002 and (2) High-Speed Uplink Packet Access (HSUPA) introduced in Release 6 in 2004. HSDPA was first deployed by AT&T in late 2005 and quickly became widely deployed around the world. As of February 2010, HSPA has been deployed by 303 operators in 130 countries, with many more being planned [2]. For the most part, HSPA was deployed as a software upgrade to existing UMTS systems.

Since Internet usage patterns in the late 1990s showed that most of the applications demanded higher throughput on the download, 3GPP UMTS evolution focused initially on improving the downlink. HSDPA defined a new downlink transport channel capable of providing up to 14.4Mbps peak theoretical throughput. This downlink transport channel called the High-Speed Downlink Shared Channel (HS-DSCH), unlike previous W-CDMA channels, uses time division multiplexing as the primary multi-access technique with limited code division multiplexing. HSDPA has 16 Walsh codes, 15 of which are used for user traffic. A single user could use 5, 10, or 15 codes to get higher throughputs, though this is often limited to 5 or 10 by UE implementations. To achieve higher speed, this channel uses a 2ms frame length, compared to frame lengths of 10, 20, 40, or 80ms used by W-CDMA channels. Practical deployments of HSDPA provided typical user throughputs in the 500kbps to 2Mbps range.

HSPA introduced a number of new advanced techniques to realize the high throughput and capacity [4,5]. These include

- **Adaptive Modulation and Coding (AMC)**: HSPDA supports QPSK and 16QAM modulation and rate 1/4 through rate 1 coding. AMC or link adaptation involves varying the modulation and coding scheme on a per user and per frame basis depending on instantaneous downlink channel quality. The idea is to maximize the throughput and system capacity by assigning each user link the highest modulation and coding technique that it can reliably support under the given signal to interference condition. HSDPA mobiles report a Channel Quality Indicator (CQI) measure to the base stations to enable the selection of the best possible modulation and coding scheme.

- **Fast Dynamic Scheduling**: Instead of scheduling users at fixed periods in time, HSDPA systems use a dynamic scheduler that attempts to exploit the diversity of channel conditions experienced by different users at different times. By scheduling delivery of packets to coincide with the fading peaks of each user and avoiding scheduling during their troughs, a dynamic scheduler can ensure that the system is always operating at the highest possible rate. A dynamic scheduler could, if so desired, allocate all the cell capacity to a single user for a very short time when conditions are favorable. This strategy leads to better utilization of available resources and hence increases the overall system capacity, although it may not be wise from a fairness or customer satisfaction point of view. In HSDPA, to enable faster scheduling, the scheduler is located at the Node-B as opposed to the RNC as in W-CDMA.

- **Hybrid Automatic Repeat Request (H-ARQ)**: Delays and inaccuracies in channel quality feedback could lead to incorrect link adaption causing errors. Link layer errors can be corrected using automatic repeat request (ARQ), where erroneous frames are retransmitted upon request, but multiple retransmissions can lead to intolerable delays. Hybrid-ARQ is an improved retransmission technique, where multiple erroneous retransmissions can be soft-combined to effectively recover from errors more quickly. This is referred to as *chase combining*. HSDPA also supports *incremental redundancy* where each subsequent retransmission provides additional error-correction coding in order to improve the chances of error-free reception. It should also be noted that in HSDPA, link layer retransmissions occur between the Node-B and UE as opposed to the RNC and UE as in Release 99 W-CDMA.

HSUPA, also known as Enhanced Uplink, introduced a new uplink channel called the Enhanced Dedicated Channel (E-DCH) to UMTS-WCDMA. HSUPA introduced to the uplink the same advanced technical features such as multi-code transmission, H-ARQ, short transmission time interval, and fast scheduling that HSDPA brought to the downlink. HSUPA is capable of supporting up to 5.8Mbps peak uplink throughput, with practical deployments offering typical user throughput in the 500kbps–1Mbps range. These higher uplink rates and low latency enable applications such as VoIP, uploading pictures and videos, and sending large e-mails.

1.2.4 Beyond 3G: HSPA+, WiMAX, and LTE

As of 2009, mobile operators around the world are planning their next step in the evolution of their networks. The choice they make will depend largely on their current network deployment status, the competitive pressures, and appetite for large capital investment [6,7]. It is reasonable to assume that most operators would choose from one of the following three options.

1. Deploy HSPA and its evolutionary technologies and delay migration to LTE as long as possible. Operators who have recently deployed UMTS/HSPA and wish to recoup their investment will find this option attractive.

2. Deploy WiMAX for broadband data. This option is most attractive to (a) greenfield operators who don't have legacy mobile networks and wish to quickly deploy a competitive broadband offering, (b) CDMA operators who wish to offer real broadband services quickly and do not see a viable CDMA evolutionary technology that is competitive, and (c) operators with unpaired spectrum who wish to deploy a TDD system quickly.

3. Deploy LTE as soon as possible. Many CDMA operators who find their 1X-EVDO network to be at a competitive disadvantage to the HSPA networks, and do not believe in WiMAX as a viable option, will likely wish to migrate to LTE as quickly as feasible, perhaps as early as 2010. Many operators who have not deployed 3G networks, for example, in the developing world, will likely find the option to leapfrog directly to LTE attractive.

In the following subsection we provide an overview of HSPA+ and WiMAX and compare it to LTE. Many in the industry refer to WiMAX and LTE as 4G systems, although technically they do not meet the requirements for 4G as laid out by the ITU (see Section 1.7). The 4G title is, however, somewhat justified from an engineering standpoint, as both WiMAX and LTE represent a clear break from other 3G systems in both the air-interface technology and network architecture. Each of these systems is capable of providing multi-megabits per second throughput, and achieves these high rates through the use of advanced signal processing techniques. It should also be noted that the 3GPP2 community had developed an evolution of IS-95 called IS-95 Rev. C, aka Ultra Mobile Broadband (UMB), which shares a number of technical characteristics with WiMAX and LTE. It does not, however, appear that many operators are considering deploying UMB, and therefore we have omitted it from our discussions.

1.2.4.1 HSPA+

3GPP Release 7 published in June 2007 had substantial enhancements included as a further evolution of HSPA. Release 7 HSPA, sometimes referred to as HSPA+, contains a number of additional features that improve the system capacity (including voice capacity), end-user throughput, and latency [8]. The key technical enhancements included in HSPA+ are

- **Higher-order modulation and MIMO to achieve higher peak rates**: HSPA+ introduces 64QAM as an additional downlink modulation scheme to the QPSK and 16QAM already supported in Release 6 HSPA. On the uplink, support for 16QAM is included in addition to the dual BPSK scheme supported in Release 6. Higher order modulation schemes require high signal-to-noise ratio and can only be practically used in a minority of situations and hence typically only increase the peak rate. Use of 64QAM and 16QAM pushes the peak downlink and uplink rates to 21.1Mbps and 11.5Mbps, respectively. HSPA+ also defines the use for up to two transmit antennas in the base station and two receive antennas in the mobile terminal for MIMO (multiple input multiple output) transmission supporting performance enhancing techniques such as open-loop and closed-loop transmit diversity, beamforming, and spatial multiplexing. The use of 2×2 MIMO spatial multiplexing increases the peak downlink theoretical rate to 28Mbps. While Release 7 HSPA+ does not allow the simultaneous use of 64QAM and MIMO, Release 8 does, and that takes the peak data rate to 42Mbps. It should be noted that the peak rates are seldom achieved in practical deployments. LTE further enhances the support for higher order modulation and MIMO.

- **Dual-carrier downlink operation**: In Release 8, dual-carrier operation in the downlink on adjacent carriers was also defined for HSPA+. This dual-carrier operation offers a very attractive means to achieving higher data rates when there are multiple carriers available and deployed in a single cell. Using this approach doubles the peak data rate from 21Mbps to 42Mbps as well as doubles the average data rate and substantially increases the overall cell capacity. This is unlike the case of using MIMO, which only provides peak data rate enhancements and also incurs the implementation challenges of running RF cables to multiple antennas at the base station. Given these advantages, service providers who do have multiple carriers available will likely prefer this approach. The standard allows scheduling for using dual carriers to be done on either carrier and supports load balancing between carriers in one sector.

- **Continuous packet connectivity for improved battery life**: 3GPP Release 6 HSPA requires that mobile terminals transmit the physical control channel even in the absence of any data channel transmission, which causes unnecessary battery drain. Release 7 HSPA+ allows the uplink transmission to be discontinuous such that the mobile transmitter can be completely turned off when there is no data transmission. On the downlink, similarly, discontinuous reception is supported where the mobile terminal is allowed to wake up for only parts of the frame and can go to sleep mode when there is no data to be received. Discontinuous transmission and reception are very useful power-saving techniques for bursty data applications such as Web browsing (typically, up to 50%). Discontinuous uplink transmissions also reduce interference and hence increase capacity. When applied to VoIP calls, this could provide up to 50% increase in VoIP capacity compared to Release 6.

- **Advanced mobile receivers for data rate and capacity enhancement**: Two-antenna chip equalizer is also defined as part of HSPA+ in addition to the one-antenna chip equalizer and two-antenna RAKE receivers defined in Release 6 HSPA. The antenna diversity improves signal-to-noise ratio and the chip equalizer removes intra-cell interference; together the advanced receiver allows for higher throughput transmissions in the downlink and hence improves capacity. It should be noted this comes at the cost of receiver complexity and is a key disadvantage when compared to the OFDM approach used in LTE.

- **Flexible RLC and MAC segmentation**: W-CDMA and HSPA specified a low, fixed-size Radio Link Control (RLC) layer packet structure (40 bytes, optional 80 bytes in HSPA). This was done largely to avoid having to retransmit large payloads in case of errors. With more robust link layer retransmission schemes in place for HSPA, Release 7 HSPA+ now allows the RLC block size to be flexible and can be as large as 1,500 bytes (typical IP Packet size) without requiring any segmentation at the RLC. Segmentation can be done by the MAC layer based on physical layer requirements. This flexible RLC reduces the RLC layer overhead (RLC header of 2 bytes is just 0.2% of a 1,000-byte packet versus 5% of a 40-byte packet), avoids the need for unnecessary padding to fit in a fixed size, and reduces the number of packets to process at the RLC. All of these lead to improved data throughput and peak rates.

- **Single frequency network for improved multi-cast and broadcast**: HSPA+ allows network synchronization across base stations and the use of same scrambling codes for multi-cast broadcast (MBMS) transmissions from multiple base stations. This realizes a single frequency network (SFN) for multi-cast broadcast services. Operating in SFN mode allows users at the cell-edge to combine the signals from multiple cells coherently and using an equalizer, eliminate any time-dispersion impacts. Release 6 of 3GPP allowed only for soft combining and not for a single frequency operation. Improving cell-edge performance of MBMS implies that higher-data broadcast services can be supported.

According to 3G Americas, 56 operators in 34 countries have already begun deploying HSPA+ as of May 2010 [2].

1.2.4.2 Mobile WiMAX

In 1998, the Institute of Electrical and Electronics Engineers (IEEE) formed a group called 802.16 to develop a standard for what was called a *wireless metropolitan area network* (WMAN). The group first produced a standard for fixed wireless applications in 2001 and later enhanced it to support mobility. The revised standard, called IEEE 802.16e, was completed in 2005 and is often referred to as Mobile WiMAX. The industry consortium called Worldwide Interoperability for Microwave Access (WiMAX) Forum was formed in 2001 to promote, develop, perform interoperability and conformance testing, and certify end-to-end wireless systems based on the IEEE 802.16 air-interface standards. In 2007, WiMAX was approved by ITU as an IMT-2000 terrestrial radio interface option called IP-OFDMA. The WiMAX network is designed using IP protocols, and does not offer circuit-switched voice telephony; voice services, however, can be provided using the VoIP (voice over IP). According to the WiMAX Forum, as of February 2010, there are 504 WiMAX networks deployed in 147 countries. WiMAX is generally seen as the only credible alternative to LTE for operators looking to deploy mobile broadband, though most analysts expect WiMAX to take a much smaller share of the worldwide mobile broadband market compared to LTE. It should also be noted that a number of aspects in the LTE design—especially the use of OFDM and OFDMA technology—was directly inspired by their implementation in WiMAX.

Some of the salient features of WiMAX that deserve highlighting are [10]:

- **Very High Peak Data Rates**: WiMAX peak physical layer data rate can be as high as 74Mbps when operating using a 20MHz wide spectrum. Using 5MHz spectrum, the peak physical layer (PHY) data rate is 18Mbps. These peak PHY data rates are achieved when using 64QAM modulation with rate 3/4 error correction coding.

- **OFDM/OFDMA Based Physical Layer**: The WiMAX PHY is based on Orthogonal Frequency Division Multiplexing (OFDM), a scheme that offers good resistance to multipath, and allows WiMAX to operate in non-line-of-sight (NLOS) conditions even with large bandwidths. OFDM is now widely recognized as the method of choice for mitigating multipath for broadband wireless, and in fact has been chosen by LTE as well. WiMAX also uses OFDMA as the multiple access technique, which allows users to be multiplexed in both time and frequency in a dynamic manner. OFDM and OFDMA are subjects of Chapter 3 and 4, respectively.

- **Scalable Bandwidth and Data Rate Support**: WiMAX has a very scalable physical layer architecture that allows for the data rate to scale easily with available channel bandwidth. This scalability is supported by OFDMA, where the FFT size may be scaled based on the available channel bandwidth. For example, a WiMAX system may use 128-, 512-, or 1048-bit FFTs based on whether the channel bandwidth is 1.25MHz, 5MHz, or 10MHz, respectively. This scaling may be done dynamically, and supports user roaming across different networks that may have varying bandwidth allocations.

- **Support for TDD and FDD**: IEEE 802.16e-2005 supports both Time 1 Division Duplexing (TDD) and Frequency Division Duplexing (FDD), but WiMAX implementations thus far have been TDD. TDD has been attractive to WiMAX operators since it offers flexibility in choosing uplink-to-downlink data rate ratios, the ability to exploit channel reciprocity, and perhaps more importantly because it allows implementation in non-paired spectrum.

- **Flexible and Dynamic Per User Resource Allocation**: Both uplink and downlink resource allocation is controlled by a scheduler in the base station. Capacity is shared among multiple users on a demand basis employing a burst TDM multiplexing scheme. Multiplexing is additionally done in the frequency dimension, by allocating different subsets of OFDM subcarriers to different users. Resources may be allocated in the spatial domain as well when using optional advanced antenna systems (AAS). The standard allows for bandwidth resources to be allocated in time, frequency, and space, and has a flexible mechanism to convey the resource allocation information on a frame-by-frame basis.

- **Robust Link Layer**: WiMAX supports a number of modulation and forward error correction (FEC) schemes, and supports adaptive modulation and coding (AMC) to maximize the data rate on each link. For connections that require enhanced reliability, WiMAX supports automatic retransmissions (ARQ) at the link layer and optionally supports Hybrid-ARQ as well.

- **Support for Advanced Antenna Techniques**: The WiMAX solution has a number of features built into the physical layer design that allows for the use of multiple antenna techniques such as beamforming, space-time coding, and spatial multiplexing. These schemes can be used to improve the overall system capacity and spectral efficiency by deploying multiple antennas at the transmitter and/or the receiver.

- **IP-Based Architecture**: The WiMAX Forum has defined a reference network architecture that is based on an all-IP platform. All end-to-end services are delivered over an IP architecture relying on IP protocols for end-to-end transport, QoS, session management, security, and mobility. Reliance on IP allows WiMAX to ride the declining cost curves of IP processing, facilitate easy convergence with other networks, and exploit the rich application development ecosystem that exists for IP.

1.2.4.3 Comparison of HSPA+ and WiMAX to LTE

While we provide a more detailed introduction to LTE in Section 1.3, here we offer a quick comparison of LTE with HSPA+ and WiMAX. Since LTE is the latest of the three standards, it was obviously designed to perform better than HSPA+ and WiMAX. The three, however, have a lot in common as several of the ideas in LTE are derived directly from the design experience of HSPA and WiMAX. Table 1.5 provides a summary comparing the key characteristics of HSPA+, WiMAX, and LTE.

A few key observations to make are

- While HSPA+ and LTE are both developed by 3GPP as an evolution to the currently deployed GSM/UMTS networks, WiMAX was developed independently by the IEEE and WiMAX Forum as an alternative wireless broadband technology without any backward compatibility constraints.
- Though all three systems are designed to offer great flexibility in frequency selection, early deployments of WiMAX are likely to be in the 2.3GHz, 2.6GHz, and 3.5GHz frequency bands, while most HSPA+ and LTE deployments are likely to be in bands below 2.1GHz. All else being equal, lower frequencies will provide better coverage and building penetration. LTE supports both FDD and TDD and hence affords flexibility in operating in both paired and unpaired spectrum. WiMAX is mostly deployed in TDD mode and HSPA+ only supports FDD.
- Both LTE and WiMAX use OFDM/OFDMA as the underlying modulation and multi-access technology while HSPA+ uses CDMA/TDMA. LTE uses a variation of OFDMA called Single Carrier Frequency Division Multiple Access (SC-FDMA) on the uplink that offers better power efficiency. WiMAX uses OFDMA in both uplink and downlink.
- While HSPA uses a fixed 5MHz bandwidth, both WiMAX and LTE offer a flexible bandwidth architecture supporting up to a maximum of 20MHz. This makes it possible, given sufficient spectrum, to provide much higher peak rates in LTE and WiMAX when compared to HSPA+.
- All three standards support a variety of signal processing techniques to improve performance and spectral efficiency. Hybrid-ARQ retransmission schemes, dynamic channel dependent scheduling, and multiantenna schemes such as transmit diversity, beamforming, and spatial multiplexing are supported by HSPA+, LTE, and WiMAX.

Table 1.5 Summary Comparison of HSPA+, WiMAX, and LTE

	HSPA+	**Mobile WiMAX**	**LTE**
Standard	3GPP Release 7&8	IEEE 802.16e-2005	3GPP Release 8
Frequency Bands (Early Deployments)	850/900MHz, 1.8/1.9GHz,	2.3GHz, 2.6GHz, and 3.5GHz	700MHz, 1.7/2.1GHz, 2.6GHz, 1.5GHz
Channel Bandwidth	5MHz	5, 7, 8.75, and 10MHz	1.4, 3, 5, 10, 15, and 20MHz
Peak Downlink Data Rate	28–42Mbps	46Mbps (10MHz, 2×2 MIMO, 3:1 DL to UL ratio TDD); 32Mbps with 1:1	150Mbps (2×2 MIMO, 20MHz)
Peak Uplink Data Rate	11.5Mbps	7Mbps (10MHz, 3:1 DL to UL ratio TDD); 4Mbps with 1:1	75Mbps (10MHz)
User-Plane Latency	10–40ms	15–40ms	5–15ms
Frame Size	2ms frames	5ms frames	1ms sub-frames
Downlink Multiple Access	CDMA/TDMA	OFDMA	OFDMA
Uplink Multiple Access	CDMA/TDMA	OFDMA	SC-FDMA
Duplexing	FDD	TDD; FDD option planned	FDD and TDD
Data Modulation	DS-SS: QPSK, 16QAM, and 64QAM	OFDM: QPSK, 16QAM, and 64QAM	OFDM: QPSK, 16QAM, and 64QAM
Channel Coding	Turbo codes; rate 3/4, 1/2, 1/4	Convolutional, turbo RS codes, rate 1/2, 2/3, 3/4, 5/6	Convolutional and Turbo coding: rate 78/1024 to 948/1024
Hybrid-ARQ	Yes; incremental redundancy and chase combining	Yes, chase combining	Yes, various
MIMO	Tx diversity, spatial multiplexing, beamforming	Beamforming, open-loop Tx diversity, spatial multiplexing	Transmit Diversity, Spatial Multiplexing, 4×4 MIMO Uplink: Multi-user collaborative MIMO
Persistent Scheduling	No	No	Yes

- LTE supports higher peak data rates than HSPA+ and WiMAX. In the best case, assuming 20MHz spectrum and using 4 $\times$ 4 MIMO, LTE can support up to 326Mbps on the downlink and 86Mbps on the uplink. Spectral efficiency differences between these systems, although significant, are, however, less dramatic.

- LTE supports 10ms frames and 1ms sub-frames, which is much shorter than the frame sizes supported by HSPA+ and WiMAX. Shorter frame sizes allow for faster feedback for retransmission and provide better efficiency at high-speed.

- Among the three, LTE offers the best support for VoIP. It has the lowest (5–15ms) user plane latency and lowest (50ms) call setup time. LTE also supports persistent scheduling, which significantly reduces the control channel overhead for low bit rate voice transmission and thus improves VoIP capacity. Both HSPA+ and LTE use dedicated control channels, which are more efficient for VoIP than using mapping symbols to assign resources, as is done in WiMAX.

1.2.5 Summary of Evolution of 3GPP Standards

We have thus far covered a number of cellular wireless standards and systems, tracing the evolution from first generation analog voice systems to the development of LTE. Let us now summarize the major enhancements and performance improvements that have been achieved at each step of this evolution. Since LTE was developed by the 3GPP standards body, we will focus here only on 3GPP standards evolution.

The first version of a 3G standard by 3GPP was targeted for completion in 1999, and is often referred to as 3GPP Release 99, although the actual release occurred in 2000. Several UMTS networks around the world are based on this standard. Subsequent releases are identified by a release number as opposed to year of release. Each release provided enhancements in one or more of several aspects including (1) radio performance improvements such as higher data rates, lower latency, and increased voice capacity, (2) core network changes aimed at reducing its complexity and improving transport efficiency, and (3) support for new applications such as push-to-talk, multimedia broadcast, and multicast services and IP Multimedia Services. Table 1.6 summarizes the various 3GPP releases and the enhancements that each brought.

Table 1.7 summarizes the evolution of peak data rates and latency of wireless systems that evolved from GSM via 3GPP standards. Clearly, tremendous strides have been made over the past decade in both data rate and latency. Peak data rates in early GPRS systems were as low as 40kbps, while, in theory, LTE can provide up to 326Mbps; that is almost a ten thousand–fold increase. Typical end-user speeds grew from 10–20kbps with GPRS to 0.5–2Mbps with HSPA/HSPA+, and expect to get to 2–3Mbps or more with LTE. Advances in technology have pushed us very close to realizing the Shannon limit for channel capacity, which makes achieving further gains in spectral efficiency quite challenging. Changes in protocols, frame sizes, and network architecture over the years have also resulted in dramatic reduction in latency. While GPRS and EDGE systems had user plane latencies around 350–700ms, HSPA systems got it down to less than 100ms, and LTE systems will get it below 30ms. Lower latency improves the quality of experience of real-time applications such as VoIP, gaming, and other interactive applications.

Table 1.6 3GPP Standards Evolution

3GPP Standards Release	Year Completed	Major Enhancements
Release 99	2000	Specified the original UMTS 3G network using W-CDMA air-interface. Also included Enhancements to GSM data (EDGE).
Release 4	2001	Added multimedia messaging support and took steps toward using IP transport in core network.
Release 5	2002	Specified HSDPA with up to 1.8Mbps peak downlink data rate. Introduced IP Multimedia Services (IMS) architecture.
Release 6	2004	Specified HSUPA with up to 2Mbps uplink speed. Multimedia Broadcast/Multicast Services (MBMS). Added advanced receiver specifications, push-to-talk over cellular (PoC) and other IMS enhancements, WLAN interworking option, limited VoIP capability.
Release 7	2007	Specified HSPA+ with higher order modulation (64QAM downlink and 16QAM uplink) and downlink MIMO support offering up to 28Mbps downlink and 11.5Mbps uplink peak data rates. Reduced latency and improved QoS for VoIP.
Release 8	2009	Further evolution of HSPA+: combined use of 64QAM and MIMO; dual-carrier with 64QAM. Specifies new OFDMA-based LTE radio interface and a new all IP flat architecture with Evolved Packet Core (EPC).
Release 9	2010	Expected to include HSPA and LTE enhancements.
Release 10	2012?	Expected to specify LTE-Advanced that meets the ITU IMT-Advanced Project requirements for 4G.

1.3 The Case for LTE/SAE

As fixed-line broadband adoption began growing rapidly around the world, the mobile community recognized the need to develop a mobile broadband system that is commensurate with DSL and capable of supporting the rapid growth in IP traffic. Around 2005, two groups within 3GPP started work on developing a standard to support the expected heavy growth in IP data traffic. The Radio Access Network (RAN) group initiated work

Table 1.7 Performance Evolution of 3GPP Standards

Standard	3GPP Release	Peak Downlink Speed	Peak Uplink Speed	Latency
GPRS	Release 97/99	40–80kbps	40–80kbps	600–700ms
EDGE	Release 4	237–474kbps	237kbps	350–450ms
UMTS (WCDMA)	Release 4	384kbps	384kbps	<200ms
HSDPA/UMTS	Release 5	1800kbps	384kbps	<120ms
HSPA	Release 6	3600–7200kbps	2000kbps	<100ms
HSPA+	Release 7 and 8	28–42Mbps	11.5Mbps	<80ms
LTE	Release 8	173–326Mbps	86Mbps	<30ms

on the Long Term Evolution (LTE) project and the Systems Aspects group initiated work on the Systems Architecture Evolution (SAE) project. These two groups completed their initial study by mid-2006 and transitioned it into standards development. The LTE group developed a new radio access network called Enhanced UTRAN (E-UTRAN) as an evolution to the UMTS RAN. The SAE group developed a new all IP packet core network architecture called the Evolved Packet Core (EPC). Together, EUTRAN and EPC are formally called the Evolved Packet System (EPS).

In this section we discuss the market demand drivers for the development and deployment of LTE and enumerate the key requirements that LTE design had to meet.

1.3.1 Demand Drivers for LTE

The dramatic growth of the Internet over the past decade is clearly the underlying driver for mobile broadband. The Internet today is the platform for delivering a vast variety of applications and has become the media of choice for all our information, communication, and entertainment needs. The availability of broadband access services has made it possible for users to experience the Internet in its full multimedia richness, and users now expect to have the same on-demand access to multimedia content from anywhere and while on the move. This is evidenced by the dramatic growth in wireless data subscription over the past few years. Informa Telecoms & Media, a consultancy, reports that at the end of March 2009, worldwide mobile broadband subscribers reached 225 million, representing a 93% year-on-year growth. The same consultancy predicts that there will be over 2 billion subscribers on 3G and beyond systems by 2013, 80% of whom would be on 3GPP networks [11].

We identify three broad trends that together drive demand for mobile broadband and make a compelling case for the development and deployment of LTE. These are

- **Growth in high-bandwidth applications**: Mobile applications are rapidly moving from SMS, Web and WAP access, multimedia messaging (MMS), and low MB content (e.g., ringtones) downloading to high bandwidth applications such as music downloads, video sharing, mobile video, and IPTV. The proliferation of Web sites with embedded video content and the popularity of video sharing sites such as YouTube are driving more and more users to access, view, and share video using their mobile devices. Video now accounts for a large fraction of all mobile data traffic and it is growing rapidly. Analysts predict that by 2014, more than 65% of mobile data traffic will be video [12].

- **Proliferation of smart mobile devices**: The past few years has witnessed a tremendous growth in the variety and availability of smartphones, that is, mobile phone devices with full keyboard and integrated data capabilities. Remarkable improvements in the user interface, the availability of full browsing, e-mail, and music and video playing capabilities in mobile devices are turning cell phone subscribers into prodigious consumers of wireless data services. The packaging of cameras, camcorders, GPS navigation systems, and other technologies into mobile phones has enabled a variety of exciting mobile applications and use cases, further driving the demand for these devices. According to analysts at Informa Telecoms and Media, in 2008, there were almost 162 million smartphones sold, surpassing laptop sales for the first time. They expect that by 2013 almost 25% of all phones sold will be smartphones. In fact, by mid-2009, in the United States, smartphones account for more than 30% of all mobile phone sales. Besides smartphones, a variety of other mobile devices are also emerging. These include laptops with integrated 3G interface, consumer devices with large screens, netbook computers, tablet computers, gaming devices, electronic readers, portable media players, cameras, camcorders and projectors with built-in wireless interfaces, health monitoring, asset tracking, and other machine-to-machine communication devices. Global adoption of LTE as a single standard will almost certainly lead to further proliferation of devices.

- **Intense competition leading to flat revenues**: In most of the world, the wireless market is an intensely competitive one. It can be argued that competition among service providers and device manufacturers was a key driver for the innovation and rapid growth we have seen thus far. As wireless penetration has deepened—in many countries it is higher than 100% as on average each person has more than one cell phone—mobile operators have had to poach customers from one another for growth leading to lower pricing and hence lower margins. The adoption of flat-rate pricing is leading to a widening gap between revenue and consumption. Usage and consumption is growing at a significantly higher pace, straining network resources and forcing operators to invest in upgrades. HSPA operators are reporting huge increases in mobile data consumption, and most analysts expect aggregate mobile data consumption to grow 50–100 times or more in the next five years. For example, according to Cisco Visual Networking Index, global mobile data traffic will grow from 90 petabytes (10^{15}) per month in 2009 to 3.6 exabytes (10^{18}) per month in 2014 [12]. While data revenues will also grow, the expectation is that they will grow only around two times over the same period. Clearly, operators have a strong need to reduce the cost per megabyte and find a network infrastructure and operating model that helps them achieve that. Lowering the cost per megabyte will be another key driver for LTE deployment.

1.3.2 Key Requirements of LTE Design

LTE was designed with the following objectives in mind to effectively meet the growing demand [13].

- **Performance on Par with Wired Broadband**: One of the goals of LTE was to make mobile Internet experience as good as or better than that achieved by residential wired broadband access systems deployed today. The two key network performance parameters that drive user experience are high throughput and low latency.

  To push toward high throughputs, 3GPP set the peak data rate targets to be at 100Mbps and 50Mbps for the downlink and uplink, respectively. This is an order of magnitude better than what is achieved by 3G systems today. In addition to peak data rates, which may be experienced only by a fraction of users who happen to be in close radio proximity to the base stations, an average user data rate target was also set. The LTE design goal was to achieve an average downlink throughput that is 3–4 times better than that of the original HSPA and an average uplink throughput that is 2–3 times better. It was also stipulated that these higher data rates be achieved by making a 2–4 times improvement in spectral efficiency. LTE requirements also call for increased cell edge bit rate while maintaining the same site locations as deployed today.

  To enable support for delay sensitive applications like voice and interactive gaming, it is required that the network latency is kept very low. The target round-trip latency for LTE radio network is set to be less than 10ms. This is better than the 20–40ms delay observed in many DSL systems. In addition, LTE aims to reduce latency associated with control plane functions such as session setup. Enhancing QoS capabilities to support a variety of applications is another LTE goal.

  While LTE aims for performance parity with wired broadband systems, it does so while simultaneously elevating the requirements on mobility. The system is required to support optimized high quality handoff and connections up to speeds of 15kmph with only minor degradations allowed for connections up to speeds of 120kmph. A lower quality support is envisioned for up to 350kmph.

- **Flexible Spectrum Usage**: The frequency band and amount of spectrum owned by different mobile operators around the world vary significantly. Since many LTE deployments are likely to be in refarmed spectrum that is currently used for 3G or 2G services, the amount of spectrum that could be made available for LTE will also depend on how aggressively individual operators wish to migrate to LTE. In order to be a truly global standard and to make it attractive for deployment by a wide variety of operators, 3GPP mandated a high degree of spectrum flexibility.

  Operators can deploy LTE in 900MHz, 1800MHz, 700MHz, and 2.6GHz bands. LTE supports a variety of channel bandwidths: 1.4, 3, 5, 10, 15, and 20MHz. It is also mandated that end user devices are able to operate at all the channel bandwidths lower than their maximum capability; for example, a 10MHz mobile device will support all bandwidths up to 10MHz. The smaller 1.4MHz and 5MHz channels are optimized for GSM and CDMA refarming to support deployments where operators are unable to free larger amounts of spectrum. LTE also supports both frequency division duplexing (FDD) and time division duplexing (TDD) to accommodate paired as well as unpaired spectrum allocations. However, most deployments are likely to be FDD, and for the most part, the coverage in this book will be limited to FDD.

- **Co-existence and Interworking with 3G Systems as well as Non-3GPP Systems**: Given the large base of existing mobile subscribers, it is a critical requirement that LTE networks interwork seamlessly with existing 2G and 3G systems. Most existing cellular operators are likely to phase in LTE over a period of time with initial deployments being made in areas of high demand such as urban cores. Service continuity and mobility—handoff and roaming—between LTE and existing 2G/3G systems are critical to obtain a seamless user experience. As LTE aims to be a truly global standard attractive to a variety of operators, interworking requirements have been extended to non-3GPP systems such as the 3GPP2 CDMA and WiMAX networks. Further, to facilitate fixed-mobile convergence, interworking requirements apply to all IP networks including wired IP networks

- **Reducing Cost per Megabyte**: As discussed in the previous section, there is a growing gap between wireless data consumption and revenue. To bridge this gap, it is essential that substantial reductions be achieved in the total network cost to deliver data to end users. 3GPP recognizes this issue and has made reducing the cost per megabyte of data a key design criterion for LTE. A number of design criteria are tied directly to cost efficiency. These include:

  - High-capacity, high-spectral efficiency air-interface
  - Ability to deploy in existing spectrum and reuse cell sites and transmission equipment
  - Interworking with legacy systems to allow for cost-effective migration
  - Interworking with non-3GPP systems to drive toward one global standard to achieve higher economies of scale
  - A flat architecture with fewer network components and protocols
  - A single IP packet core for voice and data
  - IP architecture to leverage larger development community and gain economies of scale through convergence with wired communication systems
  - Support for lower-cost Ethernet-based backhaul networks
  - Base stations with lower power and space requirements; could in many cases be put inside existing base station cabinets or mounted beside them
  - Support for self-configuring and self-optimizing network and technologies to reduce installation and management cost

1.4 Key Enabling Technologies and Features of LTE

To meet its service and performance requirements, LTE design incorporates several important enabling radio and core network technologies [14–16]. Here, we provide a brief introduction to some of the key enabling technologies used in the LTE design. Subsequent chapters in this book elaborate on each of these in much greater detail.

1.4.1 Orthogonal Frequency Division Multiplexing (OFDM)

One of the key differences between existing 3G systems and LTE is the use of Orthogonal Frequency Division Multiplexing (OFDM) as the underlying modulation technology. Widely deployed 3G systems such as UMTS and CDMA2000 are based on Code Division Multiple Access (CDMA) technology. CDMA works by spreading a narrow band signal over a wider bandwidth to achieve interference resistance, and performs remarkably well for low data rate communications such as voice, where a large number of users can be multiplexed to achieve high system capacity. However, for high-speed applications, CDMA becomes untenable due to the large bandwidth needed to achieve useful amounts of spreading.

OFDM has emerged as a technology of choice for achieving high data rates. It is the core technology used by a variety of systems including Wi-Fi and WiMAX. The following advantages of OFDM led to its selection for LTE:

- **Elegant solution to multipath interference**: The critical challenge to high bit-rate transmissions in a wireless channel is intersymbol interference caused by multipath. In a multipath environment, when the time delay between the various signal paths is a significant fraction of the transmitted signal's symbol period, a transmitted symbol may arrive at the receiver during the next symbol and cause intersymbol interference (ISI). At high data rates, the symbol time is shorter; hence, it only takes a small delay to cause ISI, making it a bigger challenge for broadband wireless. OFDM is a multicarrier modulation technique that overcomes this challenge in an elegant manner. The basic idea behind multicarrier modulation is to divide a given high-bit-rate data stream into several parallel lower bit-rate streams and modulate each stream on separate carriers—often called subcarriers, or tones. Splitting the data stream into many parallel streams increases the symbol duration of each stream such that the multipath delay spread is only a small fraction of the symbol duration. OFDM is a spectrally efficient version of multicarrier modulation, where the subcarriers are selected such that they are all orthogonal to one another over the symbol duration, thereby avoiding the need to have non-overlapping subcarrier channels to eliminate inter-carrier interference. In OFDM, any residual intersymbol interference can also be eliminated by using guard intervals between OFDM symbols that are larger than the expected multipath delay. By making the guard interval larger than the expected multipath delay spread, ISI can be completely eliminated. Adding a guard interval, however, implies power wastage and a decrease in bandwidth efficiency.

- **Reduced computational complexity**: OFDM can be easily implemented using Fast Fourier Transforms (FFT/IFFT), and the computational requirements grow only slightly faster than linearly with data rate or bandwidth. The computational complexity of OFDM can be shown to be $O(B \log B T_m)$ where B is the bandwidth and T_m is the delay spread. This complexity is much lower than that of a time-domain equalizer-based system—the traditional means for combating multipath interference—which has a complexity of $O(B^2 T_m)$. Reduced complexity is particularly attractive in the downlink as it simplifies receiver processing and thus reduces mobile device cost and power consumption. This is especially important given the wide transmission bandwidths of LTE coupled with multistream transmissions.

- **Graceful degradation of performance under excess delay**: The performance of an OFDM system degrades gracefully as the delay spread exceeds the value designed for. Greater coding and low constellation sizes can be used to provide fallback rates that are significantly more robust against delay spread. In other words, OFDM is well suited for adaptive modulation and coding, which allows the system to make the best of the available channel conditions. This contrasts with the abrupt degradation owing to error propagation that single-carrier systems experience as the delay spread exceeds the value for which the equalizer is designed.

- **Exploitation of frequency diversity**: OFDM facilitates coding and interleaving across subcarriers in the frequency domain, which can provide robustness against burst errors caused by portions of the transmitted spectrum undergoing deep fades. OFDM also allows for the channel bandwidth to be scalable without impacting the hardware design of the base station and the mobile station. This allows LTE to be deployed in a variety of spectrum allocations and different channel bandwidths.

- **Enables efficient multi-access scheme**: OFDM can be used as a multi-access scheme by partitioning different subcarriers among multiple users. This scheme is referred to as OFDMA and is exploited in LTE. OFDMA offers the ability to provide fine granularity in channel allocation, which can be exploited to achieve significant capacity improvements, particularly in slow time-varying channels.

- **Robust against narrowband interference**: OFDM is relatively robust against narrowband interference, since such interference affects only a fraction of the subcarriers.

- **Suitable for coherent demodulation**: It is relatively easy to do pilot-based channel estimation in OFDM systems, which renders them suitable for coherent demodulation schemes that are more power efficient.

- **Facilitates use of MIMO**: MIMO stands for multiple input multiple output and refers to a collection of signal processing techniques that use multiple antennas at both the transmitter and receiver to improve system performance. For MIMO techniques to be effective, it is required that the channel conditions are such that the multipath delays do not cause intersymbol interference—in other words, the channel has to be a flat fading channel and not a frequency selective one. At very high data rates, this is not the case and therefore MIMO techniques do not work well in traditional broadband channels. OFDM, however, converts a frequency selective broad band channel into several narrowband flat fading channels where the MIMO models and techniques work well. The ability to effectively use MIMO techniques to improve system capacity gives OFDM a significant advantage over other techniques and is one of the key reasons for its choice. MIMO and OFDM have already been combined effectively in Wi-Fi and WiMAX systems.

- **Efficient support of broadcast services**: By synchronizing base stations to timing errors well within the OFDM guard interval, it is possible to operate an OFDM network as a single frequency network (SFN). This allows broadcast signals from different cells to combine over the air to significantly enhance the received signal power, thereby enabling higher data rate broadcast transmissions for a given transmit power. LTE design leverages this OFDM capability to improve efficient broadcast services.

While all these advantages drove 3GPP to adopt OFDM as their modulation choice, it should be noted that OFDM also suffers from a few disadvantages. Chief among these is the problem associated with OFDM signals having high peak-to-average ratio (PAR), which causes non-linearities and clipping distortion when passed through an RF amplifier. Mitigating this problem requires the use of expensive and inefficient power amplifiers with high requirements on linearity, which increases the cost of the transmitter and is wasteful of power.

While the increased amplifier costs and power inefficiency of OFDM is tolerated in the downlink as part of the design, for the uplink LTE selected a variation of OFDM that has a lower peak-to-average ratio. The modulation of choice for the uplink is called Single Carrier Frequency Division Multiple Access (SC-FDMA).

1.4.2 SC-FDE and SC-FDMA

To keep the cost down and the battery life up, LTE incorporated a power efficient transmission scheme for the uplink. Single Carrier Frequency Domain Equalization (SC-FDE) is conceptually similar to OFDM but instead of transmitting the Inverse Fast Fourier Transform (IFFT) of the actual data symbols, the data symbols are sent as a sequence of QAM symbols with a cyclic prefix added; the IFFT is added at the end of the receiver. SC-FDE retains all the advantages of OFDM such as multipath resistance and low complexity, while having a low peak-to-average ratio of 4-5dB. The uplink of LTE implements a multi-user version of SC-FDE, called SC-FDMA, which allows multiple users to use parts of the frequency spectrum. SC-FDMA closely resembles OFDMA and can in fact be thought of as "DFT precoded OFDMA." SC-FDMA also preserves the PAR properties of SC-FDE but increases the complexity of the transmitter and the receiver.

1.4.3 Channel Dependent Multi-user Resource Scheduling

The OFDMA scheme used in LTE provides enormous flexibility in how channel resources are allocated. OFDMA allows for allocation in both time and frequency and it is possible to design algorithms to allocate resources in a flexible and dynamic manner to meet arbitrary throughput, delay, and other requirements. The standard supports dynamic, channel-dependent scheduling to enhance overall system capacity.

Given that each user will be experiencing uncorrelated fading channels, it is possible to allocate subcarriers among users in such a way that the overall capacity is increased. This technique, called frequency selective multiuser scheduling, calls for focusing transmission power in each user's best channel portion, thereby increasing the overall capacity. Frequency selective scheduling requires good channel tracking and is generally only viable in slow varying channels. For fast varying channels, the overhead involved in doing this negates the potential capacity gains. In OFDMA, frequency selective scheduling can be combined with multi-user time domain scheduling, which calls for scheduling users during the crests of their individual fading channels. Capacity gains are also obtained by adapting the modulation and coding to the instantaneous signal-to-noise ratio conditions for each user subcarrier.

For high-mobility users, OFDMA can be used to achieve frequency diversity. By coding and interleaving across subcarriers in the frequency domain using a uniform random distribution of subcarriers over the whole spectrum, the signal can be made more robust against frequency selective fading or burst errors. Frequency diverse scheduling is best suited for control signaling and delay sensitive services.

1.4.4 Multiantenna Techniques

The LTE standard provides extensive support for implementing advanced multiantenna solutions to improve link robustness, system capacity, and spectral efficiency. Depending on the deployment scenario, one or more of the techniques can be used. Multiantenna techniques supported in LTE include:

- **Transmit diversity**: This is a technique to combat multipath fading in the wireless channel. The idea here is to send copies of the same signal, coded differently, over multiple transmit antennas. LTE transmit diversity is based on space-frequency block coding (SFBC) techniques complemented with frequency shift time diversity (FSTD) when four transmit antenna are used. Transmit diversity is primarily intended for common downlink channels that cannot make use of channel-dependent scheduling. It can also be applied to user transmissions such as low data rate VoIP, where the additional overhead of channel-dependent scheduling may not be justified. Transmit diversity increases system capacity and cell range.

- **Beamforming**: Multiple antennas in LTE may also be used to transmit the same signal appropriately weighted for each antenna element such that the effect is to focus the transmitted beam in the direction of the receiver and away from interference, thereby improving the received signal-to-interference ratio. Beamforming can provide significant improvements in coverage range, capacity, reliability, and battery life. It can also be useful in providing angular information for user tracking. LTE supports beamforming in the downlink.

- **Spatial multiplexing**: The idea behind spatial multiplexing is that multiple independent streams can be transmitted in parallel over multiple antennas and can be separated at the receiver using multiple receive chains through appropriate signal processing. This can be done as long as the multipath channels as seen by the different antennas are sufficiently decorrelated as would be the case in a scattering rich environment. In theory, spatial multiplexing provides data rate and capacity gains proportional to the number of antennas used. It works well under good SNR and light load conditions, and hence tends to have a more pronounced effect on peak rates rather than overall system capacity. LTE standard supports spatial multiplexing with up to four transmit antennas and four receiver antennas.

- **Multi-user MIMO**: Since spatial multiplexing requires multiple transmit chains, it is currently not supported in the uplink due to complexity and cost considerations. However, multi-user MIMO (MU-MIMO), which allows multiple users in the uplink, each with a single antenna, to transmit using the same frequency and time resource, is supported. The signals from the different MU-MIMO users are separated at the base station receiver using accurate channel state information of each user obtained through uplink reference signals that are orthogonal between users.

1.4.5 IP-Based Flat Network Architecture

Besides the air-interface, the other radical aspect of LTE is the flat radio and core network architecture [15]. "Flat" here implies fewer nodes and a less hierarchical structure for the network. The lower cost and lower latency requirements drove the design toward a flat architecture since fewer nodes obviously implies a lower infrastructure cost. It also means fewer interfaces and protocol-related processing, and reduced interoperability testing, which lowers the development and deployment cost. Fewer nodes also allow better optimization of radio interface, merging of some control plane protocols, and short session start-up time.

Figure 1.3 shows how the 3GPP network architecture evolved over a few releases. 3GPP Release 6 architecture, which is conceptually very similar to its predecessors, has four network elements in the data path: the base station or Node-B, radio network controller (RNC), serving GPRS service node (SGSN), and gateway GRPS service node (GGSN). Release 7 introduced a direct tunnel option from the RNC to GGSN, which eliminated SGSN from the data path. LTE on the other hand, will have only two network elements in the data path: the enhanced Node-B or eNode-B, and a System Architecture Evolution Gateway (SAE-GW). Unlike all previous cellular systems, LTE merges the base station and radio network controller functionality into a single unit. The control path includes a functional entity called the Mobility Management Entity (MME), which provides control plane functions related to subscriber, mobility, and session management. The MME and SAE-GW could be collocated in a single entity called the access gateway (a-GW). More details about the network architecture are provided in the next section.

A key aspect of the LTE flat architecture is that all services, including voice, are supported on the IP packet network using IP protocols. Unlike previous systems, which had a separate circuit-switched subnetwork for supporting voice with their own Mobile Switching Centers (MSC) and transport networks, LTE envisions only a single evolved packet-switched core, the EPC, over which all services are supported, which could provide huge operational and infrastructure cost savings. It should be noted, however, that although LTE has been designed for IP services with a flat architecture, due to backwards compatibility reasons certain legacy, non-IP aspects of the 3GPP architecture such as

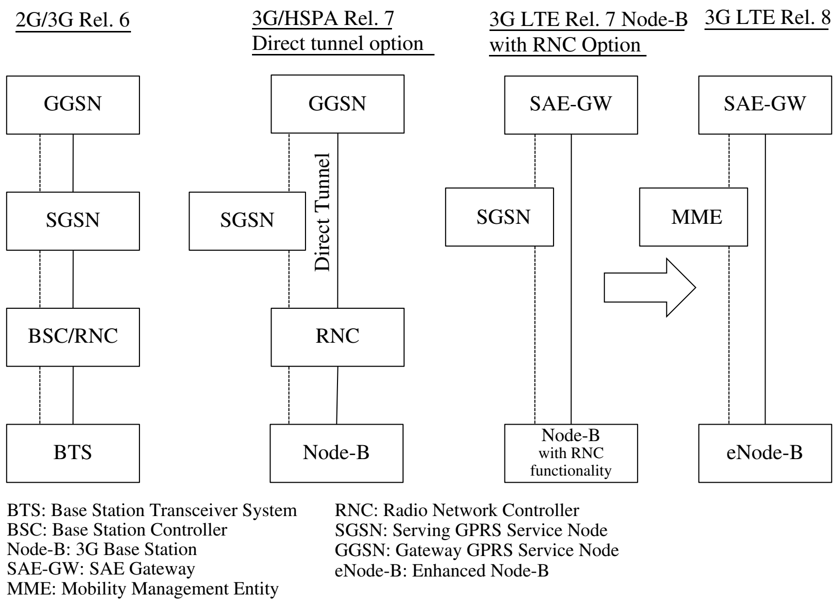

Figure 1.3 3GPP evolution toward a flat LTE SAE architecture.

the GPRS tunneling protocol and PDCP (packet data convergence protocol) still exists within the LTE network architecture.

1.5 LTE Network Architecture

While the focus of this book is on the radio network aspects of LTE, a basic understanding of the overall end-to-end architecture is useful to gain an appreciation of how services are delivered over an LTE network. To that end, we provide a brief overview of the LTE network architecture in this section.

As already mentioned, the core network design presented in 3GPP Release 8 to support LTE is called the Evolved Packet Core (EPC). EPC is designed to provide a high-capacity, all IP, reduced latency, flat architecture that dramatically reduces cost and supports advanced real-time and media-rich services with enhanced quality of experience. It is designed not only to support new radio access networks such as LTE, but also provide interworking with legacy 2G GERAN and 3G UTRAN networks connected via SGSN. Functions provided by the EPC include access control, packet routing and transfer, mobility management, security, radio resource management, and network management.

The EPC includes four new elements: (1) Serving Gateway (SGW), which terminates the interface toward the 3GPP radio access networks; (2) Packet Data Network Gateway (PGW), which controls IP data services, does routing, allocates IP addresses, enforces policy, and provides access for non-3GPP access networks; (3) Mobility Management Entity (MME), which supports user equipment context and identity as well as authenticates and authorizes users; and (4) Policy and Charging Rules Function (PCRF), which

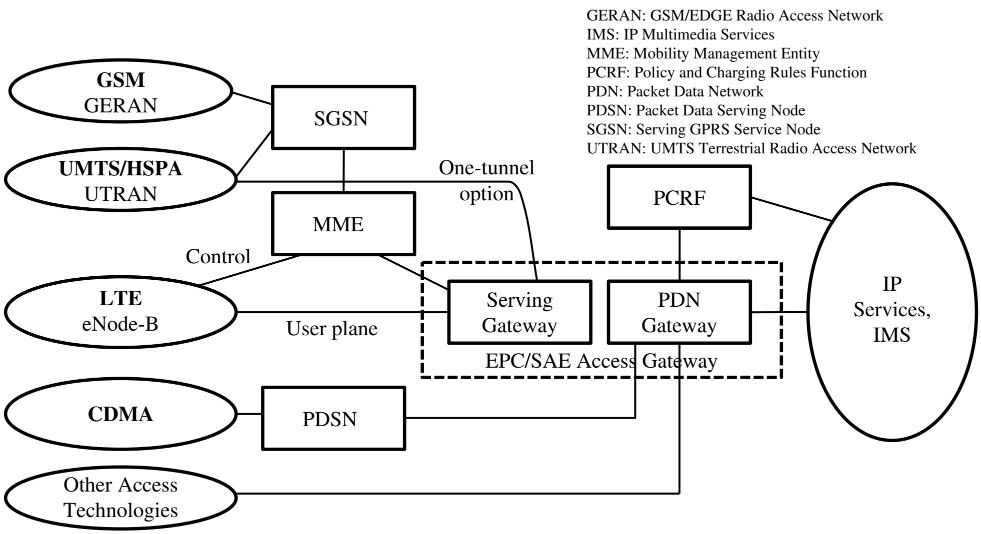

Figure 1.4 Evolved Packet Core architecture.

manages QoS aspects. Figure 1.4 shows the end-to-end architecture including how the EPC supports LTE as well as current and legacy radio access networks.

A brief description of each of the four new elements is provided here:

- **Serving Gateway (SGW)**: The SGW acts as a demarcation point between the RAN and core network, and manages user plane mobility. It serves as the mobility anchor when terminals move across areas served by different eNode-B elements in E-UTRAN, as well as across other 3GPP radio networks such as GERAN and UTRAN. SGW does downlink packet buffering and initiation of network-triggered service request procedures. Other functions include lawful interception, packet routing and forwarding, transport level packet marking in the uplink and the downlink, accounting support for per user, and inter-operator charging.

- **Packet Data Network Gateway (PGW)**: The PGW acts as the termination point of the EPC toward other Packet Data Networks (PDN) such as the Internet, private IP network, or the IMS network providing end-user services. It serves as an anchor point for sessions toward external PDN and provides functions such as user IP address allocation, policy enforcement, packet filtering, and charging support. Policy enforcement includes operator-defined rules for resource allocation to control data rate, QoS, and usage. Packet filtering functions include deep packet inspection for application detection.

- **Mobility Management Entity (MME)**: The MME performs the signaling and control functions to manage the user terminal access to network connections, assignment of network resources, and mobility management function such as idle mode location tracking, paging, roaming, and handovers. MME controls all control plane functions related to subscriber and session management. The MME provides security functions such as providing temporary identities for user terminals, interacting with Home Subscriber Server (HSS) for authentication, and negotiation of ciphering and integrity protection algorithms. It is also responsible for selecting the appropriate serving and PDN gateways, and selecting legacy gateways for handovers to other GERAN or UTRAN networks. Further, MME is the point at which lawful interception of signaling is made. It should be noted that an MME manages thousands of eNode-B elements, which is one of the key differences from 2G or 3G platforms using RNC and SGSN platforms.

- **Policy and Charging Rules Function (PCRF)**: The Policy and Charging Rules Function (PCRF) is a concatenation of Policy Decision Function (PDF) and Charging Rules Function (CRF). The PCRF interfaces with the PDN gateway and supports service data flow detection, policy enforcement, and flow-based charging. The PCRF was actually defined in Release 7 of 3GPP ahead of LTE. Although not much deployed with pre-LTE systems, it is mandatory for LTE. Release 8 further enhanced PCRF functionality to include support for non-3GPP access (e.g., Wi-Fi or fixed line access) to the network.

1.6 Spectrum Options and Migration Plans for LTE

3GPP specifications allow for the deployment of LTE in a wide variety of spectrum bands globally. It is deployable in any of the existing 2G and 3G spectrum bands as well as several new frequency bands. 3GPP and other standards bodies along with several industry consortiums continue to negotiate with authorities around the world for global harmonization of spectrum to enable larger economies of scale and faster development.

Tables 1.8 and 1.9 list a number of the more common paired and unpaired frequency bands in which LTE could be deployed in FDD or TDD mode, respectively [17, 18]. Bands 1 through 10 in FDD and bands 33 through 38 in TDD are spectrum that currently has 3GPP systems deployed. In most cases, deployment of LTE in these bands will require spectrum to be refarmed; that is, existing 2G or 3G systems will have to be vacated from those bands and replaced with LTE systems. Bands 11 through 17 in FDD mode and bands 39 and 40 in TDD mode are new spectrum that is mostly unencumbered by the presence of existing 2G/3G networks, and hence can more readily be used for LTE. Operators who have access to new spectrum will most likely begin deployment of LTE as an overlay solution to existing networks using the new spectrum. Table 1.10 summarizes the various bands by region that are likely to see LTE deployments.

Figure 1.5 shows the various spectrum options available in the United States. The 850MHz cellular band and the 1900MHz PCS band have various 3GPP and 3GPP2 systems deployed today. The advanced wireless services (AWS) spectrum and the recently auctioned 700MHz UHF spectrum are likely to be prime candidates for initial LTE deployment in the United States.

In Europe, many operators may look to refarm the 900MHz GSM band for LTE deployment. As many operators continue migration of their customers to 3G systems in the UMTS bands (1920–1980MHz/2110–2179MHz), the load on 900MHz is reducing. While some operators may deploy 3G UMTS/HSPA systems in 900MHz, others may wait for LTE to replace GSM there. HSPA requires carving out 5MHz at a time, while

Table 1.8 3GPP Designated FDD Frequency Bands for LTE

3GPP Band #	Band (Common) Name	Amount of Spectrum	Uplink (MHz)	Downlink (MHz)	Available Regions
1	2.1GHz (IMT)	2 × 60MHz	1920–1980	2110–2170	Europe, Asia, Japan, Oceania
2	1900MHz (PCS)	2 × 60MHz	1850–1910	1930–1990	North America
3	1800MHz (DCS)	2 × 75MHz	1710–1985	1805–1880	Europe, Asia
4	1.7/2.1GHz (AWS)	2 × 45MHz	1710–1755	2110–2155	United States, Canada (Future)
5	850MHz (CLR)	2 × 25MHz	824–849	869–894	North America, Oceania
6	800MHz (IMT-E)	2 × 10MHz	830–840	875–885	Japan
7	2.6GHz	2 × 70MHz	2500–2570	2620–2690	Europe (Future)
8	900MHz (GSM)	2 × 35MHz	880–915	925–960	Europe, Asia, Oceania
9	1700MHz	2 × 35MHz	1749.9–1784.9	1844.9–1879.9	Japan
10	Ext.1.7/ 2.1MHz	2 × 60MHz	1710–1770	2110–2170	North America excluding United States
11	1500MHz	2 × 25MHz	1427.9–1452.9	1475.9–1500.9	Japan
12	Lower 700MHz (UHF)	2 × 18MHz	698–716	728–746	United States
13	Lower 700MHz (UHF)	2 × 10MHz	777–787	746–756	United States
14	Upper 700MHz (UHF) public safety/private	2 × 10MHz	788–798	758–768	United States
17	Lower 700MHz (UHF)	2 × 12MHz	704–716	734–746	United States

Table 1.9 Designated TDD Frequencies for LTE

3GPP Band #	Band (Common) Name	Amount of Spectrum	Frequency	Available Regions
33	TDD 2000	20MHz	1900–1920MHz	Europe
34	TDD 2000	15MHz	2010–2025MHz	Europe and China
35	TDD 1900	60MHz	1850–1910MHz	United States/ Canada
36	TDD 1900	60MHz	1850–1910MHz	United States/ Canada
37	PCS Center Gap	20MHz	1910–1930MHz	United States/ Canada
38	IMT Extension Center Gap	50MHz	2570–2620MHz	Europe
39	China TDD	40MHz	1880–1920MHz	China
40	2.3GHz TDD	100MHz	2300–2400MHz	China

LTE allows operating with as low as 1.4MHz, which makes it attractive to spectrum-constrained operators. We are also likely to see LTE deployments in the UMTS bands as several operators have not yet fully used up all the bandwidth in those bands. Additional candidate frequencies for LTE deployment in Europe are the IMT Extension Band frequencies in the 2.6GHz range.

Next, we discuss in more detail the newer and more likely spectrum options for early LTE deployments.

- **AWS Band**: In 2006, the FCC auctioned 90MHz (2 × 45MHz) of unpaired spectrum for advanced wireless services (AWS). A total of 1,087 licenses were awarded to 104 bidders netting $13.9 billion dollars for the U.S. treasury at $0.53 permegahertz per population. This spectrum, called AWS-I, spans 1710–1755MHz for mobile

Table 1.10 Spectrum Options for LTE in Various Global Regions

	Candidate Spectrum For	
	Initial LTE Deployment	**Potential Future LTE Deployment**
North America	AWS: 2100MHz UHF: 700MHz	850MHz (refarm) 1.9GHz (refarm)
Asia Pacific	1.5GHz (Japan) 2.6GHz (Japan)	2.1GHz (Japan) 2.3–2.4GHz (China) 470–854MHz 1.8GHz (refarm)
Europe, Middle East, Africa	2.1GHz 2.6GHz	900MHz (refarm) 1.8GHz (refarm) 450MHz (refarm) 470–854MHz

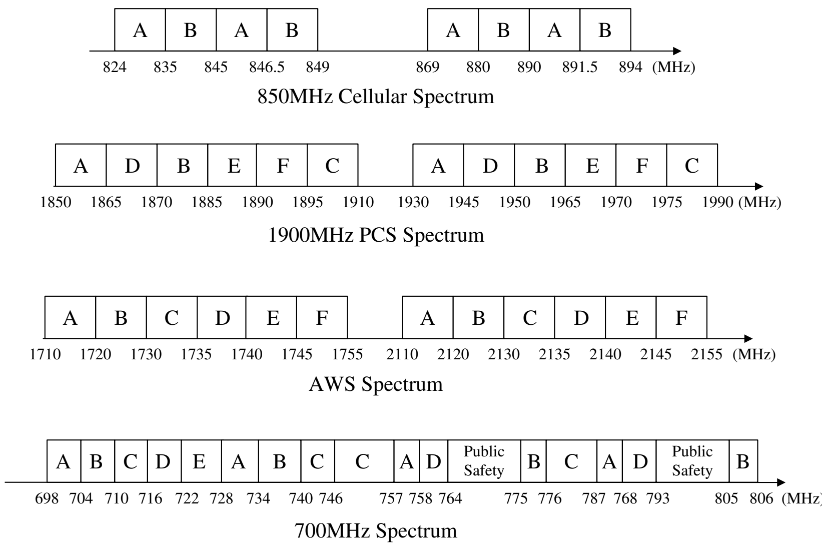

Figure 1.5 Available wireless spectrum in the United States for potential LTE deployment.

transmissions and 2100–2155MHz for base station transmissions. The upper band overlaps the IMT-2000 downlink, which spans 2110–2170MHz. The AWS spectrum was split into six pairs—three 2 × 10MHz pairs and three 2 × 5MHz pairs—for the auction. The band is used by Broadband Radio Services (BRS) and Fixed Microwave Services (FMS) operators who need to be vacated prior to deploying mobile services. Several operators in the United States have started 3G deployments in AWS, while others may wait for LTE before deploying in this spectrum. Canada auctioned AWS in 2008, and Latin American countries are expected to make it available shortly. Currently, FCC is formulating rules for auctioning additional 20MHz of paired frequencies designated AWS-II targeting 1915–1920MHz/1995–2000MHz and 2020–2025MHz/2175–2180MHz and 20MHz unpaired frequencies designated AWSIII at 2155–2175MHz. The FCC is proposing to allow TDD operation in AWS-III, but many in the industry have concerns about TDD operation right next to the AWS-I FDD spectrum.

- **700MHz UHF Band**: In 2008, the FCC auctioned 52MHz of spectrum in the 700MHz UHF band. Much of this spectrum was previously allocated to TV broadcast, and reclaimed by FCC as part of the transition to digital TV. The FCC divided the spectrum into a lower 700MHz band spanning 698–746MHz and an upper 700MHz band spanning 746–806MHz. The lower 700MHz band has several paired and unpaired spectrum blocks, each 6MHz wide and corresponding to 6MHz TV channels. The upper 700MHz band had a 2 × 5MHz paired block that was auctioned on a nationwide license basis. It also had another two 2 × 1MHz paired bands as well as a large 2 × 11MHz pair band called the "C Band." The C Band came with FCC regulations for "open access."

  A total of 101 bidders won 1,090 licenses netting about $19 billion, which was more than any other auction in the last 15 years had fetched. AT&T and Verizon, the two largest mobile operators in the United States, won the lion's share of licenses. The 700MHz spectrum was so coveted by operators due to the attractive propagation characteristics of this lower frequency band, which provides better coverage range and building penetration. This is particularly attractive for new deployments in rural and suburban areas, since it will take fewer LTE base stations to cover at 700MHz than at higher frequencies. The 700MHz auction was viewed as the last opportunity to obtain UHF spectrum, and participants paid on average $1.28 permegahertz per population for licenses, double the rate paid for AWS. Parts of the 700MHz spectrum have been licensed in large enough chunks to allow LTE operation using 10MHz and 20MHz bandwidths, allowing for the possibility of very high peak data rates.

While the United States has led the auction of 700MHz UHF spectrum, the transition to digital television is happening all over the world, and that transition will certainly yield spectrum dividends. It is very likely that parts of the 470–862MHz band spectrum traditionally occupied by analog TV will be auctioned off for new services including mobile broadband in the rest of the world as well.

- **IMT Extension Band**: In the 2000 World Radio Congress, the 2500–2690MHz band was identified as an additional IMT2000 band. European nations have begun allocating as much as 140MHz of IMT2000 expansion spectrum for FDD operation using 2500–2570MHz for uplink and 2630–2690MHz for downlink. Additional unpaired TDD allocation of up to 50MHz will also be made shortly in the 2570–2620MHz band. Like the 700MHz UHF band, this band offers the potential for LTE deployments using 20MHz channel bandwidths.

  Each operator's spectrum situation along with their competitive position and capacity for capital investment will dictate their timing and approach to deploying LTE and migrating customers to it. Operators will also have to manage the technology risk, maintain service and network quality during transition, control operational cost including transport costs, and develop a device eco-system that can support and fuel the migration of customers to LTE.

  Those operators who have obtained new spectrum for LTE will most likely deploy LTE as an overlay solution in the new spectrum beginning with dense urban areas and then building out slowly. As more and more customers migrate to LTE, these operators may begin freeing up their existing 3G spectrum and refarming them for LTE deployment. It is likely that many operators will continue to use 2G/3G circuit-switched voice network even after transitioning their data to LTE. Full voice transition to LTE may not happen until operators are convinced about the quality and capacity, have fully deployed IP Multimedia Subsystem (IMS) to support real-time services over packet bearers, and have a solid mechanism for voice handoffs across LTE and legacy domains.

1.7 Future of Mobile Broadband—Beyond LTE

Work is already under way to develop systems beyond LTE. Though many in the industry refer to LTE as a 4G system, strictly speaking it does not meet the requirements set out by the ITU for the fourth generation (4G) wireless standard. The ITU definition of a

4G system, called IMT-Advanced, requires a target peak data rate of 100Mbps for high mobility and 1Gbps for low mobility applications [19]. Besides peak data rates, IMT-Advanced also sets out requirements for spectral efficiency including peak, average, and cell-edge spectral efficiency. It envisions a peak downlink spectral efficiency of 15bps/Hz, an average downlink spectral efficiency of 2.6bps/Hz per cell, and a cell edge efficiency of 0.075bps/Hz per user. While the techniques for increasing peak efficiency are clear—higher order MIMO and higher order modulation—it is unclear yet how the cell-edge and average spectral efficiency required by IMT-Advanced can be met. Researchers and developers of wireless systems have a formidable challenge ahead.

Finding the necessary spectrum to achieve the 100Mbps and 1Gbps requirements is another challenge. The World Radio congress of 2007 identified a few new IMT spectrum, but very few places have continuous blocks of 100MHz—for example, 2.6GHz and 3.5GHz. This implies that network and spectrum sharing across operators and aggregation of non-contiguous channels from different bands may be required.

3GPP is investigating a number of technologies to realize the requirements for IMT-Advanced. The standards body has formed a study group for developing LTE-Advanced, which will then be proposed as an IMT-Advanced standard to ITU. 3GPP has developed preliminary requirements for LTE-Advanced [20] and they are shown in Table 1.11. Some of the technologies being considered for LTE-Advanced include:

- Higher order MIMO and beamforming (up to 8×8)
- Several new MIMO techniques: improved multi-user MIMO, collaborative and network MIMO, single-user uplink MIMO, etc.

Table 1.11 Summary of LTE-Advanced Target Requirements

	LTE-Advanced Target Requirement
Peak Data Rate	1Gbps downlink and 500Mbps uplink; assumes low mobility and 100MHz channel
Peak Spectral Efficiency	Downlink: 30bps/Hz assuming no more than 8×8 MIMO Uplink: 15bps/Hz assuming no more than 4×4 MIMO
Average Downlink Cell Spectral Efficiency	3.7bps/Hz/cell assuming 4×4 MIMO; 2.4bps/Hz/cell assuming 2×2 MIMO; IMT-Advanced requires 2.6bps/Hz/cell
Downlink Cell-Edge Spectral Efficiency	0.12bps/Hz/user assuming 4×4 MIMO; 0.07bps/Hz/user assuming 2×2 MIMO; IMT-Advanced requires 0.075bps/Hz/user
Latency	<10ms from dormant to active; <50ms from camped to active
Mobility	Performance equal to LTE; speeds up to 500kmph considered
Spectrum Flexibility	FDD and TDD; focus on wider channels up to 100MHz, including using aggregation
Backward Compatibility	LTE devices should work on LTE-Advanced; reuse LTE architecture; co-exist with other 3GPP systems

- Inter-cell interference co-ordination and cancellation
- Use of multi-hop relay nodes to improve and extend high data rate coverage
- Carrier aggregation to support larger bandwidths while simultaneously being backward compatible with lower bandwidth LTE
- Femto-cell/Home Node-B using self-configuring and self-optimizing networks

In the final analysis, wireless system capacity is driven by three factors: amount of spectrum, spectral efficiency, and the number of cells. Given the scarcity of useful spectrum, we are unlikely to see huge increases there in the near future. Spectral efficiency gains will also be limited since we have already developed and deployed technologies that get us close to the theoretical Shannon limit for capacity. This leaves us largely with the need to increase the number of cells—to move from microcells to pico-cells and femto-cells to achieve significant capacity gains. As we look toward achieving the IMT-Advanced requirements and beyond, much effort will be focused on evolving the topology of the cellular network and intelligently managing interference and dynamically assigning resources across a more complex topology to maximize system capacity.

1.8 Summary and Conclusions

In this chapter we provided an overview of the evolution of mobile wireless broadband systems and made the case for LTE. The key points made are

- Wireless services have grown at a remarkable rate over the past 25 years with over 4 billion users around the world today.
- Voice telephony has been the traditional killer application for wireless systems, but data consumption is growing rapidly and will dominate future growth.
- Wireless systems evolved from early single cell systems to first generation analog voice cellular systems to second generation digital voice (mostly) systems to third generation packet data systems and toward mobile broadband wireless systems.
- We provided an overview of various wireless standards: AMPS, GSM, CDMA, IX-EVDO, UMTS, HSPA, WiMAX, and LTE.
- We discussed the market drivers, salient features, and key technologies included in the LTE standard.
- We briefly described the end-to-end network architecture of LTE supporting all services over a flat IP network.
- We discussed the spectrum options for LTE deployments emphasizing the newer spectrum options that have become available.
- Provided a peek into future evolution of LTE toward a true 4G system capable of up to 1Gbps peak data rates.

Bibliography

[1] ITU Telecommunications indicators update—2009. www.itu.int/ITU-D/ict/statistics/

[2] 3G Americas. List of 3G deployments worldwide. www.3gamericas.org

[3] UMTS Forum. www.umts-forum.org

[4] Holma, H. et al. "High-Speed Packet Access Evolution in 3GPP Release 7." *IEEE Communications Magazine*, 45(12):29–35, December 2007.

[5] Holma, H. and A. Toskala. "High-Speed Downlink Packet Access." Chapter 11. *WCDMA for UMTS*. New York: John Wiley & Sons, Inc., 2002.

[6] Wiggins, R. "North American Operator Perspectives of 4G Migration Paths." *Yankee Group Survey Analysis*, August 13, 2008.

[7] Marshall, P. "HSPA+ Challenges Both WiMAX and LTE on the Road to 4G." *Yankee Group Trend Analysis*, September 29, 2008.

[8] 3G Americas White Paper. The mobile broadband revolution: 3GPP Release 8 and beyond, HSPA+, SAE/LTE and LTE-Advanced. February 2009.

[9] Bakshi, S.K. and R.T. Llamas. Worldwide Converged Mobile Device 2008–2012 Forecast Update: September 2008. *IDC*. Report 214293. September 2008.

[10] Andrews, J., A. Ghosh, and R. Muhamed. *Fundamentals of WiMAX*. Upper Saddle River, NJ: Prentice Hall, 2007.

[11] World Cellular Information Service. Iforma Telecoms and Media. May 2009.

[12] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2009–2014. www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[13] 3GPP TR 25.913., "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)," v8.0.0, December 2008.

[14] *IEEE Communications Magazine*, Special issue on LTE—LTE Part II: Radio Access, April 2009.

[15] *IEEE Communications Magazine*, Special issue on LTE—LTE Part I: Core Network, February 2009.

[16] *EURASIP Journal on Wireless Communications and Networking*, Special issue on 3GPP LTE and LTE Advanced, August 2009.

[17] 3GPP TS 36.104: "Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (Release 8)."

[18] 3G Americas White Paper. 3GPP technology approaches for maximizing fragmented spectrum allocations. July 2009.

[19] *ITU-R Report M.2134*, "Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s)," November 2008.

[20] 3GPP TR 36.913, "Requirements for Further Advancements for E-UTRA," v8.0.1, March 2009.