UNIT – IV

Evolution of Cellular Technologies: First generation cellular systems, 2G Digital cellular systems, 3G Broadband wireless systems, Beyond 3G: HSPA+, WiMAX, and LTE.

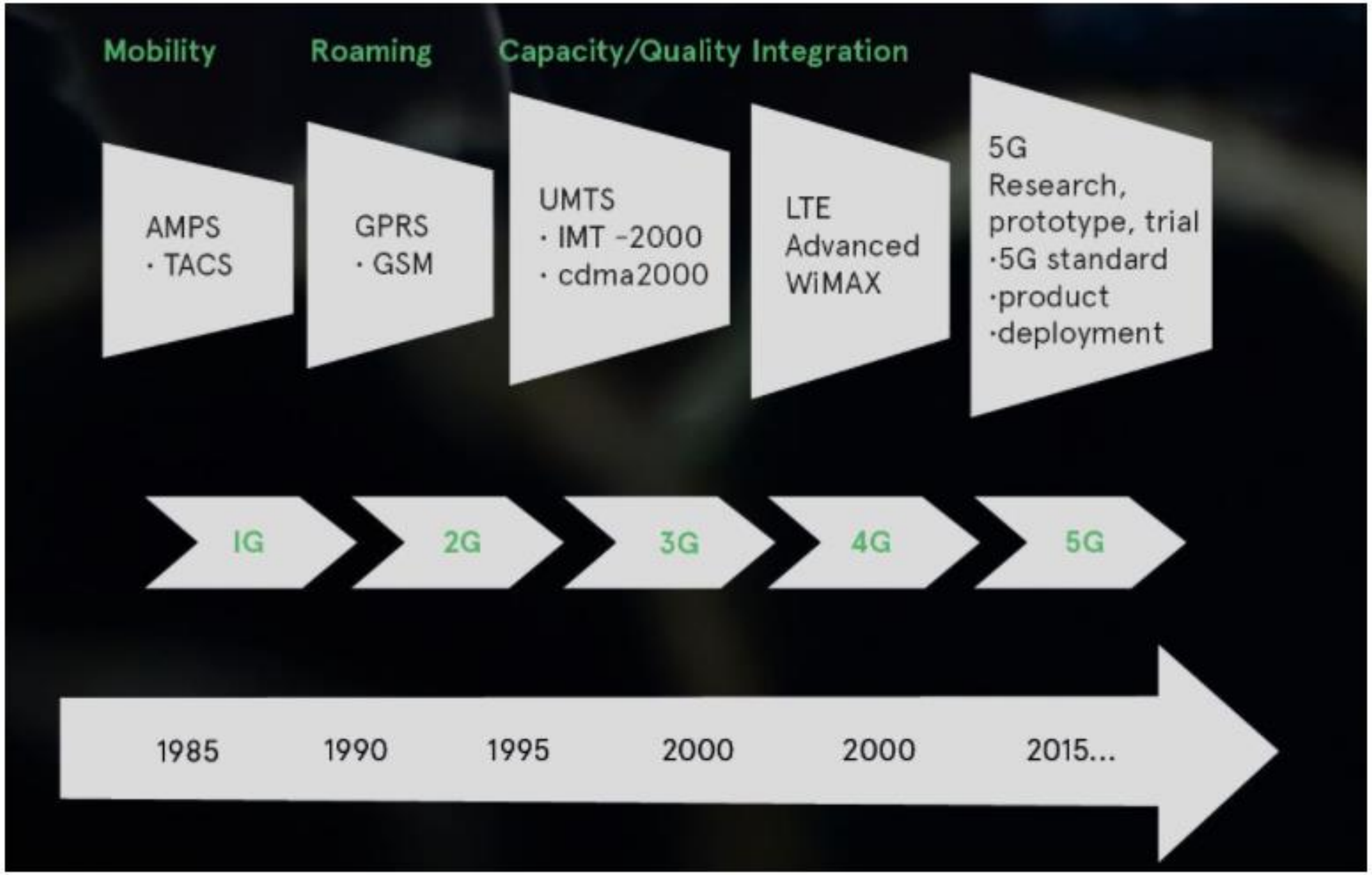
LTE: Demand drivers for LTE, Key requirements of LTE design, LTE Network architecture, Future of mobile broadband-Beyond LTE.

Source: Arunabha Ghosh, Jan Zhang, Jefferey Andrews, Riaz Mohammed, Fundamentals of LTE, Pearson Education, 2011.

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.


Mobility
Roaming
Capacity/Quality
Integration
AMPS
· TACS
GPRS
· GSM
UMTS
· IMT -2000
· cdma2000
LTE
Advanced
WiMAX
5G
Research,
prototype, trial
·5G standard
·product
·deployment
1G
2G
3G
4G
5G
1985
1990
1995
2000
2000
2015...

1. First Generation (1G) 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.
- 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 (Advanced Mobile Phone Service) in the United States
  - European Total Access Communication Systems (ETACS) in Europe
  - NTACS in Japan.
- The AMPS system was built on a 30kHz channel size, whereas ETACS and NTACS used 25kHz and 12.5kHz, respectively.
- 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.
- Besides the United States, AMPS was deployed in South America, Asia, and North America.
- AMPS systems used Frequency Modulation (FM) for the transmission of analog voice and Frequency Shift Keying (FSK) for the control channel.

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

AMPS: Advanced Mobile Phone System (America and Australia)

ETACS: European Total Access Communications System

NTT: Nippon Telephone and Telegraph System

2. The Second Generation (2G) Digital Cellular Systems

- Improvements in processing abilities enabled the development of 2G wireless systems.
- 2G systems were primarily designed for the voice services using digital modulation.
- The performance was improved in 2G systems in terms of:
  - System capacity was improved through:
    - the use of spectrally efficient digital speech codecs,
    - Multiplexing several users on the same frequency channel via time division or code division multiplexing techniques,
    - 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.
  - It uses simple encryption to provide a measure of security against eavesdropping and fraud.

- 2G systems also enabled new applications:
  - Short Messaging Service (SMS). SMS was first deployed in Europe in 1991, and quickly became a popular conversational tool.
  - Low data rate wireless data applications (like delivery of news, stock quotes, weather, and directions, etc.

- Original 2G systems supported circuit switched as well as packet switched data services.

- Examples of 2G digital cellular systems include:
  - Global System for Mobile Communications (GSM): the most widely deployed system
  - IS-95 CDMA: deployed in North America and parts of Asia
  - IS-136 TDMA systems.
  - Personal Handyphone System (PHS): deployed in China, Japan, Taiwan, and some other Asian countries

- 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.
- 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 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

2.1. GSM and Its Evolution

- In 1982, many European countries came together to develop and standardize a pan-European system for mobile services.
- The group was called the Groupe Sp´ecial Mobile (GSM) and their main aim was to develop a system that could deliver inexpensive wireless voice services across all of Europe.
- 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.
- GSM quickly gained acceptance beyond Europe and the standard was appropriately renamed as the Global System for Mobile Communications.
- 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 Gaussian Minimum Shift Keying (GMSK- variant of FSK) modulation technique due to its constant envelope 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-General Packet Radio Service) 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.

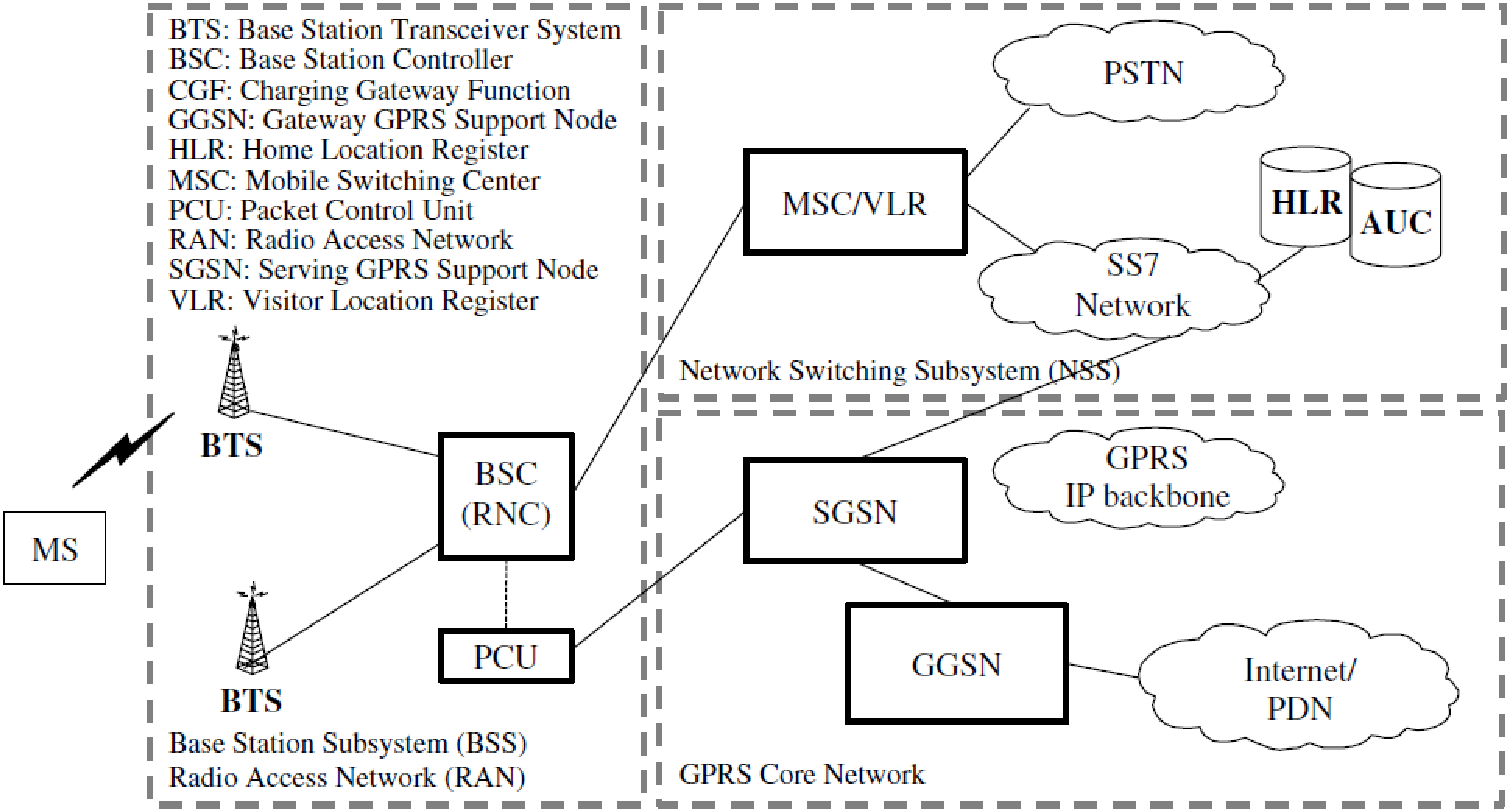


Figure 1.2 GSM network architecture.

- The original GSM architecture had two sub-components:
  I. **Base Station Subsystem (BSS)**: 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 directly to them.

  II. **Network Switching Sub-system (NSS)**: 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.

- 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 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.

2.2. CDMA (IS-95) and Its Evolution

- In 1989, Qualcomm proposed Code Division Multiple Access (CDMA) as a more efficient, higher quality wireless technology and demonstrated a system implementation of it.
- 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.
- 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.
- Advantages of IS-95 CDMA systems over TDMA systems for voice.
  1. It enabled universal frequency reuse—that is, every cell can use the same frequency channel—which simplified frequency planning and provided increased capacity.
  2. It used RAKE receivers that effectively combined multi-path signals to produce a stronger signal thereby reducing the required transmitter power.
  3. 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.
  4. It implemented voice activity detection to turn off transmissions during silent periods, thereby reducing the overall interference level.

- To keep the interference below and improve system capacity, IS-95 implements fast (800Hz on uplink) and effective power control mechanisms.
- IS-95 CDMA technology offered better coverage and capacity than TDMA.
- In addition to voice, the original (IS-95A) system supported a single dedicated data channel at 9.6kbps.

3. 3G Broadband Wireless Systems

- 2G digital cellular systems provided improved voice quality, and support for data applications such as Internet access with low-data rate and limited capacity.
- Third generation (3G) systems providing much higher data rates, significant increase in voice capacity, and supporting advanced services and applications, including multimedia (voice telephony and interactive games, to Web browsing, e-mail, and streaming multimedia applications).
- 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 laid out the following data rate requirements as the criterion for IMT-2000:
  i. 2Mbps in fixed or in building environments
  ii. 384kbps in pedestrian or urban environments
  iii. 144kbps in wide area vehicular environments

- 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 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 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

3.1 CDMA 2000 and EV-DO

- The 3G evolution of IS-95 standard was called CDMA2000 (CDMA2000-1X) standardized by 3GPP2 in 1999.
- The data capabilities were enhanced by adding separate logical channels termed as *supplemental channels*.
- Each link can support a single fundamental channel at 9.6kbps and multiple supplemental channels up to 307kbps. This is less than the 3G requirements, and for this reason CDMA2000-1X refer to as a 2.5G system.
- The data rate can be increased up to 2Mbps through the use of multiple carriers as in CDMA2000-3X.
- 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 (EVolution, Data Only: no support for voice or other real time services).

- EV-DO is designed to provide downlink rates up to 2.4Mbps and uplink rates up to 153kbps.
- The system supports QPSK and 16QAM modulation.
- 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.

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.

- 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.

- While UMTS retains the basic architecture of GSM/GPRS networks, the 3G air-interface called Wide-band CDMA (W-CDMA).

- It is a Direct Sequence Spread Spectrum (DSSS) 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.

- 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.

- The 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.

3.3. High-Speed Packet Access (HSPA)

- HSPA, is the term used to refer to the combination of two key enhancements by 3GPP to UMTS-WCDMA:
  i. High-Speed Downlink Packet Access (HSDPA) introduced in Release 5 in 2002 and
  ii. 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.

- HSDPA defined a new downlink transport channel called High-Speed Downlink Shared Channel (HS-DSCH) capable of providing up to 14.4Mbps peak theoretical throughput.

- HSDPA has 16 Walsh codes, 15 of which are used for user traffic.

- HSPA introduced a number of new advanced techniques to realize the high throughput and capacity. These include:
  i. **Adaptive Modulation and Coding (AMC)**: HSDPA 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 with the highest modulation and coding technique.
  ii. **Fast Dynamic Scheduling**: HSDPA systems use a dynamic scheduler that attempts to exploit the diversity of channel conditions experienced by different users at different times. A dynamic scheduler could allocate all the cell capacity to a single user for a very short time when the conditions are favorable.
  iii. **Hybrid Automatic Repeat Request (H-ARQ)**: 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.

- HSUPA introduced a new uplink channel called the Enhanced Dedicated Channel (E-DCH) to UMTS-WCDMA.
- 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.

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.

- Most operators would choose from one of the following three options:

  i. Deploy HSPA and its evolutionary technologies (Ex. HSPA+)

  ii. Deploy WiMAX for broadband data.

  iii. Deploy LTE as soon as possible.

4.1 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.
- The key technical enhancements included in HSPA+ are:
  i. **Higher-order modulation and MIMO to achieve higher peak rates**:
     - It introduces 64QAM as an additional downlink (BS to MS) modulation scheme to the existing QPSK and 16QAM in Release 6 HSPA. For the uplink (MS to BS) , 16QAM is included in addition to the dual BPSK scheme.
     - Use of 64QAM and 16QAM pushes the peak downlink and uplink rates to 21.1Mbps and 11.5Mbps, respectively.
     - Uses two transmit antennas in the base station and two receive antennas in the mobile terminal for MIMO (2x2 MIMO).
     - The use of 2 × 2 MIMO spatial multiplexing increases the peak downlink theoretical rate to 28Mbps.

ii. Dual-carrier downlink operation:

- 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.

iii. **Continuous packet connectivity for improved battery life**:

- HSPA+ allows the uplink transmission to be discontinuous such that the mobile transmitter can be completely turned off when there is no data transmission.
- 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.

iv. Advanced mobile receivers for data rate and capacity enhancement:

- Two antenna chip equalizer is also defined 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 allows for higher throughput transmissions in the downlink and hence improves capacity.

v. Flexible RLC and MAC segmentation:

- HSPA+ now allows the RLC block size to be flexible and can be as large as 1,500 bytes.
- Segmentation can be done by the MAC layer based on physical layer requirements.
- All these lead to improved data throughput and peak rates.

vi. 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.

4.2. Mobile WiMAX

- In 1998, the IEEE formed a group called 802.16 to develop a standard 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 (Worldwide Interoperability for Microwave Access).
- 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).

Features of WiMAX:

i. Very High Peak Data Rates:

- Peak physical layer (PHY) data rates are achieved when using 64QAM modulation with rate ¾ error correction coding.
- Peak physical layer data rate can be as high as 74Mbps when using a 20MHz wide spectrum and 18Mbps when using a 5MHz spectrum.

ii. OFDM/OFDMA Based Physical Layer:

- The WiMAX PHY is based on Orthogonal Frequency Division Multiplexing (OFDM).
- OFDM offers good resistance to multipath and allows WiMAX to operate in non-line-of-sight (NLOS) conditions even with large bandwidths.
- WiMAX also uses OFDMA as the multiple access technique, which allows users to be multiplexed in both time and frequency in a dynamic manner.

iii. 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.

iv. Support for TDD and FDD:

- IEEE 802.16e-2005 supports both TDD and FDD.
- TDD has been attractive to WiMAX operators since it offers flexibility in choosing uplink-to-downlink data rate ratios.

v. 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.

vi. 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.

vii. Support for Advanced Antenna Techniques:

- The WiMAX allows 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.

viii. 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.

4.3. Comparison of HSPA+ and WiMAX to LTE

- 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.
- Most HSPA+ and LTE are operating in bands below 2.1GHz, WiMAX are likely to be in the 2.3GHz, 2.6GHz, and 3.5GHz frequency bands.
- HSPA+ only supports FDD, WiMAX is mostly deployed in TDD mode and LTE supports both FDD and TDD.
- Both LTE and WiMAX use OFDM/OFDMA while HSPA+ uses CDMA/TDMA.
- LTE uses a variation of OFDMA called Single Carrier Frequency Division Multiple Access (SC-FDMA) on the uplink. WiMAX uses OFDMA in both uplink and downlink.
- HSPA uses a fixed 5MHz bandwidth and WiMAX, LTE offer a flexible bandwidth architecture supporting up to a maximum of 20MHz. This 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

Latency **measures the time it takes for some data to get to its destination across the network**. It is usually measured as a **round trip delay** - the time taken for information to get to its destination and back again

	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

Summary of Evolution of 3GPP Standards

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.

Release 9	2009 Q4	SAES Enhancements, WiMAX and LTE/UMTS Interoperability. Dual-Cell HSDPA with MIMO, Dual-Cell HSUPA. LTE HeNB. Evolved multimedia broadcast and multicast service (eMBMS).
Release 10	2011 Q1	LTE Advanced fulfilling IMT Advanced 4G requirements. Backwards compatible with release 8 (LTE). Multi-Cell HSDPA (4 carriers).
Release 11	2012 Q3	Advanced IP Interconnection of Services. Service layer interconnection between national operators/carriers as well as third party application providers. Heterogeneous networks (HetNet) improvements, Coordinated Multi-Point operation (CoMP). In-device Co-existence (IDC).
Release 12	2015 Q1	Enhanced Small Cells (higher order modulation, dual connectivity, cell discovery, self configuration), Carrier aggregation (2 uplink carriers, 3 downlink carriers, FDD/TDD carrier aggregation), MIMO (3D channel modeling, elevation beamforming, massive MIMO), New and Enhanced Services (cost and range of MTC, D2D communication, eMBMS enhancements)[16]
Release 13	2016 Q1	LTE-Advanced Pro. LTE in unlicensed, LTE enhancements for Machine-Type Communication. Elevation Beamforming / Full-Dimension MIMO, Indoor positioning.[17]
Release 14	2017 Q2	Energy Efficiency, Location Services (LCS), Mission Critical Data over LTE, Mission Critical Video over LTE, Flexible Mobile Service Steering (FMSS), Multimedia Broadcast Supplement for Public Warning System (MBSP), enhancement for TV services over eMBMS, massive Internet of Things, Cell Broadcast Service (CBS)[18]
Release 15	2018 Q2	First **5G NR ("New Radio")** release. Support for 5G Vehicle-to-x service, IP Multimedia Core Network Subsystem (IMS), Future Railway Mobile Communication System[19]
Release 16	2020 Q3	The 5G System - Phase 2: 5G enhancements, NR-based access to unlicensed spectrum (NR-U), Satellite access[20]
Release 17	2022 Q1	TSG RAN: Several features that continue to be important for overall efficiency and performance of 5G NR: MIMO, Spectrum Sharing enhancements, UE Power Saving and Coverage Enhancements. RAN1 will also undertake the necessary study and specification work to enhance the physical layer to support frequency bands beyond 52.6GHz, all the way up until 71 GHz. TSG SA groups focused on further enhancements to the 5G system and enablers for new features and services: Enhanced support of: non-public networks, industrial Internet of Things, low complexity NR devices, edge computing in 5GC, access traffic steering, switch and splitting support, network automation for 5G, network slicing, advanced V2X service, multiple USIM support, proximity-based services in 5GS, 5G multicast broadcast services, Unmanned Aerial Systems (UAS), satellite access in 5G, 5GC location services, Multimedia Priority Service...
Release 18	2023 Q4	5G-Advanced. Introducing further machine-learning based techniques at different levels of the wireless network. Edge computing, Evolution of IMS Multimedia Telephony Service, Smart Energy and Infrastructure, Vehicle-Mounted Relays, Low Power High Accuracy Positioning for industrial IoT scenarios, Enhanced Access to and Support of Network Slice, Satellite backhaul in 5G...[21][22]

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

v · t · e	Cellular network standards	[hide]
	List of mobile phone generations	
0G radio telephones (1946)	MTS · IMTS · Altai · OLT · MTA - MTB - MTC - MTD · AMTS · Autotel (PALM) · ARP · B-Netz · AMR	
1G (1979)	AMPS family	AMPS - N-AMPS · TACS - ETACS
	Other	NMT · C-450 · Hicap · Mobitex · DataTAC · CT1
2G (1991)	GSM/3GPP family	GSM · CSD - HSCSD
	3GPP2 family	cdmaOne (IS-95)
	AMPS family	D-AMPS (IS-54 and IS-136)
	Other	CDPD · iDEN · PDC · PHS · CT2
2G transitional (2.5G, 2.75G)	GSM/3GPP family	GPRS · EDGE/EGPRS - Evolved EDGE
	3GPP2 family	CDMA2000 1X (TIA/EIA/IS-2000) · CDMA2000 1X Advanced
	Other	WiDEN · DECT
3G (2001)	3GPP family	UMTS (UTRA-FDD / W-CDMA (FOMA) · UTRA-TDD LCR / TD-SCDMA · UTRA-TDD HCR / TD-CDMA)
	3GPP2 family	CDMA2000 1xEV-DO Release 0 (TIA/IS-856)
3G transitional (3.5G, 3.75G, 3.9G)	3GPP family	HSPA (HSDPA · HSUPA) · HSPA+ (DC-HSDPA) · LTE (E-UTRA)
	3GPP2 family	CDMA2000 1xEV-DO Revision A (TIA/EIA/IS-856-A) · EV-DO Revision B (TIA/EIA/IS-856-B) · EV-DO Revision C
	IEEE family	Mobile WiMAX (IEEE 802.16e) · Flash-OFDM · iBurst (IEEE 802.20) · WiBro
	ETSI family	HiperMAN
4G (2009) IMT Advanced (2013)	3GPP family	LTE Advanced (E-UTRA) · LTE Advanced Pro (4.5G Pro/pre-5G/4.9G)
	IEEE family	WiMAX (IEEE 802.16m) (WiMax 2.1 (LTE-TDD / TD-LTE) · WiBro)
5G (2019) IMT-2020 (2020)	3GPP family	5G NR · 5G-Advanced · NR-IIoT · LTE-M · NB-IoT
	Other	DECT-5G
Related articles	Cellular networks · Mobile telephony · History · Comparison of standards · Channel access methods (FDMA (OFDMA) · TDMA (STDMA) · SSMA (CDMA) · SDMA) · Spectral efficiency comparison table · Frequency bands (GSM · UMTS · PCS · LTE · 5G NR) · Mobile broadband · Multimedia Broadcast Multicast Service · NGMN Alliance · Push-to-talk · MIMO · VoLTE · ViLTE · Wi-Fi calling · Osmocom	

5. Long Term Evolution (LTE)

- In telecommunications, **Long Term Evolution** (**LTE**) is a standard for wireless broadband communication for mobile devices and data terminals, based on the GSM/EDGE and UMTS/HSPA technologies.
- It increases the capacity and speed using a different radio interface together with core network improvements.
- 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 on the Long Term Evolution (LTE) project and the Systems Aspects group initiated work on the Systems Architecture Evolution (SAE) project.
- The LTE group developed a new radio access network called Enhanced UTRAN (E-UTRAN). 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).

5.1. Demand Drivers for LTE

- The growth of the Internet over the past decades is the demand driver for mobile broadband.

- The Internet today is the media of choice for all our information, communication and entertainment needs.

- Three broad trends that together drive demand for mobile broadband and make a compelling case for the development and deployment of LTE.
  i. **Growth in high-bandwidth applications**: such as music downloads, video sharing, mobile video, and IPTV.
  ii. **Increase of smart mobile devices**:
  iii. **Intense competition leading to flat revenues**:

5.2. Key Requirements of LTE Design

i. **Performance on Par with Wired Broadband**
ii. **Flexible Spectrum Usage**: LTE supports a variety of channel bandwidths: 1.4, 3, 5, 10, 15, and 20MHz.
iii. **Co-existence and Interworking with 3G Systems as well as Non-3GPP Systems (**3GPP2 CDMA and WiMAX**)**
iv. **Reducing Cost per Megabyte**
   - 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
   - A single IP packet core for voice and data
   - A flat architecture with fewer network components and protocols
   - Interworking with non-3GPP systems to drive toward one global standard to achieve higher economies of scale
   - Interworking with legacy systems to allow for cost-effective migration
   - High-capacity, high-spectral efficiency air-interface
   - Ability to deploy in existing spectrum and reuse cell sites and transmission equipment

Key Enabling Technologies and Features of LTE

1. Orthogonal Frequency Division Multiplexing (OFDM)

2. SC-FDE and SC-FDMA (power efficient transmission scheme for the uplink)

3. Channel Dependent Multi-user Resource Scheduling

4. Multiantenna Techniques
   i. Transmit diversity,
   ii. Beamforming,
   iii. Spatial multiplexing,
   iv. Multi-user MIMO

5. IP-Based Flat Network Architecture: “Flat” here implies fewer nodes and a less hierarchical structure for the network.

6. LTE Network Architecture

- 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.

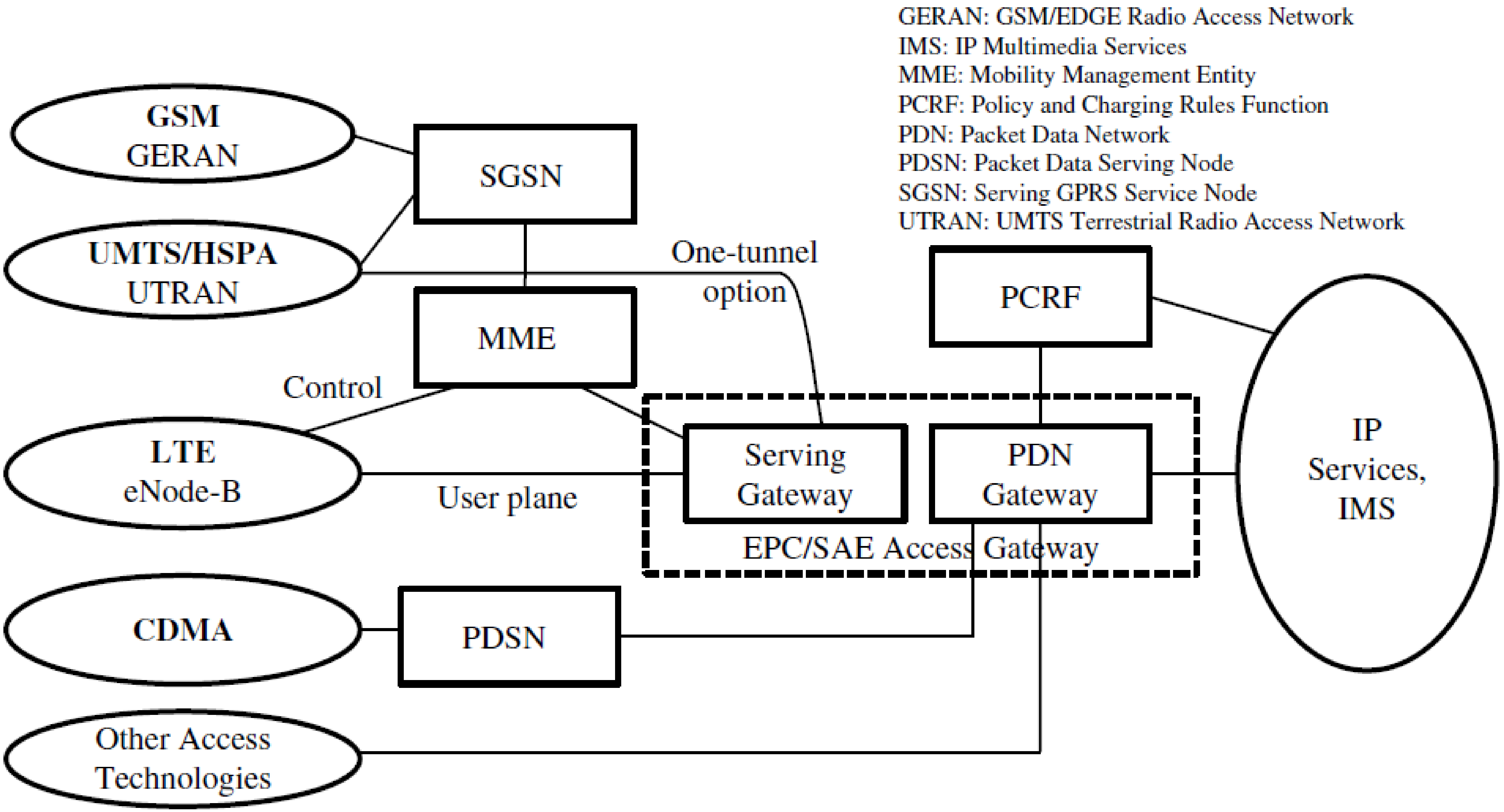


Figure 1.4 Evolved Packet Core architecture.

- The EPC includes four new elements:

  i. **Serving Gateway (SGW),** which terminates the interface toward the 3GPP radio access networks;

  ii. **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;

  iii. **Mobility Management Entity (MME),** which supports user equipment context and identity as well as authenticates and authorizes users;

  iv. **Policy and Charging Rules Function (PCRF),** which manages QoS aspects.

(i) Serving Gateway (SGW):

- The SGW acts as a termination point between the RAN and core network, and manages user plane mobility.
- It serves as the mobility announcer 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 legal interception, packet routing and forwarding, transport level packet marking in the uplink and the downlink, accounting support for per user, and inter-operator charging.

(ii) 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 announcer 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.

(iii) 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 legal 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.

(iv) 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.

7. Future of Mobile Broadband-Beyond LTE

- Many in the industry refer to LTE as a 4G system, but strictly speaking it does not meet the requirements set out by the ITU for the fourth generation (4G) wireless standard.
- Wireless system capacity is driven by three factors: amount of spectrum, spectral efficiency, and the number of cells.
- 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.
- It predicts 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.
- Requires higher order MIMO and higher order modulation.

- 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.
- Some of the technologies being considered for LTE-Advanced include:

i. Higher order MIMO and beamforming (up to 8 × 8)
ii. Several new MIMO techniques: improved multi-user MIMO, collaborative and network MIMO, single-user uplink MIMO, etc.
iii. Inter-cell interference co-ordination and cancellation
iv. Use of multi-hop relay nodes to improve and extend high data rate coverage
v. Carrier aggregation to support larger bandwidths while simultaneously being backward compatible with lower bandwidth LTE
vi. Femto-cell/Home Node-B using self-configuring and self-optimizing networks

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