Chapter 1

Wireless Access Technologies

1.1 Introduction

Wireless links are broadly utilized for point-to-point, point-to-multi-point, and mesh applications, in fixed or mobile, satellite or terrestrial applications, as backhaul or as user access networks, and from scan-zone to ad-hoc, relay, and wide-area applications. A great asset of wireless access is that it enables user mobility in its broad sense, whether nomadic or at high speeds. Phased evolution of true user mobility is enabled through seamless connectivity at multiple levels. Geographically, the user may be connected through one or more personal area (PAN), home or office (e.g., Femto cell), local area (LAN), metropolitan area (MAN – campus, hot-zone, municipality, mesh), or wide area (WAN) network(s). There is further granularity in wireless access, increasingly enabled through sensing, mobile tags, and near-field communication (NFC). Sensors are expected to enable communication between connected "things" (sensors, grids, tags), people, and machines, reaching tens of billions within five-plus years, and providing a broad range of (new) applications such as health and bio-engineering, environment and geo-engineering, robotics, and many others. A user's mobility is also maintained both through inter-technology and intra-technology handoff within an increasingly multi-cell and heteregenous communication space. The former may occur when moving from one cell to another in a given cellular network, and the latter may occur when the user's session and application is maintained while the access moves from one technology (e.g., Wireless LAN) to another (e.g., 3G or 4G). Although the user may have some level of awareness with respect to the access or connectivity mechanism, the user's communication space is ultimately (and increasingly) virtual, with the user aware of his or her intention, application, preferences, interaction, and experience, but typically not the access mechanism or network technology. This goal of creating an increasingly natural communication, which is more user-centric and less technology-centric, makes the enabling role of technologies and technologists more significant, more exciting, and perhaps more complex (certainly not less). In addition, a so-called natural communication may be enhanced by the application enabler, or the user terminal, as it discovers and utilizes the smart user space (proximity) capabilities.

A wireless access network must obviously allow the end user(s) to access the network. This includes the signaling, transmission, and communication aspects over wireless links, and provides coverage, capacity, and a user experience with such attributes as data rate, latency, and quality of service, among others. A group of users share the resources and are awarded access, governed by a certain discipline. At the heart of this discipline lies a multiple access mechanism. How can an increasingly large number of users access the same network, and even the same channel, at the same time? Multiple access mechanisms (e.g., FDMA, TDMA, CDMA, or OFDMA, all of which are defined later in this chapter) have evolved through generations of wireless systems to enable this, while enhancing such capabilities as data speed, capacity, flexibility, and cost efficiency.

Coverage is particularly significant in wireless network design, in reach, indoor penetration, and continuity. Capacity is another design fundamental. This is an end-to-end attribute but greatly impacted by the wireless access component. There is a need for small cell sites and more transmission carriers (and use of bandwidth) to provide sufficient capacity when there is a greater number of users, or more accurately, greater simultaneous traffic. Generally, wide-area cellular network design optimization is limited (or dictated) by coverage in low traffic areas, and by capacity in high traffic areas. With the explosive growth in wireless traffic, addressing capacity constraints requires multiple strategies above and beyond the traditional methods. A significant emerging paradigm is dynamic configuration, optimization, and management enabled by Self-Organizing Network (SON) mechanisms.

This brings us to the important concept of the frequency spectrum. A radio tone has a frequency, and a radio signal carrying information has a range of frequency content. Modulation at the transmitter, based on and coupled with a given multiple access mechanism, allows wireless communication over particular frequency bands. These bands are designated by local regulatory authorities, and generally coordinated by regional and global (e.g., the International Telecommunication Union [ITU]) bodies. They are typically licensed (e.g., bands used by service providers in mobile cellular technologies), but also unlicensed (e.g., typical bands used by WLAN and Bluetooth, among others).

Mobile communications systems were traditionally designed and optimized for voice communication. Although voice continues to be the dominant application, data applications have grown dramatically over the years, from basic messaging, downloads, browsing, and positioning applications (enabled by second generation (2G) systems and their enhanced versions) to an incredible growth of multimedia and content-based applications (particularly enabled by third generation – 3G – systems and beyond). The core network (discussed in the next chapter) is evolving to provide a ubiquitous application environment in conjunction with a common service architecture, and seamless access, interfacing with one or more access techniques. This is a phased evolution to an all-IP or packet (heterogeneous) network, already introduced, with a flat (or flatter) architecture which allows seamless mobility across different access technologies. A new era is already here, with content-centric and IP-centric wireless networks.

The ITU has defined the family of 3G systems (International Mobile Telecommunications for the Year 2000, IMT-2000) and has set out the goals and attributes of the next-generation IMT-Advanced systems as shown in Figure 1-1 [ITU03]. Industry standards bodies (e.g., the 3rd Generation Partnership Project, 3GPP, and 3GPP2; also the IEEE 802.x committees) have developed definitions for generations of mobile and nomadic communication access (and core) technologies (e.g., LTE, Long-Term Evolution), working with other standards groups such as the Internet Engineering Task Force (IETF) (to leverage universal protocols and elements) and the Open Mobile Alliance (to align on and seek service enabler definition and interfaces).

This chapter starts with access network concepts and moves on to introduce access technologies and standards. As this is truly a broad topic, this chapter highlights key concepts and technologies but does not claim to be inclusive of all forms of access layer concepts, technologies, or implementations. Furthermore, it does not intend to promote or validate any particular technology. While significant technology attributes and design goals are highlighted, it must be noted that the products, innovations, implementation environment and wisdom, customer solutions, operational ingenuity, and inter-carrier initiatives can provide a variety of prospects and capabilities, above and beyond fundamental concepts, standards and reference models, technology goals, and common core practices.

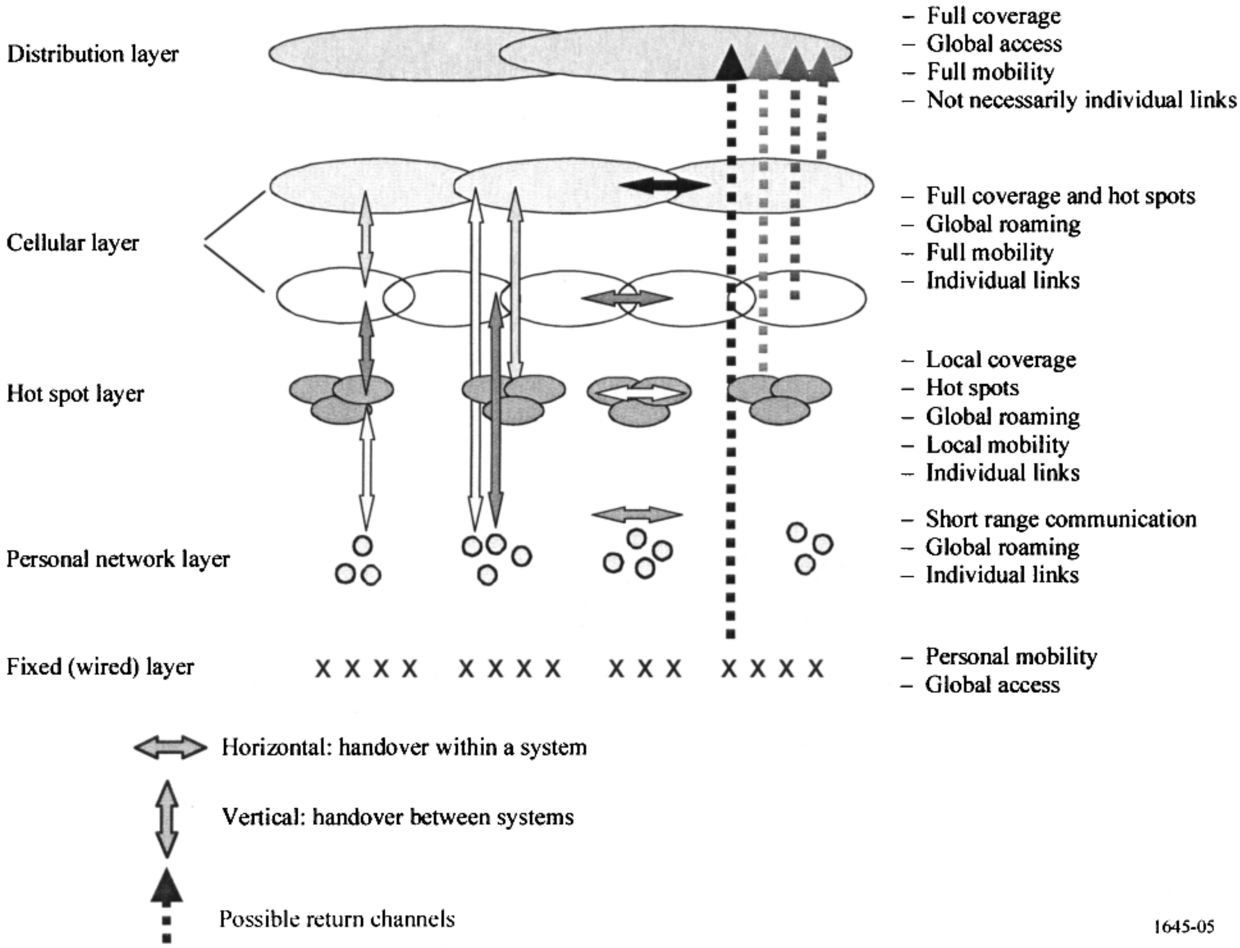


Figure 1-1: ITU IMT-Advanced Vision of Complementary Interconnected Access Systems

1.2 Wireless Access

1.2.1 Fundamental Access Layer Considerations

Wireless access technologies are concerned with the lower layers, particularly transmission and link layer functions. These functions are not fixed, and through generations of technologies, particularly mobile cellular, some of the core network functions (e.g., in mobility management) have moved to the edges and been taken up by the so-called access technologies. Figure 1-2 identifies some of the key functions.

Key attributes of access technologies include:

- Modulation and Coding
- Multiple Access Mechanism
- Spectral Efficiency
- Frame Structure and Radio Signal Generation
- Bandwidth Support
- Antenna Structure/Function Support (e.g., MIMO, Multiple Input Multiple Output)
- Resourcing and Channel Mapping

- Mobility Management Support and Handovers
- Short Transmission Time Interval
- Access Layer Security and QoS
- Detection and Equalization
- Re-Transmission Support
- Frequency Re-use Support (e.g., Fractional)
- Other Access Layer Innovations, such as
    - Link Adaptation
    - Interference Cancellation
    - Fast Scheduling
    - Bandwidth Aggregation

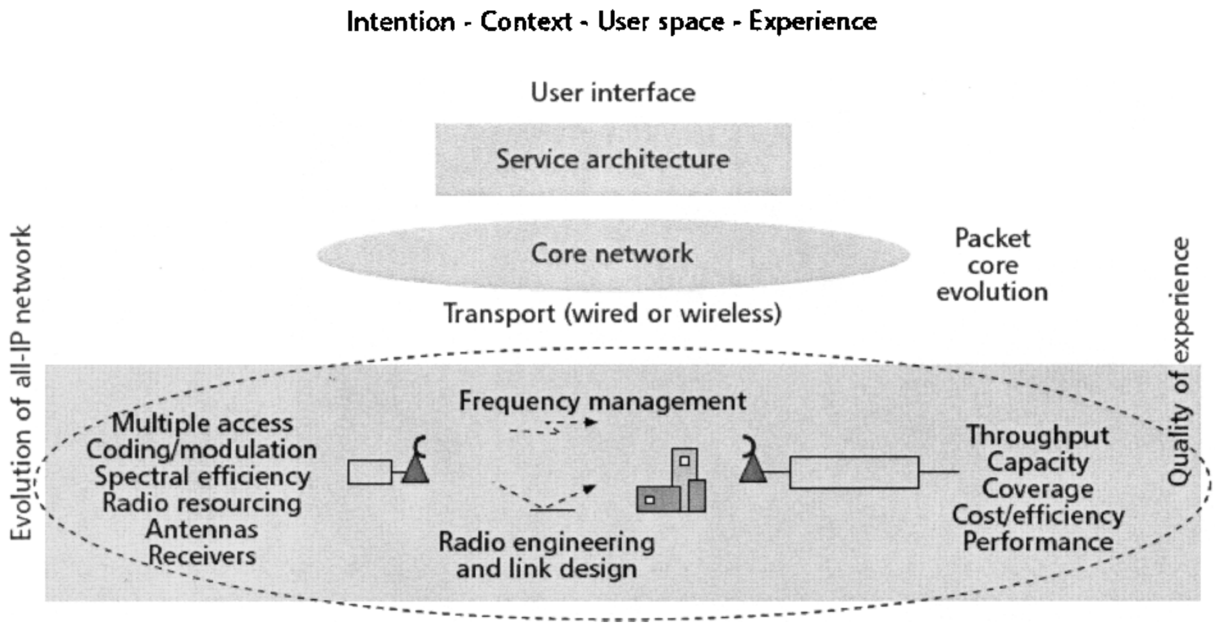


Figure 1-2: Wireless Access Functions Foundational to an End-to-End Communication System

Research, standardization, and a great deal of innovation have led to the realization of wireless access technologies. To make use of these technologies, access networks are designed, configured, put in operation, and managed. This includes such important considerations as:

- Wireless Link, Cell, Antenna, and Architecture Design
- Coverage
- Capacity
- Frequency Management
- Performance Requirements
- Interactions with Core, Servicees, Network Management, and Terminal Equipment

- End-to-End Design, Configuration, and Operation

A number of key wireless access technology attributes and network design considerations are discussed in detail in the following sections and broadly addressed in the context of wireless technology standards evolution. Furthermore, Chapter 4 of this book is dedicated to Radio Engineering, and Antennas. Finally, Chapter 7 on Fundamental Knowledge gives reference to access layer and transmission concepts.

1.2.2 Spectrum Considerations

Wireless communication is obviously based on the transmission of (radio) signals with a certain frequency content as part of the electromagnetic spectrum. The frequency spectrum is apportioned among users based on the variety of different applications and its suitability for each, competition, regional and global (International Telecommunication Union – Radiocommunication Sector, ITU-R; World Radio-communication Conference, WRC) alignment, historical reasons, and other regulatory considerations.

Some significant spectrum considerations, in relation to access technologies are briefly highlighted here:

- Frequencies below ~3 GHz have been suitable for non-line-of-sight (NLOS) applications such as mobile cellular. Higher frequencies, however, have also been used extensively (e.g., for satellite communication).
- Higher frequencies have higher (free-space) power loss and shorter reach, for the same transmit power. For example, frequencies such as those in the 1.7–2.7 GHz range may (particularly) be used if or where capacity is a concern and lower ones such as 0.7–1 GHz may (particularly) be used if coverage is a consideration. In practice, a combination of considerations, however, may result in the use of one or more bands.
- To meet growing capacity requirements (e.g., for mobile applications), sufficient frequency spectrum is needed. This is to meet broadband speed and high-traffic volume (in addition to technology) requirements. ITU-R leads in the identification of global spectrum needs for future systems.
- In a communication session, the two-way communication paths (duplex) need to be divided, either in frequency (Frequency Division Duplex, FDD) or in time (Time Division Duplex, TDD). The frequency channel plan is obviously different in each case. Specifically, uplink and downlink frequencies are distinct and separated in the FDD case, as in many mobile cellular systems today. There is a growing trend to support a dual FDD/TDD mode seamlessly, to leverage spectrum resources and to roam between networks of the same or different service providers.
- Wireless systems are designed with ingenuity, particularly to avoid interference. Interference can potentially come from a variety of sources including the spectrum band structure. Interference cancellation and coordination schemes (e.g., in a multi-cell environment where low-power small cells are inserted within a macro network) are among the new and emerging standards, innovations, and best deployment practices.
- Significant considerations are regional and global frequency band alignment, along with multi-band multi-mode user device support. The latter is enabled by technology feasibility evolution (e.g., receiver front-end innovations) and also new breakthrough paradigms such as carrier-aggregation (3GPP standards in Release 10 [3GP11a, 3GP11b] and beyond). These trends enable

user roaming, a strong technology ecosystem, and cost-effective (user-terminal) product availability and innovations.

As examples, mobile cellular operation in the Americas includes some or all of the frequency bands at 700 MHz, 850 MHz, 1900 MHz, 1700 / 2100 MHz (Advanced Wireless Services, AWS), and 2.5+ GHz. Similarly, such frequency bands as 800/850 MHz, 900 MHz, 1800 MHz, and 2.1 GHz, among others, are used in much of the rest of the world. In addition, there are frequency bands used for satellite communications, Wireless LANs (2.4 GHz and 5 GHz), point-to-point, distribution, microwave, radar, and other systems.

1.2.3 Generic Picture

Wireless access technologies allow connectivity and communication over wireless link(s). They are based on principles of radio engineering, with such attributes as propagation, power, antenna technology, and link analysis and design. Furthermore, a wireless access network sets up intelligent wireless connectivity, with increasing sophistication in speed, performance, flexibility, and efficiency, to enable user access, networking ,and applications.

Figure 1-3(a) shows a generic wireless transmission system with common functions of transmission, propagation, and reception. Figure 1-3(b) shows an example of a wireless (mobile) access system architecture as a key component of the end-to-end communication network.

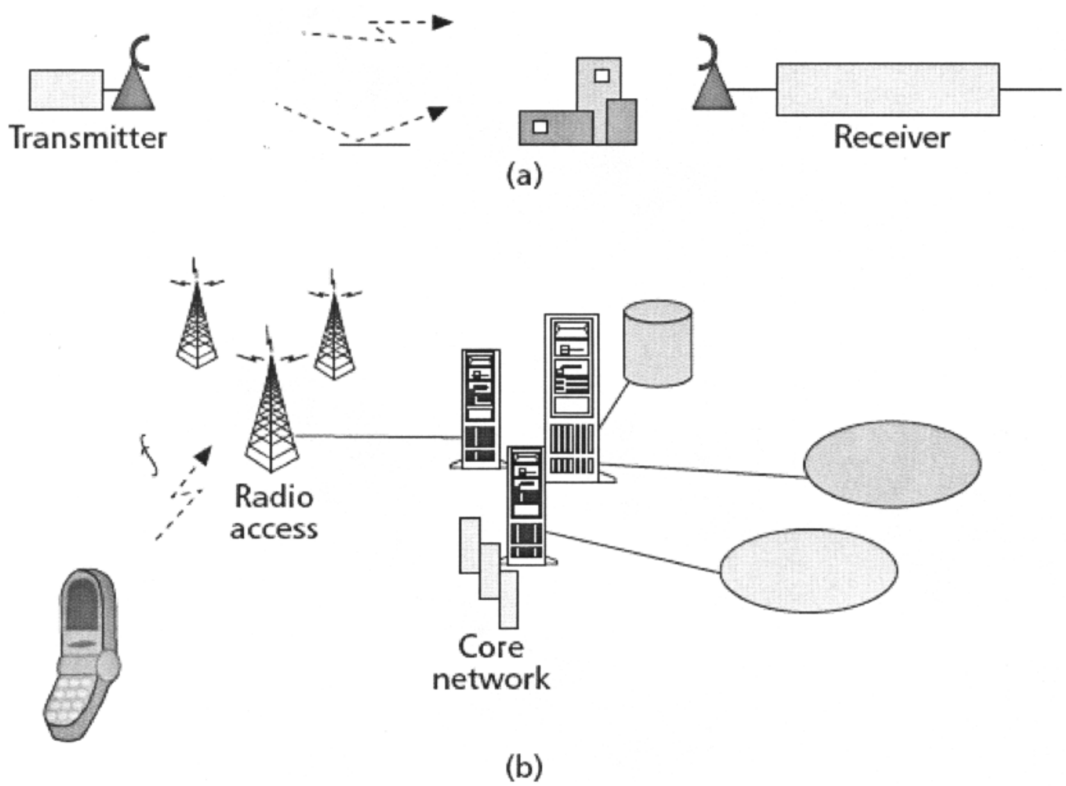


Figure 1-3: (a) Simplified View of a Generic Wireless Transmission System; (b) a (Cellular) Network Example

Although overly simplified, this figure helps to illustrate how all wireless systems, both in their variety and in their evolution, deal with such concepts as transmission/reception (e.g., coding and modulation), antennas, link and propagation attributes, spectrum, multiple access etiquette (for shared systems), and others. For example, moving from third generation (3G) mobile access technologies to beyond 3G is enabled by technologies that leverage advanced forms of coding and modulation, multiple access, and antenna technologies, among others.

All wireless communication systems, satellite or terrestrial, fixed or mobile, personal, local, or wide-area, dedicated or shared, transport (backhaul) or access, regardless of frequency bands or topologies (point-to-point, point-to-multipoint, or mesh), have a similar fundamental anatomy. Furthermore, they have such similar concerns and considerations as coverage, capacity, transmitting power, interference, received signal power, infrastructure, and of course, performance and efficiency. The detailed attributes, however, vary depending on design and application goals, access technology, links, mobility, or frequency spectrum. Some details are provided for the case of mobile cellular systems in section 1.3.

1.2.4 Multiple Access Mechanisms

1.2.4.1 FDMA

Frequency Division Multiple Access or FDMA is an access technology that is used by radio systems to share the radio spectrum. In an FDMA scheme, the given Radio Frequency (RF) bandwidth is divided into adjacent frequency segments. Each segment is provided with bandwidth to enable an associated communications signal to pass through a transmission environment with an acceptable level of interference from communications signals in adjacent frequency segments.

FDMA also supports demand assignment (e.g., in satellite communications) in addition to fixed assignment. Demand assignment allows all users apparently continuous access to the transponder bandwidth by assigning carrier frequencies on a temporary basis using a statistical assignment process.

FDMA has been the multiple access mechanism for analog systems. It is not an efficient system on its own, but can be used in conjunction with other (digital) multiple access schemes. In this hybrid format, FDMA may be viewed as a higher-level frequency band plan, facilitating the splitting of channel bandwidths, upon which sophisticated digital multiple access schemes can be applied, allowing the system to be shared by an increasing number of users.

1.2.4.2 TDMA

Time division multiple access (TDMA) is a channel access method for shared-medium (radio) networks. It allows several users to share the same frequency channel by dividing the signal into different timeslots. The users' information is transmitted in rapid succession, each individual using its own timeslot, one after the other. This allows multiple stations to share the same transmission medium (e.g., radio frequency channel) while using only the part of its bandwidth that is required. TDMA is used in second-generation (2G) digital cellular systems, and is part of their evolution. Examples include the Global System for Mobile Communications (GSM), Interim Standard IS-136, Personal Digital Cellular (PDC), Integrated Digital Enhanced Network (IDEN), General Packet Radio Service (GPRS), and Enhanced Data Rates for GSM Evolution (EDGE). It is also used in the Digital Enhanced Cordless Telecommunications (DECT) standard for portable phones and in some satellite systems. Figure 1-4 shows the TDMA frame structure.

TDMA features (and concerns) include simpler handoff and less stringent power control, while potentially more complexity in cell breathing (borrowing resources from adjacent cells), synchronization overhead, and frequency/slot allocation (in comparison to CDMA). On its own, TDMA is limited by the number of timeslots and the fast transition between them. However, in addition to being used in many existing systems, it has the potential to be further leveraged in future hybrid multiple-access systems.

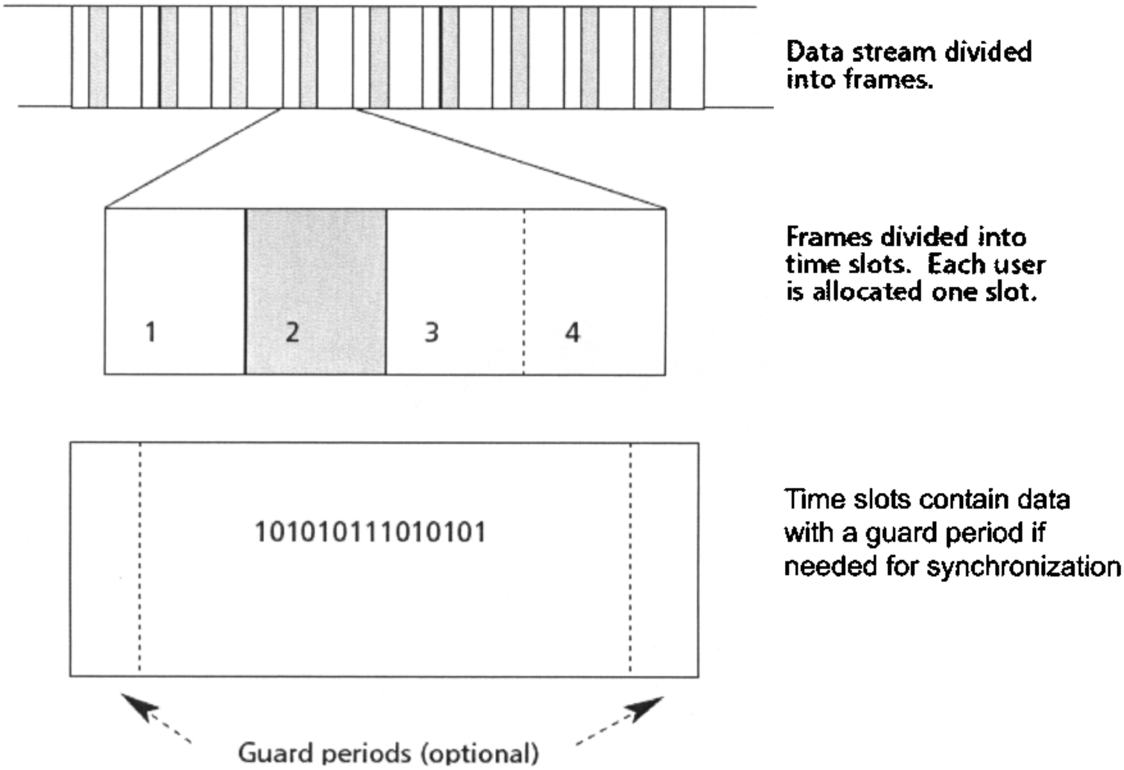


Figure 1-4: TDMA Frame Structure

1.2.4.3 CDMA

Code division multiple access (CDMA) is a channel access method utilized by various radio communication technologies. It employs a form of spread spectrum and a special coding scheme (where each transmitter is assigned a code). The spreading ensures that the modulated coded signal has a much higher bandwidth than the user data being communicated. This in turn provides dynamic (trunking) efficiency, allowing capacity versus signal-to-noise ratio tradeoffs.

The multiple user signals share the same time, set of frequencies, and even space, but remain distinct as each is modulated (or correlated) with a distinct code. The codes are (quasi-) orthogonal such that a cross-correlation of a received signal with the "wrong" codes results in a spread (and hence suppressed) "noise," while the auto-correlation with the "right" code results in the (de-spread) desired output. The signal-to-noise power ratio decreases with increasing number of users (or load on the system). This implies that with lower load, higher quality is achievable, while conversely, if some degradation is tolerable, the system allows higher capacity.

CDMA has been used in many communication and navigation terrestrial and satellite systems. Most notably, it has been used in third-generation (3G) mobile cellular systems (Universal Mobile

Telecommunications System, UMTS; cdma2000; Time-Division Synchronous CDMA, TD-SCDMA) for its strong features such as capacity/throughput, spectral efficiency, and security, among others.

1.2.4.4 TD-CDMA and TD-SCDMA

Time-Division CDMA and Time-Division-Synchronous CDMA use CDMA channels (5 and 1.6 MHz, respectively) and apply TDMA by slicing in time. As such, TDD transmission is used and the same frequencies can be used for uplink and downlink transmission. This is a key feature that the scheme exploits to improve capacity.

TD-CDMA and TD-SCDMA are 3G technologies standardized by 3GPP with different chip-rate options: UMTS Terrestrial Radio Access (UTRA) TDD-HCR (High Chip Rate) and UTRA TDD-LCR (Low Chip Rate), respectively.

TD-SCDMA has been introduced in China. For more information, the reader is directed to www.tdscdma-forum.org and www.tdscdma-alliance.org.

1.2.4.5 OFDM and OFDMA

Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing technique that subdivides the available bandwidth into multiple frequency sub-carriers as shown in Figure 1-5. In an OFDM system, the input data stream is divided into several parallel sub-streams of reduced data rate (and thus increased symbol duration), and each sub-stream is modulated and transmitted on a separate orthogonal sub-carrier. The increased symbol duration improves the robustness of OFDM to delay spread. Furthermore, the introduction of the CP (Cyclic Prefix) can completely eliminate ISI (Inter-Symbol Interference) as long as the CP duration is longer than the channel delay spread. The CP is typically a repetition of the last samples of data portion of the block that is appended to the beginning of the data payload.

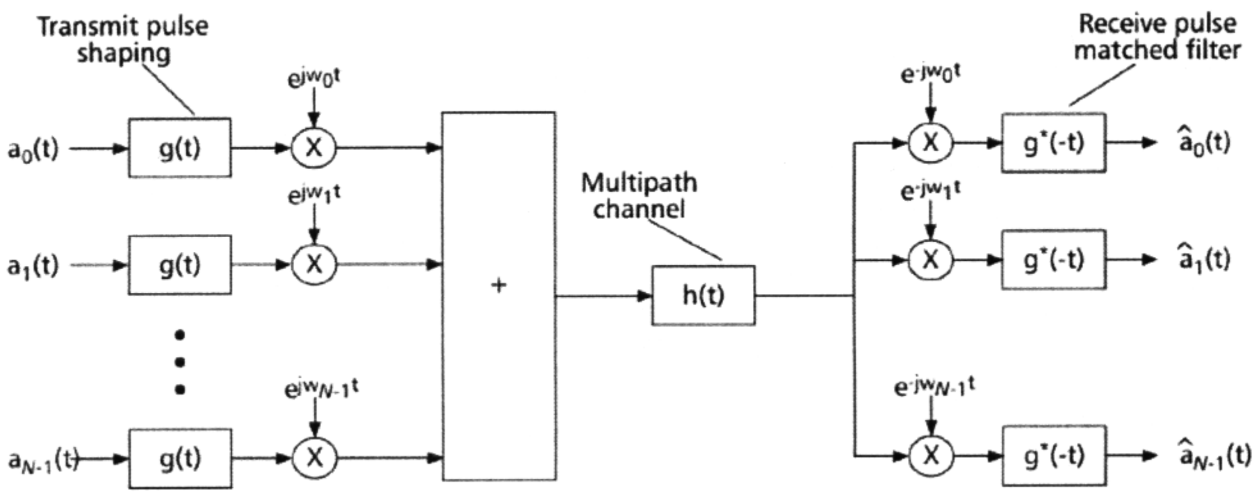


Figure 1-5: Basic Architecture of an OFDM System

OFDM exploits the frequency diversity of the multi-path channel by coding and interleaving the information across the sub-carriers prior to transmission. OFDM modulation can be realized with efficient IFFT (Inverse Fast Fourier Transform), which enables a large number of sub-carriers (up to 2048) with low complexity. In an OFDM system, resources are analyzed in the time domain by means of OFDM symbols and in the frequency domain by means of sub-carriers. The time and frequency resources can be organized into sub-channels for allocation to individual users.

OFDMA (Orthogonal Frequency Division Multiple Access) is a multiple-access/multiplexing scheme that provides for the multiplexing of data streams from multiple users onto the downlink sub-channels, and uplink multiple accesses by means of uplink sub-channels. This allows simultaneous low data rate transmission from several users. Based on feedback information about the channel conditions, adaptive user-to-subcarrier assignment can be achieved. If the assignment is done sufficiently fast, this further improves the OFDM robustness to fast fading and narrow-band co-channel interference, and makes it possible to achieve even better system spectral efficiency.

The OFDMA symbol structure consists of three types of sub-carriers as shown in Figure 1-6:

- Data sub-carriers for data transmission;
- Pilot sub-carriers for estimation and synchronization purposes; and
- Null sub-carriers for no transmission; used for guard bands and DC carriers.

Active (data and pilot) sub-carriers are grouped into subsets of sub-carriers called sub-channels.

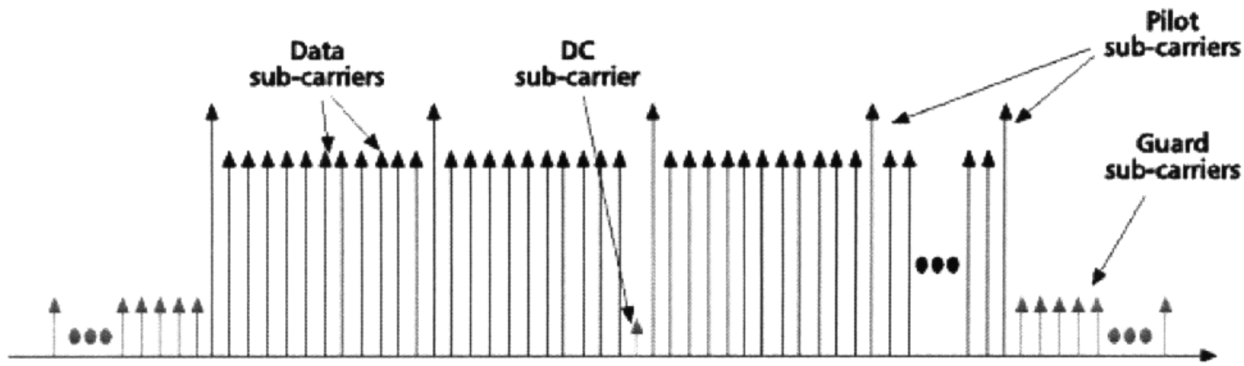


Figure 1-6: OFDMA Sub-Carrier Structure

OFDMA has certain elements of resemblance to CDMA, and even a combination of other schemes (considering how the resources are partitioned in the time-frequency space).

Put simply, OFDMA enhances the capacity of the system significantly and yet efficiently. Advanced OFDMA systems address such concerns as required flexibility in wide-area mobility, complexity in adaptive sub-carrier assignment, co-channel interference mitigation, and power consumption.

Advanced technologies such as systems beyond third-generation mobile are defined to leverage OFDMA's great potential for significant capacity and efficiency improvement, together with other innovations (e.g., in coding and modulation and in antenna technologies).

1.3 Mobile Cellular Architecture and Design Fundamentals

Mobile cellular networks have grown rapidly since the inception of commercial services in 1983. The network has evolved from pure circuit voice communications to high-quality voice and multimedia support and high-speed connectivity (access). The evolution of wireless mobile networks has been driven by the need to support mobile services, high efficiency, and the evolving user experience.

A simplified wireless network architecture is illustrated in Figure 1-7. The user terminal is wirelessly connected to and thus supported by a Base Transceiver Station (BTS). This base station and a number of others are connected to a Base Station Controller (BSC). Traditional circuit voice is supported through a Mobile Switching Center (MSC) both directly (not shown) and in connection to a Public Switched Telephone Network (PSTN). The BSC can also be connected to an IP Gateway to support various packet data services.

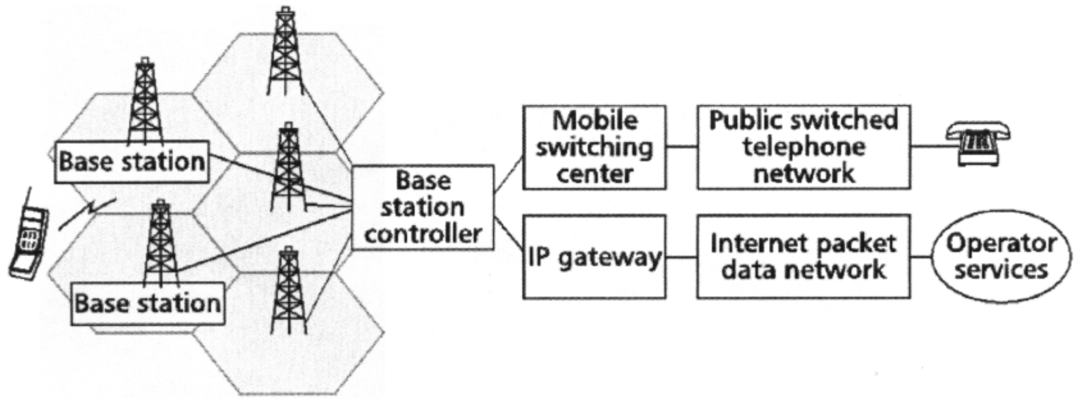


Figure 1-7: A Basic Wireless Cellular System

The quality of the wireless access connectivity is measured by the call drop rate, access failure rate, blocking probability, packet loss rate, and network reliability.

1.3.1 Capacity and Coverage

Capacity and coverage engineering are needed to achieve the desired access connectivity. Coverage is defined as the geographical area that can support continuous wireless access connectivity with the desired reliability and minimum guaranteed quality of service. It is heavily impacted by the terrain, RF environment, applications, and interference. Capacity is defined as the maximum number of users a network can serve with given resources and reliable access connectivity. It relies on traffic loading, traffic pattern, cell site equipment capability, and hardware dimensioning.

Some access mechanisms have a theoretically deterministic capacity based on their channel structure (e.g., FDMA and TDMA systems), while others may have dynamic allocation and allow some degradation (say in voice quality) in exchange for capacity (e.g., CDMA systems).

For example, a FDMA-based analog system (Advanced Mobile Phone System, AMPS) has a channel bandwidth of 30 kHz. Therefore, a 10-MHz cellular band can support 333 FDMA channels. With a frequency reuse of seven, this is equivalent to a radio channel capacity of 15 channels per sector for a site with three sectorized cells.

A TDMA system can further divide the time slot (typically) among three users and thus increase the capacity to 45 channels per sector.

CDMA capacity is a function of the required signal bit-energy-to-noise-density ratio (E_b/N_o), spreading factor (chip rate B_{ss} divided by data rate R), channel activity factor (D), sectorization gain (G_s), and frequency reuse factor (K). The maximal number of users a CDMA sector can support, or the reverse link (uplink) pole capacity, is

$$N = 1 + \frac{B_{ss}}{R} \cdot \frac{1}{E_b / N_o} \cdot \frac{1}{D} \cdot G_s \cdot K \tag{1}$$

For example, assuming 1.2288 Mb/s chip rate, 9.6 kb/s channel data rate, a frequency reuse factor of 0.66, and a channel activity factor 0.4, the uplink (or reverse) channel capacity is around 36 traffic channels in a three-sector cell for cdmaOne with a 7 dB requirement for E_b/N_o. This number increases to 72 for cdma2000-1x with the required E_b/N_o reduced to 4 dB. Typically, the cdma2000 operational capacity is around 50% of those maximal pole capacity numbers due to forward link interference limitations. This results in a commercial operational capacity of 36 users in 1.25 MHz, or around 288 users over 10 MHz.

The coverage area is determined by the operating frequency, radio receiver sensitivity, and required signal-to-noise ratio that an access technology can support. Typically, cellular network coverage is determined by the reverse link due to limited mobile station transmit power.

In a CDMA based system, the capacity and coverage enhancement are achieved by optimization of various power management components. This includes sector level and link level power management. Therefore, a CDMA system must be optimized from a system point of view, so that the system can tolerate a maximal interference level. Figure 1-8 implies that when the system loading is above 75% of the reverse link pole capacity, as specified in (1), the coverage will shrink dramatically.

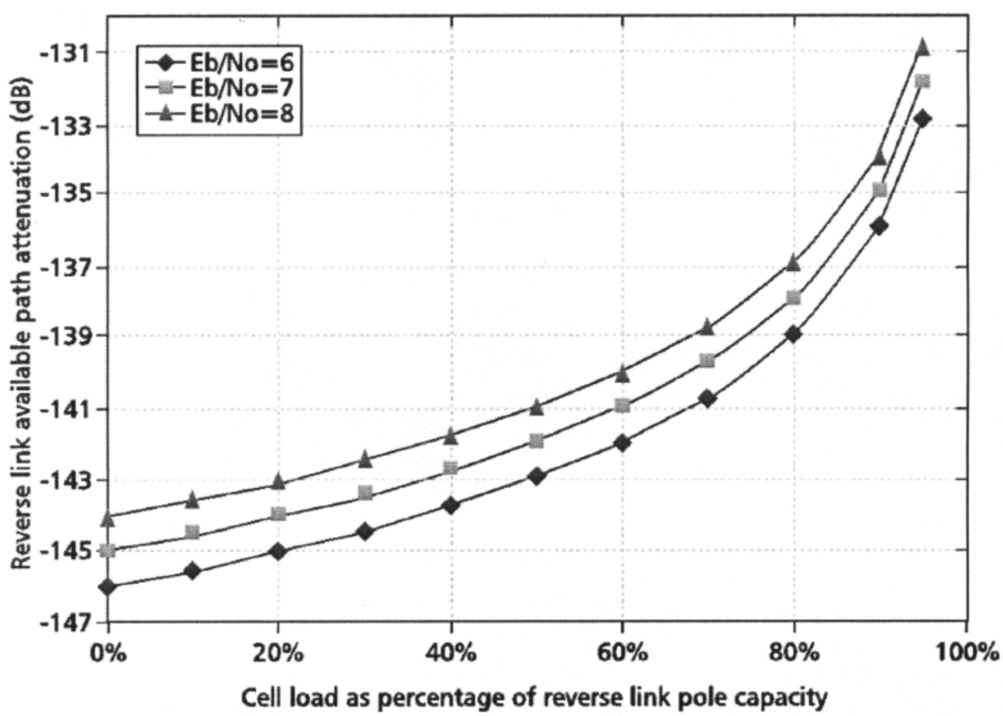


Figure 1-8: Capacity and Coverage of a CDMA Radio Network

This capacity and coverage tradeoff becomes even more important in support of IP multimedia services, where both impact the overall quality of service. Commercial cellular networks deployed worldwide have continuously grown through cell splitting and sectorization, in addition to technology advancements, to optimize capacity, coverage, quality, and cost considerations and trade-offs.

It is important to note that as in any other engineering practice, innovation, implementation, and the desired service and experience should be targeted while maximizing the cost efficiency. As indicated earlier, generally, the design of a low-traffic area (cell) is governed by coverage, and that of a high-traffic area by capacity, given performance requirements.

1.3.1.1 Wireless traffic load analysis

Distribution of traffic

The role of a wireless network is to supply voice and data over a sufficiently wide geographic area. On the demand side of the equation, there are assumptions regarding the number of subscribers who will use the network and the amount of traffic each subscriber will generate. It is not sufficient for the network to be able to supply traffic in aggregate to meet the aggregate demand, since demand varies with time and location. The goal of network design is for it to be highly probable that there is a sufficient supply of locally available network resources to satisfy the demand at any given point in time. This section will examine the distribution of traffic in both geography and time.

In the design of a network consisting of distinct cell sites and sectors, it is common practice to deploy higher cell site densities in densely populated areas since there is good correlation between population density and the level of traffic. However, there will always be sectors that carry much higher traffic levels than surrounding sectors despite attempts to equalize traffic. Consideration must be given to ensure that subscribers in busy sectors see acceptable performance, balanced with the service provider's desire to maximize utilization of network resources.

Traffic will also not be evenly distributed in time. Voice traffic exhibits a daily pattern which is observable at both the network level and sector level. Data traffic at the sector level appears to change randomly from one hour to the next making it much more unpredictable.

Spatial distribution of traffic

Once commercial service has begun, it is common practice to analyze sector traffic loading on a weekly basis. There are some differences between how voice traffic and data traffic are measured. It will be explained in the next section that voice traffic for a sector follows a fairly regular daily pattern while the sector data traffic level appears much more random due to its volatility. Because voice traffic appears more regular, a weekly traffic report will typically indicate how much voice traffic each sector in the network carries during a typical weekday busy hour. Busy hour voice traffic is measured in erlangs or equivalently minutes of use: 1 erlang is equivalent to 60 minutes of voice traffic. Since sector data traffic experiences much more volatility, there is no standard method for the weekly reporting of data traffic. For the exercise of examining the distribution of sector data traffic across a network, it will be assumed that sector data traffic is measured in bytes transmitted during the busy weekday hours (7AM – 10PM). Table 1-1 is an example of a weekly traffic report.

A large network is typically subdivided into a number of clusters. The average cluster in an urban area will consist of several dozen cell sites, with each cell site typically supporting three sectors. Rural clusters tend to have many fewer cell sites, typically 10 to 20 at most. When analyzing sector traffic distribution, it is advisable to restrict the analysis to one cluster at a time. Cell sites in the same cluster share the same morphology (i.e., urban, suburban, rural). The variation in sector traffic within a cluster is a function of some less observable random factor, whereas variation in sector traffic across different morphologies can be explained by differences in population densities. The sector traffic in Table 1-1 represents only a portion of the cell sites in a newly deployed urban cluster. The average busy hour sector voice traffic for the three dozen sectors shown in the table is 14 erlangs, while the average daily sector data traffic transmitted during the busy weekday hours is approximately 2.5 Gbytes. As can be seen, there are large variations in sector voice traffic and even larger variations in sector data traffic.

Sector ID	Voice Sector Traffic (Erlangs)	Data Sector Traffic (Bytes)
137_2	28.284	4,365,099,849
137_3	11.7	2,127,861,090
137_4	20.649	4,168,707,627
169_1	20.55	3,207,151,391
169_2	11.266	1,818,055,685
169_3	22.483	5,526,755,843
170_1	0.718	40,416,440
170_2	2.133	125,678,960
170_3	2.083	170,029,760
201_1	27.75	5,360,934,127
201_3	14.2	4,294,135,440
373_1	5.717	1,380,927,814
402_1	12.451	1,731,847,955
406_1	2.7	243,596,411
406_3	0.667	39,325,800
407_1	13.817	1,516,597,744
407_2	21.183	2,621,158,140
407_3	38.084	8,923,106,692
502_1	7.1	698,434,405
502_2	0.567	21,995,600
505_1	6.4	1,413,580,646
507_1	9.85	1,062,948,327
519_3	3.55	1,671,208,893
522_1	15.983	1,790,521,069
588_1	14.183	1,632,050,063
588_2	14.684	3,538,614,073
588_3	13.05	3,089,046,865
601_1	6.183	715,005,462
604_2	2.767	102,456,262
606_1	21.334	3,358,938,686
606_2	13.2	3,066,103,932
606_3	9.7	2,358,217,166
867_1	9.55	2,570,042,812
867_2	20.5	3,981,103,772
867_3	17.434	3,618,978,927
881_1	22.817	3,311,845,732

Table 1-1: Sample Weekly Traffic Report

Although obtaining the average and standard deviation of the sector traffic values for a cluster is useful, more insight can be gained by comparing the observed sector traffic values with different probability density functions. Below are histograms for voice (Figure 1-9) and data (Figure 1-10) traffic for two typical clusters alongside some possible probability density functions.

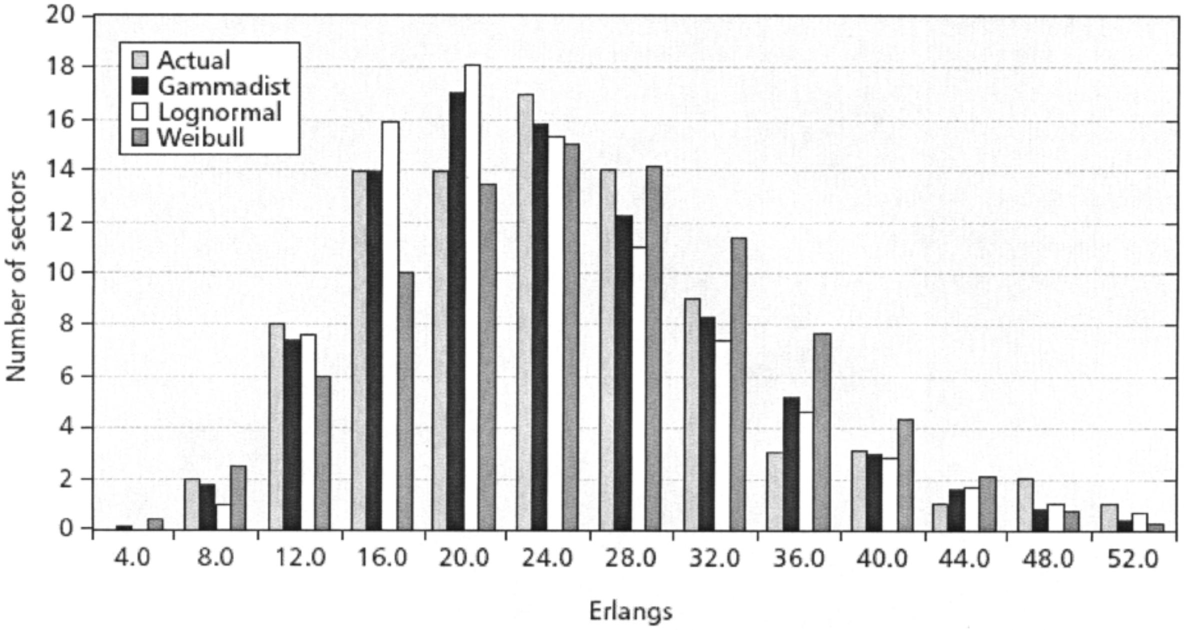


Figure 1-9: Voice Traffic Histogram for an Urban Cluster of Cell Sites

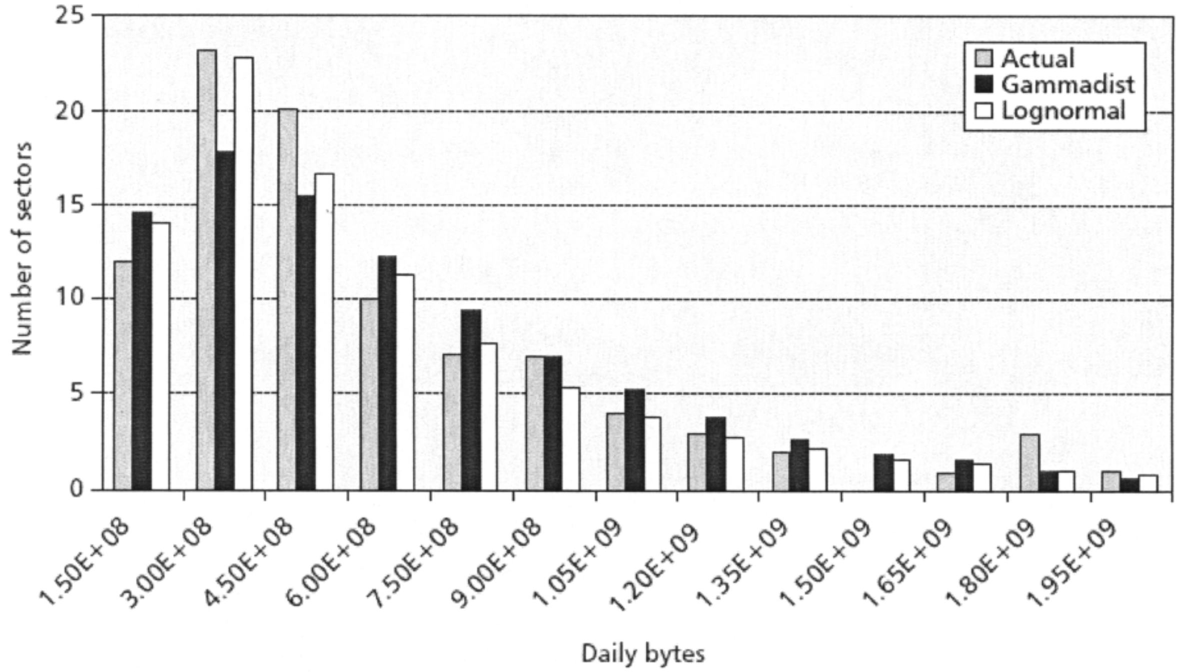


Figure 1-10: Data Traffic Histogram for an Urban Cluster of Cell Sites

Looking at the charts, it would appear that both the gamma and lognormal distributions match the voice and data traffic histograms quite nicely. The chi-square test is a tool for testing goodness-of-fit, and both the gamma and lognormal distribution pass the test for most clusters. It would be desirable if some explanatory model for traffic distribution were developed. However, there are insights that can still be obtained by assuming certain probability distributions. For example, it was mentioned above that sector data traffic exhibits greater variability than sector voice traffic. Assume that a sector is considered busy if its traffic is in 95^{th} percentile. Although only 5% of the cell sites are considered busy, those cell sites carry a disproportionate amount of the traffic. Assuming a certain probability distribution for data traffic, the busiest 5% of the sectors can carry 20% of the traffic in the cluster. Since voice traffic is more evenly distributed, the busiest 5% of the sectors will only carry 10% of the cluster traffic. Compared to voice traffic, it is twice as likely for data traffic in a sector to reside in the 95th percentile.

The distribution of traffic for a cluster is not stationary over long periods of time. When a network is first deployed, there will be large variations in sector traffic for both voice and data. Due in part to the network planner's effort to equalize traffic among the sectors, traffic tends to become more evenly distributed with cell splitting over time.

Time distribution of traffic

There is much literature on the modeling of voice and data traffic. Much of it is based on the study of stochastic processes and in particular Poisson models and queuing theory for the study of connection-oriented circuit switched voice traffic. Data traffic has not been so easily modeled since the Internet is used for a wider variety of applications. There has been evidence that shows that data traffic is statistically self-similar and that Poisson models used to analyze voice traffic do not capture the fractal behavior exhibited by data traffic. In any case, it is not the intention of this section to analyze the short term characteristics of voice and data traffic. Rather, the analysis here focuses on the daily patterns of voice and data traffic at the sector level. An analogy can be made between the characterization of RF fading and what is being proposed here in the analysis of the time distribution of traffic. RF signal strength fading is divided into two components: short term and long term fading. Short term fading is generally recognized as being Rayleigh distributed, while it is generally recognized that long term fading is log-normal and independent of the nature of the short term fading component. This section assumes that data traffic can similarly be divided into two components. Only the longer term components (hourly variations) will be examined while the short term statistics (traffic variations within the hour) will be ignored, or in the case of circuit switched voice traffic it can be assumed that the Poisson model can be applied. It should be mentioned that adherents of the fractal model of data traffic will argue that longer term traffic patterns should be analyzed simultaneously with the short term traffic patterns. To make the analysis simpler for those who do not have a strong background in probability, the short term and long term traffic patterns are analyzed separately with a focus on the longer term component.

Hourly sector voice traffic

Voice traffic has an easily recognizable daily pattern as can be seen in Figure 1-11, which is a five-day snapshot of the hourly traffic for three sectors of a particular cell site.

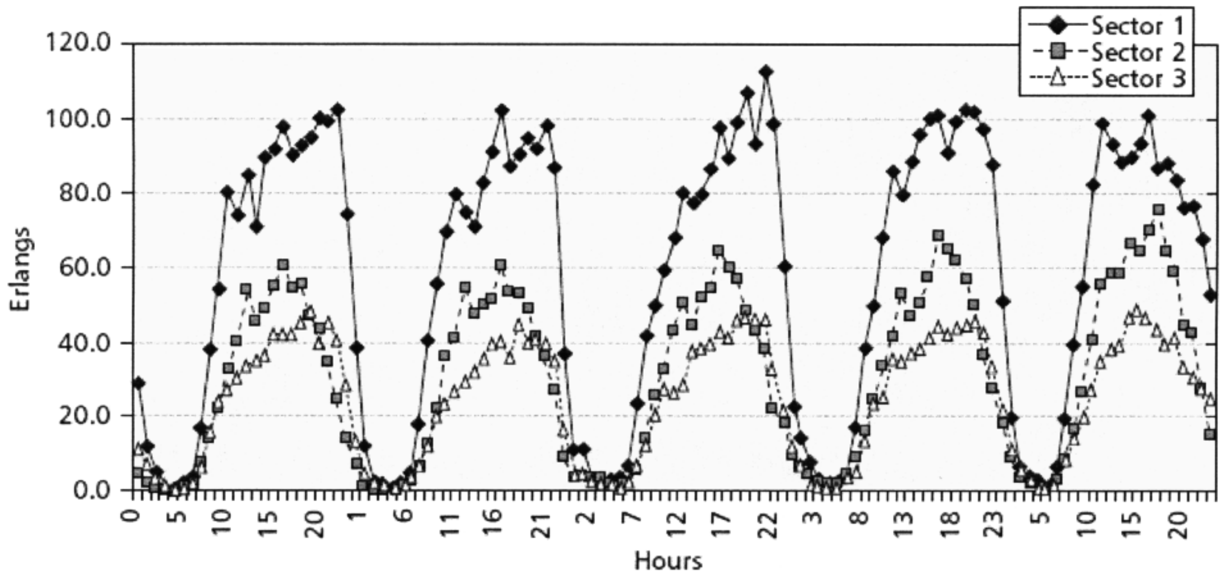


Figure 1-11: Hourly Voice Traffic for Three Sectors

The hourly traffic has a strong cyclical component with a less dominant random component superimposed. It is relatively easy to plan sufficient network resources to accommodate the voice traffic demand, due to the lack of day-to-day volatility in voice traffic. It is also relatively easy to calculate the relationship between monthly voice traffic and busy hour traffic for a particular sector. There are a couple of definitions for the term busy hour traffic, but it suffices to say it is a measure of the amount of traffic in the busiest hour of the day. On average, the monthly voice traffic for a sector is 300 times the busy hour traffic. Hence, if one is given the monthly voice traffic for a sector, the busy hour traffic can be calculated by dividing the monthly traffic by 300. If voice traffic were evenly distributed, the monthly voice traffic would be 720 times the busy hour traffic assuming there are 30 days in the month (744 times for a 31 day month). Ideally it would be beneficial to have the ratio of monthly traffic to busy hour traffic be as big as possible, since the network must be designed to carry the busy hour traffic.

Note the imbalance of sector traffic loading for the cell site shown in the above figure. This was examined in the section describing the spatial distribution of traffic. Depending on the technology deployed, it is possible for the busier sector to expropriate resources from less busy sectors to somewhat mitigate the effects of traffic imbalance.

Hourly sector data traffic

The hourly pattern for sector data traffic is much more volatile than for voice as can be seen in the traces shown in Figure 1-12, representing hourly data traffic for three different sectors over a one-week span.

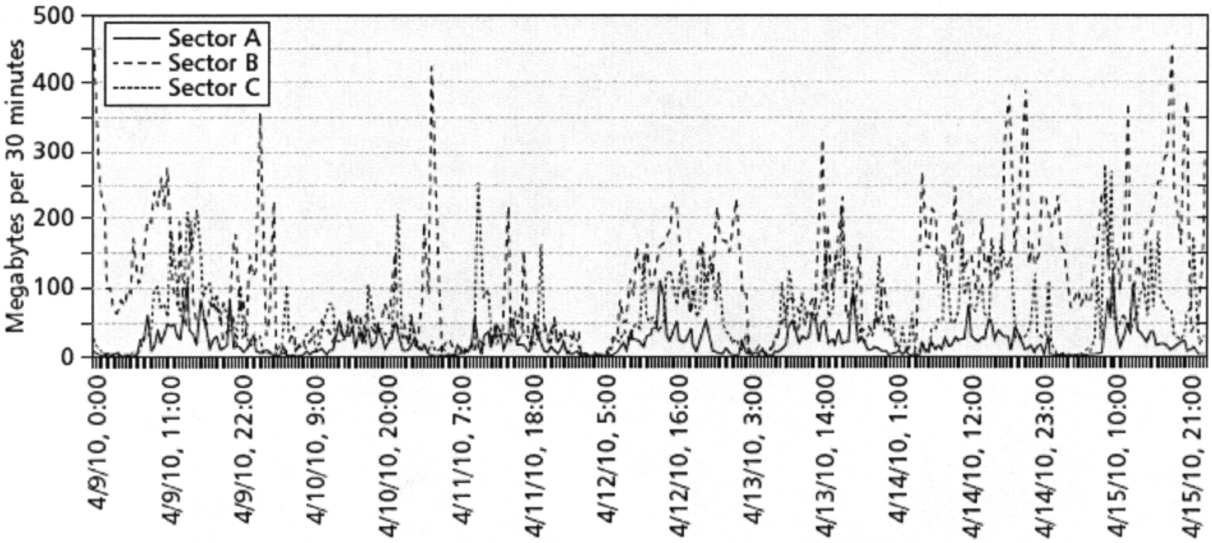


Figure 1-12: Half-Hourly Data Traffic for Three Sectors

As with voice traffic, there is a cyclical component since usage is definitely lower in the early hours of the morning. However, the random component of the data traffic is much stronger. If one takes the logarithm of the hourly sector data traffic, it appears that the resulting signal looks like white noise as can be seen in Figure 1-13, which is a 15 day trace for one sector.

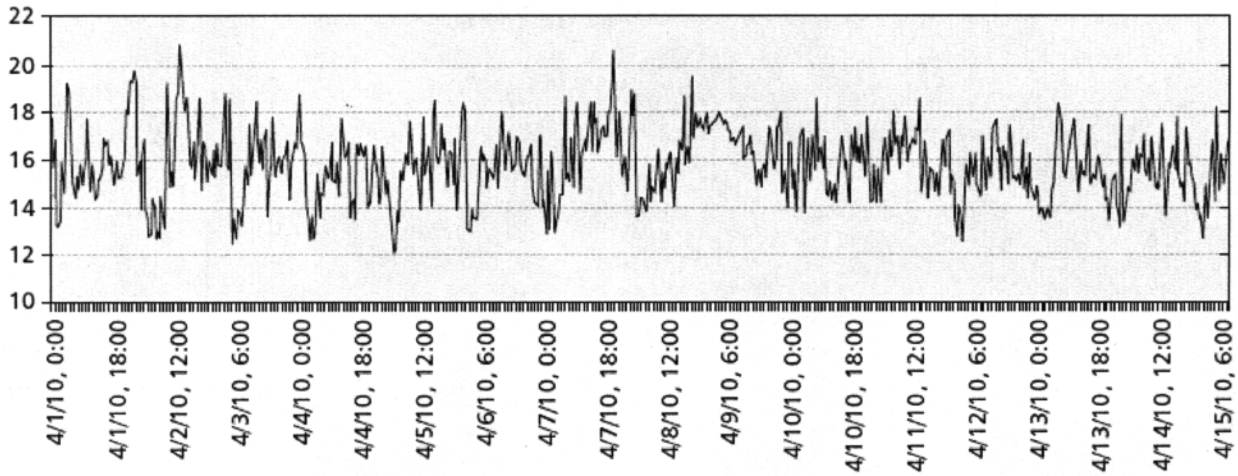


Figure 1-13: Logarithm of Half-Hourly Data Traffic for a Particular Sector

This suggests that the hourly traffic during the busy hours of the day should conform to a lognormal distribution. The histogram in Figure 1-14 compares the hourly sector data traffic with the lognormal probability distribution for a particular sector (early morning data traffic, from 1 AM to 8 AM is excluded).

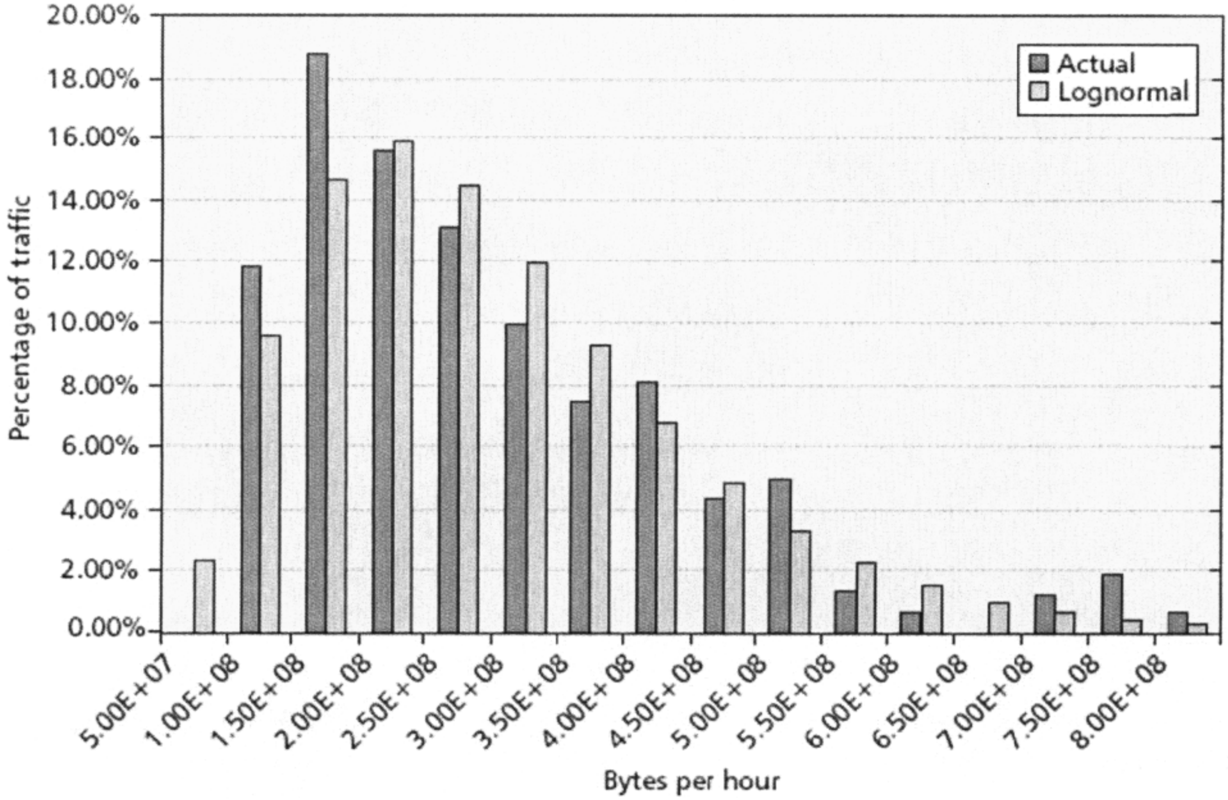


Figure 1-14: Histogram Comparing the Hourly Traffic with the Lognormal Distribution

The data in above graph pass the chi-square goodness-of-fit test for the lognormal distribution if the data traffic in the early morning hours is excluded.

Due to the volatility of data traffic, the concept of busy hour traffic is a bit more difficult to apply. If one were to use the same definition for busy hour traffic as used for circuit switched voice traffic planning, the monthly traffic would be 200 times the busy hour traffic. This means that data traffic is less evenly distributed in time than voice traffic. However, unlike voice, there could be certain hours where data traffic can significantly exceed the average busy hour traffic. Combined with the fact that the network will have busy sectors (often called data hotspots), it will be very difficult to accommodate data traffic spikes for every sector in a network all of the time.

1.3.1.2 Key access design considerations and trends for capacity and coverage

It must be noted that there is an increasing trend towards multi-cell design and seamless mobility across smart user spaces. Furthermore, networks become virtual in how they employ the physical network as suited to serve the intention/application and enhance the user's experience. To this end, network management, which is discussed at length in Chapter 3, becomes more dynamic, adaptive, and re-configurable (self-organizing). This is linked to access network design, deployment, and operation (such as performance optimization), and therefore is intimately linked to such wireless access considerations as coverage, capacity, and configuration plug and play (such as cell insertion and deletion), among others.

User access is becoming increasingly seamless across user spaces as shown in Figure 1-15.

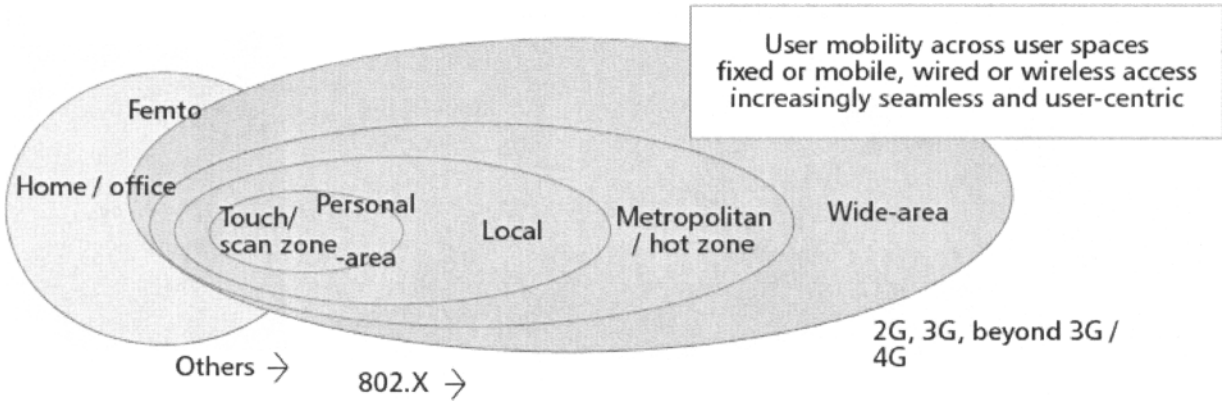


Figure 1-15: User's Seamless Mobility across Multiple Cells and Technologies

1.3.2 Mobility Management

1.3.2.1 Motivation

Mobility Management is responsible for supervising and controlling the mobile user terminal (or mobile station, MS) in a wireless network. The fact that a MS is not tethered and can move around freely presents an interesting set of challenges. Furthermore, the radio spectrum is a scarce resource that must be managed efficiently. Mobility management can be divided into registration and paging, admission control, power control, and handoff (also referred to as handover). Registration is to inform the network about the presence and location of the MS. Paging is the process by which the network alerts the MS to an incoming call or message. Admission control determines when the MS gets access to the network based on the priority of the request compared to network resource availability. Power control is necessary to keep interference levels at a minimum in the air interface and to provide the required quality of service. Handoff is needed in cellular systems to handle the mobility when the user is moving from the coverage area of one cell site to another, or to the service of another wireless technology. Figure 1-16 locates some of these features for a simplified radio access architecture.

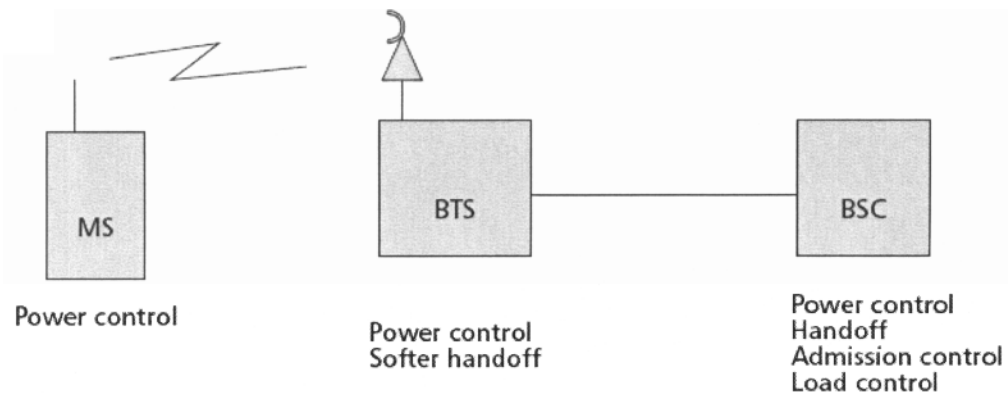


Figure 1-16: High Level Radio Access Architecture

Figure 1-17 shows the main states of the MS. Upon MS power up, the handset goes through an initialization state and acquires the preferred wireless network. Idle is the state the MS is in when not on an active call or connected to the network. Typically this is the state the MS is in the most. During this state the MS monitors overhead messages from the network or listens for incoming calls. System access refers to when the mobile attempts to access the network with the intent of setting up a traffic channel for a voice or data call. The connected or traffic state is when the MS has a dedicated connection to the network for the transfer of voice or data packets.

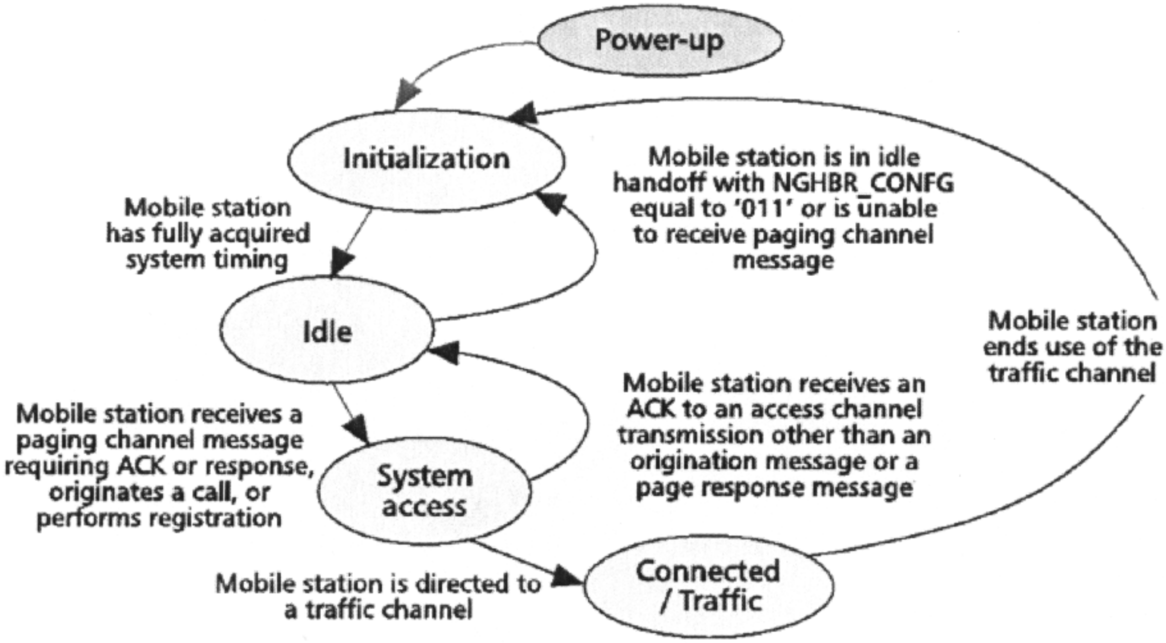


Figure 1-17: Main States of a Mobile Station

The concepts in this section are meant to provide perspective (and potentially examples) on mobility management considerations. It must be noted that differences do exist among various systems and advancements bring about new ways of doing things. Ultimately however, one can appreciate that a user device deals with powering up and down and moving between different modes and that it gets paged or registered and initialized, among other management functions.

1.3.2.2 Registration

Registration is the event by which a MS notifies the cellular system of its location, status, identification, and capabilities. The purpose of registration is to allow the network to efficiently page the MS when establishing a mobile-terminated call. Two types of registrations may exist:

i) Autonomous: triggered by some event or condition
   a. Power up registration – the MS powers on or switches serving system.
   b. Power down registration – the MS powers down (preventing unnecessary attempts to reach a user).
   c. Timer based registration – the MS registers when a timer expires. The timer is set by the network operator. This allows the system to de-register a MS that fails to register on power-down (i.e., moves out of coverage range).
   d. Distance based registration – the MS registers when the distance between the current base station and the base station where it last registered exceeds a specified threshold. This is particularly useful if the MS is not highly mobile.

   e. Zone based registration – the MS registers when it enters a new zone. A zone is defined by the network operator. Some technologies allow the MS to maintain a list of zones in which it is registered.

ii) Non-autonomous: explicitly requested by the base station or implied, based on other messages sent to the MS

   a. Parameter change registration – the MS registers when a specific parameter (e.g., frequency band) has changed.
   b. Implicit registration – this occurs when the MS and base station exchange messages which convey sufficient information to identify the MS and its location.
   c. Ordered registration – the base station orders a MS to register (e.g., while on a traffic channel).

Not all registration methods are necessarily supported for a given network. It will depend on vendor implementation and operator configuration to optimize overhead signaling due to registrations, as the frequency of registrations can place a high load on reverse access channels.

1.3.2.3 Paging

When a MS is powered on, after going through initialization and network selection process, it goes into an idle state. In this state, it listens to the network for overhead messages containing network information or pages indicating that a call is being made to the MS. In this idle state, the MS is monitoring what is commonly referred to as a paging channel.

There is a link between the amount of pages sent and the quantity of registrations. A balance is needed and proper system design is required to efficiently page the MS for mobile-terminated calls. The more often the MS registers, the more precisely the network knows its location so that paging can be targeted to a smaller group of cells, reducing messaging that consumes precious wireless channel capacity.

1.3.2.4 Slotted mode

Typically a MS spends much of its time in the idle mode. In order to conserve battery life and maximize standby time for a mobile terminal, wireless technologies implement a sleep or slotted mode of operation. In slotted mode, a MS is able to power down some of its electronics and periodically wake up to check for new overhead messages or page messages indicating there is an incoming call. The network and MS must be synchronized so that pages for a specific MS are broadcast when it is awake. The longer the sleep period, the better the battery life, but this comes at the expense of a longer duration to page the MS to complete an incoming call. A sleep period of between 2–5 seconds is typically found in mobile networks.

1.3.2.5 Admission control

The air link in a wireless system is a shared resource and is intended to support a finite amount of capacity or users. If new users were indiscriminately allowed to join the network, at some point they would start to have a negative impact on the existing wireless connections that have been established with other users. For example, in CDMA based systems, as more users are allowed to establish connections, loading increases on the forward and reverse links. In turn the power levels for the existing connections must increase to overcome this loading increase. For those existing connections at the cell edge, the MS and/or the base station may already be at maximum power, so with the increased loading, the call quality cannot be guaranteed.

Admission control adds network intelligence to the call establishment process so that before adding a new connection or user, the system first ensures that it has sufficient resources so as to not affect existing customers. As these resources can be on the forward or reverse links, both are looked at separately and a call is only admitted if it passes both forward and reverse link admission control. Resources that can be part of admission control include:

- noise rise (reverse link systems);
- base transceiver station (BTS) power (forward link CDMA systems);
- codes (for CDMA systems);
- available frequencies or timeslots (FDMA or TDMA systems); and
- call processing resources.

For example, for the reverse link noise rise criteria, new calls from a mobile would not be admitted by the admission control algorithm if the resulting interference is predicted to be higher than a pre-defined threshold value.

For voice calls, if admission control rejects a new user, it is treated as a blocked call and the user must try again later. However, some technologies allow calls to be re-directed to a neighboring cell if it has capacity and is deemed to be able to handle the connection due to overlapping coverage. For data connections, it is possible for the network to downgrade the throughput of existing data calls to allow more users access to the network.

1.3.2.6 Power control

To achieve high capacity and quality in wireless systems, they must employ power control. The goal of power control is to minimize the transmission power on both the forward and reverse links to conserve system resources and also minimize interference to other users.

In CDMA based systems, with all mobiles using the same frequency assignment, reverse link power control is fundamentally needed to ensure that each mobile signal will be received at the cell site at the same level to deal with the well known near-far problem. Because mobiles in a given cell are always on the move, some will be close to the base station and some will be much further away. The closer mobiles would have stronger signals back to the base station and cause unnecessary interference on the reverse link unless their power is controlled. In addition, system capacity is maximized if the transmit power of each mobile is controlled such that it is received at the base station with the minimum required signal level, to keep the system noise floor as low as possible. On the forward link, there is a different type of problem. Mobiles that are near the cell edge need more power from the base station than those that are close to the base station, for similar performance.

Reverse link power control is made up of an open loop, a fast closed loop, and an outer loop. Reverse link loop power control is made up of both an open loop and a fast closed loop. Reverse link open loop power control is determined by the mobile. It measures the received power level from the base station and adjusts its transmit power accordingly. If it receives a strong signal, it can determine that the path loss going back to the base station is low, and it therefore lowers its transmit power. The required mobile transmit power can be determined by a calibration constant which factors in cell loading, cell noise figure, antenna gain, and power amplifier output.

Reverse link closed or inner loop power control is a function of the base station. The goal of the closed loop component is for the cell to provide rapid corrections to the mobile's open loop estimate to maintain the optimum transmit power level. The cell measures the relative received power level of each of its associated mobiles and rapidly compares it to an adjustable threshold. Each mobile can then be instructed to increase or decrease its power level. This closed loop corrects for any variation required in the open loop estimate to accommodate gain tolerances and unequal propagation losses between the forward and reverse links. In the case of cdma2000-1x, closed loop power control operates at 800 Hz on both the forward and reverse links. In Wideband CDMA (W-CDMA), this mechanism operates at 1500 Hz.

The reverse link outer loop power control serves to maintain communications quality by setting the target for the closed loop by periodically adjusting a signal-to-interference (SIR) target or setpoint based on the frame error rate (FER). If the FER is low, this wastes capacity and thus the SIR target is decreased. If the frame error rate is poor, this affects quality and the SIR target is increased.

Similar fast closed and outer loop algorithms are also implemented on the forward link for cdma2000-1x and W-CDMA. An example is shown in Figure 1-18.

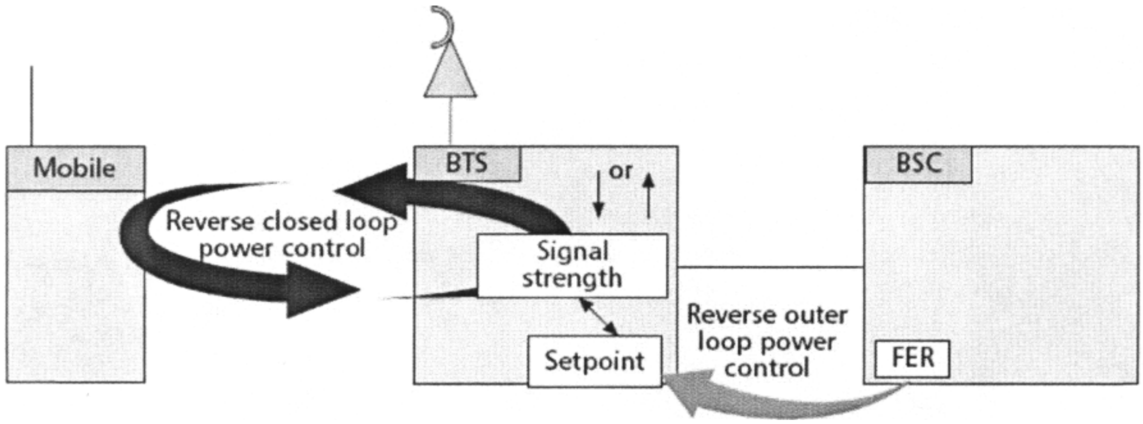


Figure 1-18: cdma2000-1x Reverse Link Power Control

1.3.2.7 Hand-off (inter-technology & intra-technology)

Hand-off (or handover) is one of the key features that enables a wireless network to support mobility. Hand-off is the ability to maintain communication between the MS and the network as the MS travels from the coverage area of one cell tower to another. As mentioned earlier, the two primary states of a MS are idle and connected mode and hand-offs are necessary for both.

In idle mode, the MS is monitoring the network for changes in network information or page messages for incoming calls. In order to receive these reliably, the MS should be communicating with the tower that can provide the best radio signal. This requires it to hand-off as the MS moves and the strongest signal comes from a new tower. Sometimes this process is also referred to as cell re-selection. When the MS is in idle state and communicating with a given tower, the network broadcasts information in the overhead messages about the surrounding or neighbor cells. The MS uses this information to periodically scan the strength and quality of the signals from neighboring towers, and if they are deemed to be better, the MS switches to the new tower to continue to listen to the network. This hand-off may trigger a registration criterion to be met so that the MS will update the network with its new location via a registration message. However, in many cases the network will not know or be concerned that the MS is monitoring a new tower.

In the connected mode, the MS has a voice or data connection with the network and reliable hand-off is even more important to maintain quality of service as the MS moves about. There are commonly two types of hand-off; soft hand-off and hard hand-off. Soft hand-off is also referred to as a "make before break" hand-off and hard hand-off is known as a "break before make" hand-off.

CDMA based technologies use a soft hand-off, which indicates that the MS is in communication with multiple base stations simultaneously, all with identical frequency assignments. This type of hand-off provides diversity on both the forward and reverse links at the boundaries between base stations. While connected, the MS is continually searching for the presence of neighboring sectors or cell sites by monitoring the quality of their pilot channels. If a pilot of sufficient strength is detected, the MS will send a message to the base station(s) with which it is communicating, containing information about the new pilot. If the base station decides that a soft hand-off should take place, it will check for and allocate resources at the new cell site and will send a hand-off message back to the MS directing it to perform a soft hand-off. Similarly, if a pilot with which the MS is in soft hand-off falls below a specific quality criterion, the MS will report this to the base station, and the network will remove this connection to the MS. With soft hand-off, as the MS moves from (say) cell A to B, cell B would be added to the MS as a hand-off leg before cell A is removed and hence this is described as a make before break hand-off mechanism. Softer hand-off is a special form of soft hand-off and applies to the situation where the MS is in hand-off with multiple sectors from the same cell site.

On the other hand, hard hand-off occurs when the MS transitions between base stations that operate on different frequencies or with different technologies. FDMA- and TDMA-based systems utilize hard hand-offs. In this situation the neighboring cell sites use different frequency assignments and the MS must retune itself to a new frequency assignment before it can continue the connection. Hence, this is known as a break before make hand-off. Hard hand-off can also apply to CDMA-based technologies when multiple frequency assignments are present (e.g., when a second carrier is laid on top of the first for capacity needs).

There is a fundamental difference in hand-off mechanisms between CDMA-based systems (cdma2000-1x or W-CDMA) and TDMA systems (GSM). TDMA uses discontinuous transmission, so there are gaps in time when the MS is not communicating with a base station. This provides an opportunity to make intersystem measurements with a single receiver on alternate frequency assignments or even technologies in the case of a GSM to UMTS hand-off.

On the other hand, CDMA-based technologies use continuous transmission and reception. Therefore, W-CDMA, as an example, introduces a compressed mode to create short gaps, on the order of a few milliseconds, in both the transmission and reception functions and provides the MS an opportunity to make GSM measurements.

1.4 Wireless Access Technology Standardization

1.4.1 Motivation

Wireless access standards are designed to specify users' connectivity to networks and access to services through a user terminal. In doing this, they define the essential functions and protocols, relying on and interacting with the user terminal capabilities at one end, and working with the core network at the other. An access technology is a transmission system to deal with communication through the wireless channels to achieve its connectivity and performance goals; it is designed as a multi-user sub-network with a multiple-access scheme, sharing of resources, and fast scheduling of simultaneous users.

As expected, standardized technologies aim to define interoperability and inter-working, a rich set of attributes, a graceful evolution path, and potentially strong product ecosystem. It must be noted that proprietary systems or system elements may also be introduced at different layers to provide differentiation, ease of implementation, or time-to-market advantage. The generations of wireless access technology, however, have increasingly been about standardized systems, building regional and global ecosystems, and enabling technology availability and user roaming. Typically, it has taken several years from the start of an access standard definition to its commercial launch, and naturally it typically stays in operation much longer. Recent years have seen explosive growth in wireless traffic, particularly given the increasingly mobile world, and have witnessed a proliferation of global deployments to provide high-speed wireless connectivity, communication, and content.

1.4.2 Design Goals and Technology Elements

It is intuitively appealing to think of a wireless access technology standard as one that has certain design attributes, in terms of:

- Connectivity, access;
- Mobility, coverage, roaming;
- Throughput, latency, performance, data symmetry;
- Efficiency; and
- Universality (technology availability, global ecosystem, user roaming).

Although these attributes are fundamental, there may be differences in how they are defined, depending on the system's role and its requirements:

- Low or high mobility;
- Personal-area, local-area, hot-zone/metro, wide-area, near-field (scan-zone);
- Satellite or terrestrial; line-of-sight (LOS) or non-LOS; and
- Indoor coverage extension or home network (e.g., Femtocell)

So far in this section, the goals and requirements, or attributes from a user or an application viewpoint, have been identified (i.e., what and why). An insight into technology elements and functional capabilities should then follow to address these goals and requirements in their phased evolution (i.e., how).

To meet particular system requirements, a number of technology elements may be expected to be outlined in a standard, and during its evolution through generations of access technology:

- Coding, modulation, spectral efficiency, round-trip transmission, receiver structure;
- Antenna technology, diversity, channel bandwidth and structure, FDD vs. TDD;
- Multiple-access mechanism, user-access scheduling; and
- Resource sharing and allocation, power management, topology and distribution architecture.

Although an access standard is generally not tied to any particular frequency band, the latter has significant impact on access technology planning and development. The implications of choosing one band vs. another include coverage, interference considerations, (indoor) signal penetration, line-of-sight constraints, user terminal ecosystem and availability, and potentially capacity.

We must bear in mind that there is no fixed definition for "access" technology and its boundaries. Different wireless networks are defined, some with different levels of architectural and functional details; moreover, the functions themselves evolve, while the entire network may be becoming more distributed and flatter, heteregenous, and with intelligence moved to the edges.

1.4.3 Technology Framework Definition and Standardization

The International Telecommunication Union (ITU) is the leading United Nations agency for information and communication technologies. It has three core sectors, radiocommunication, telecommunication standardization, and telecommunication development, in addition to organizing global telecom events. The radiocommunication sector (ITU-R) in particular has several Study Groups, on such topics as spectrum management, radiowave propagation, satellite services, terrestrial services, broadcasting services, and science services (http://www.itu.int/ITU-R).

A framework for the third generation (3G) network has been defined by ITU's International Mobile Telecommunications – 2000 (IMT-2000) family. The concept was born as early as the mid-1980s and the framework matured by 1999. This motivated global collaboration to define 3G standards with such design goals as flexibility, interoperability, affordability, compatibility, and modularity in mind. ITU-R Recommendation M.1457 [ITU11] identified five radio interfaces, while a sixth (based on WiMax, Worldwide Interoperability for Microwave Access) air interface was added to this family in 2007:

- IMT-DS (Direct Sequence) – W-CDMA/UTRA FDD
- IMT-MC (Multi-Carrier) – cdma2000
- IMT-TC (Time-Code) – UTRA TDD (TD-CDMA, TD-SCDMA)
- IMT-SC (Single Carrier) – EDGE
- IMT-FT (Frequency-Time) – DECT
- IMT-OFDMA TDD WMAN (Wireless MAN) – WiMAX

IMT-Advanced was subsequently defined through a set of requirements issued by ITU-R starting in 2008 for 4G mobile phone and Internet access services.

The industry players in telecommunications, computing, broadcasting, and applications, whether manufacturers, developers, service providers, or operators, have been involved for years in the development of wireless technology standards. With the growth of mobile communication, advances in technology, availability of new spectrum, and the need for universal cost-effective solutions to enable rich systems and ecosystems, broad terminal availability, and users' ability to roam, third-generation (3G) standards have been defined through global partnership projects (GPPs) involving standards bodies from different regions. Specifically, 3GPP and 3GPP2 have specified wireless access technologies (among others) for 3G and beyond.

The 3rd Generation Partnership Project, 3GPP, was established in 1998. The collaborating regional standards bodies, known as Organizational Partners, include the Association of Radio Industries and Businesses (ARIB), the China Communications Standards Association (CCSA), the European Telecommunications Standards Institute (ETSI), the Alliance for Telecommunications Industry Solutions (ATIS), the Telecommunications Technology Association of Korea (TTA), and the Telecommunication Technology Committee (TTC, Japan). The project is run by a Project Coordination Group, under which there are four Technical Specification Groups, each with a number of working groups (see Figure 1-19; more details can be found at http://www.3gpp.org).

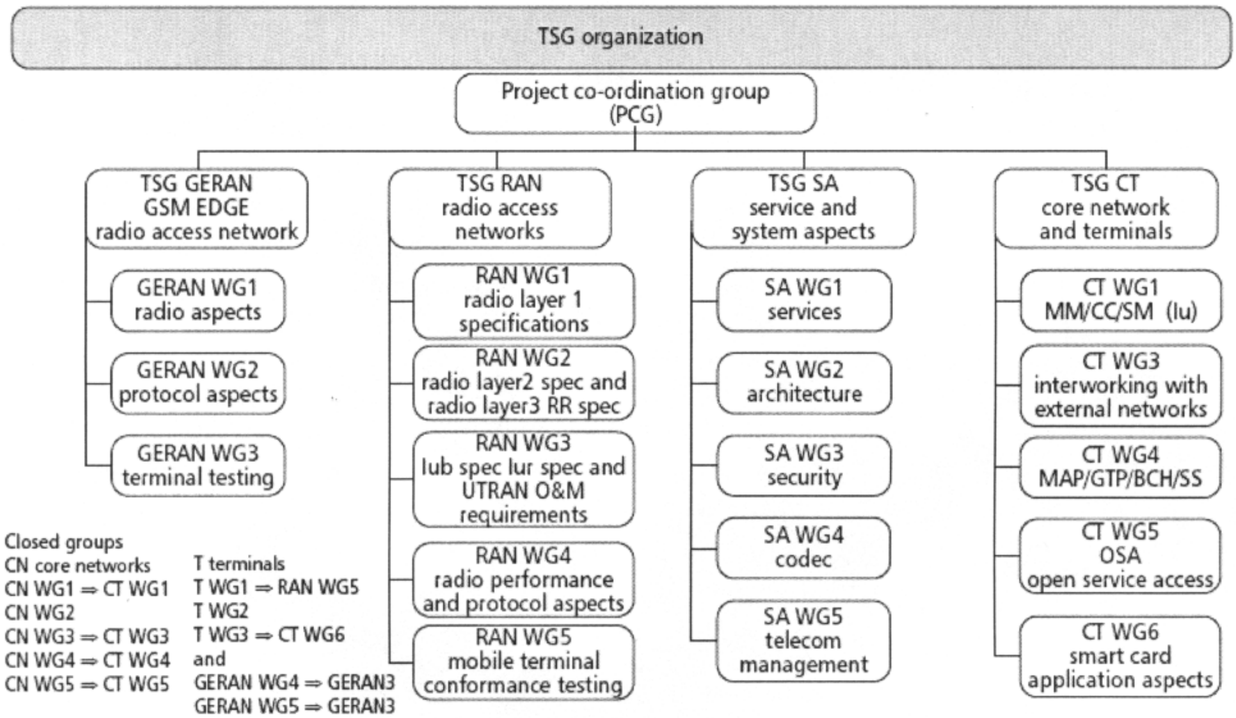


Figure 1-19: 3GPP Project Coordination and Technical Specification Structure

The scope of 3GPP has covered 3G systems based on evolved GSM core networks and the radio access technologies they support, Universal Terrestrial Radio Access (UTRA – both FDD and TDD), in addition to the maintenance and evolution of GSM technical specifications and reports, including evolved radio access technologies such as GPRS and EDGE. It has further defined systems beyond 3G and the phased evolution of IP networks, specifically Long-Term Evolution (LTE) and Evolved Packet Core (EPC). The work has been published in a number of Releases (e.g., Release 10 published in mid-2011). The technologies are described further in subsequent sections.

In parallel, 3GPP2 was born, inspired by the 3GPP partnership project concept, and out of the IMT-2000 initiative, with a focus on global specifications for systems (supported by ANSI/TIA/EIA-41 [ANS01]) towards 3G (cdma2000) and beyond (Ultra Mobile Broadband, UMB). 3GPP2 organizational partners include the regional standards bodies ARIB, CCSA, TIA (the Telecommunications Industry Association), TTA and TTC. Figure 1-20 shows the structure of the 3GPP2 Technical Specifcation Groups.

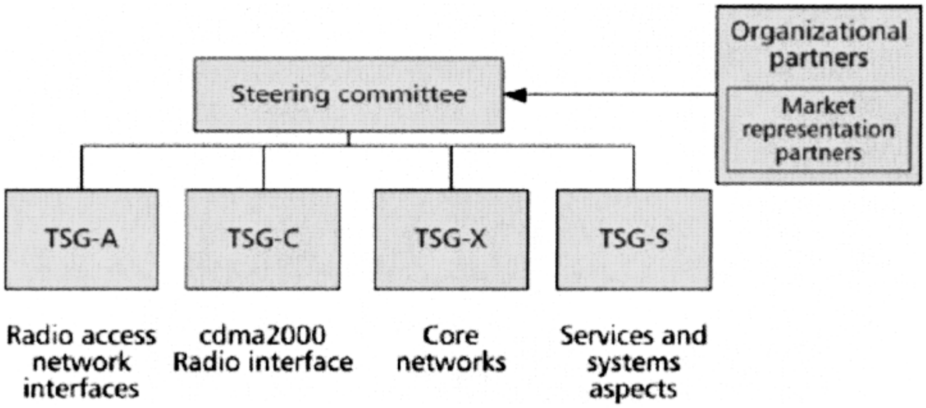


Figure 1-20: 3GPP2 Technical Specification Structure (Working Groups not Shown)

The IEEE has been involved in the creation of a broad range of standards in a wide range of areas within its scope (see http://standards.ieee.org). In particular, IEEE Project 802 (or 802 LAN/MAN) has developed standards with focus on the data link and physical layers, the bottom two layers in the Open Systems Interconnection (OSI) layered architecture and the corresponding sub-layer structure. The many working groups within the Project 802 family include those that focus on wireless technology standards, extending to personal-area networks (PANs), including:

- IEEE 802.11 – Wireless LAN;
- IEEE 802.15 – Wireless PAN;
- IEEE 802.16 – Broadband Wireless Access; and
- IEEE 802.20 – Mobile Broadband Wireless Access.

These, along with the working group for wireless sensor standardization, form the so-called IEEE Wireless Standards Zone. Each of these work streams covers a range of specifications that typically evolve in versions, revisions, or support of user requirements. For example, the 802.16 working group has specified broadband wireless access across all scenarios of fixed, nomadic, or high user mobility within a wide-area network. Furthermore, industry forums work extensively to further define, certify, and promote related technologies, variety of profiles, and products. Again as an example, the WiMAX Forum, with a number of working groups, certifies and promotes the compatibility and interoperability of broadband wireless products based on the harmonized IEEE 802.16/ETSI HiperMAN (High Performance Radio Metropolitan Area Network) standard (see http://www.wimaxforum.org).

1.4.4 Mobile Technology Generations and Nomadic Implementations

Figure 1-21 shows a simplified view of mobile cellular access technology evolution, in addition to highlighting nomadic broadband wireless access. Not all technologies or evolutionary steps are shown. Moreover, the context (e.g, Generation label) may not necessarily represent all scenarios accurately.

To provide an understanding of these technologies, the GSM evolution path (3GPP), Interim Standard IS-95 (cdmaOne) evolution path (3GPP2), IEEE 802.11 (WLAN), IEEE 802.16 (WiMAX), and OFDMA-based technologies beyond 3G are outlined in some detail in subsequent sections, in addition to an introduction to personal, home, and near-field communications.

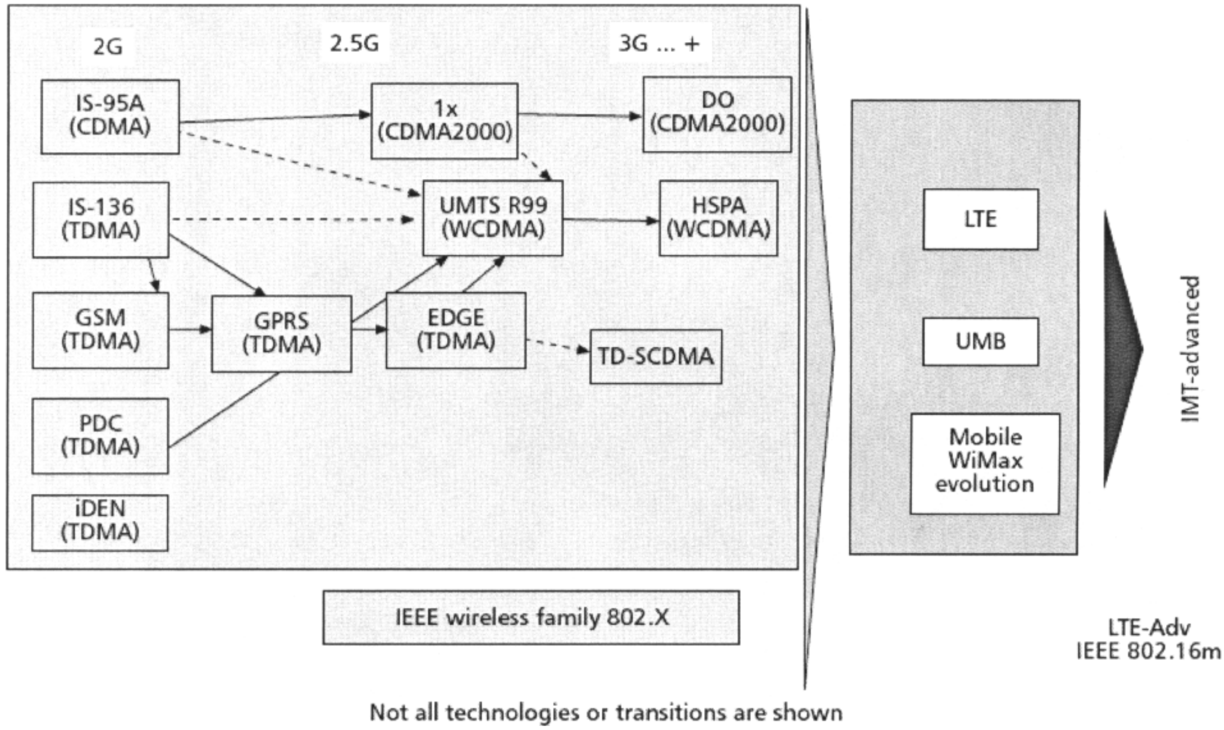


Figure 1-21: Evolution of Mobile Access Technologies

1.5 Digital Mobile Cellular Technologies – GSM to LTE

The preceding sections outlined wireless access technology design and spectrum considerations, multiple access schemes, mobility management, and standards definitions. In this section, a number of global wide-area mobile access technologies are discussed in some detail, including those of the second and third generations, based on TDMA and CDMA. OFDMA-based wide-area technologies are discussed later in the section on beyond 3G.

Again, it must be noted that the goal in this chapter has been to provide an end-to-end appreciation of wireless access technologies, with some details, particularly on global mobile and nomadic technologies. As such, it is neither inclusive of all technologies and scenarios, nor does it provide comparable details about competing or complementing technologies. Furthermore, every implementation has its own attributes and rationale, based on its own market, context/history, goals, and roadmap, with parameters which may vary from those represented in standards, or presented here. Similar concepts and mechanisms, however, apply to a variety of wireless access technologies, depending on applications and features, enabling technologies, architectural layers and details, and also ecosystem maturity.

1.5.1 3GPP Wireless Access Technologies

The GSM evolution path and wireless access standards specified by 3GPP are described in further detail in this section. The section starts with the widely implemented TDMA-based technologies of GSM, GPRS, (and briefly) EDGE, followed by UMTS Phase 1, and then High Speed Packet Access (HSPA) evolution. Long Term Evolution (LTE) is later discussed in some detail.

As also suggested in Figure 1-21 on the evolution of access technologies, the movement between different paths varies, based on needs and roadmaps. For example, operators with PDC or 3GPP2 technologies may have chosen to implement UMTS technologies, or a 3G operator may be in a position to choose any of the OFDMA-based technologies in its roadmap beyond 3G. As a significant example, LTE has gained global interest by virtually all mobile communication players.

1.5.2 GSM, GPRS, EDGE

In this section, we describe the evolution and enhancements of the GSM/UMTS standards and networks from GSM phase 1 to HSPA. GSM Phase 1 is a circuit-switched mobile network technology using TDMA, providing voice services and short-message service (SMS). The subsequent phases of GSM introduced packet services (GPRS) while keeping some fundamental principles such as TDMA radio transmission, the Mobile Application Part (MAP) signaling protocol for roaming, and the security features. UMTS phase 1 (often referred to as Release 99) has kept the network principles of GSM and GPRS but has a completely new radio access interface based on CDMA.

1.5.2.1 Main principles of GSM

GSM is a mobile digital technology developed in several phases. Though a second generation (digital) system (2G), the main principles of GSM phase 1 were set as early as 1987. It was primarily optimized to provide circuit switched voice services, although basic data services, notably SMS, were soon introduced. This section describes the radio interface of GSM and the main architectural principles of GSM phase 1.

GSM radio interface

The GSM radio interface is based on the FDD mode and TDMA with eight time slots per radio carrier. In other words, each uplink time slot is paired with a downlink time slot. Each radio carrier requires a 200-kHz uplink and a 200-kHz downlink. A time slot may be used for one of the following sets of logical GSM channels, although there are other possibilities: one TCH (Traffic Channel) full rate, two TCHs half rate, eight SDCCHs (Stand Alone Dedicated Control Channels), or one CCCH/BCCH (Common Control Channel, Broadcast Control Channel). The TCHs are used to transmit voice or data whereas the SDCCHs can only be used for signaling purposes or SMS transmission.

In Europe, the Middle East, Africa, and Asia, the GSM system generally operates in the following bands:

900 MHz (174 radio carriers):	Uplink: 880-915 MHz	Downlink: 925-960 MHz
1800 MHz (374 radio carriers):	Uplink: 1710-1785 MHz	Downlink: 1805-1880 MHz

In the Americas, on the other hand, the operating band is as follows:

1900 MHz (298 radio carriers):	Uplink: 1850-1910 MHz	Downlink: 1805-1880 MHz

It should be noted, however, that GSM is defined independently of the frequency resources meaning that it can operate in other bands as well.

A generic example will help explain what this means for a GSM operator. A typical spectrum allocation for a GSM operator may be 20 MHz which is sufficient for 100 carriers. A frequency reuse scheme will generally be used. As a result, around eight carriers may be available in each cell, which means 64 TDMA time slots per cell. Among these, four time slots may be used to accommodate the signaling traffic (for instance one timeslot for the CCCH/BCCH and three other timeslots to provide 24 SDCCHs). Therefore, 60 timeslots are available in each cell to accommodate voice traffic. If only Traffic Channel

Full Rate Speech (TCH/FS) is used, this allows 60 simultaneous voice calls. If Traffic Channel Half Rate Speech (TCH/HS) is used exclusively, 120 simultaneous voice calls are possible.

Protocol aspects

The signaling protocols of the radio interface are divided into a structure of three layers, which is similar to that of the DSS1 (Digital Subscriber Signaling System 1) protocols on the D channel in ISDN (Integrated Services Digital Network) and which is based on the OSI reference model.

According to the configuration requested by the mobile station, Layer 2 offers either a connectionless information transfer in unacknowledged mode (on point-to-multipoint or multipoint-to-point channels) or connection-oriented information transfer in acknowledged mode on a dedicated control channel. Layer 3 of the radio interface is subdivided into three sub-layers: Radio Resource (RR), Mobility Management (MM), and Connection Management (CM). The CM sub-layer comprises parallel entities: Supplementary Services handling, Short Message Service, and Call Control (CC).

GSM Phase 1 architecture

The radio coverage of a cell is provided by a Base Transceiver Station (BTS). Each BTS is linked to a BSC (Base Station Controller); a BSC and the BTSs which are linked to it constitute a BSS (Base Station Sub system). Each BSC is linked to a MSC (Mobile Switching Center), as shown in Figure 1-22. The interface between the BSS and the NSS (Network Sub-System) is called the A interface. Viewed physically, information flows between mobiles and BTSs, but viewed logically, the mobile communicates with entities in the BSS and in the MSC. Layer 1 and Layer 2 are handled by the BTS, the RR sub-layer is handled by the BSC and the MM and CC-sub-layers are handled by the MSC.

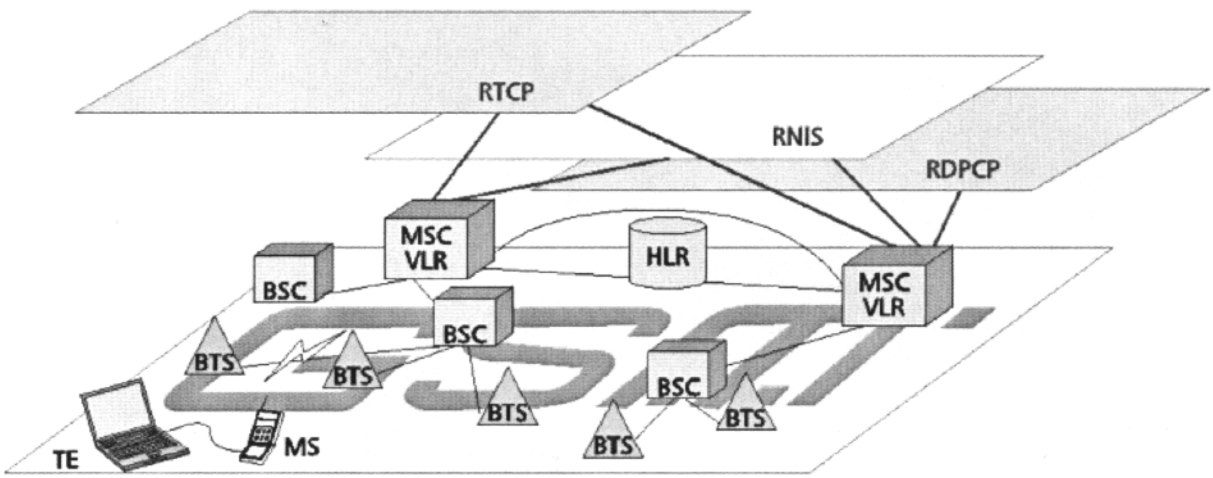


Figure 1-22: Basic Cellular (GSM) Network Architecture

There exist in fact slight exceptions to these general rules but this mapping essentially means:

- The BTS handles the radio transmission.
- The BSC organizes the allocation, release, and supervision of the radio channels, these actions being performed according to commands received from the MSC.
- The MSC handles the call establishment and call release, the mobility functions, and every aspect related to the subscriber's identity.

Schematically, the behavior is as follows: the MS makes a first access on the RACH (Random Access Channel, a multipoint to point channel) of the selected cell. In response to this, the BSC allocates the MS a first dedicated channel. After the MS has seized this radio channel, a dedicated link will exist between the MS and the BSC; the MS uses this link to send an initial message which includes its identity and the reason for the access (e.g., a requested service). Upon receipt of this message, the BSC establishes a signaling connection with MSC dedicated to this MS.

The core elements of a GSM network include the Mobile Switching Center (MSC), the Home Location Register (HLR), and the Visitor Location Register (VLR), as key functional elements. The MSC has an interface with the BSC, on the access side, and to the back-end and fixed networks, as indicated earlier. The MSC is a digital exchange entity, able to perform all necessary functions to handle the calls to and from mobile subscribers located in its area, and furthermore, it is able to cope with the mobility of the subscribers, using the HLR and VLR. The signaling exchanges between these entities are specified in the Mobile Application Part (MAP), which is the protocol used to provide roaming.

Core network technologies and architectures are covered in detail in Chapter 2.

SIM features in GSM

The GSM mobile station (user terminal) has two distinct elements: the mobile equipment which is able to connect with the network, and a chip card (namely the Subscriber Identity Module, SIM) which contains all subscriber-related data. There is a standardized interface between these two elements. Although, much of this is a back-end and networking concern, a brief overview is offered in here to complete the notion of access using the SIM. The data stored in the SIM include:

- The International Mobile Subscriber Identity (IMSI);
- The Ki key; which is linked to the IMSI and is allocated at subscription and stored unchanged; and
- The authentication security algorithm A3 and the key generation security algorithm A8.

These data are used for two security features, namely the authentication procedure and ciphering. The authentication procedure enables the network to validate the mobile subscriber identity, and thus protects the network against unauthorized use. When the MSC receives a mobile identity (IMSI) transmitted on the radio path, it triggers an authentication procedure. The network sends a random number RAND to the mobile station in order to check that it contains the Ki linked to the claimed IMSI. The Mobile Station applies algorithm A3 to RAND and Ki in order to compute the answer to be sent to the network.

The purpose of the ciphering procedure is to prevent an intruder from listening to what is transmitted over the radio interface. This protection covers both the signaling and the user data, for both voice and non-voice services. The layer 1 data flow transmitted on dedicated channels (SDCCH or TCH) is the result of a bit-per-bit addition of the user data flow and of a ciphering stream generated by the ciphering/deciphering algorithm. This algorithm uses both a ciphering key and the TDMA frame number. The ciphering key (Kc) is computed independently on both the MS side and the network side by the authentication procedure; algorithm A8 is used to derive Kc.

The SIM card is provided by the network operator; thus the network operator can control the security features even in a roaming situation. In addition, the SIM serves as a tool to support other features and services. See section 3.5.4 for more on the SIM and GSM security.

1.5.2.2 GPRS and EDGE – GSM evolution

After the success of GSM phase 1, it became necessary to define new features in GSM networks. These included service consistency even when roaming outside the home network, enhanced throughput to support data services, and the ability of the SIM to become an active device able to control the MS (SIM toolkit). These new features were developed to be compatible with legacy user devices, and their introduction was optional.

Introduction of packet mode in GSM

Data services were already defined in the first phase of GSM. These were circuit-switched data services which yielded the allocation of a TCH (one TDMA timeslot). The throughput was very low, typically 9.6 kb/s. Therefore it was highly desirable to increase the throughput of the radio interface. One method to achieve this for a given call is to utilize more than one TDMA time slot on the radio interface. Such a feature has been standardized as HSCSD (High Speed Circuit Switched Data). The main advantage of HSCSD is its simplicity. The GSM MSC and A interface are unchanged as long as the number of utilized time slots is equal or less than four, because in these cases a 64 kbits/s circuit is sufficient on the A interface. The drawback of HSCSD is its inefficient use of radio resources.

To solve this problem another service was designed, GPRS (General Packet Radio Service). GPRS is a set of GSM bearer services that provide packet-mode transmission and interworking with external packet data networks. GPRS allows the service subscriber to send and receive data in an end-to-end packet transfer mode without utilizing network resources in circuit-switched mode. The service aspects of GPRS are specified in GSM 02.60 [3GP99] and the technical realization is specified in GSM 03.60 [3GP98].

To accommodate sporadic transfers of large volumes of data, GPRS encompasses allocation and release mechanisms that optimize the use of the radio resources. During a data call, these resources (i.e., one or more time slots) are allocated only when data is being transmitted; they are then released, although the data-transfer session can be kept between the MS and the network. In addition, GPRS is well suited to asymmetric data transfer, typically with larger downlink speed. To take that into account, GPRS can allocate more time slots in the downlink than in the uplink.

GPRS was designed to allow a smooth sharing of radio resources between speech and data. In order to accommodate the data traffic, the network operator can decide for each radio carrier how many timeslots are allocated to GPRS traffic and how many timeslots are allocated to voice traffic. This sharing can be performed dynamically.

With a time slot, the following throughputs can be obtained over the radio interface according to the different coding schemes:

CS-1: up to 9.05 kb/s CS-2: up to 13.4 kb/s CS-3: up to 15.6 kb/s CS-4: up to 21.4 kb/s

More than one time slot can be allocated for a data transfer. Typically, a GPRS MS may allocate up to four time slots in the downlink and two time slots in the uplink, thus allowing up to 85.6 kb/s in the downlink.

GPRS architecture

GPRS was designed to allow network operators to reuse the radio coverage deployed for voice. In addition, it was necessary to define two new functional entities on the core network side:

- The Serving GPRS Support Node (SGSN) is the node that controls the BSC serving the MS. It handles mobility, paging, security features, and interface with the BSC.
- The Gateway GPRS Support Node (GGSN) works with the packet data networks (fixed and mobile). It is connected to the SGSN through an IP network; it contains routing information for GPRS users.

These network entities have been defined to work with IP networks.

After the rollout of GPRS, a GSM network includes circuit-switched and packet-switched domains. The basic architecture is shown in Figure 1-23. For a detailed discussion of GPRS architecture, including the SGSN and GGSN, see section 2.3.3 in the next chapter.

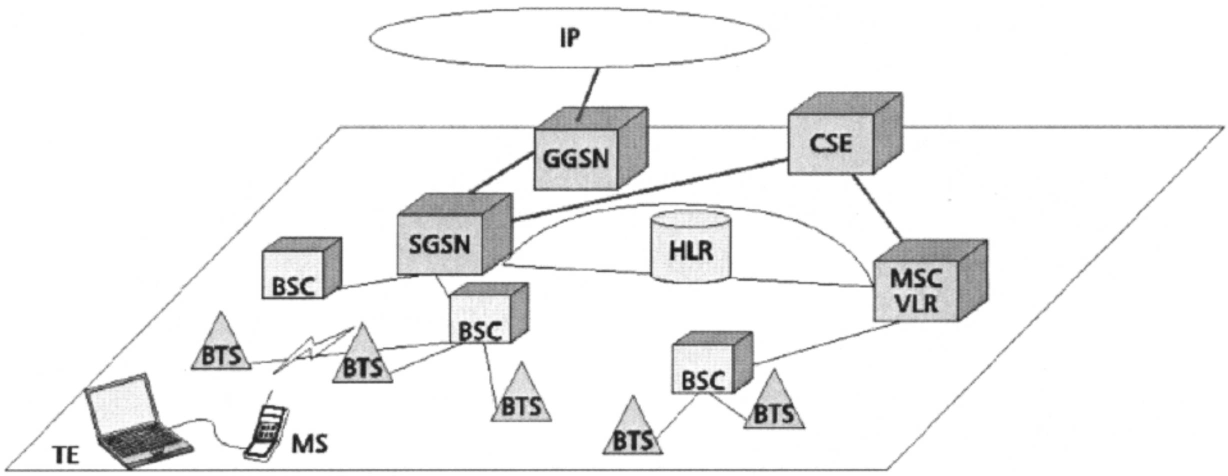


Figure 1-23: Evolved GSM Architecture (GPRS)

EDGE

EDGE (Enhanced Data Rates for GSM Evolution) uses more advanced modulation to increase the throughput at the radio interface. In a time slot, the following throughputs can be obtained over the radio interface, depending on the coding scheme: 28.8 kb/s, 32.0 kb/s and 43.2 kb/s. As in GPRS, a MS can be allocated more than one timeslot.

EDGE time slots are used with the GPRS architecture to provide packet services with increased data throughput; this is known as EGPRS (Enhanced GPRS). Further advancements have been proposed to enhance EDGE capabilities ($EDGE^+$).

1.5.3 UMTS Phase 1

UMTS (Universal Mobile Telecommunications System) was designed by a joint effort of the GSM community and other players as a Third Generation (3G) system, compatible with GSM to the extent possible and meeting the goals of IMT-2000 set by the ITU. To organize this common work, a new joint standardization forum was developed as a Partnership Project (3GPP).

The UMTS phase 1 specifications are based on the following key principles:

- A completely new radio interface using Wideband CDMA (WCDMA), and
- Reuse of the network, services and security principles of GSM and GPRS.

1.5.3.1 Radio interface

Whereas GSM radio technology is based on TDMA, the design of the UMTS radio interface is based on CDMA technology. A completely new radio interface was designed by ETSI and developed further by 3GPP. This radio interface is formed by two modes of operation in two different parts of the spectrum: FDD in paired-band configurations (for uplink and downlink) and TDD in an unpaired one.

The FDD component is built on a WCDMA concept which is based on direct-sequence CDMA with a 3.84 Mc/s chip rate and is designed both for flexibility for third generation services and for optimized GSM compatibility. The physical layer offers flexible multi-rate transmission capabilities and a service multiplexing scheme. An efficient support for packet access has been defined with a dual-mode packet transmission scheme supporting various multimedia services.

The TDD component is a TD-CDMA scheme, with both time and code multiplexing. It uses joint detection in the receiver on the uplink as well as on the downlink and requires neither high power control accuracy nor a soft handoff. This mode offers flexibility in downlink and uplink time slot allocation to meet asymmetric traffic requirements and it allows for the easy implementation of adaptive antennas. Basic system parameters such as carrier spacing, chip rate, and frame length are harmonized. FDD/TDD dual mode operation is thereby facilitated, providing a basis for the development of low-cost terminals.

Each UMTS WCDMA FDD radio carrier requires a 5 MHz downlink and a 5 MHz uplink. A UMTS WCDMA FDD radio carrier may transmit around 50 simultaneous voice calls in circuit mode. However, as mentioned earlier, the CDMA scheme provides trunking efficiency, with no fixed time or frequency slots per user, and therefore allows trade-offs between traffic load and performance attributes, such as throughput and the level of tolerable degradation. UMTS specifications provide the details. In Europe, the Middle East, Africa, and Asia, UMTS generally operates in the FDD 1920-1980 MHz band for uplinks and the 2110-2170 MHz band for downlinks, though other bands are possible (e.g., re-farming of 900 MHz). In the Americas, different frequency bands have been used notably the frequency bands around 850 MHz and 1900 MHz.

The split of the radio interface protocol stack into three layers is similar to GSM. Layer 1 is the physical layer with the new radio technology (WCDMA and TD-CDMA). Layer 2 is split into two sub-layers: the Media Access Control (MAC) sub-layer and the Radio Link Control (RLC) sub-layer. Layer 3 encompasses three sub-layers: RRC (radio resource control), MM (mobility management), and CC (call control). The FDD component of the WCDMA radio interface provides radio bearers for both circuit-switched (e.g., voice) and packet-switched communication, up to 384 kb/s (downlink) and 12 kb/s (uplink) in UMTS Phase 1. The radio interface protocol architecture is specified in UMTS 25.301 [3GP11a].

1.5.3.2 UMTS Phase 1 architecture

The architecture of the UMTS radio access network (UTRAN) is fundamentally similar to the GSM architecture, in terms of the Node B (base station) and Radio Network Controller (RNC) components. The functionality split, however, is somewhat different from that of GSM.

The core network of UMTS Phase 1 reuses the principles of GSM and GPRS. It comprises the MSC, VLR, HLR, SGSN, and GGSN (all introduced earlier) with a functional splitting quite similar to that of GSM. As in GSM, messages are exchanged directly between the mobile terminal and the core network, without any translation by the RNC or Node B. All UMTS radio resource control functionalities are located in the RNC, including handoff functions. This is different from GSM, where control of the handoff process is shared between the visited MSC and the BSC. The circuit domain is quite similar to that of GSM, but there has been more evolution in the packet domain, although it is based on GPRS. First of all, the GPRS interface between the SGSN and the BSC (the Gb interface) is completely changed. Indeed, a tunnel is established between the SGSN and the RNC. Unlike GSM, the transcoders are controlled by the MSC and not by the access sub-network. Lastly, the SIM is kept in UMTS and is known as the USIM (UMTS SIM).

UMTS specifications 23.101 [3GP11b] and 23.121 [3GP02] give the general UMTS architecture principles and requirements for UMTS Phase 1 (Release 99).

1.5.3.3 GSM/UMTS interworking

From the start, GSM/UMTS handoff and roaming were defined. The protocol for roaming (MAP) is common to GSM and UMTS. In addition, the UMTS Mobile Stations typically support GSM at a minimum, and generally support multiple modes and multiple bands. It was also decided to develop a core network common to GSM and UMTS, thus allowing GSM/UMTS operators to deploy a single core network enabling the different access technologies, as shown in Figure 1-24.

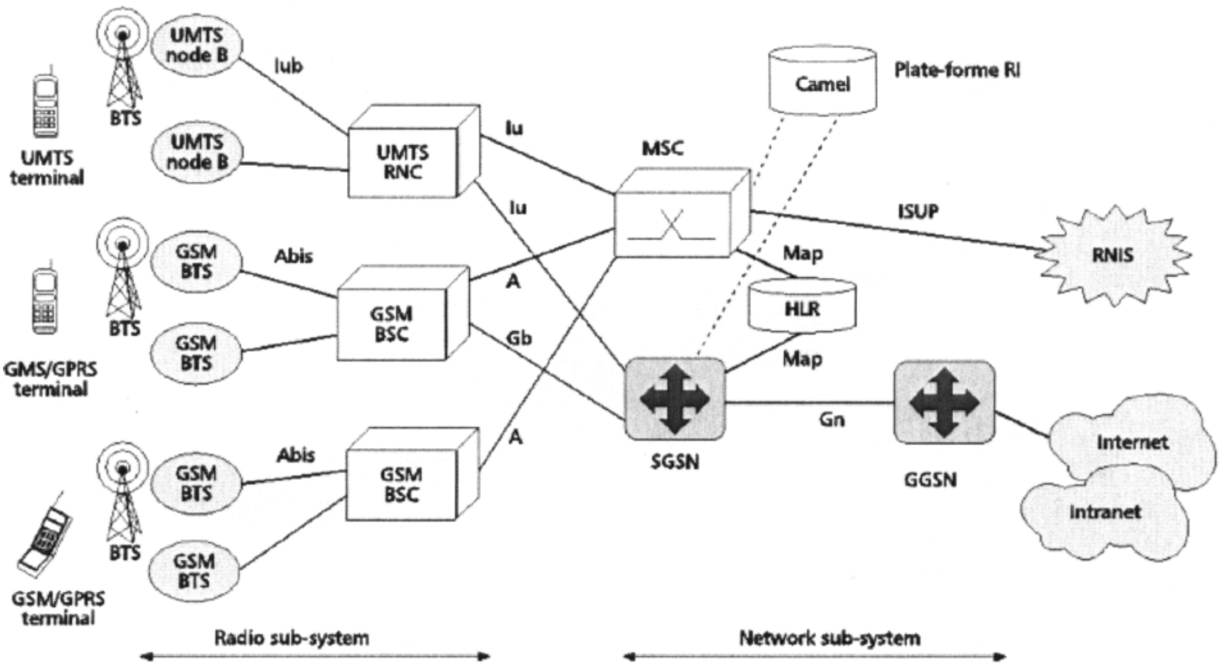


Figure 1-24: GSM Radio Access and UMTS Radio Access with the Same Core Network

1.5.4 HSPA (UMTS Evolution)

3GPP Release 5 defined the evolution of the UMTS access network, High Speed Downlink Packet Access, (HSDPA [3GP04]), with its significant enhancements to downlink throughput capabilities. In order to improve the data throughput in the uplink, High Speed Uplink Packet Access (HSUPA) was defined in the framework of 3GPP Release 6 [3GP06]. The different phases are generally defined with much consideration to the smooth and graceful evolution of phased implementations.

1.5.4.1 HSDPA (High-Speed Downlink Packet Access)

The growing importance of IP-based applications for mobile access made it necessary to evolve the UMTS radio interface to meet the requirements of new and expected applications:

- Packet data transmission,
- High-throughput with asymmetry between uplink and downlink, and
- Low time constraint and non-uniform quality of service requirements (traffic in bursts).

This led to the standardization of HSDPA by 3GPP in its Release 5, with two major improvements:

- The optimization of the spectral efficiency by a better allocation of radio resources, enabling a variety of speed profiles depending on the number of codes, modulation, and channel coding, reaching a defined peak data rate of 14.4 Mb/s; and
- The reduction of transmission delays.

HSDPA is an optimization of UMTS. The same frequency bands used for WCDMA Phase 1 may be used.

A fundamental goal of HSDPA, as is evident from its name, is to provide high throughput in the downlink. To achieve this, it uses methods known from GSM/EDGE standards, including link adaptation and the HARQ (Hybrid Automatic Repeat reQuest) retransmission algorithm. In addition, HSDPA exploits a new dimension of diversity that has not been exploited by other 3GPP systems: the multi-user diversity that takes advantage of the multiplicity of users to optimize the use of radio resources. This multi-user diversity is extracted using a fast scheduling algorithm, built in Node B. This scheduler selects (every 2 ms) the most appropriate MS (or user equipment, UE) to which data should be sent.

Radio interface

A simplified and basic functionality of HSDPA is shown in Figure 1-25. Node B estimates the channel quality of each HSDPA user on the basis of, for instance, power control, ACK/NACK ratio (i.e., ratio of packet transmission acknowledgements and non-acknowledgements), and HSDPA-specific user feedback (CQI, Channel Quality Indicator). Scheduling and link adaptation are then conducted at a fast pace that depends on the scheduling algorithm and the user prioritization scheme.

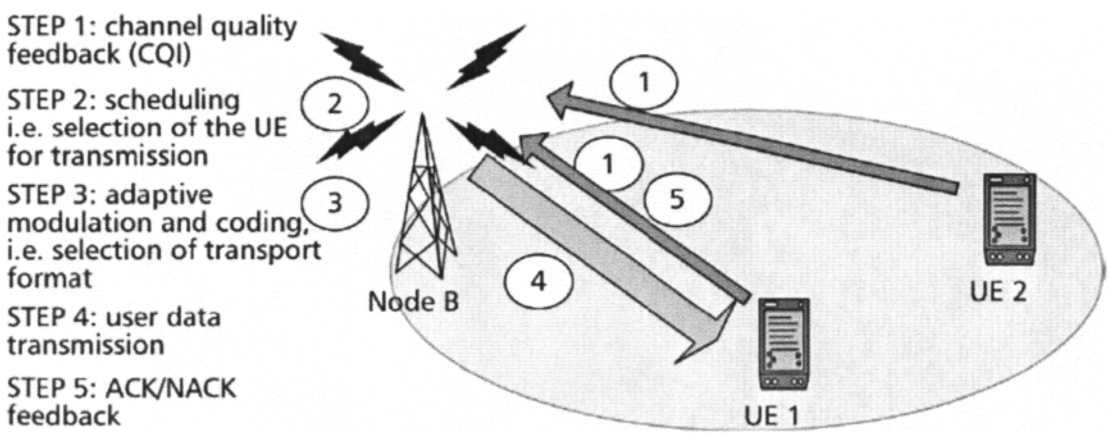


Figure 1-25: Basic Functionality of HSDPA Access

HSDPA relies on a new downlink transport channel, the High Speed Downlink Shared Channel (HS-DSCH). This channel is supported by new physical channels with distinct functions, on the uplink and downlink, for data traffic or signaling.

In HSDPA, two fundamental features of UMTS/WCDMA, variable Spreading Factor (SF) and fast power control, are disabled and replaced by adaptive modulation and coding, extensive multi-code operation, and a fast and spectrally efficient retransmission strategy. This allows selecting, for users in good radio conditions, a coding and modulation combination that provides better throughput, with the same transmitted power as for UMTS channels. To enable a large dynamic range for HSDPA link adaptation and maintain good spectral efficiency, a user may simultaneously use up to 15 codes of SF 16. Also, a new modulation is introduced, 16-QAM (Quadrature Amplitude Modulation), in addition to Quadrature Phase Shift Keying (QPSK). The use of more robust coding, fast HARQ, and multi-code operation removes the need for variable SF. Table 1-2 shows some possible modulation and coding schemes.

CQI Value	Transport Block Size	Number of Codes	Modulation
1	137	1	QPSK
2	173	1	QPSK
7	650	2	QPSK
10	1262	3	QPSK
15	3319	5	QPSK
16	3565	5	16-QAM
30	25558	15	16-QAM

Table 1-2: Applicable Modulation and Coding Schemes (MCS) for a Given Reported CQI

To allow the system to benefit from short-term radio channel variations, packet scheduling decisions are done in Node B. If desired, most of the cell capacity may be allocated to one user for a very short time, when its radio conditions are the most favorable. Thus, an MCS providing high user payload (i.e., a larger transport block size) can be used. The classical 10-ms frame of UMTS has been divided into five sub-frames, or TTIs (Transmission Time Intervals), of 2 ms. In the optimum scenario, scheduling tracks fast-fading of user equipment (UE), as shown in Figure 1-26.

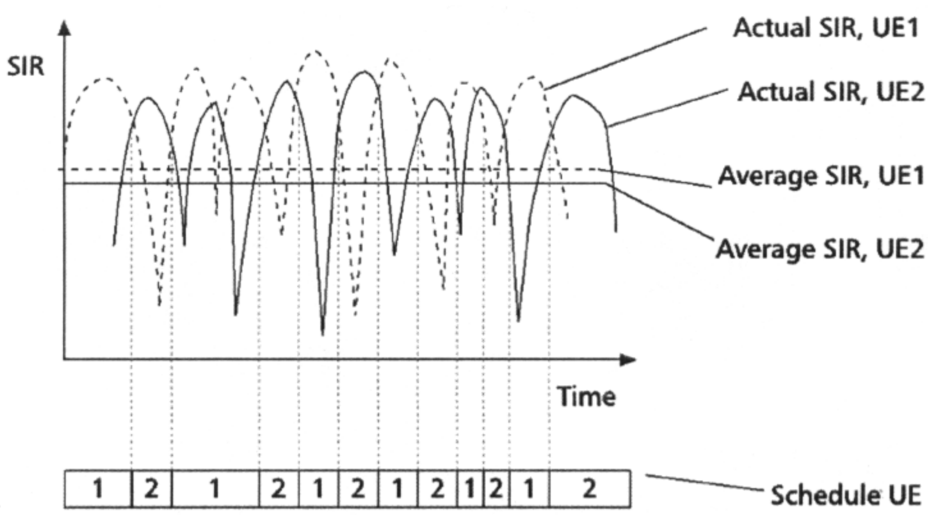


Figure 1-26: Example of Scheduling the User with Maximum Signal-to-Interference Ratio (SIR)

The choice of an appropriate scheduling algorithm is a crucial point for deploying HSDPA efficiently, since this algorithm has a direct effect on the throughput achievable by end users. Several categories of algorithms may be implemented, from fair resource sharing to efficient algorithms that aim at maximizing the cell throughput. A compromise is to use algorithms that aim at finding the middle ground between fairness and efficiency, at the expense of increased complexity.

The combining of physical layer packets (HARQ) basically means that the terminal stores the received data packets in soft memory and if decoding has failed, the new transmission is combined with the old one before channel decoding. The retransmission can be either identical to the first transmission (Chase Combining) or contain different bits compared with the channel encoder output that was received during the last transmission (Incremental Redundancy). With this incremental redundancy strategy, one can achieve both a diversity gain and an improved decoding efficiency.

Radio access network architecture

In 3GPP Release 5, the architecture of the radio access network with HSDPA remains the same as in Release 99, with Node B and the RNC. However, some upgrades were needed in nodes and interfaces to deploy HSDPA compared to UMTS Release 99. The major impact on access network nodes is that the HS-DSCH is terminated in Node B instead of the RNC. This means that a small part of the 3GPP Release 99 functionalities, initially located in the RNC, have been moved down to Node B: e.g., the HARQ functionality (as part of the MAC layer) and scheduling functionality, which are implemented in a new MAC entity. Therefore, software upgrades are necessary in Node B and the RNC. Concerning interfaces, the major issue is a dimensioning one: since HSDPA provides higher bit rates, interfaces (labeled Iu-PS and Iub) should be re-dimensioned to support a higher throughput than for UMTS Release 99.

Concerning the MS (or UE), enhancements were necessary. For example, the new HARQ functionality requires more buffering and computational power; moreover, advanced receivers are needed, as the traditional Rake receiver is not sufficient to decode more than five simultaneous codes efficiently.

A significant trend has been to move toward a flatter architecture to enable seamless mobility across different access networks. In 3GPP Release 7 (2007) and Release 8 (2008), enhancements of the architecture are introduced that enable deployment of a so-called flat architecture, by collapsing Node B and the RNC into a single node.

Physical layer performance

Cell throughput and the user throughput depend on several factors:

- Radio link conditions: A user with good radio link quality will be allocated a modulation and coding scheme (MCS) that will provide a higher throughput than if the link quality is poor.
- Scheduling algorithm: This has a major impact as discussed earlier in this section.
- Load of the cell: The user is scheduled more frequently and throughput is higher with less cell load.
- UE category: 12 categories of HSDPA-capable UEs have been defined by 3GPP, according to their capacity to simultaneously decode several codes, the modulations they can support, and the periodicity at which data can be scheduled. The maximum achievable bit rate for a UE varies depending on these parameters, from 1.8 Mb/s to 14.4 Mb/s (the theoretical peak rate).

- Power allocated to the HS-DSCH: The power allocated to HSDPA channels may be set to a fixed value or may be the remaining available power after power is allocated for Release 99 dedicated and control channels.
- Number of codes allocated to HS-DSCH: This depends on the UE category but also on the operator's configuration. For example, fewer codes are available if a carrier is shared with a Release 99 Dedicated Channel (DCH).

1.5.4.2 HSUPA (Enhanced DCH)

HSUPA is actually identified in the 3GPP specifications as Enhanced DCH (E-DCH) or enhanced Uplink. It is a feature added to UMTS in 3GPP Release 6 [3GP06] to handle high data rate packet services in the uplink, with a maximum (target) data rate of 5.8 Mb/s.

The motivation for development of HSUPA was fundamentally the same as HSDPA, but in this case addressing the need for enhanced uplink speeds. HSUPA introduces better handling of radio and network resources and also transmission time in the uplink communication.

Contrary to HSDPA, HSUPA is not based on a shared channel, but rather on an optimization of the Release 99 uplink DCH, by the use of traditional DCH features:

- A new enhanced dedicated transport channel E-DCH;
- Power control to adapt E-DCH to a changing environment;
- Transport format selection according to the current buffer status and available power;
- A soft handoff that benefits from inherent uplink macro-diversity; and
- A predictable bit rate.

Moreover, some HSDPA-like enhancements are introduced:

- MAC functions are moved from the RNC to Node B to reduce the Round Trip Time (RTT).
- Short uplink TTI is introduced (2ms as an option; 10ms as default), which also reduces RTT.
- Improved re-transmission (HARQ) is used to benefit from combining received packet versions.
- Multi-code operation and low spreading factor are supported to increase the peak data rate, with the definition of several UE categories corresponding to various multi-code and SF configurations.
- Node B scheduling is applied to control the uplink interference level, the cell capacity, and the UE QoS:
    - Node B dynamically allocates scheduling grants to *all* users in the cell, according to their rate requests, QoS requirements, current uplink cell load, and the maximum uplink target cell load.

The process of scheduling is illustrated in Figure 1-27. It is, by nature, less efficient than in HSDPA, as the entity that performs the scheduling (Node B) is not the one that allocates the resources (the UE).

One UE has at most one E-DCH transport channel that can be mapped over a variable number of physical channels. There are other physical channels in the uplink and downlink for traffic and signaling (control).

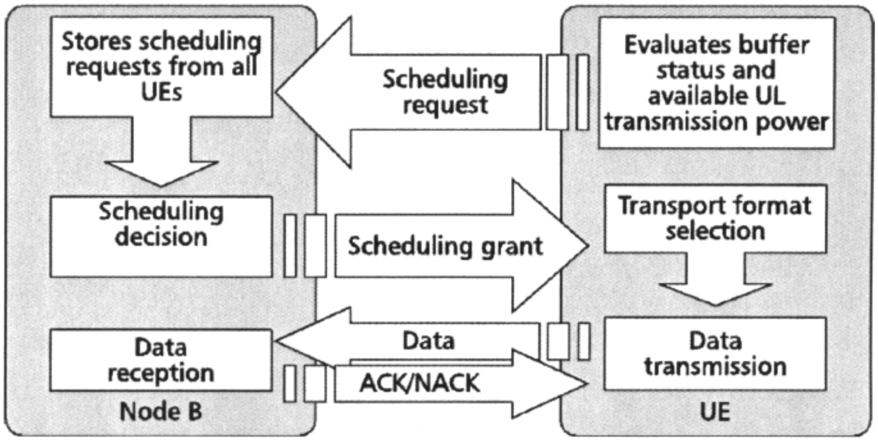


Figure 1-27: Simplified View of HSUPA Node B Uplink Scheduling

Macro-diversity

As in Release 99 and contrary to HSDPA, soft and softer handoffs are supported for the E-DCH channel. This exploits the available uplink macro-diversity to improve the radio link transmission for users at the cell edge and is particularly necessary to provide seamless mobility to delay-sensitive services. However, this feature also adds some complexity to the Node B scheduler and the HARQ algorithm. The number of HSUPA physical channels to monitor for UE is considerably higher with soft handoff on E-DCH.

In summary, HSUPA aims to increase uplink transmission throughput, decrease delays, and improve coverage, compared to Release 99. HSUPA introduces a new uplink dedicated transport channel called Enhanced Dedicated Channel (E-DCH). E-DCH is very similar to DCH, with some improvements to support a shorter sub-frame, and techniques such as HARQ and Node B scheduling. Because of the uplink configuration, HSUPA is more complex than HSDPA, and more signaling consuming. The HSUPA scheduler controls the radio resource less tightly than does the HSDPA scheduler.

USIM and UICC

It is possible to access a GSM network using a SIM card, as indicated earlier, and a UMTS network using a USIM card. A UICC (Universal Integrated Circuit Card) can provide both capabilities, in addition to an increasing number of other applications, within embedded or removable memory. The ETSI Smart Card Platform (SCP) project and the ISO develop and maintian standards and uniform platforms.

1.5.4.3 HSPA+

There is a broad deployment of HSPA technology around the world today, mostly based on Release 6 or beyond, allowing high speed access in both the downlink and the uplink.

3GPP has continued to define further enhancements to the HSPA standards, specifically through the recommendations in Release 7 to define HSPA+ versions. The principal additional advancements include:

- Use of higher-level modulation (64 QAM) in addition to 16 QAM and QPSK;
- Use of Multiple Input Multiple Output (MIMO) antenna technology; and
- Concatenation of two or more transmission carriers (particularly DC or Dual-Carrier).

These advanced technologies have allowed HSPA+ deployments around the world, enabling high speed wireless access at defined peak rates of 21, 28, 42 (or more) Mb/s.

1.5.5 Long Term Evolution (LTE)

3GPP started work on the evolution of 3G in 2004. A set of high level requirements was identified, including reduced cost per bit, increased service provisioning, flexibility in the use of existing and new frequency bands, simplified architecture, open interfaces, and reasonable terminal power consumption.

A feasibility study of UMTS Long Term Evolution (LTE) was subsequently started. The objective was to develop a framework for the evolution of 3GPP radio-access technology toward a high-data-rate, low-latency, and packet-optimized radio access. The study focused on the following aspects:

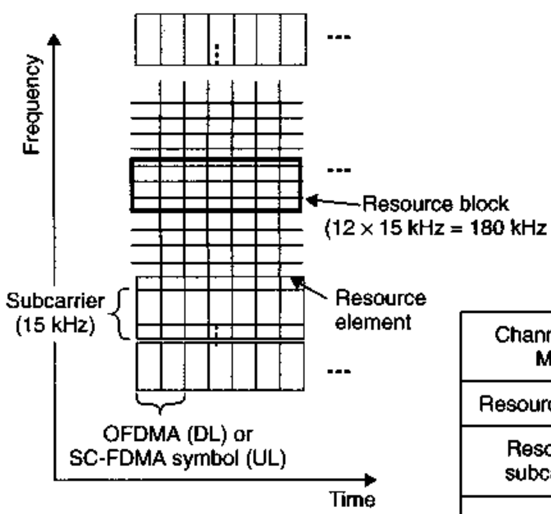
- The radio-interface physical layer (downlink and uplink), to support flexible transmission bandwidth up to 20 MHz, by introducing new transmission schemes and advanced multi-antenna technologies;
- Radio interface layer 2 and 3 and signaling optimization;
- UTRAN architecture, identifying the optimum network architecture and the functional split between Radio Access Network (RAN) network nodes; and
- RF-related concerns.

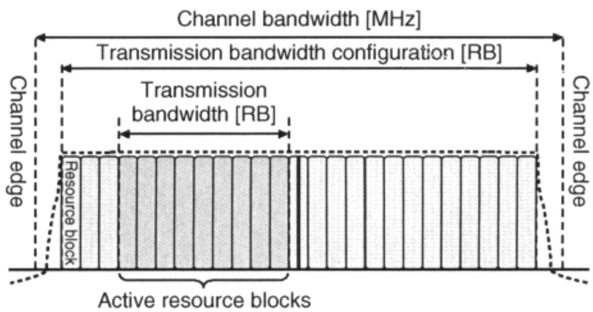
A set of basic requirements resulted from the first part of the study:

- Peak data rate – an instantaneous downlink peak data rate of 100 Mb/s within a 20 MHz downlink spectrum allocation (5 bps/Hz) and an instantaneous uplink peak data rate of 50 Mb/s (2.5 bps/Hz) within a 20 MHz uplink spectrum allocation;
- Control-plane latency – a transition time of less than 100 ms from a camped state to an active state and a transition time of less than 50 ms from a dormant state to an active state;
- Control-plane capacity – at least 200 users per cell supported in the active state for spectrum allocations up to 5 MHz;
- User-plane latency – as low as several milliseconds;
- User throughput – an average downlink user throughput per MHz that is three to four times that of HSDPA and average uplink user throughput per MHz that is two to three times that of Enhanced Uplink (Release 6);
- Spectral efficiency – the same improvement factors as for throughput;
- Mobility – performance optimized for low mobility but maintaining high mobility across the cellular network at speeds greater than 120 km/h (even up to 500 km/h depending on the frequency band);
- Coverage – the above throughput, spectrum efficiency, and mobility targets met for 5 km cells, and with a slight degradation for 30 km cells;
- Enhanced Multimedia Broadcast Multicast Service (eMBMS);
- Paired and unpaired spectrum arrangements;
- Spectrum flexibility and scalability;
- Co-existence and inter-working with existing 3GPP radio access technologies;

- Architecture and migration – a single E-UTRAN architecture and optimized backhaul communication protocols;
- Radio Resource Management requirements for enhanced end-to-end QoS support, efficient support for transmission of higher layers, and load sharing and policy management across different radio access technologies; and
- Complexity optimization (in terms of a limited number of options and no redundant mandatory features).

A number of multiple access candidate schemes have been considered, taking into account the objective of supporting both FDD and TDD operation. OFDMA was selected for the downlink, while single carrier frequency division multiple access (SC-FDMA) was chosen for the uplink. OFDMA is an attractive solution for the downlink, not only for its increased spectral efficiency but also for its low implementation complexity attributes. This becomes even more crucial with the use of MIMO and the inherent orthogonality in transmission that eliminates intracell interference. While OFDMA could have been an attractive multiple access scheme for the uplink, OFDM signals have a high peak-to-average power ratio (PAPR). A large PAPR requires a large back-off in the power amplifier and decreases the coverage area, resulting in poor cell edge performance. To address the PAPR issue and at the same time preserve the advantage of the "orthogonality" of OFDM, and therefore combine the benefits of OFDMA and single carrier transmission, an OFDMA scheme was chosen, called single carrier FDMA (SC-FDMA).





Channel BW, MHz	1.4	3	5	10	15	20
Resource blocks	6	15	25	50	75	100
Resourced subcarriers	72	180	300	600	900	1200
IDFT/DFT size	128	256	512	1024	1536	2048

(I) DFT - (Inverse) discrete fourier transform

Figure 1-28: LTE Transmission Channel Structure Formed of Resource Blocks

The resource block structure includes 12 subcarriers each, as shown in Figure 1-28, thus providing a great deal of flexibility and efficiency, and therefore both high throughput and support of variety of channel bandwidth (i.e., a large link budget for a variety of data streams, agnostic to channel size, etc.). Note that the discrete Fourier transform (DFT) size is chosen to be greater than the total resourced subscarriers with the difference set to zero. See the 3GPP standards (Release 8 and beyond) for details.

Adaptive modulation and coding are used in the downlink to adapt user data rates and QoS requirements to the channel quality. Various coding schemes have been considered, such as duo-binary turbo, rate compatible/quasi cyclic low density parity check (RC/QCLDPC), concatenated zigzag LDPC, turbo single parity check (SPC) LDPC, and shortened turbo codes through insertion of temporary bits. These all vary in performance merits for different block sizes and complexity assumptions.

To address the interference-limited scenarios resulting from universal frequency reuse, interference mitigation can be deployed in several forms:

- Inter-cell interference randomization, by deploying cell-specific scrambling, cell-specific interleaving, or random frequency hopping;
- Interference avoidance, by means of fractional frequency reuse – users are allocated among multiple classes according to their distance from the cell center, and different bandwidth allocation patterns are assigned to different user classes; and/or
- Interference cancellation by means of multiple antenna processing.

Multiple antenna techniques are considered in 3GPP LTE for increased data rates and improved link quality through the use of spatial multiplexing and diversity gains. As these schemes are deployed in combination with the packet scheduler, performance optimization needs to be studied, taking into account both spatial and multi-user diversity gains at a system level (multi-cell) sense, in order to include realistic interference modeling. In the single user MIMO case, for example in the per antenna rate control (PARC) scheme, spatial multiplexing is implemented by transmitting parallel data streams to a single user in order to improve the link rate, while in a multi-user MIMO case, multiple spatial streams are transmitted to different users to increase the system throughput. Space division multiple access (SDMA) can be realized through sectorization, multi-user beam forming, or multi-user MIMO precoding. Decisive factors in the realistic assessment of candidate MIMO approaches are the system level performance under realistic channel and interference modeling assumptions and the required channel state information, overhead signaling, and pilot design constraints.

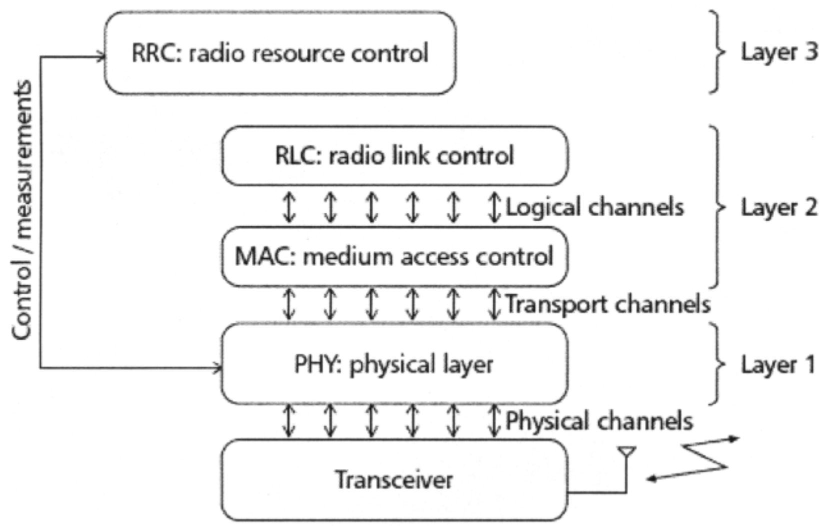


Figure 1-29: A Model of the Layers in LTE and a Schematic View of Channel Mappings

In summary, LTE is a broadband wireless access technology (with a flexible set of capabilities) defined by 3GPP in Release 8 (2008), and enhanced in subsequent releases, to enable high data rates, high capacity, and reduced latency, among other features, with significant enhancements in spectral and resource efficiencies. It supports both TDD and FDD schemes, and enhanced broadcast/multicast, with transmission bandwidths ranging from 1.25 MHz to 20 MHz. The layer mapping is shown in Figure 1-29. OFDMA is used in the downlink and single-carrier FDMA in the uplink. In addition, such elements as sophisticated antenna systems (e.g., 2×2, 2×4, etc. MIMO) and coding/modulation schemes (e.g., QPSK, 16QAM, 64QAM) will allow an evolution and/or variety of LTE (product) capabilities. LTE is expected to support service continuity and hand-off across a variety of 3GPP and non-3GPP access technologies.

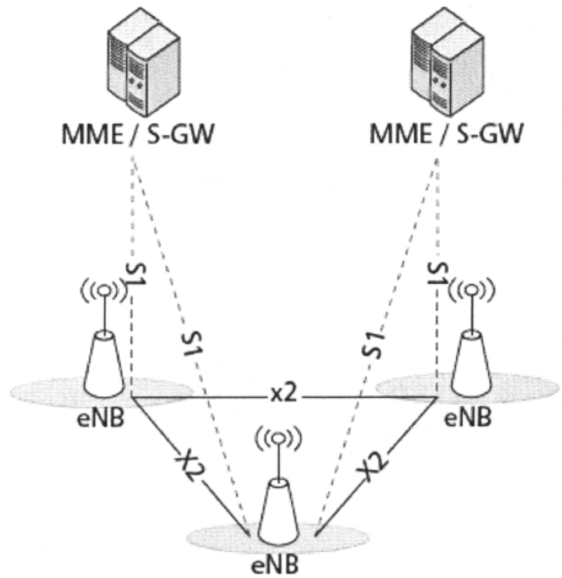


Figure 1-30: LTE/EPC End-to-End Simplified View

LTE is defined as part of an end-to-end all-IP network which can be simplified into two nodes, the LTE access functions within an enhanced Node B (eNB) and the Evolved Packet Core (EPC), as shown in Figure 1-30. The EPC includes a bearer gateway (with a Serving GW facing the eNBs) and a Mobility Management Entity (MME) for control and management functions. Key interfaces defined in the standards are those between eNBs (labeled X2) and between an eNB and a MME (labeled S1).

1.6 3GPP2 Radio Access Standards Evolution

Figure 1-31 shows a high-level view of 3GPP2 radio access technology evolution. Some details on cdmaOne to cdma2000 evolution (and beyond) are provided in this section.

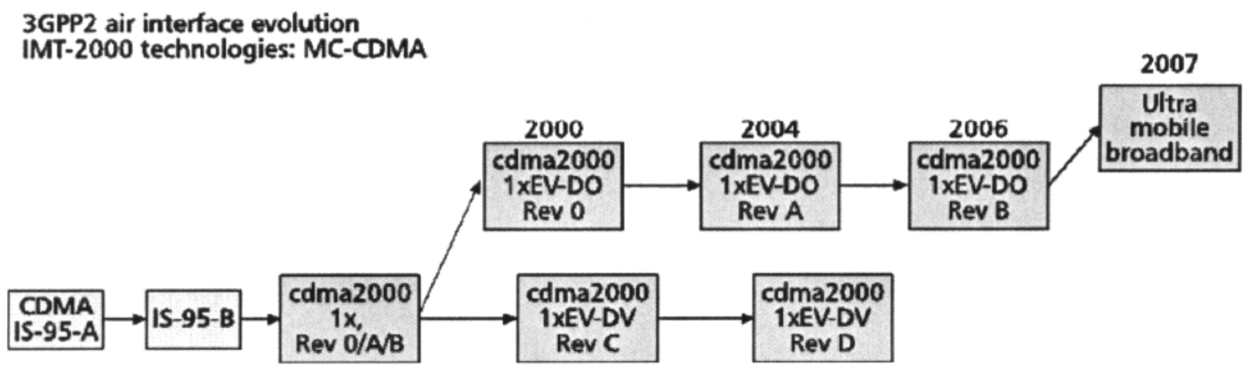


Figure 1-31: Evolution of 3GPP2 Access Technology Standards

1.6.1 cdmaOne and cdma2000-1X

cdmaOne is the first commercial CDMA network based on ANSI-95 standards. cdma2000-1X doubled the spectral efficiency as shown in Figure 1-32. The spectral efficiency here is defined by the sector capacity (in Mb/s) for both the forward link (base-to-mobile station) and the reverse link (mobile-to-base station) divided by the total required bandwidth (MHz). The spectral efficiency was significantly enhanced by definition of the evolved version (data-optimized) cdma2000-1xEV-DO Rev 0, and subsequently Rev A.

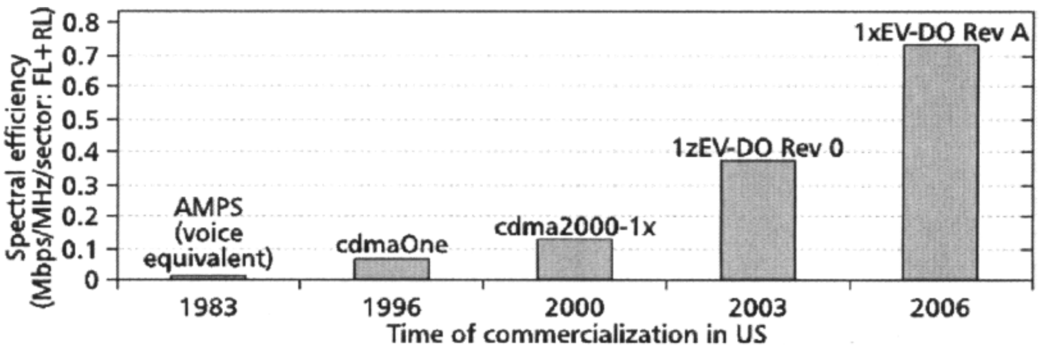


Figure 1-32: Evolution of Spectral Efficiency in 3GPP2

A cdmaOne network has pilot, sync, and paging control channels on the forward link and an access control channel on the reverse link. These control channels support forward- and reverse-link traffic channels. The forward-link channels are orthogonally covered by a Walsh function and then spread by a quadrature pair of pseudo-random noise (PN) sequences at a fixed chip rate of 1.2288 Mchips per second. Note that in the spread spectrum concept, the high rate spreading signal is defined by "chips", distinct from the information symbols. After the spreading operation, the in-phase (I) and quadrature (Q) signals are applied to the inputs of the I and Q baseband filter. The (QPSK) modulated signals are then sent over the air as shown in Figure 1-33.

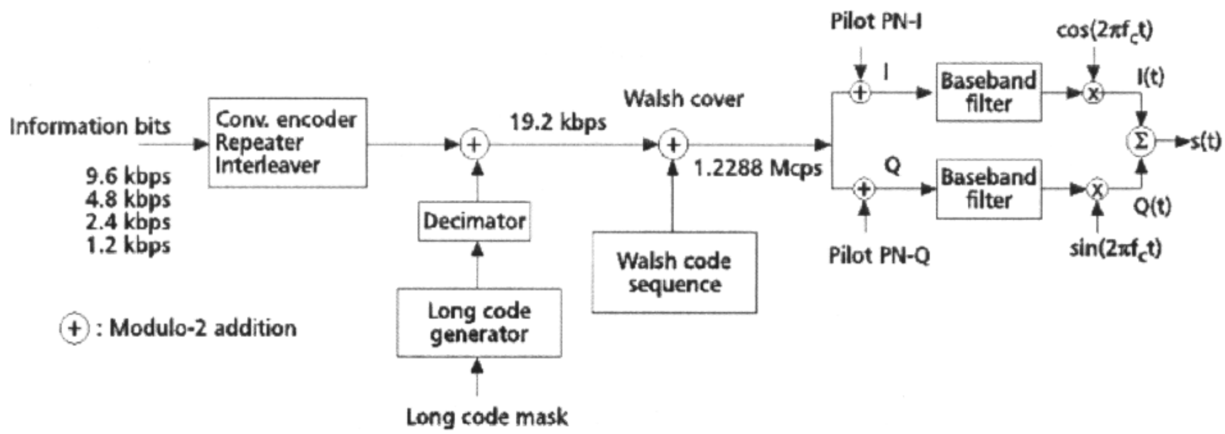


Figure 1-33: Block Diagram of Basic cdmaOne Forward-Link Transmission

The pilot channel is an unmodulated all-zero signal transmitted continuously by each CDMA base station to provide mobile stations with timing for initial system acquisition, phase reference for coherent demodulation, and signal strength for handoff decisions. The sync channel is a modulated spreading signal to transmit the sync channel message, which conveys key information to mobile stations, such as protocol revisions, system identification number (SID), system time, pilot PN sequence offset index, and others. The paging channel sends control information to CDMA mobile stations that have not been assigned to a traffic channel. Forward traffic channels are used by the base station to pass user data and signaling messages to mobile stations while on a call. Forward traffic channels can operate at different rates depending on the service options being supported.

When the mobile station is turned on, it will first complete pilot acquisition, and change its de-spreading to the sync channel to receive sync channel messages. Mobile stations use sync information to synchronize their system timing to the CDMA system time. Mobile stations then perform system registration initialization and begin to monitor the paging channel. Once a mobile station is paged or wants to access the network, the mobile station will switch to the traffic channel to start communication.

The reverse-link transmission is achieved by using 42-bit PN codes, referred to as long codes. Each subscriber uses a unique long code. The reverse-link transmission is illustrated in Figure 1-34.

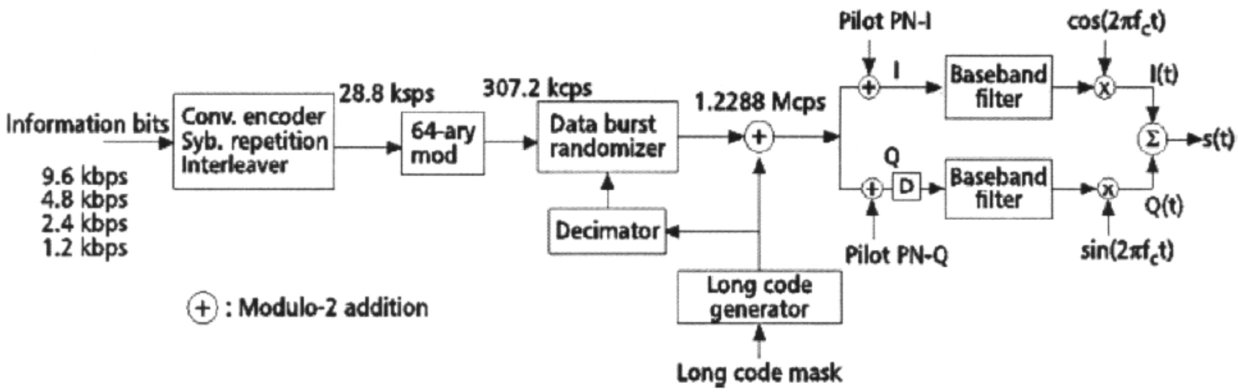


Figure 1-34: Block Diagram of Basic cdmaOne Reverse-Link Transmission

Access channels are used by mobile stations that are not engaged in a call to send messages to the base station. Typical messages sent include registration, call origination messages, and responses to requests or orders received from the base station. Reverse traffic channels are used by mobile stations to transmit user data and signaling information to the base station while on a call. The reverse traffic channels can operate at different rates depending on the service options being supported.

cdma2000-1x maintains the basic cdmaOne traffic channel structure and expands it to forward and reverse fundamental channels. It introduces forward and reverse supplemental channels, as well as associated forward and reverse dedicated control channels. Variable data rates in cdma2000 are achieved through variable spreading rates (factors) from 4 to 256 times instead of the fixed 128 times in cdmaOne. Both the forward and reverse link support up to a 153.6 kb/s physical link data rate. A reverse link pilot channel is added to support a coherent receiver on the reverse link. Powerful convolution and turbo codes are specified that double the voice capacity compared to cdmaOne, as well as supporting 144 kb/s packet data applications. The control channels are also upgraded to Enhanced Access Control Channels and Forward and Reverse Common Control Channels with higher rates and shorter frames. A quick paging channel and a broadcast channel are introduced to improve call setup time and battery life.

Power control is essential for a CDMA system to control interference and ensure reliable system operation. Link level radio power management consists of forward link power control, reverse link power control, and soft/softer handoff. The link level power management determines the sector capacity. The two-fold increase in capacity from cdmaOne to cdma2000-1x was largely due to the introduction of fast forward link power control. The forward link power control update rate increased from around 50 Hz in cdmaOne based on control messages, to a dedicated control channel at 800 Hz in cdma2000. Reverse link power management has both open-loop and closed-loop power control. The open loop allows a mobile station to set its transmit power based on the strength of the received power on the forward link, while closed loop supports power control to a desired reverse link traffic channel E_b/N_o, directed by the base station. These mechanisms ensure that both the mobile station and the base station transmit at the minimal required power level.

Soft and softer handoffs are also defined in cdma2000 to ensure make-before-break communication (as discussed earlier). Soft handoff refers to a handoff between two adjacent sectors belonging to different cell sites. Softer handoff is a handoff between two adjacent sectors of the same cell site. Although soft handoff improves the voice quality and handoff performance, it ties up multiple channel receivers, and decreases the capacity.

cdma2000-1x has also introduced various bearer service profiles to support voice-only, data-only, and mixed voice and data services over traffic channels. Medium access layer, link access layer, and upper layer protocols provide an efficient way to transmit bursty packet data traffic with differentiated QoS capability. New network elements were also introduced to address data mobility, IP address, packet data routing, authentication, authorization, and accounting as illustrated in Figure 1-35.

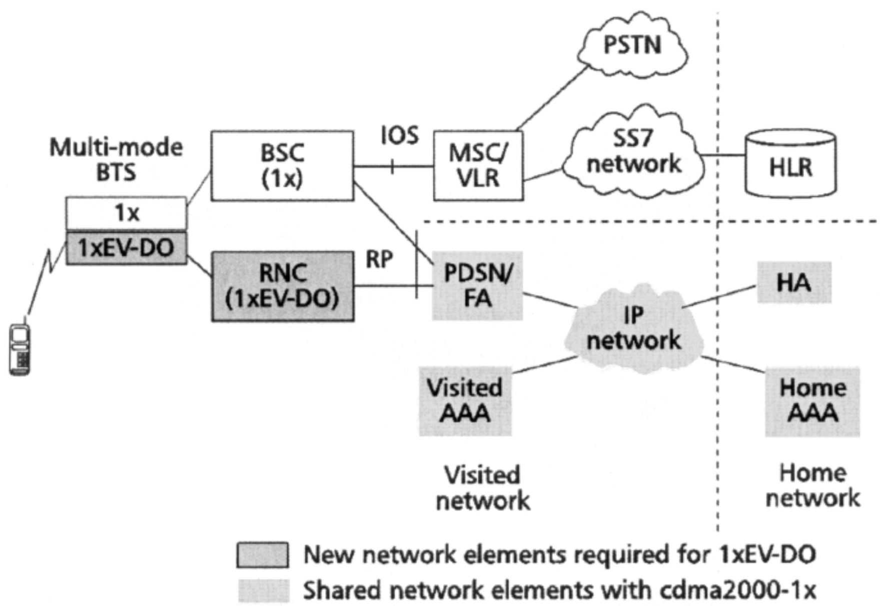


Figure 1-35: cdma2000 and 1xEV-DO Network Architecture

1.6.2 cdma2000-1xEV-DO (Rev 0 and Rev A)

cdma2000-1xEV-DO is designed for a high data rate, flexible latency, and high quality applications. The 1xEV-DO high-speed packet data network is an integral part of the cdma2000 family of standards. It has the same spectrum bandwidth as that of cdma2000-1x and is spread by the same PN sequences as cdma2000-1x. The hybrid mode supports a smooth and seamless handoff between 1xEV-DO and cdma2000-1x. An integrated 1xEV-DO and cdma2000-1x network architecture is shown in Figure 1-35.

This architecture provides a spectrally efficient means for both delay-sensitive (e.g., conversational) and delay-tolerant (e.g., data) services. The integrated network can share packet data network elements, such as the Packet Data Serving Node (PDSN), Foreign Agent (FA), Authentication, Authorization and Accounting (AAA), and Home Agent (HA). Only a Radio Network Controller (RNC) and dedicated 1xEV-DO base station modem cards are needed to upgrade a deployed cdma2000-1x network.

A cdma2000-1xEV-DO Rev 0 network is dedicated to packet data traffic, and is optimized for maximum data throughput. The system takes advantage of the burst- and delay-tolerant nature of data to increase the throughput efficiency. High spectral efficiency in 1xEV-DO is achieved on a shared full power and full code forward link fat pipe through Adaptive Modulation and Coding (AMC), fast scheduler, and HARQ.

The forward traffic channel is a common shared channel for all access terminals and their control signals. The modulation and coding are adaptive to the channel carrier-to-interference ratio (CIR). Accordingly, QPSK, 8-PSK, and 16 QAM modulations with various turbo coding are used to achieve data rate ranges from 38.4 kb/s to 2.457 Mb/s in a 1.25 MHz channel as shown in Table 1-3. The transmission data rate to each terminal is adapted to the RF channel condition and decided by the terminal. Therefore, users under good RF conditions will transmit at higher data rates than users in poor RF conditions. The Data Rate Control (DRC) channel on the reverse link provides fast feedback of the data rate and the best serving sector at a 1.667 ms slot interval. Fast cell selection supports virtual soft hand-off. Only the best serving sector is transmitting to the terminal at a time, reducing interference and hardware resource consumption.

Data Rate (kb/s)	Number of Slots	Code Rate	Modulation	CIR (dB)
38.4	16	1/5	QPSK	-11.5
76.8	8	1/5	QPSK	-9.7
153.6	4	1/5	QPSK	-6.8
307.2	2	1/5	QPSK	-3.9
614.4	1	1/3	QPSK	-3.8
307.2	4	1/3	QPSK	-0.6
614.4	2	1/3	QPSK	-0.8
1228.8	1	1/3	QPSK	1.8
921.6	2	1/3	8-PSK	3.7
1843.2	1	1/3	8-PSK	3.8
1228.8	2	1/3	16-QAM	7.5
2457.6	1	1/3	16-QAM	9.7

Table 1-3: Modulation and Coding Schemes - 1xEV-DO Rev 0

The fast scheduler is enabled by channel state information feedback from the DRC channel as well. The scheduler takes advantage of rapidly changing fading channel characteristics, and serves users when they have better than average channel CIR. This achieves multiple user diversity gain. The transmission time and duration are decided by the base station based on both the history of the transmission and the usage pattern. This adaptive data scheduler can support fairness and differentiation among users.

cdma2000 1xEV-DO Rev A is designed for versatile multimedia services, both delay-sensitive and delay-tolerant applications. Major improvements over EV-DO Rev 0 are increased data rates, improved reverse link, and Multiple Flow Packet Application to support delay-sensitive applications with more symmetric data rate requirement, such as voice and video telephony.

EV-DO Rev A increases the forward link data rate to 3.072 Mb/s by increasing the physical layer packet size from 4096 bits at 2.457 Mb/s in Table 1-3 to 5120 bits per slot. Reverse link data rates are expanded from 4.8 kb/s to 1.843 Mb/s. Higher data rates and better packing efficiency improve the forward and reverse link spectral efficiency, and enable VoIP capability, among other enhancements.

EV-DO Rev A reverse link performance is improved through HARQ and two transmission modes, as compared to EV-DO Rev 0, which has a similar reverse link structure as cdma2000-1x. HARQ achieves higher effective data throughput by earlier termination of multiple sub-packet transmissions. HARQ exploits power control imperfections due to radio channel and interference variations by using a-posteriori channel feedback. Two transmission modes are High Capacity (HiCap) and Low Latency (LoLat) modes. HiCap has a termination target of four sub-packets, while LoLat has a termination target of two to three sub-packets. HiCap achieves higher sector capacity gain with lower required bit-energy-to-noise-density ratio. LoLat minimizes transmission delay and achieves a lower packet error rate.

A multiple flow packet application supports spectral efficiency and latency trade-offs for each application flow. A service provider can deliver various multimedia applications with distinctive flow characteristics for each Radio Link Protocol (RLP) flow over EV-DO Rev A. EV-DO Rev A base stations manage radio resources to meet user throughput, latency, and packet loss requirements and ensure end-to-end QoS. Forward-link scheduler, reverse-link traffic power and medium-access control, call-admission control, backhaul QoS support and overload control, together form an integrated and effective resource management system.

Forward link QoS is managed by a RF scheduler that has a queue for each RLP flow. It assigns the packets in accordance with the needs of each flow QoS profile to perform Expedited Forwarding (EF), Assured Forwarding (AF), and Best Effort (BE) resource allocation. Voice flow receives the highest delay- and jitter-sensitive EF priority to ensure voice quality. Background file download is allocated BE.

Reverse link QoS is controlled by a token bucket scheme to ensure that average and peak resources utilized by each reverse traffic channel are less than or equal to the limitations imposed by the RAN. The limitations are specified by Traffic-to-Pilot ratios (T2P). LoLat has higher T2P ratios for the first two to three sub-packets. HiCap has the same T2P ratios for all 4 sub-packets as illustrated in Figure 1-36.

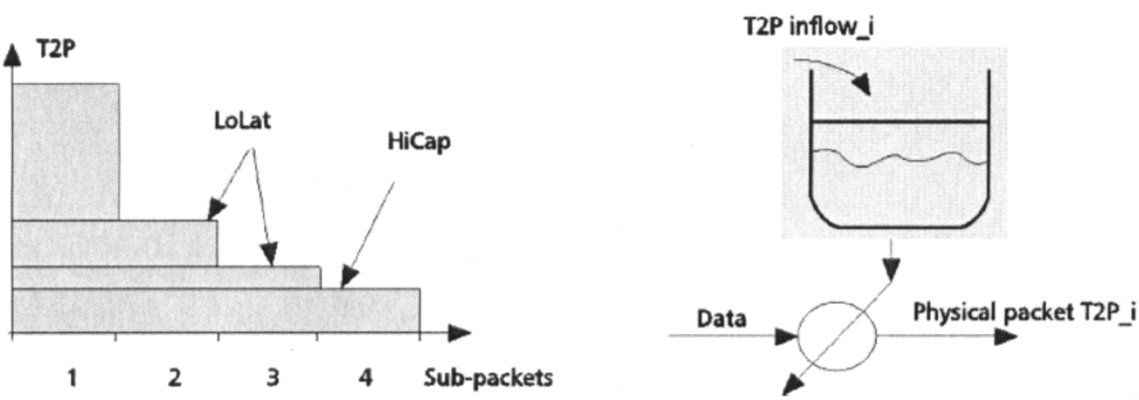


Figure 1-36: Reverse Link Resource Management for QoS

EV-DO Rev A has improved physical, MAC, and higher layer network efficiency and latency performance for multimedia services. The spectral efficiency for packet data applications has achieved 0.72 Mb/s/MHz/sector. EV-DO can also support voice user capacity of 35 Erlangs using a 1.25 MHz bandwidth, and it can also support a wide range of multimedia services.

1.6.3 Ultra Mobile Broadband

The 3rd Generation Partnership Project 2 (3GPP2) standards body engaged in a similar activity to the 3GPP LTE effort, aiming at evolving the cdma2000 high-rate packet data (HRPD) 3G system into the next generation. EV-DO Rev C standard, now known as Ultra Mobile Broadband (UMB), was specified and released in 2007. It is an OFDMA solution, using sophisticated control and signaling mechanisms, radio resource management (RRM), adaptive interference management, and advanced antenna techniques, such as MIMO, SDMA (Space Division Multiple Access), and beam-forming.

UMB aims to address a large cross-section of advanced mobile broadband services by economically delivering voice and multimedia. UMB supports inter-technology hand-offs and seamless operation with existing cdma2000 systems.

The basic target requirements for UMB are:

- High-Speed Data – peak rates of 288 Mb/s (with 2x20 MHz FDD, 4x4 MIMO) download and 75 Mb/s (with 2x20 MHz FDD, 1x2 MIMO) upload;
- Increased Data Capacity – ability to deliver both high-capacity voice and broadband data in all environments - fixed, pedestrian, and fully-mobile in excess of 300 km/h;
- Low Latency – an average latency of 14.3 ms over-the-air to support Voice over IP (VoIP), push-to-talk, and other delay-sensitive applications with minimal jitter;
- Increased VoIP Capacity – up to 1000 simultaneous VoIP users within a single sector, 20 MHz of bandwidth in a mobile environment without degrading concurrent data throughput capacity;
- Coverage – large wide-area network coverage areas equivalent to existing cellular networks, with either ubiquitous coverage for seamless roaming or non-contiguous coverage for hot zone applications;
- Mobility – robust mobility support with seamless handoffs;
- Converged Access Network – an advanced IP-based RAN architecture being developed by 3GPP2 to support multiple access technologies and advanced network capabilities, such as enhanced QoS, with fewer network nodes and lower latencies;
- Multicasting – support for high-speed multicast of rich multimedia content; and
- Transmission Bandwidth – deployable in flexible bandwidth allocations between 1.25 MHz and 20 MHz.

The UMB air interface supports both TDD and FDD modes and several coding schemes, including turbo and LDPC (optional). OFDMA is used for uplink and downlink traffic, while for uplink control channel transmission both OFDMA and CDMA are used. Orthogonal access schemes (such as OFDMA) eliminate intracell interference but require centralized assignment of resources to users, thus requiring additional signaling and possibly adding to the overall latency. On the other hand, non-orthogonal access schemes can take advantage of "soft capacity" and do not require explicit signaling for resource allocation. However, they involve more complex receivers and control methods to achieve a similar link performance as orthogonal schemes. For this reason, for the UMB uplink control channel (which is by nature bursty, delay-sensitive, and with small payloads), a hybrid scheme is used, composed of both OFDMA and a non-orthogonal multi-carrier CDMA (MC-CDMA) component. Both uplink and downlink support a variety of modulation mechanisms.

The UMB downlink supports two MIMO schemes.

- Single codeword (SCW) MIMO with closed loop rate and rank adaptation: A single packet is encoded and sent on a number of spatial beams for rate adaptation. The initial UMB design will be based on SCW MIMO.
- Multi-codeword (MCW) MIMO with per-layer rate adaptation: Multiple packets are encoded separately before spatial multiplexing.

UMB also supports adaptive interference management for increased cell-edge data rates. Furthermore, flexible resource allocation is optimized for low overhead signaling through the classification of assignments as "persistent" or "non-persistent". Persistent assignments eliminate bandwidth request latency for delay-sensitive applications, whereas non-persistent assignments are best suited for best-effort traffic. Seamless handoffs and advanced QoS mechanisms enable enhanced performance and support for real time services.

1.7 IEEE and Other Wireless Access Technologies

Although some access technologies compete with each other as optimal choices to serve an application, given the other considerations, their complementary nature must be appreciated. This complementary nature across user domains and sensitivity to the application and user requirements, within a cooperative and dynamic communication environment, is gaining increasing momentum and significance.

1.7.1 Wireless Local Area Network (WLAN)

The WLAN protocol is defined by the IEEE 802.11 standard which was originally published in 1997 and later updated with a major revision in 2007. There are various versions of WLAN as denoted by the letter next to 802.11, all of which are amendments to the original IEEE 802.11 standard. Within the IEEE 802.11 family, the following standards and amendments exist.

- IEEE 802.11 – The WLAN standard, originally 1 Mb/s and 2 Mb/s, 2.4 GHz RF and infrared (IR) (1997). All others below are Amendments to this standard. Recommended Practices 802.11F and 802.11T were withdrawn/cancelled.
- IEEE 802.11a – 54 Mb/s, 5 GHz standard (1999)
- IEEE 802.11b – Enhancements to 802.11 to support 5.5 and 11 Mb/s (1999)
- IEEE 802.11c – Bridge operation procedures; included in IEEE 802.1D (2001)
- IEEE 802.11d – International (country-to-country) roaming extensions (2001)
- IEEE 802.11e – Enhancements: QoS, including packet bursting (2005)

- IEEE 802.11g – 54 Mb/s, 2.4 GHz standard (backwards compatible with b) (2003)
- IEEE 802.11h – Spectrum Managed 802.11a (5 GHz) for European compatibility (2004)
- IEEE 802.11i – Enhanced security (2004)
- IEEE 802.11j – Extensions for Japan (2004)
- IEEE 802.11-2007 – New release includes amendments a, b, d, e, g, h, i, and j. (2007)
- IEEE 802.11k – Radio resource measurement enhancements (2008)
- IEEE 802.11n – Higher throughput improvements using MIMO antennas (2009)
- IEEE 802.11p – WAVE—Wireless Access for the Vehicular Environment (2010)
- IEEE 802.11r – Fast BSS transition (FT) (2008)
- IEEE 802.11s – Mesh Networking, Extended Service Set (ESS) (2011)
- IEEE 802.11u – Interworking with non-802 networks (2011)
- IEEE 802.11v – Wireless network management (2011)
- IEEE 802.11w – Protected Management Frames (2009)
- IEEE 802.11y – 3650–3700 MHz Operation in the U.S. (2008)
- IEEE 802.11z – Extensions to Direct Link Setup (DLS) (2010)
- IEEE 802.11mb – Maintenance of the standard; will become 802.11-2011 (2011)
- IEEE 802.11aa – Robust streaming of Audio Video Transport Streams (anticipated 2012)
- IEEE 802.11ac – Very High Throughput <6 GHz; potential improvements over 802.11n: better modulation scheme (expected ~10% throughput increase); wider channels (80 or even 160 MHz), multi user MIMO (anticipated 2012)
- IEEE 802.11ad – Very High Throughput 60 GHz (anticipated 2012)
- IEEE 802.11ae – QoS Management (anticipated 2011)
- IEEE 802.11af – TV Whitespace (anticipated 2012)
- IEEE 802.11ah – Sub 1GHz (anticipated 2013)
- IEEE 802.11ai – Fast Initial Link Setup

Today's commercial WLAN products are mostly based on the 802.11a, b, g, and n protocols. While 802.11a was the first wireless networking standard, the first standard broadly implemented was 802.11b, followed by 802.11g. IEEE 802.11n (next-generation) has the objective of speeds above 100 Mb/s using such advanced technologies as MIMO, and with flexibility in the choice of modulation scheme and operational frequency (2.4 or 5 GHz). Standards c–f, h, and j are service amendments and extensions or corrections to previous specifications. 802.11i was introduced to fix the security weaknesses of the WEP (Wireless Encryption Protocol) that came with the original 802.11 standard.

1.7.1.1 Protocol description

As with other 802.x protocols, 802.11 deals with the data link and physical layers of the OSI (Open System Interconnection) protocol stack. The data link layer functions are covered by the MAC (Media Access Control) protocol of the 802.11 standard. Figure 1-37 shows the relevance of 802.11 in the OSI protocol stack.

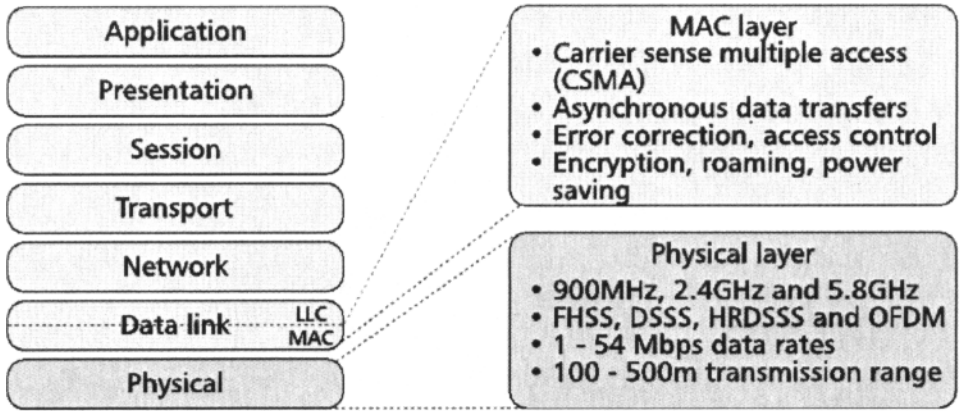


Figure 1-37: The IEEE 802.11 Protocol Stack

1.7.1.2 MAC layer

Following are some of the major functions of the MAC layer.

- It utilizes CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) as its basic access mechanism. The main aspect of this method is that it does not transmit if the medium is thought to be occupied by other users, but only transmits when the medium is believed to be available for communication. Upon sensing that the medium is free for a specified time called DIFS (Distributed Inter Frame Space), the transmitting station is allowed to transmit. The receiving station will then check the CRC (Cyclic Redundancy Check) of the received packet and send an ACK (Acknowledgement). The receipt of an ACK by the sender station will ensure that no collision has taken place. If the sender does not receive any ACK within a given time frame, a retransmission will occur. The packet will be discarded by the sender if the number of retransmissions reaches a set maximum limit.
- The 802.11 standard provides a mechanism for "virtual carrier sense" with an acknowledgement-based signaling protocol. A station willing to transmit a packet first sends a short packet called a Request To Send (RTS) which will contain the source, destination, and duration of the following transaction. If the receiving station is free, it will send a response with another short packet called a Clear To Send (CTS) that denotes the sender can now transmit its message. All stations receiving either the RTS or the CTS will set their Network Allocation Vector (NAV) for the given duration and use this information (along with the physical carrier sense) to sense the medium.
- A simple send-and-wait algorithm is used to address the fragmentation and reassembly functions. The transmitting station is not allowed to send any new fragment until it receives an ACK for the sent fragment or it decides that the fragment was retransmitted too many times.
- 802.11 uses exponential back-off algorithm to resolve contention between multiple stations attempting to access the medium at the same time. This method requires each station to wait for a random number of slots before reattempting to access the medium.

1.7.1.3 Physical layer

Following are some of the highlights of the 802.11 Physical Layer.

- An 802.11 protocol is allowed to operate in the unlicensed 915 MHz, 2.4 GHz, and 5 GHz Industry, Science and Medical (ISM) bands.
- The 802.11a protocol operates on 5 GHz Unlicensed National Information Infrastructure (U-NII) band with 12 non-overlapping channels. It uses a 52 subcarrier OFDM-based modulation.
- Both the 802.11b and 802.11g protocols use the 2.4 GHz ISM spectrum with three non-overlapping channels. Since ISM spectrum is free, 802.11b and 11g equipment may occasionally suffer interference from other household devices such as microwave ovens and cordless telephones.
- The 802.11b protocol uses Direct Sequence Spread Spectrum (DSSS) modulation while 802.11g uses an OFDM-based modulation.
- The 802.11n protocol builds on previous 802.11 standards by adding MIMO to the physical layer. MIMO uses multiple transmitter and receiver antennas to improve the system performance. 802.11n operates in both the 2.4 GHz and 5 GHz spectrum.

Table 1-4, with data taken from Wikipedia [Wik11], briefly compares physical layer characteristics.

Protocol	Release Date	Operating Frequency (GHz)	Realistic Throughput (Mb/s)	Maximum Data Rate (Mb/s)	Modulation Technique	Range Radius (Meters)	
						Indoor	Outdoor
Legacy	1997	2.4	0.9	2		~20	~100
802.11a	1999	5	23	54	OFDM	~35	~120
802.11b	1999	2.4	4.3	11	DSSS	~38	~140
802.11g	2003	2.4	19	54	OFDM	~38	~140
802.11n	2009	2.4 and 5	74	248	DSSS or OFDM	~70	~250

Table 1-4: Physical Layer Characteristics of Various 802.11 Protocols

1.7.1.4 Network architecture

Figure 1-38 shows a typical reference architecture of an 802.11-based WLAN. The network is subdivided into regions called Basic Service Sets (BSS) which are controlled by a radio base station called the Access Point (AP). The boundary of each BSS is defined by the range of the AP for providing wireless connectivity to the MSs within that BSS. The interconnection between multiple BSSs is typically handled by an Ethernet-based backbone network. However, the BSSs can be connected via a wireless backbone network as well. The interconnected BSS area is called an Extended Service Set (ESS) in the standard.

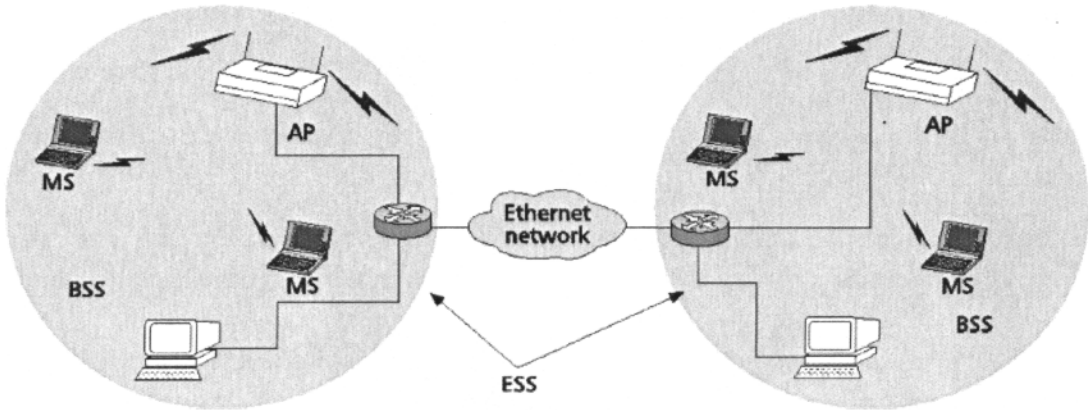


Figure 1-38: IEEE 802.11 WLAN Network Reference Model

A network architecture where the MSs directly talk to each other and are not connected to a wired network (e.g., the Internet and/or a private IP-based network) is called an Independent BSS (IBSS) as shown in Figure 1-39. These MSs can only talk to each other and thereby build their own LAN (Local Area Network).

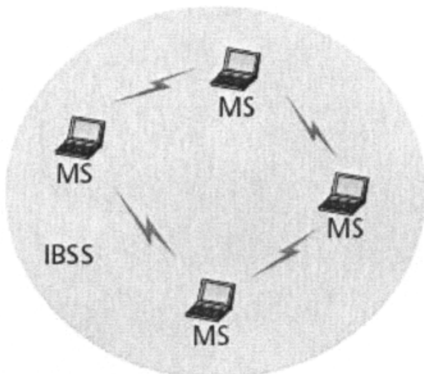


Figure 1-39: An IEEE 802.11 Ad-Hoc Network

In an IBSS, a MS can only communicate with another MS if they are in direct radio contact with each other. There is no central node (e.g., an AP) to which all the MSs can connect, and the connections between the MSs are established on an as-needed basis. In such a case, the IBSS is also called an Ad-hoc Network, which is usually small and short-lived (relative to a BSS and/or an ESS). For example, in a conference setting, the presenter and/or the participants could exchange their files without having to log onto the conference center's private network.

IEEE 802.11 has had a great and growing success. The emerging and future wireless access paradigms include a heteregenous environment of multiple technologies and cells, with WiFi playing a significant role.

1.7.2 Wireless Personal Area Networks (WPAN)

Wireless Personal-Area Networks (WPANs) enable wireless connectivity and communications between devices or sensors within a few meters to tens of meters of each other. They typically operate at low power and have a range of capabilities from low to high data rates. Examples include the Infrared Data Association (IrDA), Bluetooth, Zigbee, and Ultra-wideband (UWB).

The sub-working groups within IEEE 802.15 cover a range of capabilities, from simple and low-rate (e.g., Zigbee) interaction of devices and sensors (802.15.4), to high data rate definition (802.15.3) for such applications as short range multimedia imaging or vehicular communication systems. The 802.15.1 has been a cooperative effort with the Bluetooth Special Interest Group (Bluetooth SIG, formed in 1998, www.bluetooth.org). Many devices, particularly mobile user terminals, are equipped with Bluetooth.

The IEEE 802.15 WPAN task groups are listed in Table 1-5 [IEE11].

IEEE 802.15 WPAN Task Group	Scope
802.15.1	WPAN / Bluetooth
802.15.2	Co-existence
802.15.3	High-Rate WPAN
802.15.4	Low-Rate WPAN
802.15.5	Mesh Networking
802.15.6	Body Area Networks (BAN)

Table 1-5: IEEE 802.15 WPAN Task Groups

UWB is a technology that uses a large bandwidth, potentially shared with other users, to transmit information at low power. It is intended to provide a range of applications, notably high-data-rate personal-area networking (PAN). While technical, spectrum, and regulatory concerns have been debated, and the question of co-existence is expected to be further addressed or coordinated, UWB has received a flurry of attention, research, and innovation, as a technology with a great deal of promise.

The parameters of importance in wireless PAN naturally include such attributes as transmit power, range, data rate, spectrum, co-existence/interference, configuration/set-up, pairing, and mesh networking.

1.7.3 WiMAX

WiMAX is a broadband wireless technology that is designed to support both delay-sensitive (conversational or interactive) and delay-tolerant (non-real-time) applications. It has made significant advancements as a candidate for broadband wireless applications.

The Mobile WiMAX air interface is based on the OFDMA protocol as specified in IEEE 802.16-2009 [IEE09]. The mobility enhancements of mobile amendment IEEE 802.16e provide improved multi-path performance in non-line-of-sight environments and support for scalable channel bandwidth operation from 1.25 to 20 MHz (as outlined by the WiMAX Forum in February 2006 [WiM06a, WiM06b]).

The Mobile Technical Group (MTG) in the WiMAX Forum has defined several mobile WiMAX profiles that describe various capacity-optimized and/or coverage-optimized configurations. Initial mobile WiMAX profiles, however, will cover the 5, 7, 8.75, and 10 MHz channel bandwidths for licensed worldwide spectrum allocations in the 2.3 GHz, 2.5 GHz, and 3.5 GHz frequency bands.

The Network Working Group (NWG) of the WiMAX forum defined the higher-level networking specifications for mobile WiMAX systems beyond the IEEE 802.16 standard. The combined effort of IEEE 802.16 (http://www.ieee802.org/16) and the WiMAX Forum (http://www.wimaxforum.org) has helped define the end-to-end system solution.

- Mobile WiMAX supports target peak data rates of up to 63 Mb/s on the downlink and up to 28 Mb/s on the uplink in a 10 MHz channel. This requires the use of MIMO antennas, flexible sub-channelization schemes, efficient MAC frames, and enhanced Modulation and Coding Schemes (MCS).
- The dynamic allocation of RAN resources based on service flows is another advanced feature of mobile WiMAX. Service flows enable the RAN to utilize its resources efficiently based on such QoS requirements as low latency.
- Mobile WiMAX supports disparate allocations of spectrum based on particular requirements and is designed to scale within a variety of channelization schemes between 1.25 MHz and 20 MHz.
- Mobile WiMAX provides a security solution by implementing Extensible Authentication Protocol (EAP)-based authentication, Advanced Encryption Standard – CTR mode with CBC-MAC (AES-CCM)-based authenticated encryption, and other message authentication codes. (See Chapter 3 for detailed information on security codes and protocols.)
- Mobile WiMAX supports Subscriber Identity Module/Universal Subscriber Identity Module (SIM/USIM) cards, smart cards, digital certificates, and username/password associated with relevant EAP methods for credential management.
- Since fast handoff is a critical requirement for supporting delay-sensitive applications, mobile WiMAX has an optimized handoff scheme with a mute time of 50 milliseconds.

1.7.3.1 Network architecture

Figure 1-40 shows the network reference architecture for mobile WiMAX. It depicts the key normative reference points R1-R5. Each of the entities, MS, ASN (Access Service Network), and CSN (Connectivity Service Network) represent a grouping of functional entities; each of these functions may be realized in a single physical device or may be distributed over multiple devices. The ASN consists of all the radio components within the network access provider domain while the CSN consists of core network components (e.g., AAA server, user database, inter-working gateway, etc.). As shown, both the visited and home NSPs (Network Service Providers) have been accommodated in the network architecture via the R5 interface, while R2 defines a specified interface between a NSP and user terminal (subscriber or mobile station). While the ASP (Application Service Provider) or the Internet is shown connected to the CSN, the interface between them is left open at this time and is assumed to be implementation dependent.

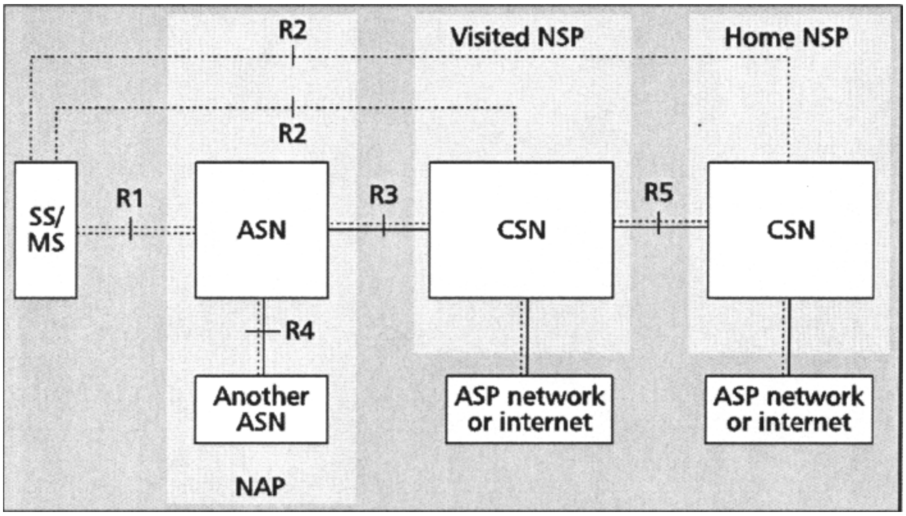


Figure 1-40: WiMAX Network Reference Model

1.7.3.2 Protocol description

The WiMAX physical layer (OFDMA PHY) supports sub-channelization in both the downlink and the uplink. The minimum frequency-time resource unit of sub-channelization is one slot, which is equal to 48 data tones (sub-carriers).

There are two types of sub-carrier permutations for sub-channelization; diversity and contiguous. The diversity permutation draws sub-carriers pseudo-randomly to form a sub-channel. It provides frequency diversity and inter-cell interference averaging. The contiguous permutation groups a block of contiguous sub-carriers to form a sub-channel. The permutation scheme enables multi-user diversity by choosing the sub-channel with the best frequency response.

In general, diversity sub-carrier permutations perform well in mobile applications while contiguous sub-carrier permutations are well suited for fixed, portable, or low mobility environments. These options enable the system designer to trade off mobility for throughput.

The MAC layer of IEEE 802.16 supports both busrty data traffic for bandwidth intensive applications and lower-bandwidth continuous traffic for delay-sensitive (conversational) applications. The resources allocated to the user device by the MAC scheduler can vary from a single time slot to the entire frame allowing a large range of throughput variation. Additionally, the MAC scheduler has the ability to allocate the resources ahead of sending each frame by including that information in the message before each frame.

QoS in the MAC layer of mobile WiMAX is implemented via service flow as shown in Figure 1-41. Service flow is a unidirectional flow of packets (identified by the term SF ID) that contains specific QoS parameters associated with that WiMAX "connection" (a unidirectional logical link between the peer MACs at the mobile and base station, identified by the term Connection ID or CID). The QoS parameters associated with the service flow include a traffic flow "classifier" and the "QoS category."

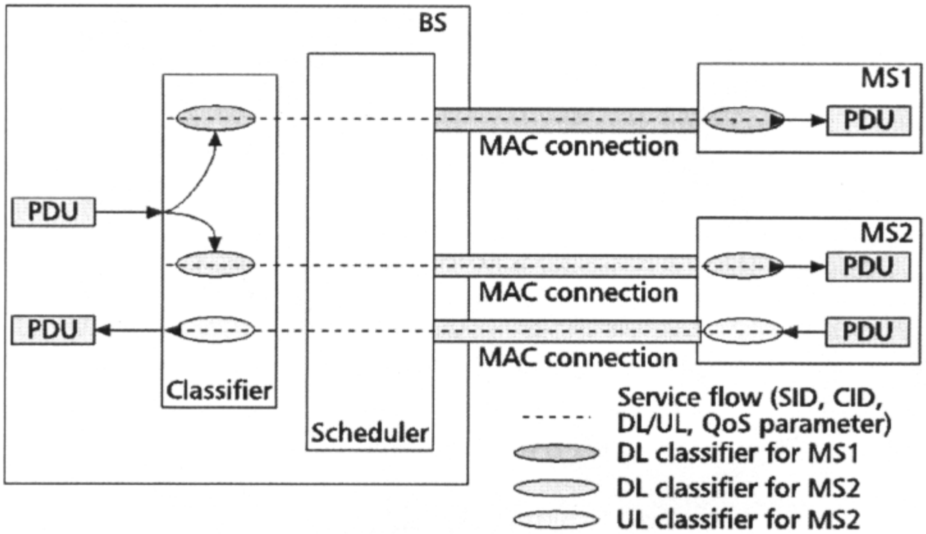


Figure 1-41: MAC Layer QoS Model for Mobile WiMAX

As shown, a protocol data unit (PDU, or basic message), whether in uplink (MS to BS) or downlink transmission, is sent to the classifier associated with the service flow, where it is translated into a specific scheduler priority according to its QoS category. The scheduler then transmits that PDU based on its priority in relation to the available resources at that specific instant.

Mobile WiMAX supports a wide range of data services and applications with varied QoS requirements. These are summarized in Table 1-6.

QoS Category	Proposed Applications	QoS Specifications
UGS Unsolicited Grant Service	VoIP and PTT	Maximum sustained rate Maximum latency tolerance Jitter tolerance
rtPS Real-Time Packet Service	Streaming audio or video	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Traffic priority
ertPS Extended Real-Time Packet Service	Voice with activity detection (VoIP)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Jitter tolerance Traffic priority
nrtPS Non-Real-Time Packet Service	File Transfer Protocol (FTP)	Minimum reserved rate Maximum sustained rate Traffic priority
BE Best-Effort Service	Data transfer, web browsing, etc.	Maximum sustained rate Traffic priority

Table 1-6: Mobile WiMAX Quality of Service Categories

1.7.3.3 Scheduling

The mobile WiMAX MAC scheduling service provides optimized delivery of both delay-sensitive and delay-tolerant applications over broadband wireless access. The main aspects of this service are:

- Fast Data Scheduler – The MAC scheduler, located at each BS, allocates the available RF resources for bursty data traffic under time-sensitive channel conditions. Each PDU has well-defined QoS characteristics (associated with its SF) that allows the scheduler to provide over the air (OTA) transmission priority.
- Scheduling for the downlink and uplink – The scheduling service is provided in both directions. Bandwidth requests through a ranging channel, piggyback requests, and polling methods are used to support uplink bandwidth demands. Downlink resource allocation is performed by the downlink scheduler based on the service flow priority against the available resources.
- Dynamic Resource Allocation – The MAC scheduler allows frequency- and time-based resource allocation in both directions on a-per frame basis. A MAP message delivers the resource allocation information at the beginning of each frame, allowing for finer resource management per frame in response to the variations in traffic and/or channel conditions. Furthermore, each resource allocation can consist of one slot or the entire frame.
- QoS-Oriented Scheduling – The scheduler provides QoS-based data transport per MAC connection as indicated earlier. The scheduler can dynamically allocate/de-allocate RF resources in both the downlink and the uplink based on the QoS parameters associated with each connection.
- Frequency-Selective Scheduling – The MAC scheduler is capable of operating on various types of sub-channels. While using an Adaptive Modulation and Coding (AMC)-based continuous permutation method, the sub-channels may vary in their attenuations. The frequency-selective scheduling can allocate the strongest sub-channel available to a mobile user. Additionally, the frequency-selective method can increase system capacity with a slight increase in Channel Quality Indicator (CQI) overhead over the uplink.

1.7.3.4 Mobility management

Two important aspects of mobility management addressed by mobile WiMAX are power consumption and seamless handoff.

- Power Management – Mobile WiMAX supports two modes, sleep and idle, within a connection state, for efficient power consumption. Sleep mode is a connection state in which the MS turns off its communication with the BS for pre-negotiated periods of time. Idle mode, on the other hand, is a mechanism for the MS to be periodically available for downlink transmission without the re-registering with the BS. Idle mode allows the MS to be reachable in a highly mobile environment.
- Handoff – Three handoff methods are supported within the 802.16e standard – Hard Handoff (HHO), Fast Base Station Switching (FBSS), and Macro Diversity Handover (MDHO). Of these, HHO is mandatory while FBSS and MDHO are optional. The WiMAX Forum has developed several techniques for optimizing HHO within the 802.16e framework. These improvements have been developed with the goal of keeping Layer 2 handoff delays to less than 50 ms.

- In HHO, the MS must go through the entire registration process when it changes the BS.
- In FBSS, the MS maintains continuous RF communication with a group of BSs that are called its "active set". The MS is also assigned an "anchor" base station within its active set. The anchor base station manages the uplink/downlink signaling and traffic bearer. Transition from one anchor base station to another is performed based on the signal strength measured by the MS on its CQI channel without exchanging any explicit HO (Hand Off) signaling messages. An important requirement of FBSS is that the data destined for the MS are received by all base stations that are in its active set.
- In MDHO, the signaling and bearer communications over the RF resources are performed between the MS and all of the BSs that are in its active set. This is done for both uplink and downlink transmission.

1.7.3.5 Security

Mobile WiMAX exploits advanced technologies to provide security. These include mutual device/user authentication, flexible key management protocol, strong traffic encryption, control and management plane message protection, and security protocol optimizations for fast handoffs. The reader is again referred to Chapter 3 for a detailed discussion of wireless security.

1.7.4 Broadcast/Multicast Distribution over Cellular

Broadcast/Multicast services such as mobile TV and video applications are increasingly common multimedia content applications enabled by evolving wireless systems. The distribution systems may be:

- Satellite ("S") and/or terrestrial ("T"), or
- Cellular network and/or overlay access.

These systems leverage sophisticated technologies for such functions as coding, modulation, error correction, media formatting and presentation, content protection and management, time-slicing, radio-networking, and data-casting, among others. Typically frequencies below 800 MHz have high capabilities for non-line-of-sight reach and indoor penetration for an application such as over-the-air TV, although higher frequencies are also used, e.g., for high-capacity direct access. An end-to-end block diagram indicating the wireless-access component is shown in Figure 1-42.

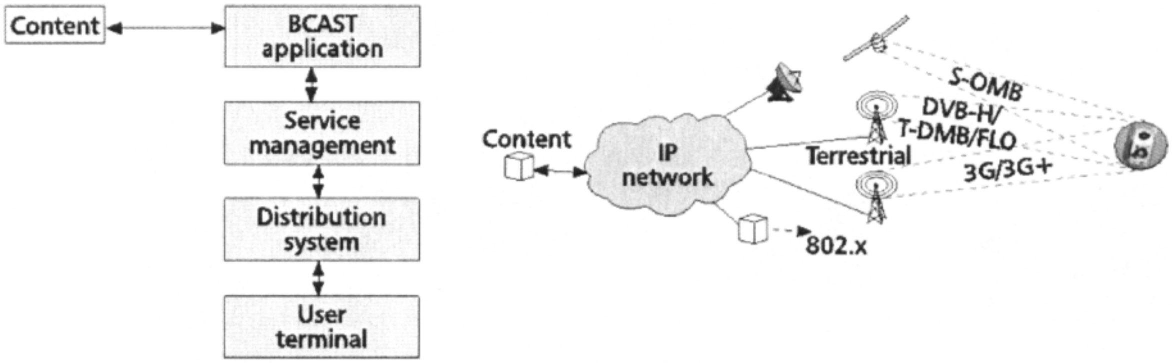


Figure 1-42: Simplified End-to-End Broadcast/Multicast System

The Open Mobile Alliance has worked to develop standards for service enablers, including unified broadcast/multicast service enabler standards, with adaptation to a number of distribution systems.

Examples of mobile broadcast/multicast distribution systems, integrated within or overlaid on top of the mobile cellular systems, include but are not limited to:

- MBMS, 3GPP Multimedia Broadcast/Multicast Service and its enhanced version eMBMS;
- BCMCS, 3GPP2 Broadcast and Multicast Services;DVB-H, Digital Video Broadcast – Handheld;
- DMB (Digital Multimedia Broadcasting;
- MediaFLO, Forward-Link Only Technology – Qualcomm;
- ATSC M/H; and others.

1.7.5 Femtocells

A femtocell may be viewed as a local (e.g., home) coverage area, serving a limited number of users, but as a somewhat independent extension of a wide-area cellular network. The fundamental design goal is for the cell to have as many features of the wide network as possible, with minimal impact on it (e.g., in terms of performance, capacity, efficiency, etc.).

The macro-cellular network features and attributes which may be supported (within assigned policy) include:

- Services at comparable quality;
- Radio interface(s), signaling;
- Mobile terminals (governed by authorization policy and admission control); and
- Mobility management, handoff, operational management, security, and others.

The overall architecture is intuitively simple. Each femtocell has a base station at low power and local (home) coverage serving authorized mobile devices, which may move in and out of the cell. The femtocell home network is connected through existing (IP) broadband connection to the Internet and a cellular network as shown in Figure 1-43.

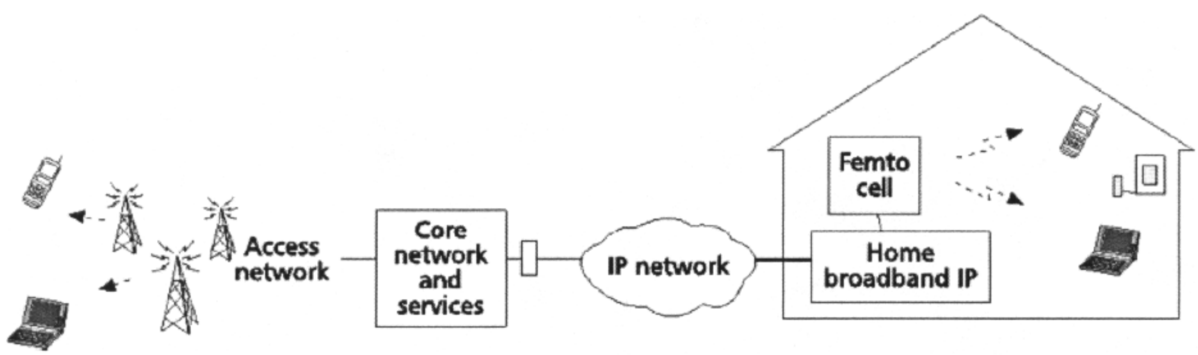


Figure 1-43: A Femtocell as an (Independent) Extension of a Wide-Area Network

The macro-cellular core network must be capable of supporting a large number of femto cells, again without noticeable compromise in efficiency, performance or security.

1.7.5.1 Femtocell specification in 3GPP

In 3GPP, femtocells are defined as customer-premises equipment that connects a 3GPP mobile device over a 3GPP air interface to a mobile operator's network using a broadband IP backhaul [3GP11c]. In addition, femtocells can be deployed by the end user using a consumer-grade backhaul connection. This is facilitated by a standardized management interface that allows the mobile operator to remotely configure all the necessary operating parameters.

3GPP started work on defining the specifications for femtocells starting with Release 8 for both UMTS and LTE. The work covers the network architecture, radio, security, testing, and network management aspects. 3GPP specifications for Release 8, Release 9, and Release 10 include femtocell functionality.

1.7.5.2 Femtocell architecture

The UMTS femtocell architecture (see Figure 1-44) includes the femtocell access point and femto gateway, respectively termed the Home Node B and Home Node B Gateway in 3GPP specifications. The interface between these two network elements is called the IuH.

The Home Node B contains the Node B and most of the RNC functions – the radio interface, radio resource management, medium access control (MAC), etc. The Home Node B Gateway aggregates the connections from multiple Home Node Bs to the core network and also presents the core network with an Iu-PS and/or Iu-CS interface to Packet Switched or Circuit Switched network, respectively.

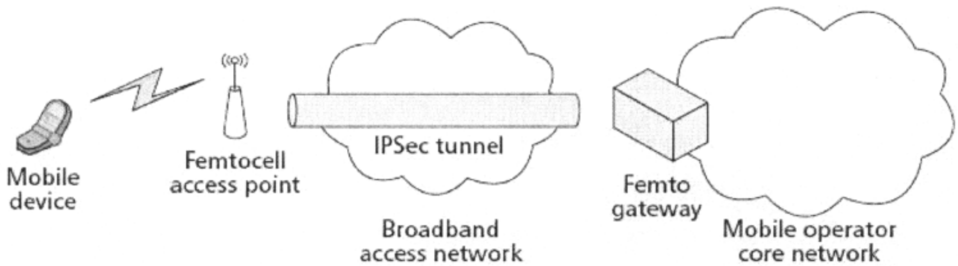


Figure 1-44: Generic View of Femtocell Architecture

An LTE femtocell has a similar architecture, the only differences being that the femto gateway is an optional element and the interface between the femtocell access point and the mobile operator core network is called S1.

1.7.5.3 Security aspects

Security is one of the most important aspects of femtocell architecture. As the femtocell access point itself is not within a secured mobile network operator's premises, it is more susceptible to additional security threats. In addition, the mobile network operator needs to ensure that any communication via the femtocell access point can be done in a secure manner. There is also the need to ensure that the mobile operator's network is protected from threats originating from a rogue femtocell access point.

To that end, 3GPP designed the interface between the femtocell access point and the mobile operator core network using an Internet Protocol Security (IPSec) tunnel that terminates at the Security Gateway in the mobile operator's core network (see Figure 1-45). All communication between the femtocell access point and the mobile operator core network is secured by this tunnel.

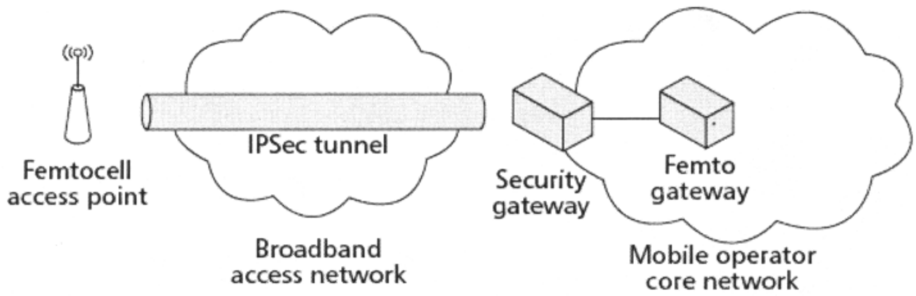


Figure 1-45: Interface between the Femtocell Access Point and the Mobile Network

The Security Gateway also performs mutual authentication of the femtocell access point, for example, when the femtocell access point initially connects with a mobile operator's core network.

1.7.5.4 Femtocell connectivity with the mobile operator core network

For a femtocell access point to provide services, it must first be connected to a mobile operator's core network. The first point of contact for the femtocell access point is the Security Gateway, where mutual authentication is performed. Once this process is complete, an IPSec tunnel is established between the femtocell access point and the Security Gateway. Then the femtocell access point is registered on the mobile operator's network. At this point, the femtocell access point will be configured with the appropriate radio parameters by the operator's management system.

The femtocell access point can also detect the configuration and parameter settings of the macro network directly by "listening" to the information broadcast by the macro network on the 3GPP air interface in order to set its own suitable radio parameters.

1.7.5.5 Access control

There are three modes of operation for a 3GPP femtocell:

- Open – access given to any subscriber allowed access to the mobile operator's network;
- Closed – access given to a defined set of subscribers, typically subscribers of the same mobile operator's network; and
- Hybrid – access given to any subscriber allowed access to the mobile operator's network; however, preferential treatment is given to a defined set of subscribers.

1.7.5.6 Mobility

For mobile devices in the idle state, the mobile device will scan for any available cells. When a femtocell is detected as the best cell, the mobile device will check to see if it is allowed access to that femtocell before selecting the femtocell to camp on. If the mobile device is not allowed access, then the mobile device will camp on the next best cell, if it is available, and so on.

For mobile devices in the connected state, when the device moves between macro network coverage and femtocell coverage, handover will be performed. In the case where the target cell is a femtocell, checks will be made prior to handover to ensure the mobile device is allowed access to the femtocell. For the case where the macro network and femtocell are both UMTS, this is a hard handover. Handover is also supported when the mobile device moves between different femtocells.

1.7.5.7 Network management

For femtocells, a standardized management interface is extremely important, as it allows for the remote configuration of radio parameters and the collection of performance counters and fault management information. The Broadband Forum's procedures have been used as the basis for 3GPP femtocell network management.

1.7.5.8 End user perspective

The main requirement for the end user is that the femtocell access point must allow zero-touch installation that needs no intervention by the end user, apart from physically plugging in the power cord and cable for IP connectivity.

1.7.6 Near-Field Communication and RFID

Radio-Frequency Identification (RFID) is a mechanism for reading data stored on tags over distances typically within centimeters to potentially tens of meters. There has been an increasing interest in RFID, particularly for enterprise applications such as inventory tracking. RFID tags may be passive, semi-passive, or active. Passive ones do not have a power source and are activated by the tag reader.

Near-Field Communication (NFC) allows wireless connectivity over a short range, typically within centimeters, enabling such applications as secure and reliable mobile payment and ticketing (in a crowd of users and in the presence of other applications). NFC extends the capabilities of RFID and is compatible with it. It can co-exist with WPAN, e.g., to configure or pair with it. Despite some overlap between the two, the distinctions between NFC and WPAN are self-evident in terms of attributes such as range, power, data rate, set-up time, topology, and applications. As with other access mechanisms, however, their complementary nature must be appreciated to be effectively leveraged as applicable.

It is worth noting that mobile (2D) barcodes are also finding a significant market in mobile commerce, among other applications, typically using optical (camera) scanning of information (e.g., a URL).

1.7.7 Satellite Systems

Satellite communication has advanced in the course of the last several decades. There is obviously a great deal of science, technology, engineering, and operations involved in the design and structure, launch and propulsion, orbit selection, power, weight, tracking, and control, among other aspects. From a communication perspective, similar concepts apply as have been discussed so far, and also as are covered in Chapter 4. These include transmission and reception concepts such as modulation, coding and detection, antenna technologies, operational frequencies, and receiver structures in terms of sensitivity, noise, filtering, amplification, equalization, figure of merit, etc.

There have of course been different systems intended for different satellite services, with Mobile Satellite Service (MSS) being a notable example. Wireless access technologies, as we have seen, can be any of a broad range of enablers including satellite communication or a hybrid satellite/terrestrial system. Not only are services such as connectivity, communication, and content increasingly and seamlessly made possible by a variety of mechanisms and potentially in a multi-technology environment, but the mobile standards we have discussed (such as LTE) may be deployed in multiple ways.

1.8 Wireless Access Technology Roadmap: Vision of the Future

1.8.1 Motivation and Design Objectives

Wireless technology evolution has attracted a great deal of interest in research, standardization, industry forum initiatives, innovations, and regulatory fora, in an effort to shape design goals and specify technical requirements to realize the vision and potential requirements of ubiquitous connectivity, communication, and content, to serve an increasingly mobile world society, as represented by Figure 1-46. In the same framework, a number of global and regional initiatives continue to define the roadmap and enable the future communication space.

Design goals for the systems beyond 3G/4G include:

- High data rate (user experience, speed) and capacity (traffic volume);
- Low latency (real-time and near-real-time), high performance, constant connectivity;
- Spectral efficiency;
- Cost/resource efficiency;
- Flexibility (e.g., resource allocation), adaptability (e.g., interference management), seamless mobility, scalability (e.g., spectrum);
- Enhanced broadcast/multicast and end-to-end QoS; and
- Co-existence and inter-working with other access technologies.

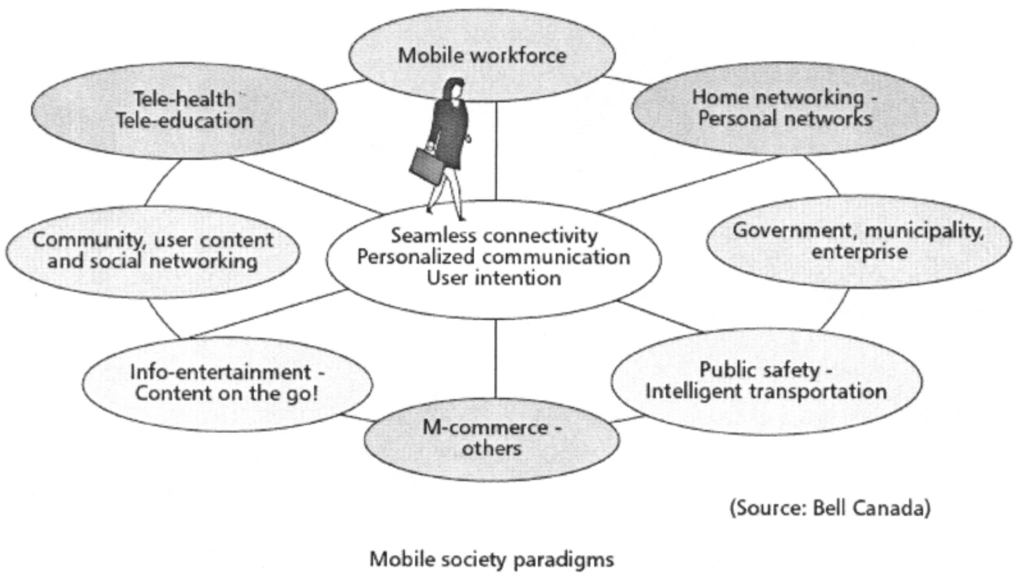


Figure 1-46: Enabling Connectivity, Communication, and Content on the Go

Some of these goals (such as seamless mobility and inter-working, end-to-end QoS, etc.) are also tied to the evolution of the core packet network, which in parallel is maturing towards a heterogeneous all-IP flat (or at least flatter) architecture. Core network evolution is the subject of Chapter 2.

Wireless access technologies beyond 3G leverage such sophisticated, efficient, and high-capacity technologies or mechanisms as OFDMA, MIMO, and advanced coding/high-level modulation (e.g., 16 or

64 QAM), among others, to meet their goals. There is a flurry of activities to define the requirements and technologies for the next 5-10 years and beyond.

1.8.2 Technology Roadmap Long-Term Initiatives

1.8.2.1 ITU IMT-Advanced

"IMT-Advanced" has been developed by the ITU in consideration of evolving marketplace needs for future wireless communications, along with the required technologies, spectrum, and other issues associated with the worldwide advancement of IMT-2000 systems. This evolving definition for next generation (fourth generation) systems has a baseline defined by ITU-R Recommendation M.1645 [ITU03]. This baseline was also taken into account at the World Radiocommunication Conference (WRC) in 2007 for the identification of additional frequency spectrum for mobile and wireless communications.

IMT-Advanced goes beyond IMT-2000 to provide advanced mobile multimedia services, with significant improvement in performance and user experience across both fixed and mobile networks. The key features of IMT-Advanced include:

- A high degree of commonality, flexibility, and efficiency;
- Superior user experience and user-friendly applications and devices;
- Inter-working of access technologies and global roaming; and
- Enhanced peak data rates to support advanced services and applications – envisioned peak aggregate user data rates of ~100 Mb/s for high user mobility and ~1 Gb/s for low user mobility (new nomadic/local-area wireless access).

The objectives of IMT-Advanced were addressed in 3GPP Release 10 and continue to be addressed in subsequent releases. Figure 1-47 shows the evolving capabilities of IMT-2000 and IMT-Advanced.

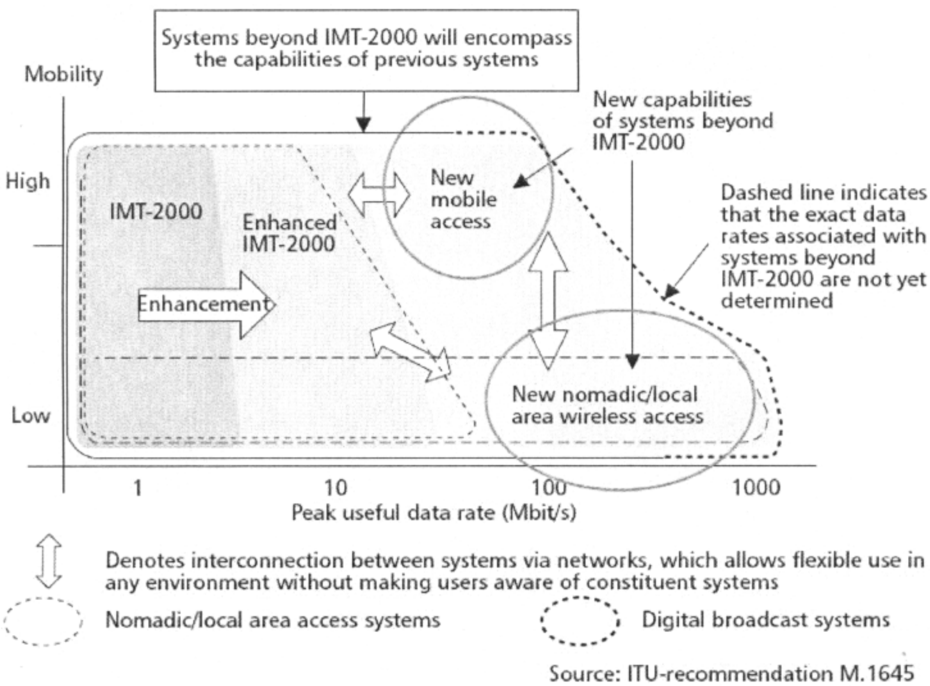


Figure 1-47: Capabilities of IMT-2000 and Systems beyond IMT-2000 (IMT-Advanced)

1.8.2.2 Next Generation Mobile Networks

The Next Generation Mobile Networks (NGMN) initiative consists of a group of mobile operators (Members), who along with other stakeholders in the mobile ecosystem collectively comprise the group of Partners. NGMN intends to provide a coherent vision for technology evolution beyond 3G (specifically an LTE/EPC roadmap) for the delivery of broadband wireless services in the decade beyond 2010.

The vision of NGMN is to "provide a platform for innovation by moving towards one integrated network for the seamless introduction of mobile broadband services. The initial objective of the alliance was the commercial launch of a new experience in mobile broadband communications and to ensure a long and successful cycle of investment, innovation and adoption of new and familiar services that would benefit all members of the mobile ecosystem" [NGM11]. In the phase beyond the introduction of LTE, NGMN continues to guide standardization and the overall ecosystem with respect to the requirements of future networks such as interoperability, converged operational excellence and network management, multi-mode multi-band (user device) technologies, spectrum and band requirements, TDD/FDD dual and seamless support, etc. A number of publications, including a white paper on technical achievements, provide more details.

1.8.2.3 Wireless World Research Forum

The Wireless World Research Forum (WWRF) is a global organization which was founded in August 2001. It has a large number of members from across the globe, representing all sectors of the mobile communications industry and the research community. The objective of the Forum is to formulate visions on strategic future research directions in the wireless field, among industry and academia, and to generate, identify, and promote research areas and technical trends for mobile and wireless system technologies.

Forum activities aim towards the creation of a shared global vision for the future of wireless, intended to drive research and standardization. In addition to influencing regional and national research programs, WWRF members contribute to the work done within the ITU, UMTS Forum, ETSI, 3GPP, 3GPP2, IETF, and other relevant bodies regarding commercial and standardization issues derived from the research work. As part of the effort to shape a common vision for the future of wireless, the WWRF has published a number of white papers, addressing the technical areas of the Working Groups and Special Interest Groups, as well as several generations of the WWRF "Book of Visions" or System Concept document [WWR11].

1.8.2.4 Other initiatives

A large number of research and innovation initiatives exist, particularly in the areas of future radio, future networks, future Internet, smart networks, machine-to-machine, etc., all with involvement from academia, industry, governments, regional commissions and bodies, and global forums.

1.8.3 Technology Trends and Final Words

Communication systems have fundamental attributes in terms of transmission, reception, channel performance, networking, session management, etc. Wireless systems in turn have similar considerations with respect to radio engineering, antennas, operational frequencies, and receiver sensitivity and performance, among others. There is variety, however, in terms of design goals (and constraints), enabling technologies, performance objectives, and applications. In mobile cellular communications, there is a great deal of consideration in terms of radio engineering, capacity and coverage, spectrum and band aspects, mobility and user management, networking, and other aspects. The enabling technologies are becoming more user-centric, more adaptive, reconfigurable, and dynamic, creating a certain level of abstraction such that the intention is served in a smart user space with context and proximity awareness, but somewhat transparent to the technology used. In this context, there is also an increasing trend towards multi-cell and heterogeneous networks.

There is a broad range of wireless access technologies: terrestrial, satellite-based or hybrid; fixed, nomadic, or mobile; point-to-point and line-of-sight or non-line-of-sight; mesh, relay, or ad hoc; and a possible combination of femto, personal, local, or wide-area networks. New mobile networks are already IP-centric and content-centric. This is a new era. In addition, the functions of different elements have evolved as shown in this chapter, including more intelligence moved to the edges. Scalability and flexibility in the design and deployment will be essential characteristics in order to achieve adaptability to varying conditions, related to the radio environment, the usage scenario, and the network conditions.

Personalization, adaptive and reconfigurable devices, ambient awareness, and multi-modal "natural" user interaction in smart user spaces with "enhanced" reality, among others, are trends for vision, research, and innovation. Such technologies as cognitive radio, self-organizing networks, and smart beamforming, coupled with advanced technologies in other areas, such as sensing, robotics, nano-engineering, and others, will enable this vision of future user-centric, context-aware, ubiquitous, and intention-based communication across all user spaces.

Finally, it must be noted that identification of design objectives and requirements, and definition of technology innovations and solutions, will not sufficiently succeed without adequate modeling and performance evaluation methodologies and systems. These concepts are not new but the environment in which wireless access technologies operate has evolved remarkably and thus demands new modeling and evaluation criteria, in the presence of new user interaction paradigms, dynamic user interfaces and access mechanisms, traffic growth and patterns, mixed services, interference sources, and time-varying communication parameters.

Wireless technologies co-exist with non-wireless ones (particularly optical fiber). Furthermore, a variety of wireless mechanisms and technologies potentially cooperate. Similar fundamental concepts apply, although differences exist, as discussed in this chapter, not only in different environments but in technology evolution and with new paradigms, towards an increasingly seamless and dynamic communication environment to serve and empower the mobile world.

1.9 References

[3GP98] 3rd Generation Partnership Project, Technical Specification Group Service and Systems Aspects, *Digital cellular telecommunication system (Phase 2+); General Packet Radio Service (GPRS); Service description; Stage 2*, Specification TS 03.60, V7.9.0, 1998.

[3GP99] 3rd Generation Partnership Project, Technical Specification Group Services, *Digital cellular telecommunications system (Phase 2+); General Packet Radio Service (GPRS); Service description, Stage 1*, Specification GSM 02.60, V8.1.0, 1999.

[3GP02] 3rd Generation Partnership Project, Technical Specification Group Service and Systems Aspects, *Architectural Requirements for Release 1999 (Release 1999)*, Specification TS 23.121, V3.6.0, 2002.

[3GP04] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *High Speed Downlink Packet Access (HSDPA); Overall description; Stage 2 (Release 5)*, Specification TS25.308, V5.7.0, Release 5, 2004.

[3GP06] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *FDD Enhanced Uplink; Overall description; Stage 2 (Release 6)*, Specification TS25.309, V6.6.0, 2006.

[3GP11a] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *Radio Interface Protocol Architecture (Release 10)*, Specification TS 25.301, V10.0.0, 2011.

[3GP11b] 3rd Generation Partnership Project, Technical Specification Group Service and Systems Aspects, *General Universal Mobile Telecommunications System (UMTS) architecture (Release 10)*, Specification 23.101, V10.0.0, 2011.

[3GP11c] 3rd Generation Partnership Project, Technical Specification Group Service and Systems Aspects,*Service requirements for Home Node B (HNB) and Home eNode B (HeNB)*, Specification TS 22.220, V11.3.0, 2011.

[ANS01] American National Standards Institute, Telecommunications Industry Association, and Electronic Industries Alliance, *Cellular Radio-Telecommunications Intersystem Operations*, Standard ANSI/TIA/EIA-41-E, 2001.

[IEE09] Institute of Electrical and Electronics Engineers, Working Group on Broadband Wiureless Access Standards. *Air Interface for Fixed and Mobile Broadband Wireless Access System*, Standard 802.16-2009.

[IEE11] Institute of Electrical and Electronics Engineers, www.ieee802.org/15, IEEE 802.15 Working Group for WPAN.

[ITU03] International Telecommunication Union, Radiocommunication Sector, *Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000*, Recommendation ITU-R M.1645, 2003.

[ITU11] International Telecommunication Union, Radiocommunication Sector, *Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-2000 (IMT-2000)*, Recommendation ITU-R M.1457-10, 2011.

[NGM11] Next Generation Mobile Networks, http://www.ngmn.org, 2011.

[Wik11] Wikipedia, *IEEE 802.11*, http://en.wikipedia.org/wiki/IEEE_802.11, 2011.

[WiM06a] WiMAX Forum, *Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation*, 2006

[WiM06b] WiMAX Forum, *Mobile WiMAX – Part II: Competitive Analysis*, 2006.

[WWR11] Wireless World Research Forum, http://www.wireless-world-research.org, 2011.

1.10 Suggested Further Reading

Although not specifically cited in this chapter, the following references are suggested by the authors as sources of useful background and/or detailed information.

3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *Feasibility Study for Enhanced Uplink for UTRA FDD*, Technical Report TR25.896 V6.0.0, 2004.

3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *Physical channels and mapping of transport channels onto physical channels (FDD) (Release 5)*, Specification TS25.211 V5.8.0, 2005.

3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *Physical layer procedures (FDD) (Release 5)*, Specification TS25.214, V5.11.0, 2005.

3rd Generation Partnership Project, Technical Specification Group Radio Access Network, *Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)*, Technical Report TR25.913 V7.3.0, 2006.

3rd Generation Partnership Project 2, Technical Specification Group C: Radio Access, *cdma2000 High Rate Packet Data Air Interface Specification*, Technical Report 3GPP2 C.S0024-A, Version 2.0, 2005.

A. Alexiou, et al., *Duplexing, Resource Allocation and Inter-Cell Coordination-Design Recommendations for Next Generation Systems*, Wireless Communications and Mobile Computing, Wiley Online Library, vol. 5, no. 1, 2005.

A. Alexiou and D. Falconer, *Challenges and Trends in the Design of a New Air Interface*, IEEE Vehicular Technology Magazine, vol. 1, no. 2, 2006.

C. Antón, P. Svedman, M. Bengtsson, A. Alexiou, and A. Gameiro, *Cross-Layer Scheduling for Multi-User MIMO Systems*, IEEE Communications Magazine, vol. 44, no. 9, 2006.

R. Bachl, P. Gunreben, S. Das, and S. Tatesh, *The Long Term Evolution Towards a New 3GPP Air Interface Standard*, Bell Labs Technical Journal, vol. 11, no. 4, 2007.

S. Das, et al., *EV-DO Revision C: Evolution of the cdma2000 Data Optimized System to Higher Spectral Efficiencies and Enhanced Services*, Bell Labs Technical Journal, vol. 11, no. 4, 2007.

G. Nair, J. Chou, T. Madejski, K. Perycz, P. Putzolu, and J. Sydir, *IEEE 802.16 Medium Access Control and Service Provisioning*, Intel Technology Journal, vol 08, no. 3, 2004.

R. Tafazolli (editor), *Technologies for the Wireless Future, Wireless World Research Forum (WWRF)*, Volume 1, John Wiley and Sons, 2005.

R. Tafazolli (editor), *Technologies for the Wireless Future, Wireless World Research Forum (WWRF)*, Volume 2, John Wiley and Sons, 2006.

Telecommunications Industry Association, *Mobile Station – Base Station Compatibility Standard for Wideband Spread Spectrum Cellular Systems*, Standard ANSI/TIA/EIA-95-B, 1999.

H. Yagoobi, *Scalable OFDMA Physical Layer in IEEE 802.16 Wireless MAN*, Intel Technology Journal, vol. 08, no. 3, 2004.

J. Yang, S-H. Shin, and W. C.Y. Lee, *Design Aspects and System Evaluations of IS-95 based CDMA System*, Proceedings of ICUPC, 1997.

J. Yang and J. Lin, *Optimization of Power Management in a CDMA Radio Network*, Proceedings of IEEE Vehicular Technology Conference, 2000.

J. Yang, *Performance and Deployment of a Mobile Broadband Wireless Network based on IS-856 (EV-DO)*, Proceedings of the 2004 World Wireless Congress, 2004.

J. Yang, *Multimedia Services over 1xEV-DO Mobile Broadband Network*, Proceedings. of SATEC, October 2006.