Chapter 10. Cellular Networks

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"Mobile phones are misnamed. They should be called gateways to human knowledge." (Ray Kurzweil).

10.1 Introduction

Guglielmo Marconi demonstrated the feasibility of wireless communications in 1896 with his invention of the wireless telegraph. Ever since this time, the idea of communicating to anyone from anywhere without being physically tethered to an infrastructure has captured our imagination and interests as a society. Wireless communications, such as two-way push-to-talk (PTT) and citizen bands (CB) radios, have been around for decades; unfortunately they are limited in distance and easily intercepted by eavesdroppers. For most of us, wireless communications are only useful if it enables us to privately connect to anyone at any time. As such, an interface to the PSTN is necessary.

In 1946, AT&T offered the first mobile\(^1\) radio-telephone service in St. Louis. Because only a single antenna was used to cover an entire metropolitan area, only 12 to 20 calls could be made simultaneously (AT&T). Maintaining the mobile telephone infrastructure to support a limited number of users meant that the costs, which were high, had to be passed on to the user. While this was a major milestone in the history of the mobile telephone, it was clear that technical advances were needed in order to increase the number of simultaneous calls while keeping costs affordable for the average subscriber.

A significant conceptual innovation came a year later in 1947 when Bell Labs engineers, Donald H. Ring and W. Rae Young, developed the concept of cellular telephone service. With the cellular concept, a service area was divided into separate radio communication cells vice a single large radio coverage area. By operating multiple smaller cells, frequency reuse could be achieved, thereby supporting greater numbers of simultaneous calls across the service area. However, the concept was ahead of the actual technology\(^2\) that was available at the time, and the necessary frequency spectrum to make it a reality unavailable.

It should be pointed out that other wireless telephone efforts took place in different countries during this period of time. As an example, the Dutch National radiotelephone service began operations in 1949, and the Swedish Telecommunications Administration developed an automatic mobile telephone system, MTA, in 1951. In 1952, the Japanese Nippon Telephone and Telegraph company began research into radiotelephones. (Farley, 2005)

Several engineers, Joel Engel and Richard Frenkiel of Bell Labs, and Marty Cooper of Motorola, worked together to successfully demonstrate the cellular concept by making the first cellular call in April 1973. By this time, solid state circuitry and automated cell switch technologies had

\(^{1}\) "Mobile radio-telephones" were installed in automobiles. Considering the technology available at the time, handheld models would've been much too heavy.

\(^{2}\) Technologies not yet available included low cost transceivers, and technology needed for cells to handoff calls as users moved from one cell to another. In addition, the frequency spectrum needed was not yet available from the FCC.
matured. While the prototype phone weighed 45 ounces and had a battery life that only allowed 30 minutes of talk time, it proved the viability of the concept. Although the demonstration got the attention of the FCC, it would take another eight years before additional frequency spectrum was allocated for cellular communications. In October 1981, FCC finally allocated two frequency bands in the 800MHz range. (The Foundations of Mobile and Cellular Telephony, 2015)

As the popularity of cellular communications began to spread globally, numerous technical innovations were introduced to help service providers keep up with the ever growing demand for services despite the limited frequency spectrum available. Although the FCC has allocated more spectrum over years, it is still an issue today. In addition, the lack of interoperability between cellular systems has presented challenges for both providers and consumers. While numerous standards committees strive towards developing and adopting fully compatible standards, newer challenges for the cellular industry have emerged as a result of the popularity of the Internet. Today, consumers desire access to multimedia applications and high speed streaming. No longer are we satisfied with the basic voice call, as the smartphone has combined communications, information, and entertainment into a single mobile handheld device. Meeting future demands efficiently will necessitate the convergence of several communications disciplines such as the Internet, mobile phone, PSTN, and computer.

### 10.2 Regulation and Standardization

Each nation has regulatory authority over its telecommunications systems. In the United States, **FCC** is a federal agency in charge of regulating both wired and wireless communications within the country. However, considering the global nature of telecommunications, a coordinating entity such as the **ITU**, which falls under the authority of the United Nations, is essential in addressing any **information and communications technologies (ICT)** issues, especially those that impact more than one country. ICT encompasses numerous communications areas including wireless, Internet, satellite, radio astronomy, and maritime navigation. Therefore, ITU plays an important role in the coordination and assistance of both the regulatory and standardization efforts.

The allocation of frequency spectrum and the standardization of network interfaces are essential to achieving global telecommunications interoperability; however the processes involved in any regulatory or standardization effort is arduous and time consuming. The cellular industry works closely with regulatory agencies to expand the availability of frequency spectrum and to ensure that government policies do not stifle growth or innovation. In addition, as communications capabilities converge the standardization process must ensure system interoperability. The cellular industry, once the domain of the telephone industry, has now converged with other domains such as the Internet, computer networking and wireless LANs.

There are numerous standardization organizations involved for every aspect of ICT. Below is a sample listing of standardization organizations involved with some aspect of the cellular industry.
Cellular Telecommunications and Internet Association (CTIA): Founded in 1984, CTIA represents the U.S. wireless industry comprised of manufacturers and service providers. CTIA’s primary purpose is to advocate policies to the federal government on behalf of industry partners.

Institute of Electrical and Electronics Engineers (IEEE): Dating back to 1884, IEEE has been involved in all aspects of the electronic, electrical and computing fields. They are actively involved in the research and standardization of digital communications, including Mobile WiMAX IEEE 802.16 which is a 4G cellular standard.

GSM Association (GSMA): Formed in 1982 by the Confederation of European Posts and Telecommunications (CEPT), GSMA represents over 200 companies comprised of manufacturers, Internet companies, and service operators in the development of the GSM standard.

3rd Generation Partnership Project (3GPP): 3GPP is comprised of seven telecommunications standard organizations intended to advance technologies and produce specifications in support of cellular network technologies. Technical specification groups include Radio Access Networks (RANs), Services & Systems Aspects (SA), and Core Network and Terminals (CT). While their name identifies 3G, the partnership has worked actively on 4G and future generation cellular technologies.

Open Mobile Alliance (OMA): Formed by mobile operators, manufacturers, and IT companies, OMA is a non-profit organization that develops open specifications to ensure interoperable communication systems around the world. In addition to supporting mobile communications, OMA is involved with machine-to-machine (M2M) and Internet-of-Things (IoT) device communications.

European Telecommunications Standards Institute (ETSI): ETSI is a non-for-profit organization recognized by the European Union, with membership from organizations based in 67 countries. ETSI produces ICT standards including GSM and Long Term Evolution$^3$ (LTE).

Telecommunications Industry Association (TIA): TIA is a global trade association in ICT focusing on standardization, policy initiatives, and business opportunities.

American National Standards Institute (ANSI): ANSI’s heritage dates back to 1919 when it was called the American Engineering Standards Committee (AESC). Initially working on national safety codes, AESC actively participated in the creation of the International Standards Association (ISA) which eventually became the International Organization for Standardization (ISO). In 1987, ANSI accepted administrative responsibility for ISO/IEC's Joint Technical Committee on Information Technology (JTC1).

European Conference of Postal and Telecommunications Administrations (CEPT): CEPT, which was established in 1959, is a consortium of 48 member countries across Europe. The

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$^3$ LTE is a registered trademark owned by ETSI, however many other organizations have played key roles in the development of the standard.
organization collaborates on policy issues that include telecommunications, use of radio spectrum, and postal regulations.

International Organization for Standardization (ISO): ISO is an international non-governmental organization dedicated to developing international standards on a broad scope of topics including ICT, food safety, agriculture, healthcare, and numerous other technologies. Consisting of membership from 163 countries, ISO is headquartered in Geneva, Switzerland.

The advancements made within the cellular industry from first generation (1G) to fourth generation (4G) systems demonstrates the need for a fully combined global effort involving technical innovation, policy making, and standardization.

10.3 The Cellular Concept

Prior to the creation of the cellular concept, the mobile radio-telephone system used a single large broadcast antenna to cover a given service area. In order for a mobile user to connect to the wired PSTN, an operator typically had to intervene to establish a connection for the user. In addition, some early systems provided only half-duplex communications requiring a push-to-talk (PTT) feature on the handset. Obviously, new technologies would have to be created to make these early systems viable. However, one of the biggest hurdles even back then was the lack of available frequency spectrum.

Let's consider an example of an early mobile radio-telephone system depicted in figure 10.1. A single antenna is used to provide communications for an entire service area. In designing this system, you would have to take the following into consideration:

- To cover such a large area, powerful transmitters would be required by both the service provider base station and mobile user device. This would require mobile users to carry large power supplies, thus increasing both the size and weight of the handheld unit.

- Use of carriers at the lower frequency spectrum (e.g., low MHz range) would be required to lessen the impact of attenuation over distance. An added benefit is that lower frequencies (e.g., MHz range) do not require as strict a line-of-sight (LOS) requirement between transmitters compared to higher frequencies (e.g., GHz range). While these lower frequency systems can be impacted by obstacles, thus creating "shadow" areas of lower signal strength, it is not as big an impact when compared to higher frequency attenuation in the GHz range.

- In order to avoid interference between users, separate frequency channels are required per connection. For full-duplex communications, this means the allocation of separate transmit and receive channels (i.e., two channels per connection) are required.

- The availability of frequency spectrum for use on mobile communications systems is, and has always been, an issue. As such, only a limited number of users within the single service area can communicate simultaneously.
Finally, the single antenna and transceiver equipment serving the entire service area would introduce a single-point-of-failure.

Early mobile radio-telephone systems, to include first generation (1G) cellular phone systems, operated using analog signals. The use of analog signals for voice communications results in the inefficient use of limited frequency spectrum. This is because frequency channels must be dedicated to each call, as opposed to digital channels which are shared to support several virtual voice calls. In addition, the natural human speech pattern results in many pauses, or empty spaces, during which information is not exchanged. Once digitized, these natural pauses in speech can be filled with voice data from other virtual calls, thus improving overall spectral efficiency. Further efficiencies can be gained using digital compression techniques. As we will see, the advantages of using digital techniques were the key drivers leading to fully digital 2G cellular standards.

In our example of the single antenna system in figure 10.2, let's say that a service provider was allocated 20 channels in the 35MHz range for mobile communications. Within the service area, the operator would only be able to simultaneously service 20 users in half-duplex mode, or 10 users in full-duplex mode (i.e., two channels per call). This limits the number of overall calls made on the system, thus limiting any revenue from these calls. Since the bottom line for all service providers is their return-on-investment (ROI), costs for operations and maintenance would be passed onto the users, who would be burdened with paying high prices for an inefficient system. This was the case in the 1940's when mobile radio-telephone services began.

Figure 10.1. Early Mobile Radio-Telephone - Single Antenna, Single Operating Area.
The cellular concept improves the number of simultaneous calls that can be made within a service area without requiring additional frequency spectrum. The first step is to divide the service area into smaller "cells" or operating areas. In the case of figure 10.2, four cells have replaced the single service area of the previous example. The size of the cell is determined by the amount of transmit power emanating from the cell’s main antenna. By reducing the transmit power, the RF coverage area and the cell size is reduced. Since the mobile user connects to the cell’s main antenna, which is a shorter distance compared to the previous single antenna example, the power required to communicate using the mobile handset is much less. This translates into longer on-air times and smaller handheld devices. The coverage areas of the four cells overlap one another. As such, adjacent cells operating the same sets of frequency channels would interfere with one another especially in the overlap areas. To avoid this, adjacent cells, such as cell 1 and 2 in figure 10.2, must operate on different frequencies. However, since cell 1 and cell 4 are not adjacent, they can operate at the same frequencies without fear of interfering with one another. By being able to share the same frequencies within the overall service area service providers can support more users. This is termed frequency reuse. In our example, the service provider was allocated enough frequency space to enable 10 simultaneous full-duplex calls. Cells 1, 2, and 3 operate on channel pairs 1 to 4, 5 to 7, and 8 to 10 respectively. Cell 4 can use the same channel pairs as cell 1, therefore the number of simultaneous calls that can be supported is $4 + 3 + 3 + 4 = 14$. For this simple example, 4 additional calls are supported by dividing the service area into four cells, compared to only 10 calls with the single operating area. If we were to decrease the cell size in order to divide the service area even further, then we could increase the number of concurrent callers dramatically. We will see this in the next example (figure 10.3).
Figure 10.3 demonstrates how increasing the number of cells increases frequency reuse and the number of subscribers supported. The service area has been divided into 38 smaller cells. The cell pattern for frequency reuse remains the same as before. In other words, the 10 full-duplex channels (one transmit and one receive channel per call) are divided into a three cell pattern, or cluster, where each of the three cells are assigned unique channel frequencies. Therefore, the frequency reuse pattern (N)\(^4\), in this case is N=3. The total number of channels available, K, is K=10. We can determine the number of channels per cell and the total number of simultaneous calls supported across the entire service area by doing the following calculations.

\[
\begin{align*}
N \text{ (reuse pattern)} &= 3 \\
K \text{ (total number of channel pairs available)} &= 10 \\
K/N \text{ (number of channel pairs per cell)} &= 10/3 = 3.33 \\
\text{Number of simultaneous calls} &= K/N \times \text{number of cells} = 3.33 \times 38 = 126.54 \approx 126
\end{align*}
\]

From these calculations, we see that dividing the service area further into 38 cells, that we have dramatically increased the number of simultaneous calls from 14 to 126. The smaller cells sizes also translates to smaller batteries and greater air time for users.

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\(^4\) Frequency reuse pattern of N cells represents a "cluster". The cluster pattern is repeated across the service area.
Example 10.1. A service provider is allocated $K=28$ full-duplex channels to support calls within a busy urban area. The provider decides that the number of cells needed to cover the area is 50. You care asked to determine which cell repeating pattern should be select to enable the greatest number of simultaneous calls: $N=3$ or $N=7$?

Solution.

(a) For $N$ (cell reuse pattern) = 3 and $K$ (total number of channels available) = 28:

Number of channels per cell = $K/N = 28/3 = 9.334$ or $\approx 9$

Total number of simultaneous calls = $50$ (cells) x $9$ (channels per cell) = 450

(b) For $N$ (cell reuse pattern) = 7 and $K$ (total number of channels available) = 28:

Number of channels per cell = $K/N = 28/7 = 4$

Total number of simultaneous calls = $50$ (cells) x $4$ (channels per cell) = 200

Therefore, you select a cell reuse pattern of 3, since this gives you the greatest number of simultaneous calls.

From example 10.1, we can conclude that the smaller the frequency reuse pattern ($N$), the greater the number of simultaneous calls that can be supported. However, the cell size, which is principally determined by the power and signal direction emanating from the cell's antenna, is not exact and can easily be influenced by propagation effects such as weather, multipath reflection, RFI, and other phenomena. As such, service providers may choose larger frequency reuse patterns, which in turn provides more distance between cells operating on the same sets of frequencies. Of course, innovation within the industry never ceases, and we will see how modern 4G cellular systems strive toward a reuse pattern of $N=1$, which maximizes the number of calls for a given spectral allocation.

The cellular concept is a great solution when limited frequency spectrum is available, but it comes at the cost of increased overall system complexity. For instance, each cell has a main antenna and suite of equipment associated with it. All cell calls must be connected to the cellular providers network through a backhaul connection, and eventually to the PSTN or other network such as the Internet. As a mobile user moves from one cell to another, the system must automatically disconnect and reconnect the user from cell to cell. Finally, the operations for such a complex system requires sophisticated switching and network management equipment, and highly skilled individuals to both operate and maintain it.

There are a few broad categorizations that describe the size of the cell itself. A macrocell covers a relatively large area that is approximately 60 miles wide. Small Cells is a general term used for smaller cell sizes such as microcell, picocell and femtocell. The microcell is approximately 4.3 miles wide, while the picocell covers just a few city blocks. The femtocell creates a wireless cell that can be as small as a home or the size of a floor in a large building. What differentiates the femtocell is the backhaul connection to the service provider network.
Since many homes and businesses have broadband connections to the Internet, the femtocell, which connects to the mobile phone through cellular frequencies, uses this connection as a backhaul to the service providers network. This enables the service provider to cover areas of poor cellular reception in a cost effective manner, while improving cellular coverage for the user.

The amount of transmit power from an omnidirectional antenna, which is typically depicted on paper as a hexagon, is not the only way to shape cell coverage. Use of directional smart antennas enable providers to divide the cell into pie-shaped sectors that operate on different frequencies. Smart antennas using electronic beamforming techniques can be programmed to modify coverage areas in response to changing traffic patterns during the day. So the cell dimensions and shape can be modified to match the coverage areas as needed.

As the concentration of users begin to increase in specific locations within the service area (e.g., development of high-rise apartments, business buildings, shopping and restaurant areas, etc.), the cell serving the area will need to increase its capacity to meet the growing mobile user base. Increasing the capacity of a cell is termed **cell densification**. The following are ways that cell densification can be achieved.

- **Addition of new frequency channels.** The service provider can request additional frequency spectrum, but this is extremely difficult to accomplish. Taking years of effort to go through the government's regulatory and legislative processes, lobbyists are hired by the wireless industries to work these issues on a full-time basis. The addition of new frequency bands is a strategic effort rather than one that can provide immediate relief for increased service demands.

- **Dynamic frequency allocation.** The concentration of calls within a service area is related to the concentration of mobile users. This concentration can be dynamic depending upon the time of day, as well as the day of the week. As an example, business offices will have much lower concentrations of calls during non-business hours as opposed to business hours. Therefore, for a service provider, it would make sense to allocate the number of channels based upon call activity vice fixed cell allocations. However, dynamic allocation can be very difficult to accomplish because of the complexity it introduces when attempting to avoid the assignment of identical frequencies to adjacent cells. The cell reuse pattern, or cluster, and the frequency reuse distances are factors that must be taken into consideration when determining the effectiveness of implementing dynamic allocation.

- **Frequency borrowing.** Frequency borrowing is similar to dynamic frequency allocation, but is performed at a lower level between adjacent cells. As discussed, call activity concentrations can change throughout the service area, and with frequency borrowing, cells can borrow unused frequencies from their adjacent neighbors. To illustrate how this can be helpful, imagine that a cell serving a business district is adjacent to a cell

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5 The hexagon is used to depict a cell created by an omnidirectional antenna; however the actual physical pattern is circular resulting in overlapping coverage between adjacent cells.
serving the restaurant district. During normal business hours, call activity is greatest in the business cell. During extremely busy hours when the business cell's frequency allocation isn't enough, it can borrow unused frequencies from its neighbor, the restaurant cell. At the end of the day restaurant cell activity becomes greater than the business cell activity as patrons begin to arrive. If the restaurant cell becomes overloaded with call activity, it can borrow unused frequencies from the business cell. Under these types of circumstances, frequency borrowing can be an effective strategy. However, frequency borrowing can also be very complex since all cells involved in frequency borrowing must avoid interference with each of its adjacent neighbors.

- **Network densification.** One common method used to increase capacity within a cell is to divide the cell's area into smaller cells and/or sectors. Network cell densification enables providers to increase the frequency reuse factor, which in turn increases their capacity to support larger numbers of calls. However, as discussed previously, increasing the number of cells by decreasing cell size, translates into more cell handoffs as mobile users move in-between smaller cells. This increases not only the complexity, but also the required number of cellular base stations, antennas, and backhaul connections to the main provider network.

- **Use of Femtocells.** As described, femtocells are small cells that operate on cellular frequencies, but instead of using its own backhaul links, it uses the host's broadband connection (i.e., Internet) as a way to connect back to the service provider's network. This can be an effective strategy for supporting large businesses or hotels where a high concentration of call activity exists. Femtocells improve cellular connection within large buildings where foundational structures can negatively impact signal strength. Therefore, femtocells are a benefit to businesses as well as to the service provider.

- **Technical solutions.** An effective method to increase data capacity over a frequency channel is to implement digital data techniques designed to improve spectral efficiency. Previous first generation (1G) cellular systems were analog and required dedicated frequency channels per call. Obviously, this used up valuable frequency spectrum and severely limited the number of calls that could be made. With the introduction of digital communication techniques, single channels could be divided by time using TDMA, which meant that several calls could simultaneously operate on the same channels. With direct sequence spread spectrum (DSSS) techniques such as CDMA, spectral efficiency improved as guard bands were no longer needed to separate channels resulting in an increased throughput. Eventually, OFDM was adopted which improved spectral efficiency even further. The use of M'ary modulation techniques increased the number of bits per symbol, thus increasing data rates and overall system capacity. Of course the adoption of sophisticated digital techniques requires more powerful and smart network devices, to include advanced antenna designs such as MIMO. Technical innovation in wireless communications continues to move forward,

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6 Spectral efficiency is measured in data rate over Hz.
and its past implementations have helped service providers meet exponentially growing service demands.

- **Inter-Cell Interference Coordination (ICIC).** We learned that a frequency reuse pattern of $N=1$ makes the greatest number of channels available to each cell. Of course, this means that each cell operates all of the service provider channels in the system, leading to adjacent cell interference near the edges of the cell. However, if the adjacent cells shared operating information, then the cells could coordinate ways to avoid channel interference within the overlap areas. This sharing of information and the algorithms designed to avoid interference is termed **Inter-cell Interference Coordination (ICIC).** The basic idea is to ensure that users near the edges of the cell do not operate on channels used by other users near the edge of an adjacent cell. As an example, a user near an edge could be reassigned to a different channel if the possibility of interference was determined ahead of time.

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**Side Bar: Why cells are depicted by hexagons**

It's obvious that the RF pattern emanating from an omnidirectional antenna is not shaped like a hexagon. However, when determining the distance between the center of adjacent cells, the geometry of the hexagon lends itself to an easy calculation for planning purposes. To illustrate, let's say "$r$" equals the radius of a circular cell, which also equals the propagation distance from an antenna located at the center. You want to determine the distance, "$d$", between cell centers. The idea is to eliminate any gaps in coverage. If we were to use circles, as in the figure below, the distance between cell centers is $d=2r$, which creates a gap in coverage between all adjacent cells. Obviously, you'd want to reduce cell spacing to some distance less than $2r$ (i.e., $d<2r$). The question becomes what distance to choose.
By using a hexagon, you have a shape that can be used for planning purposes to avoid potential gaps in coverage between cells (see figure below). A hexagon can be seen as six connected equilateral triangles where "r" is the distance from the center of the hexagon to a corner of one of the triangles. The height of the equilateral triangle is, \( \text{height} = \frac{d}{2} = \frac{\sqrt{3}}{2} \times r \), where "d" equals the distance between adjacent cell centers. Therefore, if two or more hexagons are adjacent to one another, using a distance between cell centers of "d" will prevent potential gaps in coverage.

It is also critical for us to determine the spacing between cells operating on the same sets of frequencies in order to avoid adjacent cell interference. This spacing is termed the frequency reuse distance, "D", and we will need to include the cell reuse pattern, "N".

The diagram below depicts our four cell service area operating with a cluster of three (N=3). We want to know the distance "D" between the repeating cell #1.
In this case, we include "N" into our equation: Frequency Reuse Distance, \( D = r \times \sqrt{3N} \).

Therefore, for a cell repeating pattern of \( N=3 \), the distance between cells operating the same sets of frequencies is "\( D \)". As the cluster size \( (N) \) increases, the distance between cells operating at the same frequencies also increases.

10.4 Cellular Architecture

There are certain functions that all cellular phone systems must perform regardless of the specific standard\(^7\) used. The most obvious function is an ability for the mobile station (MS), (a.k.a., mobile equipment, ME), to connect wirelessly to a cellular base station (BS), (a.k.a., base transceiver station, BTS), which is comprised of the antenna and transceiver equipment. All of the BS’s within the service area must have backhaul connections to the main service providers network, which is called the network subsystem (NS). Within the NS is the mobile switch center (MSC), (a.k.a., mobile telecommunications switching office, MTSO), whose function is to switch calls between the ME and PSTN or other network, and between MEs. In addition, the MSC is involved in the handoff of an MS as it move from one cell to another. A final function is an ability for the cellular network to authenticate and identify users in order to bill and provide services.

10.4.1 Base Station Subsystem (BSS)

The MS connects wirelessly to the base station subsystem (BSS) through an "air interface". For first generation (1G) analog systems, connection to the air interface was pretty straightforward, requiring knowledge of the control channel frequencies, assigned traffic frequencies, and modulation techniques. Digital techniques were introduced with second generation (2G) systems, which involved a more sophisticated air interface that could support either TDMA time slot assignments or CDMA PN codes. In addition to supporting digital modulation techniques, 2G systems were also required to define and support digital protocols above the physical layer. With 2.5 generation (2.5G) and third generation (3G) systems, packet switching was introduced on some standards (i.e., GSM’s General Packet Radio Service or GPRS), opening the path to Internet connectivity from the a user's MS. Today we have fourth generation (4G) systems that use smart phones, and as such, require support for the entire OSI protocol stack (i.e., physical to applications layers).

Mobile users access the cellular system through Demand Assigned Multiple Access (DAMA) techniques that assigns available channels to users on a demand basis. However, since there are typically more subscribers than channels, call blocking can occur during times of emergencies or special events when unanticipated traffic volume causes system overload. With early analog systems, the only access technique was through frequency channel assignment or Frequency Division Multiple Access (FDMA). Digital technologies enabled the sharing of

\(^7\) However, the description that follows is principally based upon the GSM architecture.
frequency channels by assigning time slots to each call using **Time Division Multiple Access (TDMA)**. In this case, the combination of TDMA and FDMA helped to increase the number of calls that could be supported simultaneously. **Code Division Multiple Access (CDMA)**, still in use on 3G systems today, enables multiple users to share the same frequency bandwidth by assigning unique, orthogonal **Pseudorandom Noise (PN) codes** to each call. Finally, **Orthogonal Frequency Division Multiple Access (OFDMA)** assigns sets of orthogonal subcarriers to each call and is more spectrally efficient than CDMA.

![Typical GSM Architecture](image)

**Figure 10.4. Basic GSM Cellular Architecture.**

The BSS is comprised of several components as shown in figure 10.4. Each cell has a **base stations (BS)** that contains one or more RF antennas with associated transceiver equipment. The power transmitted, as well as the RF pattern emitted from the antenna, defines the size and shape of the cell footprint. Each cell broadcasts control signals that are used throughout the cell for control and signaling purposes. An MS entering the service area will receive controls signals from all of the BS' within its range, and will then select the BS it intends to communicate with, typically based upon signal strength.

One or more BS' are controlled by a **base station controller (BSC)**. The responsibility of the BSC is to allocate useable channel frequencies to the BS, track mobile user equipment (i.e., monitor signal strength) as it moves throughout the cells, and manage call hand-offs between the cells under its control. If, however, the MS departs the set of cells controlled by the BSC, the BSC
must coordinate with the *mobile switching center (MSC)* to facilitate an inter-BSC hand-off. BSCs also serve to aggregate control and traffic information from cells for delivery to the MSC through backhaul channels. Backhaul channels are typically over fiber optic cables; however, broadband wireless systems such as WiMAX BWA are also used.

### 10.4.2 Network Subsystem (NS)

The NS is the service provider's wired network that controls and manages the cellular system. While the BSS provides the mobile user wireless access to the network, the NS essentially does the heavy lifting of switching calls, maintaining subscriber data bases, providing security, and establishing connections to external networks. It is comprised of several key components but the most important one is the *mobile switching center (MSC)*. The MSC serves in all phases of support to the mobile user including initial logon to the system, establishment and termination of calls, and call handoffs between cells within the service area. There are several databases connected to the MSC that serve important functions. These databases are listed below.

**Home Location Register (HLR).** The HLR database contains subscriber information and is used on TDMA, CDMA and GSM systems. For GSM systems an *International Mobile Subscriber Identity (IMSI)* number that is associated with each user is stored in both the HLR database and the Subscriber Identity Module (SIM) chip that is placed into the phone. The HLR is also updated with the location of the mobile unit as it moves throughout the service area.

**Visitor Location Register (VLR).** The VLR database, which contains similar information as the HLR, is used to update the location of roaming users within the service area. The VLR database is updated with location information to help the MSC locate users without having to constantly query the HLR. The VLR also supports roaming subscribers from different service providers that have sharing agreements in place between the cellular providers.

**Authentication Center (AuC).** The AuC is used to authenticate subscribers when the MS is initially powered on. For GSM systems, this means authenticating the SIM cards attached to the mobile device. Failure to authenticate prevents the mobile equipment from being able to use cellular services. Once authenticated, the AuC provides encryption keys for secure voice, data, and message traffic.

**Equipment Identity Register (EIR).** Removable GSM SIM cards are placed into mobile phones to provide specific subscriber information including the IMSI. There is also an unique number associated with mobile equipment called an *International Mobile Equipment Identity (IMEI)* number. The IMEI helps to identify legitimate devices on the network, and can also be used to stop stolen phones from accessing the network. The EIR maintains a list of all IMEI numbers used by subscribers within the system.

Finally, gateways are used to interconnect the cellular network to the PSTN and to other networks such as the Internet. “Gateway” is an often used, and general term that can be used to mean many things. As we have seen in this textbook, a gateway typically enables the interconnection of disparate networks operating on different protocols. In this way, a gateway
is a highly intelligent device that is able to interface any protocol layer of the OSI reference model through protocol conversion or simple network tunneling techniques.

10.4.3 Mobile Call Process

Each cell base station communicates to mobile phones using control and traffic channels. *Control channels* are involved in mobile phone initialization, call setup and termination, and mobile user location registration. Once the mobile phone has been registered with the cellular provider, *control channels* communicate periodically with the mobile unit even if no calls are in progress. Once a call has been established between users, a *traffic channel* is assigned for the actual exchange of information between users. Both control and traffic channels operate in the *forward* (network to mobile user) and *reverse* (mobile unit to the network) direction.

As soon as an MS is turned on, it begins to scan control signals emanating from nearby BS'. Cellular control channels are shared between all mobile units within the cell, and therefore in order to avoid interference, each mobile unit must ensure that the channel is clear prior to transmission. Control channels from adjacent cells operate at different frequencies and the MS selects the BS control channel that has the greatest signal strength. Once selected, a handshaking procedure takes place which involves participation by the MSC in order to identify the mobile user as an authorized subscriber eligible to receive services. After successful completion of the handshaking process, the control channel continues to periodically communicate with the mobile unit to monitor and register its location.

When a subscriber wishes to make a call, the control channel is used for call setup. The first step is to make sure that the shared control channel is clear. If it is, the mobile unit transmits a call setup request by sending the "called" phone number to the BS. The BS forwards this request to the MSC. If the call is to another MS within the same service area, the MSC checks the location registries (i.e., VLR and HLR) to determine its location. If information on the called unit is found, the MSC will send out a paging request to the BS where the mobile unit was last known to be. The paging request is broadcast throughout the cell, and if recognized and accepted, the called unit sends an acknowledgment to the MSC. Upon call acceptance, the MSC allocates available send and receive traffic channels for use by the mobile units. In the event that no information regarding the called unit is found in the registries, the MSC instructs all BS' to page their mobile units within each cell in an attempt to find the called MS. If no response is received, then the call cannot be placed.

Finally, if a call from a mobile unit is made to a wired telephone on the PSTN, then the MSC sends the call request through an NS gateway to the PSTN. In reverse, a call from the PSTN will go through an NS gateway to the MSC, and the registry lookup and paging process is initiated.

During an active call, mobile subscribers typically move between cells requiring the departing BS to handoff the call to the arriving BS. With the older analog systems, handoffs between cells were abrupt, essentially terminating the connection to one BS prior to establishing a connection with the new BS. This was termed a *hard handoff*, which was sufficient for analog voice calls since it did not significantly impact call quality. However, *hard handoffs* do not work well with digital communications, often leading to lost data and call disruption. As such, *soft*
handoffs, were designed to ensure that the outgoing BS did not terminate the call until the arriving BS had established a connection with the mobile unit. Handoffs between cells is based upon the measured signal strength emanating from the BS. There are several algorithms not discussed in this text, that are used with soft handoffs to prevent call drops in environments where multipath fading or other phenomena is of concern.

When the call is terminated, the MSC is notified and the traffic channels are made available to support the next call request.

10.5 Cellular Generations

Implementation of new technologies are captured as generational changes to the cellular system concept. It is a way to define how the newest technology innovations are introduced in order to meet exponentially increasing subscriber numbers, as well as to meet subscriber desires for services beyond the traditional voice call. The technology innovations implemented also address methods to improve spectral efficiencies in light of the constrained availability of frequency spectrum.

Figure 10.5 is a high-level description of the various cellular generations. It should be noted that during the historical development of mobile systems, other standards and specifications not indicated in the figure nor discussed in the following sections, were developed for region-specific cellular phone systems. The next several sections discusses some of the major standards adopted throughout the generations.
Figure 10.5. Generations of Cellular Advances. *Note, this is not an all inclusive list of cellular systems or standards.*

10.5.1 First Generation (1G)

Introduced in the late 1970s, first generation cellular systems are consider analog systems although this mainly describes the RF interface between mobile phones and base stations. Most service providers incorporated digital control channels as well as digital switching within their network subsystem. Since initial subscriber numbers were manageable, analog systems easily met service demands despite bandwidth inefficiencies, limited spectrum availability, and lack of wireless privacy. First generation systems were monumental in that they introduced the world to cellular telephone technology, and demonstrated the feasibility of the cellular concept.

Several 1G standards were developed around the globe. In the U.S. the **Advanced Mobile Phone System (AMPS)** was developed through a joint effort between AT&T and Motorola. Operating in the 850MHz band, FCC allocated frequencies that consisted of two frequency blocks. **Forward (network to mobile user)** channel frequencies went from 869MHz to 894MHz, while **reverse (mobile user to network)** channel frequencies went from 824MHz to 849MHz. The bandwidth of each channel was 30kHz wide, for a total availability of 832 channels; however, since both forward and reverse channels are needed for full-duplex communications, only half, or 416 channel pairs, were actually available. Of the 416 available channel pairs, 21 pairs were used for control signaling and 395 pairs allocated for user traffic. The assignment of
a channel pair required that a 45MHz separation exist between the forward and reverse channels. The digital control channels used FSK modulation, while analog traffic channels were modulated using FM.

The United Kingdom adopted the **Total Access Communications System (TACS)**, which was based upon AMPS. TACs differed from AMPS in that is operated in the 900MHz band, and used smaller 25kHz bandwidth channels, which increased the number of total channels available. TACS gained wide acceptance in Europe, with a version (JTACS) used in Japan.

The **Nordic Mobile Telephone (NMT)** system operated in Sweden, Denmark, Finland, and Iceland in the early 1980's. NMT operated in the 450MHz band using FSK to modulate control channels, and FM for traffic channels. Security, like all analog systems, was an issue.

Early 1G systems were developed mainly for local or regional markets, and therefore numerous incompatible standards that existed made roaming difficult if not impossible. Today, 1G analog systems have largely been replaced by digital systems.

**10.5.2 Second Generation (2G)**

As the popularity of mobile phones grew, the industry realized the need to increase communications capacity within the constraints of the allocated frequency spectrum. By the 1990's, with the advances made in computer technologies and integrated chip designs, cellular providers began to adopt digital communications as the solution to increase overall capacity. Dubbed "second generation" (2G) cellular, several incompatible standards were developed based upon TDMA or CDMA technologies. With TDMA, voice traffic was digitized and assigned specific TDM time slots within a frequency channel. By doing this, a single frequency channel could support several TDM digital voice calls. This was in comparison to the 1G analog systems using FDM where channels were fully dedicated for the duration of each call. CDMA followed a method in which digitized voice calls went through a spread spectrum process, each call separated by unique PN code. While digital communications provided greater capacity, it also added more complexity, requiring voice coding and decoding and sophisticated modulation methods.

In North America, **Digital-AMPS (D-AMPS)**, described in TIA Interim Standard IS-54, which eventually became IS-136, was developed to enable backward compatibility with AMPS. By keeping the 1G frequency assignments and channel bandwidths, both AMPS and the newer 2G D-AMPS could be supported. This enabled a graceful upgrade for users transitioning from 1G to 2G systems. Each frequency channel was divided into six time slots each supporting 8kbps. Four time slots were allocated per full-duplex call (i.e., two time slots each in the forward and reverse directions). Use of TDMA therefore increased the number of channels from 832 to 2,496 (i.e., 3 x 832). Since D-AMPS used the same 21 control channels as AMPS, the number of full-duplex calls supported went from 395 to 1,185. With IS-136 came additional services such as text messaging and the use of TDMA on control channels. The modulation method used was termed $\pi/4$ DQPSK (Differential Quarternary Phase Shift Keying), which is a variant of QPSK.
The **Global System for Mobile Communications (GSM)** was adopted as a CEPT\(^8\) standard primarily in Europe. GSM was compatible with ISDN and operated in both the 800MHz and 900MHz frequency bands. The frequency channel structure was different from D-AMPS, in that each channel was 200kHz instead of 30kHz wide. Each GSM frequency channel was divided into eight TDM time slots. A single call required one slot in the forward direction and one slot in the reverse direction for a total of two time slots per call. The modulation method used was a variant of *continuous-phase, frequency-shift\(^9\)* keying called GMSK (*Gaussian Minimum Shift Keying*). Originally intended for digital voice communications, GSM expanded its services by introducing **Short Message Service (SMS)** and an **ETSI** packet switching standard called **GPRS (General Packet Radio Service)**. Considered a 2.5G capability, TDM time slots were dynamically allocated for use by GPRS packets in order to connect to the Internet. GPRS allowed the mobile user to maintain a persistent connection to the Internet at a bit rate of up to 21.4kbps. The next phased upgrade to GPRS was called **EDGE (Enhanced Data Rates for GSM Evolution)**, which provided higher data rates up to 68.4kbps using 8PSK (M=8) modulation over a single channel. In addition, multiple time slots could be combined increasing overall throughput.

In North America about the same time as the GSM effort, **IS-95 CDMA\(^10\) (Code Division Multiple Access)**, also called **cdmaOne**, replaced D-AMPS as a 2.5G standard. With IS-95 CDMA, users shared the same forward and reverse frequency bandwidths which were both 1.228MHz wide. The forward link was divided into 64 logical channels separated by unique PN codes. There were four types of logical channels. Channel 0 was the *pilot channel* that transmitted a continuous signal to provide phase, timing, and signal strength information to mobile units. Channels 1 through 7 were paging channels used for signaling purposes. Channel 23 provided synchronization, system time, and information regarding the protocols used. Finally, channels 8 to 31 and 33 to 63 were allocated for user traffic. Traffic channels initially supported 9600 bps, which was later revised to 14.4kbps. On the reverse link, which was also 1.228MHz wide, 94 total logical channels supported 32 access\(^11\) and 62 traffic channels. The use of CDMA spread spectrum technology had several advantages over TDMA systems:

- As a spread spectrum technology, signals were more immune to RFI and other RF impairments.
- CDMA had better multipath resistance, especially when specialized RAKE receivers were used. *Note - RAKE receivers essentially take the multiple signal copies received, and sends these copies through digital signal processors that adjusts their time and phase delays. This allowed copies to be constructively combined.*

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\(^8\) ETSI is currently responsible for the GSM standard.

\(^9\) Continuous-phase, frequency-shift keying was developed in the 1950s. In a nutshell, it is a modulation method in which the delta between highest and lowest carrier frequency shifts is identical to 1/2 of the bit rate. Doing this minimizes the modulation index

\(^10\) CDMA was developed by Qualcomm, who went on to develop 3G CDMA2000 in alignment with IMT-2000 requirements.

\(^11\) Access channels were used as signaling channels similar to the forward link paging channels.
• Since unique PN codes were required by each communicating pair, eavesdropping was extremely difficult, making data transmissions more secure.

• With FDMA/TDMA systems, once the maximum number of channels were allocated, all other attempted calls were blocked. However, with CDMA, additional calls can still be serviced, with a gradual degradation occurring in the form of increased bit errors. Eventually, system overload would be reached when bit errors became unmanageable. This was considered a *graceful degradation* of the system, vice the more abrupt call blocking scenario when the systems maximum number is reached.

To address the global incompatibility of 2G standards, the ITU-R published the *International Mobile Telecommunications-2000 (IMT-2000)* standard, intended for 3G systems but also covering 2.5G systems, in an attempt to produce a single compatible standard for all providers and manufacturers. GSM TDMA and cdmaOne (IS-95) CDMA were accepted as IMT-2000 alternative approaches and dubbed 2.5G standards. IMT-2000 3G standards would eventually adopt only CDMA approaches.

### 10.5.3 Third Generation (3G)

As 2000 approached and the popularity of the Internet and mobile phone continued to grow, the mobile phone industry recognized that users wanted support for multimedia data and Internet connectivity, as well as an ability to roam away from local cellular infrastructures. This meant that higher data rates needed to be supported, and a global standard was required that would allow users to connect through any cellular provider regardless of location.

IMT-2000 was intended to address the following needs:

• **Support for higher data rates.** Second generation systems used first generation frequency allocations in most cases. In order to increase data rates, greater spectrum allocations were needed along with technologies that could maximize spectral efficiency.

• **Support for other forms of data beyond voice.** It was clear that users wanted mobile access to the Internet and other data services using their mobile units. This meant that the cellular system, including mobile equipment, needed to be smarter. This also signaled the end of circuit switching in favor of packet switching techniques.

• **Support for seamless roaming.** Mobile users, especially international travelers, wanted to use a single mobile phone anywhere, vice having to own or rent specific phones designed to work with specific regions or service providers.

• **Affordability.** For the industry to continue to grow, 3G equipment and services needed to be affordable to both service providers and their users.

• **Backward compatibility with existing 2G systems.** While 3G represented the future at the time, it was understood that the migration from 2G might take a while. To ensure 2G continued to be supported, backward compatibility was needed.
• **Modular design.** The ability to upgrade and expand 3G was needed to enable system growth, and to enable the implementation of modern technologies over time.

• **Data rates based upon user mobility.** The data rates available to a user is dependent upon the users mobility. IMT-2000 categorizes available data rates based upon fixed indoor up to 2.048Mbps, slow moving up to 384kbps (e.g., walking), and high-speed up to 144kbps (e.g., vehicle) user mobility.

While the effort by ITU captured in IMT-2000 was needed, 3G, like its predecessors 1G and 2G, continued to produce incompatible standards and systems. Part of this was intentional, since the various 3G alternatives were evolved from existing 2G systems, and complete system replacements were not the intent of IMT-2000.

We will discuss two major 3G standards that were derived from GSM and cdmaOne (i.e., WCDMA and CDMA2000 respectively). Today, both standards are in use, and smartphones typically support connectivity to either 3G or 4G systems.

As an upgrade to GSM in 1999, ETSI released the **Universal Mobile Telecommunications System (UMTS)** 3G wireless standard, which adopted **Wideband CDMA (WCDMA)** in partnership with the **3rd Generation Partnership Project** (3GPP). UMTS WCDMA carriers are 5MHz wide and operate in **Frequency Division Duplex (FDD)** or **Time Division Duplex (TDD)** modes. UMTS FDD is typically found in North America, and consists of separate forward and reverse frequencies allocated from 25 frequency bands ranging from 700MHz to 2100MHz. Forward and reverse logical channels separated by PN codes are assigned per call. UMTS TDD is used in Europe where forward and reverse logical channels are assigned according to time vice frequency. In this case, data exchange occurs on the same frequency, but at different times, which is advantageous for smaller cells, especially when adequate FDD separation between forward and reverse frequency channels are not possible. Starting in 2006, UMTS improved **downlink** (forward link) speeds up to 14.4Mbps by implementing **High Speed Downlink Packet Access (HSDPA)**, by using 16-QAM (M=16) modulation vice the original QPSK (M=4) which was used on WCDMA. At the same time, UMTS introduced **High Speed Uplink Packet Access (HSUPA)** on the **uplink** (reverse link) which improved bit rates up to 5.74Mbps using **High Speed Uplink Packet Access (HSUPA)**. Like HSDPA, HSUPA also used adaptive modulation schemes which improved the number of bits represented by a symbol (i.e., M'ary modulation).

**CDMA2000 (IS-856)** was the successor to cdmaOne (IS-95) and was approved by ITU-R as part of the IMT-2000 family of standards. Unlike WCDMA, CDMA2000 initially operated on a 1.25MHz channel. The air interface standard consisted of a data format called **1xEV-DO (1x Evolution-Data Only)**, and a voice format call **1xEV-DV (1x Evolution - Voice Only)**. While the 1xEV-DO data standard was successful, the voice 1xEV-DV technology failed. The data 1xEV-DO standard went through several versions, each providing improved uplink and downlink bit rates. **1xEV-DO Revision A** enabled 1.8Mbps uplink and 3.1Mbps downlink bit rates. **1xEV-DO Revision B** improved these bit rates to 5.4Mbps uplink and 14.7Mbps downlink rates by increasing the

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12 3GPP was involved in the release of the original GSM standard.
13 “1x” referred to the CDMA spreading rate which was 1.2288 Megachips per cycle.
channel bandwidth from 1.25MHz to 5MHz. Similar to WCDMA, bit rate improvements were achieved using M'ary modulation techniques. Unfortunately, WCDMA and CDMA2000 are not compatible standards.

10.5.4 Fourth Generation (4G)

At an ITU assembly in January 2012 held in Geneva, IMT-Advanced goals were agreed to as an expansion to the IMT-2000 requirements. IMT-Advanced emphasized global compatibility between mobile and fixed services, the ability to interoperate between disparate cellular access systems, a commonality of wireless user equipment, an ability to achieve worldwide roaming, and enhanced bit rates. Packet switching technologies were emphasized over traditional circuit switched concepts which had dominated previous cellular generations. Numerous service providers around the world began to evolve their systems towards the IMT-Advanced goals in 2013.

Two major 4G technologies emerged, 3GPP's Long Term Evolution (LTE) and IEEE 802.16 Mobile WiMAX (Worldwide Interoperability of Microwave Access). Both technologies are based upon packet switching concepts that provide persistent connectivity to the Internet, and both replaced CDMA with the more spectrally efficient OFDMA (Orthogonal Frequency Division Multiple Access). Unfortunately, LTE and WiMAX are not interoperable. Today, in North America, LTE is the predominant 4G technology used by most service providers.

10.5.4.1 Long Term Evolution (LTE)

Unlike 3G, LTE allowed for broadband wireless backhaul connectivity from base stations to mobile network switches using access methods such as WiMAX BWA. Both FDD and TDD are supported, although FDD is predominant in North America, while TDD is offered by China Mobile (Cory Beard, 2016). In addition, traditional circuit switched voice calls were replaced with IP-based packet voice. However, today's smartphones enables mobile users to connect to traditional circuit switched 3G voice as well as 4G IP voice.

The initial LTE standard specified by 3GPP, releases 8 and 9, did not meet the original IMT-Advanced 4G bit rate requirements and was therefore considered by some as an enhanced 3.9G capability. However, despite the noncompliance, ITU allowed LTE to be called a 4G capability, understanding that follow-on releases would upgrade LTE to meet IMT-Advanced requirements.

LTE was developed to provide an upgrade path from 3G WCDMA and CDMA2000 systems. In order to meet global roaming requirements mobile smartphones were required to support multiple carrier frequencies. Use of OFDMA and MIMO (multiple Input Multiple Output) antenna systems were used as a way to increase spectral efficiency and to effectively deal with multipath fading. Peak bit rates specified were 75Mbps uplink using SC-FDMA\(^{14}\), and 300Mbps downlink using OFDMA.

\(^{14}\)SC-FDMA (Single Carrier FDMA) is used for uplinks (mobile user to network communications) because it enabled greater efficiency in terms of the transmitted power from a mobile device.
To make LTE more compliant with the 4G requirements, 3GPP released LTE-Advanced release 10 in 2011. LTE-Advance improved upon LTE in several ways:

- The number of LTE antennas used in a MIMO array was increased to a maximum 8 by 8 antenna array (8 x 8 pattern) for downlinks, and a maximum 4 by 4 antenna (4 x 4) array for uplinks.
- *Inter-Cell Interference Coordination (ICIC)* between cells which existed in LTE was improved.
- The SC-FDMA uplink was improved by applying a *clustering* concept to SC-FDMA. LTE SC-FDMA uplinks were allocated using contiguous frequency blocks, which tended to complicate the scheduling of uplink resource allocations to user devices. Clustered SC-FDMA allowed for non-contiguous frequency blocks to be allocated, thus making resource scheduling more flexible.
- *Carrier Aggregation (CA)* was introduced to enable up to five carriers to be combined in both the uplink and downlink directions, in order to increase bit rates. CA enabled a maximum aggregated bandwidth of 100MHz.

LTE-Advance is considered a *true 4G* standard that increases peak uplink and downlink bit rates to 500Mbps and 1Gbps, respectively.

The overall LTE and LTE-Advanced architecture has taken on several nomenclature changes when compared to the GSM architecture. Components and interfaces are identified, and the RF air interface and network cores are still separated. The LTE architecture is shown in figure 10.6, with description provided below.
Figure 10.6. Long Term Evolution (LTE) Basic Architecture.

The LTE **Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)** is similar to the GSM base station subsystem. User *mobile equipment* (*ME*) connects wirelessly to base stations called **Evolved Node B (eNodeB)** which differs from traditional 3G base stations, in that they perform cell control functions thus eliminating the need for separate base station controllers (*BSCs*). eNodeB base stations are connected to one another through an **X2 interface** that consists of two types, an **X2-C** for control and **X2-U** for user data. The X2-C (control) interface between base stations is used during mobile user hand offs between cells, as well as coordination between cells regarding potential frequency conflicts (i.e., *Inter-Cell Interference Coordination* or *ICIC*). The X2-U interface is used to enable a smooth handoff from one cell to another.

The **Evolved Packet Core (EPC)**, which is similar to the GSM Network Subsystem (NS), is the fixed cellular network that provides management, gateway connectivity to external networks, and switching. The EPC is connected to the E-UTRAN through the **S1 interface** which, like the X2 interface, is divided into *control and data* links. These control and data connections can be either wired (e.g., fiber optic) or wireless (e.g., WiMAX BWA). For control, the **S1-MME** interface is used to connect individual eNodeBs to the **Mobility Management Entity (MME)** system, which is responsible for managing control and signaling to the UEs. Because the MME is involved in user access, handoffs, and transfers to other networks such as 3G cellular, it must be capable of tracking UEs through the system, and executing required security procedures such as authentication and the negotiation of the security algorithms. Because the MME is responsible for UE control functions, it interacts with the **Home Subscriber Server (HSS)**, which has a similar function as the GSM HLR and VLR databases. The HSS maintains database information on subscribers, and together with the MME, assists in authentication, call setup
and security. User call traffic between the eNodeB and EPC is supported by the S1-U (user) interface, which connects the eNodeB to the Serving Gateway (SGW). The SGW routes user IP traffic between eNodeBs within the same service area, as well as to external networks such as the Internet by sending the IP packets to the Packet Data Network Gateway (PGW). The PGW acts as the external gateway for the service network, performing IP routing, filtering and inspection of packets originating from an external networks.

To increase capacity, LTE adopted a frequency reuse pattern of N=1, which translates to the ability of all cells to operate on all allotted frequencies. Of course this presents potential interference in the overlap regions of adjacent cells. To prevent potential interference between MEs, adjacent cell eNodeBs must coordinate the use of frequencies within shared overlap areas. Inter-cell Interference Coordination (ICIC) can be implemented using several methods. With ICI Coordination and Avoidance, adjacent cells coordinate their intended use (i.e., schedule) of resource blocks defined by time, frequency, and transmit power levels. Restrictions are then applied in order to avoid mutual interference of scheduled resources. ICI randomization applies a pseudo-random sequence to transmitted codewords. If an adjacent cell operates on the same frequency, the interfering codewords be separated. ICI cancellation can also be used through signal cancellation techniques; however, this would require specific information regarding the interfering signal which would be difficult to obtain.

10.5.4.2 Mobile Worldwide Interoperability of Microwave Access (WiMAX 802.16e)

The WiMAX Forum was established in 2001 to define a total wireless mobile system by adopting the IEEE 802.16e (2005) air interface standard. The WiMAX Forum's Network Working Group (NWG) developed the standards that were intended for use by manufacturers and operators in building interoperable mobile WiMAX systems. The mobile WiMAX standard describes requirements for high bit rate IP connectivity which are in compliance with IMT-Advanced 4G requirements. Like LTE and LTE-Advanced, mobile WiMAX uses OFDMA as an access technology, MIMO technology, and supports both FDD and TDD operations.

The basic components of the WiMAX architecture are the Mobile Stations (MS), the Access Service Network (ASN) which encompasses the air interface to the MS, and the Connectivity Service Network (CSN) which covers the core network functions.

The ASN consists of one or more base stations (BS) that are comprised of transceivers and antennas that connect to the MS through the cell's RF wireless links. Each BS connects to an ASN Gateway at the OSI RM physical (layer 1) and data link layers (layer 2). One or more ASN Gateways exist within the ASN. Through the ASN Gateway, control functions and data traffic are passed to the BS from the CSN.

The CSN is the IP core network that provides similar functions as the GSM network subsystem. As an IP network, it provides interfaces to external networks including the Internet and other IP networks. There are a number of services that can be implemented within the CSN depending upon the service provider. Three key components include:
• **Authentication, Authorization and Accounting (AAA)** server, which provides cellular network access to approved users.

• The **Home Agent (HA)** is a critical service that supports user mobility. Since mobile phones roam and may change IP addresses as it moves from one region or service area to another, the HA keeps track of the device's location so that data traffic intended for the user will be delivered despite its location.

• Multiple gateways and servers are used to connect to external networks such as the PSTN, Internet, etc. and to provide services such as DNS or DHCP.

![WiMAX Architecture](image.png)

Figure 10.7. Mobile Worldwide Interoperability of Microwave Access (WiMAX 802.16e) Architecture.

Mobile WiMAX was released before 4G LTE; however, it was soon overtaken by LTE in many parts of the world. In 2012, the WiMAX Forum decided not to pursue WiMAX 2.0 in light of the popularity of 4G LTE. Part of the reason for LTE's popularity was that it offered a smooth transition from 3G UMTS, thus enabling service providers to upgrade their systems, vice adopting a new technology such as WiMAX. The global popularity of GSM and UMTS, also played a key factor in the competition, favoring LTE as the next natural step to 4G services. Sprint, who once championed WiMAX in 2010, announced just a year later in 2011 that it would phase out WiMAX in favor of LTE.
10.5.5 Fifth Generation (5G)

ITU-R is collaborating with industry manufacturers, service providers, standards organizations, and research institutions in developing the *International Mobile Telecommunications-2020 (IMT-2020)* standard framework for mobile communications. Built upon the previous IMT-2000 and IMT-Advanced efforts, IMT-2020 represents the next natural step towards building a truly global 5G mobile broadband network standard that promotes seamless connectivity of voice and data. Draft 5G performance requirements were agreed to during a working group meeting held in Geneva, Switzerland, in February 2017, with final approval anticipated in November 2017. Once these requirements are approved, detailed specifications will be reviewed, with the finished standards expected in 2020.

The requirements discussed in the February 2017 ITU-R meeting included:

- Minimum peak downlink and peak uplink speeds of 20Gbps and 10Gbps respectively. Typical rates seen by users are lower, but must be a minimum of 100Mbps for downlink and 50Mbps for uplink.

- Improved peak spectral efficiency for downlink (30bps per Hz) and uplink (15bps per Hz).

- Mobile networks must be able to service a minimum of 1 million devices per square kilometer, with a latency of less than 4 milliseconds. This latency requirement is reduced to 1 ms for critical system devices (e.g., medical system).

- Radio access networks (RANs) must be energy efficient to minimize network power consumption. This requirement also considers low energy devices that operate on wake/sleep cycles.

- Mobile user movement based on a defined QoS is categorized as *stationary* (0 km/h), *pedestrian* (0 to 10 km/h), *vehicular* (10 to 120km/h) and *high speed vehicular* (120 to 500 km/h). The later high speed vehicular speeds represent high speed trains.

Although detailed specifications and proposals have yet to be written and finalized as of the date of this writing, most experts agree that 5G will be based on OFDM, OFDMA, and MIMO technologies. Along with the current and additional frequency spectrum, 5G may also use ISM unlicensed bands in such a way as to avoid interference with 802.11 or 802.15 systems. Obviously, in order to improve spectral efficiencies and limit inter-cell interference, mobile systems will need to use smart technologies such as cognitive radios and smart antennas, as well as have an ability to form dynamic ad hoc networks.

Central to the excitement surrounding 5G are the potential applications that can be supported. These include the Internet-of-Things (IoT), driverless cars, remote robot-aided surgery, smart homes, robotics, and smart transportation. The ideas and concepts that can benefit from high speed wireless systems are only limited by the imagination. The ever increasing thirst for
mobile data also places manufacturer and service providers in a good position for market creation and profit.

Even before the finalization of IMT2020 standards, many companies within the industry have already begun to work on their own 5G efforts. As examples, AT&T and Verizon plan initial deployments in 2019. In fact, Verizon expects some aspects of its 5G systems to be deployed as early as 2017. Qualcomm, who developed IS-95 CDMA, is working on a new 5G modem which will be used on the Snapdragon mobile platform in 2019. South Korea’s KT mobile operator plans to unveil 5G capability during the 2018 Olympic Winter Games in 2018. There are many more initiatives and partnerships that are too numerous to cite here.

As the global market prepares for the arrival of 5G capability, industry giants are teaming up with one another on a global scale. The prize for being the first and most dominant version of a standard has historically been increased market share and return-on-investment (ROI). Like the cellular generations that preceded 5G, there will always be a certain amount of incompatibilities, as well as the identification of winners and losers. In the end however, the benefits of technology innovation to the average consumer will be great and ongoing. The past story and yet-to-be-future story of the cellular industry has been replayed throughout the entire telecommunication arena. For the technophile, it is a dynamic and interesting field full of adventure.
Key Terms - ch10

Access Service Network (ASN)
Advanced Mobile Phone System (AMPS)
Authentication Center (AuC)
Backhaul
Base Station (BS)
Base Station Controller (BSC)
Base Transceiver Station (BTS)
Cell densification
Cellular Phone System
cdmaOne
CDMA2000
Cluster
Code Division Multiple Access (CDMA)
Connectivity Service Network (CSN)
Control channel
Demand Assigned Multiple Access (DAMA)
Digital AMPS
Enhanced Data Rates for GSM Evolution (EDGE)
Equipment Identity Register (EIR)
Evolved Node B (eNodeB)
Evolved Packet Core (EPC)
Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
Femtocell
Forward link
Frequency Division Multiple Access (FDMA)
Frequency reuse pattern
General Packet Radio Service (GPRS)
Global System for Mobile Communications (GSM)
Hard handoff
Home Location Register (HLR)
Home Subscriber Server (HSS)
Inter-Cell Interference Coordination (ICIC)
International Mobile Equipment Identity (IMEI)
International Mobile Subscriber Identity (IMSI)
International Mobile Telecommunications-2000 (IMT-2000)
International Mobile Telecommunications-2020 (IMT-2020)
International Mobile Telecommunications-Advanced (IMT-Advanced)
Long Term Evolution (LTE)
Macrocell
Microcell
Mobile Radio-Telephone System
Mobile Equipment (ME)
Mobility Management Entity (MME)
Mobile Stations (MS)
Mobile Switch Center (MSC)
Mobile Telecommunications Switching Office (MTSO)
Network Subsystem (NS)
Orthogonal Frequency Division Multiple Access (OFDMA)
Packet Data Network Gateway (PGW)
Picocell
Reverse link
Serving Gateway (SGW)
Small cells
Soft handoff
Time Division Multiple Access (TDMA)
Total Access Communications System (TACS)
Traffic channel
Visitor Location Register (VLR)
Universal Mobile Telecommunications System (UMTS)
WCDMA
Worldwide Interoperability of Microwave Access (WiMAX)
Chapter 10 Problems:

1. Select the correct statement(s) regarding the single antenna mobile radio-telephone system offered by service providers prior to the wide-spread use of the cellular concept.
   a. Single antenna mobile systems had the simplicity and ability to reach out to large numbers of subscribers in urban areas.
   b. With a single antenna system, the mobile telephone power supplies were small and easily carried by users.
   c. Since available frequency channels were limited, a single antenna system could not easily support numerous simultaneous calls.
   d. Single antenna systems used high GHz frequencies in order to maximize data rates.

2. Select the correct statement(s) regarding the cellular network concept.
   a. The number of mobile cellular users that can be supported within a single base station cell increases as the cell size (i.e., "footprint") increases.
   b. For areas where congestion occurs due to a high number of cellular users, base station transmit power should be increased in order to increase data throughput.
   c. Cell sizes ("footprint") can be decreased by decreasing base station transmit power.
   d. The only way to increase the number of mobile users that can be supported within a given cell, is to obtain additional frequency bandwidth.

3. By dividing a mobile service area into smaller cells, frequency reuse can be achieved. As the cell size decreases, more cells cover a given area, and the ability to reuse frequency channels within the service area become greater.
   a. True
   b. False

4. You are designing a cellular system where the available channels for the entire system is $K=300$. The anticipated requirement per cell is 50 channels. You have a choice to choose a $N=16$ or $N=4$ reuse pattern. Which do you choose and why?
   a. $N=16$, which equates to 18 channels per cell. This is insufficient to support requirements.
   b. $N=16$, which equates to 75 channels per cell. This is more than sufficient to support anticipated use per cell.
   c. $N=4$, which equates to 50 channels per cell. This meets the anticipated requirement.
   d. $N=4$, which equates to 75 channels available per cell. This meets and exceeds the per cell requirement.

5. As the cell reuse pattern ($N$) increases, the overall number of simultaneous calls that can be supported within the service area also increases.
   a. True
   b. False
6. When designing a cellular system, a N=1 cell reuse pattern means:
   a. Only one user will be allocated communication channels within a single cell
   b. All allocated frequency channels in the system can be used in each cell
   c. A minimum of one cell space must be used to separate cells that are allocated the same channels
   d. None of the above are correct
   b

7. As the number of cells within a service area increases (i.e., the service area coverage remains the same, but the cells are decreased in size so that more cells support the service area), what will happen?
   a. Since each cell has a base station that must be connected to the main providers network, system complexity increases as the number of cells increase.
   b. If the service area remains the same and the cell sizes decrease, mobile users will experience more handoffs between cells.
   c. As the number of cells increase and cell size decreases, greater frequency reuse can be achieved
   d. All of the above
   d

8. The _______ connects to the mobile user through cellular frequencies; however, backhaul connection to the service provider network is provided by the host broadband connection (e.g., Internet).
   a. Femtocell
   b. Picocell
   c. Macrocell
   d. None of the above
   a

9. Identify some of the ways that cell densification can be accomplished.
   a. Use of CDMA or OFDMA
   b. Borrowing channels from neighboring cells
   c. Use of ICIC methods
   d. All of the above
   d

10. Select the correct statement(s) regarding cellular systems
    a. As cell sizes shrink, frequency reuse decreases significantly
    b. As cell sizes shrink, the complexities of switching mobile traffic between cells increases
    c. As cell sizes increase, frequency reuse increases
    d. As cell sizes increase, so does the complexities of switching mobile traffic between cells
    b

11. Which of the following cellular concepts can be used to increase the number of subscribers within a single cell.
    a. Frequency borrowing
    b. Cell splitting
    c. Cell sectoring
    d. All of the above
    d
12. In a GSM cellular architecture identify the components belonging to the Network Subsystem.
   a. VLR, HLR, AuC
   b. BSC, MSC, BTS
   c. BTS, BSC, PSTN
   d. PSTN, MSC, BSC
   a

13. Identify the ways in which cellular providers address increasing subscriber numbers.
   a. Addition of new frequency channels
   b. Frequency borrowing between adjacent cells
   c. Network densification
   d. All of the above
   d

14. OFDM is a spread spectrum technology similar to CDMA.
   a. True
   b. False
   b

15. Which system provides the air interface to the mobile station?
   a. BSS
   b. BSC
   c. MSC
   d. MS
   a

16. Each base station broadcasts control signals that are used throughout the cell for control and signaling purposes.
   a. True
   b. False
   a

17. If a mobile user departs the set of cells controlled by the BSC, the BSC must coordinate with the mobile switching center (MSC) to facilitate an inter-BSC hand-off.
   a. True
   b. False
   a

18. During a network soft hand-off between cells, the ME (Mobile User) is continuously connected to both BTS' until the hand-off is complete.
   a. True
   b. False
   a
19. Identify the components of a GSM *Network Subsystem*.
   a. HLR
   b. MSC
   c. EIR
   d. AuC
   e. VLR
   f. All of the above are components of the NS

20. In a GSM cellular network, when does the mobile equipment (ME) first connect to the Mobile Switching Center (MSC)?
   a. When the ME is turned on
   b. When the ME attempts to make a call
   c. Only if the called party is not within the same BSC area
   d. Only if the called party is not within the cellular service's network

21. Control channels in a cellular system have a dual purpose. Control channels provide the control and signaling to mobile user equipment, and they are used for user traffic when needed.
   a. True
   b. False

22. Describe the mobile call process when a mobile user places a call on a cellular network.

23. What was true about cellular first generation (1G) systems?
   a. 1G used TDMA over FDM channels
   b. 1G introduced packet switching for analog circuits
   c. 1G traffic channels were analog
   d. 1G control and signaling channels were analog

24. Identify the 1G systems
   a. AMPS, TACS
   b. DAMPS, NMT, GSM
   c. CDMA2000, WCDMA
   d. LTE, WiMAX

25. Which cellular generation first introduced digital communications?
   a. 1G
   b. 2G
   c. 3G
   d. 4G
26. What was the significance of IMT-2000?
   a. Introduced international requirements for 2G
   b. Attempted to address the cellular system incompatibility issue by adopting CDMA and TDMA
   c. Introduced OFDMA and MIMO
   d. Officially introduced the cellular concept to mobile communications

27. CDMA2000 and WCDMA are both 3G standards that are fully compatible with one another because they both use direct sequence spread spectrum technologies.
   a. True
   b. False

28. Select the correct statement(s) regarding IMT-2000.
   a. IMT-2000 was an ITU attempt to define a single global standard for cellular communications
   b. TDMA and CDMA were selected as the global standard
   c. Greater spectral efficiency was one goal for IMT-2000
   d. All of the above

29. Select the correct statement(s) regarding IMT-Advanced.
   a. IMT-Advanced goals are an expansion to the IMT-2000 requirements
   b. Packet switching technologies were emphasized over traditional circuit switched concepts
   c. Long Term Evolution (LTE) and IEEE 802.16 Mobile WiMAX (Worldwide Interoperability of Microwave Access) were both 4G standards that addressed IMT-Advanced goals
   d. All of the above are correct

30. LTE was developed to provide an upgrade path from 3G WCDMA and CDMA2000 systems.
   a. True
   b. False

31. LTE-Advance is considered a true 4G standard.
   a. True
   b. False

32. The LTE Evolved Packet Core (EPC) is similar to the GSM Network Subsystem (NS) in function.
   a. True
   b. False
33. LTE adopted a frequency reuse pattern of N=1. Therefore, ICIC is required to avoid channel interference between cells.
   a. True
   b. False
   a

34. What does LTE-Advanced and mobile WiMAX have in common?
   a. Both support FDD and TDD
   b. Both operate using OFDMA as the access technology
   c. Both use MIMO technology
   d. All of the above
d

35. When implementing OFDM on either WiFi or cellular RF link, the use of guard bands between sub-carriers is not necessary.
   a. True
   b. False
   a

36. Describe the role of the WiMAX home agent.

37. IMT-2020 follows IMT-2000 and IMT-Advanced as the next steps towards providing a fully interoperable and seamless voice and data communications system.
   a. True
   b. False
   a