CHAPTER 13

Cellular Wireless Networks

13.1 **Principles of Cellular Networks**

13.2 **First-Generation Analog**

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13.4 **Second-Generation CDMA**

13.5 **Third-Generation Systems**

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13.7 **Key Terms, Review Questions, and Problems**

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Show the benefits of frequency reuse in cellular systems and how it is accomplished.
- Explain the use of femtocells and picocells for the purpose of network densification.
- Describe the handoff process and various criteria that could be used in handoff decisions.
- Analyze traffic demand and capacity requirements using network engineering tools.
- Compare the differences and improvements between first-, second-, and third-generation cellular systems.
- Contrast second-generation CDMA and TDMA approaches.
- Describe the two main options for third-generation systems.

Of all the tremendous advances in data communications and telecommunications, perhaps the most revolutionary is the development of cellular networks. Cellular technology is the foundation of mobile wireless communications and supports users in locations that are not easily served by wired networks. Cellular technology is the underlying technology for mobile telephones, smartphones, tablets, wireless Internet and wireless applications, and much more.

The next two chapters look at all aspects of cellular networks, from basic wireless communications and systems principles, to the latest fourth-generation Long-Term Evolution (LTE)-Advanced standards. We begin this chapter with a look at the basic principles used in all cellular networks. Then we look at specific cellular technologies and standards, which are conveniently grouped into four generations. The first generation is analog-based and has essentially passed from the scene. **Second-generation (2G)** systems are still in use to carry voice, and **third-generation (3G)** systems were the first to carry sufficiently high-speed data to support truly mobile networking. The next chapter studies LTE and its enhancements in LTE-Advanced. These form a suite of capabilities for fourth-generation cellular systems.

13.1 PRINCIPLES OF CELLULAR NETWORKS

Cellular radio is a technique that was developed to increase the capacity available for **mobile radio** telephone service. Prior to the introduction of cellular communication, mobile radio telephone service was provided only by a high-power transmitter/receiver. A typical system would support about 25 channels with an effective radius of about 80 km. The way to increase the capacity of the system is to use low-power systems with shorter radius and to use numerous transmitters/receivers. We begin this section with a look at the organization of cellular systems and then examine some of the details of their implementation.

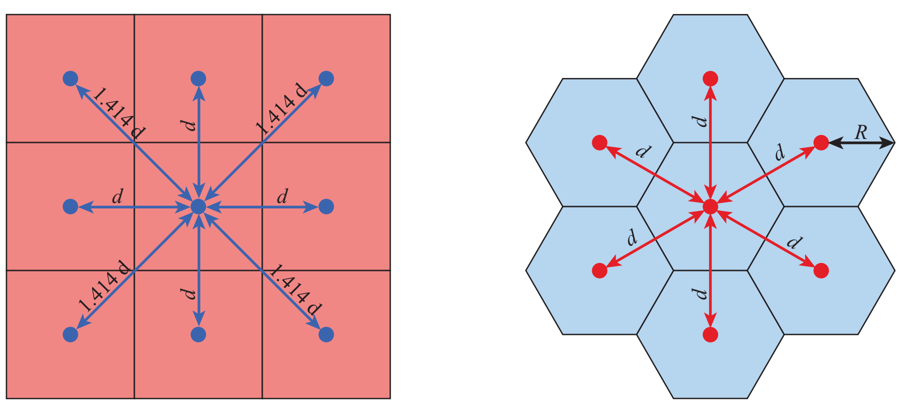
Cellular Network Organization

The essence of a **cellular network** is the use of multiple low-power transmitters, on the order of 100 W or less, even much less. Because the range of such a transmitter is small, an area can be divided into cells, each one served by its own antenna. Each cell is allocated a band of frequencies and is served by a **base station**, consisting of a transmitter, receiver, and control unit. Adjacent cells are assigned different frequencies to avoid interference or crosstalk. However, cells sufficiently distant from each other can use the same frequency band.

The first design decision to make is the shape of cells to cover an area. A matrix of square cells would be the simplest layout to define (Figure 13.1a). However, this geometry is not ideal. If the width of a square cell is d, then a cell has four neighbors at a distance d and four neighbors at a distance $\sqrt{2}d$. As a mobile user within a cell moves toward the cell's boundaries, it is best if all of the adjacent antennas are equidistant. This simplifies the task of determining when to switch the user to an adjacent antenna and which antenna to choose. A hexagonal pattern provides for equidistant antennas (Figure 13.1b). The radius of a hexagon is defined to be the radius of the circle that circumscribes it (equivalently, the distance from the center to each vertex; also equal to the length of a side of a hexagon). For a cell radius R, the distance between the cell center and each adjacent cell center is $d = \sqrt{3}R$.

In practice, a precise hexagonal pattern is not used. Certainly an antenna is not designed to have a hexagonal pattern. Variations from the ideal are also due to topographical limitations such as hills or mountains, local signal propagation conditions such as shadowing from buildings, and practical limitations in siting antennas.

Frequency Reuse In a cellular system, each cell has a base transceiver. The transmission power is carefully controlled (to the extent that it is possible in the highly variable mobile communication environment) to allow communication within the cell using a given frequency band while limiting the power at that frequency that escapes the cell into adjacent cells. In some cellular architectures, it is not practical



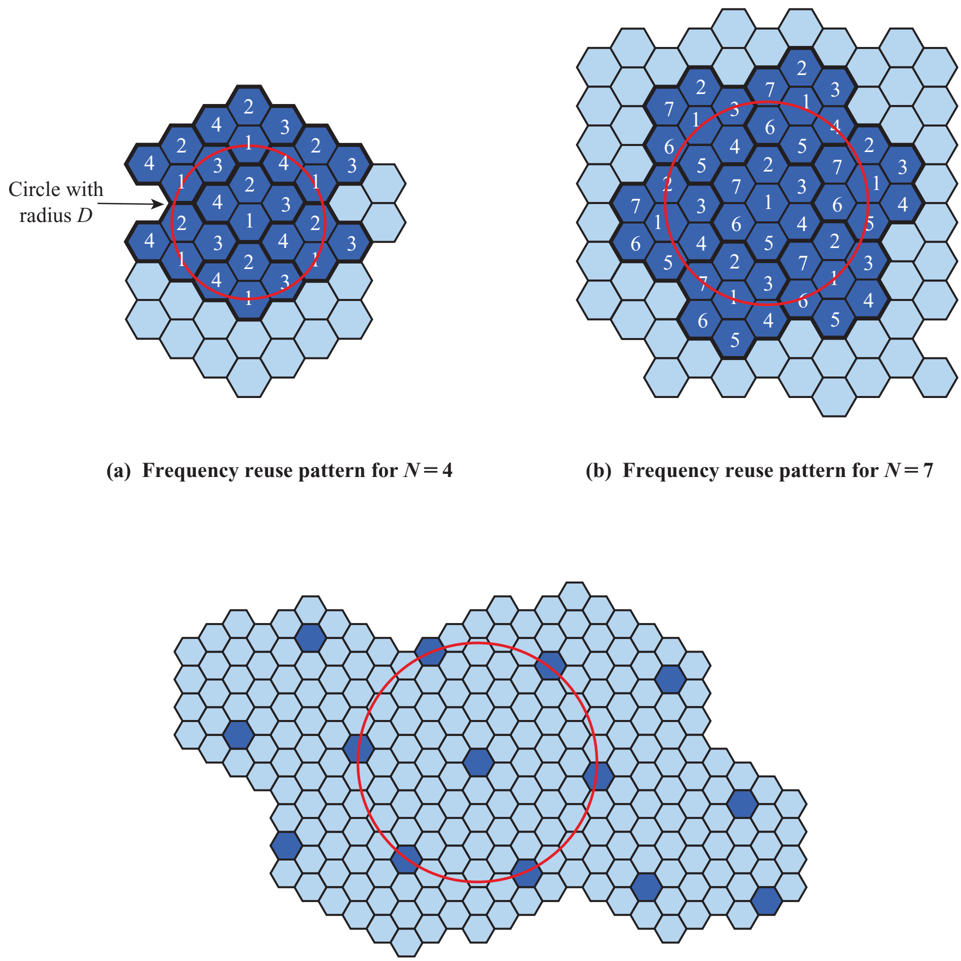
(a) Square pattern

(b) Hexagonal pattern

Figure 13.1 Cellular Geometries

to attempt to use the same frequency band in two adjacent cells.[1] Instead, the objective is to use the same frequency band in multiple cells at some distance from one another. This allows the same frequency band to be used for multiple simultaneous conversations in different cells. Within a given cell, multiple frequency bands are assigned, with the number of bands depending on the traffic expected.

A key design issue is to determine the minimum separation between two cells using the same frequency band, so that the two cells do not interfere with each other. Various patterns of **frequency reuse** are possible. Figure 13.2 shows some



(a) Frequency reuse pattern for $N = 4$

(b) Frequency reuse pattern for $N = 7$

(c) Black cells indicate a frequency reuse for $N = 19$

Figure 13.2 Frequency Reuse Patterns

[1]Exceptions include CDMA systems and fourth-generation inter-cell interference coordination and coordinated multipoint transmission systems, described subsequently.

examples. If the pattern consists of N cells and each cell is assigned the same number of frequencies, each cell can have K/N frequencies, where K is the total number of frequencies allotted to the system. For one first-generation system, $K = 395$, and $N = 7$ is the smallest pattern that can provide sufficient isolation between two uses of the same frequency. This implies that there can be at most $395/7 \approx 57$ frequencies per cell on average.

In characterizing frequency reuse, the following parameters are commonly used:

D = minimum distance between centers of cells that use the same frequency band (called cochannels)

R = radius of a cell

d = distance between centers of adjacent cells ($d = \sqrt{3}R$)

N = number of cells in a repetitious pattern (each cell in the pattern uses a unique set of frequency bands), termed the **reuse factor**

In a hexagonal cell geometry, only the following values of N are possible:

$$N = I^2 + J^2 + (I \times J) \qquad I,\ J = 0, 1, 2, 3, \ldots$$

Hence, possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on. The following relationship holds:

$$\frac{D}{R} = \sqrt{3N}$$

This can also be expressed as $D/d = \sqrt{N}$.

Increasing Capacity Through Network Densification In time, as more customers use the system, traffic may build up so that there are not enough frequency bands assigned to a cell to handle its calls. A number of approaches have been used to cope with this situation, including the following:

- **Adding new channels:** Typically, when a system is set up in a region, not all of the channels are used, and growth and expansion can be managed in an orderly fashion by adding new channels from the unused set.
- **Frequency borrowing:** In the simplest case, frequencies are taken from adjacent cells by congested cells. The frequencies can also be assigned to cells dynamically.
- **Cell splitting:** In practice, the distribution of traffic and topographic features is not uniform, and this presents opportunities for capacity increase. Cells in areas of high usage can be split into smaller cells. Generally, the original cells are about 6.5 to 13 km in size. The smaller cells can themselves be split. Also, special small cells can be deployed in areas of high traffic demand; see the subsequent discussion of small cells such as picocells and femtocells. To use a smaller cell, the power level used must be reduced to keep the signal within the cell. Also, as the mobile units move, they pass from cell to cell, which requires transferring of the call from one base transceiver to another. This process is called a **handoff**. As the cells get smaller, these handoffs become much more frequent. Figure 13.3 indicates schematically how cells can be divided to

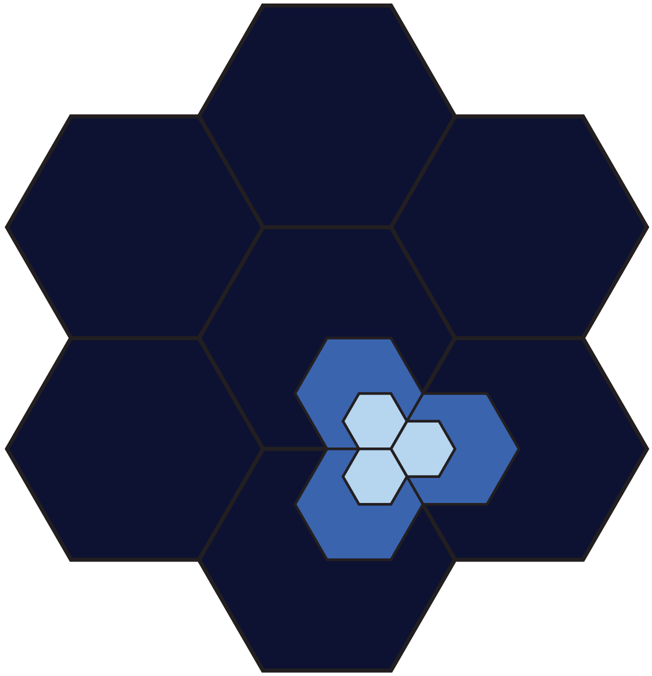


Figure 13.3 Cell Splitting

provide more capacity. A radius reduction by a factor of F reduces the coverage area and increases the required number of base stations by a factor of F^2.

- **Cell sectoring:** With cell sectoring, a cell is divided into a number of wedge-shaped sectors, each with its own set of channels, typically three sectors per cell. Each sector is assigned a separate subset of the cell's channels, and directional antennas at the base station are used to focus on each sector. This can be seen in the triangular shape of typical cellular antenna configurations, since the antennas mounted on each side of the triangle are directed toward their respective one of the three sectors.
- **Small cells:** As cells become smaller, antennas move from the tops of tall buildings or hills, to the tops of small buildings or the sides of large buildings, and finally to lampposts, where they form **picocells**. Each decrease in cell size is accompanied by a reduction in the radiated power levels from the base stations and the mobile units. Picocells are useful on city streets in congested areas, along highways, and inside large public buildings. If placed inside buildings, these are called **femtocells**, which might be open to all users or only to authorized users, for example only those who work in that building. If only for a restricted set of users, this is called a **closed subscriber group**. This process of increasing capacity by using small cells is called **network densification**. The large outdoor cells called **macrocells** are intended to support high-mobility users. There are a variety of frequency use strategies to share frequencies but avoid interference problems between small cells and macrocells, such as

having separate frequencies for macrocells and small cells or dynamic spectrum assignment between them. In the case of dynamic assignment, **self-organizing networks** of base stations make quick cooperative decisions for channel assignment as **needs require**.

- Ultimately, the capacity of a cellular network depends on how often the same frequencies (or subcarriers in the case of orthogonal frequency division multiple access) can be reused for different mobiles. Regardless of their location, two mobiles can be assigned the same frequency if their interference is tolerable. Thus, interference is the limiting factor, not location. If interference can be addressed directly, then the channel reuse patterns in Figure 13.2 might not even be required. For example, if two mobiles are close to their respective base stations, transmit powers could be greatly reduced for each connection but still provide adequate service. This reduced power would limit interference to other users of the same frequency. Then the two mobiles could use the same frequencies even in adjacent cells. Modern systems take advantage of these opportunities through techniques such as **inter-cell interference coordination (ICIC)** and **coordinated multipoint transmission (CoMP)**. These techniques perform various functions, such as warning adjacent cells when interference might be significant (e.g., a user is near the boundary between two cells) or performing joint scheduling of frequencies across multiple cells. LTE-Advanced uses these capabilities extensively; ICIC and CoMP in LTE are discussed in Chapter 14.

Example 13.1 Assume a system of 32 cells with a cell radius of 1.6 km, a total of 32 cells, a total frequency bandwidth that supports 336 traffic channels, and a reuse factor of $N = 7$. If there are 32 total cells, what geographic area is covered, how many channels are there per cell, and what is the total number of concurrent calls that can be handled? Repeat for a cell radius of 0.8 km and 128 cells.

Figure 13.4a shows an approximately rectangular pattern. The area of a hexagon of radius R is$1.5R^2\sqrt{3}$. A hexagon of radius 1.6 km has an area of 6.65 km^2, and the total area covered is $6.65 \times 32 = 213\ km^2$. For $N = 7$, the number of channels per cell is $336/7 = 48$, for a total channel capacity (total number of calls that can be handled) of $48 \times 32 = 1536$ channels. For the layout in Figure 13.4b, the area covered is $1.66 \times 128 = 213\ km^2$. The number of channels per cell is $336/7 = 48$, for a total channel capacity of $48 \times 128 = 6144$ channels. A reduction in cell radius by a factor of ½ has increased the channel capacity by a factor of 4.

Operation of Cellular Systems

Figure 13.5 shows the principal elements of a cellular system. In the approximate center of each cell is a base station (BS). The BS includes an antenna, a controller, and a number of transceivers for communicating on the channels assigned to that cell. The controller is used to handle the call process between the mobile unit and the rest of the network. At any time, a number of mobile units may be active and moving about within a cell communicating with the BS. Each BS is connected to a mobile telecommunications switching office (MTSO), with one MTSO serving multiple BSs. Typically, the link between an MTSO and a BS is by a wire line,

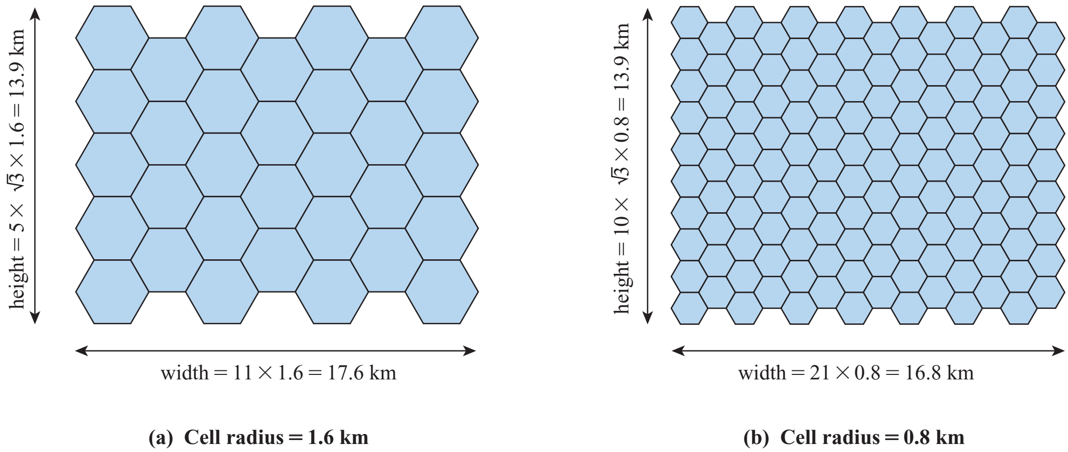


Figure 13.4 Frequency Reuse Example

although wireless links are becoming increasingly popular with technologies like WiMAX (discussed in Chapter 16). The MTSO connects calls between mobile units. The MTSO is also connected to the public telephone or telecommunications network and can make a connection between a fixed subscriber to the public network and a mobile subscriber to the cellular network. The mobile is also given access to the Internet. The MTSO assigns the voice channel to each call, performs handoffs (discussed subsequently), and monitors the call for billing information.

The use of a cellular system is fully automated and requires no action on the part of the user other than placing or answering a call. Two types of channels are available between the mobile unit and the base station: control channels and traffic channels. **Control channels** are used to exchange information having to do with setting up and maintaining calls and with establishing a relationship between a mobile unit and the nearest BS. **Traffic channels** carry a voice or data connection between

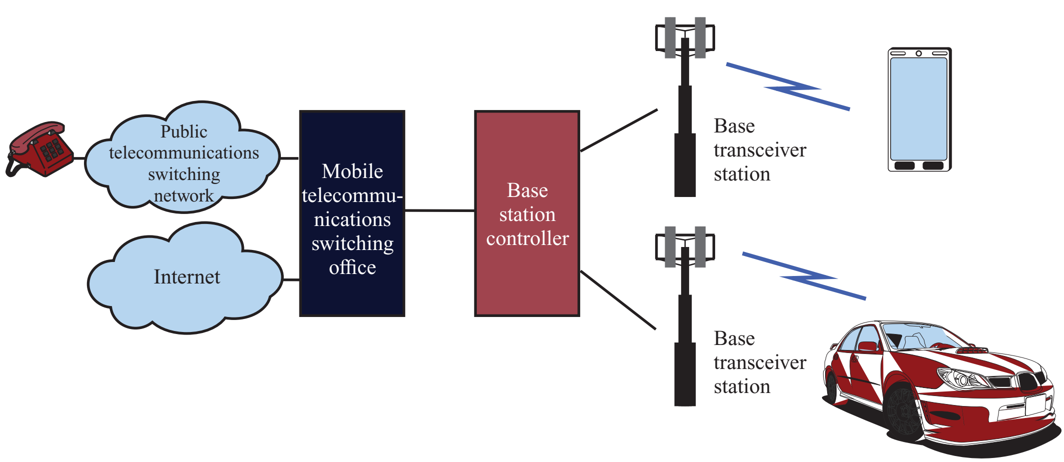


Figure 13.5 Overview of Cellular System

users. Figure 13.6 illustrates the steps in a typical call between two mobile users within an area controlled by a single MTSO:

- **Mobile unit initialization:** When the mobile unit is turned on, it scans and selects the strongest setup control channel used for this system (Figure 13.6a).

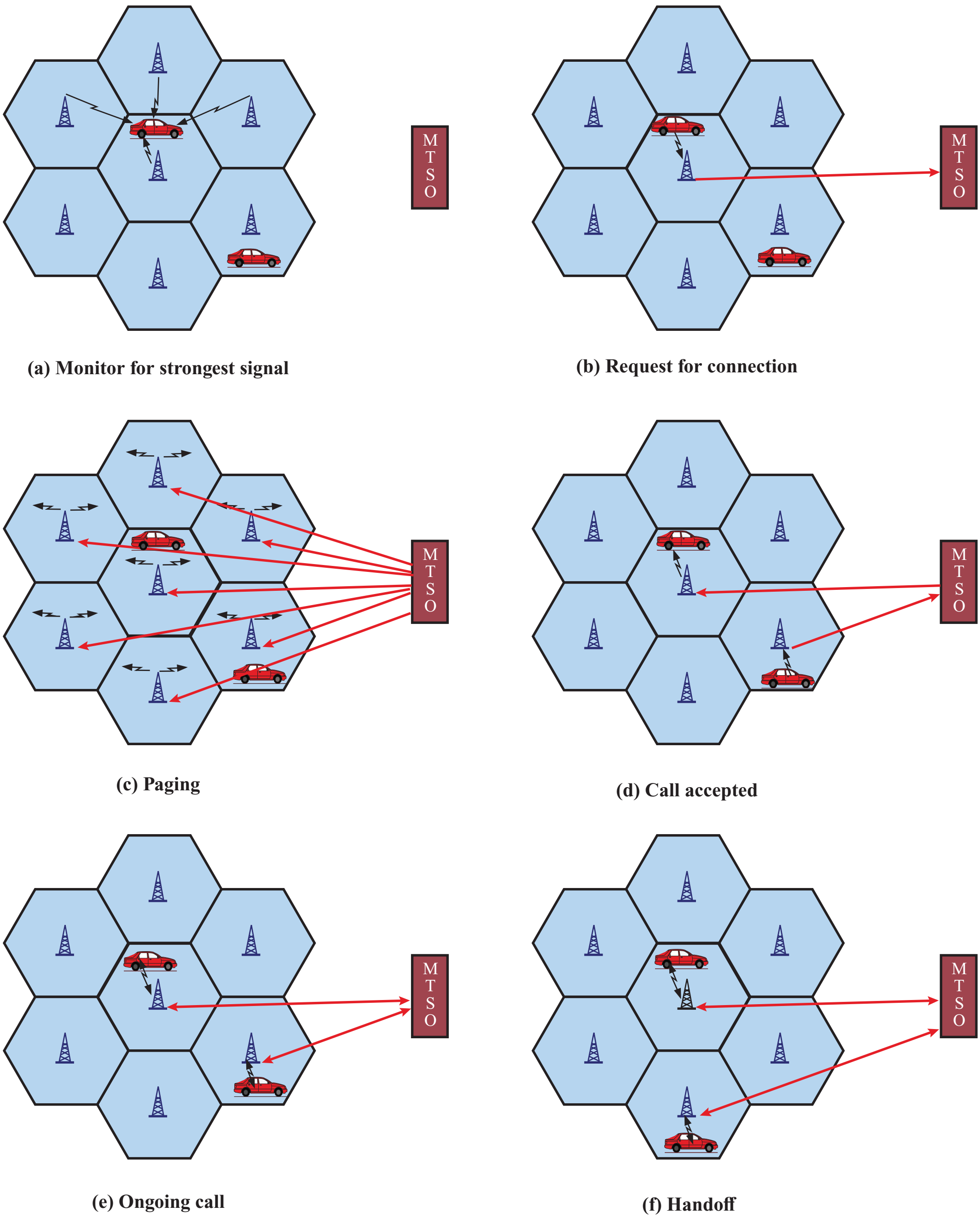


Figure 13.6 Example of Mobile Cellular Call

Cells with different frequency bands repetitively broadcast on different setup channels. The receiver selects the strongest setup channel and monitors that channel. The effect of this procedure is that the mobile unit has automatically selected the BS antenna of the cell within which it will operate.[2] Then a handshake takes place between the mobile unit and the MTSO controlling this cell, through the BS in this cell. The handshake is used to identify the user and register its location. As long as the mobile unit is on, this scanning procedure is repeated periodically to account for the motion of the unit. If the unit enters a new cell, then a new BS is selected. In addition, the mobile unit is monitoring for pages, discussed subsequently.

- **Mobile-originated call:** A mobile unit originates a call by sending the number of the called unit on the preselected setup channel (Figure 13.6b). The receiver at the mobile unit first checks that the setup channel is idle by examining information in the forward (from the BS) channel. When an idle state is detected, the mobile unit may transmit on the corresponding reverse (to BS) channel. The BS sends the request to the MTSO.
- **Paging:** The MTSO then attempts to complete the connection to the called unit. The MTSO sends a paging message to certain BSs to find the called mobile unit, depending on the called mobile unit number and the latest information on the unit's whereabouts (Figure 13.6c). The MTSO does not always know the location of every mobile if certain mobiles have been in idle modes. Each BS transmits the paging signal on its own assigned setup channel.
- **Call accepted:** The called mobile unit recognizes its number on the setup channel being monitored and responds to that BS, which sends the response to the MTSO. The MTSO sets up a circuit between the calling and called BSs. At the same time, the MTSO selects an available traffic channel within each BS's cell and notifies each BS, which, in turn, notifies its mobile unit (Figure 13.6d). The two mobile units tune to their respective assigned channels.
- **Ongoing call:** While the connection is maintained, the two mobile units exchange voice or data signals, going through their respective BSs and the MTSO (Figure 13.6e).
- **Handoff:** If a mobile unit moves out of range of one cell and into the range of another during a connection, the traffic channel has to change to the one assigned to the BS in the new cell (Figure 13.6f). The system makes this change without either interrupting the call or alerting the user.

Other functions performed by the system but not illustrated in Figure 13.6 include the following:

- **Call blocking:** During the mobile-initiated call stage, if all the traffic channels assigned to the nearest BS are busy, then the mobile unit makes a preconfigured number of repeated attempts. After a certain number of failed tries, a busy tone is returned to the user.

[2]Usually, but not always, the antenna and therefore the base station selected is the closest one to the mobile unit. However, because of propagation anomalies, this is not always the case.

- **Call termination:** When one of the two users hangs up, the MTSO is informed and the traffic channels at the two BSs are released.
- **Call drop:** During a connection, because of interference or weak signal spots in certain areas, if the BS cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the MTSO is informed.
- **Calls to/from fixed and remote mobile subscriber:** The MTSO connects to the public switched telephone network. Thus, the MTSO can set up a connection between a mobile user in its area and a fixed subscriber via the telephone network. Further, the MTSO can connect to a remote MTSO via the telephone network or via dedicated lines and set up a connection between a mobile user in its area and a remote mobile user.
- **Emergency call prioritization and queuing:** If a user identifies the call as an emergency call, calls that may experience blocking due to a busy BS may be queued and given first access when a channel becomes available.

Mobile Radio Propagation Effects

Mobile radio communication introduces complexities not found in wired communication or in fixed wireless communication. Two general areas of concern are signal strength and signal propagation effects.These are discussed in detail in Chapter 6.

- **Signal strength:** The strength of the signal between the base station and the mobile unit must be strong enough to maintain signal quality at the receiver but not so strong as to create too much cochannel interference with channels in another cell using the same frequency band. Several complicating factors exist. Human-made noise varies considerably, resulting in a variable noise level. For example, automobile ignition noise in the cellular frequency range is greater in the city than in a suburban area. Other signal sources vary from place to place. The signal strength varies as a function of distance from the BS to a point within its cell. Moreover, the signal strength varies dynamically as the mobile unit moves due to shadowing from obstructions and geography.
- **Fading:** Even if the signal strength is within an effective range, signal propagation effects may disrupt the signal and cause errors. Section 6.4 discusses fading and various countermeasures.

In designing a cellular layout, the communications engineer must take account of these various propagation effects, the desired maximum transmit power level at the base station and the mobile units, the typical height of the mobile unit antenna, and the available height of the BS antenna. These factors will determine the size of the individual cell. Unfortunately, as just described, the propagation effects are dynamic and difficult to predict. The best that can be done is to come up with a model based on empirical data and to apply that model to a given environment to develop guidelines for cell size. One of the most widely used models was developed by Okumura et al. and subsequently refined by Hata.This is discussed in Section 6.3.

Handoff

Handoff[3] is the procedure for changing the assignment of a mobile unit from one BS to another as the mobile unit moves from one cell to another. Handoff is handled in different ways in different systems and involves a number of factors. Here we give a brief overview.

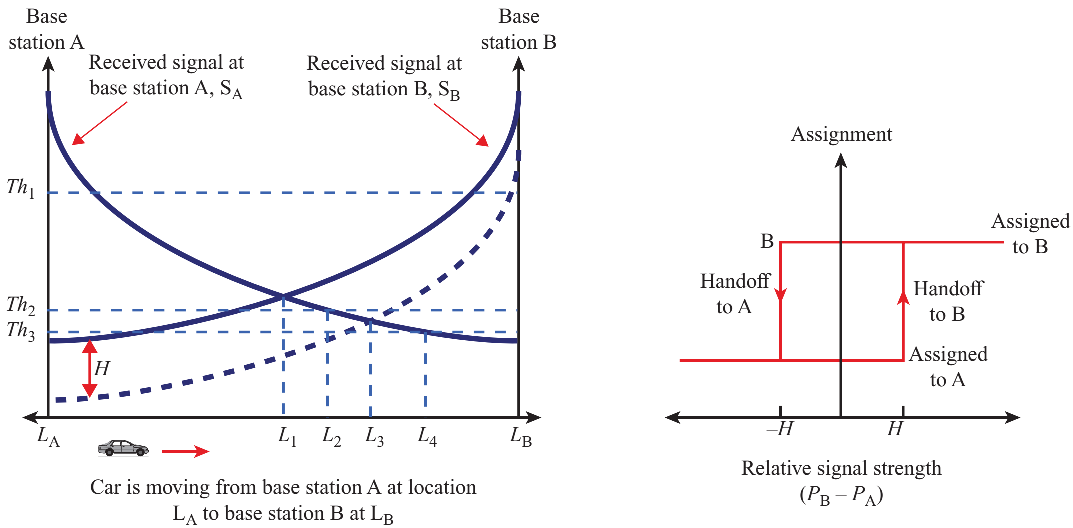
Handoff may be network initiated, in which the decision is made solely by the network measurements of received signals from the mobile unit. Alternatively, mobile unit assisted handoff schemes enable the mobile unit to participate in the handoff decision by providing feedback to the network concerning signals received at the mobile unit. In either case, the following different performance metrics may be used to make the decision:

- **Call blocking probability:** The probability of a new call being blocked, due to heavy load on the BS traffic capacity. In this case, the mobile unit is handed off to a neighboring cell based not on signal quality but on traffic capacity.
- **Call dropping probability:** The probability that, due to a handoff, a call is terminated.
- **Call completion probability:** The probability that an admitted call is not dropped before it terminates.
- **Probability of unsuccessful handoff:** The probability that a handoff is executed while the reception conditions are inadequate.
- **Handoff blocking probability:** The probability that a handoff cannot be successfully completed.
- **Handoff probability:** The probability that a handoff occurs before call termination.
- **Rate of handoff:** The number of handoffs per unit time.
- **Interruption duration:** The duration of time during a handoff in which a mobile unit is not connected to either base station.
- **Handoff delay:** The distance the mobile unit moves from the point at which the handoff should occur to the point at which it does occur.

The principal parameter used to make the handoff decision is measured signal strength from the mobile unit at the BS. Typically, the BS averages the signal over a moving window of time to remove the rapid fluctuations due to multipath effects. Figure 13.7a shows the average received power level at two adjacent base stations as a mobile unit moves from BS A, at L_A, to BS B, at L_B. The animation for this figure is especially helpful. This figure is useful in explaining various handoff strategies that have been used to determine the instance of handoff:

- **Relative signal strength:** The mobile unit is handed off from BS A to BS B when the signal strength at B first exceeds that at A. If the signal strength at B subsequently falls below that of A, the mobile unit is handed back to A. In

[3]The term *handoff* is used in U.S. cellular standards documents. ITU documents use the term **handover**, and both terms appear in the technical literature. The meanings are the same.



(a) Handoff decision as a function of handoff scheme

(b) Hysteresis mechanism

Figure 13.7 Handoff between Two Cells

Figure 13.7a, handoff occurs at point L_1. At this point, signal strength to BS A is still adequate but is declining. Because signal strength fluctuates due to multipath effects, even with power averaging, this approach can lead to a ping-pong effect in which the unit is repeatedly passed back and forth between two BSs.

- **Relative signal strength with threshold:** Handoff only occurs if (1) the signal at the current BS is sufficiently weak (less than a predefined threshold) and (2) the other signal is the stronger of the two. The intention is that so long as the signal at the current BS is adequate, handoff is unnecessary. If a high threshold is used, such as Th_1, this scheme performs the same as the relative signal strength scheme. With a threshold of Th_2, handoff occurs at L_2. If the threshold is set quite low compared to the crossover signal strength (signal strength at L_1), such as Th_3, the mobile unit may move far into the new cell (L_4) before handoff. This reduces the quality of the communication link and may result in a dropped call. A threshold should not be used alone because its effectiveness depends on prior knowledge of the crossover signal strength between the current and candidate base stations.
- **Relative signal strength with hysteresis:** Handoff occurs only if the new base station is sufficiently stronger (by a margin H in Figure 13.7a) than the current one. In this case, handoff occurs at L_3. This scheme prevents the ping-pong effect, because once handoff occurs, the effect of the margin H is reversed. The term *hysteresis* refers to a phenomenon known as relay hysteresis and can be appreciated with the aid of Figure 13.7b. We can think of the handoff mechanism as having two states. While the mobile unit is assigned to BS A, the mechanism will generate a handoff when the relative signal strength reaches

or exceeds the H. Once the mobile unit is assigned to B, it remains so until the relative signal strength falls below $-H$, at which point it is handed back to A. The only disadvantage of this scheme is that the first handoff may still be unnecessary if BS A still has sufficient signal strength.

- **Relative signal strength with hysteresis and threshold:** Handoff occurs only if (1) the current signal level drops below a threshold, and (2) the target base station is stronger than the current one by a hysteresis margin H. In our example, handoff occurs at L_3 if the threshold is either Th_1 or Th_2 and at L_4 if the threshold is at Th_3.
- **Prediction techniques:** The handoff decision is based on the expected future value of the received signal strength.

Hard or Soft Handoff When the signal strength of a neighboring cell exceeds that of the current cell, plus a threshold, the mobile station is instructed to switch to a new frequency band that is within the allocation of the new cell. This is referred to as a **hard handoff**. In **soft handoff**, a mobile station is temporarily connected to more than one base station simultaneously. A mobile unit may start out assigned to a single cell. If the unit enters a region in which the transmissions from two base stations are comparable (within some threshold of each other), the mobile unit enters the soft handoff state in which it is connected to the two base stations. The mobile unit remains in this state until one base station clearly predominates, at which time it is assigned exclusively to that cell.

While in the soft handoff state, the transmissions from the mobile unit reaching the two base stations are both sent on to the mobile switching center, which estimates the quality of the two signals and selects one. The switch sends data or digitized speech signals to both base stations, which transmit them to the mobile unit. The mobile unit combines the two incoming signals to recover the information. Soft handoff not only increases the quality of the mobile's communication, especially at cell edges, but also increases its use of system capacity. For this example, separate frequencies from two base stations are both assigned to the mobile at once. Different technologies may or may not use soft handoff. Some may use hard handoff but have fast protocols for switching between base stations.

The handoff decision is complicated by the use of power control techniques, which enable the BS to dynamically adjust the power transmitted by the mobile unit. This topic is discussed in the following section.

Power Control

A number of design issues make it desirable to include a dynamic **power control** capability in a cellular system:

1. The received power must be sufficiently above the background noise for effective communication, which dictates the required transmitted power. As the mobile unit moves away from the transmitter, the received power declines due to normal attenuation. In addition, the effects of reflection, diffraction, and scattering can cause rapid changes in received power levels over small distances. This is because the power level is the sum from signals coming from a number of different paths and the phases of those paths are random,

sometimes adding and sometimes subtracting. As the mobile unit moves, the contributions along various paths change.

2. At the same time, it is desirable to minimize the power in the transmitted signal from the mobile unit, to reduce cochannel interference (interference with channels on the same frequency in remote cells), alleviate health concerns, and save battery power.
3. In spread spectrum (SS) systems using code division multiple access (CDMA), it is desirable to equalize the *received power level at the BS* from all mobile units when the signals arrive. This is crucial to system performance because all users have the same frequency allocation.

Cellular systems use the two kinds of power control. **Open-loop power control** depends solely on the mobile unit, with no feedback from the BS, and is used in some SS systems. In SS systems, the BS continuously transmits an unmodulated signal, known as a pilot. The pilot allows a mobile unit to acquire the timing of the forward (BS to mobile) CDMA channel and provides a phase reference for demodulation. It can also be used for power control. The mobile unit monitors the received power level of the pilot and sets the transmitted power in the reverse (mobile to BS) channel inversely proportional to it. This approach assumes that the forward and reverse link signal strengths are closely correlated, which is generally the case. The open-loop approach is not as accurate as the closed-loop approach. However, the open-loop scheme can react more quickly to rapid fluctuations in signal strength, such as when a mobile unit emerges from behind a large building. This fast action is required in the reverse link of a CDMA system where the sudden increase in received strength at the BS may suppress all other signals.

Closed-loop power control adjusts signal strength in the **reverse channel** (mobile to BS) based on some metric of performance in that reverse channel, such as received signal power level, received signal-to-noise ratio (SNR), received bit error rate, or received packet error rate. The BS makes the power adjustment decision and communicates a power adjustment command to the mobile unit on a control channel. Closed-loop power control is also used to adjust power in the **forward channel**. In this case, the mobile unit provides information about received signal quality to the BS, which then adjusts transmitted power.

Traffic Engineering

For an FDMA system, the capacity of a cell is equal to the number of frequency channels and subcarriers allocated to it. Ideally, the number of available frequencies in a cell would equal the total amount of demand that could be active at any time. In practice, it is not feasible to have the capacity to handle any possible load at all times. Fortunately, not all subscribers are active at the same time and so it is reasonable to size the network to be able to handle some expected level of load. This is the discipline of traffic engineering.

Traffic engineering concepts were developed in the design of telephone switches and circuit-switching telephone networks, but the concepts equally apply to cellular networks. Consider a cell that has L potential subscribers (L mobile units) and that is able to handle N simultaneous users (capacity of N channels). If $L \leq N$, the system is referred to as *nonblocking*; all calls can be handled all the time. If $L > N$, the system is *blocking*; a subscriber may attempt a call and find the capacity fully in use and therefore be blocked. For a blocking system, the fundamental performance questions we wish to answer are the following:

1. What is the degree of blocking; that is, what is the probability that a resource request will be blocked? Alternatively, what capacity (N) is needed to achieve a certain upper bound on the probability of blocking?
2. If blocked requests are queued for service, what is the average delay until that call is put into service? Alternatively, what capacity is needed to achieve a certain average delay?

In this subsection, we briefly introduce the relevant traffic engineering concepts and give an example of their use. Online Appendix A examines the subject in more detail.

Two parameters determine the amount of load presented to a system:

$\lambda =$ the mean rate of calls (connection requests) attempted per unit time

$h =$ the mean holding time per successful call

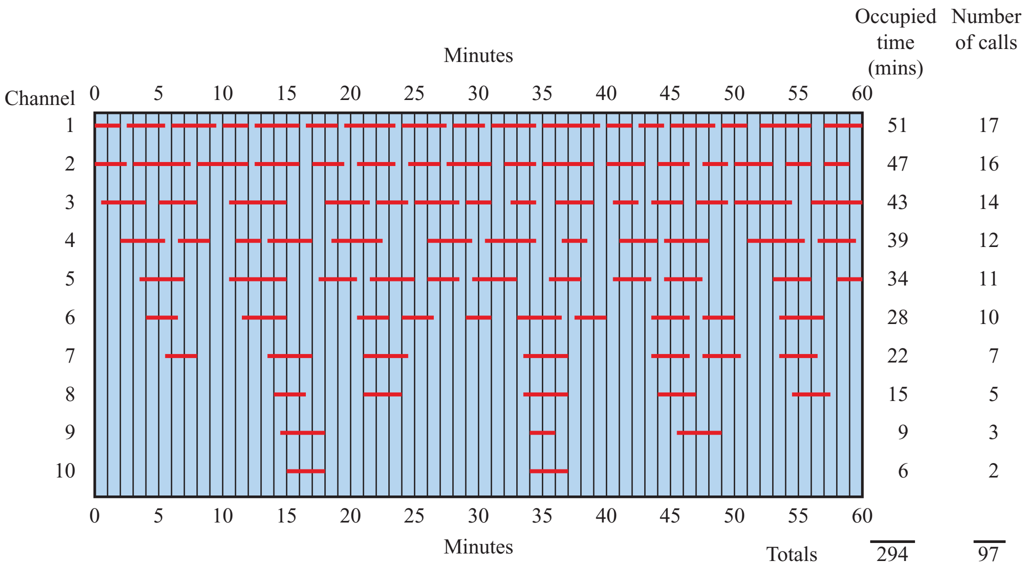
The basic measure of traffic is the **traffic intensity**, expressed in a dimensionless unit, the **Erlang**:

$$A = \lambda h$$

A can be interpreted in several ways. It is a normalized version of λ: A equals the average number of calls arriving during the average holding period. We can also view the cell as a multiserver queuing system where the number of servers is equal to the channel capacity N. The average service time at a server is h. A basic relationship in a multiserver queue is $\lambda h = \rho N$, where ρ is server utilization, or the fraction of time that a server is busy. Therefore, $A = \rho N$ and is a measure of the average number of channels required.

Example 13.2 If the calling rate averages 20 calls per minute and the average holding time is 3 minutes, then $A = 60$. We would expect a cell with a capacity of 120 channels to be about half utilized at any given time. A switch of capacity 50 would clearly be inadequate. A capacity of 60 would meet the average demand but, because of fluctuations around the mean rate A, this capacity would at times be inadequate.

Example 13.3 To clarify these concepts, consider Figure 13.8, which shows the pattern of activity in a cell with a capacity of 10 channels over a period of 1 hour. The rate of calls per minute is 97/60. The average holding time per call, in minutes, is 294/97. Thus $A = (97/60) \times (294/97) = 4.9$ Erlangs. Another way of viewing the parameter A is that it is the mean number of calls in progress. Thus, on average, 4.9 channels are engaged. The latter interpretation, however, is true only in the nonblocking case. The parameter λ was defined as the rate of calls attempted, not carried traffic.



Note: horizontal lines indicate occupied periods to the nearest 1/2 minute

Figure 13.8 Example of Distribution of Traffic in a Cell with Capacity 10

Typically, a blocking system is sized to deal with some upper limit of traffic intensity. It is generally thought unreasonable to size for the highest surge of traffic anticipated; rather, the common practice is to size the system to meet the average rate encountered during a busy hour. The busy hour is the 60-minute period during the day when the traffic is highest, in the long run. ITU-T recommends taking the average of the busy hour traffic on the 30 busiest days of the year, called the "mean busy-hour traffic," and using that quantity to size the system. The North American practice is to take the average over the 10 busiest days. One of those busiest days in the United States is usually Mother's Day in the month of May. The measurements are typically of carried rather than offered traffic and can only be used to estimate the true load.

The parameter A, as a measure of busy-hour traffic, serves as input to a traffic model. The model is then used to answer questions such as those posed in the beginning of this subsection. There are two key factors that determine the nature of the model:

- The manner in which blocked calls are handled.
- The number of traffic sources.

Blocked calls may be handled in one of two ways. First, blocked calls can be put in a queue awaiting a free channel; this is referred to as **lost calls delayed (LCD)**, although in fact the call is not lost, merely delayed. Second, a blocked call can be rejected and dropped. This in turn leads to two assumptions about the action of the user. If the user hangs up and waits for some random time interval before another call attempt, this is known as **lost calls cleared (LCC)**. If the user repeatedly attempts calling, it is known as **lost calls held (LCH)**. For each of these blocking options, formulas have been developed that characterize the performance of the system. For cellular systems, the LCC model is generally used and is generally the most accurate.

The second key element of a traffic model is whether the number of users is assumed to be finite or infinite. For an infinite source model, there is assumed to be a fixed arrival rate. For the finite source case, the arrival rate will depend on the number of sources already engaged. In particular, if the total pool of users is L, each of which generates calls at an average rate of λ/L, then, when the cell is totally idle, the arrival rate is λ. However, if there are K users occupied at time t, then the instantaneous arrival rate at that time is $\lambda(L - K)/L$. Infinite source models are analytically easier to deal with. The infinite source assumption is reasonable when the number of sources is at least 5 to 10 times the capacity of the system.

Infinite Sources, Lost Calls Cleared For an infinite source LCC model, the key parameter of interest is the probability of loss, or **grade of service**. Thus a grade of service of 0.01 means that, during a busy hour, the probability that an attempted call is blocked is 0.01. Values in the range 0.01 to 0.001 are generally considered quite good.

The equation of infinite source LCC, known as Erlang B, has the following form:

$$P = \frac{\dfrac{A^N}{N!}}{\displaystyle\sum_{x=0}^{N} \frac{A^x}{x!}}$$

where

A = offered traffic, Erlangs

N = number of servers

P = probability of blocking (grade of service)

This equation is easily programmed, and tables of values are readily available. Table 13.1 is an extract from such a table. Given the offered load and number of servers, the grade of service can be calculated or determined from a table. More often, the inverse problem is of interest: determining the amount of traffic that can be handled by a given capacity to produce a given grade of service. Another problem is to determine the capacity required to handle a given amount of traffic at a given grade of service. For both these problems, tables or suitable trial-and-error programs are needed.

Two important points can be deduced from Table 13.1:

1. A larger-capacity system is more efficient than a smaller-capacity one for a given grade of service.
2. A larger-capacity system is more susceptible to an increase in traffic.

All of the preceding discussion deals with offered traffic. If sizing is done on the basis of system measurement, all that we are likely to have is carried traffic. A program can readily be developed that accepts carried traffic as input and then

Table 13.1 Erlang B Table

	Capacity (Erlangs) for Grade of Service of:				
Number of Servers (N)	**$P = 0.02$ (1/50)**	**$P = 0.01$ (1/100)**	**$P = 0.005$ (1/200)**	**$P = 0.002$ (1/500)**	**$P = 0.001$ (1/1000)**
1	0.02	0.01	0.005	0.002	0.001
4	1.09	0.87	0.7	0.53	0.43
5	1.66	1.36	1.13	0.9	0.76
10	5.08	4.46	3.96	3.43	3.09
20	13.19	12.03	11.10	10.07	9.41
24	16.64	15.27	14.21	13.01	12.24
40	31.0	29.0	27.3	25.7	24.5
70	59.13	56.1	53.7	51.0	49.2
100	87.97	84.1	80.9	77.4	75.2

Example 13.4 To illustrate the first point, consider two cells, each with a capacity of 10 channels. They have a joint capacity of 20 channels and can handle a combined offered traffic intensity of 6.86 (3.43 per cell) for a grade of service of 0.002. However, a single cell with a capacity of 20 channels will handle 10.07 Erlangs at a grade of service of 0.002. To illustrate the second point, consider a cell of 10 channels giving a grade of service of 0.002 for a load of 3.43 Erlangs. A 30% increase in traffic (up to 4.46 Erlangs) degrades the grade of service to 0.01. However, for a cell of capacity 70 channels, only a 10% increase in traffic (from 51.0 to 56.1 Erlangs) degrades the grade of service from 0.002 to 0.01.

performs a seeking algorithm to work backward to offered traffic. The relationship between carried traffic

C and offered traffic A is

$$C = A(1 - P)$$

For small values of P, A is a good approximation of C.

Effect of Handoff One complication in cellular traffic models not found in other such models is the effect of handoff. The arrival rate of calls at a cell has two components: new calls placed by mobile units in the cell (λ_1), and calls handed off to the cell for mobile units entering the cell while connected (λ_2). The total arrival rate is $\lambda = \lambda_1 + \lambda_2$. Similarly, the completion rate consists of calls being completed normally and calls being handed off. The model must be adjusted accordingly to obtain overall arrival rates and holding times.

13.2 FIRST-GENERATION ANALOG

The rest of the chapter provides an overview of first-, second-, and third-generation cellular systems. Only high-level discussion is provided, however; to learn details about a modern cellular system operates, detailed information is instead provided in Chapter 14 for fourth-generation LTE and LTE-Advanced systems.

The original cellular telephone networks provided analog traffic channels; these are now referred to as **first-generation (1G)** systems. Since the early 1980s the most common first-generation system in North America has been the **Advanced Mobile Phone Service (AMPS)** developed by AT&T. This approach is also common in South America, Australia, and China. Although it has been replaced, for the most part, by later-generation systems, AMPS is still in use. In this section, we provide an overview of AMPS.

Spectral Allocation

In North America, two 25-MHz bands are allocated to AMPS (Table 13.2), one for transmission from the base station to the mobile unit (869–894 MHz), the other for transmission from the mobile unit to the base station (824–849 MHz). Each of these bands is split in two to encourage competition (i.e., so that in each market two operators can be accommodated). An operator is allocated only 12.5 MHz in each direction for its system. The channels are spaced 30 kHz apart, which allows a total of 416 channels per operator. Twenty-one channels are allocated for control, leaving 395 to carry calls. The control channels are data channels operating at 10 kbps. The conversation channels carry the conversations in analog using frequency modulation. Control information is also sent on the conversation channels in bursts as data. This number of channels is inadequate for most major markets, so some way must be found either to use less bandwidth per conversation or to reuse frequencies. Both approaches have been taken in the various approaches to mobile telephony. For AMPS, frequency reuse is exploited.

Operation

Each AMPS-capable cellular telephone includes a *numeric assignment module* (NAM) in read-only memory. The NAM contains the telephone number of the phone, which is assigned by the service provider, and the serial number of the phone, which is assigned by the manufacturer. When the phone is turned on, it transmits its serial number and phone number to the MTSO (Figure 13.5); the MTSO maintains a database with information about mobile units that have been reported stolen and

Table 13.2 AMPS Parameters

Base station transmission band	869 to 894 MHz
Mobile unit transmission band	824 to 849 MHz
Spacing between forward and reverse channels	45 MHz
Channel bandwidth	30 kHz
Number of full-duplex voice channels	790
Number of full-duplex control channels	42
Mobile unit maximum power	3 watts
Cell size, radius	2 to 20 km
Modulation, voice channel	FM, 12-kHz peak deviation
Modulation, control channel	FSK, 8-kHz peak deviation
Data transmission rate	10 kbps
Error control coding	BCH (48, 36,5) and (40, 28,5)

uses serial number to lock out stolen units. The MTSO uses the phone number for billing purposes. If the phone is used in a remote city, the service is still billed to the user's local service provider.

When a call is placed, the following sequence of events occurs:

1. The subscriber initiates a call by keying in the telephone number of the called party and presses the send key.
2. The MTSO verifies that the telephone number is valid and that the user is authorized to place the call; some service providers require the user to enter a personal identification number (PIN) as well as the called number to counter theft.
3. The MTSO issues a message to the user's cell phone indicating which traffic channels to use for sending and receiving.
4. The MTSO sends out a ringing signal to the called party. All of these operations (steps 2 through 4) occur within 10 s of initiating the call.
5. When the called party answers, the MTSO establishes a circuit between the two parties and initiates billing information.
6. When one party hangs up, the MTSO releases the circuit, frees the radio channels, and completes the billing information.

AMPS Control Channels

Each AMPS service includes 21 full-duplex 30-kHz control channels, consisting of 21 reverse control channels (RCCs) from subscriber to base station, and 21 **forward channels** from the base station to subscriber. These channels transmit digital data using FSK. In both channels, data are transmitted in frames.

Control information can be transmitted over a voice channel during a conversation. The mobile unit or the base station can insert a burst of data by turning off the voice FM transmission for about 100 ms and replacing it with an FSK-encoded message. These messages are used to exchange urgent messages, such as change power level and handoff.

13.3 SECOND-GENERATION TDMA

This section begins our study of second-generation cellular systems. A large amount of voice traffic is still carried on 2G systems. Data traffic is primarily carried on 3G and 4G systems, and some Voice-over-IP (VoIP) traffic is carried on 3G and 4G systems either by carriers or through user apps. It is important to understand 2G systems, so we begin with an overview and then look in detail at one type of second-generation cellular system.

From First- to Second-Generation Cellular Systems

First-generation cellular networks, such as AMPS, quickly became highly popular, threatening to swamp available capacity even with frequency reuse. Second-generation systems were developed to provide higher-quality signals, higher data rates for support of digital services, and greater capacity. The following are the key differences between the two generations:

- **Digital traffic channels:** The most notable difference between the two generations is that the first-generation systems are almost purely analog, whereas the second-generation systems are digital. In particular, the first-generation systems are designed to support voice channels using FM; digital traffic is supported only by the use of a modem that converts the digital data into analog form. Second-generation systems provide digital traffic channels. These readily support digital data; voice traffic is first encoded in digital form before transmitting. Of course, for second-generation systems, the user traffic (data or digitized voice) must be converted to an analog signal for transmission between the mobile unit and the base station (e.g., see Figure 7.16).
- **Encryption:** Because all of the user traffic, as well as control traffic, is digitized in second-generation systems, it is a relatively simple matter to encrypt all of the traffic to prevent eavesdropping. All second-generation systems provide this capability, whereas first-generation systems send user traffic in the clear, providing no security.
- **Error detection and correction:** The digital traffic stream of second-generation systems also lends itself to the use of error detection and correction techniques, such as those discussed in Chapter 10. The result can be very clear voice reception. Or voice quality comparable to 1G can be provided but at a lower signal-to-noise ratio requirement.
- **Channel access:** In first-generation systems, each cell supports a number of channels. At any given time a channel is allocated to only one user. Second-generation systems also provide multiple channels per cell, but each channel is dynamically shared by a number of users using **time division multiple access (TDMA)** or **code division multiple access (CDMA)**. We look at TDMA-based systems in this section and CDMA-based systems in Section 13.4.

Beginning around 1990, a number of different second-generation systems were deployed. Table 13.3 lists some key characteristics of three of the most important of these systems.

Time Division Multiple Access

First-generation cellular systems provide for the support of multiple users with frequency division multiple access (FDMA). FDMA for cellular systems can be described as follows. Each cell is allocated a total of $2M$ channels of bandwidth δ Hz each. Half the channels (the reverse channels) are used for transmission from the mobile unit to the base station: $f_c, f_c + \delta, f_c + 2\delta, \ldots, f_c + (M - 1)\delta$, where f_c is the center frequency of the lowest-frequency channel. The other half of the channels (the forward channels) are used for transmission from the base station to the mobile unit: $f_c + \Delta, f_c + \delta + \Delta, f_c + 2\delta + \Delta, \ldots, f_c + (M - 1)\delta + \Delta$, where Δ is the spacing between the reverse and forward channels. When a connection is set up for a mobile user, the user is assigned two channels, at f and $f + \Delta$, for full-duplex communication. This arrangement is quite wasteful, because much of the time one or both of the channels are idle.

Table 13.3 Second-Generation Cellular Telephone Systems

	GSM	IS-136	IS-95
Year introduced	1990	1991	1993
Access method	TDMA	TDMA	CDMA
Base station transmission band	935 to 960 MHz	869 to 894 MHz	869 to 894 MHz
Mobile station transmission band	890 to 915 MHz	824 to 849 MHz	824 to 849 MHz
Spacing between forward and reverse channels	45 MHz	45 MHz	45 MHz
Channel bandwidth	200 kHz	30 kHz	1250 kHz
Number of duplex channels	125	832	20
Mobile unit maximum power	20 W	3 W	0.2 W
Users per channel	8	3	35
Modulation	GMSK	$\pi/4$ DQPSK	QPSK
Carrier bit rate	270.8 kbps	48.6 kbps	9.6 kbps
Speech coder	RPE-LTP	VSELP	QCELP
Speech-coding bit rate	13 kbps	8 kbps	8, 4, 2, 1 kbps
Frame size	4.6 ms	40 ms	20 ms
Error control coding	Convolutional 1/2 rate	Convolutional 1/2 rate	Convolutional 1/2 rate forward; 1/3 rate reverse

TDMA for cellular systems can be described as follows. As with FDMA, each cell is allocated a number of channels, half reverse and half forward. Again, for full duplex communication, a mobile unit is assigned capacity on matching reverse and forward channels. In addition, each physical channel is further subdivided into a number of logical channels. Transmission is in the form of a repetitive sequence of frames, each of which is divided into a number of time slots. Each slot position across the sequence of frames forms a separate logical channel.

Global System for Mobile Communications

Before the **Global System for Mobile Communications (GSM)** was developed, the countries of Europe used a number of incompatible first-generation cellular phone technologies. GSM was developed to provide a common second-generation technology for Europe so that the same subscriber units could be used throughout the continent. The technology was extremely successful. GSM first appeared in 1990 in Europe. Similar systems were implemented in North and South America, Asia, North Africa, the Middle East, and Australia. The GSM Association claimed 6.9 billion subscriber identity module (SIM) connections at the end of 2013, an average of 1.8 SIM cards per subscriber.

GSM Network Architecture Figure 13.9 shows the key functional elements in the GSM system. The boundaries at Um, Abis, and A refer to interfaces between

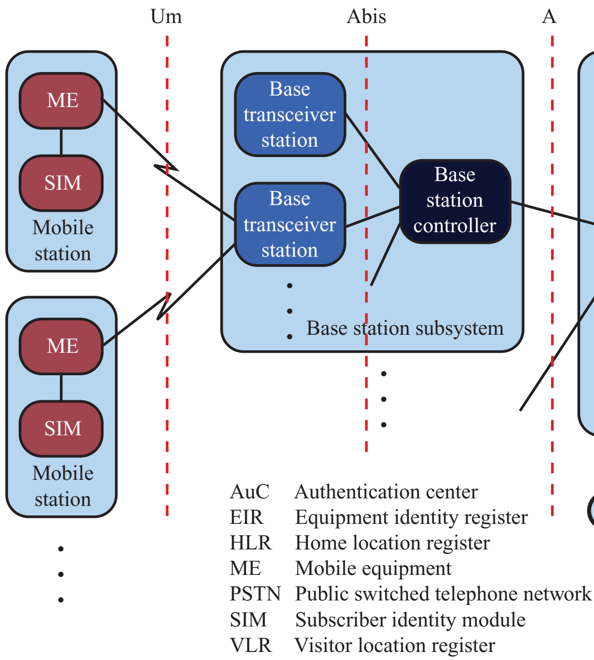


Figure 13.9 Overall GSM Architecture

functional elements that are standardized in the GSM documents. Thus, it is possible to buy equipment from different vendors with the expectation that they will successfully interoperate.

Mobile Station A mobile station communicates across the Um interface, also known as the **air interface**, with a base station transceiver in the same cell in which the mobile unit is located. The **mobile equipment** (ME) refers to the physical terminal, such as a telephone or personal communications service (PCS) device, which includes the radio transceiver, digital signal processors, and the **subscriber identity module**. The SIM is a portable device in the form of a smart card or plug-in module that stores the subscriber's identification number, the networks the subscriber is authorized to use, encryption keys, and other information specific to the subscriber. The GSM subscriber units are totally generic until a SIM is inserted. Therefore, a subscriber need only carry his or her SIM to use a wide variety of subscriber devices in many countries simply by inserting the SIM in the device to be used. In fact, except for certain emergency communications, the subscriber units will not work without a SIM inserted. Thus, the SIMs roam, not necessarily the subscriber devices.

The SIM card approach by itself made GSM very popular in many parts of the world because of ease of traveling and moving to different devices.

Base Station Subsystem A base station subsystem (BSS) consists of a base station controller and one or more base transceiver stations. Each **base transceiver station (BTS)** defines a single cell; it includes a radio antenna, a radio transceiver, and a link to a base station controller. A GSM cell can have a radius of between 100 m and 35 km, depending on the environment. A **base station controller (BSC)** may be collocated with a BTS or may control multiple BTS units and hence multiple cells. The BSC reserves radio frequencies, manages the handoff of a mobile unit from one cell to another within the BSS, and controls paging.

Network Subsystem The network subsystem (NS) provides the link between the cellular network and the public switched telecommunications networks. The NS controls handoffs between cells in different BSSs, authenticates users and validates their accounts, and includes functions for enabling worldwide roaming of mobile users. The central element of the NS is the **mobile switching center** (MSC). It is supported by four databases that it controls:

- **Home location register (HLR) database:** The HLR stores information, both permanent and temporary, about each of the subscribers that "belongs" to it (i.e., for which the subscriber has its telephone number associated with the switching center).
- **Visitor location register (VLR) database:** One important, temporary piece of information is the location of the subscriber. The location is determined by the VLR into which the subscriber is entered. The visitor location register maintains information about subscribers that are currently physically in the region covered by the switching center. It records whether or not the subscriber is active and other parameters associated with the subscriber. For a call coming to the subscriber, the system uses the telephone number associated with the subscriber to identify the home switching center of the subscriber. This switching center can find in its HLR the switching center in which the subscriber is currently physically located. For a call coming from the subscriber, the VLR is used to initiate the call. Even if the subscriber is in the area covered by its home switching center, it is also represented in the switching center's VLR, for consistency.
- **Authentication center database (AuC):** This database is used for authentication activities of the system; for example, it holds the authentication and encryption keys for all the subscribers in both the home and visitor location registers. The center controls access to user data as well as being used for authentication when a subscriber joins a network. GSM transmission is encrypted, so it is private. A stream cipher, A5, is used to encrypt the transmission from the subscriber to the base transceiver. However, the conversation is in the clear in the landline network. Another cipher, A3, is used for authentication.
- **Equipment identity register database (EIR):** The EIR keeps track of the type of equipment that exists at the mobile station. It also plays a role in security (e.g., blocking calls from stolen mobile stations and preventing use of the network by stations that have not been approved).

Radio Link Aspects

The GSM spectral allocation is 25 MHz for base transmission (935–960 MHz) and 25 MHz for mobile transmission (890–915 MHz). Other GSM bands have also been defined outside Europe. Users access the network using a combination of FDMA and TDMA (both are discussed in the next section). There are radio-frequency carriers every 200 kHz, which provide for 125 full-duplex channels. The channels are modulated at a data rate of 270.833 kbps. As with AMPS, there are two types of channels: traffic and control.

TDMA Format GSM uses a complex hierarchy of TDMA frames to define logical channels. Fundamentally, each 200-kHz frequency band is divided into eight logical channels defined by the repetitive occurrence of time slots.

At the lowest level is the time slot, also called a burst period, which has a duration of 15/26 ms, or approximately 0.577 ms. With a bit rate of 270.833 kbps, each time slot has a length of 156.25 bits.

Moving up the frame format hierarchy, 8-slot TDMA frames are typically organized into a 26-frame multiframe. One of the frames in the multiframe is used for control signaling and another is currently unused, leaving 24 frames for data traffic. Thus, each traffic channel receives one slot per frame and 24 frames per 120-ms multiframe. The resulting gross data rate is

$$\frac{114\,\text{bits/slot} \times 24\ \text{slots/multiframe}}{120\,\text{ms/multiframe}} = 22.8\ \text{kbps}$$

The GSM specification also allows half-rate traffic channels, with two traffic channels each occupying one time slot in 12 of the 26 frames. With the use of half-rate speech coders, this effectively doubles the capacity of the system. There is also a 51-frame multiframe used for control traffic.

GPRS and Edge Phase 2 of GSM introduced the **Generalized Packet Radio Service (GPRS)**, which provides a datagram switching capability to GSM. Previously, sending data traffic required opening a voice connection, sending data, and closing a connection. GPRS allows users to open a persistent data connection. It also establishes a system architecture for carrying the data traffic. GPRS has different error control coding schemes, and the scheme with the highest throughput (no error control coding, just protocol overheads) produces 21.4 kbps from the 22.8 kbps gross data rate. GPRS can combine up to 8 GSM connections; so overall throughputs of up to 171.2 kbps can be achieved.

The next generation of GSM included **Enhanced Data Rates for GSM Evolution (EDGE)**. EDGE introduced coherent 8-PSK modulation, which creates a threefold increase in data rate up to 3 bits/symbol for 8-PSK from 1 bit/symbol for GMSK for GSM. This increased the gross max data rates per channel, depending on channel conditions, up to $22.8 \times 3 = 68.4$ kbps (including overhead from the protocol headers). Using all eight channels in a 200-kHz carrier, gross data transmission rates up to 547.2 kbps became possible. Actual throughput can be up to 513.6 kbps. A later release of EDGE, 3GPP Release 7, added even higher-order modulation and coding schemes that adapt to channel conditions. Downlink data rates over 750 kbps and uplink data rates over 600 kbps can be achieved in excellent channel conditions.

GSM Signaling Protocol Architecture A number of control messages are exchanged between the key entities that deal with mobility, radio resources, and connection management. The lowest layer of the architecture is tailored to the physical link between entities. At the link layer, a data link control protocol (see Figure 4.3) known as LAPDm is used. This is a modified version of the Link Access Protocol, D channel (LAPD) protocol designed to convert a potentially unreliable physical link into a reliable data link. Above the link layer are a number of protocols that provide specific functions. These include radio resource management, mobility management, connection management, mobile application part, and BTS management.

13.4 SECOND-GENERATION CDMA

CDMA is a spread spectrum–based technique for multiplexing, introduced in Section 9.4, that provides an alternative to TDMA for second-generation cellular networks. We begin this section with an overview of the advantages of the CDMA approach and then look at the most widely used scheme, IS-95.

Code Division Multiple Access

CDMA for cellular systems can be described as follows. As with FDMA, each cell is allocated a frequency bandwidth, which is split into two parts, half for reverse (mobile unit to base station) and half for forward (base station to mobile unit). For full duplex communication, a mobile unit uses both reverse and forward channels. Transmission is in the form of direct-sequence spread spectrum (DSSS), which uses a chipping code to increase the data rate of the transmission, resulting in an increased signal bandwidth. Multiple access is provided by assigning orthogonal chipping codes to multiple users, so that the receiver can recover the transmission of an individual unit from multiple transmissions.

CDMA has a number of advantages for a cellular network over TDMA:

- **Frequency diversity:** Because the transmission is spread out over a larger bandwidth, frequency-dependent transmission impairments, such as noise bursts and selective fading, have less effect on the signal.
- **Multipath resistance:** In addition to the ability of DSSS to overcome multipath fading by frequency diversity, the chipping codes used for CDMA not only exhibit low cross correlation but also low autocorrelation. Therefore, a version of the signal that is delayed by more than one chip interval does not interfere with the dominant signal as much as in other multipath environments.
- **Privacy:** Because spread spectrum is obtained by the use of noise-like signals, where each user has a unique code, privacy is inherent.
- **Graceful degradation:** With FDMA or TDMA, a fixed number of users can access the system simultaneously. However, with CDMA, as more users access the system simultaneously, the noise level and hence the error rate increases; only gradually does the system degrade to the point of an unacceptable error rate.

A number of drawbacks of CDMA cellular should also be mentioned:

- **Self-jamming:** Unless all of the mobile users are perfectly synchronized, the arriving transmissions from multiple users will not be perfectly aligned on chip boundaries. Thus the spreading sequences of the different users are not orthogonal and there is some level of cross correlation. This is distinct from either TDMA or FDMA, in which for reasonable time or frequency guardbands, respectively, the received signals are orthogonal or nearly so.

- **Near-far problem:** Signals closer to the receiver are received with less attenuation than signals farther away. Given the lack of complete orthogonality, the transmissions from the more remote mobile units may be more difficult to recover. Thus, power control techniques are very important in a CDMA system.
- **Soft handoff:** As is discussed subsequently, a smooth handoff from one cell to the next requires that the mobile unit acquires the new cell before it relinquishes the old. This is referred to as a soft handoff and is more complex than the hard handoff used in FDMA and TDMA schemes.

Mobile Wireless CDMA Design Considerations

Before turning to the specific example of IS-95, it will be useful to consider some general design elements of a CDMA cellular system.

Rake Receiver In a multipath environment, which is common in cellular systems, if the multiple versions of a signal arrive more than one chip interval apart from each other, the receiver can recover the signal by correlating the chip sequence with the dominant incoming signal.This principle is used in the RAKE receiver and is discussed in Section 9.4.

Soft Handoff In an FDMA or TDMA system, neighboring cells use different portions of the available frequency spectrum (i.e., the frequency reuse factor N is greater than 1, typically 7). When the signal strength of a neighboring cell exceeds that of the current cell, plus a threshold, the mobile station is instructed to switch to a new frequency band that is within the allocation of the new cell. This is referred to as a hard handoff. In a typical CDMA cellular system, spatial separation of frequencies is not used (i.e., no frequency allocations like in Figure 13.2, frequency reuse factor $N = 1$), because most of the time the interference from neighboring cells will not prohibit correct reception of a DSSS signal.

For CDMA systems, soft handoff is more feasible. In soft handoff, a mobile station is temporarily connected to more than one base station simultaneously. It sends its packets to both base stations, using different spreading codes, and it receives packets from multiple base stations with the respective spreading codes. Since separate frequencies are not used in CDMA, soft handoff is simply a matter of using different codes for each base station instead of separate frequencies.

IS-95

The most widely used second-generation CDMA scheme is **IS-95**, which is primarily deployed in North America. Table 13.3 lists some key parameters of the IS-95 system. The transmission structures on the forward and reverse links differ and are described separately.

IS-95 Forward Link Table 13.4 lists forward link channel parameters. The forward link consists of up to 64 logical CDMA channels, each occupying the

Table 13.4 IS-95 Forward Link Channel Parameters

Channel	**Sync**	**Paging**		**Traffic Rate Set 1**				**Traffic Rate Set 2**			
Data rate (bps)	1200	4800	9600	1200	2400	4800	9600	1800	3600	7200	14400
Code repetition	2	2	1	8	4	2	1	8	4	2	1
Modulation symbol rate (sps)	4800	19,200	19,200	19,200	19,200	19,200	19,200	19,200	19,200	19,200	19,200
PN chips/ modulation symbol	256	64	64	64	64	64	64	64	64	64	64
PN chips/bit	1024	256	128	1024	512	256	128	682.67	341.33	170.67	85.33

same 1228-kHz bandwidth (Figure 13.10a). The forward link supports four types of channels:

- **Pilot (channel 0):** A continuous signal on a single channel. This channel allows the mobile unit to acquire timing information, provides phase reference for the demodulation process, and provides a means for signal strength comparison for the purpose of handoff determination. The pilot channel consists of all zeros.

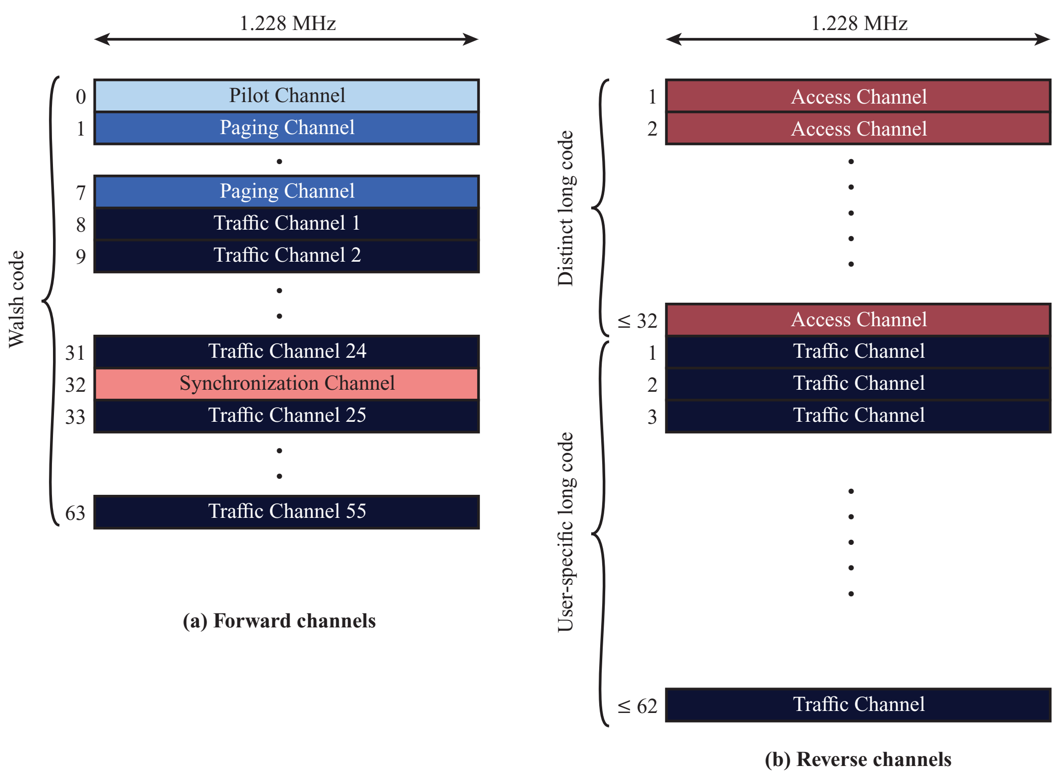


Figure 13.10 IS-95 Channel Structure

Table 13.5 IS-95 Reverse Link Channel Parameters

Channel	Access	Traffic Rate Set 1				Traffic Rate Set 2			
Data rate (bps)	4800	1200	2400	4800	9600	1800	3600	7200	14400
Code rate	1/3	1/3	1/3	1/3	1/3	1/2	1/2	1/2	1/2
Symbol rate before repetition (sps)	14,400	3600	7200	14,400	28,800	3600	7200	14,400	28,800
Symbol repetition	2	8	4	2	1	8	4	2	1
Symbol rate after repetition (sps)	28,800	28,800	28,800	28,800	28,800	28,800	28,800	28,800	28,800
Transmit duty cycle	1	1/8	1/4	1/2	1	1/8	1/4	1/2	1
Code symbols/ modulation symbol	6	6	6	6	6	6	6	6	6
PN chips/ modulation symbol	256	256	256	256	256	256	256	256	256
PN chips/bit	256	128	128	128	128	256/3	256/3	256/3	256/3

- **Synchronization (channel 32):** A 1200-bps channel used by the mobile station to obtain identification information about the cellular system (system time, long code state, protocol revision, etc.).
- **Paging (channels 1 to 7):** Contain messages for one or more mobile stations.
- **Traffic (channels 8 to 31 and 33 to 63):** The forward channel supports 55 traffic channels. The original specification supported data rates of up to 9600 bps. A subsequent revision added a second set of rates up to 14,400 bps.

Note that all of these channels use the same bandwidth. The chipping code is used to distinguish among the different channels.

IS-95 Reverse Link Table 13.5 lists reverse link channel parameters. The reverse link consists of up to 94 logical CDMA channels, each occupying the same 1228-kHz bandwidth (Figure 13.10b). The reverse link supports up to 32 access channels and up to 62 traffic channels.

The traffic channels in the reverse link are unique to each mobile unit. Each mobile unit has a unique long code mask based on its electronic serial number. The long code mask is a 42-bit number, so there are $2^{42} - 1$ different masks. The access channel is used by a mobile unit to initiate a call, to respond to a paging channel message from the base station, and for a location update.

13.5 THIRD-GENERATION SYSTEMS

The objective of the third generation of wireless communication is to provide fairly high-speed wireless communications to support multimedia, data, and video in addition to voice. The ITU's International Mobile Telecommunications for the year 2000 (IMT-2000) initiative has defined the ITU's view of third-generation capabilities as

- Voice quality comparable to the public switched telephone network.
- 144 kbps data rate available to users in high-speed motor vehicles over large areas.
- 384 kbps available to pedestrians standing or moving slowly over small areas.
- Support (to be phased in) for 2.048 Mbps for office use.
- Symmetrical and asymmetrical data transmission rates.
- Support for both packet-switched and circuit-switched data services.
- An adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic.
- More efficient use of the available spectrum in general.
- Support for a wide variety of mobile equipment.
- Flexibility to allow the introduction of new services and technologies.

More generally, one of the driving forces was the trend toward universal personal telecommunications and universal communications access. The first concept refers to the ability of a person to identify himself or herself easily and use conveniently any communication system in an entire country, over a continent, or even globally, in terms of a single account. The second refers to the capability of using one's terminal in a wide variety of environments to connect to information services (e.g., to have a portable terminal that will work in the office, on the street, and on airplanes equally well). This revolution in personal computing obviously involves wireless communication in a fundamental way. The GSM cellular telephony with its subscriber identity module, for example, is a large step toward these goals.

Personal communications services and personal communication networks (PCNs) are names attached to these concepts of global wireless communications, and they also formed objectives for third-generation wireless systems.

Both competing standards for 3G technology use code division multiple access to provide efficient use of the spectrum and high capacity.

Alternative Interfaces

Figure 13.11 shows the alternative schemes that were adopted as part of IMT-2000. The specification covers a set of radio interfaces for optimized performance in different radio environments. A major reason for the inclusion of five alternatives was to enable a smooth evolution from existing first- and second-generation systems.

The five alternatives reflect the evolution from the second-generation systems. Two of the specifications grow out of the work at the European Telecommunications Standards Institute (ETSI) to develop a **Universal Mobile Telecommunications System (UMTS)** as Europe's 3G wireless standard. UMTS includes two standards. One of these is known as **Wideband CDMA (WCDMA)**, for the air interface technology of UMTS. This scheme fully exploits CDMA technology to provide high data rates with efficient use of bandwidth. The other European effort under UMTS was known as IMT-TC, or TD-CDMA. This approach was a combination of WCDMA and TDMA technology. IMT-TC is intended to provide an upgrade path for the TDMA-based GSM systems.

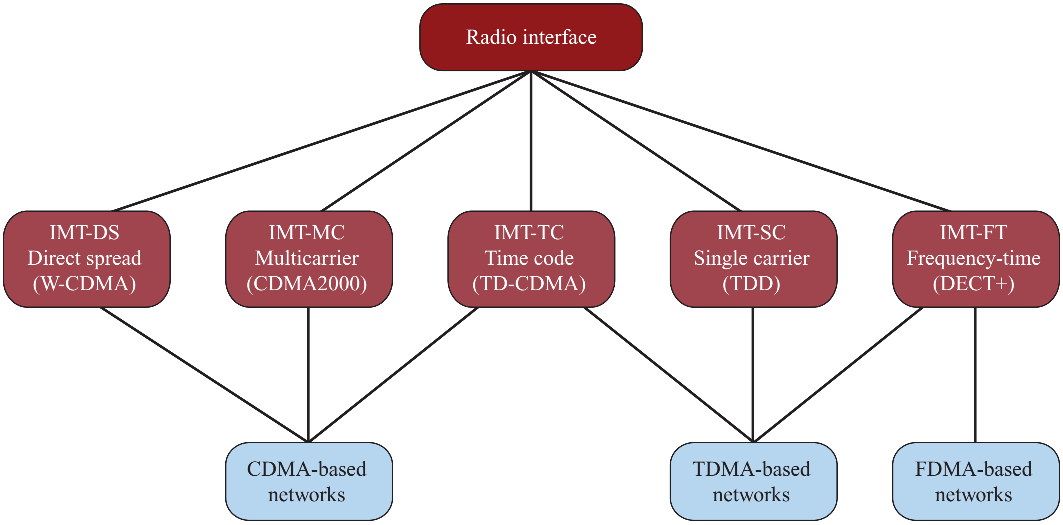


Figure 13.11 IMT-2000 Terrestrial Radio Interfaces

Another CDMA-based system, known as **CDMA2000**, has a North American origin. This scheme is similar to, but incompatible with, WCDMA, in part because the standards use different chip rates. Also, CDMA2000 uses a technique known as multicarrier, not used with WCDMA.

Two other interface specifications are shown in Figure 13.11. IMT-SC is primarily designed for TDMA-only networks. IMT-TC can be used by both TDMA and FDMA carriers to provide some 3G services; it is an outgrowth of the Digital European Cordless Telecommunications (DECT) standard.

In the remainder of this section, we present some general considerations for CDMA technology for 3G systems and then provide an overview of the UMTS/WCDMA and 1xEV-DO 3G systems.

CDMA Design Considerations

The dominant technology for 3G systems is CDMA. Although different CDMA schemes have been adopted, they share some common design issues as follows:

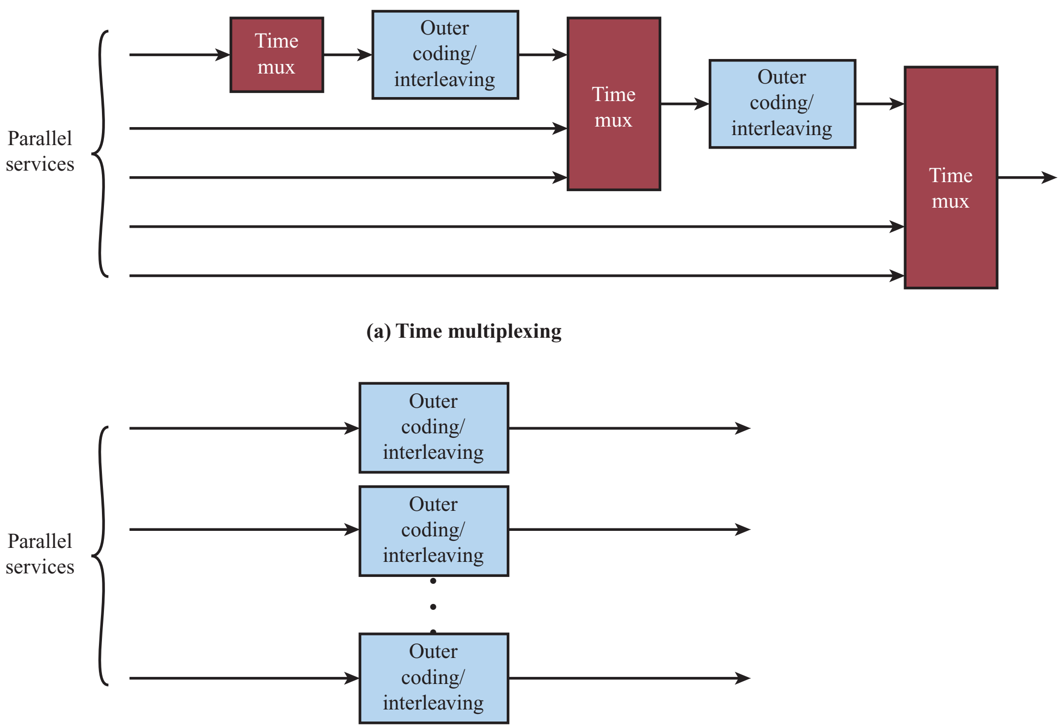
- **Bandwidth:** An important design goal for all 3G systems is to limit channel usage to 5 MHz. There are several reasons for this goal. On the one hand, a bandwidth of 5 MHz or more improves the receiver's ability to resolve multipath when compared to narrower bandwidths. On the other hand, available spectrum is limited by competing needs, and 5 MHz is a reasonable upper limit on what can be allocated for 3G.
- **Chip rate:** Given the bandwidth, the chip rate depends on desired data rate, the need for error control, and bandwidth limitations. A chip rate of 3 Mcps (mega-chips per second) or more is reasonable given these design parameters.
- **Multirate:** The term *multirate* refers to the provision of multiple fixed-data-rate logical channels to a given user, in which different data rates are provided

on different logical channels. Further, the traffic on each logical channel can be switched independently through the wireless and fixed networks to different destinations. The advantage of multirate is that the system can flexibly support multiple simultaneous applications from a given user and can efficiently use available capacity by only providing the capacity required for each service. Multirate can be achieved with a TDMA scheme within a single CDMA channel, in which a different number of slots per frame are assigned to achieve different data rates. All the subchannels at a given data rate would be protected by error correction and interleaving techniques (Figure 13.12a). An alternative is to use multiple CDMA codes, with separate coding and interleaving, and map them to separate CDMA channels (Figure 13.12b).

3G Systems

Figure 13.13 shows the evolution of wireless cellular systems. 3G systems were the first to provide megabit per second data rates and went through several upgrades. **Long-Term Evolution (LTE)** 4G systems using LTE-Advanced (the original LTE did not meet 4G requirements) provide greater data rates and more flexible quality of service (QoS) capabilities.

Two 3G standards become prominent: UMTS/WCDMA and CDMA2000.



(a) Time multiplexing

(b) Code multiplexing

Figure 13.12 Time and Code Multiplexing Principles

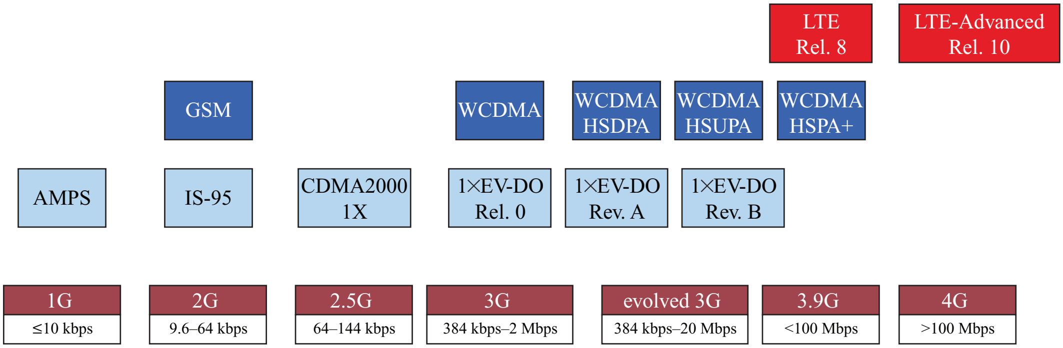


Figure 13.13 Evolution of Cellular Wireless Systems

Wideband CDMA and UMTS WCDMA is part of a group of standards from IMT-2000, UMTS, and also the **Third-Generation Partnership Project (3GPP)** industry organization. The 3GPP, which had previously released standards for GSM, released an original set of specifications known as "Release 99" in 1999 for WCDMA and UMTS. Its subsequent releases were labeled "Release 4" onwards. Many of the higher-layer core network functions of GSM were carried over from GSM to WCDMA; it was primarily the radio access technology that was changed.

WCDMA supports maximal data rates based on the speed of mobility of the user. At least 144 kbps is supported for speeds up to 500 km/h, 384 kbps for up to 120 km/h, and up to 2 Mbps for speeds up to 10 km/h using picocells. In most of the world, this is supported in frequencies from 1900 to 2025 MHz. 3GPP Release 5 introduced **High-Speed Downlink Packet Access (HSDPA)**, which improved downlink speeds to a range from 1.8 to 14.4 Mbps. HSDPA uses adaptive modulation and coding, hybrid ARQ, and fast scheduling. Release 6 then provided **High-Speed Uplink Packet Access (HSUPA)**, which increased uplink rates up to 5.76 Mbps.

High-Speed Packet Access Plus (HSPA+) was provided in Release 7 and successively improved through Release 11. Maximum data rates increased from 21 Mbps up to 336 Mbps by adding features such as 64 QAM, 2×2 and 4×4 MIMO, and dual or multicarrier combinations.

3GPP Release 8 specifications introduced LTE as a pathway to 4G. Releases 8 onward provided specifications for LTE, but also upgrades to HSPA+.For LTE, we discuss Release 8 and later 3GPP releases in Chapter 14.

CDMA2000 and EV-DO The CDMA2000 technology family first produced **CDMA2000 1xRTT** (radio transmission technology), where the name indicates that the technology operates using 1x (1 times) the 1.2288 Mcps spreading rate of a standard 1.25 MHz IS-95 CDMA channel (as opposed to the potential 3xRTT label for which the technology was never developed). Its intent was to offer near-broadband packet data speeds for wireless access to the Internet. The rates were not consistent with 3G objectives, so 1xRTT was considered a "2.5G" technology (as many also considered GPRS and EDGE).

The next step was to provide evolution of the air interface to the **Evolution-Data Only** format, **1xEV-DO**, and data/voice format, 1xEV-DV. The EV signifies that it is an evolutionary technology built on the IS-95 standard. The 1xEV-DV technology never succeeded, but 1xEV-DO was successfully deployed to provide 2.4 Mbps downlink and 153 kbps uplink data rates under the label **1xEV-DO Release 0**. These data rates are achieved using a bandwidth of only 1.25 MHz, one-quarter of the 5 MHz required for WCDMA.

1xEV-DO Revision A was approved four years later with improved maximum rates of 3.1 Mbps downlink and 1.8 Mbps uplink. Release A also supported quality of service for VoIP and advanced broadband applications. **1xEV-DO Revision B** implemented a multicarrier capability to expand from the previous 1.25 MHz to 5 MHz bandwidth, resulting in downlink and uplink rates of 14.7 Mbps and 5.4 Mbps, respectively.

What differentiates the EV-DO scheme from other 3G technologies is that it is designed for data only (DO) and is geared toward the use of IP for packet transmission and for Internet access. However, with VoIP technology, CDMA2000 1xEV-DO can support voice traffic.

This illustrates the benefits that can be provided from a data-only design. The 1xEV-DO design focuses on integration with IP-based networks. As a result, some vendors have built 1xEV-DO networks based entirely on IP technologies. Figure 13.14 shows the main elements in such an arrangement. Mobile users communicate with a base station in a nearby cell using the 1xEV-DO transmission scheme. Typically, the base station controller for a number of base stations is located in a central office to provide switching, handoff, and other services. An IP transport service is used to connect the base station to the central office. Using IP transport lowers connection costs by giving operators a choice of connection services, including frame relay, asynchronous transfer mode (ATM), broadband wireless links, and digitial

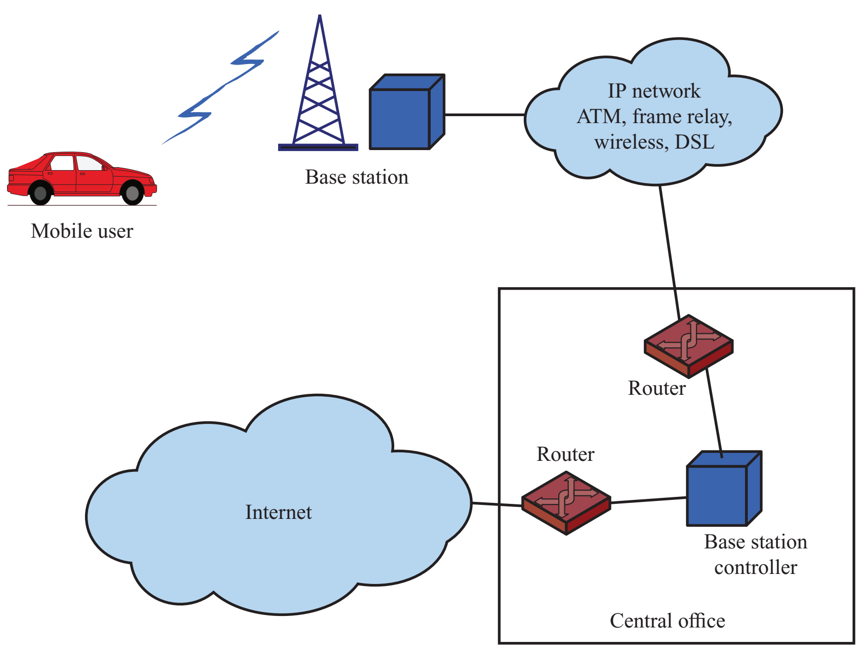


Figure 13.14 CDMA2000 1xEV-DO Configuration Elements

subscriber line (DSL). At the central office, the base station controller can route a call back out the IP network to another cellular subscriber or out over the Internet.

Because 1xEV-DO is specified as data-only, the transmission scheme can be optimized for data transfer and need not support voice requirements. Voice communications impose restrictions that inhibit efficient use of bandwidth. For example, a delay of 100 ms makes voice communication difficult. Longer delays make useful voice communication impractical. For this reason, voice frames are short, typically on the order of 20 ms, in order to minimize delays. But the use of short frames increases overhead, resulting in reduced efficiency since the headers have a large size relative to the data. In a data-only network, longer average delays can be tolerated, and QoS facilities can be used to accommodate a fraction of transmissions that require tight delay values. Accordingly, a data-only network can use longer frames, reducing overhead.

Another advantage to the longer frame is that it results in more efficient use of turbo codes (see Section 10.3). Whereas convolutional coding is well suited to the short voice frames, turbo coding is more powerful when frames are long (several hundred bits or more). Turbo coding with large frame sizes significantly improves performance by allowing the use of lower RF power while still achieving the same error rate.

In a typical data-only application, the amount of traffic from the network to the user significantly exceeds user-to-network traffic. Such applications include Web browsing and downloading e-mail. To optimize throughput and make the best use of the available bandwidth, 1xEV-DO sends and receives at different data rates.

A major difference in a data-only design as compared to a voice-optimized design is the technique used to maintain continuous communication in a noisy and variable RF environment. Voice-optimized systems use power control: users with weak signals increase their transmitting RF power to overcome path loss and/or fading while users close to the base station reduce power. In contrast, 1xEV-DO alters the data rate rather than the power when signal levels change. This is done in both directions (forward and reverse channels).

Let us consider the forward channel first. The base station always sends at full power, to assure that the mobile unit achieves the highest possible received SNR. If path loss increases, the resulting reduction in SNR yields a lower effective link capacity (using Shannon's formula) or, put another way, a higher error rate. The errors are reduced not by increasing RF power but by reducing the data rate. The data rate is reduced by increasing redundancy and altering the modulation method. Increasing the number of check bits reduces the effective rate of actual data since more bits are used for coding. Use of lower-order modulation methods (e.g., 16-QAM versus QPSK) lowers the data rate by improving the error performance. Table 13.6 shows some of the forward channel data rates for 1xEV-DO Revision B. Lower data rates increase the number of 1.67-ms time slots used, or change the code rate or modulation scheme. When using more time slots, the additional time slots provide redundant information. If the mobile unit can successfully decode a packet before all slots are sent, it sends an acknowledgment to the base station. This causes an early termination of the transmission, increasing effective throughput. The mobile unit provides continuous information about SNR conditions so that the base station can adjust its data rate.

Table 13.7 shows the data rates for the reverse channel. Because of the limited signal power on the reverse channel and poorer channel conditions when the signal

Table 13.6 CDMA2000 1xEV-DO Revision B Per-carrier Link Parameters: Forward Link[1]

Data rate (kbps)	Number of slots	Packet size (bytes)	Packet duration (ms)	Code rate	Modulation
38.4	16	128	26.67	1/5	QPSK
76.8	8	128	13.33	1/5	QPSK
153.6	4	128	6.67	1/5	QPSK
307.2	2	128	3.33	1/5	QPSK
614.4	2	256	3.33	1/3	QPSK
921.6	2	384	3.33	1/3	8PSK
1228.8	2	512	3.33	1/3	16QAM
1843.2	1	384	1.67	1/3	8 PSK
2457.6	1	512	1.67	1/3	16QAM
3686.4[2]	1	768	1.67	1/3	64QAM
4300.8[2]	1	896	1.67	1/3	64QAM
4915.2[2]	1	1024	1.67	1/3	64QAM

[1]Not a comprehensive list of all standardized options
[2]Optional

Table 13.7 CDMA2000 1xEV-DO Revision B Per-carrier Link Parameters: Reverse Link

Data rate (kbps)	Number of slots	Packet size (bytes)	Packet duration (ms)	Effective Code rate	Modulation
4.8	16	16	26.67	1/5	BPSK
9.6	16	32	26.67	1/5	BPSK
19.2	16	64	26.67	1/5	BPSK
28.8	16	96	26.67	1/5	BPSK
38.4	16	128	26.67	1/5	BPSK
57.6	16	192	26.67	1/5	QPSK
76.8	16	256	26.67	1/5	QPSK
115.2	16	384	26.67	1/5	QPSK
153.6	16	512	26.67	1/5	QPSK
230.4	16	768	26.67	1/5	QPSK
307.2	16	1024	26.67	1/5	QPSK
460.8	16	1536	26.67	1/3	8 PSK

is transmitted (since the antenna is much closer to the ground), only lower-order modulation schemes are used, which are less affected by RF channel conditions than more complex modulation schemes.

13.6 RECOMMENDED READING

[POLL96] covers the handoff problem in depth. [EVER94] and [ORLI98] provide good accounts of cellular traffic analysis. [BLAC99] is one of the best technical treatments of second-generation cellular systems. A good survey of GSM concepts is [RAHN93]; for more detail see [GARG99].

[OJAN98] provides an overview of key technical design considerations for 3G systems. Another useful survey is [ZENG00]. [PRAS00] is a much more detailed analysis. For a discussion of CDMA2000 1xEV-DO, see [BI03]. [BHUS06] and [ATTA06] provide good discussions of 1xEV-DO Revisions A and B.

ATTA06 Attar, R., et al. "Evolution of CDMA2000 Cellular Networks: Multicarrier EV-DO." *Communications Magazine, IEEE,* vol. 44, no. 3, pp. 46, 53, March 2006.

BHUS06 Bhushan, N., et al. "CDMA2000 1×EV-DO Revision a: A Physical Layer and MAC Layer Overview." *Communications Magazine, IEEE,* vol. 44, no. 2, pp. 37, 49, February 2006.

BI03 Bi, Q., et al. "Performance of 1xEV-DO Third-Generation Wireless High-Speed Data Systems." *Bell Labs Technical Journal,* vol. 7, no. 3, 2003.

BLAC99 Black, U. *Second-Generation Mobile and Wireless Networks.* Upper Saddle River, NJ: Prentice Hall, 1999.

EVER94 Everitt, D. "Traffic Engineering of the Radio Interface for Cellular Mobile Networks." *Proceedings of the IEEE,* September 1994.

GARG99 Garg, V., and Wilkes, J. *Principles and Applications of GSM.* Upper Saddle River, NJ: Prentice Hall, 1999.

OJAN98 Ojanpera, T., and Prasad, G. "An Overview of Air Interface Multiple Access for IMT-2000/UMTS." *IEEE Communications Magazine,* September 1998.

ORLI98 Orlik, P., and Rappaport, S. "Traffic Performance and Mobility Modeling of Cellular Communications with Mixed Platforms and Highly Variable Mobilities." *Proceedings of the IEEE,* July 1998.

POLL96 Pollini, G. "Trends in Handover Design." *IEEE Communications Magazine,* March 1996.

PRAS00 Prasad, R.; Mohr, W.; and Konhauser, W., eds. *Third-Generation Mobile Communication Systems.* Boston: Artech House, 2000.

RAHN93 Rahnema, M. "Overview of the GSM System and Protocol Architecture." *IEEE Communications Magazine,* April 1993.

ZENG00 Zeng, M.; Annamalai, A.; and Bhargava, V. "Harmonization of Global Third-Generation Mobile Systems." *IEEE Communications Magazine,* December 2000.

13.7 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

1xRTT	forward channel	picocells
1xEV-DO Release 0	frequency reuse	power control
1xEV-DO Revision A	Generalized Packet Radio Service (GPRS)	reuse factor
1xEV-DO Revision B	Global System for Mobile Communications (GSM)	reverse channel
Advanced Mobile Phone Service (AMPS)	handoff	second-generation (2G) network
base station	handover	self-organizing networks
CDMA2000	hard handoff	soft handoff
cell sectoring	High-Speed Downlink Packet Access (HSDPA)	third-generation (3G) network
cellular network	High-Speed Packet Access Plus (HSPA+)	Third-Generation Partnership Project (3GPP)
closed-loop power control	High-Speed Uplink Packet Access (HSDPA)	time division multiple access (TDMA)
closed subscriber group	IS-95	traffic channels
code division multiple access (CDMA)	inter-cell interference coordination (ICIC)	traffic intensity
control channels	macrocells	Universal Mobile Telecommunications System (UMTS)
coordinated multipoint transmission (CoMP)	mobile radio	Wideband CDMA (WCDMA)
Enhanced Data Rates for GSM Evolution (EDGE)	network densification	
Erlang	open-loop power control	
femtocells		
first-generation (1G) network		

Review Questions

13.1 What geometric shape is used in cellular system design?

13.2 What is the principle of frequency reuse in the context of a cellular network?

13.3 List five ways of increasing the capacity of a cellular system.

13.4 Explain the paging function of a cellular system.

13.5 List and briefly define different performance metrics that may be used to make the handoff decision.

13.6 As a mobile unit in communication with a base station moves, what factors determine the need for power control and the amount of power adjustment?

13.7 Explain the difference between open-loop and closed-loop power control.

13.8 What is the difference between traffic intensity and the mean rate of calls in a system?

13.9 What are the key differences between first- and second-generation cellular systems?

13.10 What are the advantages of using CDMA for a cellular network?

13.11 What are the disadvantages of using CDMA for a cellular network?

13.12 Explain the difference between hard and soft handoff.

13.13 What are some key characteristics that distinguish third-generation cellular systems from second-generation cellular systems?

13.14 What are the two predominant families of third-generation cellular systems?

13.15 What are the names of the technologies associated with third-generation systems? With which family of standards are each associated?

Problems

13.1 Consider four different cellular systems that share the following characteristics. The frequency bands are 825 to 845 MHz for mobile unit transmission and 870 to 890 MHz for base station transmission. A duplex circuit consists of one 30-kHz channel in each direction. The systems are distinguished by the reuse factor, which is 4, 7, 12, and 19, respectively.

a. Suppose that in each of the systems, the cluster of cells (4, 7, 12, 19) is duplicated 16 times. Find the number of simultaneous communications that can be supported by each system.
b. Find the number of simultaneous communications that can be supported by a single cell in each system.
c. What is the area covered, in cells, by each system?
d. Suppose the cell size is the same in all four systems and a fixed area of 100 cells is covered by each system. Find the number of simultaneous communications that can be supported by each system.

13.2 A cellular system is composed of both macrocells and femtocells. There are a total of 200 voice channels available. Suppose a network engineer decided to implement frequency reuse by using a fixed partition of frequencies, some to the macrocells and the rest to femtocells. Macrocells use cluster sizes of 4 and 3 sectors per cell. Femtocells use cluster sizes of 1 and no sectoring; this assumes femtocells do not interfere with neighboring femtocells.

a. If 20 channels are assigned to each femtocell, how many channels (both macrocell and femtocell channels) are potentially available to a mobile at every location?
b. From part a, if there are 20 macrocells and 20 femtocells in the area, what is the total system capacity?
c. From part a, if the femtocells are assigned to closed subscriber groups, how many channels are available to those who are not in the closed subscriber groups?
d. Instead of the results from part a, how should the channels be distributed if at least 68 channels should be available to a mobile in a femtocell?

13.3 Describe a sequence of events similar to that of Figure 13.6 for

a. a call from a mobile unit to a fixed subscriber.
b. a call from a fixed subscriber to a mobile unit.

13.4 In the discussion of the handoff procedure based on relative signal strength with threshold, it was pointed out that if the threshold is set quite low, such as Th_3, the mobile unit may move far into the new cell (L_4). This reduces the quality of the communication link and may result in a dropped call. Can you suggest another drawback of this scheme?

13.5 Hysteresis is a technique commonly used in control systems. As an example, describe the hysteresis mechanism used in a household thermostat.

13.6 A telephony connection has a duration of 23 minutes. This is the only connection made by this caller during the course of an hour. How much is the amount of traffic, in Erlangs, of this connection?

13.7 Using Table 13.1, approximate the answers to the following. Also, in each case, give a description in words of the general problem being solved. *Hint:* straight-line interpolation is adequate.

a. Given $N = 20$, $A = 10.5$, find P.
b. Given $N = 20$, $P = 0.015$, find A.
c. Given $P = 0.005$, $A = 6$, find N.

13.8 An analog cellular system has a total of 33 MHz of bandwidth and uses two 25-kHz simplex (one-way) channels to provide full duplex voice and control channels.

a. What is the number of channels available per cell for a frequency reuse factor of (1) 4 cells, (2) 7 cells, and (3) 12 cells?
b. Assume that 1 MHz is dedicated to control channels but that only one control channel is needed per cell. Determine a reasonable distribution of control channels and voice channels in each cell for the three frequency reuse factors of part (a).

13.9 As was mentioned, the one-way bandwidth available to a single operator in the AMPS system is 12.5 MHz with a channel bandwidth of 30 kHz and 21 control channels. We would like to calculate the efficiency with which this system utilizes bandwidth for a particular installation. Use the following parameters:

- Cell area $= 8$ km^2
- Total coverage area $= 4000$ km^2
- Frequency reuse factor $= 7$
- Average number of calls per user during the busy hour $= 1.2$
- Average holding time of a call $= 100$ s
- Call blocking probability $= 2\%$

a. How many voice channels are there per cell?
b. Use Table 13.1 and a simple straight-line interpolation to determine the total traffic carried per cell, in Erlangs/cell. Then convert that to Erlangs/km2.
c. Calculate the number of calls/hour/cell and the number of calls/hour/km2.
d. Calculate the number of users/hour/cell and the number of users/hour/channel.
e. A common definition of spectral efficiency with respect to modulation, or modulation efficiency, in Erlangs/MHz/km^2, is

$$\eta_m = \frac{\text{(Total traffic carried by the system)}}{\text{(Bandwidth)(Total coverage area)}}$$

Determine the modulation efficiency for this system.

13.10 A cellular system uses FDMA with a spectrum allocation of 12.5 MHz in each direction, a guard band at the edge of the allocated spectrum of 10 kHz, and a channel bandwidth of 30 kHz. What is the number of available channels?

13.11 For a cellular system, FDMA spectral efficiency is defined as $\eta_a = \dfrac{B_c N_T}{B_w}$ where

$B_c =$ channel bandwidth
$B_w =$ total bandwidth in one direction
$N_T =$ total number of voice channels in the covered area

a. What is an upper bound on η_a?
b. Determine η_a for the system of Problem 13.8.

13.12 Consider a seven-cell system covering an area of 3100 km^2. The traffic in the seven cells is as follows:

Cell number	1	2	3	4	5	6	7
Traffic (Erlangs)	30.8	66.7	48.6	33.2	38.2	37.8	32.6

Each user generates an average of 0.03 Erlangs of traffic per hour, with a mean holding time of 120 s. The system consists of a total of 395 channels and is designed for a grade of service of 0.02.

a. Determine the number of subscribers in each cell.
b. Determine the number of calls per hour per subscriber.
c. Determine the number of calls per hour in each cell.
d. Determine the number of channels required in each cell. *Hint:* you will need to extrapolate using Table 13.1.
e. Determine the total number of subscribers.
f. Determine the average number of subscribers per channel.
g. Determine the subscriber density per km^2.
h. Determine the total traffic (total Erlangs).
i. Determine the Erlangs per km^2.
j. What is the radius of a cell?