CHAPTER 5

NETWORK PLANNING

5.1 INTRODUCTION

One can envision a *telecommunications network* as a kind of medium interconnecting a collection of devices that is equipped to exchange information between them. The most common information sources are voice, data, and video. Traditional communications networks have evolved around applications using one of these specific information sources. The future of communications networks, however, is directed toward multimedia services supporting applications using a combination of all these information sources. The entire communications network consists of two types of elements, the communicating devices and the network infrastructure. The communicating devices provide an interface between the user application and the network infrastructure. These devices are usually referred to as communication *stations, terminals,* or *hosts.* The network infrastructure is a collection of point-to-point wired or wireless links and a number of switches and routers interconnecting several of these communication terminals in geographically separated locations. Traditional communication devices are connected to the communications network through a fixed connection point. The geographic location of the terminal and its connection to the infrastructure remains fixed. Figure 5.1 shows a simple traditional wired network with examples of its elements.

The future direction of communications networks is toward wireless mobile connections to the infrastructure that shall support continual connection though the geographical location of the terminal is constantly changing due to the mobility of the terminal. In order to modify the traditional fixed network infrastructures to support wireless connections, a new wireless infrastructure is needed as an interface between the backbone wired network infrastructure and the mobile communication terminals.

The mobile communication terminals need to be equipped with wireless front-ends to communicate with the wired backbone through the new wireless in-

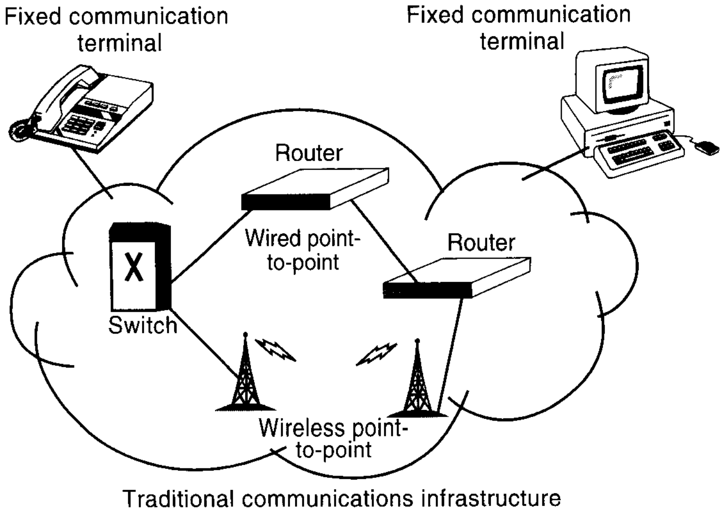


Figure 5.1 Traditional wired networks.

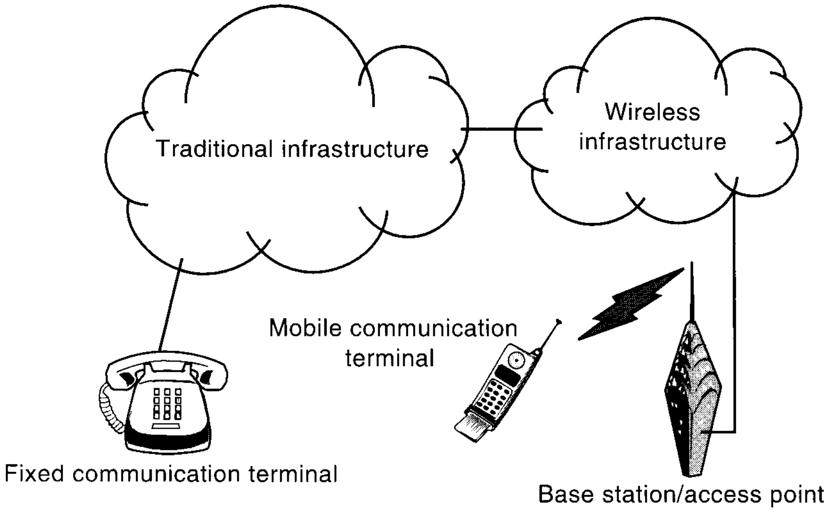


Figure 5.2 Positioning of the wireless network infrastructure in relation to the wired network infrastructure.

frastructure. Figure 5.2 shows the positioning of the wireless infrastructure in relation to the wired infrastructure.

In addition to switches, routers, and point-to-point links, the wireless network infrastructure also needs wireless transceivers to communicate with the wireless communication terminals and act as points of access to the fixed part of the wireless network infrastructure. These transceivers are referred to as *base stations* (BSs) or *access points* (APs). Any wireless base station has a limited coverage area. If the coverage area is less than the desirable coverage area for the wireless service, we need multiple base stations to cover the service area. In the case of multiple base stations operating in an area, the wireless network infrastructure needs to coordinate the continuity of a wireless connection as the mobile communication terminal moves through the coverage areas of different base stations.

5.2 WIRELESS NETWORK TOPOLOGIES

We refer to *wireless network topology* as the configuration in which a mobile terminal communicates with another. There are two fundamental types of topologies used in wireless networks. They are infrastructure, centralized, or hub-and-spoke topology, and the ad hoc or distributed topology.

5.2.1 Infrastructure Network Topology

In the infrastructure topology, there is a fixed (wired) infrastructure that supports communication between mobile terminals and between mobile and fixed terminals. The infrastructure networks are often designed for large coverage areas and multiple base station or access point operations. Most of the discussion in this section is around this type of operation. Figure 5.3 shows the basic operation of an infrastructure network with a single BS/AP. The BS/AP serves as the hub of the network, and the mobile terminals are located at the ends of the spokes. Any communication from one wireless user station to another, that is, between peers, has to be sent through the BS/AP. The hub station usually controls the mobile stations and monitors what each station is transmitting. Thus the hub station is involved in managing user access to the network.

Example 5.1: Systems That Employ Infrastructure Network Topology

All standardized cellular mobile telephone and wireless data systems use an infrastructure network topology to serve mobile terminals operating within the coverage area of any BS. The IEEE 802.11 standard and most of the wireless LAN products support infrastructure operation.

5.2.2 Ad Hoc Network Topology

Ad hoc or distributed network topology applies to reconfigurable networks that can operate without the need for a fixed infrastructure. These networks are primarily used by the military and also in a few commercial applications for voice and data transmission. Such a topology is suitable for rapid deployment of a wireless network in a mobile or fixed environment. Figure 5.4 shows two variations of the ad hoc network topology. Figure 5.4(a) is a single-hop ad hoc network where, as

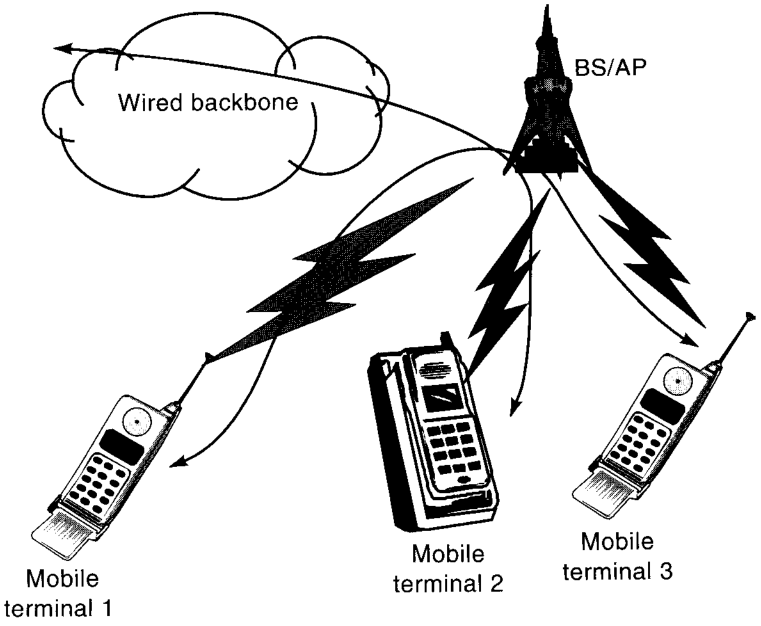


Figure 5.3 Basic operation of an infrastructure network topology.

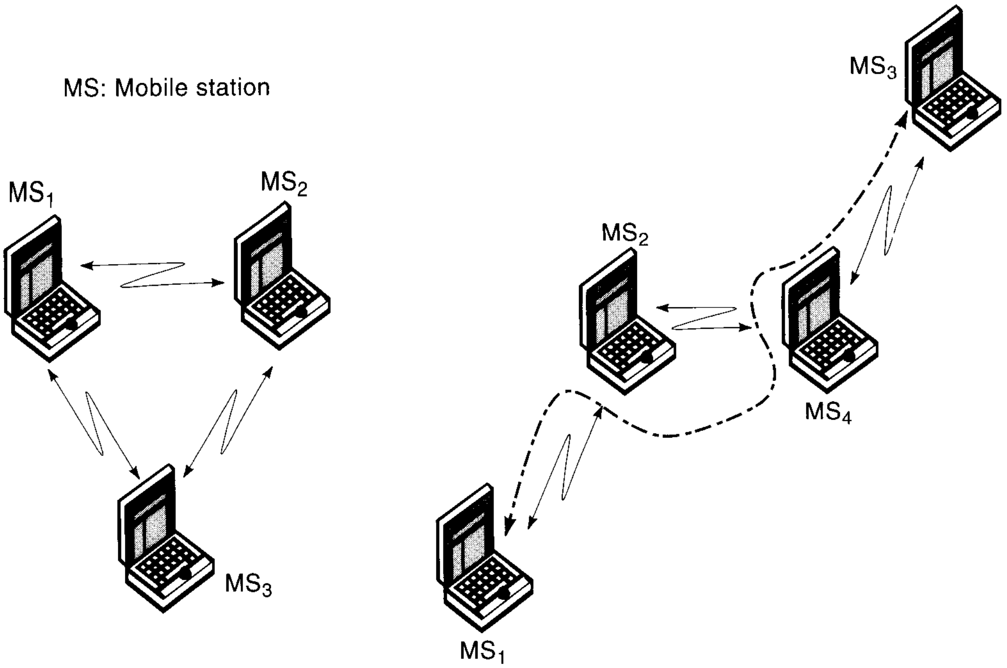


Figure 5.4 Ad hoc networking: (a) single-hop peer-to-peer topology and (b) multi-hop ad hoc networking topology.

the name implies, every user terminal has the functional capability of communicating directly with any of the other user terminals.

Example 5.2: Systems That Support Single-Hop Ad Hoc Network Topology

The IEEE 802.11 wireless LAN standard supports single-hop peer-to-peer topology for ad hoc networking. When a terminal is turned on, it first searches for a beacon signal from an AP or another terminal announcing the existence of an ad hoc network. If a beacon is not detected, the terminal takes the responsibility of announcing the existence of an ad hoc network. Several PCS services, such as PHS and NEXTEL satellite, support peer-to-peer walkie-talkie type communication among voice terminals.

In some ad hoc networking applications, where users may be distributed over a wide area, a given user terminal may be able to reach only a portion of the other users in the network due to transmitter signal power limitations. In this situation, user terminals will have to cooperate in carrying messages across the network between widely separated stations. Networks designed to function this way are called multihop ad hoc networks and are illustrated in Figure 5.4(b). In an ad hoc multihop network, each terminal should be aware of the neighboring terminals in its coverage range. The multihop network configuration was originally used in military tactical networks, where providing reliable communications under unpredictable propagation conditions and over widely varying geographic areas was important.

Example 5.3: Systems That Support Multihop Ad Hoc Network Topology

The early packet radio networks studied for military applications in 1970s were employing multihop ad hoc network topology. ETSI BRAN's HIPERLAN standard for wireless LANs that was developed during the mid-1990s, supports multihop ad hoc networking for commercial applications.

5.2.3 Comparison of Ad Hoc and Infrastructure Network Topologies

A number of attributes can be used to compare infrastructure and ad hoc network topologies.

Scalability. In peer-to-peer single-hop networks, expansion is always limited to the coverage of the radio transmitter and receiver, and there is no simple way to scale up the network coverage or capacity (wireless traffic) that can be supported by the network. In multihop ad hoc networks, as the number of terminals increases the potential coverage of the network is increased. However, the traffic handling capacity of the network remains the same. To connect an ad hoc network to the backbone wired network, one needs to use a proxy server with a wireless connection as a member of the ad hoc network. In practice all terminals supporting ad hoc networking operate in a dual mode that also supports infrastructure operation. Wireless infrastructure networks are inherently scalable. To scale up a wireless infrastructure network, the number of BSs or APs is increased to expand the coverage area or to increase the capacity while using the same available spectrum. Therefore, for wide area coverage and for applications with variable traffic loads, infrastructure networks are always used. We look at how the available capacity can be expanded in an infrastructure topology later on in this chapter.

Flexibility. Operation of infrastructure networks requires deployment of a network infrastructure which is very often time-consuming and expensive. Ad hoc networks are inherently flexible and can be set up instantly. Therefore, ad hoc networks are always used for temporary applications where flexibility is of prime importance.

Controllability. To coordinate proper operation of a radio network, we need to centrally control certain features such as time synchronization, transmitted power of the mobile stations operating in a certain area, and so on. In an infrastructure network, all these features are naturally implemented in the BS or AP. In an ad hoc network, implementation of these features requires more complicated structures demanding changes in all terminals.

Routing Complexity. In multihop peer-to-peer networks, each terminal should be able to route messages to other terminals. This capability requires each terminal to monitor the existence of other terminals and be able to connect to those available in the immediate neighborhood. For this, there is a need for a routing algorithm that directs information to the next appropriate terminal. Implementation of these features adds to the complexity of the terminal and the network operation. In infrastructure and peer-to-peer single hop ad hoc networks, this problem does not exist.

Coverage. In WLANs, coverage of the network is an issue of concern because it has an effect on the selection of the topology. In peer-to-peer single hop network topology, the maximum distance between two terminals is the range of coverage of the wireless interface used in the terminal. In an infrastructure network, two wireless terminals communicate through an AP or a BS. The maximum distance between two terminals is thus twice the range of coverage of a single wireless modem because the communicating terminals may be located at the edge of the coverage area of the BS or AP. In practice often APs or BSs are fixed in opportunistic locations using elevated mountings that increase the coverage of the wireless modem. This usually results in a maximum coverage distance between two terminals that is greater than twice the coverage distance of the same modem in an ad hoc configuration.

Reliability. Another issue of concern in small-scale WLAN operation and military applications in battlefields is resistance to failure. Infrastructure networks are "single failure point" networks. If the AP or BS fails, the entire communications network is destroyed. This problem does not exist in ad hoc peer-to-peer configurations.

Store and Forward Delay and Media Usage Efficiency. In peer-to-peer single-hop networks, information is transmitted only once, and there is no store and forward procedure. In the infrastructure topology, we have transmission of data twice, once from the source to the BS/AP and once from the BS/AP to the destination. The BS/AP also should store the message and forward it later. This adds to the delay encountered by the data packets. Multihop ad hoc networks may have several transmissions and several store and forward delays that depend on the instantaneous topology and number of hops required to send the data from the source to the destination.

5.3 CELLULAR TOPOLOGY

Cellular topology is a special case of an infrastructure multi-BS network configuration that exploits the *frequency reuse* concept. Radio spectrum is one of the scarcest resources available, and every effort has to be made to find ways of utilizing the spectrum efficiently and to employ architectures that can support as many users as theoretically possible with the available spectrum. This is extremely important especially today in light of the huge demand for capacity. Spatially reusing the available spectrum so that the same spectrum can support multiple users separated by a distance is the primary approach for efficiently using the spectrum. This is called *frequency reuse.* Employing frequency reuse is a technique that has its foundations in the attenuation of the signal strength of electromagnetic waves with distance. For instance, in vacuum or free space, the signal strength falls as the square of the distance. This means that the same frequency spectrum may be employed without any interference for communications or other purposes, provided the distance separating the transmitters is sufficiently large and their transmit powers are reasonably small (depending on the reuse distance). This technique has been used, for example, in commercial radio and television broadcast where the transmitting stations have a constraint on the maximum power they can transmit so that the same frequencies can be used elsewhere. The cellular concept is an intelligent means of employing frequency reuse. Cellular topology is the dominant topology used in all large-scale terrestrial and satellite wireless networks. The concept of cellular communications was first developed at Bell Laboratories in the 1970s to accommodate a large number of users with a limited bandwidth [MAC79].

5.3.1 The Cellular Concept

By cellular radio, we mean deploying a large number of low-power base stations for transmission, each having a limited coverage area. In this fashion, the available capacity is multiplied each time a new base station or transmitter is set up because the same spectrum is being *reused* several times in a given area. The fundamental principle of the cellular concept is to divide the coverage area into a number of contiguous smaller areas which are each served by its own radio base station. Radio channels are allocated to these smaller areas in an intelligent way so as to minimize the interference, provide an adequate performance, and cater to the traffic loads in these areas. Each of these smaller areas is called a *cell.* Cells are grouped into *clusters.* Each cluster utilizes the entire available radio spectrum. The reason for clustering is that adjacent cells cannot use the same frequency spectrum because of interference. So the frequency bands have to be split into chunks and distributed among the cells of a cluster. The spatial distribution of chunks of radio spectrum (which are called subbands) within a cluster has to be done in a manner such that the desired performance can be obtained. This forms an important part of network planning in cellular radio. The number of cells in a cluster is called cluster size or frequency reuse factor.

Two types of interference are important in such a cellular architecture. The interference due to using the same frequencies in cells of different clusters is referred to as *cochannel interference.* The cells that use the same set of frequencies or channels are called *cochannel cells.* The interference from different frequency channels used within a cluster whose side-lobes overlap is called *adjacent channel interference.* The allocation of channels within the cluster and between clusters must be done so as to minimize both of these.

The cellular concept can increase the number of customers that can be supported in the available frequency spectrum as illustrated by the following examples by deploying several low power radio transmitters.

Example 5.4: Cellular Concept

Consider a single high-power transmitter (see Fig. 5.5) that can support 35 voice channels over an area of 100 square km with the available spectrum. If seven lower power transmitters are used so that they support 30 percent of the channels over

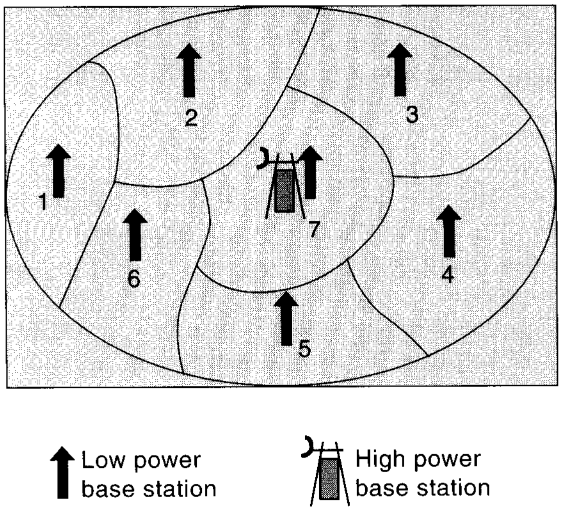


Figure 5.5 The cellular concept.

an area of 14.3 square km each, a total of ≈80 voice channels are now available in this area instead of 35. In reality, channels will have to be allocated to base stations in such a way as to prevent interference between one base station and another. In Figure 5.5, base stations 1 and 4 could use the same channels, as their coverage areas are sufficiently far apart and so also are base stations 3 and 6. Suppose the cells labeled 1, 2, 5, 6, and 7 use disjoint frequency bands and the channels used in 1 and 6 are reused in 3 and 4. The set of cells {1, 2, 5, 6, 7} forms a cluster. Cells 3 and 4 form part of another cluster. In the limiting case, the density of base stations can be made so large that the capacity is infinite. However, in practice this is impossible for several reasons that include drastic increases in the network and signaling load, number and rate of handoffs, and cost of infrastructure and network planning.

Example 5.5: Importance of Cellular Topology

We want to provide a radio communication service to a city. The total bandwidth available is 25 MHz, and each user requires 30 KHz of bandwidth for voice communication. If we use one antenna to cover the entire town, we can only support 25 MHz/30 KHz = 833 simultaneous users. Now let us employ a cellular topology where 20 lower power antennas are opportunistically located to minimize both kinds of interference. We divide our frequency band into four sets and assign one set to each cell. Each cell has a spectrum of 25 MHz/4 = 6.25 MHz allocated to it. We have a *cluster* of four cells in this example. The number of simultaneous users supported per cell is 6.25 MHz/30 KHz = 208. The number of users per cluster is 4 × 208 = 832. The total number of simultaneous users is now 832 × 5 = 4,160 because we have five clusters of four cells each. The new capacity is roughly five times the capacity with a single antenna.

Examples 5.4 and 5.5 illustrate the main benefits and elements of a cellular network planning by relating the bandwidth, number of cells, frequency reuse factor, and capacity of the network. If W is the total available spectrum, B is the bandwidth needed per user, N is the frequency reuse factor, and m is the number of cells required to cover an area, the number of simultaneous users is given by:

$$n = \frac{m(W / N)}{B} \tag{5.1}$$

In particular we observe that the capacity of the network can be increased by (a) increasing m, such as the number of cells (by reducing the size of each cell) and (b) decreasing the frequency reuse factor. A major remaining question at this point is how to assign the groups of subbands to individual cells so that interference between different users using the same subbands is acceptable. We address this issue in subsequent sections. Let us now consider some other important issues related to a cellular topology.

A cellular topology reduces the coverage requirements of both the mobile terminal and the BS. The reduction of the size of coverage lowers the required transmitted power by the mobile terminal because mobile terminals are located closer to the base stations and they require less power to communicate with the network. This increases the battery lifetime and reduces the size of a terminal. These issues are extremely important to the user of a handheld terminal. Therefore, the larger the number of cells, the larger the capacity and the smaller the size of the handheld terminal. However, we need a fixed network infrastructure to interconnect the cells and ensure that the entire system works in a coordinated manner. As we increase the number of cells, the cost and the time for deploying the network increases. In addition, as the cell size becomes smaller, the number of handoffs increases. Therefore, a reduction in the size of the cells increases the complexity of the design and deployment of the network, as well as the signaling load in the fixed part of the infrastructure. The art of designing a cellular topology involves striking a balance between all these elements, and this is the subject of details that follow in this chapter.

Another important factor in deployment of wireless cellular networks is provision for expansion. The main investment of a wireless service provider is toward the cost of the fixed infrastructure, which includes the BS and connections between them. When a service provider starts an operation, that person needs to minimize the cost of the infrastructure while continuously increasing the number of subscribers. As the number of subscribers increases, new income is generated, and the service provider can afford to expand the network by increasing the complexity of its infrastructure to support a further larger population of subscribers. Therefore, there is a need for a plan to take into account the growth of the subscriber base and thus the entire wireless network.

In summary, we need to address the following technical issues for planning a cellular network:

- Selection of a frequency reuse pattern for different radio transmission techniques
- Physical deployment and radio coverage modeling
- Plans to account for the growth of the network
- Analysis of the relationship between the capacity, cell size, and the cost of the infrastructure

5.3.2 Cellular Hierarchy

There are three reasons to use a hierarchical cellular infrastructure supporting cells of different sizes. One is to extend the coverage to the areas that are difficult to cover by a large cell. For example, cells designed to cover suburban areas have antennas on tall towers and cover a large area. Signals from these antennas, however, cannot propagate sufficiently into urban canyons or indoor environments. For urban canyons we need to install antennas at lower heights, and in indoor areas we may mount the antennas on walls to provide a comprehensive coverage. Antennas mounted in these locations are of low power and cover a smaller area, resulting in the creation of a smaller sized cell. The second reason to have a cellular hierarchy is to increase the capacity of the network for those areas that have a higher density of users. Imagine the number of cellular phone users in the downtown area of a large city and compare it with the number of mobile users on an interstate highway. To support the larger subscriber demand and higher traffic in smaller areas, we need to increase the number of cells by reducing their sizes. The third reason is that sometime an application needs certain coverage. Consider the increasing number of wireless devices that we are carrying in our bags these days and the increasing need for communication between these devices. This necessitates extremely small-sized cells that provide a wireless network for connecting laptops or notepads to cellular phones.

In a modern deployment of a cellular network, a number of cell sizes are used to provide a comprehensive coverage supporting traffic fluctuations in different geographic areas and supporting a variety of applications. One way of dividing the cells into a hierarchy is to define the following cell sizes:

- *Femtocells:* These are the smallest unit of the cellular hierarchy used for connection of personal equipment such as laptops, notepads, and cellular telephones. These cells need to cover only a few meters where all these devices are in physical range of the user.
- *Picocells:* These are small cells inside a building that support local indoor networks such as wireless LANs. The size of these networks is in the range of a few tens of meters.
- *Microcells:* These cells cover the inside of streets with antennas mounted at heights lower than the rooftop of the buildings along the streets. They cover a range of hundreds of meters and are used in urban areas to support PCS.
- *Macrocells:* Macrocells cover metropolitan areas, and they are the traditional cells installed during the early phases of the cellular telephony. These cells cover areas on the order of several kilometers, and their antennas are mounted above the rooftop of typical buildings in the coverage area.
- *Megacells:* Megacells cover nationwide areas with ranges of hundreds of kilometers and are mainly used with satellites.

Figure 5.6 illustrates the relationship between different cells with example applications. An ideal network has a hierarchy of these cells to cover airplane travelers with megacells, car drivers in suburban areas with macrocells, pedestrians in the

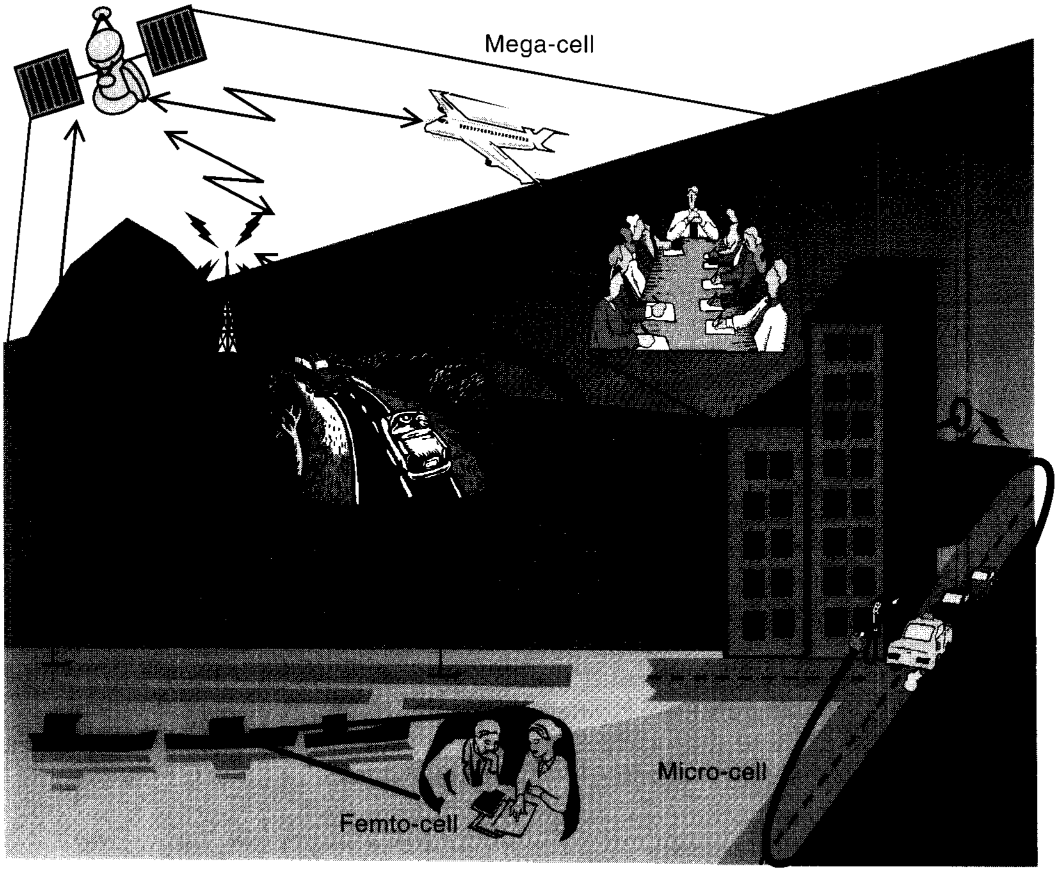


Figure 5.6 Cellular hierarchy.

streets via microcells, indoor users with picocells, and connect personal equipment with femtocells.

5.4 CELL FUNDAMENTALS

Having looked at the cellular topology and the concept of employing a cellular architecture to increase the communications capacity and to cater to a large subscriber demand in hotspots, we now consider quantitative means to characterize the interference in a cellular topology. This in turn leads to quantitative means for determining the best cluster size and simple techniques for allocating the subbands of spectrum within a cluster.

Even though in practice cells are of arbitrary shape (close to a circle) because of the randomness inherent in radio propagation, it is easier to obtain insight and

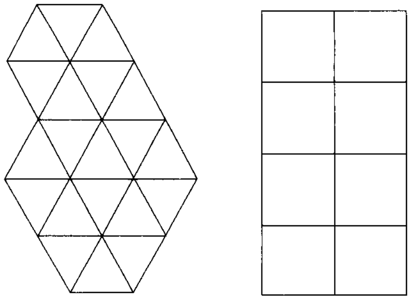


Figure 5.7 Triangular and rectangular cells.

understanding for system design by visualizing all cells as having the same shape. Also it is easier to mathematically analyze a cellular topology by assuming a uniform cell size for all cells. Once some insight is obtained as to what the effects of interference are, measurements, simulation, and a combination of these can be employed in actually determining the planning of a network.

For cells of the same shape to form a tessellation so that there are no ambiguous areas that belong to multiple cells or to no cell, the cell shape can be of only three types of regular polygons: equilateral triangle, square, or regular hexagon as shown in Figure 5.7.

A hexagonal cell is the closest approximation to a circle of these three and has been used traditionally for system design (see Figure 5.8). The argument for a hexagonal shape comes from the fact that among the three shapes mentioned, for a given radius (largest possible distance between the polygon center and its edge), the hexagon has the largest area.

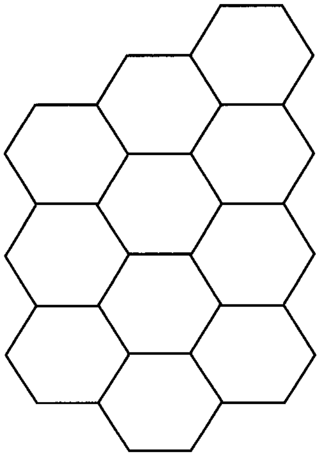


Figure 5.8 Arranging regular hexagons that can cover a given area without creating ambiguous regions.

In most of the literature and in the back of the envelope design, the hexagonal cell shape is chosen as the default cell shape. In particular cases that consider continuous distributions of traffic load and interference between different transmission schemes, a circular cell shape is employed for tractable calculation.

In order to investigate the effects of interference, which changes with distance, there is a need to come up with an elegant way of determining distances and identifying cells. Fortunately, it is possible to do this easily in the case of hexagonal cells [MAC79]. In order to maximize the capacity, cochannel cells must be placed as far apart as possible for a given cluster size. It can be shown that there are *only* six cochannel cells for a given reference cell at this distance. The relationship among the distance between cochannel cells, D_L, the cluster size, N, and the cell radius, R_L, is given by:

$$\frac{D_L}{R_L} = \sqrt{3N} \tag{5.2}$$

This quantity is also referred to as the *cochannel reuse ratio.* Values for N can only take on values of the form $i^2 + ij + j^2$ where i and j are integers.

Example 5.6: Cluster Size of $N = 7$

As described earlier, i and j can only take integer values. If we take $i = 2$ and $j = 1$, we see that $N = 4 + 2 + 1 = 7$. Selecting a cell A, we can determine its cochannel cell by moving two units along one face of the hexagon and one unit in a direction 60° or 120° to this direction. Clusters of size $N = 7$ can be created as shown in Figure 5.9. A value of $N = 7$ is employed in the United States in the advanced mobile phone service (AMPS).

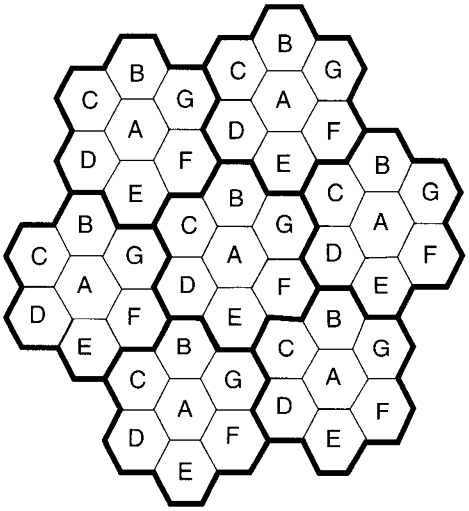


Figure 5.9 Hexagonal cellular architecture with a cluster size of $N = 7$.

The number of cells in a cluster N determines the amount of cochannel interference and also the number of frequency channels available per cell. Suppose there are N_c channels available for the entire system. Each cluster uses all the N_c channels. With fixed channel allocation, each cell is allocated N_c/N channels. It is desirable to maximize the number of channels allocated to a cell. This means that N should be made as small as possible. However, reducing N increases the signal-to-interference ratio (as discussed in the following section). There is thus a tradeoff between the system capacity and performance. The reader should note that the development frequency of reuse using hexagonal cells is for mathematical tractability only. In reality, this approximation is useful only to obtain insight into designing cellular systems. Actual deployment is far more complicated because of irregular differing cell sizes and propagation mechanisms.

5.5 SIGNAL-TO-INTERFERENCE RATIO CALCULATION

In Section 5.1, we mentioned that a cellular architecture was essential in order to reuse the available spectrum while reducing interference caused by reusing the frequency spectrum. In this section, we look in detail at the performance measures that are useful in system design, in particular the signal-to-interference ratio and its relationship with the path loss, and the grade of service.

In general, the signal-to-interference ratio can be written as follows:

$$S_r = \frac{P_{desired}}{\sum_i P_{interference,\,i}} \tag{5.3}$$

Here $P_{desired}$ is the signal strength from the desired BS and $P_{interference,i}$ is the signal strength from the ith interfering BS. The signal strength falls as some power of the distance α called the power-distance gradient or path-loss gradient. That is, if the transmitted power is P_t, after a distance d in meters, the signal strength of a radio signal will be proportional to $P_t\,d^{-\alpha}$. In its most simple case, the signal strength falls as the square of the distance in free space ($\alpha = 2$). Suppose there are two base station transmitters BS_1 and BS_2 located in an area with the same transmit power P_t and a mobile terminal is at a distance of d_1 from the first and d_2 from the second. If the mobile terminal is trying to communicate with the first BS, the signal from the second BS is interference. The *signal-to-interference* ratio for this mobile terminal will be:

$$S_r = \frac{KP_t d_1^{-\alpha}}{KP_t d_2^{-\alpha}} = \left(\frac{d_2}{d_1}\right)^{\alpha} \tag{5.4}$$

The larger the ratio d_1/d_2 is, the greater is S_r and the better is the performance. The objective in a cellular radio system is to allocate frequencies or channels to cells within a cluster so that the distance between interfering cells (cochannel or adjacent channel) is as large as possible. For urban land mobile radio, the distance power gradient increases from two (in the case of free space) to roughly four so that the received signal strength falls as the fourth power of the distance. This further improves the signal-to-interference ratio. If there are J_s interfering BS surrounding a given BSs, the general form of the signal-to-noise ratio will be:

$$S_r = \frac{d_0^\alpha}{\sum_{n=1}^{J_s} d_n^\alpha} \tag{5.5}$$

where the distance of the mobile from the given base station is d_0 and its distance from the nth base station is d_n.

Example 5.7: S_r in a Hexagonal Cellular Architecture

Recalling that there are exactly six cochannel cells with a hexagonal cellular structure, it is clear that they will all cause similar levels of interference to a mobile terminal in the given cell. So $J_s = 6$ here. Also, the distance at which the cochannel cells are located depends on the size of the cluster from Eq. (5.2). The farthest distance a mobile terminal can be from the base station of a given cell is the cell radius R. The approximate distance of the mobile terminal from the base stations of each of the cochannel cells is D_L. For land mobile radio, if only the six cochannel cells that make up the first tier of interferers are considered, $J_s = 6$, and the signal-to-interference ratio can be approximated as:

$$S_r \approx \frac{R^{-4}}{J_s D_L^{-4}} = \frac{R^{-4}}{6 D_L^{-4}} = \frac{1}{6}\left(\frac{D_L}{R}\right)^4 = \frac{3}{2}N^2 \tag{5.6}$$

In terms of dB, we can write the signal-to-interference ratio as:

$$S_r = -7.78 + 40 \log(D_L / R_L) = 1.76 + 20 \log N \tag{5.7}$$

Figure 5.10 shows how the signal-to-interference ratio given by (5.7) varies with the cluster size N. Equation (5.7) is commonly used to determine the cluster size for an adequate performance. Note that the signal-to-interference ratio is influenced by the cochannel reuse ratio D_L/R_L in that a given D_L/R_L has to be maintained for a particular S_r. However, it is an approximation because different base stations may employ different transmit powers, and the path loss model may not be as simple as the d^{-4} model used here. The S_r calculation will be different for the uplink (mobile terminal to base station communication) compared with the downlink (base station to mobile terminal communication).

We have so far assumed that the received signal strength falls as the fourth power of the distance for land mobile radio. In dB, this translates to a path loss model of the form:

$$P_r(d)\,(\text{dB}) = P_t(\text{dB}) - 40 \log d + 10 \log K \tag{5.8}$$

The factor 10 log K usually corresponds to the path loss at the first meter, or kilometer as the case may be, and d is in the same units. This path loss model may not be appropriate, especially because measurements of the received signal strength indicate that the path loss is dependent not only on the distance between the base

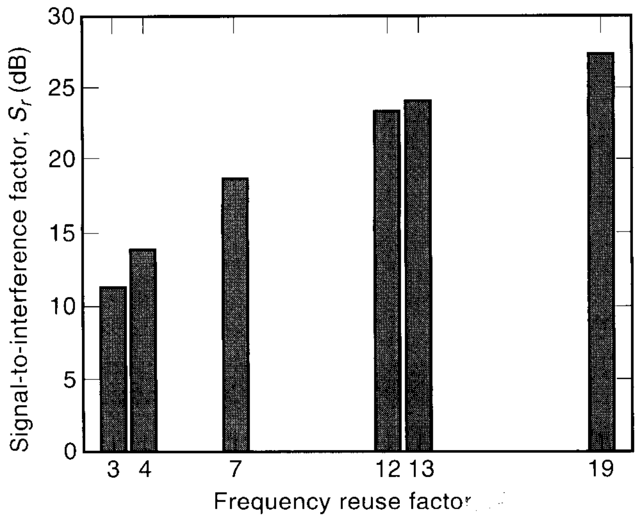


Figure 5.10 Signal-to-interference ratio, S_r, as a function of frequency reuse factor, N.

station and the mobile, but also on the radio frequency of operation and the antenna height. The path loss is also dependent on the scenario, whether the cellular architecture corresponds to land mobile radio or to a microcellular PCS application. However, this simple model is appropriate for first-cut approximations in system design.

Let us consider an example of a real cellular system that tries to bring together many of the concepts that have been considered so far in this chapter.

Example 5.8: Cellular Architecture of AMPS

As an example of cellular architecture, we consider the very first cellular radio telephone system in the United States, called *AMPS* based on an analog FM modulation scheme. Each voice channel in AMPS occupies 30 kHz of bandwidth and uses FM. Figure 5.11 shows the spectrum allocations for AMPS.

A bandwidth of 25 MHz is allocated for both the uplink and downlink so that transmission is full duplex. The 25 MHz of spectrum is divided into two blocks of 12.5 MHz each. Block A is allocated to carriers who are not traditional telephone service providers. Block B is allocated to traditional telephone service providers. Each 12.5 MHz of spectrum can support 416 channels each of which is 30 kHz wide. Of these, 395 are dedicated channels for voice, and 21 are dedicated for call control.

Based on subjective voice quality tests, it was determined that a signal-to-interference ratio of 18 dB can be tolerated while providing a good voice quality to the user. From Eq. (5.7), this means that the cluster size has to be $N = 7$. Figure 5.9 shows the cellular architecture with this cluster size. Cells with the same label use the same frequency spectrum. They are separated by a distance $D_L = 4.58\ R_L$ in this case which ensures that the signal-to-interference ratio is around 18 dB.

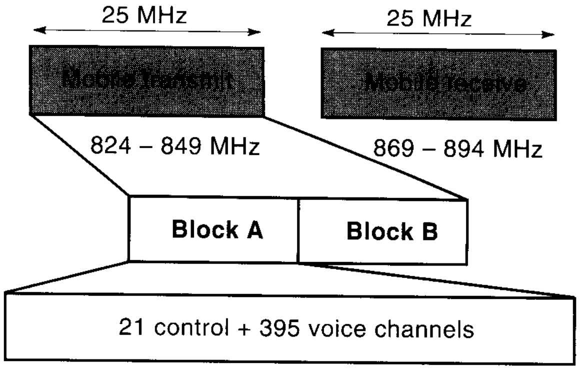


Figure 5.11 Frequency spectrum allocation for AMPS.

Let the 395 voice channels available for a service provider be numbered from 1 to 395. For example, on the downlink, 869–869.030 corresponds to channel 1, 869.030–869.060 to channel 2, and so on. Channels 1, 8, 15, . . . are allocated to cells labeled A. Channels labeled 2, 9, 16, . . . are allocated to cells labeled B and so on. This ensures that there is a sufficient separation between channels used within a cell so that adjacent channel interference is minimized. In practice, the numbering scheme is different because the entire 25 MHz of bandwidth was not initially available for AMPS. However, a separation of seven adjacent channels is maintained between channels used within a cell. It was also found in some cases that, because cells actually do not have a hexagonal shape and because the assumptions made in coming up with the value for N are not satisfied, a cluster size of $N = 12$ has to be employed for good voice quality. The reader is referred to [APP85] for another example.

5.6 CAPACITY EXPANSION TECHNIQUES

In the 1990s, the dominant source of income for the wireless telecommunication industry has been the cellular telephone service. During this period, the industry grew exponentially. Numerous companies are in fierce competition to gain a portion of the income of this profitable and prosperous industry. The main investment in deploying a cellular network is the cost of the infrastructure that includes the cost of BS and switching equipment, property (land for setting up the cell sites), installation, and links connecting the BSs. This cost is proportional to the number of BS sites. The income of the service is directly proportional to the number of subscribers. The number of subscribers grows with time and a cellular service provider has to develop a reasonable deployment plan that has a sound financial structure to account for many of these aspects. All service providers start their operation with the minimum number of cell sites to cover a service area that requires the least initial investment. As the number of subscribers increases, it generates a source of income for the service provider. At such a point of time, they can increase the investment on the infrastructure to improve service and to increase the capacity of the network to support additional subscribers. Therefore, a number of methodologies have evolved to facilitate the expansion of cellular telephone networks.

There are basically four methods to expand the capacity of a cellular network. The simplest method is to obtain additional spectrum for new subscribers. This is a very simple but expensive approach. The so-called PCS bands were sold in the United States for around $20 billion. If we assume that each new subscriber generates a profit of approximately $1,000 per year, we will still need 20 million additional subscribers to recover this amount in a year. With the fierce competition to provide the lowest cost to the customer, this has proved to be fatal. A case in example is that the top three companies that purchased the PCS bands have already filed for bankruptcy. The reader should not, however, conclude that this is not an acceptable method. With our pessimistic scenario, we are accentuating the vital importance of the need for other alternatives to expand capacity in addition to this simple approach of getting additional spectrum.

The second method to expand the capacity of a cellular network is to change the cellular architecture. Architectural approaches include cell splitting, cell sectoring using directional antennas, Lee's microcell zone technique [LEE91], and using multiple reuse factors [HAL83] (called reuse partitioning). These techniques, described in detail in the rest of this section, change the size and shape of the coverage of the cells by adding cell sites or modifying the nature of antennas to increase the capacity. These techniques do not need additional spectrum or any major changes in the wireless modem or access technique of the system that will require the user to purchase a new terminal. These features of architectural approaches distinguish them as one of the more practical and less expensive solutions to expand the network capacity.

The third method for capacity expansion is to change the frequency allocation methodology. Rather than distributing existing channels equally among all cells, it is possible to use a nonuniform distribution of the frequency bands among different cells according to their traffic need. The traffic load of each cell is dynamically changed by the geography of the service area and with time depending on the traffic load. In most downtown areas, we have the largest traffic loads during rush hours and a relatively light traffic load in the evening hours and weekends. This situation is reversed in residential areas. If we allocate channels dynamically to different cells, we can increase the overall capacity of the network. These techniques do not need any change in the terminal or physical architecture of the system, and they are implemented somewhere inside the computational devices used for network control and management.

The fourth and the most effective method to expand the network capacity is to change the modem and access technology. The cellular industry started with analog technology using FM modulation and has now evolved toward TDMA and then a CDMA air interface using digital modems. Digital technology increases the network capacity and also provides a fertile environment for integration of voice and data services. However, this migration requires the user to purchase new terminals and the service provider to install new components in the infrastructure.

5.6.1 Architectural Methods for Capacity Expansion

5.6.1.1 Cell Splitting

As the number of subscribers increase within a given area, the number of channels allocated to a cell is no longer sufficient for supporting the subscriber demand. It then becomes necessary to allocate more channels to the area that is being covered by this cell. This can be done by *splitting* cells into smaller cells and allowing additional channels in the smaller cells.

Consider Figure 5.12. In this figure, we have a cellular architecture where a cluster size of seven is employed. When the traffic load increases, a smaller cell is introduced such that it has half the area of the larger cells. This will ultimately increase the capacity fourfold (because area is proportional to the square of the radius). However, in practice, only a single small cell will be introduced such that it is midway between two cochannel cells. In this case, these are the larger cells labeled A. It is logical to thus reuse the channels allocated to these cells in the smaller cell to minimize the interference.

This approach gives rise to some problems. Let us suppose that the radius of the smaller split cell (labeled a) is $R/2$. Let the transmit power of the base station of the small cell be the same as the transmit powers of the larger cells. As far as the smaller cell is concerned, the signal-to-interference ratio is maintained because the maximum distance the mobile can be from the BS in this cell is $R/2$. So though the distance between this cell and the cochannel cells A is reduced by half, the value of S_r remains the same. On the other hand, this is not the case for the cells labeled A because the cochannel reuse ratio for these cells is now $D_L/2R$ with respect to the smaller split cell. In order to maintain the same level of interference, the transmit power of the base station in the smaller cell should be reduced. But this will increase the interference observed by the mobiles in the smaller cell. The other alternative is to divide the channels allocated to cells labeled A into two parts: those used by a and those not used by a. The channels used by a will be used in the larger cells only within a radius of $R/2$ from the center of the cell so that the cochannel reuse ratio will be maintained as far as these channels are concerned. This is called the *overlaid cell concept* where a larger *macrocell* coexists with a smaller *microcell.*

The downside of this approach is that the capacity of the larger cells is reduced which will ultimately lead to introducing split cells in their area, until such

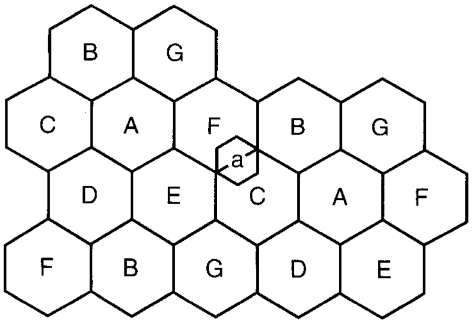


Figure 5.12 Illustrations of cell splitting for capacity expansion.

time as a chain reaction will result in the entire area being served by cells of a smaller radius. Also the BS in cells labeled A will become more complex, and there will be a need for handoffs between the overlays.

5.6.1.2 Using Directional Antennas for Cell Sectoring

The simplest and the most popular scheme for expanding the capacity of cellular systems is cell sectoring using directional antennas. This technique attempts to reduce the signal-to-interference ratio and thus reduce the cluster size, thereby increasing the capacity. The idea behind using directional antennas is the reduction in cochannel interference that results by focusing the radio propagation in only the direction where it is required. In order to achieve this, the coverage of a base station antenna is restricted to part of a cell called a *sector* by making the antenna directional. In implementing this technique, cell site locations remain unchanged, and only the antennas used in the site will be changed. The main objective here is to increase the signal to interference ratio to a level that enables us to use a lower frequency reuse factor. A lower frequency reuse factor allows a larger number of channels per cell, increasing the overall capacity of the cellular network.

As we discussed earlier [see Eq. (5.6)] the signal to interference ratio is given by:

$$S_r = \frac{1}{J_s}\left(\frac{D_L}{R}\right)^4 = \frac{9}{J_s}N^2 \tag{5.9}$$

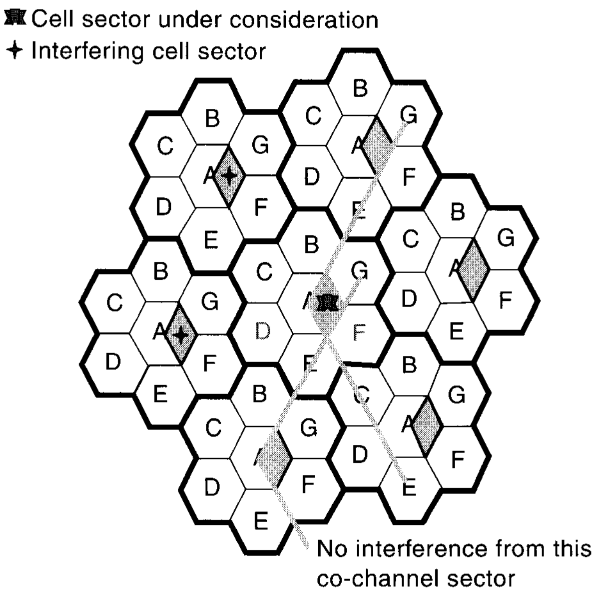
where J_s is the number of interfering cell sites. Using a sector antenna reduces the factor J_s, resulting in the interference and an increase in S_r. The most popular directional antennas employed in cellular systems are 120° directional antennas. In some cases 60° directional antennas are also employed. In the following two examples, we evaluate the impact of these antennas which enables the reuse factor to be reduced from $N = 7$ to $N = 4$ and $N = 3$, respectively. In some cases, even though the reuse factor is reduced, we see that sectorization yields a better S_r from the required 18 dB value.

Example 5.9: Three-Sector Cells and a Reuse Factor of $N = 7$

Consider a seven-cell cluster scheme with 120° directional antennas as shown in Figure 5.13. Channels allocated to a cell are further divided into three parts, each used in one sector of a cell. As shown in the figure, the number of cochannel interfering cells is reduced from six to two. Thus, there is an improvement in the signal-to-interference ratio. For omnidirectional antennas (see Examples 5.7 and 5.8), the value of S_r for a cluster size of $N = 7$ is 18.66 dB. In this case, in a manner ~~similar to Eq. (5.6),~~ the signal-to-interference ratio is given by:

$$S_r = \frac{R^{-4}}{J_s D_L^{-4}} = \frac{1}{2}\left(\frac{D_L}{R}\right)^4 = \frac{9}{2}N^2$$

$$S_r \approx \frac{R^{-4}}{J_s D_L^{-4}} = \cancel{\frac{R^{-4}}{6D_L^{-4}}} = \frac{1}{2}\left(\frac{D_L}{R}\right)^4 = \frac{9}{2}N^2 \tag{5.10}$$



No interference from this co-channel sector

Figure 5.13 Seven-cell reuse with 120° directional antennas (3-sector cells)

For $N = 7$, this will give us $S_r = 23.43$ dB. To see the importance of this gain, note that the required signal-to-noise ratio for AMPS systems is 18 dB which suggests $N = 7$. However, a larger S_r is required because of nonideal situations.

Example 5.10: Three-Sector Cells and a Reuse Factor of $N = 4$

Equation (5.10) remains unchanged in this case as there are only two interfering cells again (see Figure 5.14). With omnidirectional antennas, $J_s = 6$ and for $N = 4$, we end up with $S_r = 13.8$ dB, which is inadequate for AMPS.

It can be seen that the signal-to-interference ratio with three-sector cells is substantially better compared with omnidirectional antennas and no cell sectoring. With $N = 4$, the signal to interference ratio is 19.9 dB. This value is larger than the requirement of 18 dB based on subjective mean-opinion-score tests of voice quality.

Example 5.11: Six-Sector Cells and a Reuse Factor of $N = 4$ and $N = 3$

With 60-degree directional antennas, we have six sectors within a cell. The number of interfering cochannel cells reduces to one, and the signal-to-interference ratio can be written as

$$S_r \approx \left(\frac{D_L}{R}\right)^4 = 9N^2 \tag{5.11}$$

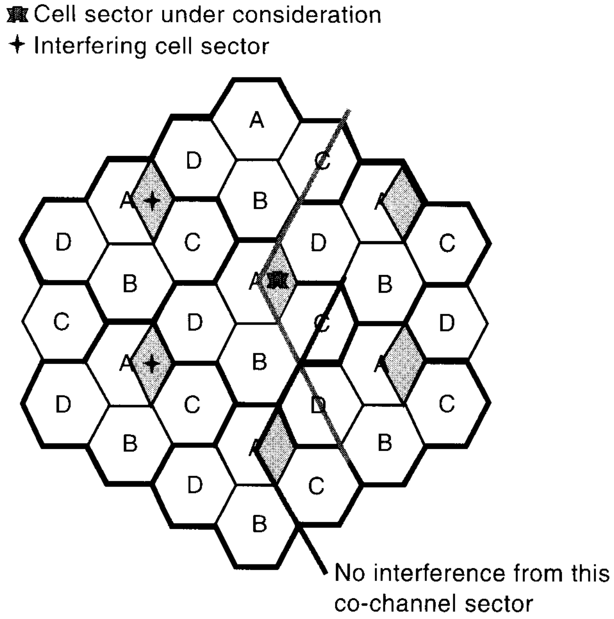


Figure 5.14 Four-cell reuse with 120° directional antennas (3-sector cells).

It is possible to employ a cluster size of four or three with six-sector cells because the signal-to-interference ratio will be 21.58 dB or 19.1 dB, respectively, which has a sufficient margin for AMPS. The cellular layout and relation to sectors in this case is left as an exercise for the readers.

In practice we cannot ideally sector a cell because ideal antenna patterns cannot be implemented. Therefore, the numbers obtained in the examples for ideal cell sectors are optimistic. However, our conclusion from these examples is that the use of sectoring increases the signal to interference ratio at the terminal. We should emphasize that in the particular examples we could reduce the frequency reuse factor from $N = 7$ to $N = 4$ or even $N = 3$ by using three- and six-sector cells, respectively. This reduction in frequency reuse from seven to four or even three would result in a capacity increase of 1.67 and 2.3, respectively, allowing an equal increase in the number of subscribers and consequently income of the service provider. The service provider needs to add these antennas to the BSs in the desired area. Compared with the cell-splitting method, using directional antennas is less effective in increasing capacity, but it can be significantly less expensive. The cost of additional cell sites, needed in cell splitting, includes costs of the property and installing the antenna mounting tower which are usually far expensive compared with deploying directional antennas. Cell splitting also requires additional planning efforts to maintain interference levels in the smaller cells. If directional antennas are used without reduction in the frequency reuse factor, the average required transmitted signal power from the mobile stations will be reduced which can potentially result in longer battery life for the user.

5.6.1.3 Lee's Microcell Method

The disadvantage of using sectors is that each sector is nothing but a new cell with a different shape, because channels have to be partitioned between the different sectors of a cell. The network load is substantially increased because a handoff has to be made each time a mobile terminal moves from one sector of a cell to another. Also, in all the discussion in the previous sections, it has been assumed that the BS antenna is located at the center of a cell, whether directional antennas are employed. In practice, employing directional BS antennas at the corners of cells can reduce the number of BSs [MAC79]. Lee's microcell zone technique [LEE91] exploits corner excited BSs to reduce the number of handoffs and eliminate partitioning of channels between sectors of a cell.

Figure 5.15 shows Lee's microcell zones concept. In this case, there is one BS per cell, but there are three "zone-sites" located at the corners of a cell. Directional antennas that span 135° are employed at these zone-sites. All three zone-sites act as receivers for signals transmitted by a mobile terminal. The BS determines which of the zone-sites has the best reception from the mobile and uses that zone-site to transmit the signal on the downlink. The zone-sites are connected to the BS by high-speed fiber links to avoid congestion and delay. Because only a single zone-site is active at a time, the interference faced by a mobile terminal from a cochannel zone-site is smaller compared with what would be the interference with an omnidirectional antenna. Consequently, the cluster size can be reduced to three, and a capacity gain of 2.33 is obtained over a seven-cell cluster scheme. Consider the following example:

Example 5.12: Lee's Microcell Zone Technique

Show that the cochannel reuse ratio D_Z/R_Z for the zones in Lee's microcell zone concept is larger than 4.6 if a cluster size of three is employed. Use Figure 5.16 for your calculations.

In this example, a cluster size of $N = 3$ is employed. Each "cell" is divided into three "zones." On the downlink, only one of the zones is active. Because the zone-sites are directional, they cause interference only in corresponding multizone sites in another cluster. The cochannel reuse ratio D_z/R_z in Figure 5.16 is clearly $6 \times \sqrt{3}/2 = 5.196$, which is larger than 4.6. Even if all six cochannel zones cause interference, the capacity is still larger by a factor of 2.33 because the cluster size is now $N = 3$ as compared to the usual value of $N = 7$.

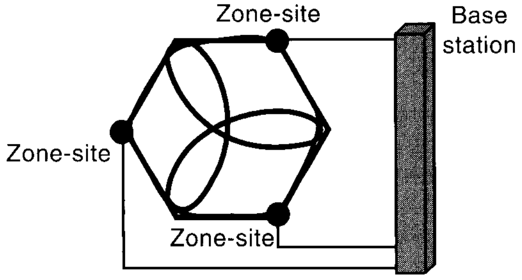


Figure 5.15 Lee's microcell zone concept.

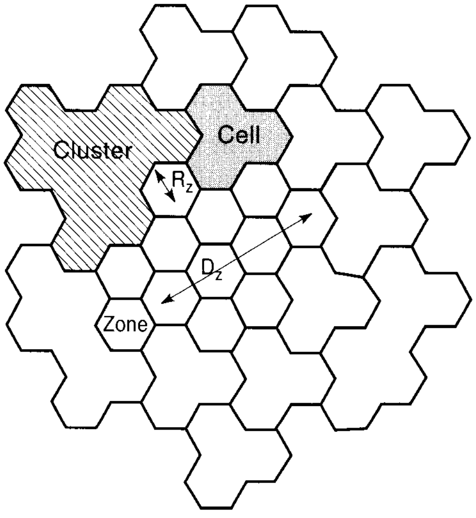


Figure 5.16 Example of Lee's microcell zone concept.

5.6.1.4

5.7.1.4 Using Overlaid Cells 7/6

The *overlaid cell concept* introduced in the section on cell splitting can be used to increase the capacity of a cellular network. Here, channels are divided among a larger macrocell that coexists with a smaller microcell contained entirely within the macrocell. The same BS serves both the macro- and microcells. Figure 5.17 illustrates the basic concept for overlaid cell concept. There are four parameters (R_1 and D_1) representing the radius of coverage and distance among cochannel cells for the macrocells; R_2 and D_2 denote the radius of coverage and the distance among cochannel cells for the microcells. The design is made such that D_2/R_2 is larger than D_1/R_1 and from Eq. (5.4) the signal-to-interference ratio (S_r) for the microcells will be substantially greater than that of the macrocells. There are two methods to exploit this situation to increase

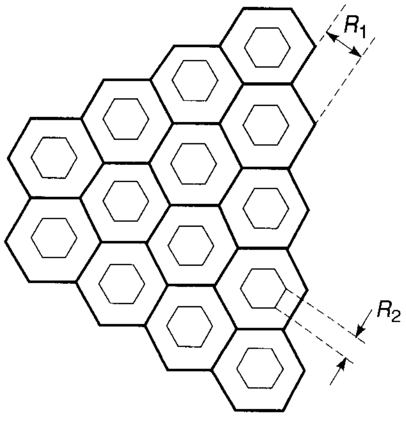


Figure 5.17 Reuse partitioning.

the capacity of the network: using split-band analog systems and reuse partitioning. Often the microcells are said to belong to an *overlay* network that is overlaid on top of an underlying macrocellular network referred to as the *underlay* network.

Split-Band Analog Systems. The split-band analog systems use a more bandwidth efficient modulation within the overlay cells. This technique is applied in analog cellular systems using FM. We have considered several examples of analog cellular systems in Chapter 1. In FM, the signal to noise requirement is inversely proportional to the square of the bandwidth. If we reduce the bandwidth to half the original value, the signal to noise ratio requirement will be increased four times (by 6 dB). If we arrange R_2 and D_2 to have a cochannel reuse ratio that is four times larger than usual, we end up with a signal to interference ratio (from Eq. (5.4)) that remains unchanged. The overlay system can then use FM with half the bandwidth of the underlay system, doubling the capacity within the overlay part of the network. An example will further clarify this situation.

Example 5.13: Band-Splitting in AMPS

The AMPS system uses a 30 kHz band for FM signals used for communication between the MS and the BS. As discussed earlier, the minimum required signal to interference ratio for this system is 18 dB. If we develop an overlay system with a 15 kHz bandwidth, the required S_r is 24 dB, which is 6 dB more than the system employing a bandwidth of 30 kHz. From Eq. (5.4) we have

$$10 \log \frac{\left(\frac{D_2}{R_2}\right)^4}{\left(\frac{D_1}{R_1}\right)^4} = 6\, dB$$

If we employ the same frequency reuse factor of $N = 7$ for the overlay and underlay networks, $D_1 = D_2$ and solving for the above equation we have $R_2 = 0.7079\, R_1$. Because the area covered by each cell is proportional to the square of the cell radius, the area of the overlay cell, A_2, will be half of the area of the underlay cell, A_1. The overlay is responsible for terminals within the smaller hexagon, while the underlay system supports users in the layer between the boundary of the overlay cell and the boundary of the underlay cell. These two areas are the same in our example. Therefore, the number of channels available to the overlay and underlay cells remain the same. If we represent this number by M then the total bandwidth used by the system is $M(15+30)$ kHz.

In the original AMPS network each service provider has 12.5 MHz of bandwidth that is divided into 416 channels, from which 395 channels are used for voice and 21 channels for control signaling. Therefore, 395 × 30 kHz of bandwidth was used for actual traffic. If we replace that system with a split-band underlay-overlay network we have

$$M(15 + 30) = 395 \times 30 \Rightarrow \mathrm{M} = 263$$

The total number of channels $M = 263$ for each of the overlay and underlay cells and $263 \times 2 = 526$ will be the total number of channels available. This number is 1.34 times larger than the original system, improving the capacity of the system by 34 percent.

Compared with cell splitting or using sectored cells, this technique provides a smaller improvement in capacity. However, it does not need any change in the hardware infrastructure. However, the MS and BS need minor changes to cope up with multiple bandwidths. To further improve the capacity of this technique, it is possible to use another layer of overlay system using even smaller cells. As we saw in Chapter 1, the Japanese analog systems use 25 kHz per user for underlay networks and 12.5 kHz (and even 6.25 kHz) for the overlay networks. The downside of underlay-overlay networks is the increased complexity at the BS for keeping track of which channel belongs to which overlay and increased number of handoffs when a mobile moves from one overlay to the next (or from a microcell to a macrocell). This requires additional complexity at the BS and handoffs when a mobile terminal moves from a microcell to a macrocell.

Reuse Partitioning. The overlaid cell concept described above can be used to increase the capacity of a cellular network through what is called the *reuse partitioning* concept [HAL83]. Here channels are divided among a larger macrocell and a smaller microcell contained entirely within the macrocell. The bandwidth in both cells remains the same. Because the radius of the microcell is smaller, the S_r for the overlay is larger, and it is able to employ a smaller cochannel reuse distance compared with the underlay or macrocell. The channels allocated to the microcell, for instance, may be reused in every third or fourth microcell, whereas the channels allocated to the macrocells can be reused in only every seventh or twelfth cell as the case may be. This requires additional complexity at the BS and handoffs when a mobile terminal moves from a microcell to a macrocell. To explain this situation, consider the following example:

Example 5.14: Reuse Partitioning of 7 and 3

Assume that in Figure 5.17 the radius of the underlay macrocells is R_1 and the radius of the microcells of the overlay is R_2. If we have an AMPS network operating on this infrastructure, the required S_r for both networks is 18 dB. From Equation (5.4), both underlay and overlay networks should have $D_1/R_1 = D_2/R_2 = 4.6$. Because R_2 is smaller than R_1, D_2 can be made smaller than D_1 by a factor equal to the ratio of R_1 to R_2. The improvement in cochannel reuse ratio comes from the fact that the microcells in the overlay are *not* contiguous to one another.

Suppose the cochannel reuse ratio without reuse partitioning was $D_L/R = Q$. The cluster size N in this case is $Q^2/3$ [from Eq. (5.4)], and the number of channels available per cell is $N_c/N = 3N_c/Q^2$. With reuse partitioning, let the ratio of the macrocell radius to the microcell radius be $\kappa = R_1/R_2$. From Example 5.14, the cluster size for the microcells can be reduced by a factor of κ^2 because the microcells are noncontiguous.

Example 5.15: Channel Allocation to Underlay and Overlay Cells

Consider Figure 5.18. Here we are using a cluster size of $N_1 = 7$ for the underlay macrocells to ensure that $D_1/R_1 = 4.6$ provides a suitable S_r for AMPS. We now overlay microcells with a radius R_2 such that the cluster size of the microcells is $N_2 = 3$. If $N_2 = 3$, we can see from Figure 5.18 that $D_2 = 3R_1$. Clearly $3R_1/R_2 = 4.6$

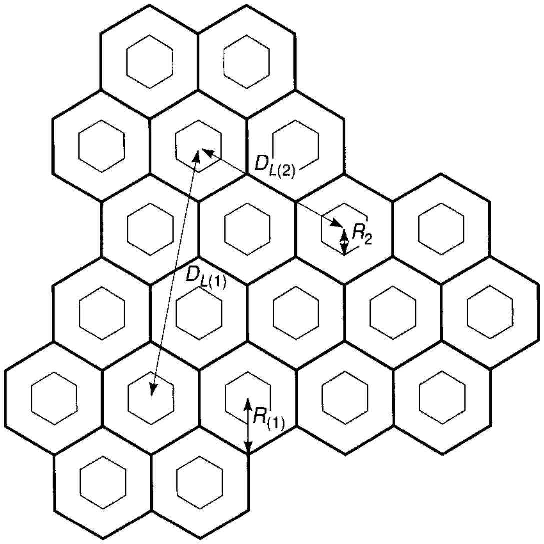


Figure 5.18 Reuse partitioning with a cluster size of seven for the macrocells and three for the microcells.

or $R_2 = 0.652R_1$. One way of allocating channels to the microcells and macrocells is to distribute them by area occupied. This may not be the best case. However, for this example, we employ this technique. The area of a cell is proportional to the square of its radius. We see that the area of a microcell is 0.652^2 times the area of a macrocell or $0.425 \times$ area of macrocell. Let the total number of channels available be N_c. If channels are distributed according to area and there are L channels available per cell, let us assume that $0.425L$ channels are allocated to the microcell and $0.575L$ channels are allocated to the macrocell.

Since the cluster sizes are 7 and 3, respectively, we have:

$$N_c = 7 \times 0.575L + 3 \times 0.425L => L = N_c/5.3$$

The total number of available channels for an AMPS operator is 395. Therefore, $L = 75$. The inner overlay uses approximately 32 channels, and the underlay uses 43 channels. Originally we had 395 channels with $N = 7$, providing approximately 56 channels per cell. The increase in the capacity is $75/56 = 1.34$, a 34 percent increase in capacity. In reality, a larger capacity can be expected because the channels allocated to the macrocells may also be used within the microcells.

Multiple overlays can provide an additional increase in capacity. As compared with the other expansion techniques, the advantages and disadvantages of the frequency reuse partitioning are very similar to frequency splitting. However, reuse partitioning does not need modification in the BS or MS radio equipment, and it can be easily applied to other modulation techniques. The derivation of S_r for frequency splitting was highly correlated with how FM works and, it cannot be extended to digital systems in a straightforward way.

5.6.1.5 Using Smart Antennas

Recently, using smart antennas for capacity expansion has attracted attention [LEH99]. Traditionally, frequency division, time division, and code division multiple access has been employed for cellular communications. Using smart antennas, users in the same cells can use the *same* physical communication channel, as long as they are not located in the same angular region with respect to a BS. Such a multiple access scheme, referred to as space division multiple access (SDMA), can be achieved by the BS *directing* a narrow antenna beam toward a mobile communicating with it. In addition to SDMA, interference between cochannel cells is greatly reduced because the antenna patterns are extremely narrow. In Section 5.7.1.2, we saw that by using sectored cells the reuse factor can be vastly reduced. Even larger advantages can be obtained with smart antennas. Simulations on a frequency-hopped GSM system have reported a capacity increase of 300 percent. A fivefold (500 percent) increase in capacity has been reported for CDMA [LEH99].

5.6.2 Channel Allocation Techniques and Capacity Expansion

In the previous section, we associated each cell with a group of channels that is assigned by the service provider to that cell. In the analysis of capacity, we assumed that all channels in a cell will be used, and we found methods to increase the number of available channels per cell in a given geographic area. We examined a variety of architectural methods to increase the number of available channels per cell. In all these schemes, the number of channels in cells of equal size were assumed to be the same. This assumption would be valid if the distribution of the users in the area was stationary and uniform over all cells. In practice, during the day, a cell in downtown areas of a city carries a high traffic that peaks during rush hour. But this very same cell does not carry a lot of traffic during late evenings or weekends. A cell in a residential area may have traffic characteristics that are the opposite of that of the cell in the downtown area. Clearly, the number of terminals in a cell changes in time, depending on the location of the cell, and this means there is a need for a more complex methodology to allocate channels to the cells dynamically based on the traffic load at a given time. A number of channel allocation strategies have been developed to address this issue [KAT96].

To address channel assignment or allocation techniques in cellular networks, we look at this problem from the point of view of a user. For the user it is not important how many channels are available or how they are allocated. A circuit switched (voice) user will dial a number, and if a channel is available the user is happy. If the call is blocked because a free channel is not available, the user will be dissatisfied with the service provider. A measure of whether channels will be available for a user when that person attempts a call is the probability of call blockage. It depends on the number of available channels and the traffic load. This is thus the quantity that represents user satisfaction. Service providers believe that a probability of call blockage of around 2 percent will keep customers happy, and they aim at this number. However, the probability of call blockage changes its value as mobile terminals move in and out of the boundaries of a cell. A service provider should maintain the number of subscribers under a particular value so that it is possible to accommodate fluctuations in the probability of call blockage over time across all the cells.

The main objective of channel allocation techniques is to stabilize the fluctuations in the probability of call blockage over the entire coverage area of a network over time. Reduction of the fluctuations in probability of call blockage allows service providers to accept a higher number of subscribers over the coverage area. This can be considered equivalent to expansion of the network through additional channels. In other words, as the number of subscribers increase, one way of accommodating such an expansion is to use a more efficient channel allocation technique to cope with the situation. Service providers use a variety of proprietary algorithms for channel allocations. These techniques can be divided into three main categories: fixed channel allocation (FCA), dynamic channel allocation (DCA), and hybrid channel allocation (HCA) techniques. We study these techniques in the following sections.

5.6.2.1 Fixed Channel Allocation (FCA)

In cellular telephony, the number of chunks of frequency spectrum available for the service provider and the bandwidth required per user governs the number of available channels. Fixed channel allocation techniques, in their simplest form, divide the available spectrum by the cluster size to determine the number of radio channels per cell. That is, if the available spectrum is W Hz and each channel needs B Hz, the total number of channels is $N_c = W/B$. If the cluster size is N, the number of channels per cell is $C_c = N_c/N$. These C_c available radio channels are then distributed in the cells in a manner so as to minimize adjacent channel interference. One obvious distribution pattern for channels among the cells is to assign adjacent radio frequency bands to different cells. In analog cellular systems, each radio channel corresponds to one user (one voice channel), whereas in digital TDMA or CDMA networks, each radio frequency channel carries several time slots or codes associated with voice channels.

Example 5.16: Fixed Channel Allocation in GSM

In the GSM cellular system, we have a pair of 25 MHz bands allocated to the downlink or forward channel and uplink or reverse channel. Each radio carrier uses 200 kHz of bandwidth, and each carrier contains eight time slots capable of supporting eight voice users. Potentially we have 125 carriers, but in practice only 124 of them are used. Let us number the channels as 1, 2, 3, . . . , 124. If the cluster size is $N = 4$, the simple FCA technique results in four sets of frequencies given by:

{1, 5, ... , 120} for the first set of cells
{2, 6, ... , 121} for the second set of cells
{3, 7, ... , 122} for the third set of cells
{4, 8, ... , 123) for the fourth set of cells

Example 5.17: AMPS and IS-136

In the U.S. cellular systems discussed in Example 5.8, each service provider has 12.5 MHz of spectrum available. In the downlink or forward channel, service providers use half of the 869–894 MHz band and in the uplink or reverse channel, half of the 824–849 MHz band. These bands are divided into 416 pairs of radio frequency bands, each having 30 kHz chunks for forward and reverse channels. In AMPS each frequency band carries one voice user, whereas in the IS-136 digital TDMA system, three users per 30 kHz of radio channel are supported via time slots. Of the 416 radio frequency channels, 21 are used for control channels and 395 for voice traffic. With FCA and a frequency reuse factor of seven, we can create the following seven sets of frequencies to minimize the interference.

{1, 8, … , 390} for the first set of cells
{2, 9, … , 391} for the second set of cells
…
{7, 14, … , 396} for the seventh set of cells

The FCA strategy described earlier is simple to implement, and if the traffic in the network is uniform, so that the number of active users in each cell is the same, and it remains constant with time, this is also an optimum channel allocation strategy. However, in practice, traffic in each cell changes with time due to the movement of mobile terminals from one cell to another. This results in higher probabilities of call blocking in some cells and lower values in others, which results in poor utilization of the available bandwidth. To equalize the utilization of channels in all cells, the obvious solution is that the cells with higher traffic load should somehow use the free channels available in low traffic cells. This is possible by a nonuniform allocation of channels to cells in the first place. When we assume that the traffic density in all the cells is the same, as illustrated by Examples 5.16 and 5.17, the channel assignment algorithm is very straightforward. We simply divide the total number of available channels by the cluster size of the system and allocate this number of channels to each cell. Using the traffic density and the number of channels in one cell, we can determine the call-blockage probability in that cell. The probability of call blockage in all other cells and consequently the average probability of call blockage in the entire network will be the same as that of one cell. Here the channel assignment algorithm and the calculation of probability of call blockage are performed in two independent steps. With a nonuniform channel allocation technique, we need to include the call blockage probability as a criterion for the channel allocation algorithm. Because the relation between the number of channels and the call-blockage probability is a complex function, this algorithm becomes significantly more complex. The following example helps in the understanding of the complexity involved.

Example 5.18: Probability of Call Blockage with Nonuniform Traffic Distribution

Assume that we have only four cells and one cluster. We simply divide our available channels N_c by four. That is, we assign $N_c/4$ channels per cell. Also assume that for a uniform distribution of the traffic, the calculated probability of blockage for each cell is the desired number (2 percent). If the traffic becomes nonuniform, the blockage rate of all four cells will be changed, and the overall average of them does not remain at 2 percent anymore. The general idea is to increase the number of channels in cells with the higher traffic load and decrease it in cells with a lower traffic load so that the overall blockage rate of the network is minimized. There are four variables, namely, the number of channels per cell and the cost function to be minimized is the probability of call blocking. This has a very complex expression involving these variables. The minimization process is far more complex than the uniformly distributed traffic case for which we know that the same number of channels per cell would provide the minimum blockage rate. This is only one dimension of the complexity of the problem. The other dimension of complexity emerges when we consider cochannel cells having different traffic densities. The optimization problem is now a function of N_c variables, and, in addition, the regular frequency reuse pattern studied earlier does not work any more. The relatively simple frequency reuse pattern strategies discussed earlier were based on the assumption that the channels are fixed and thus calculating the cochannel interference on the basis of having the same number of channels per cell. These patterns become much more complex as we start thinking of unequal number of channels per cell.

Algorithms that distribute channels among the cells according to their traffic load have been investigated. For example, a *nonuniform compact channel allocation algorithm* is discussed in [ZHA91]. This algorithm first defines a set of patterns for nonuniform distribution of channels; then it selects the pattern that minimizes the average call blocking probability in the system. Results of example simulations in [ZHA91] show that nonuniform distribution of channels adopted by this algorithm provide better call blocking probabilities in the system. The reduction in call blocking probabilities allows an average of 10 percent and a maximum of 22 percent traffic to be added to the system while maintaining the same call blocking probability as that of uniform channel allocation. Note that channels are still permanently allocated to cells here, and this still corresponds to fixed channel allocation.

5.6.2.2 Channel Borrowing Techniques

Nonuniform channel allocation is quite complicated. A simpler scheme enables high-traffic cells to *borrow* channel frequencies from low traffic cells and maintain them until significant changes in traffic pattern are measured or predicted. (In other words the high-traffic cells borrow channels from low traffic cells). These techniques are usually referred to as *channel borrowing techniques* [KAT96]. The technical issues are how can we relate the traffic distribution to the channel allocation? And which cell should we borrow the channels from? There are two methods to borrow channels: *temporary channel borrowing* and *static channel borrowing.* In *temporary channel borrowing,* high-traffic cells return the borrowed channels after the call is completed. In *static channel borrowing,* channels are nonuniformly distributed among cells according to the available statistics of the traffic and changed in a predictive manner.

Temporary channel borrowing deals with short-term allocation of borrowed channels to cells. Once a call associated with the borrowed channel is completed, the channel is returned to the cell from which it was borrowed.

Example 5.19: Temporary Channel Borrowing

Let us suppose that we had 49 cells in a region. Let the cluster size be seven. In the case of uniform traffic density, we divide the total number of available channels, N_c, into seven groups and, using prescribed reuse patterns studied in earlier sections, we assign channel groups to different cells (see Figure 5.19). The calculation of the probability of call blockage will remain the same as before and let this value be 2 percent. If we make a pool of the N_c channels and allocate them purely on the basis of demand, we have N_c different channels each with a different characteristic in terms of the traffic on them.

Some channels may not be in use, and others may be continually in use. Depending on how often a channel is used and where it is being used, it may cause a high or low interference to its cochannel elsewhere. Suppose the cell A in the central cluster in Figure 5.19 borrows a channel from the solid-shaded cell F within its cluster to accommodate extra traffic load. This means that the corresponding channel in three cells labeled F and cross-hatched in neighboring clusters are locked until this channel is released by the cell A. This is because the reuse distance for the borrowed channel has decreased since it has been moved from the solidly shaded cell F, to the cell A.

A number of methods for selecting free channels from a lightly loaded cell for borrowing by another cell are summarized in [KAT96]. These methods either make all channels available for borrowing (this is called simple borrowing schemes) or they partition the channels into borrowable and nonborrowable (such schemes are referred to as hybrid borrowing schemes). Simple borrowing schemes are found to be better under light or moderate traffic loads. A quantitative comparison of some

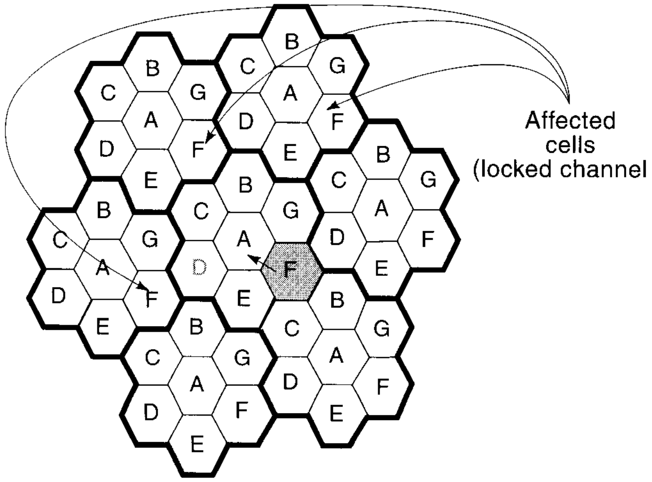


Figure 5.19 Temporary channel borrowing.

of these techniques is provided in [KUE92]. In specific examples addressed in this book, some of the suggested borrowing techniques are found to be capable of supporting up to 35 percent more traffic than uniformly distributed FCA. Channel borrowing schemes, however, require additional computational complexity, and frequent switching of channels. They may also affect handoff strategies.

5.6.2.3 Dynamic Channel Allocation (DCA)

Many researchers have studied the shortcoming of FCA techniques to accommodate temporal and spatial traffic variations and have suggested various DCA techniques in the past two decades. In DCA all channels are placed in a pool, and they are assigned to a new call according to the overall signal to interference pattern in all cells. Each channel can be used in any cell as long as it satisfies the signal to interference ratio requirements for the system. The channel is returned to the pool after the cellular call is terminated. This technique adapts well to the temporal and spatial changes in traffic load. In fact, according to [COX99], the capacity is maximized when the S_r of every set of cochannel users (users in cochannel cells using the same frequency bands) is balanced around some level that is no larger than strictly necessary. The downside is that DCA is extremely complex and inefficient under high-traffic load conditions. Although many claims have been made about the relative performance of each DCA scheme, the trade-offs and the range of achievable capacity gains are still unclear, and a number of questions remain unanswered [KAT96]. Microcellular systems of high-density personal communication networks have been shown to benefit the most out of the DCA, and the results of simulations shows a near ideal performance with DCA algorithms [KAT96].

The basic idea of the DCA is straightforward. However, a number of DCA schemes have been studied. The question then arises as to how these schemes differ from one another. In DCA, often several choices are available for assigning channels to a requesting cell. To devise a selection policy, we have to define a cost function to determine the appropriateness of the channel to be selected. This cost function quantitatively ranks the available channels based on the overall interference, average probability of call-blockage, or parameters that somehow relate to these quantities. The difference between DCA techniques lies in the selection and optimization of this cost function.

In reference [KAT96] a number of DCA schemes are introduced, and they are divided into two categories: centralized and distributed schemes. In centralized schemes, a central pool of all channels exists. The various schemes differ in the way the cost function handles the priorities in selecting a candidate channel and returning it to the central pool upon termination of the call. Distributed DCA techniques are considered for microcellular systems where channel propagation is less predictable and traffic is denser. In these schemes, the BS decides on the frequency assignment locally. Distributed DCA techniques are further divided into two classes: cell-based and interference-based techniques. Cell-based techniques require each BS to maintain a table of available channels in its vicinity and based on this table, the BS decides and assigns the channel to the users in its cell. This technique is very efficient, but the expense incurred is additional inter-BS communication traffic, which increases with the traffic in a cell. To avoid this situation, another subclass of distributed DCA schemes has evolved. Here each BS makes the channel assignment based on the RSS of the mobiles in its vicinity. In such schemes all channels are available to the BS, and the BS make its decision based on the local information without any need to communicate with other BSs. These schemes are self-organizing, simple, efficient, and fast, but they suffer from additional, unwanted cochannel interference which may result in channel interruption and network instability.

Example 5.20: Centralized DCA

In [ZHA89], a locally optimized dynamic assignment strategy is discussed. Here the particular cell allocating channels considers candidate channels based on whether they are being used in the first, second, or third tiers of cochannel cells and so on until the n-th tier. It then assigns the channel with minimum cost to the requested call from the mobile. Simulations of the locally optimized dynamic assignment scheme with 49 cells indicate that the call-blocking probability can be reduced by 40 percent for light loads compared with fixed channel assignment.

Example 5.21: Distributed DCA

Examples of a signal strength–based distributed dynamic channel assignment strategies are simulated in [GOO93]. The distributed DCA schemes are implemented for microcellular environments or one-dimensional cellular systems. Similar schemes are implemented in DECT [KAT96]. When a mobile requests a channel from the BS, the BS measures the interfering signal power on all channels not already assigned to mobiles in its cell. The channel with the maximum S_r is assigned to the mobile. For the same mean traffic, the distributed DCA strategies provide a much lower probability (around 30 to 50 percent lower) of call blocking compared with fixed channel assignment schemes. The exact increase in capacity depends on the number of mobile stations and the offered traffic load in the given cell.

Table 5.1 compares all three classes of algorithms for DCA. It also briefly summarizes the important characteristics of DCA strategies. Centralized DCA strategies do provide optimal or near optimal channel allocation. However, they require a lot of computational and signaling effort because the centralized location has to be aware of the available channel and the necessary parameters required to make an optimum decision on which channel to allocate to an incoming call. These parameters could be how channels are allocated in cochannel cells, what are the S_r values for the channel under consideration, what is the expected traffic load in and around the region, and so on. Also, because the decision mechanism is centralized, it is not robust, and a failure here could lead to an entire systemwide shutdown. In that sense, distributed DCA strategies are better. Cell-based distributed DCA strategies also can allocate channels optimally because BSs can communicate with each other to obtain knowledge of the entire system. Although the BSs make the decisions to allocate channels, the need for frequent communication and update between BSs, is a disadvantage. Signal-strength or measurement-based DCA

Table 5.1 Comparison of Three Classes of Algorithms for DCA [KAT96]

		Distributed DCA	
Algorithm	**Centralized DCA**	***Cell-Based***	***Measurement-Based***
Advantages	Near Optimum Channel Allocation	Near Optimum Channel Allocation	Suboptimal Channel Allocation Simple Assignment Algorithm Use of Local Information Minimum Communication between BSs System Capacity Increases, Efficiency, Radio Coverage Fast Real-Time Processing Adaptive to Traffic Changes
Disadvantages	High-Centralized Overhead	Extensive Communication between BSs	Increased Cochannel Interference Increased Cochannel Interference Deadlock Probability Instability

strategies do not provide optimal allocation of channels. Such schemes do, however, provide some capacity increases and are implemented in digital cordless systems like DECT.

5.6.2.4 Comparison of FCA, DCA, and HCA

Overall, DCA techniques have shown 30 to 40 percent performance improvements over the simple FCA techniques [GOO93]. Table 5.2 compares fixed and dynamic channel allocation strategies.

Under low-to-moderate traffic loads, DCA strategies perform far better than FCA techniques. Because DCA is based on random arrivals of mobiles and random allocation of channels to them, unless maximizing the "packing" of channels is an optimization criterion, it is likely that distances larger than what is required may separate cochannels. This will prevent channels from being reused as often as possible, resulting in less capacity at larger loads. DCA, however, reduces the fluctuations in the call blocking probabilities, as well as forced call terminations. FCA strategies require a lot of "offline" effort in frequency planning. DCA strategies need plenty of effort in real time for channel allocation. A unified framework for comparing all kinds of DCA strategies versus FCA is not available [KAT96], and it is hard to say which of these schemes is actually beneficial. In addition, DCA schemes that jointly optimize power control and handoff strategies have also been proposed.

Because DCA is better at lower traffic loads and FCA is better at higher traffic loads, the natural question of whether the two channel allocation techniques can be combined to provide both advantages arises. Indeed, *hybrid* channel allocation strategies have also been investigated. The total number of channels is partitioned into *fixed* and *dynamic* sets. The ratio of fixed to dynamic channels becomes important in the performance of the system. HCA schemes have been shown to perform better than FCA schemes for load increases up to 50 percent [KAT96].

Table 5.2 Comparison between FCA and DCA [KAT96]

Attribute	Fixed Channel Allocation	Dynamic Channel Allocation
Traffic load	Better under heavy traffic load	Better under light/moderate traffic load
Flexibility in channel allocation	Low	High
Reusability of channels	Maximum possible	Limited
Temporal and spatial changes	Very sensitive	Insensitive
Grade of service	Fluctuating	Stable
Forced call termination	Large probability	Low/moderate probability
Suitability of cell size	Macrocellular	Microcellular
Radio equipment	Covers only the channels allocated to the cell	Has to cover all possible channels that could be assigned to the cell
Computational effort	Low	High
Call setup delay	Low	Moderate/high
Implementation complexity	Low	Moderate/high
Frequency planning	Laborious and complex	None
Signaling load	Low	Moderate/high
Control	Centralized	Centralized, decentralized, or distributed

5.6.3 Migration to Digital Systems

Analog cellular systems had inherent capacity limitations and also had the corresponding disadvantages of analog communication systems. Migration to digital cellular systems during the early 1990s resulted in benefits for both the service providers and end users by providing additional capacity and feature flexibility. In digital AMPS or IS-136, the same 30 kHz channels employed with AMPS were deployed in TDMA format with six time slots per 30 kHz channel increasing the capacity by a factor of up to six. With full-rate voice coding, each user is allowed access to two time slots so that three users can be accommodated on each AMPS carrier. The frequency planning discussed earlier is equally applicable to such TDMA systems because they use exactly the same carriers as the AMPS systems. However, it has been found that the interference that can be tolerated by digital TDMA systems is much larger than AMPS so that a much tighter reuse ratio could be employed. For instance, for the IS-136 systems, an S_r of 12 dB is sufficient as against 18 dB for AMPS. This further increases the capacity because a reuse factor of $N = 4$ is possible. In GSM, an S_r of 9 dB is sufficient with slow frequency hopping and this enables employing a reuse factor of $N = 3$.

Digital CDMA systems can provide an even larger capacity increase because of the various interference combating capabilities of CDMA. With CDMA, the *same frequencies* can be employed in adjacent cells, thereby increasing the reuse factor to one.

5.7 NETWORK PLANNING FOR CDMA SYSTEMS

CDMA presents some unique features that are not present in traditional TDMA and FDMA systems. In TDMA and FDMA systems, the users operating in one channel are completely isolated from the users operating in other channels. The only interference comes from the fact that the same frequency bands are employed in spatially separated cells, and this interference is the cochannel interference. Of course leakage of signal from adjacent bands, causing adjacent channel interference, is also a factor, but intelligent design can reduce this effect greatly. However, in the case of CDMA, all users are operating on the same frequency channel at the same time, resulting in everyone causing cochannel interference. This problem is reduced on the downlink by employing time synchronized orthogonal codes. On the uplink, a combination of convolutional coding, spreading, and orthogonal modulation are employed to combat the effects of this interference. Network planning in the case of CDMA is far more complicated than in the case of TDMA/FDMA in that sense, but at the same time, using CDMA completely eliminates the concept of conventional frequency reuse because the same frequencies can be deployed in all cells.

Instead of defining an acceptable signal-to-interference ratio, in CDMA it is necessary to define the *quality of the signal* [HAL96]. Usually this is expressed in terms of the acceptable energy per bit to total noise ratio E_b/N_t which results in roughly a 1 percent data frame error rate. The reason for selecting this as a measure is that this frame error rate results in acceptable speech quality at the voice encoder output. The value of E_b/N_t is usually around 6 dB and depends on the speed of the mobile terminal, propagation conditions, the number of multipath signals that can be used for diversity, and so on. The value of N_t depends on the number of interfering signals and the transmit powers of the interfering users. Consequently, power control and thresholds play a very important role in the coverage of a CDMA cell and the soft handoff process associated with it. Details of power control and soft handoff in CDMA are discussed in Chapter 8.

5.7.1 Issues in CDMA Network Planning

Many of the principles that apply to TDMA/FDMA systems also apply to CDMA systems, but there are important differences. For example, the path loss is very similar to TDMA systems in that the signal strength drops roughly as the fourth power of the distance in macrocells and is quite site specific and terrain dependent. The design issues that differ are described next.

5.7.1.1 Managing the Noise Floor

In CDMA, managing the noise floor is very important. If the number of users in a particular area increases beyond that dictated by ~~Eq.~~ (~~5.12~~), the system is interference limited, and increasing the transmit power will not benefit any user or set of users as the total interference also increases. It is quite possible that interference from many cells can raise the noise floor to such a level that *holes* may be created in the region where the coding/spreading gain is not sufficient to ~~overcome the in-~~ r/4.4

Equation (4.4)

terference levels. This is illustrated in Figure 5.20 [HAL96]. If there is an isolated three-sector cell, most of the cell has an E_b/N_t larger than 7 dB, and in the regions where there is soft handoff (where the mobile terminal can connect to more than one BS), the E_b/N_t value from each BS is around 3 dB providing sufficient diversity gain to allow communication. If too many cells are deployed as shown in Figure 5.20, there may be some regions where the noise level is so high that it is impossible to communicate. It is often possible to cover the same area with fewer cells to reduce the total interference levels, and it is usually not a very good idea to cover an area by more than three cells or cell sectors. The problem becomes more severe when terrain plays a role, and in addition to site selection, it will be important to use the down tilt of antennas and the use of minimum radiated power levels to manage the noise floor.

5.7.1.2 Cell Breathing

In CDMA, the boundary of a cell is not fixed and depends on where the E_b/N_t value is reached. For example, consider the uplink E_b/N_t value that is observed at a BS. As the number of traffic channels on the uplink is increased, this value also increases and it is clear from Equation (~~5.12~~ 14.4) that the handoff boundary (where the mobile terminal has to move from one BS to another) shifts closer to the BS. This effect is called cell breathing. In order to ensure that a correct handoff is performed, the transmit power of the pilot channel of the BS (see Chapter 8 for details) must also be reduced so that the forward link handoff boundary is also maintained at the same level as the reverse link boundary. In some cases, cell breathing can have a harmful impact on the system performance, and this should be taken into account while planning the system, either by deploying more cells or offloading capacity to other carriers.

5.7.2 Migration from AMPS to IS-95 Systems

IS-95 CDMA systems typically operate on the same frequency bands allocated to AMPS and digital TDMA systems. A single CDMA channel requires removing

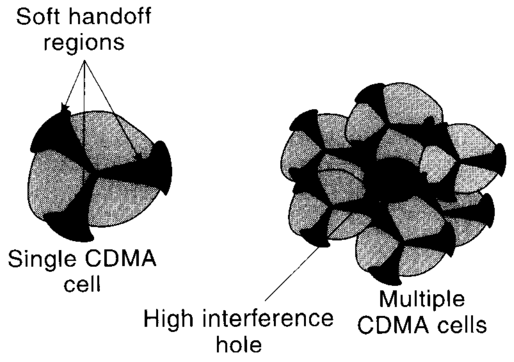


Figure 5.20 Noise floor management in CDMA.

41 contiguous AMPS channels. Because the CDMA carrier requires a different set of signal-to-interference constraints, when service providers are migrating from AMPS to IS-95 systems, care should be taken to minimize the interference between these systems. There are three possible approaches that a service provider may employ to migrate from AMPS to CDMA systems [GAR00]. They are as follows:

1. Two independent systems: one based on AMPS and the other on CDMA
2. An integrated AMPS/CDMA system
3. A partially integrated system with AMPS providing coverage at the fringes and CDMA in the core along with AMPS

The characteristics, advantages, and disadvantages of these approaches are summarized in Table 5.3.

Table 5.3 Approaches to Migrating from AMPS to IS-95

Approach	Characteristics	Advantages	Disadvantages
Independent systems	CDMA uses a separate subset of the spectrum; CDMA may cover a larger area (because of greater capacity)	• Allows independent operation and vendor independence • All digital service everywhere • Smaller number of CDMA BSs can be deployed, reducing capital costs	• Capacity loss due to spectrum segmentation • If there is dumping of analog terminals, the blocking rate for analog subscribers may increase • Operational complexity
Integrated systems	The same service provider provides both CDMA and AMPS over the entire service area	• All digital service everywhere • High-spectral efficiency • Operational simplicity • No need for dual mode phones	• Requires deployment of digital BSs everywhere and may underutilize the available capacity
Partially integrated systems	Part of the system is converted to support both AMPS and CDMA	• CDMA capacity advantage is placed only where it is required • Simpler than the independent approach in terms of operation	• Needs a buffer zone where adjacent AMPS channels are removed and cannot be operated • Digital service will not be available everywhere • Needs dual-mode phones • Voice quality changes are perceived when a handoff is made from CDMA to AMPS

QUESTIONS

5.1 Name any three advantages of an infrastructure topology over an ad hoc topology.

5.2 Compare peer-to-peer and multihop ad hoc topologies.

5.3 Name the five different cell types in the cellular hierarchy and compare them in terms of coverage area and antenna site.

5.4 Why is hexagonal cell shape preferred over square or triangular cell shapes to represent the cellular architecture?

5.5 What are the most popular frequency reuse factors for AMPS, GSM, and IS-95?

5.6 Of the following, what values are possible for a cluster size in a cellular topology? Why? Assume a hexagonal geometry: 8, 21, 23, 30, 47, 61, 75.

5.7 Name five architectural methods that are used to increase the capacity of an analog cellular system without increasing the number of antenna sites.

5.8 Explain why band splitting is not used in 2G cellular networks.

5.9 Explain why reuse-partitioning can be used for both 1G and 2G cellular networks.

5.10 What is the difference between band-splitting and underlay-overlay techniques for increasing the capacity of cellular networks? What is the effectiveness of each in improving the capacity? How do they differ from one another?

5.11 Explain how smart antennas can improve the capacity of a cellular network.

5.12 Explain why in fixed channel allocation techniques neighboring frequency channels are assigned to different cells.

5.13 How are the high interference holes in CDMA deployment created?

5.14 Compare FCA and DCA frequency assignment techniques.

PROBLEMS

5.1 Assume that you have six-sector cells in a hexagonal geometry. Draw the hexagonal grid corresponding to this case. Compute S_r for reuse factors of 7, 4, and 3. Comment on your results.

5.2 Assume that we wanted to deploy an analog FM AMPS system with half band of 15 kHz rather than the existing 30 kHz. Also assume that in analog FM, the carrier-to-interference ratio (C/I) requirement is inversely proportional to the square of the bandwidth (4 time increase in C/I for dividing the band into two).

- **a.** What is the required C/I in dB for the 15 MHz channel if the required C/I for the 30 kHz systems is 18 dB?
- **b.** Determine the frequency reuse factor N needed for the implementation of this 15 kHz per user analog cellular system.
- **c.** If a service provider had a 12.5 MHz band in each direction (up-link and down-link) and it would install 30 antenna sites to provide its service, what would be the maximum number of simultaneous users (capacity) that the system could support in all cells? Neglect the channels that are used for control signaling.
- **d.** If we use the same antenna sites but a 30kHz per channel system with $N = 7$ (instead of the 15 kHz system) what would be the capacity of the new system?

5.3 We have an installed cellular system with 100 sites, a frequency reuse factor of $N = 7$, and 500 overall two-way channels:

a. Give the number of channels per cell, total number of channels available to the service provider, and the minimum carrier-to-interference ratio (C/I) of the system in dB.

b. To expand the network, we decide to create an underlay-overlay system where the new system uses a frequency reuse factor of $K = 3$. Give the number of cells assigned to inner and outer cells to keep a uniform traffic density over the entire coverage area.

5.4 Repeat Problem 5.3 with $N = 12$.

5.5 **a.** What is the number of RF channels per cell in the GSM network described in Chapter 7? The frequency reuse factor of the GSM is $K = 4$.

b. What is the maximum number of simultaneous users per cell in this system?

c. Assume that we want to replace this GSM system with an IS-95 spread spectrum system in the same frequency bands. What is the maximum number of users per cell? Assume an ideal power control and use the practical considerations for the IS-95 system.

5.6 **a.** Determine the carrier-to-interference ratio, in dB, of a cellular system with a frequency reuse factor of $K = 7$.

b. Repeat (a) for $K = 4$.

c. If we consider multi-symbol QAM modulation for the digital transmission of the information, how many more bits per symbol can be transmitted with $K = 4$ as compared with $K = 7$ architecture?