CHAPTER 1

The Cellular Concept and the Need for Propagation Prediction

The introduction of cellular mobile radio (CMR) telephone systems in the early 1980s marked an important turning point in the application of radio technology in communications. Prior to that time, the commercial use of radio spectrum was dominated by broadcast radio and television, although other applications, such as fleet dispatch, walkie-talkies, and citizens band (CB) radio were of growing importance. Broadcast systems are intended to cover an entire metropolitan area from a single transmitter whose signal is in an assigned frequency channel. As a result, the system design goal is to achieve the largest possible coverage area in which the received power is sufficiently strong compared to background noise. This goal is achieved by locating the transmitting antenna on a tall building or tower and radiating the maximum allowed power. In fringe areas, the receiving antennas are also located atop buildings or masts whenever possible. To support the design of broadcast systems, experimental and theoretical studies were made of radio propagation over long distances of 100 km or more, accounting for the earth's curvature, refraction in the atmosphere, and large-scale terrain features.

In contrast, CMR telephone systems were designed to give mobile subscribers access to a communication system by using radio over short links at the end of an otherwise wired network. The short link is intended to cover only a fraction of the metropolitan area, so that the decrease of the radio signal with distance allows the spectrum to be reused elsewhere within the same metropolitan area. In this case the system design goal is to make the received power adequate to overcome background noise over each link, while minimizing interference to other more distant links operating at the same frequency. Achieving such a balance between coverage over the desired links, while avoiding undue interference to other links, greatly complicates the system design problem. Fueled by the enormous commercial success of CMR telephones, many additional wireless systems and applications have been introduced or proposed [1,2] that in one way or another make use of the cellular concept to accommodate many users through spatial reuse of the limited radio spectrum assigned. The purpose of this chapter is to acquaint the reader with the reuse concept and to show why the characteristics of radio propagation are a fundamental feature in determining system design.

The initial deployment of CMR in metropolitan areas employed radio links covering up to about 20 km from the subscriber to the base station (access point to the wired system). However, as more base stations have been added to accommodate the growing number of subscribers, the maximum propagation distance has been reduced significantly. For newer systems, especially those envisioned for indoor applications such as wireless local area networks (W-LANs) and wireless private branch exchanges (W-PBXs), the maximum distance may be no more than a few hundred meters. Over these short links, the buildings have a profound influence on the radio propagation. It is the influence of the buildings on the radio signal that is the principal subject of this book. We also consider the influence of terrain and vegetation, but atmospheric effects are not significant.

Cellular systems have operated in the frequency band from 450 to 900 MHz. Additional bands near 1.9 GHz are now being used throughout the world for second-generation cellular systems, while 3.9 GHz is used for wireless local loops. Unlicensed frequency bands near 900 MHz, 2.4 GHz, and 5.2 GHz are or will be used for wireless LANs, PBXs, and other applications. The wavelength is less than 1 m for these frequencies, making it significantly smaller than the typical dimensions of buildings but larger than the roughness of building materials. As a result, the propagation of radio waves can be understood and described mathematically in terms of the processes of reflection and transmission at walls and diffraction by building edges. To make use of such a description, several chapters are devoted to these processes. Understanding these processes is also important for other systems that have been proposed for operation at higher frequencies, ranging up to 30 GHz.

One cannot speak of the history of CMR, however briefly, without acknowledging the importance of integrated-circuit technology, which has allowed intelligence, control functions, and signal processing to be located in the fixed system and in the subscriber units. The steady progress in microminiaturization since the introduction of CMR is seen in the reduction in size of mobile telephone units from that of a large briefcase to today's pocket phones. Continued progress in miniaturization allows the use of more intelligence and signal processing capability to overcome the limitations imposed by the propagation characteristics of the radio channel (e.g., through the use of smart antenna systems) [3]. However, the design of systems that make use of the intelligence requires an even deeper knowledge of the radio channel.

1.1 Concept of spatial reuse

Multiple access methods allow the separation of simultaneous radio signals sent to or from an individual base station or access point and several mobile subscribers in the same local area. The first access method implemented for cellular telephones was frequency-division multiple access (FDMA), which is used in connection with analog frequency modulation (FM) of the transmitted signal. In FDMA systems for two-way transmission, each subscriber is assigned one frequency channel for the uplink from the subscriber to the base station, and a second channel for the downlink to the subscriber. In North America the currently operating FDMA system, known as AMPS (Advanced Mobile Phone System), has a total of $N_c = 395$ two-way channels, each one-way channel being 30 kHz wide [1, pp. 80–81]. In FDMA systems, spatial reuse amounts to reusing the same N_c frequency channels in different geographical subareas. In this case the frequency reuse plan must place the local areas far enough apart to limit the interference from the other cochannel signals.

The introduction of digital transmission of voice signals has led to new approaches to multiple access. One approach is time-division multiple access (TDMA), in which short segments of digitized voice, or other information, are compressed into shorter time intervals and transmitted at an assigned time slot in a recurring sequence. In one approach known as IS-54, which is intended to permit simple migration from the AMPS system, each 30 kHz AMPS channel is used to carry three digitized voice channels using three time slots [1]. A widely used system known as GSM transmits eight TDMA signals in frequency bands that are 200 kHz wide [1]. If the time slots of all subscribers and base stations are synchronized, multiple access is essentially that of FDMA during a particular time slot. As a result, spatial reuse is similar to that of FDMA.

The most recent cellular telephone systems employ digital transmission with code-division multiple access (CDMA) for distinguishing the signals to and from individual subscribers [4]. In this approach each information bit is transmitted as a coded sequence of shorter-duration bits called *chips*. Because of this encoding, a greater bandwidth must be used for an individual call than would otherwise be needed to send the information bits. However, all subscribers in the system use the same radio-frequency band, with each subscriber having a distinct code that can be distinguished upon reception. To any one subscriber, the interference from signals sent to all the other subscribers appear as background noise, whose level will be inversely proportional to the number of chips per bit (known as the *processing gain*). For one commonly employed CDMA system known as IS-95, each bit of information is transmitted using 128 chips, and the voice channel is spread over an entire 1.23 MHz band. Separate frequency bands are used for downlink and uplink transmission. In this case the spatial reuse plan must limit to an acceptable level the total interference generated by all other subscribers.

Because spatial reuse must balance the need to provide an adequate signal for each subscriber, and at the same time limit the cochannel interference due to signals for other subscribers, radio propagation characteristics play an important role in system design. In the remainder of this chapter we illustrate the concepts of spatial reuse through several examples, and through these examples show why the propagation characteristics are critical in system design. We start by describing spatial reuse in FDMA systems and then briefly discuss the interference limitations in CDMA systems.

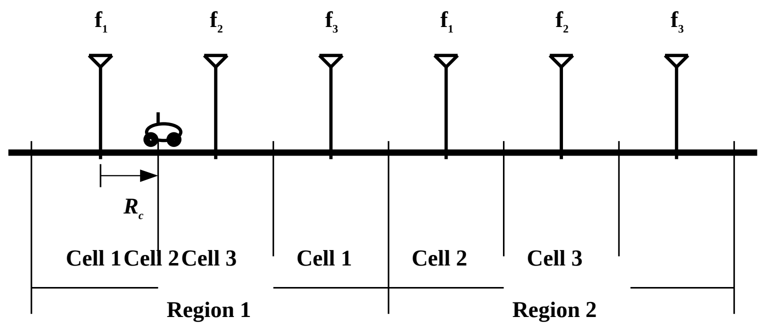

Figure 1-1 One-dimensional cellular FDMA system serving a highway and making use of three cells per frequency reuse region.

1.2 Linear cells as an example of FDMA spectrum reuse

To achieve greater capacity for FDMA systems within a single metropolitan or other large area, the area is divided into a number of regions N that reuse the same set of N_c radio-frequency channels. As a result, the total number of simultaneous phone calls is NN_c, which can be increased as demand requires by dividing the metropolitan area into a greater number N of regions. Each region is further subdivided into N_R cells, each being serviced by a base station to which are assigned a fraction N_c/N_R of the available radio-frequency channels. The base stations are connected through wired lines to switching centers that control the network and connect calls to the wired telephone network. The role of this subdivision is to separate those cells using the same frequency channels by a distance that is large enough to keep the interference small. For example, acceptable voice quality in the North American AMPS system requires that the received power P (watts) of the desired signal from the serving base station must be 50 or more times stronger than the total received interference I (watts) from all other cochannel base stations [5]. Thus the signal to interference ratio P/I must be greater than 50, which on a decibel scale is 10 log 50 = 17 dB.

Figure 1–1 shows a one-dimensional view of how regions might be divided into cells to give coverage along a highway. In this example, each region is divided into $N_R = 3$ cells of radius R_c. On the downlink, a mobile in cell 1 of region 1 will experience the lowest value of received signal P and the highest interference I from region 2 when it is near the right-hand edge of the cell, as shown. In this case the mobile is at a distance R_c from the serving base station and at a distance $(2N_R - 1)R_c$ from the nearest interfering base station using the same frequency, which is located in cell 1 of region 2 in Figure 1–1. To evaluate the ratio P/I at the cell radius, it is necessary to understand how signals propagate in the particular environment.

As discussed in Chapter 4, for propagation in free space the power P received by one antenna due to radiation of P_T watts by a distant antenna has the form $P = P_T\ A/R^n$, where A is a constant, R is the distance between the antennas, and the range index n is 2 [6]. We also show in Chapter 4 that for low base station antennas above a flat earth, a similar expression holds for large enough separation, but in this case the range index is $n = 4$ [6]. Assuming that all base stations radiate the same power, and accounting only for the interference from the nearest cochannel base station at the distance $(2N_R - 1)R_c$, the foregoing dependence for the power received by a subscriber gives the downlink signal-to-interference ratio at the cell boundary:

$$\frac{P}{I} = \frac{P_T A / R_c^{\ n}}{P_T A / [(2N_R - 1)R_c]^n} = (2N_R - 1)^n \tag{1–1}$$

If $N_R = 3$, as in Figure 1–2, the range index $n = 2$ for free space gives $P/I = 25$, which is too small, while the range index $n = 4$ for flat earth gives $P/I = 625$, which is much more than needed. To achieve signal to interference values close to 50 requires $N_R = 4$ if $n = 2$ and $N_R = 2$ if $n = 4$.

The implication of (1–1) can be seen from a simple example for coverage along a six-lane highway at rush hour. If the cars have a center-to-center spacing of 10 m, there are 100 cars per lane per kilometer, and a total of 600 cars/km. If each car has a cell phone that is used 2% of the time, there are 12 simultaneous calls per kilometer on average. If 200 channels of an AMPS system are devoted to cover these calls, then for $n = 2$ it was shown above that $N_R = 4$ and each cell will have 50 channels. In this case each cell has a diameter of $2R_c = 50/12 = 4.2$ km, which is also the spacing between base stations. However, if $n = 4$, then $N_R = 2$ and each cell has 100 channels, in which case the spacing between base stations is $2R_c = 8.4$ km. As seen from this example, the number of base stations needed to serve a given number of subscribers along a roadway is proportional to N_R if trunking efficiency is neglected. Thus the simple example of linear cells shows that the design of the fixed system is strongly dependent on the propagation characteristics of the operating environment. Since installation costs and real estate rental make base stations expensive, economic operation of cellular systems calls for the use of the least number to achieve an acceptable level of service. The foregoing analysis was for the downlink from the base station to the subscriber. A similar analysis applies to the signal-to-interference ratio on the uplink, except that the transmission power of individual mobiles is controlled by the communicating base station, so that the mobiles do not all transmit the same power.

The propagation characteristics encountered in actual metropolitan environments differ in important ways from the simple dependence indicated above. For high base stations, the range dependence of the received power is of the form $P = P_T A/R^n$, where n is typically between 3 and 4. For the low base stations of more advanced systems, A and n can depend on the direction, relative to the street grid, and n can be greater than 4. In addition to the range dependence, the signal is found to have significant random variations over two smaller scale lengths, which are referred to as *fast fading* and *shadow fading*. The effect of this fading is to greatly increase the minimum value of P/I in (1–1). For systems operating inside buildings, propagation is again different. The signal variations observed in different environments are discussed in Chapter 2.

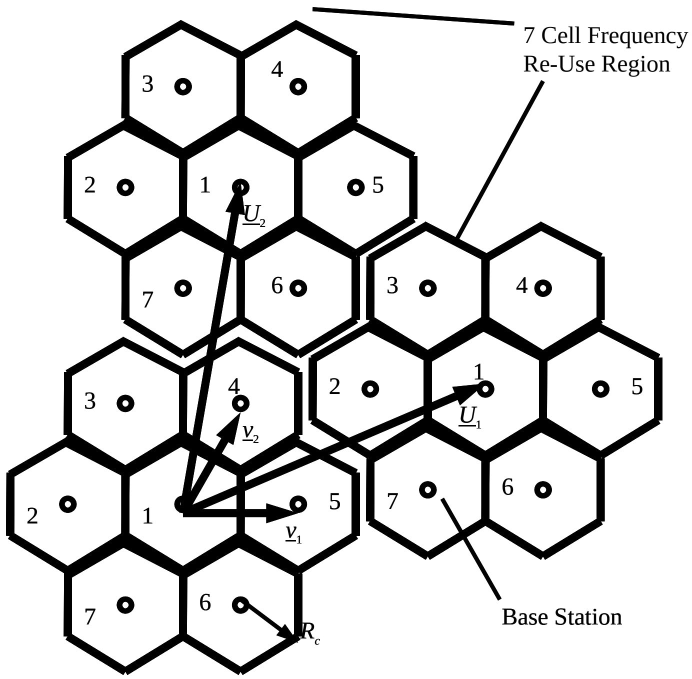

Figure 1-2 Hexagonal cells that are used to cover an area for the case of regions having a symmetric pattern with $N_R = 7$.

1.3 Hexagonal cells for area coverage

The ideas illustrated above for one-dimensional cells have been employed to achieve two-dimensional coverage over a metropolitan area using cells whose conceptual shape is in the form of a hexagon. The choice of the hexagon to represent cell shape is made because hexagons are the highest-degree regular polygons that can tile a plane and because they approximate the circular contours of equal received signal strength when the propagation is isotropic in the horizontal plane. While hexagonal cells are widely used to understand and evaluate system concepts, in actual system planning, terrain and other effects result in cells that are far less regular, even for elevated base station antennas. Also, locating the base stations is strongly influenced by the practical problem of finding acceptable sites and may not follow the regular hexagonal grid.

Hexagonal cells are shown in Figure 1–2 for the case of $N_R = 7$ cells per region. The displacements between any two cells can be expressed as a linear combination of the two basis vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ having an included angle of 60°, as shown in Figure 1–3. If the cell radius R_c is defined to be the distance from the center to any vertex of the hexagon, then $|\mathbf{v}_1| = |\mathbf{v}_2| = \sqrt{3}R_c$. The area of the parallelogram defined by $\mathbf{v}_1$ and $\mathbf{v}_2$ has the same transitional periodicity as the hexagons, hence both have the same area. Thus the area of a hexagon is given by $|\mathbf{v}_1 \times \mathbf{v}_2| = 3R_c^{\ 2}\sin 60°$.

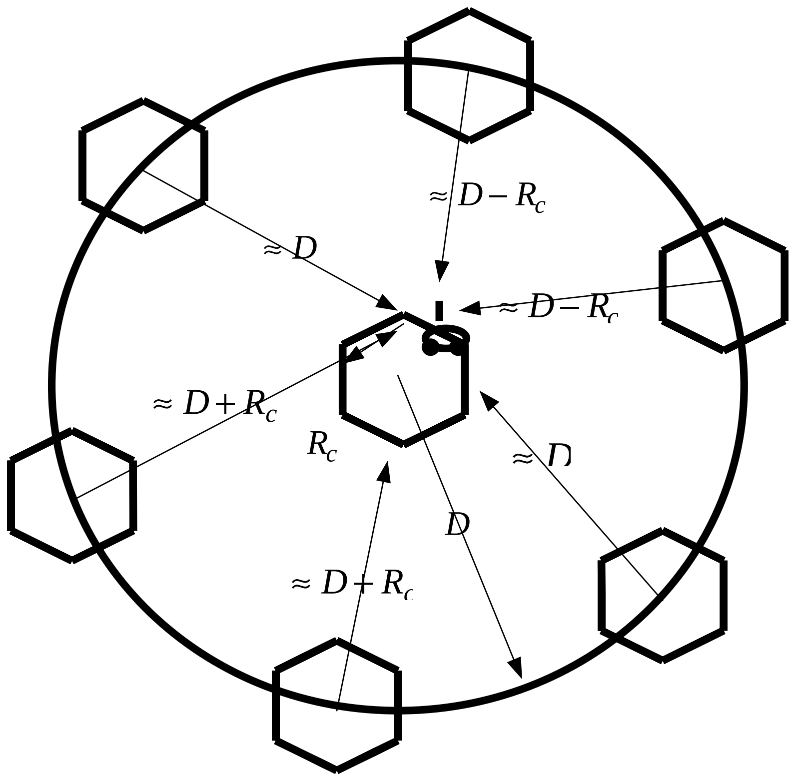

Figure 1-3 Distances to a mobile at the cell edge from interfering FDMA base stations located in the first tier of the serving base station.

The regions of frequency reuse can be composed of any integer number N_R of contiguous cells, and after the region shape is defined, all other regions are obtained by translation of the defining region through a linear combination of the frequency reuse vectors $\mathbf{U}_1$ and $\mathbf{U}_2$ [7], as indicated in Figure 1–2. The displacement between any two cells using the same frequencies can also be expressed as a linear combination of the two reuse vectors. Because the regions have the same transitional periodicity as the parallelogram defined by $\mathbf{U}_1$ and $\mathbf{U}_2$, the area of the region is given by $|\mathbf{U}_1 \times \mathbf{U}_2|$. This area is also equal to N_R times the area of an individual cell. The displacement vector can be expressed in terms of the basis vectors as

$$\begin{aligned} \mathbf{U}_1 &= k_1\mathbf{v}_1 + m_1\mathbf{v}_2 \\ \mathbf{U}_2 &= k_2\mathbf{v}_1 + m_2\mathbf{v}_2 \end{aligned} \tag{1–2}$$

where the constants $k_{1,2}$ and $m_{1,2}$ are integers. In terms of these constants, the area covered by a region is

$$|\mathbf{U}_1 \times \mathbf{U}_2| = |k_1 m_2 - k_2 m_1||\mathbf{v}_1 \times \mathbf{v}_2| \tag{1–3}$$

Since $|\mathbf{U}_1 \times \mathbf{U}_2|$ is equal to N_R times the cell area $|\mathbf{v}_1 \times \mathbf{v}_2|$, it is seen that

$$N_R = |k_1 m_2 - k_2 m_1| \tag{1–4}$$

1.3a Symmetric reuse patterns

Regions may take various shapes for different choices of the integers $k_{1,2}$ and $m_{1,2}$, which can be selected to give any integer value of N_R. Different choices of $k_{1,2}$ and $m_{1,2}$ can result in regions having different shapes but the same value of N_R. For some choices of integers $k_{1,2}$ and $m_{1,2}$, the reuse vectors $\mathbf{U}_1$ and $\mathbf{U}_2$ will be of equal magnitude and the angle between them is 60°, as shown in Figure 1–2. This choice results in a symmetric arrangement of the cochannel cells using the same frequencies into circular tiers about any reference cell. The center-to-center distance from the reference cell to the cochannel cells in a tier are all equal. In the first tier, there are six cochannel cells, as indicated in Figure 1–3, whose distance from the reference cell is $D = |\mathbf{U}_{1,2}|$. Nonsymmetric arrangements having the same value of N_R have some co-channel cells that are closer to the reference cell than the value D for the symmetric region shape, leading to higher values of interference.

For symmetric reuse patterns, only certain values of the reuse factor N_R are possible. To find these values, the coefficients k_2 and m_2 are expressed in terms of k_1 and m_1 by requiring that $\mathbf{U}_2$ have magnitude equal to that of $\mathbf{U}_1$, and be rotated 60° counterclockwise from $\mathbf{U}_1$. This can be achieved by noting that $\mathbf{v}_2$ is rotated 60° counterclockwise from $\mathbf{v}_1$ and that the vector $\mathbf{v}_2 - \mathbf{v}_1$ has the same length as $\mathbf{v}_1$ and $\mathbf{v}_2$, and is rotated 60° counterclockwise from $\mathbf{v}_2$. Thus the rotated vector $\mathbf{U}_2$ can be found in terms of the rotated basis vectors using the same coefficients as in (1–2) for $\mathbf{U}_1$, or

$$\mathbf{U}_1 = k_1\mathbf{v}_2 + m_1(\mathbf{v}_2 - \mathbf{v}_1) = -m_1\mathbf{v}_1 + (m_1 + k_1)\mathbf{v}_2 \tag{1–5}$$

Comparing (1–2) and (1–5) it is seen that $m_2 = -m_1$ and $k_2 = m_1 + k_1$. It is easily verified that $|\mathbf{U}_2|$ is the same as $|\mathbf{U}_1|$ and that the angle between them is 60°. Substituting these expressions for m_2 and k_2 into expression (1–4) gives

$$N_R = m_1^2 + m_1 k_1 + k_1^2 \tag{1–6}$$

Substituting integer values for m_1 and k_1 into (1–6) gives the values of N_R for which the cochannel cells are symmetrically located on circles about any reference cell. These values for N_R are 1, 3, 4, 7, 9, 12, 13, and so on.

1.3b Interference for symmetric reuse patterns

While (1–6) relates N_R to the reuse pattern, an alternative formulation is more useful for examining the relation between N_R and the signal-to-interference ratio for the symmetric patterns. As noted previously, the area of a region can be expressed in terms of D via $|\mathbf{U}_1 \times \mathbf{U}_2| = D^2 \sin 60^\circ$, while the area of a cell is $|\mathbf{v}_1 \times \mathbf{v}_2| = 3(R_c)^2 \sin 60°$. Because the area of a region is N_R times the area of a cell,

$$N_R = \frac{|\mathbf{U}_1 \times \mathbf{U}_2|}{|\mathbf{v}_1 \times \mathbf{v}_2|} = \frac{1}{3}\left(\frac{D}{R_c}\right)^2 \tag{1–7}$$

To evaluate the downlink interference from cochannel cells, consider a mobile at the cell radius, as shown in Figure 1–3, and for simplicity assume that the signal received from the controlling base station is $P = P_T\,A/R^n$. The distance to the nearest two cochannel base stations is approximately $D - R_c$, so that the interference signal from these two base stations is $I = 2P_T\,A/(D - R_c)^n$. The requirement on P/I for analog FM therefore becomes

$$50 \le \frac{P}{I} = \frac{1}{2}\left(\frac{D}{R_c} - 1\right)^n \tag{1–8}$$

or conversely,

$$\frac{D}{R_c} \ge 1 + \sqrt[n]{100} \tag{1–9}$$

For free-space propagation, the range index is $n = 2$, so that from (1–9) we see that $D/R_c = 11$. When this inequality is substituted into (1–7) we obtain $N_R = 40.3$, which is satisfied for a symmetric region having $k_1 = 6$, $m_1 = 1$, so that from (1–6), $N_R = 43$. Accounting for other cochannel base stations in the first tier will require even higher values of N_R. By way of comparison, for propagation over flat earth, $n = 4$, so that from (1–9), $D/Rc = 4.2$. When substituted into (1–7) this inequality requires that $N_R = 5.9$, which is well satisfied by a symmetric region when $N_R = 7$. The significance of this result is that providing adequate service to a frequency reuse region requires at least 43 base stations if $n = 2$ but only 7 base stations if $n = 4$ (assuming that the propagation is of the form $P = P_T\,A/R^n$, and accounting for only two interferers). Since the AMPS system has approximately 400 channels, each base station would handle about 10 calls for $n = 2$, but nearly 60 calls for $n = 4$, giving great savings in infrastructure costs. Even greater savings are achieved for $n = 4$ when the statistical nature of teletraffic is taken into account [2, pp. 44–54].

1.4 Sectored cells

The foregoing examples show how important the propagation characteristics are for an interference-limited system. For high base station antennas covering large cells, the range dependence is of the form $P = P_T\,A/R^n$, usually with n somewhat less than 4, about which there are additional variations that have a random nature. Accounting for the actual range index n and the additional variations, the $N_R = 7$ reuse factor is not adequate to limit the interference from all cochannel base stations for good performance of an AMPS system. For example, if the signal P from the base station is reduced by 10 dB due to a fade, P/I will be a factor of 10 smaller than found from (1–8). Note that if $n = 4$ and $D/R_c = 4.6$, as found from (1–7) for $N_R = 7$, P/I obtained from (1–8) is 82.1 not counting the fading, but only 8.21 when the fade is taken into account.

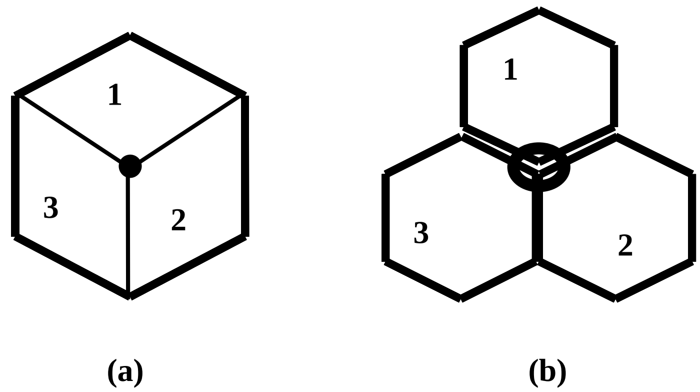

Figure 1-4 Directional antennas at the base station are used to improve signal/interference ratio: a) the conventional approach using 120° beam antennas to illuminate individual sectors in a cell; b) an N_R = 21 pattern with three cells served by a single base station.

To improve the P/I ratio without increasing the number of base stations, the cellular concept is modified by the use of directional antennas at the base station that introduce anisotropy in the coverage. Typically, three antennas having 120° beam width are used to divide each hexagon in an N_R = 7 pattern into three sectors, as indicated in Figure 1–4a. Sectorization has the effect of reducing the number of base stations that cause interference and increasing the distance from mobiles at a cell boundary to the nearest interfering base stations, at the cost of increasing the actual reuse pattern to N_R = 21. Alternatively, one can think of the cells as being organized in a symmetric reuse pattern having N_R = 21 but with the base station located at the cell vertex rather than at the center of the cell. Such an approach is suggested in Figure 1–4b, where it is seen that each base station serves three cells. Such cells can be served by antennas having 60° beam width. Because the antenna beam width is smaller for this approach than for the sectorization of Figure 1–4a, this approach will result in even lower interference from other base stations using the same frequency [8].

1.5 Spatial reuse for CDMA

To understand how the propagation characteristics influence CDMA system design, it is simplest to consider the downlink from base station to mobile. Communication to all subscribers takes place in the same band. Thus the total interference to any one subscriber will come from the signals being sent to the other subscribers in the cell and from the signals being sent to mobiles in other cells from their respective base stations. A mobile will receive all the signals being sent by its base station with equal amplitude since all signals travel over the same path. However, the relative strength of the signals received from other base stations will depend on the propagation characteristics.

Consider a mobile located at the junction of three cells labeled A, B, and C, as shown in Figure 1–5. Through a design feature in CDMA called *soft hand-off*, the subscriber can simulta-

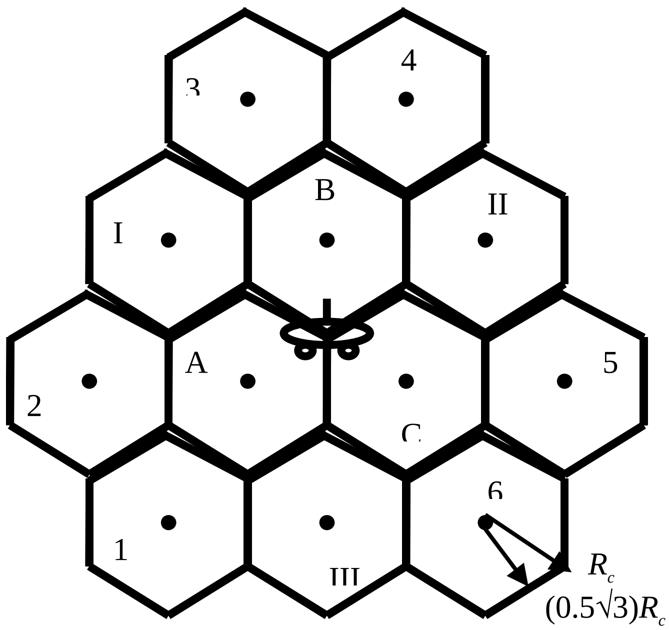

Figure 1-5 Distances from interfering CDMA cells that are located about a mobile at the intersection of three cells.

neously receive and detect the desired signal transmitted independently from the three base stations. If we again assume that the power received from a base station has the dependence $P_T A/R^n$, the sum of the received signals from three base stations is equivalent to a received power

$$P = \frac{3P_T A}{R_c^n} \qquad (1\text{–}10)$$

If there are N_s subscribers in each cell, the interference power due to transmission to the other $N_s - 1$ subscribers in the three cells A, B, C is $3(N_s - 1)P_T A / R_c^n$. Interference also comes from transmission to the N_s subscribers in the surrounding cells. For cells labeled I, II, and III in Figure 1–5, the distance from the base station to the subscriber in question is $2R_c$, while the distance to the six cells labeled 1, 2, ..., 6 is $\sqrt{7}R_c$. Thus the total interference signal I received by the subscriber from the cells shown is

$$I = 3(N_s - 1)\frac{P_T A}{R_c^n} + 3N_s\frac{P_T A}{(2R_c)^n} + 6N_s\frac{P_T A}{(\sqrt{7}R_c)^n} \qquad (1\text{–}11)$$

For adequate detection, the interference I must be less than some multiple $F > 1$ of the desired signal P. The value of F depends on the processing gain, the fraction of the time that a signal is being sent to other subscribers (voice activity factor), and so on. [4]. For this discussion the value of F is not important. After some manipulation using (1–10) and (1–11), the condition $I < FP$ can be written

$$N_s < \frac{F + 1}{1 + 1/2^n + 2/(\sqrt{7})^n} \tag{1–12}$$

From (1–12) it is seen that the number of subscribers that can be accommodated by each base station is directly dependent on the value of n. For example, if $n = 4$, then from (1–12), $N_s < 0.91(F + 1)$, while for $n = 2$ we find from (1–12) that $N_s < 0.65(F + 1)$. Thus when the signals decrease rapidly with distance ($n = 4$), the interfering signals received by a particular mobile from other base stations will be small compared to those received from the base station of the mobile's cell, and the capacity N_s is close to the capacity that would be obtained for a single cell. However, if the signals decrease more slowly with distance ($n = 2$), the contribution to the total interference from other base stations will be larger, and hence the capacity N_s will be reduced. In other words, to cover an area with a given number of users will take more base stations for $n = 2$ than for $n = 4$. Similar interference considerations apply on the uplink, but the analysis is more complex due to the base station's control of the power radiated by the subscribers. When random fading of the received signal is taken into account, it is found desirable to sector the cells, just as in the case of FDMA systems.

1.6 Summary

The foregoing discussions have demonstrated in some detail the importance of the range dependence of radio propagation for system design. Many properties of the radio channel in addition to range dependence affect the capacity and performance of radio communications. Subsequent chapters are devoted to understanding the physical properties of the radio channel and using this understanding to predict channel characteristics. At many points throughout the theoretical development, we compare the theoretical predictions with measurements that have been made.

During the development of the AMPS and related European systems, many measurements were made of the propagation characteristics using signals having a narrow bandwidth of 30 kHz or less. For systems using digital transmission, the signals generated by individual users will have a bandwidth that may be 5 MHz or more, in which case it is often convenient to think in terms of the pulse response in the time domain rather than the frequency domain. In Chapter 2 we review the results of narrowband measurements made for outdoor propagation in cities, as well as wideband pulse measurements that have been made. We also introduce the various statistical measures that have been used to account for the random nature of the channel. In Chapters 3, 4, and 5 we introduce the essential features of plane wave reflection from surfaces, spherical waves radiated from antennas, and diffraction. In Chapter 6 we discuss diffraction models that have been developed to predict the range dependence for portions of cities where the buildings have nearly uniform height. The mechanisms leading to shadow fading are discussed in Chapter 7, along with the effects of terrain and foliage. Ray models that have been developed to predict propagation in environments of high-rise or mixed-height buildings, accounting for the individual buildings in a particular region, are treated in Chapter 8.

Problems

1.1 Consider the arrangement of linear cells in Figure 1–1 and suppose that the received power varies as $P_T A/R^n$ with range index $n = 3$. Find the value of N_R to achieve $P/I \geq 50$, and find the base station separation for the teletraffic of a six-lane highway, as discussed in the paragraph following (1–1).

1.2 Show that $\mathbf{U}_2$ of (1–5) has magnitude equal to that of $\mathbf{U}_1$ and that the angle between $\mathbf{U}_1$ and $\mathbf{U}_2$ is equal to 60°.

1.3 Make up a table showing the values of N_R obtained from (1–6) for symmetric frequency reuse patterns for $1 \leq k_1 \leq 6$ and $0 \leq m_1 \leq 3$. Sketch a frequency reuse pattern for $N_R = 9, 21$.

1.4 For a subscriber at the cell edge, as in Figure 1–3, find the expression corresponding to (1–8) for P/I on the downlink that accounts for interference from all six cochannel base stations in Figure 1–3 (assume that the received power varies as $P_T A/R^n$). Solving (1–7) for D/R_c, show that when all six interferences are accounted for, the $N_R = 7$ reuse pattern satisfies the condition $P/I \geq 50$ when $n = 4$. When $n = 2$, find the value of N_R for symmetric reuse patterns that satisfies $P/I \geq 50$ accounting for the six interferences.

1.5 Consider a set of CDMA cells along a highway, as in Figure 1–1. Assume that a subscriber can receive signals from two base stations, so that a reference subscriber at the boundary of two cells receives the effective signal power $P = 2P_T A / R_c^n$. If there are N_s subscribers per cell, find the interference at the reference subscriber due to a) transmission from the base stations to the other subscribers in the two cells neighboring the reference subscriber; and b) transmission from base stations located at $3R_c$ and $5R_c$ from the reference subscriber. Derive an inequality for N_s from the condition $I < FP$. Evaluate the percent change in N_s when the range index changes from $n = 2$ to $n = 4$.

References

1. D. J. Goodman, Wireless Personal Communications Systems, Addison-Wesley, Reading, Mass., 1997.
2. T. S. Rappaport, Wireless Communications; Principles and Practice, Prentice Hall, Upper Saddle River, N. J., 1996.
3. A. F. Naguiv, A. Paulraj, and T. Kailath, Capacity Improvement with Base-Station Antenna Array Receiver in Cellular CDMA, *IEEE Trans. on Veh. Technol.*, vol. 43, no. 3, pp. 691–698, 1994.
4. A. J. Viterbi, CDMA: Principles of Spread Spectrum Communication, Addison-Wesley, Reading, Mass., 1995.
5. W. C. Y. Lee, Mobile Communications Engineering, McGraw-Hill, New York, 1982.
6. E. C. Jordan and K. G. Balmain, Electromagnetic Waves and Radiating Systems, 2nd Ed., Prentice Hall, Upper Saddle River, N.J., 1968, Chap. 10.
7. M. Mouly, Regular Cellular Reuse Patterns, Proc. 1991 Vehicular Technology Conference, pp. 681–688, 1991.
8. L. C. Wang, K. Chawla, and L. J. Greenstein, Performance Studies of Narrow-Beam Trisector Cellular Systems, Int. J. of Wireless Inf. Networks, vol. 5, no. 2, 1998.