CHAPTER 3

Cellular Concept

3.1 Introduction

The rationale behind cellular systems was given in Chapter 1, where cells were shown to constitute the design of the heart of such systems. A cell is formally defined as an area wherein the use of radio communication resources by the MS is controlled by a BS. The size and shape of the cell and the amount of resources allocated to each cell dictate the performance of the system to a large extent, given the number of users, average frequency of calls being made, average duration of call time, and so on. In this chapter, we study many parameters associated with the cell and their corresponding correlation to the cellular concept.

3.2 Cell Area

In a cellular system, the most important factor is the size and the shape of a cell. A cell is the radio area covered by a transmitting station or a BS. All MSs in that area are connected and serviced by the BS. Therefore, ideally, the area covered by a BS can be represented by a circular cell, with a radius R from the center of the BS (see Figure 3.1(a)). The many factors that cause reflections and refractions of the signals include elevation of the terrain, presence of particles in the air, and a nearby hill, valley, or tall building. The actual shape of the cell is determined by the received signal strength in the surrounding area. Therefore, the coverage area may be a little distorted (Figure 3.1(b)). An appropriate model of a cell is needed before a cellular system can be analyzed and evaluated.

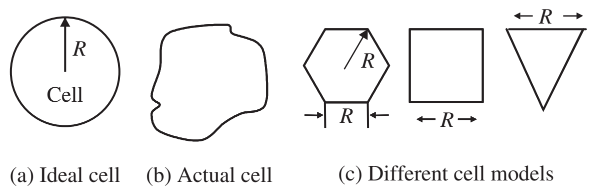


FIGURE 3.1 Shape of the cell coverage area.

There are many possible models that can be used to represent a cell boundary; the most popular alternatives—hexagon, square, and equilateral triangle—are shown in Figure 3.1(c). In most modeling and simulation, hexagons are used, as a hexagon is closer to a circle, and multiple hexagons can be arranged next to each other without having any overlapping area and without leaving any uncovered space in between. In other words, hexagons can fit just like tiles on the floor, and an arrangement of such multiple hexagons (cells) could cover a larger area over the surface of earth. The second most popular cell type is a rectangular shape, which can also function similarly to a hexagon model. The size and capacity of the cell per unit area and the impact of the shape of a cell on service characteristics are shown in Table 3.1. It is clear that if the cell area is increased, the number of channels per unit area is reduced for the same number of channels and is good for less populated areas with fewer cell phone subscribers. On the other hand, if the number of the cell phone users is increased (such as in a dense urban area), a simple-minded solution is to increase the number of the channels. A more practical option is to reduce the cell size so that the number of channels per unit area can be kept comparable to the number of subscribers. Recall that the cell area and the boundary length are important parameters that affect the handoff (known as *handover* outside North America) from a cell to an adjacent cell. Specific schemes to cope with increased traffic are considered later in this chapter in more detail.

TABLE 3.1 Impact of Cell Shape and Radius on Service Characteristics

Shape of the Cell	Area	Boundary	Boundary Length/ Unit Area	Channels/ Unit Area with *N* Channels/ Cells	Channels/ Unit Area when Number of Channels Is Increased by a Factor *K*	Channels/ Unit Area when Size of Cell Is Reduced by a Factor *M*
Square cell (side = R)	R^2	$4R$	$\frac{4}{R}$	$\frac{N}{R^2}$	$\frac{KN}{R^2}$	$\frac{M^2N}{R^2}$
Hexagonal cell (side = R)	$\frac{3\sqrt{3}}{2}R^2$	$6R$	$\frac{4}{\sqrt{3}R}$	$\frac{N}{1.5\sqrt{3}R^2}$	$\frac{KN}{1.5\sqrt{3}R^2}$	$\frac{M^2N}{1.5\sqrt{3}R^2}$
Circular cell (radius = R)	πR^2	$2\pi R$	$\frac{2}{R}$	$\frac{N}{\pi R^2}$	$\frac{KN}{\pi R^2}$	$\frac{M^2N}{\pi R^2}$
Triangular cell (side = R)	$\frac{\sqrt{3}}{4}R^2$	$3R$	$\frac{4\sqrt{3}}{R}$	$\frac{4\sqrt{3}N}{3R^2}$	$\frac{4\sqrt{3}KN}{3R^2}$	$\frac{4\sqrt{3}M^2N}{3R^2}$

3.3 Signal Strength and Cell Parameters

Cellular systems depend on the radio signals received by a MS throughout the cell and on the contours of signal strength emanating from the BSs of two adjacent cells *i* and *j*, as illustrated in Figure 3.2.

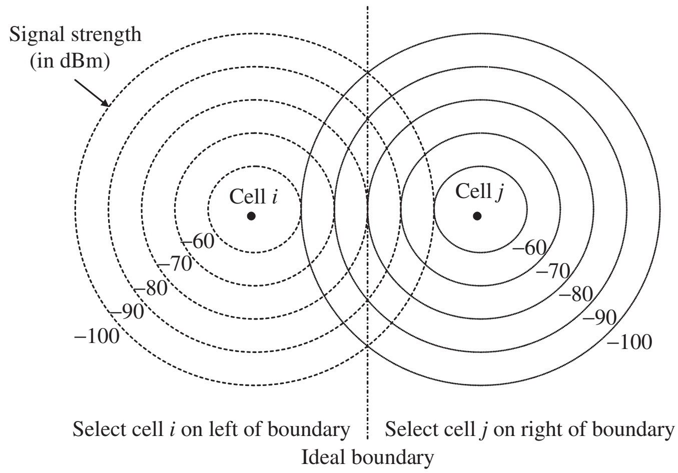


FIGURE 3.2 Signal strength contours around two adjacent cells *i* and *j*.

As discussed earlier, the contours may not be concentric circles and could be distorted by atmospheric conditions and topographical contours. One example of distorted tiles is shown in Figure 3.3.

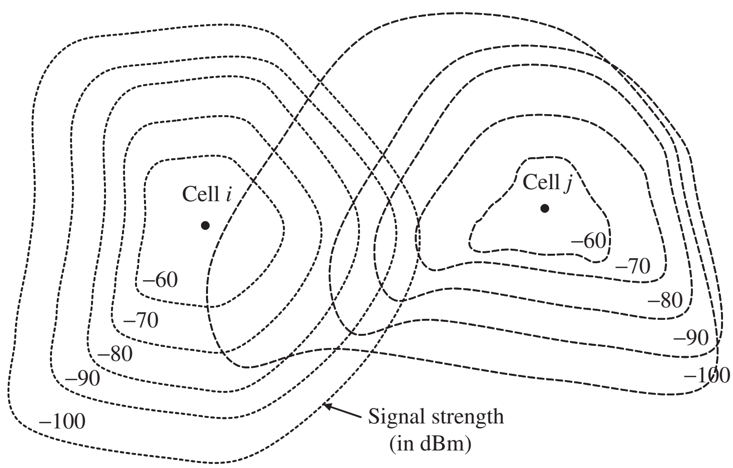


FIGURE 3.3 Received signal strength indicating actual cell tiling.

It is clear that signal strength goes down as one moves away from the BS. The variation of received power as a function of distance is given in Figure 3.4. As the MS moves away from the BS of the cell, the signal strength weakens, and at some point handoff occurs. This implies a radio connection to another adjacent cell. Handoff is illustrated in Figure 3.5, as the MS moves away from cell *i* and gets closer to cell *j*. Assuming that $P_i(x)$ and $P_j(x)$ represent the power received

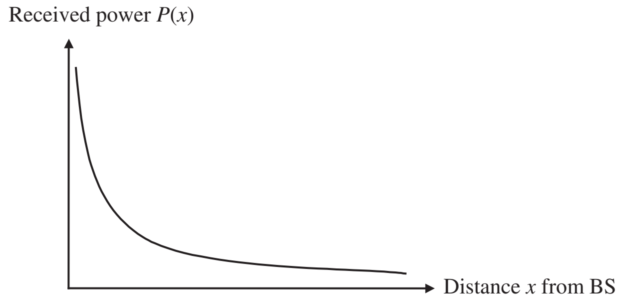


FIGURE 3.4 Variation of received power from a base station.

at the MS from BS_i and BS_j, the received signal strength at the MS can be approximated by curves shown in Figure 3.5 and the variations can be expressed by the empirical relations given in Chapter 2. At distance X_1, the received signal from BS_j is close to zero and the signal strength at the MS can be primarily attributed to BS_i. Similarly, at distance X_2, the signal from BS_i is negligible. To receive and interpret the signals correctly at the MS, the received signals must be at a given minimum power level P_{min}, and distances X_3 and X_4 represent two such points for BS_j and BS_i, respectively. This means that, between points X_3 and X_4, the MS can be served by either BS_i or BS_j, and the choice is left to the service provider and the underlying technology. If the MS has a radio link with BS_i and is continuously moving away toward BS_j, then at some point it has to be connected to the BS_j, and the change of such linkage from BS_i to BS_j is known as handoff. Therefore, region X_3 to X_4 indicates the handoff area. Where to perform handoff depends on many factors. One option is to do handoff at X_5 where two BSs have equal signal strength.

A critical consideration is that the handoff should not take place too quickly to make the MS change the BS too frequently (e.g., ping-pong effect) if the MS moves back and forth between the overlapped area of two adjacent cells due to underlying terrain or intentional movements.

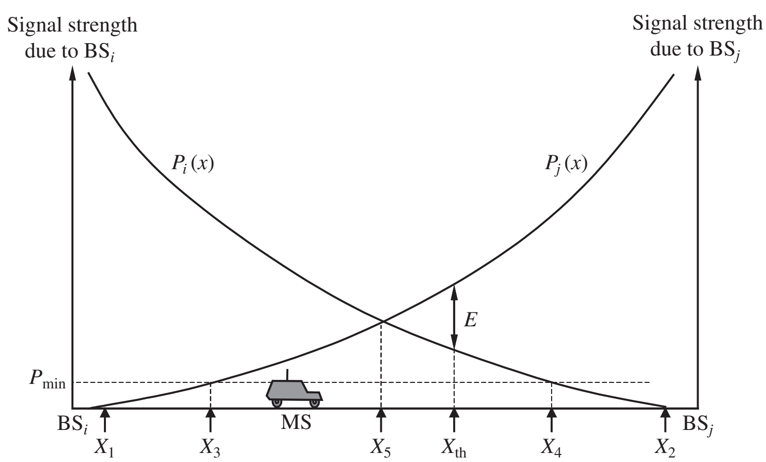


FIGURE 3.5 Handoff region.

To avoid such a "ping-pong" effect, the MS is allowed to continue maintaining a radio link with the current BS_i until the signal strength from BS_j exceeds that of BS_i by some prespecified threshold value E, as is shown by point X_{th} in

Figure 3.5. Thus, besides transmitting power, the handoff also depends on the mobility of the MS.

Another factor that influences handoff is the area and the shape of the cell. Ideally, the cell configuration matches the velocity of the MSs and there is a larger boundary where the handoff rate is minimal. The mobility of an individual MS is difficult to predict [3.1], with each MS having a different mobility pattern. Hence, it is impossible to have an exact match between the cell shape and subscriber mobility. Just to illustrate how handoff is related to the mobility and the cell area, consider a rectangular cell of area A and sides R_1 and R_2 shown in Figure 3.6. Assuming that N_1 is the number of MSs having handoff per unit length in the horizontal direction and N_2 is the similar quantity in the vertical direction, then the handoff could occur along the side R_1 of the cell or cross through the side R_2 of the cell. The number of MSs crossing along the R_1 side of the cell can be given by the component $R_1(N_1 \cos\theta + N_2 \sin\theta)$, and the number of MSs along the length R_2 can be expressed by $R_2(N_1 \sin\theta + N_2 \cos\theta)$. Therefore, the total handoff rate λ_H can be given by Equation (3.1):

$$\lambda_H = R_1(N_1 \cos\theta + N_2 \sin\theta) + R_2(N_1 \sin\theta + N_2 \cos\theta). \tag{3.1}$$

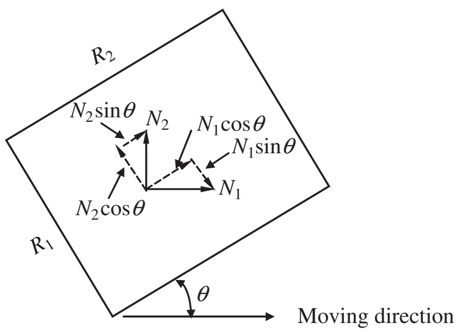


FIGURE 3.6 Handoff rate in a rectangular cell.

Assuming that the area $A = R_1R_2$ is fixed, the question is how to minimize λ_H for a given θ. This is done by substituting the value of $R_2 = A/R_1$, differentiating with respect to R_1, and equating it to zero, which gives us

$$\begin{aligned}\frac{d\lambda_H}{dR_1} &= \frac{d}{dR_1}\left[R_1(N_1 \cos\theta + N_2 \sin\theta) + \frac{A}{R_1}(N_1 \sin\theta + N_2 \cos\theta)\right] \\ &= N_1 \cos\theta + N_2 \sin\theta - \frac{A}{R_1^2}(N_1 \sin\theta + N_2 \cos\theta) \\ &= 0. \end{aligned} \tag{3.2}$$

Thus, we have

$$R_1^2 = A\frac{N_1 \sin\theta + N_2 \cos\theta}{N_1 \cos\theta + N_2 \sin\theta}. \tag{3.3}$$

Similarly, we can obtain

$$R_2^2 = A\frac{N_1 \cos\theta + N_2 \sin\theta}{N_1 \sin\theta + N_2 \cos\theta}. \tag{3.4}$$

Substituting these values in Equation (3.1), we have

$$\begin{aligned}
\lambda_H &= \sqrt{A\left(\frac{N_1 \sin\theta + N_2 \cos\theta}{N_1 \cos\theta + N_2 \sin\theta}\right)}(N_1 \cos\theta + N_2 \sin\theta) \\
&\quad + \sqrt{A\left(\frac{N_1 \cos\theta + N_2 \sin\theta}{N_1 \sin\theta + N_2 \cos\theta}\right)}(N_1 \sin\theta + N_2 \cos\theta) \\
&= \sqrt{A(N_1 \sin\theta + N_2 \cos\theta)(N_1 \cos\theta + N_2 \sin\theta)} \\
&\quad + \sqrt{A(N_1 \cos\theta + N_2 \sin\theta)(N_1 \sin\theta + N_2 \cos\theta)} \\
&= 2\sqrt{A(N_1 \sin\theta + N_2 \cos\theta)(N_1 \cos\theta + N_2 \sin\theta)}. \qquad (3.5)
\end{aligned}$$

The preceding equation can be simplified as

$$\begin{aligned}
\lambda_H &= 2\sqrt{A\left[N_1N_2 + \left(N_1^2 + N_2^2\right)\cos\theta \sin\theta\right]} \\
&= 2\sqrt{A\left(N_1^2 \sin\theta \cos\theta + N_1N_2 \sin^2\theta + N_1N_2 \cos^2\theta + N_2^2 \cos\theta \sin\theta\right)} \\
&= 2\sqrt{A\left[\left(N_1N_2 \sin^2\theta + N_1N_2 \cos^2\theta\right) + \left(N_1^2 \sin\theta \cos\theta + N_2^2 \cos\theta \sin\theta\right)\right]} \\
&= 2\sqrt{A\left[N_1N_2(\sin^2\theta + \cos^2\theta) + \left(N_1^2 + N_2^2\right)\sin\theta \cos\theta\right]} \\
&= 2\sqrt{A\left[N_1N_2 + \left(N_1^2 + N_2^2\right)\sin\theta \cos\theta\right]}. \qquad (3.6)
\end{aligned}$$

Equation (3.6) is minimized when $\theta = 0$. Hence, from Equations (3.6), (3.3), and (3.4) we get

$$\lambda_H = 2\sqrt{AN_1N_2} \qquad (3.7)$$

and

$$\frac{R_2}{R_1} = \frac{N_1}{N_2}. \qquad (3.8)$$

Intuitively, similar results can be expected for cells with other shapes. While it is relatively simple for rectangular cells, it is rather difficult to obtain similar analytical results for other types of cells. The only exception is the circular cell, where the rate of crossing the periphery is independent of direction because of the circle's regular geometry. This means that the handoff is minimized if the rectangular cell is aligned with vertical and horizontal axes and then the number of MSs crossing boundary is inversely proportional to the value of the other side of the cell. An attempt has been made for hexagonal cells in [3.2]—especially to quantify soft handoff wherein the handoff connection to the new BS is made first before breaking an existing connection in the handoff area.

When modeling handoff in cellular systems, it is sufficient to consider a single cell model for most analytical and planning purposes [3.3]. An empirical relation to compute the power received at the MS has been given in Chapter 2.

3.4 Capacity of a Cell

The offered traffic load of a cell is typically characterized by the following two important random parameters:

1. Average number of MSs requesting the service (average call arrival rate λ);
2. Average length of time the MSs requiring the service (average holding time T).

The offered traffic load is defined as

$$a = \lambda T. \tag{3.9}$$

For example, in a cell with 100 MSs, on an average, if 30 requests are generated during an hour, with average holding time $T = 360$ seconds, then the average request rate (or average call arrival rate) is

$$\lambda = \frac{30 \text{ requests}}{3600 \text{ seconds}}. \tag{3.10}$$

A servicing channel that is kept busy for an hour is quantitatively defined as one **Erlang**.

Hence, the offered traffic load for the preceding example by Erlang is

$$\begin{aligned} a &= \frac{30 \text{ calls}}{3600 \text{ seconds}} \times 360 \text{ seconds} \\ &= 3 \text{ Erlangs}. \end{aligned} \tag{3.11}$$

The average arrival rate is λ, and the average service (departure) rate is μ. When all channels are busy, an ariving call is turned away. Therefore, this system can be analyzed by a $M/M/S/S$ queing model. Since $M/M/S/S$ is a special case of $M/M/S/\infty$, the steady-state probabilities $P(i)$s for this system have the same form as those for states $i = 0, \ldots, S$ in the $M/M/S/\infty$ model, where S is the number of channels in a cell. As the sum of all $P(i)$ states equal to 1, we have

$$P(i) = \frac{a^i}{i!} P(0), \tag{3.12}$$

where $a = \lambda/\mu$ is the offered load and

$$P(0) = \left[\sum_{i=0}^{S} \frac{a^i}{i!} \right]^{-1}. \tag{3.13}$$

Therefore, the probability $P(S)$ of an arriving call being blocked is equal to the probability that all channels are busy, that is,

$$P(S) = \frac{\dfrac{a^S}{S!}}{\displaystyle\sum_{i=0}^{S} \frac{a^i}{i!}}. \tag{3.14}$$

Equation (3.14) is called the **Erlang B** formula and is denoted as $B(S, a)$. $B(S, a)$ is also called blocking probability, probability of loss, or probability of rejection.

In the previous example, if S is given as 2 with $a = 3$, the blocking probability is

$$B(2,3) = \frac{\frac{3^2}{2!}}{\sum_{k=0}^{2}\frac{3^k}{k!}} = 0.529. \tag{3.15}$$

Therefore, a fraction of 0.529 calls is blocked, and we need to reinitiate the call. Thus the total number of blocked calls is about $30 \times 0.529 = 15.87$. The efficiency of the system can be given by

$$\begin{aligned}\text{Efficiency} &= \frac{\text{Traffic nonblocked}}{\text{Capacity}}\\ &= \frac{\text{Erlangs} \times \text{portion of used channel}}{\text{Number of channels}}\\ &= \frac{3(1-0.529)}{2}\\ &= 0.7065.\end{aligned} \tag{3.16}$$

The probability of an arriving call being delayed is

$$\begin{aligned}C(S,a) &= \frac{\frac{a^S}{(S-1)!(S-a)}}{\frac{a^S}{(S-1)!(S-a)} + \sum_{i=0}^{S-1}\frac{a^i}{i!}}\\ &= \frac{SB(S,a)}{S-a[1-B(S,a)]}, \qquad \text{for } a < S.\end{aligned} \tag{3.17}$$

This is called the **Erlang C** formula. In the previous example, if $S = 5$ and $a = 3$, we have $B(5,3) = 0.11$. Therefore, the probability of an arriving call being delayed is

$$\begin{aligned}C(S,a) &= \frac{SB(S,a)}{S-a[1-B(S,a)]}\\ &= \frac{5 \times B(5,3)}{5 - 3 \times [1-B(5,3)]}\\ &= \frac{5 \times 0.11}{5 - 3 \times [1-0.11]}\\ &= 0.2360.\end{aligned}$$

3.5 Frequency Reuse

Earlier cellular systems employed FDMA, and the range was limited to a radius from 2 to 20 km. The same frequency band or channel used in a cell can be "reused" in another cell as long as the cells are far apart and the signal strengths do not interfere with each other. This, in turn, enhances the available bandwidth of each cell. A typical cluster of seven such cells and four such clusters with no overlapping area is shown in Figure 3.7.

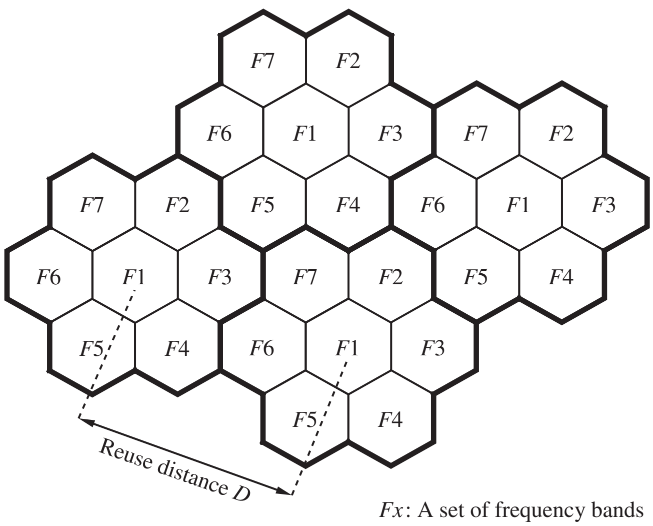


FIGURE 3.7 Illustration of frequency reuse.

In Figure 3.7, the distance between the two cells using the same channel is known as the "reuse distance" and is represented by D. In fact, there is a close relationship between D, R (the radius of each cell) and N (the number of cells in a cluster), which is given by

$$D = \sqrt{3N}R. \tag{3.18}$$

Therefore, the reuse factor q is

$$q = \frac{D}{R} = \sqrt{3N}. \tag{3.19}$$

Example 3.1 A typical cluster has seven cells as shown in Figure 3.7 and each cell has a radius of 1 km. Find the nearest frequency reuse distance and reuse factor.

Since $N = 7$ and $R = 1$ km, the reuse distance of frequency can be calculated by Equation (3.14) as

$$\begin{aligned} D &= \sqrt{3NR} \\ &= \sqrt{3 \times 7} \times 1 \\ &\approx 4.5826 \text{ km.} \end{aligned}$$

Based on Equation (3.15), the frequency reuse factor can be obtained by

$$\begin{aligned} q &= \frac{D}{R} \\ &= \sqrt{3N} \\ &= \sqrt{3 \times 7} \\ &\approx 4.5826. \end{aligned}$$

Another popular cluster size is with $N = 4$. In fact, the arguments made in selecting a rectangular versus hexagonal shape of the cell are also applicable to the size of the hex cell clusters such that multiple copies of such clusters should fit well with each other, just like a puzzle. Additional areas can be covered by additional clusters without having any overlapped area. In general, the number of cells N per cluster is given by $N = i^2 + ij + j^2$. Here i represents the number of cells to be traversed along direction i, starting from the center of a cell, and j represents the number of cells in a direction 60° to the direction of i. Substituting different values of i and j leads to $N = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 28, \ldots$; the most popular values are 7 and 4. Finding the center of all clusters around a reference cell for some selected values of N is illustrated in Figure 3.8. Repeating this for all six sides of the reference cell leads to the center for all adjacent clusters. Unless specified, a cluster of size 7 is assumed throughout this book.

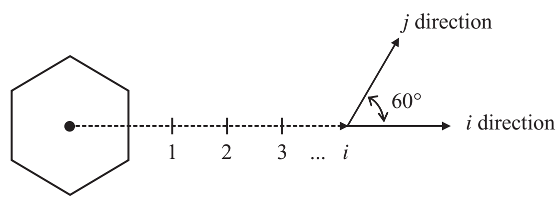


FIGURE 3.8 Finding the center of an adjacent cluster using integers *i* and *j* (directions of *i* and *j* can be interchanged).

3.6 How to Form a Cluster

In general, $N = i^2 + ij + j^2$, where i and j are integers. For computing convenience, we assume $i \geq j$. Based on the theory given in the article [3.4], we discuss a method to form a cluster of N cells as follows. (Note: this method is only for the case $j = 1$.)

First, select a cell, make the center of the cell as the origin, and form the coordinate plane as shown in Figure 3.9. The positive half of the u-axis and the positive half of the v-axis intersect at a 60-degree angle. Define the unit distance as the distance of centers of two adjacent cells. Then for each cell center, we can get an ordered pair (u, v) to mark the position.

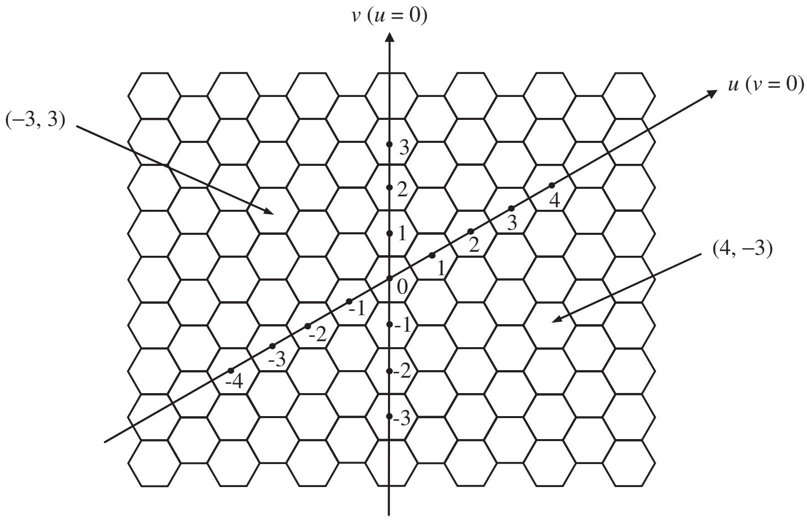


FIGURE 3.9 *u* and *v* coordinate plane.

Since this method is only for those cases $j = 1$ with a given N, integer i is also fixed by

$$\begin{aligned} N &= i^2 + ij + j^2 \\ &= i^2 + i + 1. \end{aligned} \tag{3.20}$$

Then using

$$L = [(i + 1)u + v]\mathrm{mod}N, \tag{3.21}$$

we can obtain the label L for the cell whose center is at (u, v) . For the origin cell whose center is (0, 0), $u = 0$, $v = 0$, using Equation (3.21), we have $L = 0$ and label this cell as 0. Then we compute the labels of all adjacent cells. Finally, the cells with labels from 0 through $N - 1$ form a cluster of N cells. The cells with the same label can use the same frequency bands.

Now we give an example of $N = 7$ as follows. Using Equation (3.20), we have $i = 2$. Then using Equation (3.21), we have $L = (3u + v) \bmod 7$. We can compute label L for any cell using its center's position (u, v). The results are shown in Table 3.2.

TABLE 3.2 Some Cell Labels for $N = 7$

u	0	1	−1	0	0	1	−1
v	0	0	0	1	−1	−1	1
L	0	3	4	1	6	2	5

For each cell, we use its L values to label it. The results are shown in Figure 3.10. The cells with labels 0 through 6 form a cluster of 7 cells.

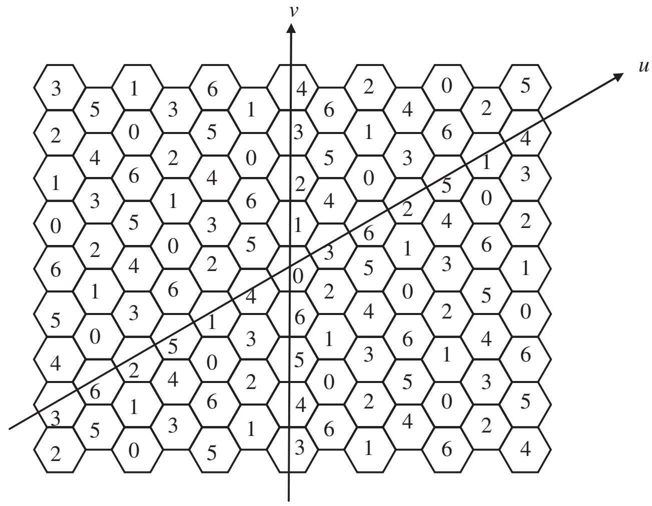


FIGURE 3.10 Cell label L for 7-cell cluster.

Using the same method, we also have the results for $N = 13$ as shown in Figure 3.11, with $i = 3$ and $j = 1$, giving $L = (4u + v) \bmod 13$. Some common reuse cluster patterns are given in Figure 3.12.

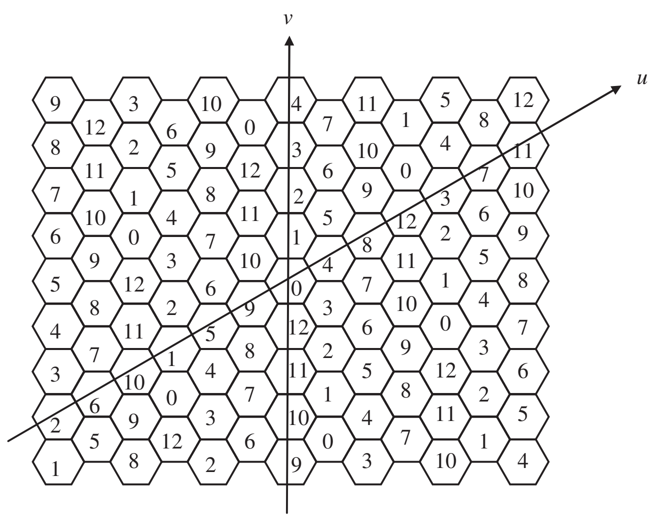


FIGURE 3.11 Cell label L for 13-cell cluster.

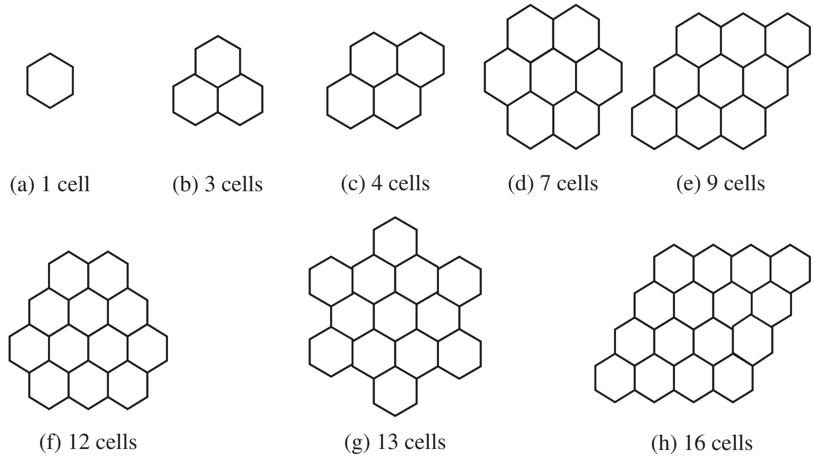


FIGURE 3.12 Common reuse pattern of hex cell clusters.

3.7 Cochannel Interference

As indicated earlier, there are many cells using the same frequency band. All the cells using the same channel are physically located apart by at least reuse distance. Even though the power level is controlled carefully so that such "co-channels" do not create a problem for each other, there is still some degree of interference due to nonzero signal strength of such cells. In a cellular system, with a cluster of seven cells, there will be six cells using cochannels at the reuse distance; this is illustrated in Figure 3.13. The second-tier cochannels, shown in the figure, are at two times the reuse distance apart, and their effect on the serving BS is negligible.

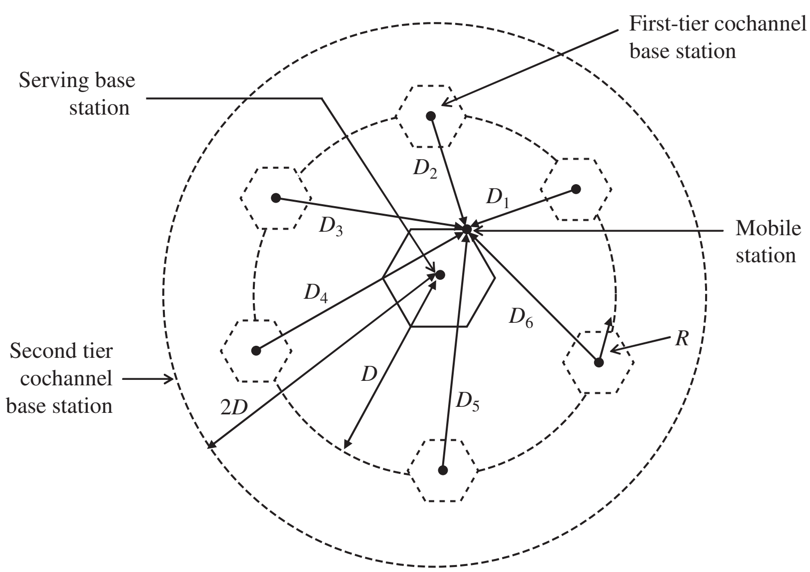


FIGURE 3.13 Cells with cochannels and their forward channel interference on transmitted signal.

The Cochannel Interference Ratio (CCIR) is given by

$$\frac{C}{I} = \frac{\text{Carrier}}{\text{Interference}} = \frac{C}{\sum_{k=1}^{M} I_k}, \tag{3.22}$$

where I_k is the cochannel interference from BS_k and M is the maximum number of cochannel interfering cells. For cluster size of 7, $M = 6$, CCIR is given by

$$\frac{C}{I} = \frac{1}{\sum_{k=1}^{M} \left(\frac{D_k}{R}\right)^{-\gamma}}, \tag{3.23}$$

where γ is the propagation path loss slope and varies between 2 and 5.

When $D_1 = D_2 = D - R$, $D_3 = D_6 = D$, and $D_4 = D_5 = D + R$ (see Figure 3.14), the cochannel interference ratio in the worst case for the forward channel (downlink) is given as

$$\frac{C}{I} = \frac{1}{2(q-1)^{-\gamma} + 2q^{-\gamma} + 2(q+1)^{-\gamma}}, \tag{3.24}$$

where $q \left(= \frac{D}{R}\right)$ is the frequency reuse factor.

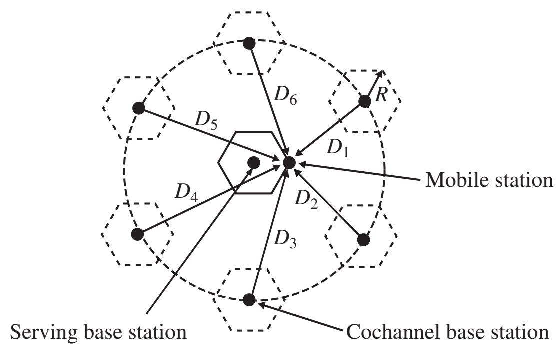


FIGURE 3.14 The worst case for forward channel interference (omnidirectional antenna).

Example 3.2 Calculate the cochannel interference ratio in the worst case for the forward channel in Figure 3.14, given $N = 7$, $R = 2$ km, and $\gamma = 1.5$.

For this system, the frequency reuse factor q can be calculated as

$$q = \sqrt{3N} = \sqrt{3 \times 7} \approx 4.5826.$$

Thus, the worst cochannel interference can be calculated by Equation (3.24) as

$$\begin{aligned}\frac{C}{I} &= \frac{1}{2(q-1)^{-\gamma} + 2q^{-\gamma} + 2(q+1)^{-\gamma}} \\ &= \frac{1}{2 \times (4.5826 - 1)^{-1.5} + 2 \times 4.5826^{-1.5} + 2 \times (4.5826 + 1)^{-1.5}} \\ &\approx 1.5374.\end{aligned}$$

There are many techniques that have been proposed to reduce interference. Here we consider only two specific ways: cell splitting and cell sectoring.

3.8 Cell Splitting

Until now, we have been considering the same size for each cell across the board. This implies that the BSs of all cells transmit information at the same power level so that the net coverage area for each cell is the same. At times, this may not be feasible, and, in general, this may not be desirable. Service providers would like to service users in a cost-effective way, and resource demand may depend on the concentration of users in a given area. Change in number of users could also occur over a period of time. One way to cope with increased traffic is to split a cell into several smaller cells; this is illustrated in Figure 3.15. This implies that additional BSs need to be established at the center of each new cell that has been added so that the higher density of calls can be handled effectively. As the coverage area of new split cells is smaller, the transmitting power levels are lower, and this helps in reducing cochannel interference.

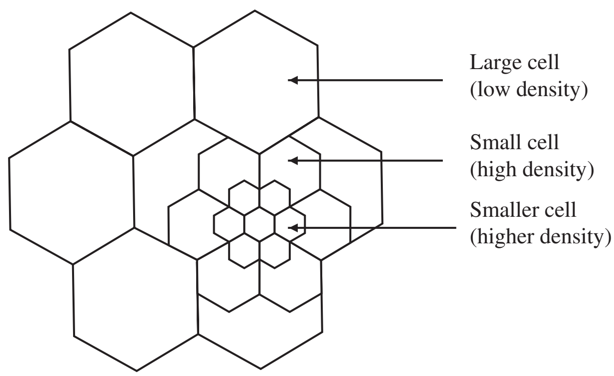
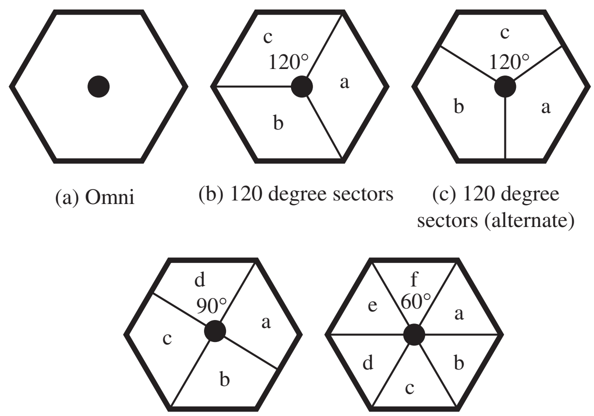


FIGURE 3.15 Illustration of cell splitting.

3.9 Cell Sectoring

We have been primarily concentrating on what are known as omnidirectional antennas, which allow transmission of radio signals with equal power strength in all directions. It is difficult to design such antennas, and most of the time, an antenna covers an area of 60 or 120 degrees; these are called directional antennas, and cells served by them are called sectored cells. Different sizes of sectored cells are shown in Figure 3.16. From a practical point of view, many sectored antennas are mounted on a single microwave tower located at the center of the cell, and an adequate number of antennas are placed to cover the whole 360 degrees of the cell. For example, the 120 degree sectored cell shown in Figures 3.16(b) and (c) requires three directional antennas. In practice, the effect of an omnidirectional antenna can be achieved by employing several directional antennas to cover the whole 360 degrees.



(a) Omni (b) 120 degree sectors (c) 120 degree sectors (alternate)

(d) 90 degree sectors (e) 60 degree sectors

FIGURE 3.16 Sectoring of cells with directional antennas.

The advantages of sectoring (besides easy borrowing of channels, which is discussed in Chapter 6) are that it requires each antenna to cover a smaller area, thus lowering the power required to transmit radio signals. It also helps in decreasing interference between cochannels, as discussed in Section 3.5. It is also observed that the spectrum efficiency of the overall system is enhanced. It is found that a quad-sector architecture of Figure 3.16(d) has a higher capacity for 90% area coverage than a tri-sector cell [3.5].

The cochannel interference for cells using directional antennas can also be computed. The worst case for the three-sector directional antenna is shown in Figure 3.17. From the figure, we have

$$\begin{aligned} D &= \sqrt{\left(\frac{9}{2}R\right)^2 + \left(\frac{\sqrt{3}}{2}R\right)^2} \\ &= \sqrt{21}R \\ &\approx 4.58R \end{aligned} \tag{3.25}$$

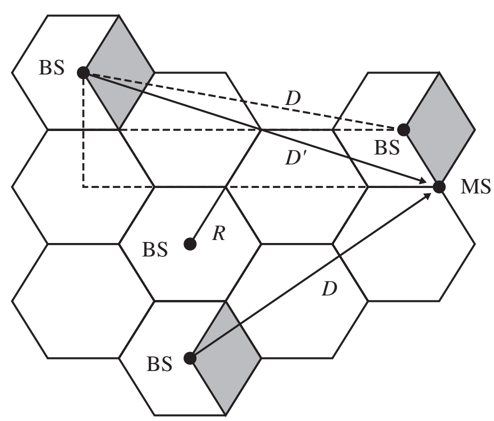


FIGURE 3.17 The worst case for forward channel interference in three sectors (directional antenna).

and

$$
\begin{aligned}
D' &= \sqrt{(5R)^2 + (\sqrt{3}R)^2} \\
&= \sqrt{28}R \\
&\approx 5.29R \\
&= D + 0.7R.
\end{aligned}
\tag{3.26}
$$

Therefore, CCIR can be obtained as

$$
\frac{C}{I} = \frac{1}{q^{-\gamma} + (q + 0.7)^{-\gamma}}. \tag{3.27}
$$

The CCIR in the worst case for the six-sector directional antenna (see Figure 3.18) when $\gamma = 4$ can be given by

$$
\frac{C}{I} = \frac{1}{(q + 0.7)^{-\gamma}} = (q + 0.7)^4. \tag{3.28}
$$

Thus, we can see that the use of a directional antenna is helpful in reducing co-channel interference.

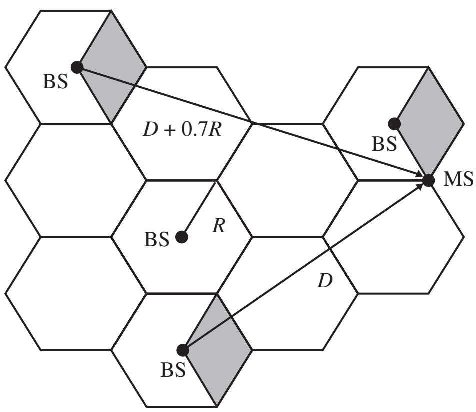


FIGURE 3.18 The worst case for forward channel interference in six sectors (directional antenna).

It is worth mentioning that there is an alternative way of providing sectored or omni-cell coverage, by placing directional transmitters at the corners where three adjacent cells meet (see Figure 3.19). It may appear that the arrangement of Figure 3.19 may require three times the transmitting towers as compared to a system with towers placed at the center of the cell. However, careful consideration reveals that the number of transmitting towers remains the same, as the antennas for adjacent cells B and C could also be placed on the towers X, and for a coverage area with a larger number of cells, the average number of towers approximately remains the same.

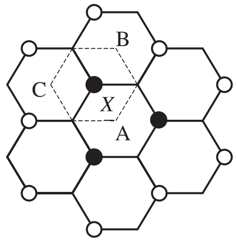


FIGURE 3.19 An alternative placement of directional antennas at three corners.

3.10 Summary

This chapter provides an overview of various cell parameters, including area, load, frequency reuse, cell splitting, and cell sectoring. As limited bandwidth has been allocated for wireless communications, the reuse technique is shown to be useful for both FDMA and TDMA schemes. In the next chapter, we discuss how a control channel can be accessed by multiple MSs and how collision can be avoided.

3.11 References

[3.1] A. Bhattarcharya and S. Das, "LeZi-Update: An Information Theoretic Approach to Track Mobile Users in PCS Networks," *ACM/Kluwer Journal on Wireless Networks*, Vol. 8, No. 2–3, pp. 121–135, May 2002.

[3.2] J. Y. Kwan and D. K. Sung, "Soft Hand Off Modeling in CDMA Cellular Systems," *Proceedings of the IEEE Conference on Vehicular Tecnology (VTC'97)*, pp. 1548–1551, May 1997.

[3.3] P. V. Orlik and S. S. Rappaport, "On the Handoff Arrival Process in Cellular Communications," *Wireless Networks*, Vol. 7, No. 2, pp. 147–157, March/April 2001.

[3.4] V. H. MacDonald, "Advanced Mobile Phone Service—The Cellular Concept," *Bell System Technical Journal*, Vol. 58, No. 1, pp. 15–41, Jan. 1979.

[3.5] O. W. Ata, H. Seki, and A. Paulraj, "Capacity Enhancement in Quad-Sector Cell Architecture with Interleaved Channel and Polarization Assignments," *IEEE International Conference on Communications (ICC)*, Helsinki, Finland, pp. 2317–2321, June 2001.

3.12 Experiments

Experiment 1

- **Background:** Cell capacity is a key concept in wireless and mobile systems. When the traffic load is increased, an appropriate strategy is desirable to enhance the effective cell capacity, such as cell splitting. Therefore,