leaks energy into the cellular frequency band. Interference on voice channels causes cross talk, where the subscriber hears interference in the background due to an undesired transmission. On control channels, interference leads to missed and blocked calls due to errors in the digital signaling. Interference is more severe in urban areas, due to the greater RF noise floor and the large number of base stations and mobiles. Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls. The two major types of system-generated cellular interference are *co-channel interference* and *adjacent channel interference*. Even though interfering signals are often generated within the cellular system, they are difficult to control in practice (due to random propagation effects). Even more difficult to control is interference due to out-of-band users, which arises without warning due to front end overload of subscriber equipment or intermittent intermodulation products. In practice, the transmitters from competing cellular carriers are often a significant source of out-of-band interference, since competitors often locate their base stations in close proximity to one another in order to provide comparable coverage to customers.

3.5.1 Co-channel Interference and System Capacity

Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called *co-channel cells*, and the interference between signals from these cells is called *co-channel interference*. Unlike thermal noise which can be overcome by increasing the signal-to-noise ratio (SNR), co-channel interference cannot be combated by simply increasing the carrier power of a transmitter. This is because an increase in carrier transmit power increases the interference to neighboring co-channel cells. To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation.

When the size of each cell is approximately the same and the base stations transmit the same power, the co-channel interference ratio is independent of the transmitted power and becomes a function of the radius of the cell (R) and the distance between centers of the nearest co-channel cells (D). By increasing the ratio of D/R, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased. Thus, interference is reduced from improved isolation of RF energy from the co-channel cell. The parameter Q, called the *co-channel reuse ratio*, is related to the cluster size (see Table 3.1 and Equation (3.3)). For a hexagonal geometry

$$Q = \frac{D}{R} = \sqrt{3N} \tag{3.4}$$

A small value of Q provides larger capacity since the cluster size N is small, whereas a large value of Q improves the transmission quality, due to a smaller level of co-channel interference. A trade-off must be made between these two objectives in actual cellular design.

Table 3.1 Co-channel Reuse Ratio for Some Values of N

	Cluster Size (N)	Co-channel Reuse Ratio (Q)
$i = 1, j = 1$	3	3
$i = 1, j = 2$	7	4.58
$i = 0, j = 3$	9	5.20
$i = 2, j = 2$	12	6

Let i_0 be the number of co-channel interfering cells. Then, the signal-to-interference ratio (S/I or SIR) for a mobile receiver which monitors a forward channel can be expressed as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} \tag{3.5}$$

where S is the desired signal power from the desired base station and I_i is the interference power caused by the ith interfering co-channel cell base station. If the signal levels of co-channel cells are known, then the S/I ratio for the forward link can be found using Equation (3.5).

Propagation measurements in a mobile radio channel show that the average received signal strength at any point decays as a power law of the distance of separation between a transmitter and receiver. The average received power P_r at a distance d from the transmitting antenna is approximated by

$$P_r = P_0\left(\frac{d}{d_0}\right)^{-n} \tag{3.6}$$

or

$$P_r(\text{dBm}) = P_0(\text{dBm}) - 10n\log\left(\frac{d}{d_0}\right) \tag{3.7}$$

where P_0 is the power received at a close-in reference point in the far field region of the antenna at a small distance d_0 from the transmitting antenna and n is the path loss exponent. Now consider the forward link where the desired signal is the serving base station and where the interference is due to co-channel base stations. If D_i is the distance of the ith interferer from the mobile, the received power at a given mobile due to the ith interfering cell will be proportional to $(D_i)^{-n}$. The path loss exponent typically ranges between two and four in urban cellular systems [Rap92b].

When the transmit power of each base station is equal and the path loss exponent is the same throughout the coverage area, S/I for a mobile can be approximated as

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}} \tag{3.8}$$

Considering only the first layer of interfering cells, if all the interfering base stations are equidistant from the desired base station and if this distance is equal to the distance D between cell centers, then Equation (3.8) simplifies to

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0} \tag{3.9}$$

Equation (3.9) relates S/I to the cluster size N, which in turn determines the overall capacity of the system from Equation (3.2). For example, assume that the six closest cells are close enough to create significant interference and that they are all approximately equidistant from the desired base station. For the U.S. AMPS cellular system which uses FM and 30 kHz channels, subjective tests indicate that sufficient voice quality is provided when S/I is greater than or equal to 18 dB. Using Equation (3.9), it can be shown in order to meet this requirement, the cluster size N should be at least 6.49, assuming a path loss exponent $n = 4$. Thus a minimum cluster size of seven is required to meet an S/I requirement of 18 dB. It should be noted that Equation (3.9) is based on the hexagonal cell geometry where all the interfering cells are equidistant from the base station receiver, and hence provides an optimistic result in many cases. For some frequency reuse plans (e.g., $N = 4$), the closest interfering cells vary widely in their distances from the desired cell.

Using an exact cell geometry layout, it can be shown for a seven-cell cluster, with the mobile unit at the cell boundary, the mobile is approximately $D - R$ from the two nearest co-channel interfering cells and approximately $D + R/2$, D, $D - R/2$, and $D + R$ from the other interfering cells in the first tier, as shown rigorously in [Lee86]. Using the approximate geometry shown in Figure 3.5, Equation (3.8), and assuming $n = 4$, the signal-to-interference ratio for the worst case can be closely approximated as (an exact expression is worked out by Jacobsmeyer [Jac94])

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}} \tag{3.10}$$

Equation (3.10) can be rewritten in terms of the co-channel reuse ratio Q, as

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-4} + 2(Q+1)^{-4} + 2Q^{-4}} \tag{3.11}$$

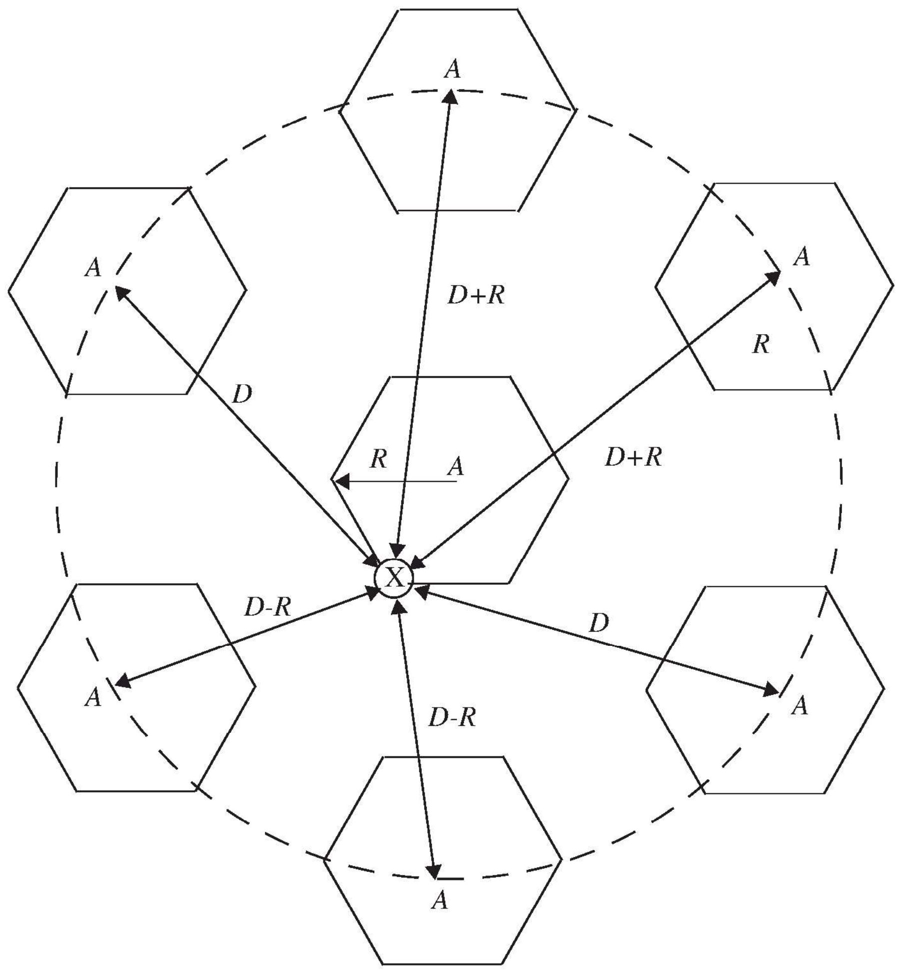

Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

For $N = 7$, the co-channel reuse ratio Q is 4.6, and the worst case S/I is approximated as 49.56 (17 dB) using Equation (3.11), whereas an exact solution using Equation (3.8) yields 17.8 dB [Jac94]. Hence for a seven-cell cluster, the S/I ratio is slightly less than 18 dB for the worst case. To design the cellular system for proper performance in the worst case, it would be necessary to increase N to the next largest size, which from Equation (3.3) is found to be 9 (corresponding to $i = 0, j = 3$). This obviously entails a significant decrease in capacity, since 9-cell reuse offers a spectrum utilization of 1/9 within each cell, whereas seven-cell reuse offers a spectrum utilization of 1/7. In practice, a capacity reduction of 7/9 would not be tolerable to accommodate for the worst case situation which rarely occurs. From the above discussion, it is clear that co-channel interference determines link performance, which in turn dictates the frequency reuse plan and the overall capacity of cellular systems.

Example 3.2

If a signal-to-interference ratio of 15 dB is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) $n = 4$, (b) $n = 3$? Assume that there are six co-channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution

(a) $n = 4$

First, let us consider a seven-cell reuse pattern.

Using Equation (3.4), the co-channel reuse ratio $D/R = 4.583$.

Using Equation (3.9), the signal-to-noise interference ratio is given by

$$S/I = (1/6) \times (4.583)^4 = 75.3 = 18.66 \text{ dB}$$

Since this is greater than the minimum required S/I, $N = 7$ can be used.

(b) $n = 3$

First, let us consider a seven-cell reuse pattern.

Using Equation (3.9), the signal-to-interference ratio is given by

$$S/I = (1/6) \times (4.583)^3 = 16.04 = 12.05 \text{ dB}$$

Since this is less than the minimum required S/I, we need to use a larger N.

Using Equation (3.3), the next possible value of N is 12, ($i = j = 2$).

The corresponding co-channel ratio is given by Equation (3.4) as

$$D/R = 6.0$$

Using Equation (3.3), the signal-to-interference ratio is given by

$$S/I = (1/6) \times (6)^3 = 36 = 15.56 \text{ dB}$$

Since this is greater than the minimum required S/I, $N = 12$ is used.

3.5.2 Channel Planning for Wireless Systems

Judiciously assigning the appropriate radio channels to each base station is an important process that is much more difficult in practice than in theory. While Equation (3.9) is a valuable rule of thumb for determining the appropriate frequency reuse ratio (or cluster size) and the appropriate separation between adjacent co-channel cells, the wireless engineer must deal with the real-world difficulties of radio propagation and imperfect coverage regions of each cell. Cellular systems, in practice, seldom obey the homogenous propagation path loss assumption of Equation (3.9).

Generally, the available mobile radio spectrum is divided into channels, which are part of an *air interface* standard that is used throughout a country or continent. These channels generally are made up of control channels (vital for initiating, requesting, or paging a call), and voice channels (dedicated to carrying revenue-generating traffic). Typically, about 5% of the entire mobile spectrum is devoted to control channels, which carry data messages that are very brief and bursty in nature, while the remaining 95% of the spectrum is dedicated to voice channels. Channels may be assigned