CHAPTER

4

Wireless Network Architecture and Operation

Upon completion of this chapter, the student should be able to:

- Discuss the cellular concept and explain the advantages of frequency reuse.
- Draw a diagram of a typical cellular cluster and explain the meaning of frequency reuse number.
- Discuss how the capacity of a cellular system may be expanded.
- Explain the difference between cell splitting and sectoring.
- Discuss the use of backhaul networks for cellular systems.
- Explain the concept of mobility management and discuss the operations it supports.
- Discuss the concepts of power management and network security.

The cellular concept and its potential for increasing the number of wireless users in a certain geographic area had been proposed many years before it was ever put into practical use. The analog technology used by the first cellular systems dictated a certain type of cellular architecture. As time has past, newer digital technologies and the public's very rapid acceptance of cellular telephones has caused the architectures of today's cellular systems to change in an effort to adjust to the new technologies and the added demand for capacity.

Capacity expansion techniques include the splitting or sectoring of cells and the overlay of smaller cell clusters over larger clusters as demand and technology changes warrant. As demand for newer data services has increased, cellular operators have turned toward the development of their own private data networks to backhaul traffic from their cell sites to a common point of presence where a connection can be made to the PSTN or the PDN.

As cellular systems have matured and become nationwide wireless networks, mobility management has taken on an even more important role in the operation of wireless cellular networks. Mobility management is used to keep track of the current location of a cellular subscriber and to assist in the implementation of cellular handoff. Although not as glamorous as mobility management, power management and wireless network security have become more important issues as the cellular industry heads into its third decade of operation and wireless system engineers fine-tune their designs to build more secure systems and achieve even greater efficiencies of operation.

This chapter will examine all of the abovementioned issues and present several examples of typical cellular architectures and network operations.

4.1 THE CELLULAR CONCEPT

As briefly outlined in Chapter 2, the concept of cellular telephone service was first proposed in the 1940s. The cellular concept would provide a method by which frequency reuse could be maximized thus in essence multiplying the number of available channels in a particular geographic location. The concept of frequency reuse itself was not new at the time for it had been the guiding principle of the licensing of AM commercial broadcasting stations for years and is still used today to determine the granting of licenses for new stations in the broadcasting bands (AM, FM, and TV) and other radio services. However, in broadcasting (a **simplex** or single-direction transmission operation) the goal is to reach as many receivers as possible with a single broadcasting transmitter. This usually entails the use of a high-power transmitter to provide coverage of some particular geographic or trading area. However, there is nothing to prevent the same frequency assignment or cochannel from being used in another area of the country where the signals from distant cochannel stations do not extend to it. Since most users of the radio frequency spectrum recognize it as a limited resource, attempts are usually made to use it as efficiently as possible.

For **duplex** or two-way radio operation, where a system design goal is to allow as many simultaneous users of the available radio spectrum as possible, the reuse of that spectrum is crucial to maximizing the number of potential users. The cellular concept provides a means of maximizing radio spectrum usage. Another benefit of cellular radio systems is that the amount of mobile output power required is not as large due to the smaller cells used and therefore the power requirements for the mobile are reduced, which allows for longer battery life and smaller mobile station form factors.

Introduction

The first mobile telephone service, offered by AT&T and the Bell Southwestern Telephone Company in St. Louis, Missouri, consisted of several colocated transmitters on the top of Southwestern Bell's headquarters. A 250-watt FM transmitter paged mobiles when there was an incoming call for the mobile. This system's high-powered base station transmitters and elevated antennas provided a large coverage area and enough signal power to penetrate the urban canyons of the city. At the same time, however, the frequencies used by the system could not be used by any other services or similar systems for approximately a seventy-five-mile radius around the base station.

The first proposed cellular system would use many low-power transmitters with antennas mounted on shorter towers, to provide a much shorter frequency reuse distance. The area served by each transmitter would be considered a cell. The first cellular systems used omnidirectional antennas and therefore produced cells that tended to be circular in shape. As the technology used to create more efficient cellular mobile systems has evolved, so has the design and implementation of the cellular concept. These changes will be outlined in this chapter.

The Cellular Advantage

The deployment of a large number of low-power base stations to create an effective cellular mobile system is a large and expensive task. The acquisition of land for cell sites; the associated hardware; radio base station transceivers and controllers; antennas and towers; the communications links between the base stations, base station controllers, and mobile switching centers; and finally, the cost of the radio frequency spectrum needed to implement the system can be enormous. Mobile service providers can only recover their costs and make a profit if they can support a sufficient number of mobile subscribers. The cellular concept allows a large enough increase in capacity to make these operations economically feasible.

The implementation of the basic cellular architecture consists of dividing up the coverage area into a number of smaller areas or cells that will be served by their own base stations. The radio channels must be allocated to these smaller cells in such a way as to minimize interference but at the same time provide the necessary system performance to handle the traffic load within the cells. Cells are grouped into **clusters** hat make use of all the available radio spectrum. Since adjacent cells cannot use the same frequency chan-iels, the total frequency allocation is divided up over the cluster and then repeated for other clusters in the ystem. The number of cells in a cluster is known as the cluster size or the **frequency reuse** factor.

For cellular architecture planning one must be concerned with interference from radio transmitters in other cells using the same radio channel and from interference from other transmitters on nearby channels. The first type of interference is known as cochannel and the latter is known as first-adjacent channel, sec-ond-adjacent channel, and so on. Using the cellular concept and careful design techniques can increase the maximum number of system users substantially. The following example will illustrate this point.

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12 kHz 8   *Example 4–1*   6 MHz

Consider the following case: a service provider wants to provide cellular communications to a particular geographic area. The total bandwidth the service provider is licensed for is 5 MHz. Each system subscriber requires 10 kHz of bandwidth when using the system. If the service provider was to provide coverage from only one transmitter site, the total theoretical number of possible simultaneous users is 500 (5 MHz/10 kHz/user = 500 users). If, however, the service provider implements a cellular system with thirty-five transmitter sites, located to minimize interference and provide total coverage of the area, determine the new system capacity.

Solution: Using a cluster size of 7, the total system bandwidth is divided by 7 yielding approximately 714 kHz of bandwidth per cell (5000 kHz/ 7 = 714 kHz), and this is repeated over the 5 clusters (35/7 = 5). Now each cell has a capacity of 71 simultaneous users (714 kHz/10 kHz/user = 71 users) or a total system capacity of 2485 users (35 cells × 71 users/cell = 2485 users). This is a system capacity increase of approximately 5 times.

Cellular Hierarchy

Before examining the technical characteristics of frequency reuse and reuse number, it is helpful to define the hierarchical structure of today's cell sizes. The wireless industry has more or less settled on some particular names to indicate the size of a cell. Going from the smallest to the largest, cells that are less than 100 meters in diameter are known as **picocells,** cells with a diameter between 100 meters and 1000 meters (1 km) are known as **microcells,** and cells greater than 1000 meters in diameter are known as **macrocells.** These definitions are also related to the various possible operating environments that one might find oneself in. Picocells are usually found in the indoor environment (e.g., inside of buildings), microcells are found in the outdoor-to-indoor and pedestrian environment (urban), and macrocells are found in the vehicular and high- antenna environment (suburban). Each of these particular environments presents a different type of radio link propagation scenario that affects the required equipment and other technical aspects of the hardware used to implement the particular type of cell.

Newer technologies have expanded our concept of cells to include the global environment served by a variety of satellite systems and smaller cells for personal area networks (PANs) usually considered being less than ten meters in diameter. Although the terms have not become universal yet, cells with global coverage have been referred to as **megacells** and very small cells have been referred to as **femtocells.** Figure 4–1 illustrates the relative coverage areas of the various cell sizes. It is entirely possible to have mixed environments that are served by several different types of cell structures simultaneously.

4.2 CELL FUNDAMENTALS

Since the first cellular systems usually employed omnidirectional antennas and thus theoretically produced circular-shaped cells, the reader might be puzzled by the cellular industry's de facto choice of a hexagon as

10 MHz

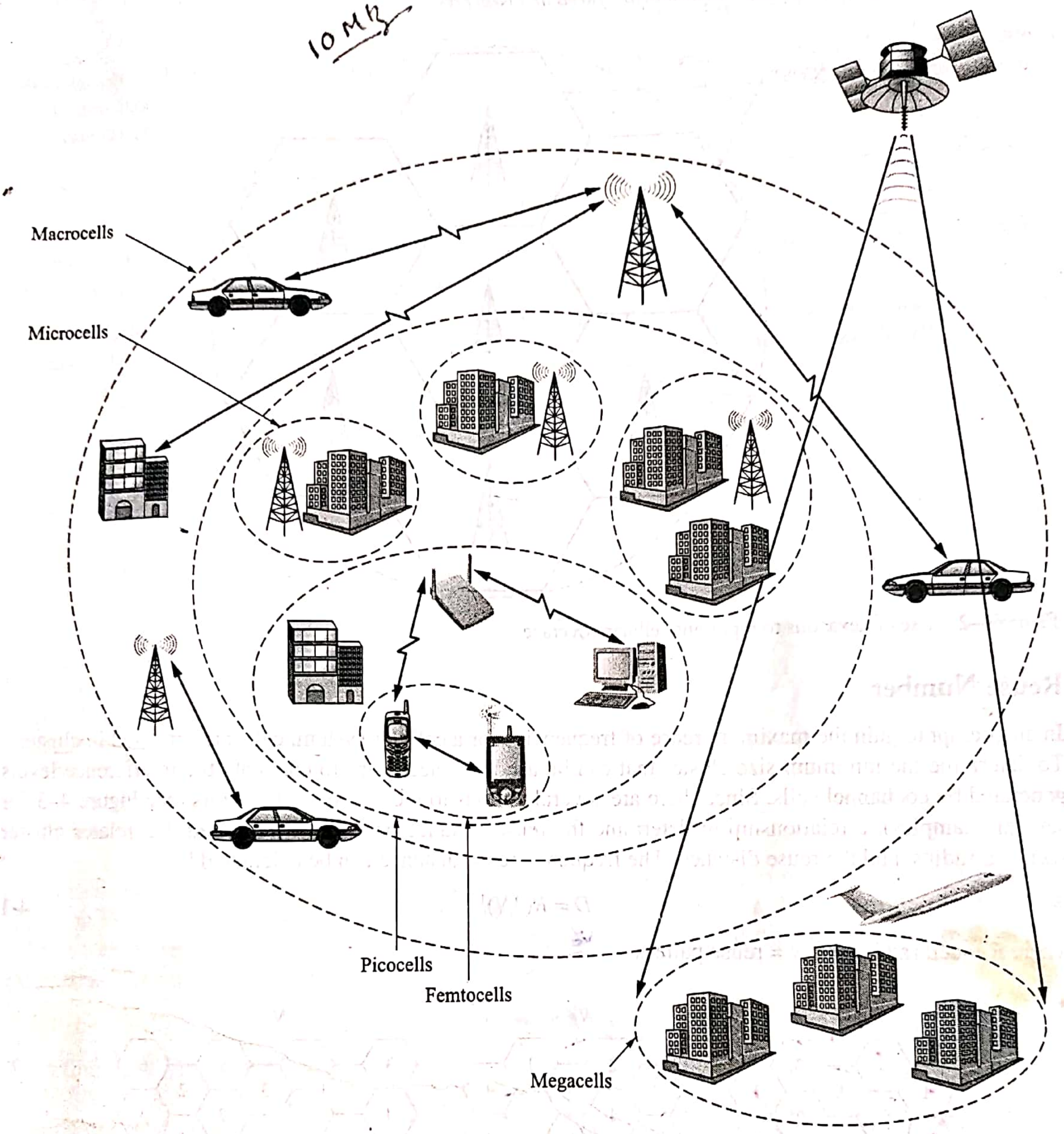

Figure 4–1 Relative coverage areas of different size cells.

shown in Figure 4–2 to represent a typical cell's coverage area in a service provider's network. Any initial consideration of the shape to use for a typical cell must be concerned with the fact that a true circular coverage area is rarely obtained in practice. Propagation conditions, terrain, and the environment (urban, suburban, etc.) all contribute to the distortion of an antenna's radiation pattern and hence coverage area. Furthermore, using circles to lay out a network's coverage area leaves gaps between adjacent tangent circles or ambiguous areas if the circles are overlapped. Referring to Figure 4–2, one can see that the use of a hexagon, however, allows for the complete theoretical coverage of an area without any overlapping cells or gaps in the coverage. Squares or equilateral triangles could also be used but the hexagon is the closest approximation to a circle. The use of hexagons also makes the theoretical calculation of several system parameters much easier.

Reuse Number

In an attempt to gain the maximum reuse of frequencies for a cellular system, cells are arranged in clusters. To determine the minimum-size cluster that can be used it is necessary to calculate the interference levels generated by cochannel cells. Since there are several options to the size of cell clusters (see Figure 4–3 for several examples), a relationship to determine the reuse distance has been determined that relates cluster size, cell radius, and the reuse distance. The frequency reuse distance can be calculated by:

$$D = R(3N)^{1/2} \tag{4-1}$$

where R = cell radius and N = reuse pattern.

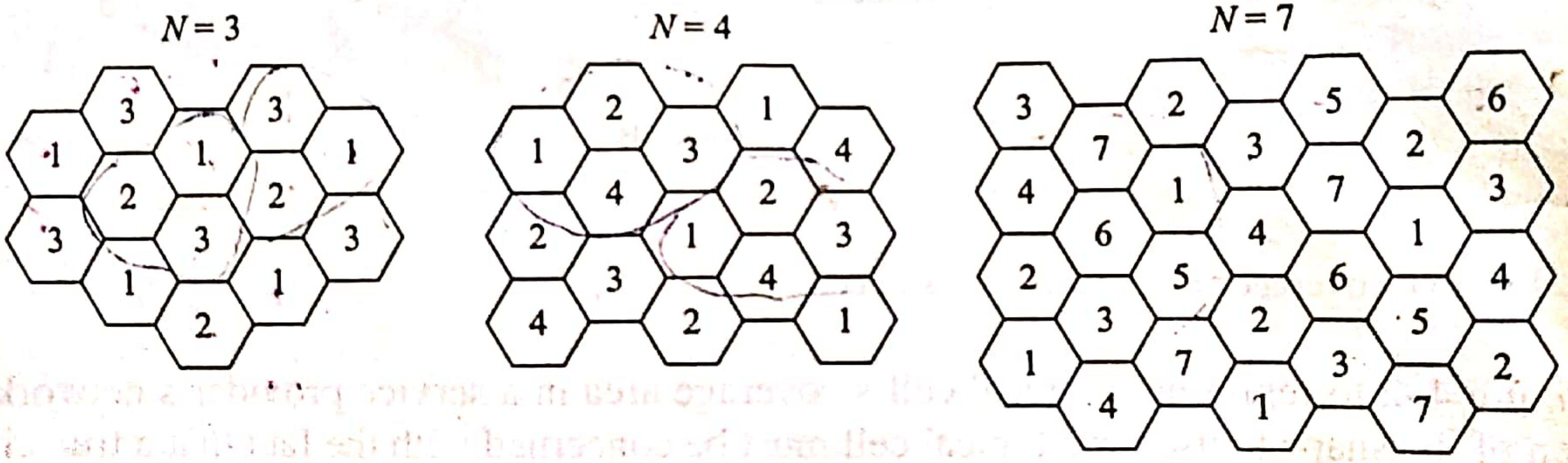

Figure 4–3 Various cellular reuse patterns.

Values of N can only take on numbers calculated from the following expression: $i^2 + ij + j^2$ where i and are integers.

As can be seen from Equation 4-1, the smaller the value of N the closer the reuse distance and therefo the larger the system capacity or total number of possible users. It should be pointed out that reducing th size of the reuse distance D may provide the ability to handle more subscribers but it also increases netwo costs in terms of the required hardware and acquisition of cell sites, increases the complexity of the network, and increases the number of operations required to provide mobility. The following example will illustrate the relationship between cluster size and reuse distance.

Example 4–2

For a mobile system cluster size of 7, determine the frequency reuse distance if the cell radius is five kilometers. Repeat the calculation for a cluster size of 4.

Solution: Figure 4–4 shows the typical arrangement for a cluster size of $N = 7$ and the reuse distance for cell 3. This is the cluster size typically used for the first-generation AMPS system used in the United States.

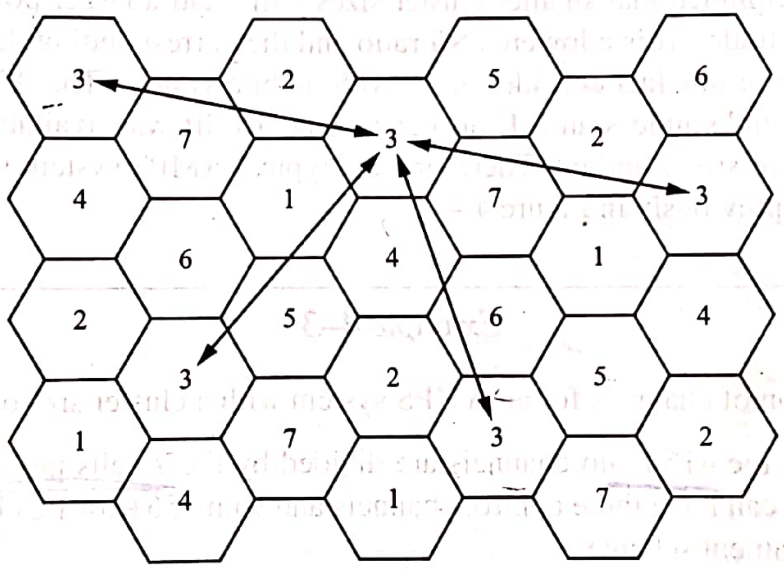

Figure 4–4 A frequency reuse diagram with the reuse distance, D, indicated (cluster size $N = 7$).

As mentioned earlier, using the expression $i^2 + ij + j^2$, one can show that a possible value for N is 7. As shown in Figure 4–4, the hexagons (cells) are arranged with one hexagon in the center of a cluster and six other hexagons surrounding the middle hexagon. Adjacent clusters repeat the previous pattern. The reuse distance is found from the following equation:

$$D = R(3N)^{1/2}$$

Therefore, for a cluster size of 7,

$$D = 5(3 \times 7)^{1/2} = 5(21)^{1/2} = 5(4.5823) = 22.913 \text{ km}$$

For a cluster size of 4, the reuse distance is given by:

$$D = 5(3 \times 4)^{1/2} = 5(12)^{1/2} = 5(3.464) = 17.32 \text{ km}$$

As can be seen, a smaller cluster size results in a smaller reuse distance.

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Cellular Interference Issues

As already covered in the previous section, the frequency reuse distance can be calculated from Equation 4-1. Additionally, more complex calculations can yield the signal-to-interference ratio for a particular cluster size, *N*. The **signal-to-interference ratio** (S/I or SIR) gives an indication of the quality of the received signal much like the time-honored signal-to-noise ratio (SNR) measurement. Using a fairly simple mathematical model for S/I ratio calculations involving omnidirectional cells yields the results tabulated in Table 4–1 for several common values of *N*:

Table 4–1 Signal-to-interference ratio for various cluster sizes.

-to-interference ratio Q

$= 10 \log \left[\frac{1}{6}\left(\frac{D}{R}\right)^4\right]$

dB

$10 \log \left[\frac{1}{6}\left(\sqrt{3N}\right)^4\right]$

$= 18.7$ dB

Cluster Size, N	S/I Ratio
3	11.3 dB
4	13.8 dB
7	18.7 dB
12	23.3 dB

The reader should be reminded that smaller cluster sizes will yield a larger possible subscriber base but as shown in Table 4–1 the trade-off is a lowered S/I ratio and the corresponding decrease in radio link quality. As a practical example of this fact consider the AMPS mobile system. The AMPS system did not yield usable voice-quality radio links unless an S/I ratio exceeding 18 dB was available. This value of S/I was only possible for a cluster of size 7 and up. Therefore, the typical AMPS system was deployed with a cluster size of $N = 7$ as shown previously in Figure 4–4.

Example 4–3

Show a possible distribution of channels for an AMPS system with a cluster size of $N = 7$.

Solution: For this situation, the 416 radio channels are divided by the 7 cells per cluster to yield 59+ channels per cell site. Each cell can have three control channels and some 56+ traffic channels. Table 4–2 shows one possible channel assignment scheme.

Table 4–2 A possible assignment of AMPS channels for a cluster size of 7.

Cell 1	*Cell 2*	*Cell 3*	*Cell 4*	*Cell 5*	*Cell 6*	*Cell 7*
Control Channels						
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
Traffic Channels						
22	23	24	25	26	27	28
29	30	31	32	33	34	35
36	37	...	...	...	...	...
...	...	...	...	...	...	401
402	403	404	405	406	407	408
409	410	411	412	413	414	415
416						

Note how each cell has a channel spacing of 7×30 kHz = 210 kHz and that this channel allocation is repeated in each cluster of 7 cells. Another way of assigning channels when the cluster size is 7 will be introduced later.

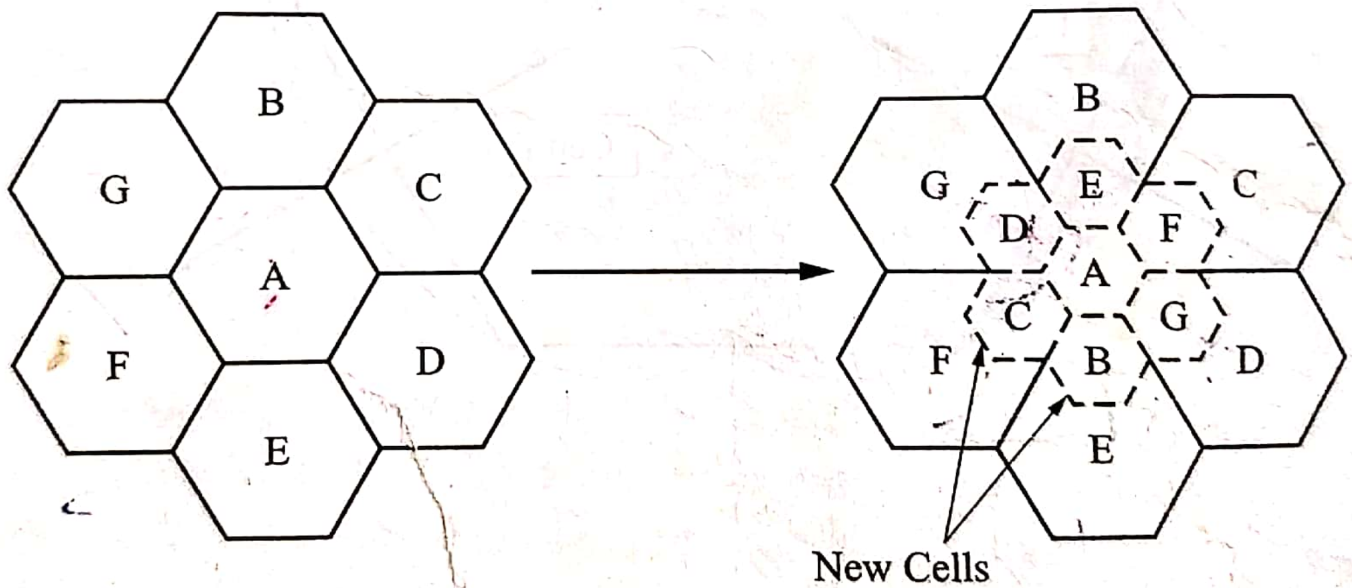
4.3 CAPACITY EXPANSION TECHNIQUES

As cellular mobile telephone service grew in popularity during the 1990s, the need to expand system capacity also grew. Most cellular providers will initially implement their systems by providing service in a coverage area with the least amount of initial investment (i.e., the least number of cell sites). As demand grows the system is usually expanded with additional cell sites to handle the increased traffic. There are several ways in which a service provider may increase capacity. The first and simplest method is to obtain additional frequency spectrum. Although this sounds like a fairly straightforward approach, it has proven to be one of the most expensive. Government auctions have sold frequency spectrum to service providers in countries all around the world. The fairly recent auctions of the PCS bands in the United States by the FCC in the mid-1990s yielded approximately $20 billion. The results of those high prices caused several of the top bidders for that spectrum to eventually declare bankruptcy. Another problem with this approach is that in many instances there is no frequency spectrum available to be auctioned off. In the United States as in many countries worldwide, previous spectrum allocations and incumbent radio services or applications are inhibiting and in some cases preventing the expansion of new advanced wireless mobile technologies. This topic will be treated more fully in other chapters.

The other approaches to capacity expansion are either architecturally or technologically enabled. Changes in cellular architecture like cell sectoring, cell splitting, and using various overlaid cell schemes can all provide increased system capacity. Another technique is to employ different channel allocation schemes that effectively increase cell capacity to meet changes in traffic patterns. Lastly, the adoption of next-generation technology implementations tends to provide an inherent capacity expansion within the new technology itself. The next few sections will provide more detail about these different methods.

Cell Splitting

If a cellular service provider initially deploys a network with fairly large cells, the coverage area will be large but the maximum number of subscribers will be limited. If a portion or portions of the system experience an increasing traffic load that is pushing the system to its limit (subscribers experience a high rate of unavailable service or blocking) then the service provider can use a technique known as **cell splitting** to increase capacity in the overburdened areas of the system. Consider the following example of cell splitting shown in Figure 4–5. Assume that Cell A has become saturated and is unable to support its traffic load. Using cell splitting, six new smaller cells with approximately one-quarter the area of the larger cells are inserted into the system around A in such a way as to be halfway between two cochannel cells. These



4.16
59 channels + 3

Figure 4–5 Increasing capacity by cell splitting.

smaller cells will use the same channels as the corresponding pair of larger cochannel cells. In order that the overall system frequency reuse plan be preserved, the transmit power of these cells must be reduced by a factor of approximately 16 or 12 dB.

Cell splitting will work quite well on paper; however, in practice many times the process is not as smooth as one would desire. Very often, due to the difficulty of acquiring appropriately located cell sites, the conversion process will be prolonged and different size cells will exist in the same area. In these cases, it is necessary to form two groups of channels in the old cell; one group that corresponds to the small-cell frequency reuse requirements and another group that corresponds to the old-cell reuse requirements. Usually the larger cell channels are reserved for highly mobile traffic and therefore will have fewer handoffs than the smaller cells. As the splitting process moves toward completion the number of channels in the small cells will increase until eventually all the channels in the area are used by the lower-power group of cells and the original Cell A has had its power reduced and also joins the new smaller cluster. As traffic increases in other areas of the system this process may be repeated over again. Eventually the entire system will be rescaled with smaller cells in the high-traffic areas and larger cells on the outskirts of the system or in areas of low traffic or low population density.

Cell splitting effectively increases system capacity by reducing the cell size and therefore reducing the frequency reuse distance thus permitting the use of more channels.

Cell Sectoring

Another popular method to increase cellular system capacity is to use **cell sectoring.** Cell sectoring use directional antennas to effectively split a cell into three or sometimes six new cells. The vast majority of cellular providers use this technique for any of the cellular systems presently in operation. As shown in Figure 4–6, the new cell structure now uses three-directional antennas with 120-degree beamwidths to "illuminate" the entire area previously serviced by a single omnidirectional antenna. Now the channels allocated to a cell are further divided and only used in one sector of the cell.

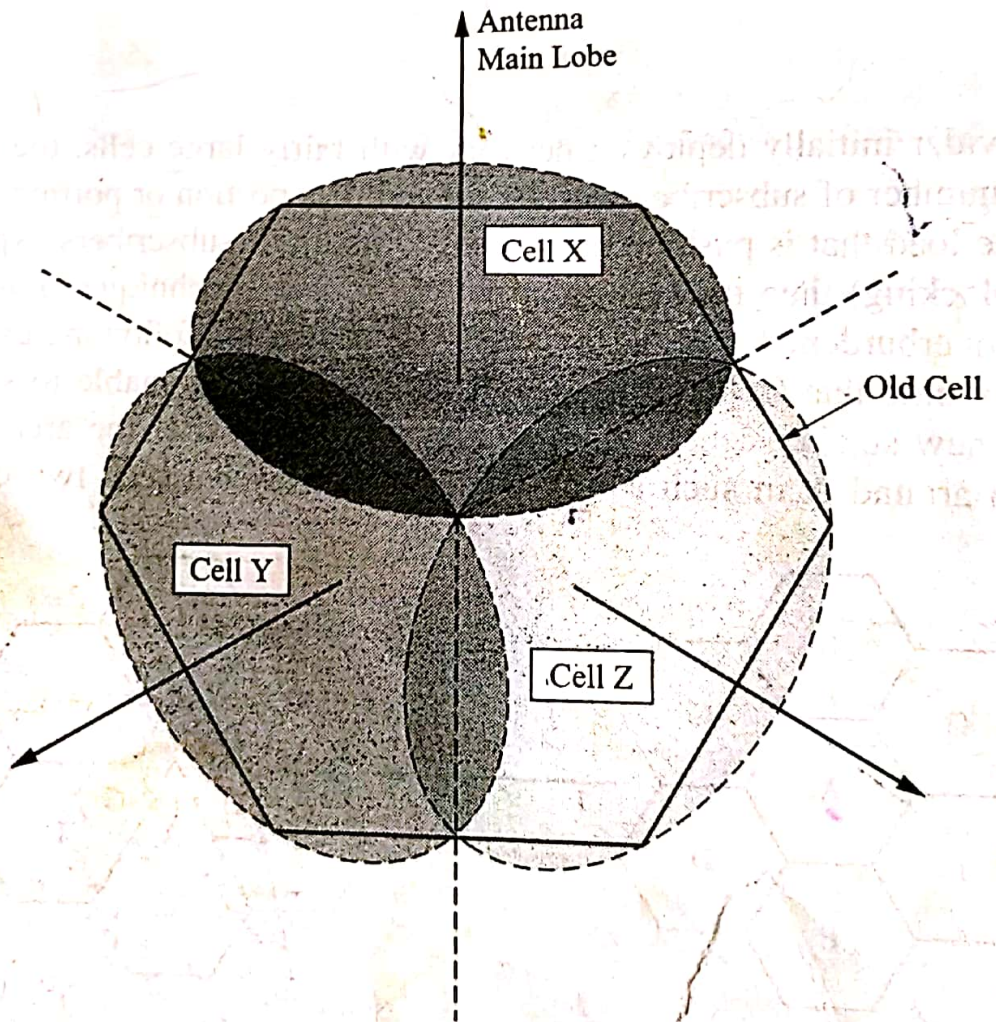


Figure 4–6 Increasing capacity by cell sectoring.