Chapter 3

The Cellular Engineering Fundamentals

3.1 Introduction

In Chapter 1, we have seen that the technique of substituting a single high power transmitter by several low power transmitters to support many users is the backbone of the cellular concept. In practice, the following four parameters are most important while considering the cellular issues: system capacity, quality of service, spectrum efficiency and power management. Starting from the basic notion of a cell, we would deal with these parameters in the context of cellular engineering in this chapter.

3.2 What is a Cell?

The power of the radio signals transmitted by the BS decay as the signals travel away from it. A minimum amount of signal strength (let us say, x dB) is needed in order to be detected by the MS or mobile sets which may the hand-held personal units or those installed in the vehicles. The region over which the signal strength lies above this threshold value x dB is known as the coverage area of a BS and it must be a circular region, considering the BS to be isotropic radiator. Such a circle, which gives this actual radio coverage, is called the foot print of a cell (in reality, it is amorphous). It might so happen that either there may be an overlap between any two such side by side circles or there might be a gap between the

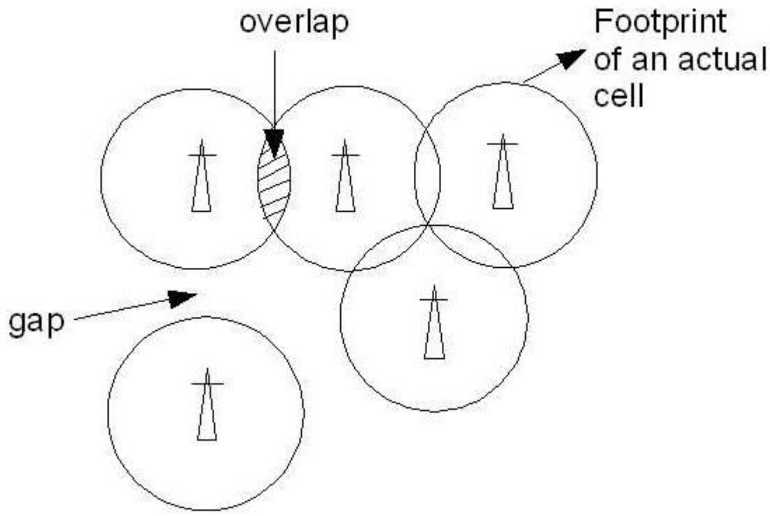

Figure 3.1: Footprint of cells showing the overlaps and gaps.

coverage areas of two adjacent circles. This is shown in Figure 3.1. Such a circular geometry, therefore, cannot serve as a regular shape to describe cells. We need a regular shape for cellular design over a territory which can be served by 3 regular polygons, namely, equilateral triangle, square and regular hexagon, which can cover the entire area without any overlap and gaps. Along with its regularity, a cell must be designed such that it is most reliable too, i.e., it supports even the weakest mobile with occurs at the edges of the cell. For any distance between the center and the farthest point in the cell from it, a regular hexagon covers the maximum area. Hence regular hexagonal geometry is used as the cells in mobile communication.

3.3 Frequency Reuse

Frequency reuse, or, frequency planning, is a technique of reusing frequencies and channels within a communication system to improve capacity and spectral efficiency. Frequency reuse is one of the fundamental concepts on which commercial wireless systems are based that involve the partitioning of an RF radiating area into cells. The increased capacity in a commercial wireless network, compared with a network with a single transmitter, comes from the fact that the same radio frequency can be reused in a different area for a completely different transmission.

Frequency reuse in mobile cellular systems means that frequencies allocated to

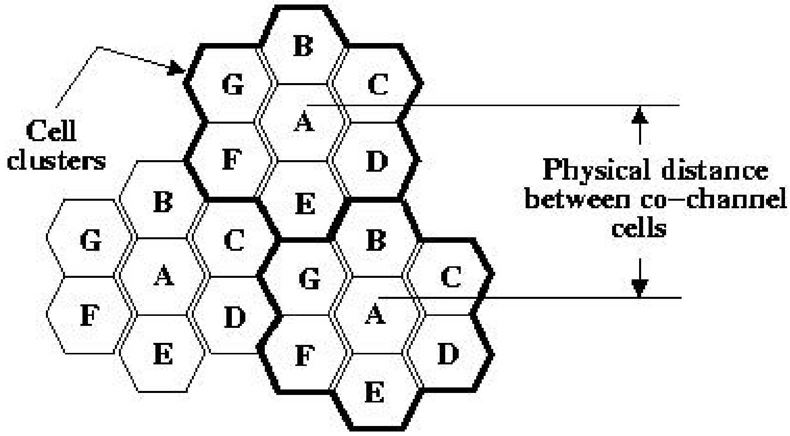

Figure 3.2: Frequency reuse technique of a cellular system.

the service are reused in a regular pattern of cells, each covered by one base station. The repeating regular pattern of cells is called cluster. Since each cell is designed to use radio frequencies only within its boundaries, the same frequencies can be reused in other cells not far away without interference, in another cluster. Such cells are called 'co-channel' cells. The reuse of frequencies enables a cellular system to handle a huge number of calls with a limited number of channels. Figure 3.2 shows a frequency planning with cluster size of 7, showing the co-channels cells in different clusters by the same letter. The closest distance between the co-channel cells (in different clusters) is determined by the choice of the cluster size and the layout of the cell cluster. Consider a cellular system with S duplex channels available for use and let N be the number of cells in a cluster. If each cell is allotted K duplex channels with all being allotted unique and disjoint channel groups we have $S = KN$ under normal circumstances. Now, if the cluster are repeated M times within the total area, the total number of duplex channels, or, the total number of users in the system would be $T = MS = KMN$. Clearly, if K and N remain constant, then

$$T \propto M \tag{3.1}$$

and, if T and K remain constant, then

$$N \propto \frac{1}{M}. \tag{3.2}$$

Hence the capacity gain achieved is directly proportional to the number of times a cluster is repeated, as shown in (3.1), as well as, for a fixed cell size, small N decreases the size of the cluster with in turn results in the increase of the number of clusters (3.2) and hence the capacity. However for small N, co-channel cells are located much closer and hence more interference. The value of N is determined by calculating the amount of interference that can be tolerated for a sufficient quality communication. Hence the smallest N having interference below the tolerated limit is used. However, the cluster size N cannot take on any value and is given only by the following equation

$$N = i^2 + ij + j^2, \qquad i \geq 0, j \geq 0, \tag{3.3}$$

where i and j are integer numbers.

Ex. 1: Find the relationship between any two nearest co-channel cell distance D and the cluster size N.

Solution: For hexagonal cells, it can be shown that the distance between two adjacent cell centers = $\sqrt{3}R$, where R is the radius of any cell. The normalized co-channel cell distance D_n can be calculated by traveling 'i' cells in one direction and then traveling 'j' cells in anticlockwise 120^o of the primary direction. Using law of vector addition,

$$D_n^2 = j^2 \cos^2(30^o) + (i + j\sin(30^o))^2 \tag{3.4}$$

which turns out to be

$$D_n = \sqrt{i^2 + ij + j^2} = \sqrt{N}. \tag{3.5}$$

Multiplying the actual distance $\sqrt{3}R$ between two adjacent cells with it, we get

$$D = D_n\sqrt{3}R = \sqrt{3N}R. \tag{3.6}$$

Ex. 2: Find out the surface area of a regular hexagon with radius R, the surface area of a large hexagon with radius D, and hence compute the total number of cells in this large hexagon.

Hint: In general, this large hexagon with radius D encompasses the center cluster of N cells and one-third of the cells associated with six other peripheral large hexagons. Thus, the answer must be $N + 6(\frac{N}{3}) = 3N$.

3.4 Channel Assignment Strategies

With the rapid increase in number of mobile users, the mobile service providers had to follow strategies which ensure the effective utilization of the limited radio spectrum. With increased capacity and low interference being the prime objectives, a frequency reuse scheme was helpful in achieving this objectives. A variety of channel assignment strategies have been followed to aid these objectives. Channel assignment strategies are classified into two types: fixed and dynamic, as discussed below.

3.4.1 Fixed Channel Assignment (FCA)

In fixed channel assignment strategy each cell is allocated a fixed number of voice channels. Any communication within the cell can only be made with the designated unused channels of that particular cell. Suppose if all the channels are occupied, then the call is blocked and subscriber has to wait. This is simplest of the channel assignment strategies as it requires very simple circuitry but provides worst channel utilization. Later there was another approach in which the channels were borrowed from adjacent cell if all of its own designated channels were occupied. This was named as *borrowing strategy*. In such cases the MSC supervises the borrowing process and ensures that none of the calls in progress are interrupted.

3.4.2 Dynamic Channel Assignment (DCA)

In dynamic channel assignment strategy channels are temporarily assigned for use in cells for the duration of the call. Each time a call attempt is made from a cell the corresponding BS requests a channel from MSC. The MSC then allocates a channel to the requesting the BS. After the call is over the channel is returned and kept in a central pool. To avoid co-channel interference any channel that in use in one cell can only be reassigned simultaneously to another cell in the system if the distance between the two cells is larger than minimum reuse distance. When compared to the FCA, DCA has reduced the likelihood of blocking and even increased the trunking capacity of the network as all of the channels are available to all cells, i.e., good quality of service. But this type of assignment strategy results in heavy load on switching center at heavy traffic condition.

Ex. 3: A total of 33 MHz bandwidth is allocated to a FDD cellular system with two 25 KHz simplex channels to provide full duplex voice and control channels. Compute the number of channels available per cell if the system uses (i) 4 cell, (ii) 7 cell, and (iii) 8 cell reuse technique. Assume 1 MHz of spectrum is allocated to control channels. Give a distribution of voice and control channels.

Solution: One duplex channel = 2 x 25 = 50 kHz of spectrum. Hence the total available duplex channels are = 33 MHz / 50 kHz = 660 in number. Among these channels, 1 MHz / 50 kHz = 20 channels are kept as control channels.

(a) For N = 4, total channels per cell = 660/4 = 165.

Among these, voice channels are 160 and control channels are 5 in number.

(b) For N = 7, total channels per cell are 660/7 $\approx$ 94. Therefore, we have to go for a more exact solution. We know that for this system, a total of 20 control channels and a total of 640 voice channels are kept. Here, 6 cells can use 3 control channels and the rest two can use 2 control channels each. On the other hand, 5 cells can use 92 voice channels and the rest two can use 90 voice channels each. Thus the total solution for this case is:

6 x 3 + 1 x 2 = 20 control channels, and,

5 x 92 + 2 x 90 = 640 voice channels.

This is one solution, there might exist other solutions too.

(c) The option N = 8 is not a valid option since it cannot satisfy equation (3.3) by two integers i and j.

3.5 Handoff Process

When a user moves from one cell to the other, to keep the communication between the user pair, the user channel has to be shifted from one BS to the other without interrupting the call, i.e., when a MS moves into another cell, while the conversation is still in progress, the MSC automatically transfers the call to a new FDD channel without disturbing the conversation. This process is called as *handoff*. A schematic diagram of handoff is given in Figure 3.3.

Processing of handoff is an important task in any cellular system. Handoffs must be performed successfully and be imperceptible to the users. Once a signal

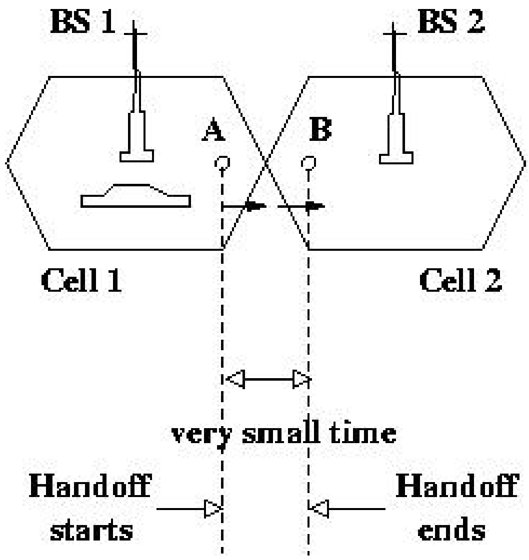

Figure 3.3: Handoff scenario at two adjacent cell boundary.

level is set as the minimum acceptable for good voice quality ($P_{r_{min}}$), then a slightly stronger level is chosen as the threshold (P_{r_H})at which handoff has to be made, as shown in Figure 3.4. A parameter, called power margin, defined as

$$\Delta = P_{r_H} - P_{r_{min}} \tag{3.7}$$

is quite an important parameter during the handoff process since this margin Δ can neither be too large nor too small. If Δ is too small, then there may not be enough time to complete the handoff and the call might be lost even if the user crosses the cell boundary.

If Δ is too high o the other hand, then MSC has to be burdened with unnecessary handoffs. This is because MS may not intend to enter the other cell. Therefore Δ should be judiciously chosen to ensure imperceptible handoffs and to meet other objectives.

3.5.1 Factors Influencing Handoffs

The following factors influence the entire handoff process:
(a) Transmitted power: as we know that the transmission power is different for different cells, the handoff threshold or the power margin varies from cell to cell.
(b) Received power: the received power mostly depends on the Line of Sight (LoS) path between the user and the BS. Especially when the user is on the boundary of

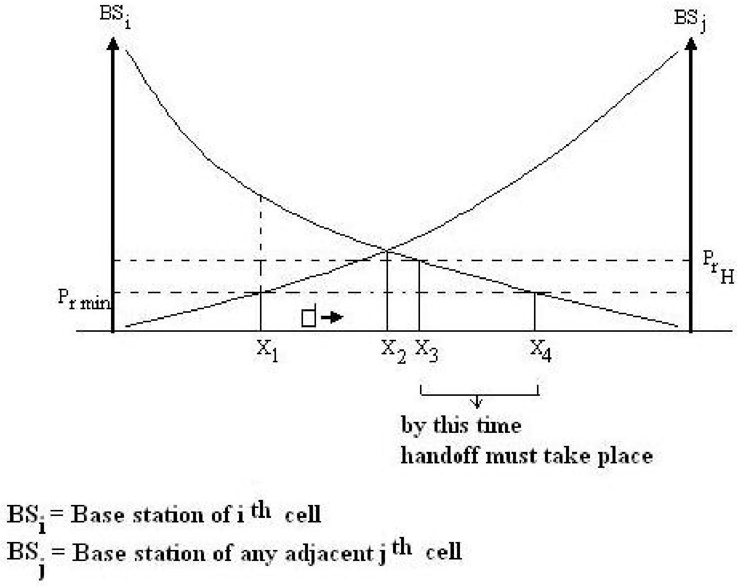

Figure 3.4: Handoff process associated with power levels, when the user is going from i-th cell to j-th cell.

the two cells, the LoS path plays a critical role in handoffs and therefore the power margin Δ depends on the minimum received power value from cell to cell.
(c) Area and shape of the cell: Apart from the power levels, the cell structure also a plays an important role in the handoff process.
(d) Mobility of users: The number of mobile users entering or going out of a particular cell, also fixes the handoff strategy of a cell.
To illustrate the reasons (c) and (d), let us consider a rectangular cell with sides R_1 and R_2 inclined at an angle θ with horizon, as shown in the Figure 3.5. Assume N_1 users are having handoff in horizontal direction and N_2 in vertical direction per unit length.
The number of crossings along R_1 side is : $(N_1 cos\theta + N_2 sin\theta)R_1$ and the number of crossings along R_2 side is : $(N_1 sin\theta + N_2 cos\theta)R_2$.
Then the handoff rate λ_H can be written as

$$\lambda_H = (N_1 cos\theta + N_2 sin\theta)R_1 + (N_1 sin\theta + N_2 cos\theta)R_2. \tag{3.8}$$

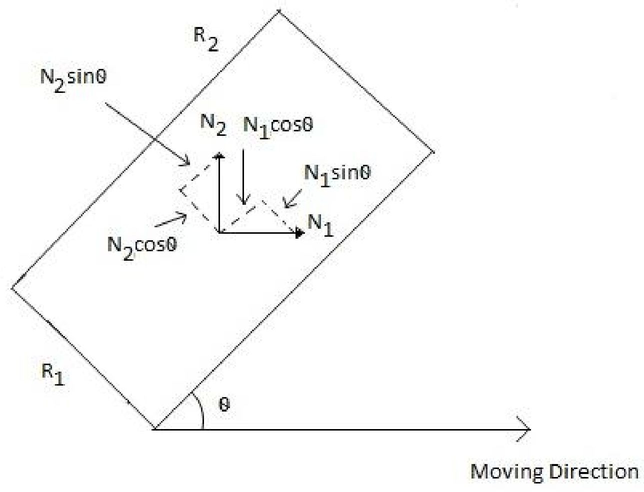

Figure 3.5: Handoff process with a rectangular cell inclined at an angle θ.

Now, given the fixed area $A = R_1R_2$, we need to find λ_H^{min} for a given θ. Replacing R_1 by $\frac{A}{R_2}$ and equating $\frac{d\lambda_H}{dR_1}$ to zero, we get

$$R_1^2 = A(\frac{N_1sin\theta + N_2cos\theta}{N_1cos\theta + N_2sin\theta}). \tag{3.9}$$

Similarly, for R_2, we get

$$R_2^2 = A(\frac{N_1cos\theta + N_2sin\theta}{N_1sin\theta + N_2cos\theta}). \tag{3.10}$$

From the above equations, we have $\lambda_H = 2\sqrt{A(N_1N_2 + (N_1^2 + N_2^2)cos\theta sin\theta)}$ which means it it minimized at $\theta = 0^o$. Hence $\lambda_H^{min} = 2\sqrt{AN_1N_2}$. Putting the value of θ in (3.9) or (3.10), we have $\frac{R_1}{R_2} = \frac{N_1}{N_2}$. This has two implications: (i) that handoff is minimized if rectangular cell is aligned with X-Y axis, i.e., $\theta = 0^o$, and, (ii) that the number of users crossing the cell boundary is inversely proportional to the dimension of the other side of the cell. The above analysis has been carried out for a simple square cell and it changes in more complicated way when we consider a hexagonal cell.

3.5.2 Handoffs In Different Generations

In 1G analog cellular systems, the signal strength measurements were made by the BS and in turn supervised by the MSC. The handoffs in this generation can be termed as Network Controlled Hand-Off (NCHO). The BS monitors the signal strengths of voice channels to determine the relative positions of the subscriber. The special receivers located on the BS are controlled by the MSC to monitor the signal strengths of the users in the neighboring cells which appear to be in need of handoff. Based on the information received from the special receivers the MSC decides whether a handoff is required or not. The approximate time needed to make a handoff successful was about 5-10 s. This requires the value of Δ to be in the order of 6dB to 12dB.

In the 2G systems, the MSC was relieved from the entire operation. In this generation, which started using the digital technology, handoff decisions were mobile assisted and therefore it is called Mobile Assisted Hand-Off (MAHO). In MAHO, the mobile center measures the power changes received from nearby base stations and notifies the two BS. Accordingly the two BS communicate and channel transfer occurs. As compared to 1G, the circuit complexity was increased here whereas the delay in handoff was reduced to 1-5 s. The value of Δ was in the order of 0-5 dB. However, even this amount of delay could create a communication pause.

In the current 3G systems, the MS measures the power from adjacent BS and automatically upgrades the channels to its nearer BS. Hence this can be termed as Mobile Controlled Hand-Off (MCHO). When compared to the other generations, delay during handoff is only 100 ms and the value of Δ is around 20 dBm. The Quality Of Service (QoS) has improved a lot although the complexity of the circuitry has further increased which is inevitable.

All these types of handoffs are usually termed as hard handoff as there is a shift in the channels involved. There is also another kind of handoff, called soft handoff, as discussed below.

Handoff in CDMA: In spread spectrum cellular systems, the mobiles share the same channels in every cell. The MSC evaluates the signal strengths received from different BS for a single user and then shifts the user from one BS to the other without actually changing the channel. These types of handoffs are called as soft handoff as there is no change in the channel.

3.5.3 Handoff Priority

While assigning channels using either FCA or DCA strategy, a guard channel concept must be followed to facilitate the handoffs. This means, a fraction of total available channels must be kept for handoff requests. But this would reduce the carried traffic and only fewer channels can be assigned for the residual users of a cell. A good solution to avoid such a dead-lock is to use DCA with handoff priority (demand based allocation).

3.5.4 A Few Practical Problems in Handoff Scenario

(a) Different speed of mobile users: with the increase of mobile users in urban areas, microcells are introduced in the cells to increase the capacity (this will be discussed later in this chapter). The users with high speed frequently crossing the micro-cells become burdened to MSC as it has to take care of handoffs. Several schemes thus have been designed to handle the simultaneous traffic of high speed and low speed users while minimizing the handoff intervention from the MSC, one of them being the 'Umbrella Cell' approach. This technique provides large area coverage to high speed users while providing small area coverage to users traveling at low speed. By using different antenna heights and different power levels, it is possible to provide larger and smaller cells at a same location. As illustrated in the Figure 3.6, umbrella cell is co-located with few other microcells. The BS can measure the speed of the user by its short term average signal strength over the RVC and decides which cell to handle that call. If the speed is less, then the corresponding microcell handles the call so that there is good corner coverage. This approach assures that handoffs are minimized for high speed users and provides additional microcell channels for pedestrian users.

(b) Cell dragging problem: this is another practical problem in the urban area with additional microcells. For example, consider there is a LOS path between the MS and BS1 while the user is in the cell covered by BS2. Since there is a LOS with the BS1, the signal strength received from BS1 would be greater than that received from BS2. However, since the user is in cell covered by BS2, handoff cannot take place and as a result, it experiences a lot of interferences. This problem can be solved by judiciously choosing the handoff threshold along with adjusting the coverage area.

(c) Inter-system handoff: if one user is leaving the coverage area of one MSC and is entering the area of another MSC, then the call might be lost if there is no handoff in this case too. Such a handoff is called inter-system handoff and in order to facilitate this, mobiles usually have roaming facility.

3.6 Interference & System Capacity

Susceptibility and interference problems associated with mobile communications equipment are because of the problem of time congestion within the electromagnetic spectrum. It is the limiting factor in the performance of cellular systems. This interference can occur from clash with another mobile in the same cell or because of a call in the adjacent cell. There can be interference between the base stations operating at same frequency band or any other non-cellular system's energy leaking inadvertently into the frequency band of the cellular system. If there is an interference in the voice channels, cross talk is heard will appear as noise between the users. The interference in the control channels leads to missed and error calls because of digital signaling. Interference is more severe in urban areas because of the greater RF noise and greater density of mobiles and base stations. The interference can be divided into 2 parts: co-channel interference and adjacent channel interference.

3.6.1 Co-channel interference (CCI)

For the efficient use of available spectrum, it is necessary to reuse frequency bandwidth over relatively small geographical areas. However, increasing frequency reuse also increases interference, which decreases system capacity and service quality. The cells where the same set of frequencies is used are call co-channel cells. Co-channel interference is the cross talk between two different radio transmitters using the same radio frequency as is the case with the co-channel cells. The reasons of CCI can be because of either adverse weather conditions or poor frequency planning or overly-crowded radio spectrum.

If the cell size and the power transmitted at the base stations are same then CCI will become independent of the transmitted power and will depend on radius of the cell (R) and the distance between the interfering co-channel cells (D). If D/R ratio is increased, then the effective distance between the co-channel cells will increase and interference will decrease. The parameter Q is called the frequency reuse ratio and is related to the cluster size. For hexagonal geometry

$$Q = D/R = \sqrt{3N}. \tag{3.11}$$

From the above equation, small of 'Q' means small value of cluster size 'N' and increase in cellular capacity. But large 'Q' leads to decrease in system capacity but increase in transmission quality. Choosing the options is very careful for the selection of 'N', the proof of which is given in the first section.

The Signal to Interference Ratio (SIR) for a mobile receiver which monitors the forward channel can be calculated as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} \tag{3.12}$$

where i_0 is the number of co-channel interfering cells, S is the desired signal power from the baseband station and I_i is the interference power caused by the i-th interfering co-channel base station. In order to solve this equation from power calculations, we need to look into the signal power characteristics. The average power in the mobile radio channel decays as a power law of the distance of separation between transmitter and receiver. The expression for the received power P_r at a distance d can be approximately calculated as

$$P_r = P_0(\frac{d}{d_0})^{-n} \tag{3.13}$$

and in the dB expression as

$$P_r(dB) = P_0(dB) - 10n\log(\frac{d}{d_0}) \tag{3.14}$$

where P_0 is the power received at a close-in reference point in the far field region at a small distance do from the transmitting antenna, and 'n' is the path loss exponent. Let us calculate the SIR for this system. If D_i is the distance of the i-th interferer from the mobile, the received power at a given mobile due to i-th interfering cell is proportional to $(D_i)^{-n}$ (the value of 'n' varies between 2 and 4 in urban cellular systems).

Let us take that the path loss exponent is same throughout the coverage area and the transmitted power be same, then SIR can be approximated as

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} D_i^{-n}} \tag{3.15}$$

where the mobile is assumed to be located at R distance from the cell center. If we consider only the first layer of interfering cells and we assume that the interfering base stations are equidistant from the reference base station and the distance between the cell centers is 'D' then the above equation can be converted as

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0} \tag{3.16}$$

which is an approximate measure of the SIR. Subjective tests performed on AMPS cellular system which uses FM and 30 kHz channels show that sufficient voice quality can be obtained by SIR being greater than or equal to 18 dB. If we take n=4 , the value of 'N' can be calculated as 6.49. Therefore minimum N is 7. The above equations are based on hexagonal geometry and the distances from the closest interfering cells can vary if different frequency reuse plans are used.

We can go for a more approximate calculation for co-channel SIR. This is the example of a 7 cell reuse case. The mobile is at a distance of D-R from 2 closest interfering cells and approximately D+R/2, D, D-R/2 and D+R distance from other interfering cells in the first tier. Taking $n = 4$ in the above equation, SIR can be approximately calculated as

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + (D+R)^{-4} + (D)^{-4} + (D+R/2)^{-4} + (D-R/2)^{-4}} \tag{3.17}$$

which can be rewritten in terms frequency reuse ratio Q as

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-4} + (Q+1)^{-4} + (Q)^{-4} + (Q+1/2)^{-4} + (Q-1/2)^{-4}}. \tag{3.18}$$

Using the value of N equal to 7 (this means Q = 4.6), the above expression yields that worst case SIR is 53.70 (17.3 dB). This shows that for a 7 cell reuse case the worst case SIR is slightly less than 18 dB. The worst case is when the mobile is at the corner of the cell i.e., on a vertex as shown in the Figure 3.6. Therefore N = 12 cluster size should be used. But this reduces the capacity by 7/12 times. Therefore, co-channel interference controls link performance, which in a way controls frequency reuse plan and the overall capacity of the cellular system. The effect of co-channel interference can be minimized by optimizing the frequency assignments of the base stations and their transmit powers. Tilting the base-station antenna to limit the spread of the signals in the system can also be done.

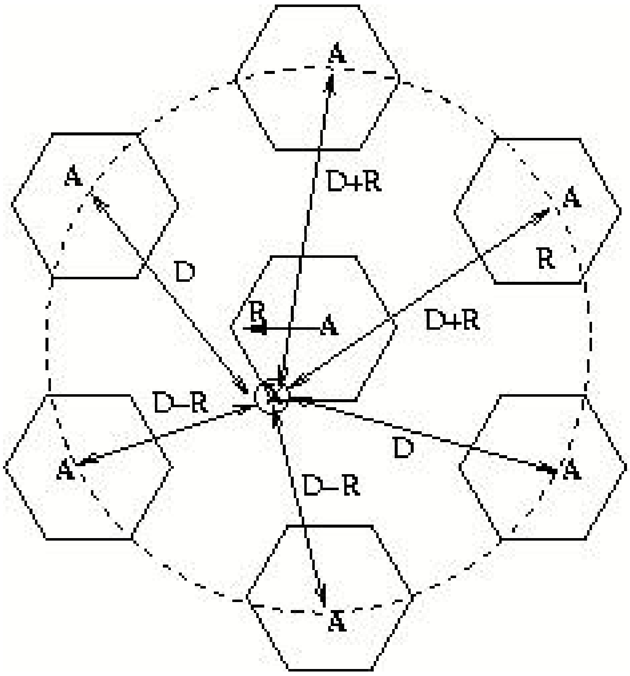

Figure 3.6: First tier of co-channel interfering cells

3.6.2 Adjacent Channel Interference (ACI)

This is a different type of interference which is caused by adjacent channels i.e. channels in adjacent cells. It is the signal impairment which occurs to one frequency due to presence of another signal on a nearby frequency. This occurs when imperfect receiver filters allow nearby frequencies to leak into the passband. This problem is enhanced if the adjacent channel user is transmitting in a close range compared to the subscriber's receiver while the receiver attempts to receive a base station on the channel. This is called near-far effect. The more adjacent channels are packed into the channel block, the higher the spectral efficiency, provided that the performance degradation can be tolerated in the system link budget. This effect can also occur if a mobile close to a base station transmits on a channel close to one being used by a weak mobile. This problem might occur if the base station has problem in discriminating the mobile user from the "bleed over" caused by the close adjacent channel mobile.

Adjacent channel interference occurs more frequently in small cell clusters and heavily used cells. If the frequency separation between the channels is kept large this interference can be reduced to some extent. Thus assignment of channels is given such that they do not form a contiguous band of frequencies within a particular cell and frequency separation is maximized. Efficient assignment strategies are very much important in making the interference as less as possible. If the frequency factor is small then distance between the adjacent channels cannot put the interference level within tolerance limits. If a mobile is 10 times close to the base station than other mobile and has energy spill out of its passband, then SIR for weak mobile is approximately

$$\frac{S}{I} = 10^{-n} \tag{3.19}$$

which can be easily found from the earlier SIR expressions. If n = 4, then SIR is −52 dB. Perfect base station filters are needed when close-in and distant users share the same cell. Practically, each base station receiver is preceded by a high Q cavity filter in order to remove adjacent channel interference. Power control is also very much important for the prolonging of the battery life for the subscriber unit but also reduces reverse channel SIR in the system. Power control is done such that each mobile transmits the lowest power required to maintain a good quality link on the reverse channel.

3.7 Enhancing Capacity And Cell Coverage

3.7.1 The Key Trade-off

Previously, we have seen that the frequency reuse technique in cellular systems allows for almost boundless expansion of geographical area and the number of mobile system users who could be accommodated. In designing a cellular layout, the two parameters which are of great significance are the cell radius R and the cluster size N, and we have also seen that co-channel cell distance $D = \sqrt{3N}R$. In the following, a brief description of the design trade-off is given, in which the above two parameters play a crucial role.

The cell radius governs both the geographical area covered by a cell and also the number of subscribers who can be serviced, given the subscriber density. It is easy to see that the cell radius must be as large as possible. This is because, every cell requires an investment in a tower, land on which the tower is placed, and radio transmission equipment and so a large cell size minimizes the cost per subscriber.

Eventually, the cell radius is determined by the requirement that adequate signal to noise ratio be maintained over the coverage area. The SNR is determined by several factors such as the antenna height, transmitter power, receiver noise figure etc. Given a cell radius R and a cluster size N, the geographic area covered by a cluster is

$$A_{cluster} = NA_{cell} = N3\sqrt{3}R^2/2. \tag{3.20}$$

If the total serviced area is A_{total}, then the number of clusters M that could be accommodated is given by

$$M = A_{total}/A_{cluster} = A_{total}/(N3\sqrt{3}R^2/2). \tag{3.21}$$

Note that all of the available channels N, are reused in every cluster. Hence, to make the maximum number of channels available to subscribers, the number of clusters M should be large, which, by Equation (3.21), shows that the cell radius should be small. However, cell radius is determined by a trade-off: R should be as large as possible to minimize the cost of the installation per subscriber, but R should be as small as possible to maximize the number of customers that the system can accommodate. Now, if the cell radius R is fixed, then the number of clusters could be maximized by minimizing the size of a cluster N. We have seen earlier that the size of a cluster depends on the frequency reuse ratio Q. Hence, in determining the value of N, another trade-off is encountered in that N must be small to accommodate large number of subscribers, but should be sufficiently large so as to minimize the interference effects.

Now, we focus on the issues regarding system expansion. The history of cellular phones has been characterized by a rapid growth and expansion in cell subscribers. Though a cellular system can be expanded by simply adding cells to the geographical area, the way in which user density can be increased is also important to look at. This is because it is not always possible to counter the increasing demand for cellular systems just by increasing the geographical coverage area due to the limitations in obtaining new land with suitable requirements. We discuss here two methods for dealing with an increasing subscriber density: Cell Splitting and Sectoring. The other method, microcell zone concept can treated as enhancing the QoS in a cellular system.

The basic idea of adopting the cellular approach is to allow space for the growth of mobile users. When a new system is deployed, the demand for it is fairly low and users are assumed to be uniformly distributed over the service area. However, as new users subscribe to the cellular service, the demand for channels may begin to exceed the capacity of some base stations. As discussed previously,the number of channels available to customers (equivalently, the channel density per square kilometer) could be increased by decreasing the cluster size. However, once a system has been initially deployed, a system-wide reduction in cluster size may not be necessary since user density does not grow uniformly in all parts of the geographical area. It might be that an increase in channel density is required only in specific parts of the system to support an increased demand in those areas. Cell-splitting is a technique which has the capability to add new smaller cells in specific areas of the system.

3.7.2 Cell-Splitting

Cell Splitting is based on the cell radius reduction and minimizes the need to modify the existing cell parameters. Cell splitting involves the process of sub-dividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna size and transmitting power. This increases the capacity of a cellular system since it increases the number of times that channels are reused. Since the new cells have smaller radii than the existing cells, inserting these smaller cells, known as microcells, between the already existing cells results in an increase of capacity due to the additional number of channels per unit area. There are few challenges in increasing the capacity by reducing the cell radius. Clearly, if cells are small, there would have to be more of them and so additional base stations will be needed in the system. The challenge in this case is to introduce the new base stations without the need to move the already existing base station towers. The other challenge is to meet the generally increasing demand that may vary quite rapidly between geographical areas of the system. For instance, a city may have highly populated areas and so the demand must be supported by cells with the smallest radius. The radius of cells will generally increase as we move from urban to sub urban areas, because the user density decreases on moving towards sub-urban areas. The key factor is to add as minimum number of smaller cells as possible

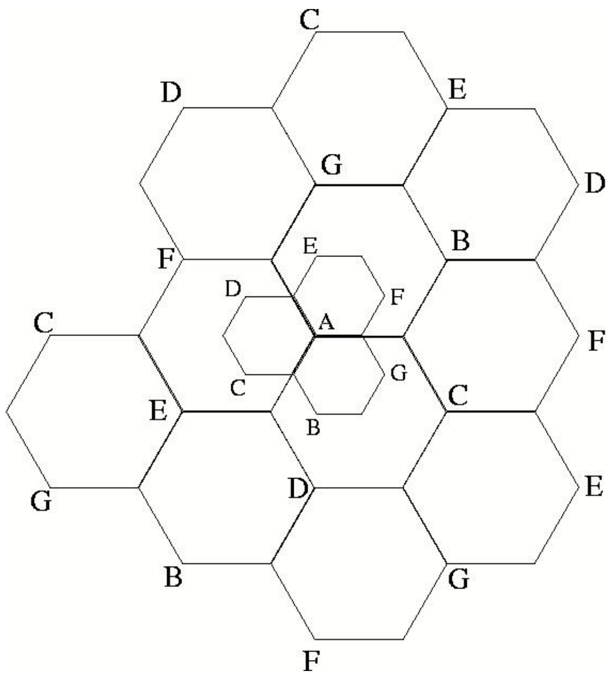

Figure 3.7: Splitting of congested seven-cell clusters.

wherever an increase in demand occurs. The gradual addition of the smaller cells implies that, at least for a time, the cellular system operates with cells of more than one size.

Figure 3.7 shows a cellular layout with seven-cell clusters. Consider that the cells in the center of the diagram are becoming congested, and cell A in the center has reached its maximum capacity. Figure also shows how the smaller cells are being superimposed on the original layout. The new smaller cells have half the cell radius of the original cells. At half the radius, the new cells will have one-fourth of the area and will consequently need to support one-fourth the number of subscribers. Notice that one of the new smaller cells lies in the center of each of the larger cells. If we assume that base stations are located in the cell centers, this allows the original base stations to be maintained even in the new system layout. However, new base stations will have to be added for new cells that do not lie in the center of the larger cells. The organization of cells into clusters is independent of the cell radius, so that the cluster size can be the same in the small-cell layout as it was in the large-cell layout. Also the signal-to-interference ratio is determined by cluster size and not by cell radius. Consequently, if the cluster size is maintained, the signal-to-interference ratio will be the same after cell splitting as it was before. If the entire system is replaced with new half-radius cells, and the cluster size is maintained, the number of channels per cell will be exactly as it was before, and the number of subscribers per cell will have been reduced.

When the cell radius is reduced by a factor, it is also desirable to reduce the transmitted power. The transmit power of the new cells with radius half that of the old cells can be found by examining the received power PR at the new and old cell boundaries and setting them equal. This is necessary to maintain the same frequency re-use plan in the new cell layout as well. Assume that PT1 and PT2 are the transmit powers of the larger and smaller base stations respectively. Then, assuming a path loss index n=4, we have power received at old cell boundary = P_{T1}/R^4 and the power received at new cell boundary = $P_{T2}/(R/2)^4$. On equating the two received powers, we get $P_{T2} = P_{T1}$ / 16. In other words, the transmit power must be reduced by 12 dB in order to maintain the same S/I with the new system lay-out.

At the beginning of this channel splitting process, there would be fewer channels in the smaller power groups. As the demand increases, more and more channels need to be accommodated and hence the splitting process continues until all the larger cells have been replaced by the smaller cells, at which point splitting is complete within the region and the entire system is rescaled to have a smaller radius per cell.

If a cellular layout is replaced entirety by a new layout with a smaller cell radius, the signal-to-interference ratio will not change, provided the cluster size does not change. Some special care must be taken, however, to avoid co-channel interference when both large and small cell radii coexist. It turns out that the only way to avoid interference between the large-cell and small-cell systems is to assign entirely different sets of channels to the two systems. So, when two sizes of cells co-exist in a system, channels in the old cell must be broken down into two groups, one that corresponds to larger cell reuse requirements and the other which corresponds to the smaller cell reuse requirements. The larger cell is usually dedicated to high speed users as in the umbrella cell approach so as to minimize the number of hand-offs.

Ex. 4: When the AMPS cellular system was first deployed, the aim of the system designers was to guarantee coverage. Initially the number of users was not significant. Consequently cells were configured with an eight-mile radius, and a 12-cell cluster size was chosen. The cell radius was chosen to guarantee a 17 dB

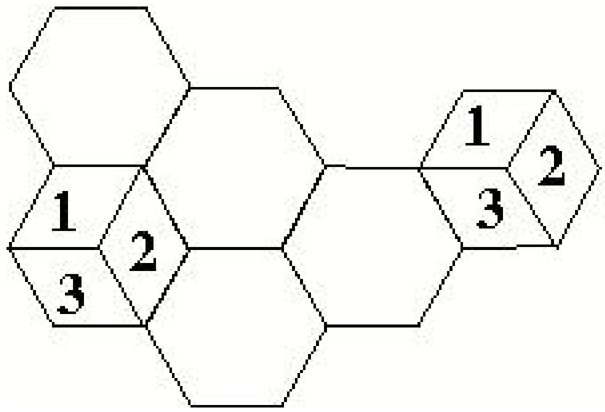

Figure 3.8: A cell divided into three 120^o sectors.

signal-to-noise ratio over 90% of the coverage area. Although a 12-cell cluster size provided more than adequate co-channel separation to meet a requirement for a 17 dB signal-to-interference ratio in an interference-limited environment, it did not provide adequate frequency reuse to service an explosively growing customer base. The system planners reasoned that a subsequent shift to a 7-cell cluster size would provide an adequate number of channels. It was estimated that a 7-cell cluster size should provide an adequate 18.7 dB signal-to-interference ratio. The margin, however, is slim, and the 17 dB signal-to-interference ratio requirement could not be met over 90 % of the coverage area.

3.7.3 Sectoring

Sectoring is basically a technique which can increase the SIR without necessitating an increase in the cluster size. Till now, it has been assumed that the base station is located in the center of a cell and radiates uniformly in all the directions behaving as an omni-directional antenna. However it has been found that the co-channel interference in a cellular system may be decreased by replacing a single omni-directional antenna at the base station by several directional antennas, each radiating within a specified sector. In the Figure 3.8, a cell is shown which has been split into three 120^o sectors. The base station feeds three 120^o directional antennas, each of which radiates into one of the three sectors. The channel set serving this cell has also been divided, so that each sector is assigned one-third of the available number cell of channels. This technique for reducing co-channel interference wherein by using suit-

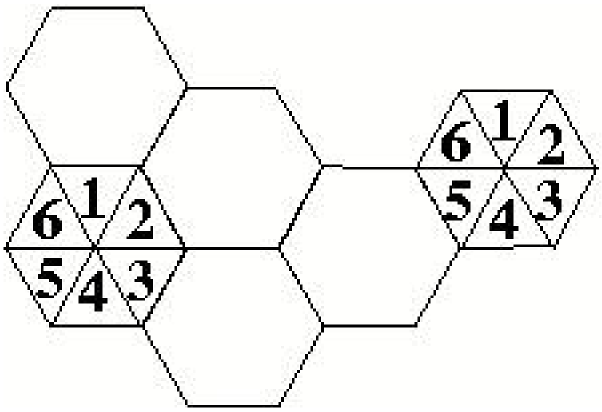

Figure 3.9: A seven-cell cluster with 60^o sectors.

able directional antennas, a given cell would receive interference and transmit with a fraction of available co-channel cells is called 'sectoring'. In a seven-cell-cluster layout with 120^o sectored cells, it can be easily understood that the mobile units in a particular sector of the center cell will receive co-channel interference from only two of the first-tier co-channel base stations, rather than from all six. Likewise, the base station in the center cell will receive co-channel interference from mobile units in only two of the co-channel cells. Hence the signal to interference ratio is now modified to

$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{2} \tag{3.22}$$

where the denominator has been reduced from 6 to 2 to account for the reduced number of interfering sources. Now, the signal to interference ratio for a seven-cell cluster layout using 120^o sectored antennas can be found from equation (3.24) to be 23.4 dB which is a significant improvement over the Omni-directional case where the worst-case S/I is found to be 17 dB (assuming a path-loss exponent, n=4). Some cellular systems divide the cells into 60^o sectors. Similar analysis can be performed on them as well.

Ex. 5: A cellular system having a seven-cell cluster layout with omni-directional antennas has been performing satisfactorily for a required signal to interference ratio of 15 dB. However due to the need for increasing the number of available channels, a 60^o sectoring of the cells has been introduced. By what percentage can the number of channels N_{total} be increased assuming a path-loss component n=4?

Solution: The seven-cell cluster layout with 60^o sectoring is shown in the Figure 3.9.

It is easy to see that the shaded region in the center receives interference from just one first-tier cell and hence the signal to interference ratio can be obtained suitably as

$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{1} = \frac{(\sqrt{(3)(7)})^4}{1} = 26.4dB. \quad (3.23)$$

Since the SIR exceeds 15 dB, one can try reducing the cluster size from seven to four. Now, the SIR for this reduced cluster size layout can be found to be

$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{1} = \frac{(\sqrt{(3)(4)})^4}{1} = 21.6dB. \quad (3.24)$$

The S/I ratio is still above the requirement and so a further reduction in the cell cluster size is possible. For a 3-cell cluster layout, there are two interfering sources and hence the S/I ratio is found to be

$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{1} = \frac{(\sqrt{33})^4}{2} = 16.07dB. \quad (3.25)$$

This is just above the adequate S/I ratio and further reduction in cluster size is not possible. So, a 3-cluster cell layout could be used for meeting the growth requirements. Thus, when the cluster size is reduced from 7 to 3, the total number of channels increased by a factor of 7/3.

The calculations in the above example are actually an idealization for several reasons. Firstly, practical antennas have side lobes and cannot be used to focus a transmitted beam into a perfect 120^o sector or 60^o sector. Due to this, additional interference will be introduced. Next, it is also a cause of concern that a given number of channels are not able to support as many subscribers when the pool of channels is divided into small groups. This is due to a reduction in Trunking Efficiency, a term which will be explained later on. Because sectoring involves using more than one antenna per base station, the available channels in the cell are divided and dedicated to a specific antenna. This breaks the available set of channels into smaller sets, thus reducing the trunking efficiency. Moreover, dividing a cell into sectors requires that a call in progress will have to be handed off (that is, assigned a new channel) when a mobile unit travels into a new sector. This increases the complexity of the system and also the load on the mobile switching center/base station.

3.7.4 Microcell Zone Concept

The increased number of handoffs required when sectoring is employed results in an increased load on the switching and control link elements of the mobile system. To overcome this problem, a new microcell zone concept has been proposed. As shown in Figure 3.10, this scheme has a cell divided into three microcell zones, with each of the three zone sites connected to the base station and sharing the same radio equipment. It is necessary to note that all the microcell zones, within a cell, use the same frequency used by that cell; that is no handovers occur between microcells. Thus when a mobile user moves between two microcell zones of the cell, the BS simply switches the channel to a different zone site and no physical re-allotment of channel takes place.

Locating the mobile unit within the cell: An active mobile unit sends a signal to all zone sites, which in turn send a signal to the BS. A zone selector at the BS uses that signal to select a suitable zone to serve the mobile unit - choosing the zone with the strongest signal.

Base Station Signals: When a call is made to a cellular phone, the system already knows the cell location of that phone. The base station of that cell knows in which zone, within that cell, the cellular phone is located. Therefore when it receives the signal, the base station transmits it to the suitable zone site. The zone site receives the cellular signal from the base station and transmits that signal to the mobile phone after amplification. By confining the power transmitted to the mobile phone, co-channel interference is reduced between the zones and the capacity of system is increased.

Benefits of the micro-cell zone concept: 1) Interference is reduced in this case as compared to the scheme in which the cell size is reduced.

2) Handoffs are reduced (also compared to decreasing the cell size) since the microcells within the cell operate at the same frequency; no handover occurs when the mobile unit moves between the microcells.

3) Size of the zone apparatus is small. The zone site equipment being small can be mounted on the side of a building or on poles.

4) System capacity is increased. The new microcell knows where to locate the mobile unit in a particular zone of the cell and deliver the power to that zone. Since

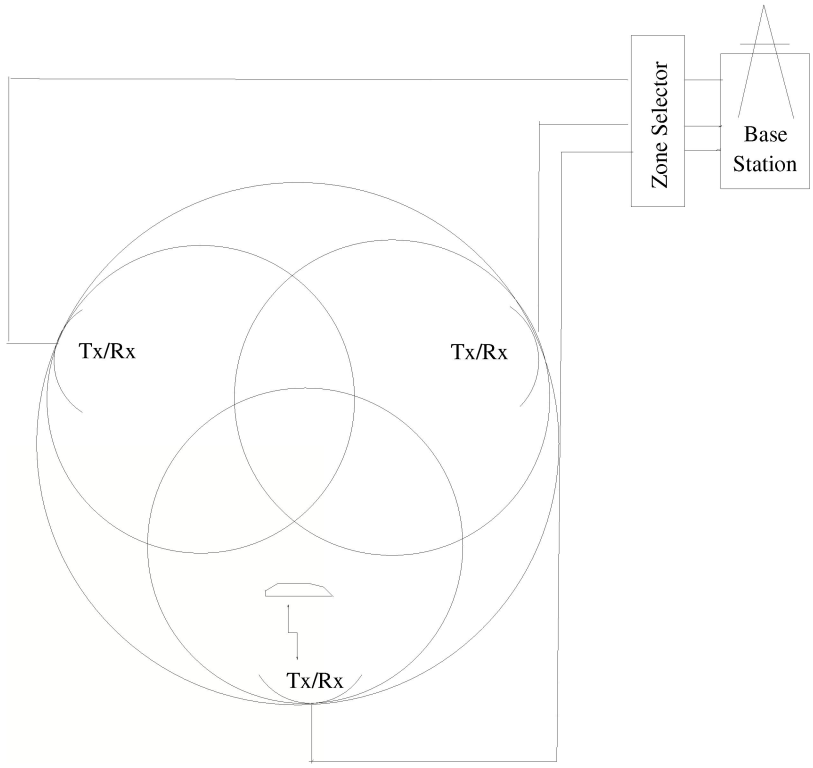

Figure 3.10: The micro-cell zone concept.

the signal power is reduced, the microcells can be closer and result in an increased system capacity. However, in a microcellular system, the transmitted power to a mobile phone within a microcell has to be precise; too much power results in interference between microcells, while with too little power the signal might not reach the mobile phone.This is a drawback of microcellular systems, since a change in the surrounding (a new building, say, within a microcell) will require a change of the transmission power.

3.8 Trunked Radio System

In the previous sections, we have discussed the frequency reuse plan, the design trade-offs and also explored certain capacity expansion techniques like cell-splitting and sectoring. Now, we look at the relation between the number of radio channels a cell contains and the number of users a cell can support. Cellular systems use the concept of trunking to accommodate a large number of users in a limited radio spectrum. It was found that a central office associated with say, 10,000 telephones requires about 50 million connections to connect every possible pair of users. However, a worst case maximum of 5000 connections need to be made among these telephones at any given instant of time, as against the possible 50 million connections. In fact, only a few hundreds of lines are needed owing to the relatively short duration of a call. This indicates that the resources are shared so that the number of lines is much smaller than the number of possible connections. A line that connects switching offices and that is shared among users on an as-needed basis is called a trunk.

The fact that the number of trunks needed to make connections between offices is much smaller than the maximum number that could be used suggests that at times there might not be sufficient facilities to allow a call to be completed. A call that cannot be completed owing to a lack of resources is said to be blocked. So one important to be answered in mobile cellular systems is: How many channels per cell are needed in a cellular telephone system to ensure a reasonably low probability that a call will be blocked?

In a trunked radio system, a channel is allotted on per call basis. The performance of a radio system can be estimated in a way by looking at how efficiently the calls are getting connected and also how they are being maintained at handoffs.

Some of the important factors to take into consideration are (i) Arrival statistics, (ii)Service statistics, (iii)Number of servers/channels.

Let us now consider the following assumptions for a bufferless system handling 'L' users as shown in Figure 3.11:

(i) The number of users L is large when compared to 1.

(ii) Arrival statistics is Poisson distributed with a mean parameter λ.

(iii) Duration of a call is exponentially distributed with a mean rate μ_1.

(iv) Residence time of each user is exponentially distributed with a rate parameter μ_2.

(v) The channel holding rate therefore is exponentially distributed with a parameter $\mu = \mu_1 + \mu_2$.

(vi) There is a total of 'J' number of channels ($J \leq L$).

To analyze such a system, let us recapitulate a queuing system in brief. Consider an M/M/m/m system which is an m-server loss system. The name M/M/m/m reflects

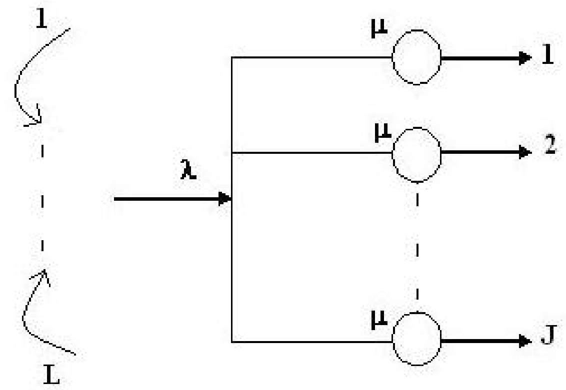

Figure 3.11: The bufferless J-channel trunked radio system.

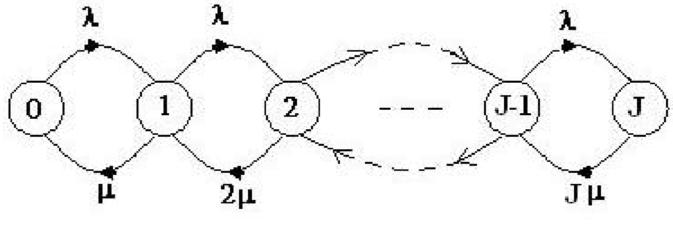

Figure 3.12: Discrete-time Markov chain for the M/M/J/J trunked radio system.

standard queuing theory nomenclature whereby:
(i) the first letter indicates the nature of arrival process(e.g. M stands for memoryless which here means a Poisson process).
(ii) the second letter indicates the nature of probability distribution of service times.(e.g M stands for exponential distribution). In all cases,successive inter arrival times and service times are assumed to be statistically independent of each other.
(iii) the third letter indicates the number of servers.
(iv) the last letter indicates that if an arrival finds all 'm' users to be busy, then it will not enter the system and is lost.
In view of the above, the bufferless system as shown in Figure 3.11 can be modeled as M/M/J/J system and the discrete-time Markov chain of this system is shown in Figure 3.12.

Trunking mainly exploits the statistical behavior of users so that a fixed number of channels can be used to accommodate a large, random user community. As the number of telephone lines decrease, it becomes more likely that all channels are busy for a particular user. As a result, the call gets rejected and in some systems, a queue may be used to hold the caller's request until a channel becomes available. In the telephone system context the term Grade of Service (GoS) is used to mean the probability that a user's request for service will be blocked because a required facility, such as a trunk or a cellular channel, is not available. For example, a GoS of 2 % implies that on the average a user might not be successful in placing a call on 2 out of every 100 attempts. In practice the blocking frequency varies with time. One would expect far more call attempts during business hours than during the middle of the night. Telephone operating companies maintain usage records and can identify a "busy hour", that is, the hour of the day during which there is the greatest demand for service. Typically, telephone systems are engineered to provide a specified grade of service during a specified busy hour.

User calling can be modeled statistically by two parameters: the average number of call requests per unit time λ_{user} and the average holding time H. The parameter λ_{user} is also called the average arrival rate, referring to the rate at which calls from a single user arrive. The average holding time is the average duration of a call. The product:

$$A_{user} = \lambda_{user} H \tag{3.26}$$

that is, the product of the average arrival rate and the average holding time–is called the offered traffic intensity or offered load. This quantity represents the average traffic that a user provides to the system. Offered traffic intensity is a quantity that is traditionally measured in Erlangs. One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied. For example, a channel that is occupied for thirty minutes during an hour carries 0.5 Erlang of traffic.

Call arrivals or requests for service are modeled as a Poisson random process. It is based on the assumption that there is a large pool of users who do not cooperate in deciding when to place calls. Holding times are very well predicted using an exponential probability distribution. This implies that calls of long duration are much less frequent than short calls. If the traffic intensity offered by a single user is A_{user}, then the traffic intensity offered by N users is A = NA_{user}. The purpose of the statistical model is to relate the offered traffic intensity A, the grade of service P_b, and the number of channels or trunks C needed to maintain the desired grade of service.

Two models are widely used in traffic engineering to represent what happens when a call is blocked. The blocked calls cleared model assumes that when a channel or trunk is not available to service an arriving call, the call is cleared from the system. The second model is known as blocked calls delayed. In this model a call that cannot be serviced is placed on a queue and will be serviced when a channel or trunk becomes available.

Use of the blocked-calls-cleared statistical model leads to the Erlang B formula that relates offered traffic intensity A, grade of service P_b, and number of channels K. The Erlang B formula is:

$$P_b = \frac{A^K/K!}{\sum_{n=0}^{K} A^n/n!} \tag{3.27}$$

When the blocked-calls-delayed model is used, the "grade of service" refers to the probability that a call will be delayed. In this case the statistical model leads to the Erlang C formula,

$$P[delay] = \frac{A^K/[(K-A)(K-1)]!}{A^K/[(K-A)(K-1)]! + \sum_{n=0}^{K} A^n/n!}. \tag{3.28}$$

Ex. 6: In a certain cellular system, an average subscriber places two calls per hour during a busy hour and the average holding time is 3 min. Each cell has 100 channels. If the blocked calls are cleared, how many subscribers can be serviced by each cell at 2 % GoS?

Solution: Using Erlang B table, it can be seen that for $C = 100$ and $GoS = P_b = 2\%$, the total offered load A=87.972 Erlangs. Since an individual subscriber offers a load of A_{user} = (2 calls / 60 min)3 min = 0.1 Erlang, the maximum number of subscribers served is

$$N = A/A_{user} = 87.972/0.1 \approx 880. \tag{3.29}$$

Ex. 4: In the previous example, suppose that the channels have been divided into two groups of 50 channels each. Each subscriber is assigned to a group and can be served only by that group. How many subscribers can be served by the two group cell?

Solution: Using the Erlang B table with $C = 50$ and $GOS = P_b = 2\%$, the total offered load per group is

$$A = 40.255 Erlangs \tag{3.30}$$

Thus the maximum number of users per group is

$$N_{group} = A/A_{user} \approx 403. \tag{3.31}$$

Thus, counting both the groups, maximum number of users in the two group cell is 806.

The above example indicates that the number of subscribers that can be supported by a given number of channels decreases as the pool of channels is sub-divided. We can express this in terms of the trunking efficiency, defined as the carrier load per channel, that is,

$$\xi = (1 - P_b)A/C. \tag{3.32}$$

This explains why the sectoring of a cell into either 120^o or 60^o sectors reduces the trunking efficiency of the system. Thus the system growth due to sectoring is impacted by trunking efficiency considerations.

3.9 References

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