

# Cellular Based Wireless Communication

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## 5.1 Introduction

Originally, the focus of mobile radio systems design was towards increasing the coverage of a single transceiver. A single powerful base station was employed to provide connectivity to all mobile devices in a service area. Since spectrum length allocated for private communication is limited, it led to spectral congestion in the service area when large number of mobile clients became concurrently active in the same service area. Typically, in radio communication system, a user requires about 30kHz for voice communication. Therefore, if a high power antenna is mounted on a large tower to cover an entire town, it can support just about  $25\text{MHz}/30\text{kHz} = 833$  users, assuming that 25MHz spectral band is available for private communication. An obvious way to get around the technical limitations and increase both the capacity and coverage is to some how be able to reuse allocated frequencies without interferences. The idea was driven by a simple counter thought to the use of high powered transceiver. When a limited range transceiver is used then the wireless connectivity can be provided only in a small finite area of few hundred square meters. However, the frequency of an already deployed transceivers can now be reused by deploying another similar transceiver at a distance where the new transceiver does not interfere with the transceivers which were deployed earlier. In other words, spectral congestion can be eliminated by developing an architecture that would allow spatial multiplexing.

The concept of cellular architecture [6, 3, 5, 9] became the turning point in wireless communication technologies based on frequency reuse. The success of spatial multiplexing depends not only on elimination of interferences but also to provide continuous uninterrupted coverage. To provide continuous coverage, the uncovered gaps in coverage area should be serviced by the transceivers operating with frequencies different from the previously deployed transceivers. The proposed deployment of transceivers is equivalent to partitioning of a large coverage area using certain small finite continuous area which may be appropriately called as a cell and serviced by a single transceiver.

The frequency reuse problem can be viewed in terms of map coloring. In a map, regions are typically demarcated by different colors. If two adjacent regions are colored by same color then it is difficult to distinguished one from the other. Since multi-colored printing is expensive, as few colors as possible should be used for map coloring. So colors are reused. It is well known that map coloring can be accomplished by use of four colors [?].

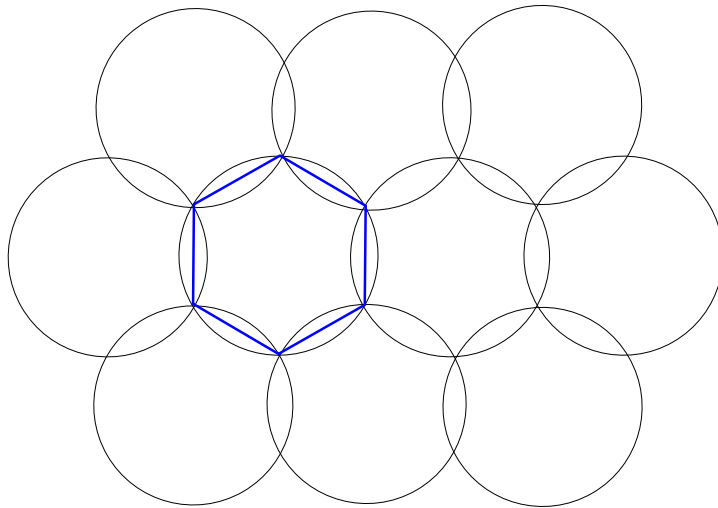


Figure 5.1: Cell packing of a coverage area.

Frequency reuse can be seen many ways similar to reuse of colors in map coloring. There are, however, many differences. Frequency reuse requires a minimum separation between cells which is dependent on the strength of signal interferences between the cells. However, one single color can be used for coloring two regions in a map provided a separation of one region exists in between the two. The problems like co-channel and adjacent channel interferences which are encountered in planning of frequency reuse have no parallels in the map coloring.

Under ideal scenario, wireless signals may be assumed to propagate equally in all directions. Therefore, a cell representing the coverage area of an antenna can be considered as a circle. To provide continuous coverage in a service area, we need to find a packing of the desired area using circles each of the area equal to that of a cell. The packing has to be done in a way that there are no uncovered gaps in the service area. This is possible in the way illustrated by Figure 5.1 where the circles overlap minimally. The common chords of a circle with adjacent overlapping circles define a hexagonal area within that circle as indicated by the hexagon in the above figure. The collection of hexagons like the one shown in the figure packs the service area without leaving gaps. From here on, we will consider a cell to be a regular hexagon as explained. In reality, however, this is not the case. Radio waves

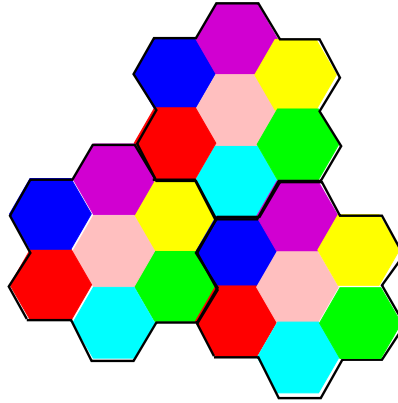


Figure 5.2: Frequency reuse concept.

like light waves are affected by reflection, refraction, diffraction, absorption, polarization and scattering. In reality terrain structures could be very different from one coverage area to another. There may be tall buildings, hillocks and tall trees which come in the way of signal transmission. The actual shape of a cell is typically determined by field measurements radio signal propagation. But for convenience in presentation of basic ideas, the assuming the cell to have a hexagonal boundary would suffice.

### 5.1.1 Frequency planning

Figure 5.2 illustrates the frequency reuse concept. The set of cells in same shade, use the same frequency. Typically, an antenna is designed to work over the entire frequency spectrum. But it is possible to block most part of the spectrum and leave only a small group of selected channels on an antenna. So, a cell can be assigned a selected group of channels for communication inside it. The group of channels allocated to one cell will thus be different from the groups of channels assigned to the antennas of its geographically adjacent cells. The process of allocating channel groups to cells in a coverage area is called frequency reuse or frequency planning.

If a system has  $C$  duplex channels then each cell  $x$  can be allocated a set of  $C_x$  channels, where  $C_x < C$ . Assuming that  $C$  channels are equally divided among a group of  $N$  cells where each cell gets  $C_x$  number of channels,  $C = N \times C_x$ . The group of  $N$  cells which collectively share  $C$  channels is

called a cluster. If there are  $R_c$  replicated clusters, the capacity  $K$  of the system is  $K = R_c \times N \times C_x = R_c \times C$ . This means that the capacity of a cellular system is directly proportional to the number of clusters. Since a cluster defines a full reuse of the set of allocated frequencies, the size of a cluster is the determining factor for capacity of a cellular based wireless communication system.

The cells which use same frequencies for communication are referred to as co-channel cells. Co-channel interferences can be minimized by increasing the reuse distance. So, if the cell radius is not changed, the cluster size  $N$  should be increased in order to increase the co-channel distance. But if  $N$  becomes large then a given service area can be covered by only a few number of clusters. So, the capacity of the service area, which depends on the replication of clusters, can not be increased substantially. On the other hand, if the value of  $N$  is decreased then more clusters will be needed to cover the service area, so the capacity will increase. When cluster size becomes small, the distance between co-channel cells will become small. Though it allows reuse of the same frequency only more frequently, the co-channel interferences increase. Thus, in order to maximize the capacity over a coverage area while it is desirable to keep  $N$  low, care should be taken so that co-channel interferences do not begin to affect the quality of communication.

The effect of frequency reuse can be best understood through a simple example. Suppose, initially a single, high power transceiver was operating with a private spectrum of 25MHz. This transceiver was replaced by 28 low power transceivers. Let the cluster size be 7. Then the effective spectrum allocation increases by 4 fold to  $25\text{MHz} \times 4 = 100\text{MHz}$  after replacement of the high power transceiver. Each cell gets an allocation of  $25\text{MHz}/7 = 3.57\text{MHz}$  of spectrum under the new system. Assuming voice communication to require 30KHz, each cell can support up to  $3.57\text{MHz}/30\text{kHz} = 119$  users. The number of users in each cluster remains at  $119 \times 7 = 833$ . However, due to 4 replications of clusters, the total number of users that can be supported under the new system increases 4 fold to  $833 \times 4 = 3332$ .

With underlying assumption of a hexagonal layout of cells, it is possible to derive the formula for reuse distance. Let us first examine the geometry of a hexagonal cell. As shown in Figure 5.3, the length of a side of a regular hexagon inscribed in a circle of radius  $R$  is also equal to  $R$ . The each side of this regular hexagon is at a distance  $R\sqrt{3}/2$  units from the center of hexagon. The area of such a hexagon is  $6(\sqrt{3}/4)R^2$  unit<sup>2</sup>. Now let us see how reuse distance can be calculated. But before, that we should abstracted out the

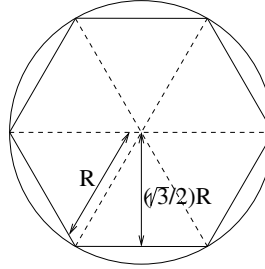


Figure 5.3: A regular hexagon inscribed in circle of radius  $R$ .

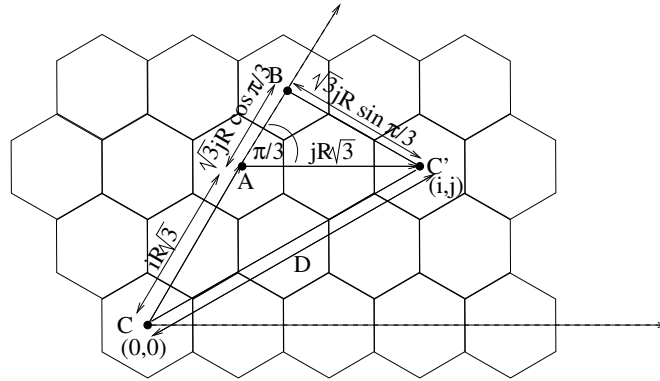


Figure 5.4: Cell distance using hexagonal cell geometry

unit for measurement of distance from consideration. To realize it, we assume the centers of cells to be at integer coordinates. The arrangement of the cell centers according to hexagonal layout, thus, form a grid system whose axes are at an angle of  $\pi/3$ . Using the above fact and simple some properties of regular hexagon, the following lemma provides the relationship between the distance of a co-channel cell from a cell.

**Lemma 1** *Let the coordinate of a cell  $C$  be  $(0,0)$  and that of its co-channel cell  $C'$  be  $(i,j)$ . Then co-channel distance  $D = CC'$  is equal to  $R\sqrt{3(i^2 + ij + j^2)}$ , where  $R$  denotes the length of a side of the regular hexagon representing a cell.*

**Proof:** Consider the Figure 5.4. Since, the coordinates of the cell centers are given by a pair of integers, and the axes of the coordinate system between

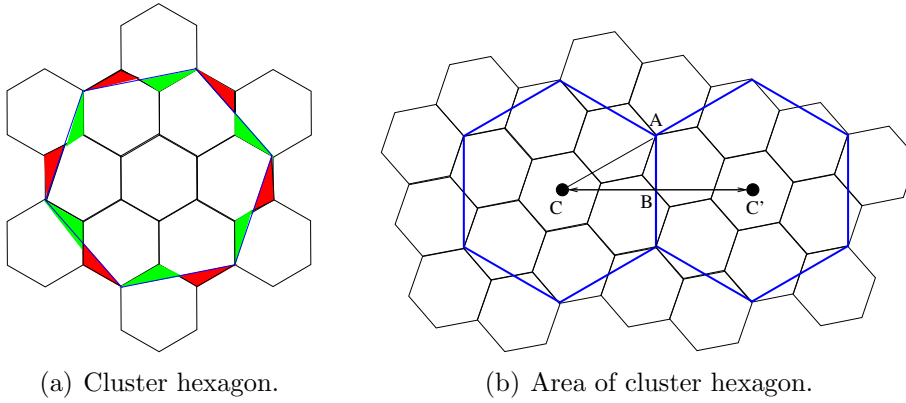


Figure 5.5: Cluster area approximates to a regular hexagon.

them form an angle of  $\pi/3$ ,  $C'$  can be reached from  $C$  by traversing  $i$  cells in one axial direction then turning  $\pi/3$  in clockwise and then hopping  $j$  cells in the other axial direction. From the above figure, distance  $AB = jR \cos \pi/3$ ,  $BC' = jR \sin \pi/3$ . So

$$\begin{aligned}
 D^2 &= (\sqrt{3}iR + \sqrt{3}jR \cos \pi/3)^2 + (\sqrt{3}jR \sin \pi/3)^2 \\
 &= R^2(3i^2 + 6ij \cos \pi/3 + 3j^2 \cos^2 \pi/3 + 3j^2 \sin^2 \pi/3) \\
 &= R^2(3i^2 + 3ij + 3j^2) \\
 &= 3R^2(i^2 + ij + j^2)
 \end{aligned}$$

□

Each cell in a cluster is assumed to have identical wireless range, and equal number of channels. So, the number of cells,  $N$ , per cluster can be obtained by determining the area of the cluster and then dividing it by the area of a cell. The area of a cluster can be found easily from the simple analysis of hexagonal geometry.

**Lemma 2** *The cluster size  $N = i^2 + ij + j^2$ .*

**Proof:** Consider the diagram in Figure 5.5(a). Let the large regular hexagon enclosing a cluster be referred to as cluster hexagon for brevity. Consider the shaded tiny triangles in the figure. A pair of adjacent shaded triangles one inside and the other outside the cluster hexagon are congruent. So the area of the cluster of cells is equal to the cluster hexagon indicated in Figure 5.5(a).

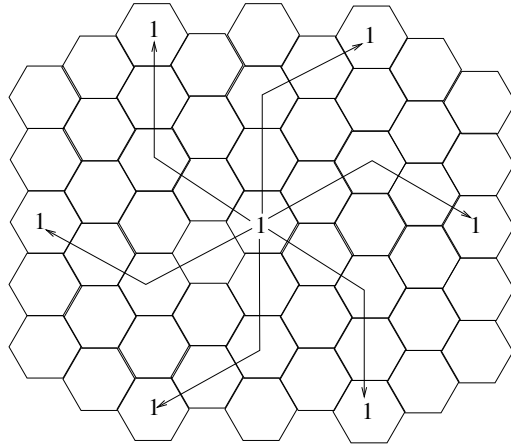


Figure 5.6: Co-channel cells

Now consider Figure 5.5(b). The distance between the centers  $C$  and  $C'$  of two adjacent cluster is  $D$ . The angle  $CAB$  is equal to  $\pi/3$ . So, the length  $CA = (D/2)/\sin \pi/3 = D/\sqrt{3}$  which is equal to the radius of the cluster hexagon.

As explained earlier, the area of a single hexagonal cell of side  $R$  is  $6R^2\sqrt{3}/4$ . Since, a cluster is also a regular hexagon of side  $D/\sqrt{3}$ , its area is given by  $Cluster_{area} = 6 \frac{D^2}{4\sqrt{3}}$ . Since the area of cluster divided by the area of one cell should be equal to  $N$ , we have

$$N = \left( \frac{D^2}{4\sqrt{3}} \right) / \left( \frac{R^2\sqrt{3}}{4} \right) = \frac{D^2}{3R^2} = \frac{3R^2(i^2 + ij + j^2)}{3R^2} \\ = i^2 + ij + j^2$$

□

Figure 5.6 depicts co-channel cells of a cell which use the same frequency. Here  $i = 2$  and  $j = 2$ , and cluster size is  $N = 2^2 + 2 \cdot 2 + 2^2 = 12$ . The ratio  $D/R = \sqrt{3N}$  denoted by  $Q$  represents co-channel reuse ratio. A small value of  $Q$  means  $N$  is small. This leads to large capacity. However, when  $Q$  is large, it leads to low interference; hence better transmission quality. A trade off has to be made between capacity and transmission quality.



### 5.1.2 Co-channel Interference

Co-channel interference is one of the major problem faced by service providers in setting up wireless communication service. For a good understanding of how interference could affect communication it is important to examine radio signal measurement and propagation.

Decibel is the unit used for the measurement of relative strengths of radio signals from two different radios. 10 decibels equals one Bel which represents the power ratio of 1:10. A power ratio of 1:100 equals 2 Bels or 20 decibels. Similarly, the power ratio 1:1000 is measured as 3 Bels or 30 decibels. The power gain due to amplification is measured by the relative power strengths of the input power  $P_1$  and the amplified power  $P_2$ . When the measurement of power ratio is made with reference to 1 watt then the unit of measurement is denoted by dB or dBW. Sometimes instead of dB, the measurement of power ratio in decibels is done with reference to one milliwatt, and the unit of measurement for power ratio is denoted by dBm. Unless stated otherwise, the unit of measurement here will be dBm. 0 dBm equals 1 milliwatt. In general, a power of  $P$  watts equals  $x$  dBm, where

$$x = 10 \log_{10} \left( \frac{P}{10^{-3}} \right) = 30 + 10 \log_{10} P$$

The use of log scale in measurement of relative power strengths simplifies the calculation. With the log scale, the expression of  $\log_{10} (P_2/P_1)$  gives the measurement of relative power strength due to amplification in Bels. For example, if an amplifier outputs 100 watt with an input of 100 milliwatts, then the power gain due to amplification is  $\log_{10}(100/0.1) = \log_{10} 1000 = 3$  Bels or 30 deciBels. In the case of radio signal measurements, power ratios are usually very small. So, deciBels is the preferred unit for expressing smaller power ratios. Accordingly, the formula  $10 \log_{10} (P_2/P_1)$  is normally used for measuring relative power strengths between the two radio sources. A negative gain, which indicates a decay or signal attenuation, is represented by a power ratio less than 1.

Let us examine a realistic looking example to understand the significance of log scale in computation. Suppose, a micro-wave system uses a 10 watt transmitter. This transmitter is connected by a cable with 0.7 dB loss to a 13 dB antenna. Let atmospheric loss be 137 dB on transmission. The receiver antenna with 11 dB gain connected to cable with 1.3 dB loss to the receiver. Then the power at the received can be calculated as follows:

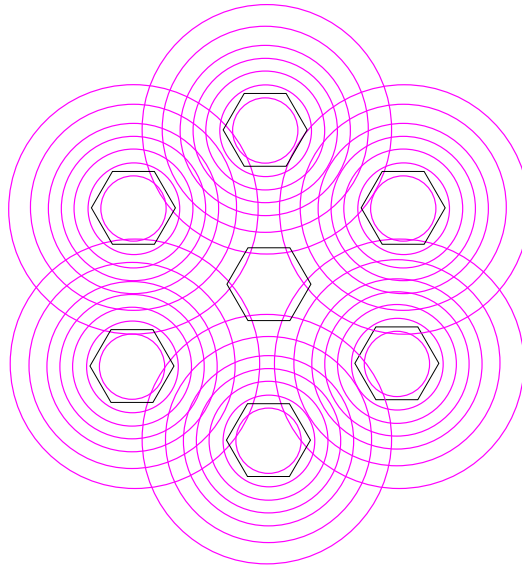


Figure 5.7: Interferences due to propagation of co-channel signals.

Transmitter output: 10 watts = 10000 mW.

Amplification gain at transmitter:  $10\log_{10}(10000/1) = 40$  dBm.

Then the relative strength of power at the receiver equals  $(40 - 0.7 + 13 - 137)$  dBm = -84.7 dBm. Including the amplification gain, atmospheric loss and loss due to cable connecting amplifier to its antenna. On the receiver side, the antenna and the connecting cable together lead to  $(11 - 1.3)$  dBm gain. So the net power received by the receiver is  $(-84.7 + 9.7)$  dBm = -75 dBm.

The co-channel interferences experienced by a cell is due to the use of same group channels in the nearby cells. The quality of the signals received from the current base station is affected by co-channel interferences. As Figure 5.7 depicts the wireless signals from the base stations in co-channel cells around a cell ripple out much like waves in water when a stone is thrown into the center of a pond. The strength of co-channel interferences with relative to the strength of signals from the current cell, provides a measure for the quality of communication. The Signal to Interference Ratio (SIR) should be monitored by individual mobile terminals. If the strength of interference increases with relative to that of signals then communication quality deteriorates. A Mobile

Terminal (MT) experiencing low SIR should try to switch to a neighboring cell which may provide better SIR. The SIR is given

$$S/I = S / \left( \sum_{i=1}^{i_0} I_i \right),$$

where  $I_i$  is the interfering signal received from co-channel  $i$ , and  $i_0$  is the number of adjacent co-channel cells.

In free space, the average signal strength known to decay according a power law involving the distance between transmitter and the receiver. Let  $d$  is the distance between the transmitter and the receiver, and  $P_0$  be the power received at a close-in reference point in the far-field region of the transmitter antenna. Then the average received power  $P_r$  at receiver from the transmitting antenna is given by:

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

In reality  $P_r$  is proportional to the expression in the right hand side of the equation. Here, the constant of proportionality is assumed to be 1, but it actually will depends on antenna gain, path loss exponent and carrier wavelength. The above equation for power received when expressed in terms of dBm becomes

$$P_r(\text{dBm}) = P_0(\text{dBm}) - 10n \log_{10} \left( \frac{d}{d_0} \right).$$

Now let us examine the topological configuration of cells, and study how a MT may arrive at a better approximation of SIR. Suppose, the MT is at a distance  $D_i$  from  $i$ -th co-channel cell. The distance is measured from the cell center where the corresponding base station is located. So, the signal attenuation from  $i$ th co-channel cell is proportional to  $D_i^{-n}$ . The signal strength beamed from the current base station to the mobile terminal is proportional to  $R^{-n}$ , where  $R$  is the radio range of the base station. Assuming all interfering co-channel base stations to be at equal distance from the MT,

the SIR (in dB) is equal to

$$\begin{aligned} S/I &= \left( R^{-n} / \left( \sum_{i=1}^{i_0} D_i^{-n} \right) \right) \\ &= \frac{(D/R)^n}{i_0} \\ &= \left( \left( \sqrt{3N} \right)^n / i_0 \right). \end{aligned} \tag{5.1}$$

The minimum SIR for good voice quality is known to 18 dBm. Thus, in order to check whether a cluster size of  $N = 7$  in a cellular based wireless system with the path loss exponent  $n = 4$  would meet the requirement of voice quality, let us compute SIR value received by a MT which is located at center of its current cell. Using equation 5.1:

$$\begin{aligned} 10 \log_{10}(S/I) &= 10 \log_{10} \left( \left( \sqrt{3N} \right)^4 / i_0 \right) \\ &= 10 \log_{10} \left( \left( \sqrt{21} \right)^4 / 6 \right) \\ &= 10 \log_{10} 73.5 \\ &= 10 \times 1.865 \\ &= 18.65 \end{aligned}$$

As the SIR value is above the required threshold of 18 dBm, cluster size of 7 is ok when path loss exponent is 4.

When cell sectorization is used with  $120^\circ$  sectors, the number of co-channel cells which is reduced from 6 to 2 for  $N = 7$ . Therefore,

$$S/I = \frac{1}{2} \left( \sqrt{3N} \right)^n$$

Thus the increase in SIR with sectorization is 3 times over that without sectorization.

The scenario that a MT will located at the center of the current cell, occurs very rarely. So, topological configuration of the current cell, its co-channel cells and the position of MT should be taken into account for computing SIR. Figure 5.8 [10] depicts a realistic topological configuration. It is assumed that MT is located at the boundary of its current cell where the signal strength from current base station is at the minimum level. With

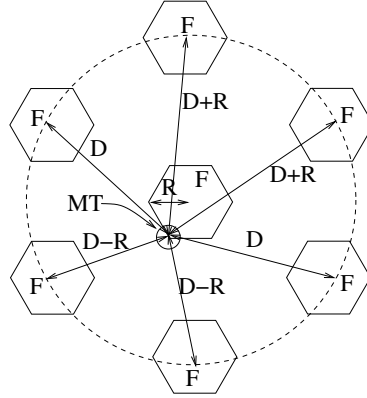


Figure 5.8: Co-channel interference considering exact cell geometry.

cluster size of 7, there will be two co-channel cells at a distance  $D - R$  from MT, two at a distance  $D$  and two others at a distance  $D + R$  as indicated in Figure 5.8. So ratio of power strengths of current base station and the other interfering base stations, with path loss factor  $n = 4$ , is

$$\begin{aligned} S/I &= \frac{R^{-4}}{2(D - R)^{-4} + 2D^{-4} + 2(D + R)^{-4}} \\ &= \frac{1}{2(\sqrt{21} - 1)^{-4} + 2(\sqrt{21})^{-4} + 2(\sqrt{21} + 1)^{-4}} \end{aligned}$$

The above expression is equal to 49.56. In terms of decibels the value of SIR will thus be  $10 \log_{10} 49.56 = 17$  dBm. Since the value of SIR is lower than acceptable threshold the voice quality will not be good.

### 5.1.3 Cell splitting and sectoring

As observed earlier, frequency reuse can be increased using smaller cells. But smaller cells will lead to shorter co-channel distance; and therefore, increase in co-channel interferences. The challenge is to keep interference low and increase the capacity. After a cellular service area has been planned and infrastructure is in place, any incremental change like adding channels to a cell for handling increase in traffic load is expensive and difficult to execute. However, two simple ideas, namely,

1. Cell splitting

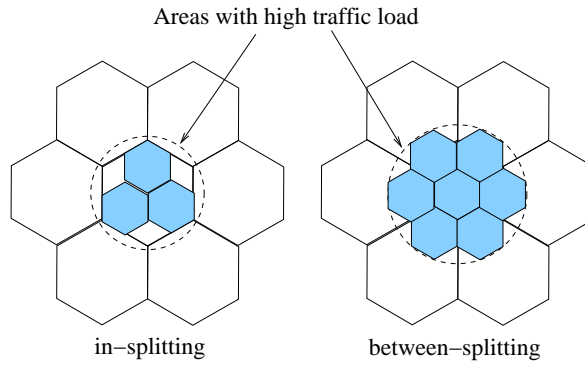


Figure 5.9: Cell splitting.

## 2. Cell sectoring

are found to be quite effective for handling increase in traffic load.

Cell splitting allows creation of smaller cells out of a standard cell. The advantage of cell splitting is that it uses the same idea of spatial multiplexing with smaller cells called microcells. The antennas can be placed on the top of buildings, hills and even on lamp posts. Smaller cells are placed in or between large cells. Figure 5.9 illustrates the two possible splittings where radius of every microcell is half the radius of a standard cell. Splitting increases the number channels because the number of channels per unit area increases. But the trade off is in terms of increase in co-channel interference. As equation 5.1 in section 5.1.2 indicates, co-channel interference can be controlled by keeping the ratio  $D/R$  unchanged. If  $D$  is decreased,  $R$  must also be decreased to keep the ratio at same value. Thus, the transmission power of newly introduced microcells must be reduced to avoid the co-channel interference.

Let  $P_s$  be output power of the transceiver of a standard cell, and  $P_m$  be output power of the transceiver of a microcell. Then the received power  $P_r$  at cell boundaries of the two cells are:

$$\begin{aligned} P_r[\text{original cell}] &\propto P_s R^{-n} \\ P_r[\text{micro-cell}] &\propto P_m (R/2)^{-n} \end{aligned}$$

It means that the ratio of transmit powers of a microcell versus a normal cell is 1:16 when path loss exponent is 4. It is not necessary to split all the cells. Sometimes it becomes difficult to exactly identify the coverage area

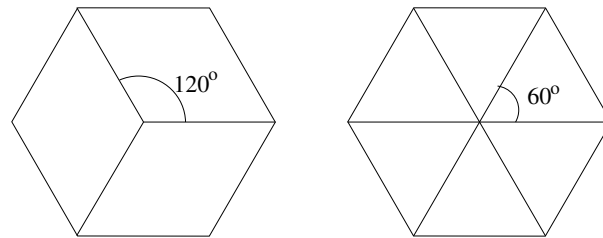


Figure 5.10: Cell sectoring.

that would require cell splitting. So in practice different cell sizes may co-exist. This calls for careful fine-tuning of power outputs by transceivers so that a safe distance is maintained among the co-channel cells and the co-channel interference is kept at a minimum level. But it makes the channel assignment quite complicated. As we observed, two different transmit powers will be needed to support cell splitting. The channels in a normal cell need to be broken into two groups: (i) corresponding to normal transmit power, and the other (ii) corresponding to a reduced transmit power. The splitting determines the sizes of two channel groups. Initially, only a few channels belong to the small power group, but as traffic grows more and more channels will be required, causing the group of channels with smaller power to grow in size. The splitting continues until the channels used in an area are all of low power. In addition to this presence of dual cell size calls for better channel switching with mobility of users. The movements within microcells will lead to more frequent channel switching compared to the movements within normal cells.

Cell sectoring is also used to address the problem of capacity increase. With this approach transmit power of a channel is concentrated into a finite sector of the cell. The omni-directional antenna of the cell is replaced by several directional antennas. The sectoring causes receipt of co-channel interference and transmission only within a specified region of the cell. So, it leads to greater reuse of frequencies. Normally a cell is partitioned into three sectors of  $120^\circ$  or six sectors of  $60^\circ$  each as in Figure 5.10. When sectoring is used the channels used in a particular cell are broken into sectorized groups and channels of a group are used only in one sector. As may be observed from Figure 5.11, with cluster size of 7, the cells labeled  $F$  are co-channel cells. Each cell can receive signals only two co-channel cells to its left. So, the

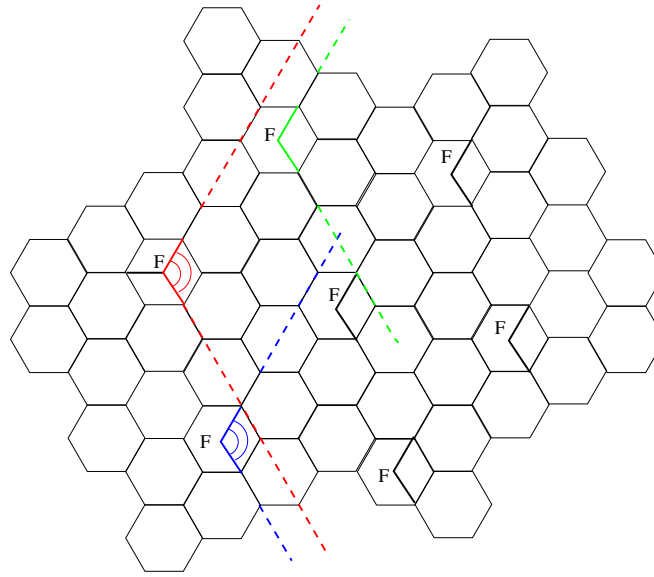


Figure 5.11: Cell sectoring.

cells at the center, which is within the signal propagation cones of its two co-channel cells on the left, may receive signals only from these two cells. The signal propagation cone of the co-channel cell vertically up to the left does not include the center cell, so the latter cell is not affected by co-channel interference due to that the former cell.

#### 5.1.4 Traffic intensity

Another important measurement related to capacity is traffic intensity. This measurement an estimation of traffic pattern, pick load, channel requirements, etc., in a Telecom system. The traffic intensity varies over the day. The probability of securing a connection in busy hours is directly related to traffic intensity. The unit of measurement is *Erlang* [2]. One Erlang is equal to the total traffic generated by the voice calls amounting to 60 minutes. For example, if there are 40 calls in one hour with each call of average duration of 5 minutes, then the traffic in Erlang is:

$$\text{Traffic in hour} = (40 \times 5)/60 = 3.33 \text{ Erlangs.}$$



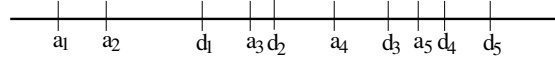


Figure 5.12: Distribution of the arrival of requests and their servicing.

Formally, in a lossy system, Grade of Service (GoS), which determines the probability of call blocking, is computed by *Erlang B* traffic model. Erlang B traffic model is used by Telecom companies to determine number of lines required to run service based on anticipated traffic and future expansion.

Let  $\lambda$  be arrival rate and  $\mu$  be service rate. Then  $1/\lambda$  is the average time between arrival of two consecutive requests and  $1/\mu$  is the average service time. For example, if the average duration of a connection is 3 minutes, then  $1/\mu = 0.05$  (hour), equivalently, in an average  $\mu = 20$  calls can be serviced per hour. To illustrate a concrete case, refer to Figure 5.13 depicting the arrival of call requests and the servicing of these requests for 5 users. The intervals  $I_i = a_{i+1} - a_i$ , for  $1 \leq i \leq 4$  represent the inter-arrival time. The duration of call services are represented by intervals  $S_1 = d_1 - a_1$ ,  $S_2 = d_2 - d_1$ ,  $S_3 = d_3 - d_2$ ,  $S_4 = d_4 - d_3$ ,  $S_5 = d_5 - d_4$ . The arrival and service rates are given by expressions  $1/E(I_i)$  and  $1/E(S_i)$  respectively, where  $E(.)$  represents the expected values of the corresponding intervals.

The inter-arrival times for connection requests is typically modeled by Poisson distribution [12]. A Poisson process is a sequence of events which are randomly spaced in time. In a wireless network different users seek connections at different times independent of one another. Therefore, the call requests (representing events) in a cell can be represented by a Poisson process. The rate  $\lambda$  of a Poisson process is the average number of number events (arrival of call requests) per unit time over a long period. The probability of  $n$  call requests arriving during an interval of time  $[0, \delta)$  under Poisson process is,

$$Pr[n_{t+\delta} - n_t = n] = \frac{(\lambda\delta)^n}{n!} e^{-\lambda\delta}, \text{ for } n = 0, 1, \dots,$$

where  $n_t$  denotes the number of arrivals since the time  $t = 0$ , and  $\delta$  is the call inter-arrival time. For example, if we observe system from some arbitrary time  $t \geq 0$  during a small interval of time  $\delta \geq 0$ , the probabilities of arrival

of number of call requests are:

$$\begin{aligned} Pr[n_{t+\delta} - n_t = 0] &= 1 - \lambda\delta + O(\delta^2) \\ Pr[n_{t+\delta} - n_t = 1] &= \lambda\delta + O(\delta^2) \\ Pr[n_{t+\delta} - n_t \geq 2] &= O(\delta^2), \end{aligned}$$

where  $O(\delta^2)$  represents the probability of more than 1 call request arriving in time  $\delta$ . Since,  $\delta$  is small, no more than 1 call request can arrive at the system during this interval. Therefore, the event of two or more calls arriving in the system within an interval of  $\delta$  can be considered as impossible. In other words, terms of  $O(\delta^2)$  can be safely ignored.

Assume that the number of channels is  $C$ . It means  $C$  connection requests can be service concurrently. Therefore, we have  $M/M/C/C$  kind of queuing system [2] with following parameters:

- The arrival process is Poisson with arrival rate  $\lambda$ .
- The service time is exponential with servicing rate  $\mu$ .
- The number of servers or the channels for serving the connection requests is  $C$ .
- The capacity or number clients which can be in the queue is also  $C$ .

The service scenario is best understood as a system with a limited number service lines connecting a large number of input lines (one for each call request) as shown in Figure 5.13(a). Figure 5.13(b) illustrates the same, but depicts how some of the services requests are met and others are dropped with probability of dropping a request being  $P_b$ .

Initially, 0 channels are used by system. Over a small interval the system may continue in state 0 with a probability of  $1 - \lambda\delta$ . The system will change to state 1 from state 0 with a probability  $\lambda\delta$ . But if one channel is already in use (i.e., system in state 1) then transition to state 0 will take place with a probability of  $\mu\delta$ . This implies that the systems continues in state 1 with a probability of  $1 - \lambda\delta - \mu\delta$ . So the system states and transitions is depicted by Figure 5.14 Over a long period of time, the system reaches steady state. In steady system if  $n$  channels remain occupied then, writing global balance equation for steady state equation, we get

$$\begin{aligned} \lambda\delta P_{n-1} &= n\mu\delta P_n, n \leq C \\ \lambda P_{n-1} &= n\mu P_n \\ P_1 &= (\lambda P_0)/\mu \end{aligned}$$

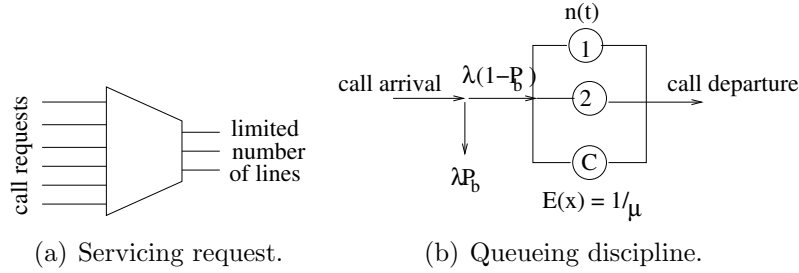


Figure 5.13: Queuing discipline and service of call requests.

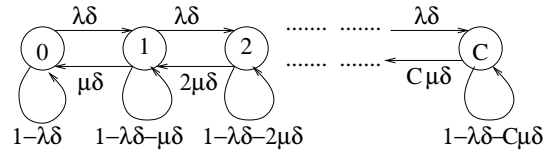


Figure 5.14: Markov chain representing system state and transitions.

Solving the recurrence in balance equation,

$$P_n = P_0 \left( \frac{\lambda}{\mu} \right)^n \frac{1}{n!}.$$

Note that the sum of probabilities of the system being any of the states  $n = 0, 1, 2, \dots$ , is 1. So, we have  $\sum_0^C P_n = 1$ . Now substituting for  $P_n$  in summation in terms of  $P_0$ ,

$$\sum_0^C P_0 \left( \frac{\lambda}{\mu} \right)^n \frac{1}{n!} = 1$$

Therefore,

$$P_0 = \frac{1}{\sum_{n=0}^C \left( \frac{\lambda}{\mu} \right)^n \frac{1}{n!}}.$$

We already know that  $P_C = P_0 \left( \frac{\lambda}{\mu} \right)^C \frac{1}{C!}$ . This leads us to the expression for  $P_C$  as follows:

$$P_C = \frac{\left( \frac{\lambda}{\mu} \right)^C \frac{1}{C!}}{\sum_{n=0}^C \left( \frac{\lambda}{\mu} \right)^n \frac{1}{n!}}$$

The traffic intensity is determined by the ratio of arrival and departure rates. This ratio should not be allowed to exceed 1, otherwise request queue will build up. So, traffic intensity is actually a measure of congestion in the system. Let the traffic intensity be represented by  $A = \lambda/\mu$ . Now substituting  $A$  for traffic intensity Erlang B formula becomes:

$$P_C = \frac{A^C \frac{1}{C!}}{\sum_{n=0}^C A^n \frac{1}{n!}}.$$

The above formula is known as *blocked call cleared* formula as it determines the GoS for traffic system without a queue for blocked calls. Using Erlang B formula, the probability that a client's call request will not be serviced in a blocked call cleared system is:

$$Pr[\text{call blocking}] = \frac{A^C/C!}{\sum_{n=0}^C A^n/n!}.$$

To make computation of probability simple, the right hand side of the above equation can be rewritten as follows:

$$\frac{A^C/C!}{\sum_{k=0}^C A^n/n!} = \frac{1}{1 + \sum_1^C \left(\frac{C}{A}\right) \left(\frac{C-1}{A}\right) \dots \left(\frac{C-n+1}{A}\right)}$$

The expression under summation in the numerator can be unrolled and recast using Horner's rule as follows:

$$\frac{C}{A} + \frac{C}{A} \cdot \frac{C-1}{A} + \dots + \frac{C}{A} \cdot \frac{C-1}{A} \dots \frac{1}{A} = \frac{C}{A} \left( \dots \left( 1 + \frac{2}{A} \left( 1 + \frac{1}{A} \right) \right) \dots \right).$$

The use of above expression restricts round-off and truncation errors in computation.

For an illustration of usage of Erlang B formula consider the following example. Suppose there are 240 connection requests per hour in peak time. So, the arrival rate is  $\lambda = 240$ . Let the average call duration be 3 minutes, or 0.05 hour, then the service rate  $\mu = 20$ . It gives  $A = 240/20 = 12$ . Note that average number of request per hour  $1/\lambda$ , and the average call duration is  $1/\mu$ . Hence, the ratio  $A = \lambda/\mu$  being equal to the product of the average number of requests and the average duration of the calls, is called the *busy*

*hour traffic* (BHT). If there are 25 channels then the probability of call being blocked due to non-availability of a channel is given by

$$P_b = \frac{12^{25} \frac{1}{25!}}{\sum_{n=0}^{25} 12^n \frac{1}{n!}} = 3.78 \times 10^{-4}.$$

For a fixed value of  $A$ , we can indeed prove that the call blocking probability for busy hour traffic decrease with increase in  $C$ . When the number of channels increased by 1, the number of channels become  $C + 1$ . In steady state, balance equation tells us that  $(C + 1)\mu P_{C+1} = \lambda P_C$ . Applying a sequence of simplifications we get:

$$\begin{aligned} P_{C+1} &= \frac{\lambda}{\mu} \frac{P_C}{C+1} = \frac{A}{C+1} \cdot \frac{A^C/C!}{1 + \sum_1^{C+1} A^k/k!} \\ &< \frac{A^C/C!}{\frac{C+1}{A} \sum_1^{C+1} A^n/n!} \\ &= \frac{A^C/C!}{\sum_0^C A^{n+1}/(n+1)!} \\ &= \frac{A^C/C!}{\sum_0^C ((C+1)/(n+1))(A^n/n!)} \\ &< \frac{A^C/C!}{\sum_0^C A^n/n!} = P_C. \end{aligned}$$

The boundary values for the above probability distribution function are  $Pr[C = 0] = 1$ , and  $Pr[C = \infty] = 0$ . Since the function is monotonic, with a given value of  $A$ , and a given value of call blocking probability  $p$ , there is a smallest integer  $C$ , such that the inequality  $Pr[C] < p$  holds. This implies that the method of bisection can be applied to obtain the value of  $C$ .

## 5.2 Channel assignment

Frequency planning consistent with the twin objective of increasing capacity and guaranteeing minimum co-channel interference is very important for efficient communication over wireless interfaces. The objective of frequency reuse can be met by employing different techniques such as partitioning the spectrum along frequency, time, or code. Frequency division scheme partitions spectrum allocating distinct frequency bands. A small guard band is

placed between bands to separate the frequencies. Time division achieves channel separation by disjoint time intervals called slots, while code division ensures channel separation by using different modulation codes. It is possible to combine different channel separation schemes. For example, time division and frequency division can be combined to divide frequency band (from frequency division) into time slots. The bottom line of division principles is to maximize the separation of a channel with desired quality and also to maximize channel utilization.

Broadly speaking channel assignments can be classified either as fixed or dynamic. The choice of specific channel assignment policy affects the performance. The impacts are felt in terms of quality of services as a connected mobile device moves from one cell to another. For example, an active communication may get terminated if mobile terminal moves from one cell to another which has no free channel. Thus channel assignment is one of the critical element of mobile communication.

Each cell is allocated a fixed number of channels in a fixed channel assignment scheme. A new connection in a cell can be activated only if there is a free channel. If all the channels are occupied then the request for a connection can not be accommodated. It means an active communication will get terminated if a connected mobile terminal moves from a cell to another having no free channel. Many variations to fixed channel assignment scheme exists in order to eliminate the unpleasant interruptions during an ongoing communication. The process by which an active connection can be maintained as a mobile terminal moves from one cell to another is called *handoff*. Handoff provides the basic capability of mobility with an active connection in a cellular based wireless communication system, a detailed discussion on handoff can be found in section 5.1.

In dynamic channel allocation schemes, no channel is permanently allocated to any cell. Each time a base station requires a channel to be allocated for a call, it requests the mobile switching center (MSC) for a channel allocation. The switch then allocates a channel using some sophisticated algorithms that can take care of the future call blocking, the volume of inter-cell and intra-cell handoffs, and co-channel interferences among other things. The effectiveness of dynamic channel allocation depends on MSC collecting real-time data on channel occupancy, traffic distribution and received signal strength indication (RSSI) of all channels on a continuous basis. So, dynamic channel allocation increases both storage and computational load on the MSCs.

Channel assignment schemes can be implemented either in centralized or in distributed fashion. In centralized assignment channels are assigned by a central controller whereas in distributed assignment channels are assigned either by the local cell or by the cell where the call originated or selected by mobile device.

A general approach for the solution of the channel assignment problem is to use graph abstraction for representing cellular system, and transform the problem into a graph coloring problem. Then, the existing solutions for graph coloring can be applied for solving channel assignment problem. However, in most general setting, the channel assignment can be posed as constraint satisfaction problem. An  $n \times n$  symmetric matrix  $C = \{c_{ij}\}$ , known as compatibility matrix is defined, where  $c_{ij}$  represents the minimum frequency separation required between cells  $i$  and  $j$ , and  $n$  represents the number of cells. The minimum separation between frequencies used by two cells ensures that communication in each cell to be free from interference due to communication in the other. Since frequency bands are evenly spaced, they can be identified by integers. The number of channels required for each cell is represented by a requirement vector  $M = \{m_i\}$ ,  $i = 1, \dots, n$ . The frequency assignment vector  $F = \{F_i\}$  is such that  $F_i$  is a finite subset of the positive integers which defines the frequencies assigned to cell  $i$ .  $F$  is admissible provided it satisfies the following constraints:

$$\begin{aligned} |F_i| &= m_i, \text{ for } i = 1, \dots, n \\ |f - f'| &\geq c_{ij}, \text{ where } f \in F_i \text{ and } f' \in F_j \end{aligned}$$

The first constraint is needed to satisfy the channel requirement and the second constraint is needed to satisfy the interference free compatibility between each pair of cells. The largest integer contained in  $F$  is called the span of the frequency assignment. Note that the largest integer represents the minimum number of channels required for the frequency assignment. So,  $F$  with the minimum span constitutes the solution to the problem channel assignment. The problem is known to be NP hard [3].

Interference graph plays an important role in planning channel assignment. Such a graph is defined as follows:

- Every vertex represents a cell or a base station.
- Each edge  $(u, v)$  is associated with a weight  $W(u, v)$  which is proportional to the strength of interference between signals from cells represented by  $u$  and  $v$ .

- Each vertex  $v$  is associated with a non-negative integer which indicates channel requirements for the cell represented by  $v$ .

In theory, such a graph is a complete graph. To avoid interference, two channels  $a$  and  $b$  can be used in different cells  $u$  and  $v$  provided  $|a - b| \leq W(u, v)$ . There is also a system wide number  $W$  for channel separation within same cells. That is, if channels  $a$  and  $b$  are used in a common cell, then  $|a - b| \leq W$ .

### 5.2.1 Fixed Channel Assignment

In fixed channel assignment (FCA) scheme, a fixed number of channels is assigned to each cell. The set of available channels is partitioned into  $N$  disjoint sets, where  $N$  is the cluster size. As we already know  $N = D^2/3R^2$  is related to reuse distance  $D$ , and cell radius  $R$  by the relation.

In a FCA scheme, each of the  $N$  cells in a cluster are assigned the same number of channels. If the distribution of traffic load is uniform, then the uniform channel distribution works fine. The overall average call blocking (connection not materializing due to non-availability of a channel) probability will be same as call blocking probability in a cell. But, hardly ever such an ideal situation is realizable. There may be both temporal and spatial fluctuations in traffic across the cellular service area. Due to short term variations in traffic, most of the times FCA is not able to maintain the quality of service and network capacity that may be attainable even with static traffic demand.

### Borrowing

To remedy this, when a request for connection is placed in a cell that has no nominal free channels, a common sense driven approach is to borrow a free channel from one of its neighboring cells. The cell which borrows is referred to as the *acceptor* while cell which lends is known as the *donor*. The selection of a free channel from a donor cell should be such that it does not adversely affect the donor cell's ability to satisfy a subsequent request for connection, and at the same time the borrowed channel does not introduce added interferences on existing connections in the acceptor cell. In other words, the selection of both the donor cell and the channel to be borrowed should minimize:



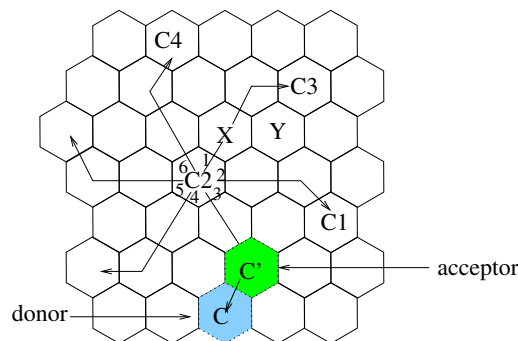


Figure 5.15: Borrowing affects co-channels cells of donor cell.

1. The probability of donor cell not being able service a connection request to non availability of a nominal channel, and
2. The interference due to communication over the borrowed channel on the existing active communications in the acceptor cell.

The first condition can be met by selecting one of the neighboring cells (of the acceptor cell) that has the largest number of free channels as the donor cell. The strategy of Borrowing From Richest (BFR) will also most likely meet the second condition. Because with the availability of more channels, the probability of the borrowed channel interfering with the other active channels in the acceptor's cell will be expectedly low. Once the borrowed channel has been identified, it is locked in the co-channel cells of the donor cell which are within channel reuse distance from the acceptor cell. Consider for example, cell  $C'$  borrows from cell  $C$  as shown in Figure 5.15. The borrowed channel should be locked in cells  $C_1$  and  $C_2$  as these cells are more close to  $C'$  than to  $C$  leading to increased co-channel interference in  $C'$ . Thus the borrowing becomes possible only when the borrowed channel is simultaneously free in three nearby co-channel cells. The borrowing of a channel affects several channels. However, if borrowing is planned carefully then the same channel may concurrently serve as a borrowed channel in different acceptor cells. For example, in Figure 5.15 if cell  $C'$  has already borrowed channel  $c$  from  $C$  then, the cell  $X$  which is a neighbor of  $C_2$  can not borrow  $c$ , although  $C$  and  $X$  could simultaneously use the same channel  $c$  without interference as they are three cells apart. Also as channel  $c$  is locked in  $C$ ,  $C_1$  and  $C_2$ , cell  $Y$  can not borrow it from cell  $C_3$ , because for this borrowing to be permitted

$c$  must be free in  $C1$  and  $C2$ . Here again,  $Y$  and  $C'$  are three cells apart, so they could have used  $c$  simultaneously without interference.

A borrowing strategy that considers the effects of channel lockings on the expected future connections requests; and selects a candidate that minimizes the lockings would be an improvement over the BFR scheme. The underlying idea of such a method is to select a candidate channel that maximizes the number of nominal free channels in co-channel cells of the donor cell which are within reuse distance  $D$  from the acceptor cell.

An improvement to simple borrowing could be directional locking. Let us re-examine the simple borrowing explained earlier in Figure 5.15. The acceptor cell  $C'$  borrowed a channel  $c$  from neighboring donor cell  $C$ . Following this,  $c$  is locked in all directions in the cells  $C$ ,  $C1$ , and  $C2$  as these three cells are within reuse distance  $D$  from  $C'$ . But in cell  $C2$ , locking of  $c$  should suffice in directions 2, 3, 4 only. This would leave  $c$  unlocked in directions 1, 5, 6 in  $C2$ . Cell  $X$  being in direction 1 from  $C2$ , could then find  $c$  free for borrowing. Since  $X$  and  $C$  are not within reuse distance  $D$ , the simultaneous use of channel  $c$  in these two cells would not create any problem. Of course, whether  $c$  can actually be borrowed by  $X$  or not will depend on its locking status cells  $C3$  and  $C4$ . Borrowing with Directional Channel Locking (BDCL) improves simple borrowing scheme by allowing simultaneous use of borrowed channel in many different cells.

But any sophisticated borrowing method will incur penalties for complex searchings, so a simpler option could be to borrow the first available (BFA) channel from a neighboring cell. However, for implementing BFA, the initial channels assignment is bit different than direct assignment of channels to cells as is done in other FCA schemes. The set of channels is first divided into groups and each group is assigned to cells at a reuse distance  $D$ . The channels in a group are numbered in sequence. A group of channels assigned to a cell is subdivided further into two subgroups  $A$  and  $B$ . The channels belonging to  $A$  are used exclusively for calls originating from a cell. A cell  $C$  can lend channels to another neighboring cells  $C'$  only when one is available in subgroup  $B$  of  $C$ . On arrival of a call request, the nominal channels in the cell are scanned in order and the first available channel is assigned for the call. If no nominal channel is found, then (acceptor) cell  $C'$  searches for a free channel in an adjacent cell  $C$  having largest number of channels in group B available for borrowing. As explained earlier, a channel is considered available for borrowing provided it is also free in two other co-channel cells (using directional locking strategy) of that chosen neighboring cell. The free

channel encountered first in this order is borrowed. This method is known as Borrowing with Channel Order (BCO) strategy. Interestingly, BCO compares favorably with the system that performs exhaustive complex searches to identify the channel to be borrowed from a neighboring cell. Furthermore, it has an advantage over other methods by being computationally less expensive.

After communication over the borrowed channel is complete, that borrowed channel should be returned to the donor cell. Since borrowing is done due to non-availability of a nominal free channel, the question which naturally arises is whether borrowed channel should be returned as soon as one of the nominal channels of the acceptor cell becomes free. Interestingly, the decision whether or not to free a borrowed channel could influence systems performance.

Channel reallocation concept is used in conjunction with directional lockings to improve the performance of the system and minimize connections on borrowed channels. The rules for channel reallocation are as follows.

1. When a nominal channel becomes free and there is an active connection on a higher order nominal channel in the same cell then this connection is transferred to the lower order nominal channel.
2. When a nominal channel in local cell becomes free and there is an active connection on a borrowed channel from a neighboring cell, then the borrowed channel is returned to neighboring by transferring the connection to newly freed nominal channel.
3. When borrowed channel becomes free due to termination of a connection in neighboring cell, and there is another active connection on a lower order borrowed channel in the same cell, then communication on lower order channel is transferred to the higher order channel. This requires a channel switching neighboring cell.
4. A nominal channel in a cell may be blocked due to lending by a co-channel cell to a different cell. If such a channel becomes is completely unlocked (in all six directions), then any active connection on either on a borrowed channel or on a higher order channel is immediately switched to the unlocked channel. It leads to a channel switching in local cell.

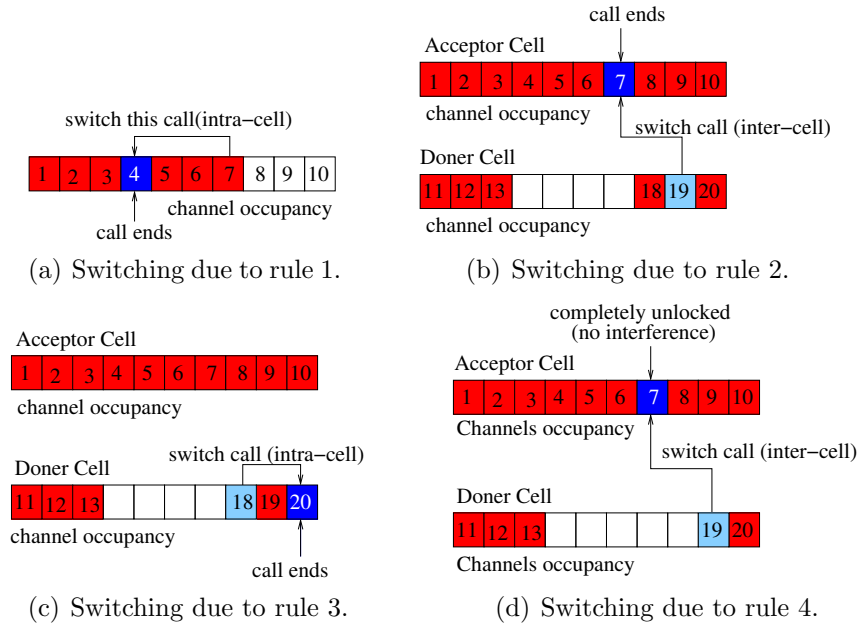


Figure 5.16: Channel switching with borrowing.

The reallocation rules are illustrated by Figure 5.16. Figure 5.16(a) shows a channel switching within same cell. It happens because there is ongoing communication on a lower order nominal channel, i.e., channel no. 7 when a higher order nominal channel, i.e., channel number 4 becomes free. Figure 5.16(b) shows a channel switching that takes place between two cell. The acceptor cell on the top has borrowed channel no. 19 from the donor cell at the bottom. Once nominal channel 7 becomes free in the acceptor cell then channel 19 is returned back to the donor cell. An inter-cell handoff is executed to realize such a channel switching. Figure 5.16(c) illustrates switching where borrowed channel of the donor is switched to a lower order channel if a lower order channel becomes free in the donor cell. Finally, Figure 5.16(d) illustrates switching when a locked nominal cell become unlocked in acceptor cell. Note this case refers to situation where borrowing is implemented with directional locking, and channel 7 is also be locked in other directions due to borrowing by another adjacent cell.

The channel borrowing strategies outlined above result in lower blocking than fixed allocation under light and moderate traffic conditions [14]. Under

heavy traffic condition channel borrowing could create domino effect due to blocking of borrowed channels in respective co-channel cells. These cells being deprived of their nominal channels would in turn have to resort to borrowing thus creating the domino effect that would require a comprehensive channel reallocation strategy as in [14]. So fixed channel allocation sometimes may provide better performance than schemes relying on channel borrowing.

### 5.2.2 Dynamic Channel Assignment Policies

Due to temporal bursts in traffic, at times FCA schemes may not be able to result in efficient channel utilizations. DCA schemes have been proposed as remedies. In a DCA no channel is allocated permanently to any cell. Channels are allocated to cells on need basis. After a connection terminates, the channel used by it is returned back to central pool. So, key idea behind DCA scheme is to evolve a procedure for evaluation of the cost in using each candidate channel for a connection request. The cost function should take into account the number of future call blocking, the distribution of channel occupancy under the current traffic conditions, co-channel/adjacent channel interferences, acceptable average call blocking and other QoS related to radio measurements at the clients. So, DCA strategies can be designed to adaptively adjust to traffic conditions. The design of a perfect cost function is understandably difficult as it needs to balance complex trade offs in optimization involving several attributes such as current channel assignment future channel assignment, traffic condition, co-channel interference, adjacent channel interference, temporal bursts in traffic, radio measurements at end devices. These difficulties in design of cost function made DCA an intensive research area [5].

DCA algorithms are of two types based on the type controls, viz., centralized and distributed. In centralized DCA, a central controller determines the channel allocation for each connection request. There is no fundamental difference between different centralized DCA schemes except that the cost function for selection of a channel employed by the one differs from the other. Some of the basic approaches under this category are:

- First available (FA): it assigns the first available channel ensuring that the channel reuse constraints are not violated. The search for the candidate channel is fast, and the scheme is straightforward. FA is found to perform better than most FCA schemes by 20% over low and moderate

traffic conditions.

- Locally optimized dynamic assignment (LODA): it assigns the channel in response to a request from a cell by minimizing the future call blocking possibilities in cells in the vicinity.
- Channel reuse optimization: it tries to optimize reuse distance while allocating a channel for new request. The fundamental idea behind this approach is maximizing spatial multiplexing. The shorter is the reuse distance, the greater is the channel reuse over the service area. Therefore, with this scheme network capacity also increases.
- Maximum use in reuse ring: it selects the channel for allocation by finding the one that is used in most cells in co-channel set. Note that co-channel cell form a reuse ring as indicated earlier in Figure 5.10.
- Mean square: it selects the channel that minimizes the mean square of the distance among cells using same channel.
- Nearest neighbor: it selects the available channel occupied in the nearest cell in distance  $\geq D$ .

Most of channel reuse optimization schemes [5] as described above try employ local optimizations. The 1-clique [7] scheme, however, employs a global optimization scheme. It builds a graph for each channel where each vertex represents a cell, and two vertices in this graph are connected by an edge if and only if the cells corresponding to the end vertices do not have co-channel interference. So, each graph reflects channel allocations possibilities. An actual channel assignment is done from several possibilities so that as many vertices as possible, still remain available for allocation. The scheme works fine for small number of channels and a small service area (with few cells). But for large number of cells and large number of channels the computation time becomes prohibitive.

Distributed DCA (DDCA) schemes depend either on local information about availability of free channels in the neighborhood of the requesting cell or rely on signal measurements [11]. The focus of the most of the work in DDCA schemes has been on channel reuse [1] sometimes even at the cost of interference.

The cell based DDCA schemes rely on local information. Each cell keeps track of free channels by storing the information in an augmented channel

Cell Number	Channel Number										Free Channels
	1	2	3	4	5	6	7	8	...	$M$	
$i$		x						x	...		0
$i_1$	x			x			x		...		0
$i_2$			x						...		2
$i_3$	x				x		x		...		0
$i_4$			x			x			...	x	4
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$i_{k_i}$			x		x				...		3

Figure 5.17: ACO matrix of cell  $i$ .

occupancy (ACO) matrix along with sufficient additional information that lets base station to determine if a channel can be assigned. ACO matrix at cell  $i$  is an  $(M + 1) \times (k_i + 1)$  matrix, where  $M$  is the number of channels in the system and  $k_i$  is the number of neighboring cells within the co-channel interference distance from cell  $i$ . Figure 5.17 shows ACO matrix for some cell  $i$ . If the column corresponding to a channel has no entry it means that channel is free and can be assigned to cell  $i$ . The entry in the last column gives the number of assignable channels available for the corresponding cells. Note that this number should be equal to the number of empty columns in ACO matrices of the corresponding cells. For example, as  $ACO[i, M + 1] = 0$ , the cell  $i$  does not have any assignable free channel. This also means no empty column exists in the ACO matrix for cell  $i$ . Similarly,  $ACO[i_2, M + 1] = 2$  means there are 2 assignable free channels in cell  $i_2$ , equivalently, ACO matrix of cell  $i_2$  has 2 empty columns.

Since no free channels are available in a cell as in  $i$ , it searches for a column among those which do not have an entry in the first row; and finds one among them that has least number of entries. So, only columns corresponding channels not occupied by cell  $i$  can be candidates for selection. For example, column 6 of the ACO matrix has only one entry for row  $i_4$ . It indicates that channel 6 is currently occupied by only cell  $i_4$ . Since,  $ACO[i_4, M + 1] = 5$ , cell  $i_4$  has 5 assignable free channels. Therefore, the ongoing call in cell  $i_4$  can be on channel 6 can possibly be shifted to one of the free channels. If the shifting is successful then channel 6 becomes assignable in cell  $i$ . The contents of ACO matrix is updated by collecting channel occupancy

information from interfering cells. In general, the column of ACO matrix having minimum number of entries is chosen as candidate for call shifting. Each cell corresponding to each entry of the chosen column is requested to shift its ongoing call from the current channel to a free channel. When each of the requested cells reports completion of call shifting, the chosen channel is declared free and assignable in the requester cell. However, requests to multiple cells for shifting could cause unpredictable delays and lead high probabilities of failures. So, from implementation prospectives, only one channel shifting request is usually permitted.

In addition to co-channel interference, adjacent channel interference (ACI) caused by use of close frequency channels results in premature handoffs, call drops, and cross connectivity. The effects of ACI can be minimized by use of sophisticated channel filters, but can not be eliminated altogether. DCA methods discussed so far have focused on only co-channel interference. But it is possible to address the issue of ACI by adding extra restriction on the channel selection from the ACO matrix in DDCA algorithm described above. Let ACI effects be negligible with channel separation of  $N_{adj}$ . Then for every column which have an entry in the first row of the ACO matrix for a cell,  $N_{adj} - 1$  adjacent columns either to left or right can not have an entry in the first row. It means if a channel  $k$  has been allocated to a cell  $i$  then all channels corresponding to adjacent columns  $k - j$ , and also those corresponding to adjacent columns  $k + j$ , for  $j = 1, \dots, N_{adj} - 1$ , can not be allocated by the cell  $i$ .

At the time of assigning a new channel  $c$  to cell  $i$ , the algorithm should ensure that the channels corresponding to  $N_{adj} - 1$  adjacent columns to the left or to the right of column  $c$  for the row  $i$  in ACO matrix do not have a entry in the first row of ACO matrix for cell  $i$ . It means those group of channels should not have been allocated earlier to cell  $i$ .

The channel allocation algorithm works as follows. When cell  $i$  receives a connection request, it searches the first row of the ACO matrix for a consecutive group of  $2N_{adj} - 1$  empty entries such that column corresponding to the column at the center of the group is empty. If the search is successful, the cell  $i$  assigns the channel represented by the central column. If no group of  $2N_{adj} - 1$  empty columns can be found, then cell  $i$  looks for a group of consecutive  $2N_{adj} - 1$  empty columns in the first row where center column  $c$  has a single entry and the related cell (let it be  $j$ ) has an assignable free channel as indicated by a non-zero entry in  $ACO[j, M + 1]$ . After the column  $j$  has been identified, cell  $i$  requests cell  $j$  to shift the ongoing call on the



channel  $c$  to one of its free channels. Once the shifting is over, and  $j$  reports the completion, cell  $i$  can assign channel  $c$  to new call request.

As an example, suppose  $N_{adj} = 2$ . To satisfy a request for assigning a new channel, a search is initiated for a group of 3 consecutive columns having no entries in first row of the ACO matrix provided in Table 5.17. Any such group can only be identified between columns 3-7. However, no group of 3 empty columns can be found between columns 3-7. So, we try to find a group of 3 columns such that center column has just one entry and that the cell related to the entry has assignable free channels. The columns 5-7 provide such a group, with only cell  $i_4$  occupying the channel 6. Since  $i_4$  has 4 assignable free channels it can be requested to shift the ongoing communication from channel 6 to some free channel handling the adjacent channel interference restrictions. After cell  $i_4$  vacates channel 6, cell  $i$  can allocate the channel to new request.

Some DDCA techniques considers the channel allocation as a resource sharing problems [4]. The underlying idea is that channel is a resource which must be shared among neighboring cells in a mutual exclusive manner. There are two important differences in classical mutual exclusion (ME) and channel sharing among neighboring cells.

- Firstly, in classical ME two competing processes are not allowed to share a resource, but a channel sharing among cells are permitted as long as they satisfy the constraint of reuse distance.
- Secondly, in channel allocation, not a single but a collection of resources should be handled.

There are many DCA schemes, the channel assignment techniques. Interested readers may look at some excellent references [5] for more details on the topic.

### 5.2.3 Handoff

Mobility is the key feature of a cellular based wireless communication system. However, in a bid to increase the capacity, increasingly smaller cell size are used. Maintaining continuity of service became a challenge with use of reduced cell size. Normally on cell crossings, a mobile user experiences deterioration in the quality of ongoing communication. The deterioration of service is attributed to one of the following two reasons:

1. **Signal quality deterioration.** The quality of a signal is determined by a set of parameters such as, RSS, Signal to Noise Ratio (SNR), and bit error rate (BER). RSS attenuates with distance from base station, slow fading (shadow fading or lognormal fading) and fast fading (Rayleigh fading) [10].
2. **Traffic load.** When capacity of current cell of mobiles has either reached or is about to reach its maximum capacity.

With smaller cells, the frequency of cell crossing by a mobile user is expected increase. Under this circumstance, the continuity of an active connection with a mobile user can only be achieved by handoffs (or handovers) through a sequence of intermediaries (intermediate cells).

The RSS from the base station of the cell from which a mobile user is moving away decays gradually. As opposed to this, the RSS from the cell, into which the mobile is moving, increases gradually. If the link to new base station is formed before or almost immediately as the link to old base station goes down, then it is possible to keep connection active. Thus, a handoff is the transition of signal transmission from one base station to another geographically adjacent base station. By executing a handoff *in-session* mobility to a user can be supported. As explained in section 5.2, a frequency switching may sometimes be needed when a mobile terminal is moving within a cell. Such a switching is called an intra-cell handoff. Our attentions here, however, is limited to only inter cell handoffs.

Cells overlap, so a mobile terminal or the device could be within the range of multiple base stations around the boundary of a cell. It facilitates maintenance of an active connection while user migrates from one cell to a geographically adjacent cell. The network decides — with or without the assistance of user's mobile handset (MH) — which base station will handle the transmission of signals from and to the MH. Handoff should be transparent to user. In other words, it should provide assurance that the communication will neither be lost nor be terminated unless user's hardware is out of the range of all base stations.

The important first step of a handoff process is the early detection of the handoff condition. The handoff can then be initiated before the current connection is broken. Once an active connection is completely severed there is no way to restore it. A particular signal level is needed for acceptable level of ongoing communication. In the case of voice communication it could be between -90dBm to -100dBm. A slightly stronger signal level is used

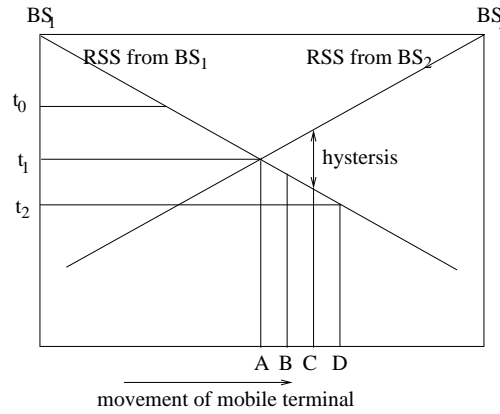


Figure 5.18: Handoff scenarios at cell boundaries

as the threshold for initiation of handoff process. The margin between the threshold signal for handoff and the minimum usable signal level is known as the handoff *hysteresis*  $\Delta$ . Formally, hysteresis can be defined as

$$\Delta = S_{handoff} - S_{min},$$

where  $S_{handoff}$  represents the threshold for performing handoff, and  $S_{min}$  denotes the minimum level of signal strength needed for voice communication. The value of  $\Delta$  can neither be too large nor be too small for the handoff to work smoothly.

Figure 5.18 depicts the different handoff situations when a mobile terminal travels from station  $BS_1$  to  $BS_2$  along a straight line. At time  $t_0$  the mobile host receives signal only from  $BS_1$ . At time  $t_1$  received signal strengths from both base stations become comparable. But as the mobile user reaches point  $B$ , the signal strength received from  $BS_2$  dominates that from  $BS_1$ , even though the signal from the latter is still above the acceptable level. The handoff must begin after mobile terminal reaches point  $A$  and completed before it reaches point  $C$ . If handoff latency is  $\delta t$  then, the handoff must be performed before  $\delta t$  time before reaching the threshold  $C$  beyond which the signal strength drops below the acceptable level for communication to go on. Therefore, handoff should start when strength of signal from  $BS_1$  is little higher and should be completed on or before reaching  $C$ . The delay between initiation and completion of handoff is indicated as hysteresis. If handoff is not complete before  $C$  the signal from  $BS_1$  deteriorates, and when

mobile reaches point  $D$ , the call gets terminated.

It has already been indicated that handoff should be performed when the received signal strength is below a certain threshold. However, the signal measurement mechanism for handoff should not be considered as a simple one-off instantaneous measurement. The reason is due to multipath fading, instantaneous measurement of signal may not provide a correct estimation of distance between the mobile and its current base station. So, the signal strength should be measured over a certain time interval, and the average of such measurements should be the basis for the decision to perform a handoff.

The window of time for performing handoff is provided by length of hysteresis. To reduce the overhead of handoffs, the attempt should to optimize  $\Delta$ . The value of  $\Delta$  depends on several factors such as:

- Environment.
- Speed of direction of mobile's movement.
- Time required to perform handoff.

The use of hysteresis is aimed at reducing the ping-pong effect. However, the delay also not without cost. It increases interference, reduces the quality of service. The delay could as well lead to a call dropping. A velocity adaptive handoff algorithm could enforce more frequent measurement of signal strengths by adjusting length of averaging window in which RSSs from neighboring BSs are averaged. The direction parameter assigns more weightage to execution of handoff in favor of BSs towards which the mobile is moving, while handoff decision is discouraged to the BSs from which the distance of MH is increasing [8].

#### 5.2.4 Handoff policies

A simple approach would be to prioritize the channel assignment for handoff requests before the new call requests. It results in in a tolerable increase in call blocking probability while reducing the probability of dropped calls.

Another approach is to pre-allocate a certain number of handoff channels called guard channels. Only these channels will be used for handoffs. If the guard channels are not available then the handoff will be serviced by other channels. However, if all guard channels are occupied then, a handoff call have to compete with new call for allocation of the channels outside

the guard band of channels. This strategy keeps the probability of a call blocking under an acceptable level, but increases the probability of a dropped call. There is also a possibility that guard channels are under utilized, while new call requests can not be met due to non-availability of free channels. Such a situation leads to an inefficient spectrum utilization. The concept of reserved channels would be appropriate for dynamic channel assignment scheme. Because the guard channels can be allocated from a central pool. So the non-availability of a free channel for new call requests does not become a local problem.

Typically, when no channel is available, new call requests are made to wait in a queue with the hope that handoff calls or some of the ongoing connections may release their respective channels. Once a channel becomes free, one of the queued new call request can be serviced. The strategy works well because, a user any way has to wait for an interval of time before expecting establishment of a connection against his/her request. In the case of a handoff too, there is a certain finite time interval during which the existing call connection is retained, and a new channel is assigned for the handoff. Therefore, it is also possible to enqueue a handoff request albeit for a small interval of time. The position of handoff request in the queue depends on how close the mobile is to the boundary of the cell. Higher priorities can be assigned to the mobiles that are closed to be boundary or moving very fast while lower priorities can be assigned to the mobiles still inside the boundary, or are moving slowly.

Whichever entity (the network or the mobile terminal) that makes the handoff decision uses some metrics. It applies the relevant algorithms on the basis of those metrics, and assures required performance guarantees. The most critical metric for a handoff decision is the measurements of signal strengths received at the mobile from the current base station and the neighboring base stations which are probable candidates to handle the frequency switching. The measurement process should be able to avoid unnecessary handoffs. For example effecting handoff during a temporary fading will result in *ping pong* effect and put pressure on network due to unnecessary handoffs. On the other hand, if a distance dependent fading, due to mobile user moving away from current base station, is not properly detected it could result in termination of the connection before the handoff could be initiated.

### 5.2.5 Handoff protocols

Three types of entities involved in a handoff:

1. User's mobile handset (MH),
2. Base station (BS) to which MH is currently connected and BSs in the neighborhood of MH's movements, and
3. MSCs controlling the above group of BSs.

So, both network entities (BSs and MSCs) as well as user's MH may initiate and control a handoff process. Based the nature of controlling entity or the entities, the handoff protocols can classified into three basic types.

- Network controlled.
- Mobile assisted.
- Mobile controlled.

In network controlled protocol, the decision for handoff is based on measurements of RSSs of mobile terminal at a number of adjoining base stations. The entire handoff process which includes measurements, channel switching and network switching, etc., takes approximately around 100-200ms. As opposed to this, in mobile assisted handoff process MH measures the RSSs it receives from BSs in its neighborhood and the decision for handoff is made by the network entities. Mobile assisted handoff may take upto 1 second. In mobile controlled handoff user's MH takes decision to execute handoff. This type of handoff requires a short reaction time, just about the order of 0.1 seconds. MH measures RSS of neighboring BSs and interference levels of all channels. Then it initiates handoff if the signal strength of serving BS is lower than another neighboring BS by a pre-determined threshold. Mobile controlled handoff being a completely decentralized process, relieves the network from a high overhead specially in a high density micro-cellular system.

Several different mechanisms exist for realizing handoff. However, the common goals which every handoff mechanism should try to achieve. These are:

1. Handoffs should be performed quickly.

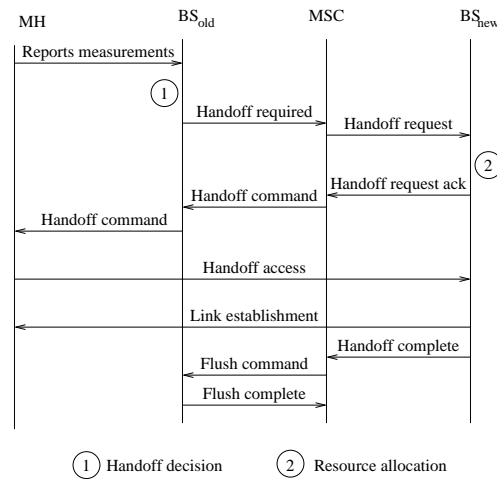


Figure 5.19: The generic procedure of handoff

2. Interruption in connection due to a handoff should be imperceptible to users.
3. Handoffs should be performed infrequently.
4. Handoffs should be performed successfully.

Figure 5.19 illustrates the generic procedure for execution of handoff. The mobile terminal reports about the signal measurements to serving base station. If the serving base station decides about the handoff, it informs the Mobile Switching Center (MSC) that a handoff is required. The MSC then send a handoff request to the new base station. The new base station allocates the required resources for the handoff and sends handoff request accept to the MSC. Then the MSC issues handoff command to the old base station which informs the same to the mobile terminal. The mobile terminal requests for a link establishment with the new base station. After link has been established, handoff completion command is issued by the new base station to the MSC. Following this, the MSC instructs the old base station to flush the resources for the mobile terminal being used for communication. The old base station flushes the resources and the handoff is complete. The basic handoff procedure described above may be augmented by other participating components such as one or more base station controllers (BSC) and

one or more MSCs depending on the structure of the network. There are many resources to be managed in wireless cellular communication system. These include channel assignment, signal to interference ratio (SIR), transmit power control, etc. All these may influence handoff decisions in some way other. So, for a better overall performance, adaptive handoff protocols have been designed by integrating such resource optimization with handoff decisions [13].

### Review questions

1. Coverage of a wireless communication network can be increase by using high power transceivers. What are the problems in this approach?
2. Why the shape of a cell in a cellular based wireless system is hexagon?
3. Find the distance between two co-channel cells assuming the range of a base station to be 500 m.
4. How cell splitting and sectoring help to increase frequency reuse?
5. What is the unit for measuring relative strengths of wireless signals and the noise?
6. What is the unit for measurement of traffic intensity?
7. What are the problems and advantages of fixed channel assignment?

### Exercises

1. Suppose a base stations of range 1 km used to cover an area of  $6.28 \text{ km}^2$ . The effective power of such a base station is 400W. What will be the total energy requirement for the entire area of coverage?
2. Assuming that a base station with a range of 500 m with an effective power of 100 mW, what will be total energy requirements at all the cells to cover the same area as in question 1?
3. Suppose in cellular base wireless communication system, the cluster size 7, and it uses cell sectorization of  $60^\circ$ . Let the path loss exponent be 2. Determine the SIR.



4. If a PSTN receives 250 calls per hour, and each call lasts in an average 6 minutes, what is the traffic intensity?
5. Suppose a total of 30MHz of bandwidth is allocated to cellular based wireless communication system which employs frequency division duplexing. It uses two 25kHz simplex channels to provide full duplex voice and control channels. Out of the allocated bandwidth 1MHz is dedicated for control channels, and the remaining are for voice channels. Compute the number of voice and control channels available in each cell under the equitable distribution assuming (a) 4-cell reuse, (b) 7-cell reuse, and (c) 12-cell reuse.
6. Write a program in Java or C for computing Erlang B formula for traffic intensity in cellular based wireless communication system.
7. Suppose a service provider wants to design a cellular system consisting of 400 cells in which each cell has 18 channels. The service requirements demands that call blocking probability can be at most 2%, if each user makes in an average 2 calls of 3 minutes duration per hour. Use Erlang B calculator to determine the number of users which the system can support.
8. Consider a single cell with 60 channels. When all channels are busy, calls are blocked. Let the call arrival be governed by Poisson process at the rate of 1 call per active user per hour. During busy hours 75% of the users are active. The call duration is distributed exponentially with mean call holding time being 2minutes. What is the maximum load the cell can support for 2% call blocking? What is the maximum total number of users the system can support? (Hint: for second part, compute the maximum number of active users during busy hours).
9. Give a recursive expression for Erlang B formula, and write a computer program for computing Erlang B table using the recurrence relation. (Hint: the base case of recursion is  $Pr[0, A] = 1$ , where  $Pr[C, A]$  denotes the call blocking probability for the system with  $C$  channels and traffic intensity  $A$ ).
10. A cellular system is to be operated with an allowed SIR = 12dB. A mobile node moving at the maximum speed of 54 Km/h along a straight line is forced to handoff after 4 minutes when it crosses the cell for

the maximum distance. Estimate the co-channel antenna spacing, and power threshold  $P_{th}$  assuming handoff process takes 5 seconds. Given  $P_0 = 0$  dB at 1 m,  $n = 3$ . (Assume path loss equation is given by  $P_r = P_0 - 10n \log \left( \frac{d_i}{d_0} \right)$ .)

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