Chapter 2
Cellular System

2.1 Introduction

In the older mobile radio systems, single high power transmitter was used to provide coverage in the entire area. Although this technique provided a good coverage, but it was virtually impossible in this technique to re-use the same radio channels in the system, and any effort to re-use the radio channels would result in interference. Therefore, in order to improve the performance of a wireless system with the rise in the demand for the services, a cellular concept was later proposed. This chapter will examine several parameters related with the cellular concept.

2.2 The Cellular Concept

The design aim of early mobile wireless communication systems was to get a huge coverage area with a single, high-power transmitter and an antenna installed on a giant tower, transmitting a data on a single frequency. Although this method accomplished a good coverage, but it also means that it was practically not possible to reuse the same frequency all over the system, because any effort to reuse the same frequency would result in interference.

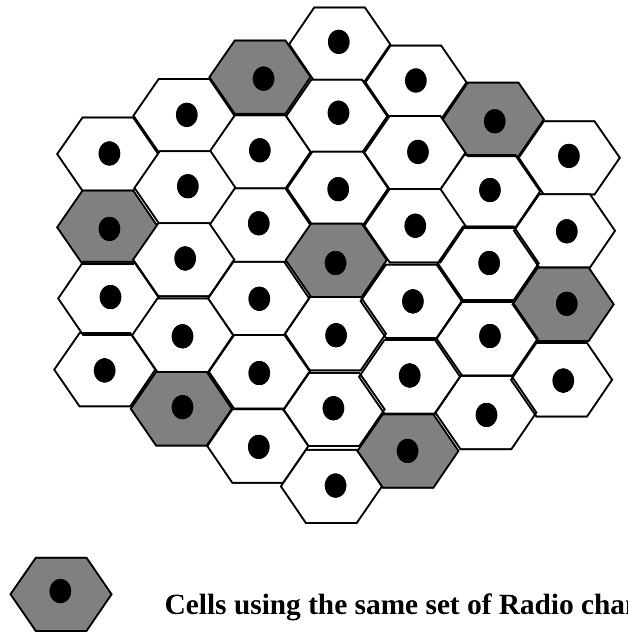
The cellular concept was a major breakthrough in order to solve the problems of limited user capacity and spectral congestion. Cellular system provides high capacity with a limited frequency spectrum without making any major technological changes [1]. It is a system-level idea in which a single high-power transmitter is replaced with multiple low-power transmitters, and small segment of the service area is being covered by each transmitter, which is referred to as a cell. Each base station (transmitter) is allocated a part of the total number of channels present in the whole system, and different groups of radio channels are allocated to the neighboring base stations so that all the channels present in the system are allocated to a moderately small number of neighboring base stations.

The mobile transceivers (also called mobile phones, handsets, mobile terminals or mobile stations) exchange radio signals with any number of base stations. Mobile phones are not linked to a specific base station, but can utilize any one of the base stations put up by the company. Multiple base stations covers the entire region in such a way that the user can move around and phone call can be carried on without interruption, possibly using more than one base station. The procedure of changing a base station at cell boundaries is called *handover*. Communication from the Mobile Station (MS) or mobile phones to the Base Station (BS) happens on an uplink channel also called reverse link, and downlink channel or forward link is used for communication from BS to MS. To maintain a bidirectional communication between a MS and BS, transmission resources must be offered in both the uplink and downlink directions. This can take place either using Frequency-Division Duplex (FDD), in which separate frequencies are used for both uplink and downlink channels, or through Time-Division Duplex (TDD), where uplink and downlink communications take place on the same frequency, but vary in time.

FDD is the most efficient technique if traffic is symmetric, and FDD has also made the task of radio planning more efficient and easier, because no interference takes place between base stations as they transmit and receive data on different frequencies. In case of an asymmetry in the uplink and downlink data speed, the TDD performs better than FDD. As the uplink data rate increases, extra bandwidth is dynamically allocated to that, and as the data rate decreases, the allotted bandwidth is taken away.

Some of the important cellular concepts are:

- Frequency reuse
- Channel Allocation
- Handoff
- Interference and system capacity
- Trunking and grade of service
- Improving coverage and capacity



Cells using the same set of Radio channels

Fig. 2.1: Cellular Network

2.3Frequency Reuse

Conventional communication systems faced the problems of limited service area capability and ineffective radio spectrum utilization. This is because these systems are generally designed to provide service in an autonomous geographic region and by selecting radio channels from a particular frequency band. On the other hand, the present mobile communication systems are designed to offer a wide coverage area and high grade of service. These systems are also expected to provide a continuous communication through an efficient utilization of available radio spectrum. Therefore, the design of mobile radio network must satisfy the following objectives i.e., providing continuous service, and wide service area, while efficiently using the radio spectrum.

In order to achieve these objectives, the present mobile systems use cellular networks which depend more on an intelligent channel allocation and reuse of channels throughout the region [146]. Each base station is allocated a set of radio channels, which are to be used in a geographic area called a *cell*. Base stations in the neighboring cells are allocated radio channel sets, which are entirely different. The antennas of base station antennas are designed to get the required coverage within the specific cell. By restricting the coverage area of a base station to within the cell boundaries, the same set of radio channels can be used in the different cells that are separated from each other by distances which are large enough in order to maintain interference levels within limits. The procedure of radio sets selection and allocation to all the base stations present within a network is called *frequency reuse* [132].

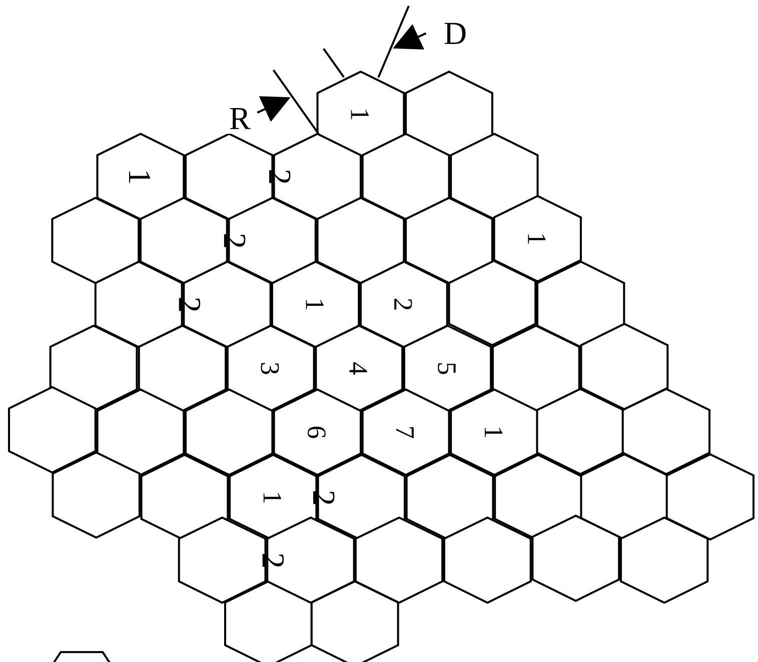
Fig. 2.1 shows the frequency reuse concept in a cell in a cellular network, in which cells utilize the same set of radio channels. The frequency reuse plan indicates where different radio channels are used. The hexagonal shape of cell is purely theoretical and is a simple model of radio coverage for each base station, although it has been globally adopted as the hexagon permits the easy analysis of a cellular system. The radio coverage of a cell can be calculated from field measurements. Although the actual radio coverage is very amorphous, a natural shape of a cell is required for an organized system design. While a circle is generally chosen to represent the coverage area of BS, but the circles present in the neighborhood cannot cover the entire region without leaving gaps or overlapping regions. Therefore, when selecting the cell shapes which can cover the entire geographical region without overlapping, there are three choices possible: a hexagon, square, and triangle. A particular design of the cell chosen in order to serve the weakest mobiles within the coverage area, and these are generally present at the cell boundaries of the cell. As hexagon covers the largest area from the center of a polygon to its farthest point, therefore, hexagon geometry can cover the entire geographic region to the fullest with minimum number of cells. When hexagon geometry is used to cover the entire geographic area, the base stations are either put up at the center of the cell, these cells are also called center excited cells or at the three of the six vertices (edge excited cells). Generally, center excited cells use omni-directional antennas and corner excited cells use directional antennas, but practically considerations for placing base stations are not exactly the same as they are shown in the hexagonal layouts.

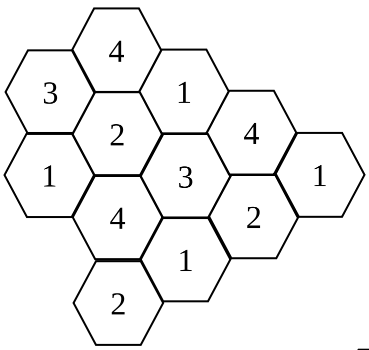
2.3.1 Channel Reuse Schemes

The radio channel reuse model can be used in the time and space domain. Channel reuse in the time domain turns out to be occupation of same frequency in different time slots and is also called Time Division Multiplexing. Channel reuse in the space domain is categorized into:

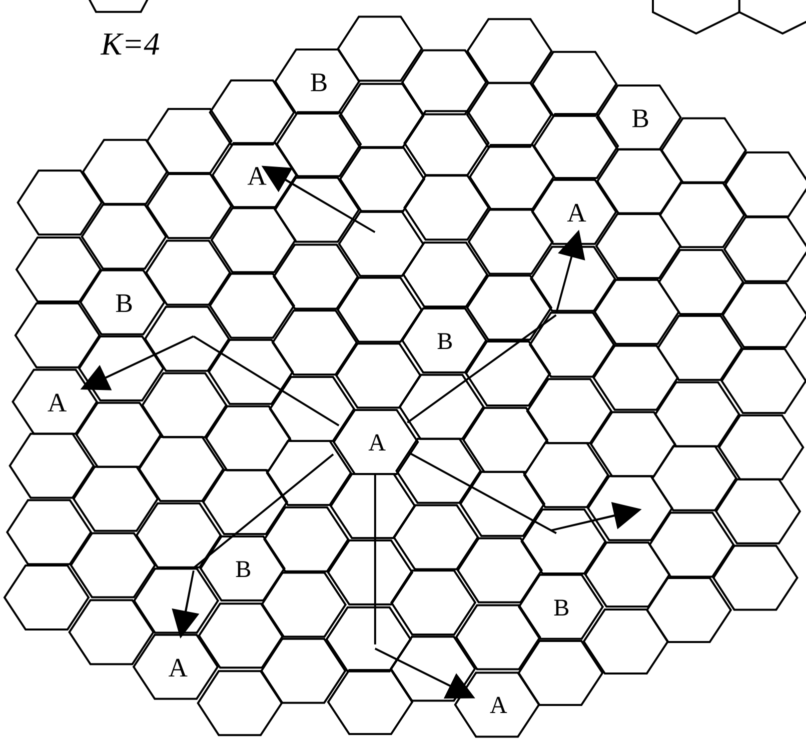
a) Same channel is allocated in two different areas, e.g. AM and FM radio stations using same channels in two different cities.

b) Same channel is frequently used in same area and in one system the scheme used is cellular systems. The entire spectrum is then divided into K reuse sets.





K=4



q=D/R=4
K=7

Fig. 2.2: K-Cell Reuse Pattern

2.3.2 **Locating Co-channel Cells in a Cellular Network**

Cells, which use the same set of channels, are called co-channels cells. For determining the location of co-channel cell present in the neighborhood, two shift parameters *i* and *j* are used where i and j are separated by 60^0, as shown in Fig. 2.3 below. The shift parameters can have any value 0, 1, 2....,n.

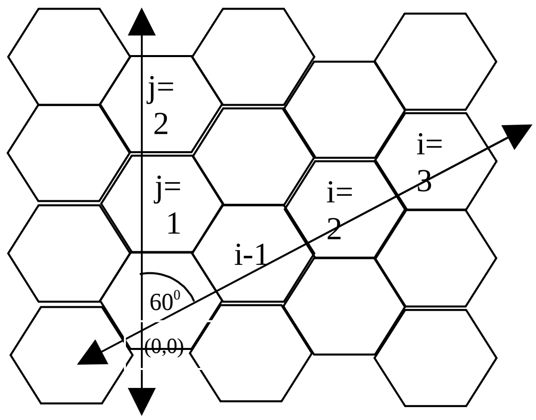


Fig. 2.3: Shift Parameters *i* and *j* in Hexagonal Network

To find the location of nearest co-channel cell, mark the center of the cell as (0, 0) for which co-channel cells are to be located. Define the unit distance as the distance of centre of two adjacent cells, and follow the two steps given below:

Step 1**:** Move *i* number of cells along *i* axis

Step 2**:** Turn 60^0 anti-clockwise and move *j* number of cells

The technique of locating co-channel cells using the preceding procedure is shown in Fig. 2.4 for *i*=3 and *j*=2. The shift parameters *i* and *j* measures the number of neighboring cells between co-channel cells.

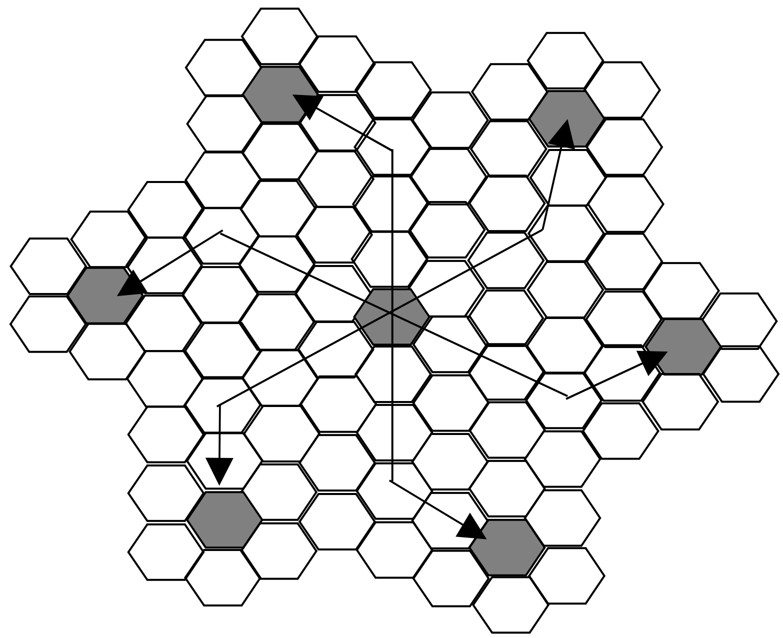


Fig. 2.4: Locating Co-channel Cells when $i=3$ & $j=2$

The relationship between cluster size K and shift parameters i & j, is given below:

Let *'R'* be the distance between the center of a regular hexagon to any of its vertex. A regular hexagon is one whose all sides are also of equal length i.e. *'R'*. Let *'d'* be the distance between the centre of two neighboring hexagons, and following steps are followed while calculating the size of a cluster *'K'*.

Step 1: To show that $d = \sqrt{3}R$

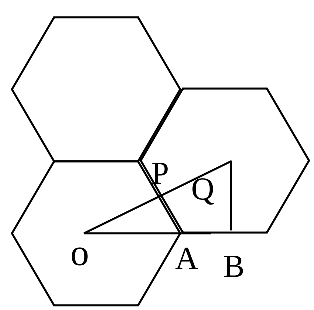


Fig. 2.5: Distance Between two adjacent cells

From the geometry of the Fig. 2.5, OA = R and AB = R/2 (2.1)

$$\text{Then, } OB = OA + AB = R + R/2 = 3R/2 \quad (2.2)$$

Then, in right-angled ΔOAP

$$OP = OA \sin 60^0 = \left(\sqrt{3}/2\right)R \quad (2.3)$$

Let the distance between the centers of two neighboring hexagonal cells, OQ, be denoted by 'd', then,

$$OQ = OP + PQ \text{ (where } OP = PQ)$$

Therefore, $$d = \left|\left(\sqrt{3}/2\right)R\right| + \left|\left(\sqrt{3}/2\right)R\right|$$

$$\text{Hence, } d = \sqrt{3}R \quad (2.4)$$

Step 2: Area of a small hexagon, $A_{small\ hexagon}$ W

The area of a hexagonal cell with radius R is given as

$$A_{small\ hexagon} = \left(3\sqrt{3}/2\right) \times R^2 \quad (2.5)$$

Step 3: To find the relation between D, d and shift parameters

Let 'D' be the distance between the center of a particular cell under consideration to the centre of the nearest co-channel cell.

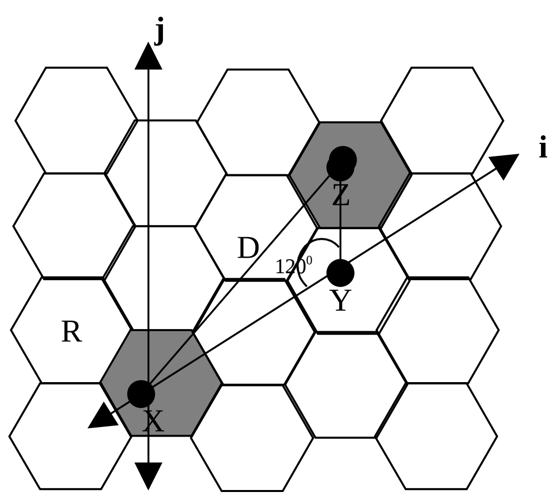


Fig. 2.6: Relationship Between K and Shift Parameters *(i & j)*

Using cosine formula ΔXYZ in Fig. 2.6, we have

$$XZ^2 = XY^2 + YZ^2 - 2 \times XY \times YZ \cos 120^0$$

$$\text{or, } D^2 = (i \times d)^2 + (j \times d)^2 - 2 \times (i \times d) \times (j \times d) \cos 120^0$$

$$D^2 = (i \times d)^2 + (j \times d)^2 - 2 \times (i \times d) \times (j \times d) \times (-1/2)$$

$$D^2 = (i \times d)^2 + (j \times d)^2 + (i \times d) \times (j \times d)$$

$$D^2 = d^2 (i^2 + j^2 + i \times j) \qquad (2.6)$$

$$D^2 = 3 \times R^2 \times (i^2 + j^2 + i \times j) \qquad (2.7)$$

Step 4: To find the area of a large hexagon, $A_{large\ hexagon}$

By joining the centers of the six nearest neighboring co-channel cells, a large hexagon is formed with radius equal to D, which is also the co-channel cell separation. Refer Fig. 2.7.

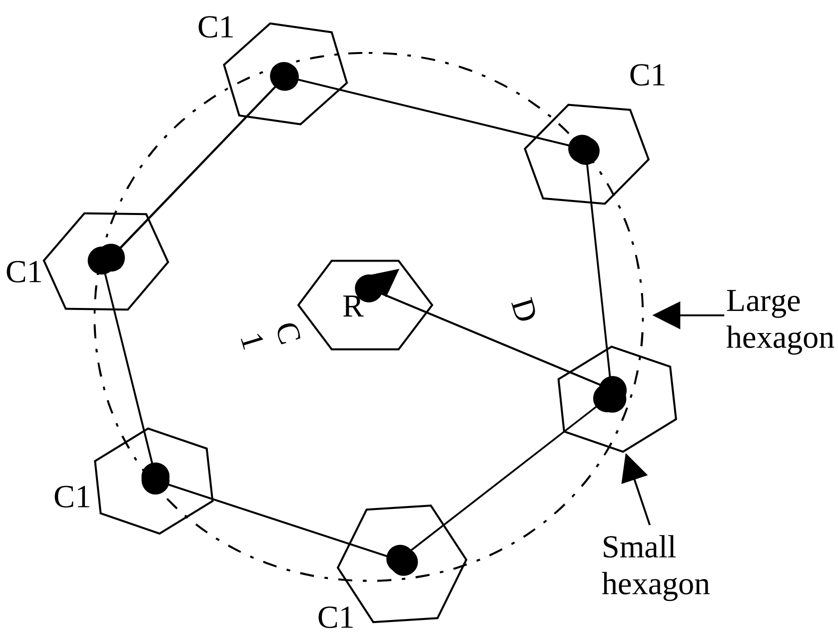


Fig. 2.7: Larger Hexagon in the First Tier

The area of the large hexagon having a radius D can be given as

$$A_{large\ hexagon} = \left(3\sqrt{3}/2\right) \times D^2 \qquad (2.8)$$

Using equation 2.7

$$A_{large\ hexagon} = \left(3\sqrt{3}/2\right)\times 3\times R^2\times\left(i^2 + j^2 + i\times j\right) \tag{2.9}$$

Step 7: To find the number of cells in the large hexagon (L)

Number of cells in large hexagon

$$L = A_{\text{large hexagon}} / A_{\text{small hexagon}} \tag{2.10}$$

Using equations 2.9, 2.5 & 2.10, we get

$$L = 3 \times (i^2 + j^2 + i \times j) \tag{2.11}$$

Step 8: Find the correlation between L and cluster size K

It can be seen from Fig. 2.8, that the larger hexagon is created by joining the centers of co-channel cells present in the first tier contains 7 cells of the central cluster plus 1/3rd of the number of 7 cells of all the neighboring six clusters. Therefore, it can be calculated that the larger hexagon consisting of the central cluster of *K* cells plus 1/3rd the number of the cells connected with six neighboring clusters present in the first tier.

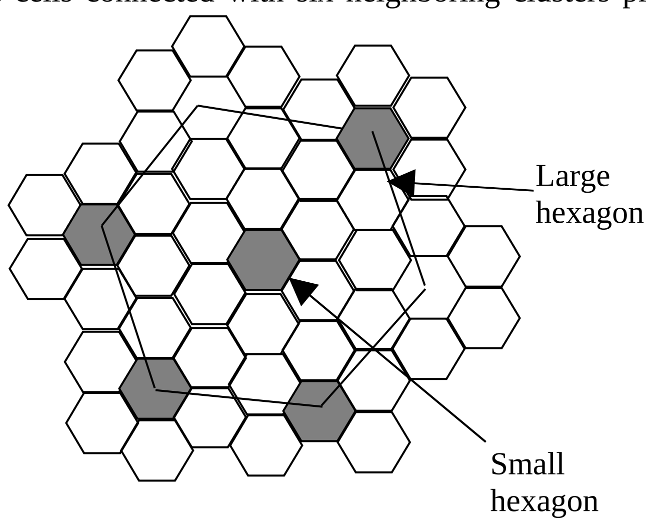


Fig. 2.8: Number of Clusters in the First Tier for N=7

Hence, the total number of cells enclosed by the larger hexagon is

$$L = K + 6 \times [(1 / 3) \times K)$$

$$L = 3 \times K \tag{2.12}$$

Step 9: To establish relation between K and shift parameters

From equation 2.11 and 2.12, we get

$$3 \times K = 3 \times (i^2 + j^2 + i \times j)$$

$$K = (i^2 + j^2 + i \times j) \tag{2.13}$$

The Table 2.1 shows the frequency reuse patterns along with the cluster sizes

Table 2.1: Frequency Reuse Pattern and Cluster Size

Frequency Reuse Pattern ***(I, j)***	**Cluster Size** ***$K = (i^2 + j^2 + i \times j)$***
(1, 1)	3
(2, 0)	4
(2, 1)	7
(3, 0)	9
(2, 2)	12
(3, 1)	13
(4, 0)	16
(2, 3)	19
(4, 1)	21
(5, 0)	25

2.3.3 Frequency Reuse Distance

To reuse the same set of radio channels in another cell, it must be separated by a distance called frequency reuse distance, which is generally represented by D.

Reusing the same frequency channel in different cells is restricted by co-channel interference between cells. So, it is necessary to find the minimum frequency reuse distance D in order to minimize the co-channel interference. Fig. 2.9 illustrates the separation of cells by frequency reuse distance in a cluster of 7 cells. In order to derive a formula to compute D, necessary properties of regular hexagon cell geometry are first discussed.

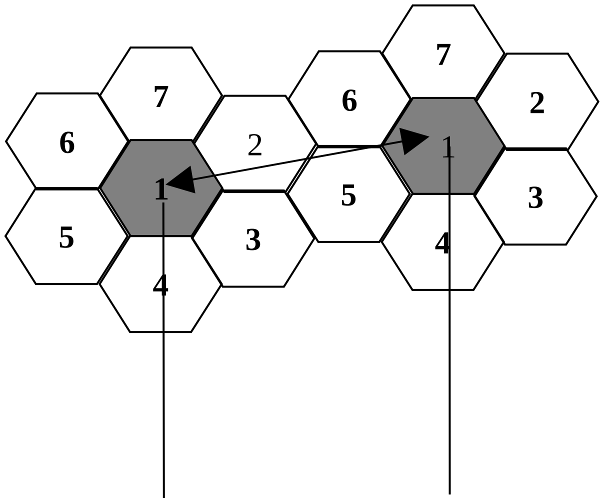


Fig. 2.9: Frequency Reuse Distance

The frequency reuse distance (D), which allows the same radio channel to be reused in co-channel cells, depends on many factors:

- the number of co-channel cells in the neighborhood of the central cell
- the type of geographical terrain
- the antenna height
- the transmitted signal strength by each cell-site

Suppose the size of all the cells in a cellular is approximately same, and it is usually calculated by the coverage area of the proper signal strength in every cell. The co-channel interference does not depend on transmitted power of each, if the cell size is fixed, i.e., the threshold level of received signal at the mobile unit is tuned to the size of the cell.
The co-channel interference depends upon the frequency reuse ratio, q, and is defined as

$$q = D / R$$

Where D is the distance between the two neighboring co-channel cells, and R is the radius of the cells. The parameter q is also referred to as the frequency reuse ratio or co-channel reuse ratio. The following steps are used to find the relationship between frequency reuse ratio q and cluster size K

Fig. 2.10 shows an array of regular hexagonal cells, where R is the cell radius. Due to the hexagonal geometry each hexagon has exactly six equidistant neighbors.

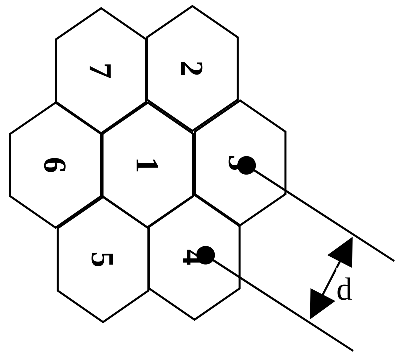


Fig. 2.10: Distance Between Two Adjacent Cells (d)

Let d be the distance between two cell centers of neighboring cells. Therefore,

$$d = \sqrt{3}R$$

The relationship between D, d, and shift parameters is

$$D^2 = 3 \times R^2 \times (i^2 + j^2 + i \times j)$$

As $K = i^2 + j^2 + i \times j$

$$D^2 = 3 \times R^2 \times K$$

$$\frac{D^2}{R^2} = 3 \times K$$

$$\frac{D}{R} = \sqrt{3K}$$

As $q = D/R$

$$q = \sqrt{3K}$$

Thus, the frequency reuse ratio q can be computed from the cluster size K. Table 2.2 shows the frequency reuse ratios for different cluster sizes, K

Table 2.2: Frequency Reuse Ratio and Cluster Size

Cluster Size K	**Frequency Reuse Ratio** $q = \sqrt{3K}$
3	3.00
4	3.46
7	4.58
9	5.20
12	6.00
13	6.24
19	7.55
21	7.94
27	9.00

As the D/R measurement is a ratio, if the cell radius is decreased, then the distance between co-channel cells must also be decreased by the same amount, for keeping co-channel interference reduction factor same. On the other hand, if a cell has a large radius, then the distance between frequency reusing cells must be increased proportionally in order to have the same D/R ratio.

As frequency reuse ratio (q) increases with the increase in cluster size (K), the smaller value of K largely increase the capacity of the cellular system. But it will also increase the co-channel interference. Therefore, the particular value of q (or K) is selected in order to keep the signal-to-cochannel interference ratio at an acceptable level. If all the antennas transmit the same power, then with the increase in K, the frequency reuse distance (D) increases, and reduce the likelihood that co-channel interference may occur. Therefore, the challenge is to get the optimal value of K so that the desired system performance can be achieved in terms of increased system capacity, efficient radio spectrum utilization and signal quality.