Chapter 2

FREQUENCY ALLOCATION: ISSUES AND SOLUTIONS

"There are very few things in the world of technology that are as financially important and frustratingly arcane as the allocation and use of radio spectrum."

— The Times, April 10, 2007

2.1 INTRODUCTION

To begin with it is obligatory to take up a very fundamental concept of wireless communication that it is basically transmitting and receiving audio signals and information using electromagnetic waves in open space. Since it is a wireless communication, these electromagnetic waves travel without wires. The information from a sender to receiver is usually carried out over a well-defined frequency band, which is also known as bandwidth. Each channel has a fixed frequency bandwidth and capacity. In order to optimize the use of wireless communication, it is needed to somehow wisely allocate these frequency bandwidths so that one can accommodate more than one user. Thus, the frequency assignment problem involves the assignment of the frequency spectrum (i.e. time slots or channels) to the transmitter or the connecting links so that all transmitters (links) assigned the same frequency may transmit in such a way that there is no collision.

A large number of research studies have formed the base of this frequency assignment problem over the last two decades. A survey report is given in engineering literature on channel assignment strategies has been presented by Katzela and Naghshineh [Katzela &
Naghshineh, 1996]. The relationship to graph coloring and multi-coloring has been set out in detail by Hale [Hale, 1980]. The relationship between channel assignment and graph multi-coloring is proved by Lata Narayanan [Narayanan, 2001]. The relationship between channel assignment and graph labeling is discovered by Janssen and Kilakos [Janssen & Kilakos, 2000].

2.2 ISSUES IN FREQUENCY ALLOCATION

There are few significant and the classic features of the radio frequency spectrum are listed as below:

1. The radio frequency spectrum is spread over a huge global region; hence, it does not respect international geographical boundaries.

2. There is an immense possibility of overlapping interference in the use of radio frequency spectrum and involves some applications of engineering to make certain interference free process of mobile networks.

3. Radio frequency spectrum must be used innovatively, optimally and carefully in an efficient manner because unlike other natural resources, radio frequency spectrum is wasted if it is not used appropriately and is not consumed properly upon its usage. Therefore, radio frequency spectrum utilization is to be shared among the numerous radio stations.

The drawback of the radio frequency spectrum is mostly because of the following reasons:

- Dissemination features of various kinds of radio frequencies.
- Accessibility of equipment and technology for various kinds of applications of the radio frequency spectrum.
- The appropriateness of complete radio frequency spectrum for precise uses.
- Frequency planning for avoiding interference between transmitters using the same frequencies, frequencies has to distribute carefully.
The problem of vulnerability and interference related to the mobile communication system are due to time congestion in the electromagnetic bandwidth. Frequency spectrum is the limiting feature responsible for the good performance of mobile cellular systems. In the same cell of mobile network, a clash with another mobile or a call in the nearby cell can cause interference. Interference can also occur between the base stations operating at same frequency band or any other non-cellular system's energy leaking accidentally into the frequency band of the cellular system. If interference is caused in the voice channels, cross-talks can be heard between the users. These cross talks are similar to noise between the users. Sometimes there are issues like missed calls or error calls, these are because of the interference in the control channels of digital signaling. Since there is larger radio frequency noise and huge density of mobiles and their base stations, the invention is more precisely in urban area.

Frequency management plays a vital role in developing better communication between mobile users and base stations. Thus, for the growth of good communications plans appropriate management of frequency is very much essential because the existing frequency band is highly limited in nature. In selection of frequencies, during the planning phase, if proper care is not taken then the selected frequencies might interfere with each other. Frequency assignment is the procedure that assigns frequencies to the cells of a mobile cellular system. The important attention of the research regarding frequency assignment is to find schemes and solutions that give utmost frequency reuse without violating the interference constraints so that blocking is minimum.

There are mainly two important issues considered: One is interference and the second is frequency reuse. Interference constraints are further divided into various kinds.

The limitations are mainly described by three types of constraints:

1. **Frequency constraints** which identify the amount of present frequencies (channels) in the radio bandwidth.

2. **Traffic constraints** are those which identify the minimum amount of frequencies essentially used by each station in a network to serve a geographic area. These traffic constraints are not imposed by any regulations but determined by the operators of the telecommunications.
3. **Interference constraints** are more categorized as:

- **Co-channel constraints** – It relates that the same frequency is not allotted to adjacent pairs of radio cells at the same instance of time, in order to avoid co-channel interference. Though the efficiency of system’s spectrum can be increased by frequency reuse, but if the system is not correctly planned, then interference due to the mutual use of the similar kind of channels might occur. Such type of interference is known as co-channel interference. Among all interferences that occur in a cellular radio co-channel interference is very much critical.

The possibility of co-channel interference is situated more in the demanding hours of a cellular system. The total dominance of co-channel interference can be attained by not using the frequency reuse concept that is inconsistent to the concept of the cellular radio. The reuse distance D is taken into account by the system planner. In cellular system when the size of each cell is almost equal, co-channel interference does not depend on the transmitted power and shows a relation between the reuse of the cell R and the reuse distance D.

The factor Q is defined as $$Q = \frac{D}{R} = \sqrt{3K}$$ with various names the co-channel interference reducing factor or reuse distance factor and the measure of co-channel interference. The Q factor defines better spectral efficiency inside a cell and this is also related to the total number of cells in the cluster K.

- **Adjacent channel and co-site constraints** – Adjacent channel states that the adjacent frequencies are not allotted to neighboring radio cells at the same instance of time. Co-site constraints mean that any pair of frequencies allotted to a cellular network, every cell with an assigned channel is requires a positive distance in the network.

The interference caused between two adjacent channels of the similar (co-site interference) or adjacent cells (adjacent channel interference) is a second source of noise along with the co-channel interference. Hence, this
is very important that the adjacent channel is not the nearby neighboring channel inside a communication, but rather the nearest allotted channel in the same cell and can be reused at a number of channels apart. The damaged receiver cleans that permit adjoining frequencies to inform leak into the band due to equipment limitations are also responsible for co-site and adjacent channel interference.

The problem can be severe particularly if the neighboring channel user is transmitting in close range to the receiver a weaker signal. In order to solve this problem, many different techniques can be used. The total frequency spectrum is generally split into two halves so that the reverse channels that compose the uplink (mobile to base station) and the forward channels that compose the downlink (base station to mobile) can be separated by half of the spectrum.

Careful channel assignment can also be highly helpful in reducing the Co-site and adjacent channel interference. By keeping the frequency separation between each channel in a given cell as large as possible, these types of interference may be reduced considerably. Some designers also prevent a source of adjacent channel interference by preventing the use of adjacent channels in geographically adjacent cell sites. This strategy, however, is dependent on the cellular pattern. For instance, if a seven-cell cluster is chosen, adjacent channels are inescapably assigned to adjacent cells.

These constraints are basically some limitation over the utilization of frequency in the frequency assignment problem. Various types of constraints are defined. The most important limitation is the frequency constraint which can be resolved by the frequency reuse by the stations. The level of receiving the signal quality that can be attained in each channel is determined by the number of channels with a predetermined quality.

2.3 PRINCIPLE OF FREQUENCY REUSE

The cellular system specifically involves a smart assignment and the reuse of frequency (i.e. channels) all over the area of coverage. Every mobile base station is assigned a set of
radio frequencies which is used inside a slight geographical area defined as a cell. Further, in the neighboring cells, the base stations are allocated those frequency sets which contain entirely dissimilar frequencies than the neighboring cells. In short, the designing procedure of assigning and selecting frequency groups for every mobile base station inside a system is termed as frequency planning or frequency reuse concept. Figure 2.1 demonstrates the cellular frequency reuse concept. Here, the cells are named with the similar alphabet using the similar set group of frequencies. There are three clusters shown here in figure 2.1 of size as 7. The cell of the same alphabet in the three clusters uses the similar set of frequencies; they are termed as co-channel cells. For example cells A of cluster1, cluster2 and cluster3 are called co-channel cells. But, the cells C to D in the cluster are called neighboring or adjacent cells. Thus, interference due to co-channel cells is called as co-channel interference and interference due to adjacent cells is known as adjacent channel interference.

![Figure 2.1 Frequency Reuse pattern](image)

The frequency bandwidth spectrum assigned to a mobile communication system is very limited. The cellular concept has been bringing together for appropriate utilization of the frequency. The cellular concept supports frequency reuse by declaring that instead of using equal set of channels for providing services to total residents of a mobile communication system, the geographical area of the system should be divided into smaller identical size parts generally referred to as cells. Figure 2.2 shows frequency
reuse at distance 2 means same frequency is used by the cell which is located at a distance 2 from each other. The available frequency channels also split into several sets, and the similar collection of frequencies is reused by sets of non-neighboring cells i.e. the similar collection of frequencies can be reused by two cells which are located at a positive distance, thus the radio interference between them is acceptable. By reducing the size of cells, the cellular network is able to increase its capacity, and serve more subscribers.

Figure 2.2 Example of frequency reuse at distance 2

**Determination of frequency reuse factor N**

For a homogeneous system, N is given as

\[ N = i^2 + j^2 + ij \]

Where \( i \) and \( j \) are positive integer values used to obtain the nearest neighbors between co-channel cells.

**Steps To Determine the Nearest Co-Channel Neighbors**

The following two-step rule can be used to determine the location of the nearest co-channel cell.

**Step 1:** Move \( i \) cells along any chain of hexagons;

**Step 2:** Turn 60 degrees counterclockwise and move \( j \) cells.
Figure 2.3 shows the method of locating co-channel cells in a cellular system using the preceding rule for $i=2$ and $j=0$. Figure 2.4 depicts a cluster of size 7 for $i=1$ and $j=2$ and Figure 2.5 shows a cluster of cells of size 12 using preceding rule for $i=2$ and $j=2$. 

Figure 2.3 Cluster for $i=2$ and $j=0$  
Figure 2.4 Cluster for $i=1$ and $j=2$  
Figure 2.5 Cluster for $i=2$ and $j=2$
The u-v axis is used to calculate the distance between points $C_1$ and $C_2$ (as shown in figure 2.6). The u-v axes are chosen so that u-v axes passes through the centers of the hexagons. $C_1$ and $C_2$ are the centers of the hexagonal cells with coordinates $(u_1,v_1)$ and $(u_2,v_2)$. 

$$D = \left\{(u_2 - u_1)^2 (\cos 30^\circ)^2 + [(v_2 - v_1) + (u_2 - u_1) (\sin 30^\circ)]^2 \right\}^{1/2}$$

$$= \left\{(u_2 - u_1)^2 + (v_2 - v_1)^2 + (v_2 - v_1) (u_2 - u_1)\right\}^{1/2}$$

If we assume $(u_1, v_1) = (0, 0)$, or the origin of the coordinate system is the center of a hexagonal cell, and restrict $(u_2, v_2)$ to be a positive integer-valued $(i, j)$. Then normalized distance $D_{\text{norm}}$ be the distance from the candidate of the center cell to the center of a nearest co-channel cell, normalized, with respect to the distance between the centers of two adjacent cells, $\sqrt{3}R$. It may be noted that the normalized distance between two adjacent cells (either with $i=1$ and $j=0$ or with $i=0$ and $j=1$) is unity.

The co-channel interference is a function of $q$ where $q = D/R$. But $D$ (distance between any two cells) is a function of $N_1$ and $S/I$. $N_1$ is the number of co-channel interfering cells and $S/I$ are the received signal to interference ratio at the desired mobile receiver.

![Figure 2.6 Coordinate system](image-url)
Assuming that the first cell is centered at the origin \((u = 0, v=0)\), the distance between any two cells will be:

\[
D_{\text{norm}} = [i^2 + j^2 + ij]^{1/2}
\] (2.1)

\[
D = (D_{\text{norm}})(\sqrt{3}R)
\] (2.2)

Using equation (2.1) co channel separation \((D)\) will be

\[
D^2 = 3R^2[i^2 + j^2 + ij]
\] (2.3)

Since the area of a hexagon is proportional to the square of the distance between the center and vertex, the area enclosed by the large hexagon is:

\[
A_{\text{large}} = k [3R^2(i^2 + j^2 + ij)]
\] (2.4)

where \(k\) is a constant.

Similarly the area enclosed by the small hexagon is given as

\[
A_{\text{small}} = k(R^2)
\] (2.5)

By comparing equations (2.4) and (2.5), we can write

\[
\frac{A_{\text{large}}}{A_{\text{small}}} = 3(i^2 + j^2 + ij) = \frac{D^2}{R^2}
\] (2.6)

From symmetry, we can see that the large hexagonal encloses the center cluster of \(N\) cells plus one third of the number of cells associated with six other peripheral hexagons. Thus, the total number of cells enclosed in the large hexagon is equal to \(N + 6(N/3) = 3N\). Since the area is proportional to the number of cells, \(A_{\text{large}} = 3N\) and \(A_{\text{small}} = 1\).

\[
\frac{A_{\text{large}}}{A_{\text{small}}} = 3N
\] (2.7)

Substituting equation (2.7) into (2.6) we get

\[
\frac{D^2}{R^2} = 3N
\] (2.8)

\[
\frac{D}{R} = q = \sqrt{3N}
\] (2.9)
Where \( q \) is reuse ratio and \( N \) is cluster size or reuse factor.

**Frequency reuse Ratio**

The frequency reuse ratio is represented by \( q \).

It is expressed as: \( q = D/R \). The reuse factor \( N \) is computed for different values of \( i \) and \( j \) as shown in Table 2.1. The frequency reuse ratio \( q \) is computed from \( D \) and \( R \) and is given in Table 2.1.

<table>
<thead>
<tr>
<th>Frequency reuse pattern</th>
<th>Cluster size</th>
<th>Frequency reuse ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( i )</td>
<td>( j )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>28</td>
</tr>
</tbody>
</table>

Equation (2.9) is important because it affects the traffic carrying capacity of a cellular system and the co-channel interference. If \( q \) is reduced, then the number of cells per cluster also gets reduced. If total Radio Frequency channels are fixed, then the number of channels per cell is increased, thereby increasing the system capacity. On the other hand, co-channel interference is increased with small \( q \). The reverse is true when \( q \) is increased:
an increase in q reduces co-channel interference and also the traffic capacity of the cellular system.

### 2.4 MULTIPLE ACCESS TECHNOLOGIES FOR FREQUENCY ALLOCATION

The sharing of the spectrum is required to achieve high capacity by allocating the bandwidth simultaneously. Hence, there are more than one access schemes. Bandwidth is being shown to be one of the resources that have to be shared. Generally a predefined number of frequency bandwidth is assigned to a cellular system. Multiple access techniques with frequency allocation are then arranged so that numerous users can share the existing frequency spectrum in a well-organized manner. Multiple access systems identify how signals coming from various sources can be merged proficiently for communication over a specified radio frequency spectrum and then divided at the endpoint without any interference. The three basic access methods currently used in mobile systems are listed below:

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)

#### 2.4.1 Frequency Division Multiple Access (FDMA):

In a wireless environment, individual users are allotted individual channels. The channels are frequency band which is unique for each user. The entirely allowed radio spectrum is partitioned innumerable slices of frequency and that each band or channel is allocated to each user. The allocation of the radio channel can also be done on demand basis. The case of FDMA describes that, users share the presented bandwidth in the frequency pool, and a user is assigned a slice of frequency band also termed as channel. In FDMA scheme, if an assigned channel is not consumed by a user it will be idle and it will not be used by some other user. FDMA requires proper filtering of receiver side to avoid adjacent channel interference. If voice channels are assigned in FDMA, then, the mobile
unit and base station start transmitting simultaneously. Another feature of frequency division multiple access (FDMA) is that it requires narrow bandwidth with less complexity.

In FDMA scheme, the complete frequency band is divided into P equal sub-channels that prevent co-channel interference. This P frequency bandwidth is assigned to P users as shown in Figure 2.7. If one avoids the minimum amount of loss in frequency to the guard bands, the capacity of every sub-channel is defined as R/P, where R denotes the capacity related with the total frequency band. Every source entity can then be allocated one (or more) of sub-channels for its particular use. The prime benefit of FDMA is defined as the capability to provide P concurrent transmission of packets (one per sub channel) without any clash.

![Frequency Division Multiple Access technique](image)

**Figure 2.7 Frequency Division Multiple Access technique**

### 2.4.2 Time Division Multiple Access (TDMA):

While FDMA uses frequency bands, the Time division multiple access (TDMA) utilizes time instead of frequency. TDMA divides the entire frequency bandwidth into M equal size slots that are then organized into synchronous frames as shown in Figure 2.8. Conceptually, each slot represents one channel that has a capacity equal to C/M, where C is again the capacity of the entire frequency bandwidth. In figure 2.8 several users share the time slots of the entire time available. Each user can then be assigned one (or more) time slots in which it can access the channel. Consequently packet transmission in a TDMA system occurs in a serial fashion, with each user taking turns accessing the channel.
When we consider the case where each user is assigned only one slot per frame, however, there is a delay of \((M-1)\) slots between successive packets from the same user. Once again, channel resources may be underutilized when a user has no packet(s) to transmit in the frame in its slots. The characteristic quality of TDMA states that each user in time division multiple access schemes shares the same carrier frequency but with non-overlapping time slots.

2.4.3 Code Division Multiple Access (CDMA):

Whereas the FDMA and TDMA separate transmission into different frequencies or instances of time, CDMA allows transmissions to accommodate the frequency band at the same time to avoid any interference. In order to avoid collisions, specialized coding techniques are used which retrieve the information from the collective signal. Transmissions will not interfere with one another as long as two users have sufficiently distinct codes. The widely used spectrum technique utilized by CDMA systems shown in figure 2.9, whereby a spreading code (called a pseudo-random noise or PN code) is allowed multiple users to share a block of the frequency spectrum.

The CDMA adds one more dimension which is the code dimension. So every user is allowed all the time and all the frequency bands for communication but they share a
particular code. In CDMA technique many users share the same carrier frequency. Since the same channel is shared by several users, there may be a problem of near-far effect.

Effective distribution of the information bits across an artificially broadband channel is done by CDMA. Due to this, the frequency diversity of each transmission is increased and makes it less liable to fading and failing the level of interference that might affect other cells which are functioning with the same spectrum. It also makes straightforward system design and deployment since all users share a common frequency band. However, CDMA systems need new specialized and expensive hardware which are usually more challenging to manage.

The reduced level of interference is the main advantage in CDMA when compared to other multiple access schemes. Since each user is allocated an individual pseudo-random code word that is orthogonal to all other code words of remaining users at the receiving end the receiver selectivity tunes to receive the intended signal of the user. Proper power control measures are done in CDMA to avoid near far problems. If the spreading sequences are not exactly orthogonal from one user to another user there may be chances of the self-jamming problem in CDMA. CDMA has a better soft capacity limit than TDMA and FDMA. CDMA has fewer interference problems due to the allocation of unique codes to each user and this multiple access technique is preferred for defense areas than other multiple access techniques.

![Figure 2.9 Code Division Multiple Access technique](image-url)
2.5 FREQUENCY ASSIGNMENT TECHNIQUES

In mobile network technology, the channel (frequency) assignment is generally classified into different categories according to the nature of the assignment strategy. For example, Fixed (or Static) channel assignment (FCA), hybrid channel assignment (HCA) and dynamic channel assignment (DCA). In the first fixed channel assignment (FCA) scheme, channels are normally allotted to cells allowing to the fixed calculated traffic amount. In Dynamic Channel Assignment (DCA), channels are allotted dynamically as a person receives calls. However, dynamic channel assignment is disadvantageous as it involves more intricate control and takes more time. In Hybrid Channel Assignment (HCA), there are two sets of channels one is FCA and the other one is DCA. A hybrid scheme is a combination of both the dynamic and fixed (or static) schemes. In the case of BCA (Borrowing Channel Assignment) scheme, the assignment of channel is static at the very outset. In the case of incoming calls within a cell whose channels are properly engaged, the cell has to borrow appropriate channels from its adjacent cells and thus this borrowing prevents from blocking of calls.

2.5.1 Fixed Channel Assignment (FCA)

Fixed channel assignment (FCA) is the easiest off-line assignment scheme. Different types of existing systems operate with the use of static channel assignment, in which channels are eternally allocated to cells for limited use. The same channels are used by the cells having the same reuse distance. This evenly distribution of channels is effective only if traffic is also evenly distributed, but it does apply if traffic is non-uniformly distributed. Thus, the outcome of even channel distribution is poor channel utilization. There are not enough channels to serve calls when the traffic load is high in cells; at the same time, idle channels may exist in some other cells with low traffic. In FCA, the amount of insignificant channels allocated to every cell is determined by the anticipated traffic in that specific cell of network. Therefore, more channels are allocated to heavily weighted cells.

In 1979, MacDonald [MacDonald, 1979] suggested that, in FCA scheme all vertices are divided into independent sets, every such set is allocated a distinct group of channels and
it works well with uniform distribution of the traffic. However, it doesn’t work well with non-uniform channel distribution case. It is described by Janssen et.al., 2000 [Janssen et. al., 2000] that this is the most suited method for particularly $k$ colorable graphs. Contiguous and temporal traffic variations affects FCA, hence, high degree performance of channel efficiency is not attained. This FCA scheme is very much efficient and precise in design for cells with inactive, heavy traffic loads. Though disadvantageous in a certain way it is not without its advantages and the biggest advantage is its low call service time. The method of selecting a channel to complete a call due to the previously allocated channels among cells an elaborate control is no more required. Hence, different calls are either served or blocked but do not have to wait.

Proper frequency planning is required so as to reach improved results in mobile networks functioning through the FCA scheme. The existing frequency band is generally divided into a group of channels with the same set of frequencies bandwidth, and channels are arranged with numbers from 1 to maximum N. Two channels are required by a mobile user— one for the mobile to base station link [Serizawa & Goodman, 1993] and another one for the base station-to-mobile station link.

### 2.5.2 Dynamic Channel Assignment (DCA)

All dynamic channel assignment (DCA) schemes share the key features that all channels are reserved in a principal place and are allocated vigorously to radio cells when new calls are received by the structure. If the interference constraints are fulfilled than a channel is suitable for use in any cell. DCA schemes differ in the context of norms which are used to allocate channel from the predefined set of all suitable channels. These channels also differ in their structure either distributed or centralized. A huge variety of selection criteria for a channel can be found in the existing literature. The algorithm proposed by Zhang and Yum [Zhang & Yum, 1989] maximizes the reuse: the most utilized channel, often at distance $r$ but least often at distance $r+1$ and $r+2$ is used. Many of the newly suggested DCA schemes are centered on measurement of signal strength from different suitable frequencies and target to maximize the reuse of channels (e.g. see [Zhang & Yum, 1989]). A commonly used strategy found in [Cox & Reudink, 1972], [I
& Chao, 1993], [Prakash et.al, 1995] is the completely greedy approach of using the smallest number of channels, amongst suitable channels.

2.5.3 Hybrid Channel Algorithm (HCA)

HCA is defined as another form of FCA that is used to allocate minimal sets of channels to cells and which divides this collection of channels into reserved borrowable channels. The cells may use all channels from its own set, both fixed and variable ones, but may only use the variable channels from its neighbors, provided they are not being used by any of the neighbors. Many hybrid strategies have been studied by Kahwa and Georganas [Kahwa & Georganas, 1978], but performance bounds are not generally given. Jordan and Schwabe [Jordan & Schwabe, 1996] examine a simple hybrid channel assignment strategy; the performance results for minor values of reuse distance are not as decent as the borrowing strategies.

2.5.4 Borrowing Channel Algorithm (BCA)

In order to enhance the performance of fixed assignment, one point has been to allocate insignificant groups of frequencies with FCA, but it permits the borrowing of existing channels [Janssen et.al., 1999], [Narayanan & Shende, 2001], [McDiarmid & Reed, 1999]. A simplified technique is composed of two-phase algorithm. In the first phase, each cell uses channels as required by it from its own set of frequencies while, in the second phase, a cell borrows frequency channels whenever required from its adjacent cells.

However, the second phase is needed to resolve the clashes affected by two adjacent neighbors who are trying to borrow the same channel from a common neighbor. This kind of mechanism is to restrict from the borrowing. For e.g., a green node can borrow only red channel, red nodes can borrow black channels and black nodes can borrow only green channels. The concept of channel borrowing is done in long-term borrowing. The borrowing is done with other cells or borrowing channels from another face of the same cell can also be done. This technique is suitable for slowly developing cellular systems. The cell-splitting technique is used in cells to handle different traffic densities. But,
implementation of the cell-splitting technique is very dear and thus requires more funding. Hence, if it is impossible to do without it and is highly essential for the system, only, then it should be used. The channel borrowing technique helps to avoid cell splitting in the system. It is the chief advantage of the channel borrowing technique.

There are four different types of algorithms for assigning frequencies. In spite of so many frequency assignment schemes, FCA is still most popular for frequency allocation. We have considered the same.

2.6 CLASSIFICATION OF FREQUENCY ASSIGNMENT PROBLEM

FAP is a vital practical well known optimization problem occurring in mobile network design. Different versions of Frequency Assignment Problem (FAP) could be expanded by taking maximum advantage of traffic, reducing the total amount of frequencies band used and reducing the interference among the cells of mobile network. Four different models of the FAP can be described for Fixed Channel assignment (FCA) scheme.

2.6.1 Minimum Order FAP (MO-FAP)

This refers to assigning channels so that there is not any interference and there is a minimum number of different frequencies which are used. The MO-FAP problem can be explained more competently by allowing for accurate and experimental procedures. The maximum number of heuristic techniques suggested has been derived from CALMA project. Kapsalis in 1995 [Kapsalis et. al., 1995] observed the experimental performance of a genetic algorithm. The obtained results are not as much pleasing because an optimum solution has been obtained in only two cases. One in numerous local search techniques, such as Tabu search and second in simulating annealing are described in detail by Tiourine et.al., 20000 [Tiourine et. al., 2000]. The heuristics were optimal, merging the bounds i.e. upper and lower bounds for 6 for a total of 10 numbers of instances of test cases. Tabu search with a changed evolutionary approach called evolutionary search, has been put forward by Crisan and Muhlenbein [Crisan &
This empirical alternative consists of the repetitive mutation of a result created on a fixed mutation operator.

2.6.2 Minimum Span FAP (MS-FAP)

MS-FAP is the upmost considered FCA schemes. In MS-FAP, investigative methods have been presented by several scholars and lower bounds have been verified widely on the Philadelphia distances. These heuristic methods have been building up, but they seem to be not so exact for giving an optimal solution in all cases; more difficult standard instances are essential to differentiate among heuristics. The first heuristics was proposed in the 1970s and 1980s ([Box, 1978], [Sivarajan et.al., 1989], [Zoellner & Beall, 1977]). Box [Box, 1978] put forward a simple iterative technique based on a ranking of channel requirements of different cells in descending order of assigning difficulty. This is a measure of how hard it is to find an equivalent frequency satisfying a given channel requirement. The order is changed when a denial occurs, and channels are assigned to each cell based on the assignment difficulty during each iteration. Zoellner and Beall [Zoellner & Beall, 1977] have proposed a technique, investigating co-channel interference that allocates channels using a frequency approach.

Hurley et.al., in 1997 [Hurley et. al., 1997] designed a software system called FA Soft that operates as a planning tool for frequency allocation and suggested possible heuristics like tabu search, simulated annealing and genetic algorithms based on Philadelphia instances. In 1998 Valenzuela et.al, suggested [Valenzuela et. al., 1998] and applied the genetic algorithm and checked their model on eight Philadelphia instance. In three cases, the optimal solution was found. An application of the Tabu search is discussed in [Tiourune et. al., 2000]. In 1994 Kim and Kim [Kim & Kim, 1994] put forward a competent two-phase optimization method for the MS – FAP based on the notion of frequency reuse patterns. Their heuristics was tried on randomly produced instances.

2.6.3 Minimum (total) Interference FAP (MI-FAP)

In this scheme assignment of channels is done from a restricted channel set, and the total sum of weighted interference is minimized. From MI –FAP case, a lot of heuristics have
been put forward by various research groups. Genetic algorithms and Tabu search appear to be mainly famous for this frequency assignment formulation. In the structure of the CALMA project, Tiourine et.al., 2000 [Tiourine et.al., 2000] used simulated annealing and variable depth first search. A genetic algorithm was recommended by [Kapasalis et. al., 1995]. Kolen [Kolen, 1999] has proposed a genetic algorithm with optimized crossover that generated the best child of two parents. In addition to the research on the CALMA instances, numerous researchers have emerged. The Hopfield used neural network model for solving combinatorial problems. In 1991 Kunz [Kunz, 1991] proposed the first Hopfield model to find adequate solutions for the FCA problem, including co-channel and co-site interference constraints. A large number of iterations were required by Kunz’s neural network model to reach the final solution. In 1992 Funabiki and Takefuji, in 1995 Lochtie and Mehlet [Funabiki & Takefuji, 1992] [Lochtie & Mehlet, 1995] suggested neural network based solution for MI-FAP. Smith and Palaniswami [Smith & Palaniswami, 1997] devised the MI-FAP as a nonlinear integer programming and used a Hopfield and a self-organized neural network to the problem. It has been formulated in it that the weight of the interference depends on the distance between the assigned frequencies. The genetic algorithmic approach has been discussed by [Kim et. al., 1996], [Lai & Coghill, 1996], [Crisan & Muhlenbein, 1998], [Ngo & Li, 1998]. Dorne and Hao [Dorne & Hao, 1995] applied evolutionary search to a number of cases for a network of size 300 nodes. An assignment satisfying all the co-site constraints was represented. Tabu search was used by Castelino et.al. [Castelino et. al., 1996] to find an assignment with minimum unweighted interference for instances with up to 726 nodes.

2.6.4 Minimum Blocking FAP (MB-FAP)

MB-FAP continues to be a subject of interest in research in a number of readings and are generally explained with accurate logical clarifications such as integer programming procedures. One such heuristic explained with simulated annealing approach was described by [Mathar & Mattfeldt, 1993]. In the case of MB–FAP assignment of frequencies is done in such a manner without interference and also minimizes the complete blocking possibility in the considered network. The authors examined the use of various procedures which are constructed on the simulated annealing approach with
suitable model. In all computational tests, all alternatives have been exposed to provide suitable results when matched to optimal solution achieved by logical methods. Several other models have also been proposed.

*There are four types of classifications of frequency allocation problem is described for fixed channel assignment schemes. We follow minimum order FAP (MO-FAP) approach in our experimental analysis.*

## 2.7 FREQUENCY ASSIGNMENT SOLUTION METHODS

### 2.7.1 The Greedy Strategy

The greedy strategy is generally understood to be a non-coloring strategy in the inline setting. However it also makes sense for the static problem, and a distributed recoloring version of the greedy strategy was expressed and analyzed by Narayanan [Narayanan, 2001]. A greedy strategy makes a frequency assignment by iteratively selecting a node and then assigning a feasible frequency to it. The selection of nodes and assignment of frequency follows some rules designed to optimize the objective function.

From the interference graph a sequence of nodes is formed, and then the frequencies are allocated to the nodes according to this sequence which is either in ascending or in descending order. In particular three different kinds of sequences are reconsidered:

(a) Maximum degree first: the nodes are arranged in descending order of their degree;

(b) Minimum degree first: the nodes are arranged in ascending order of their degree;

(c) Random sequence: the nodes are arranged in unsorted order of their degree;

Cozen and Roberts [Cozen & Roberts, 1982] suggested greedy T-coloring which is a frequency exhaustive sequential heuristic. In essence, the algorithm repetitively assigns colors to the nodes of the graph through the minimum possible feasible color allowing to some previously defined vertex coloring.
2.7.2 Sequential Heuristic Method

A sequential heuristic method was introduced by Metzger [Metzger, 1970] for solving FAP using simple graphs coloring. Sequential assignment methods are also termed as greedy methods, which involves three different modules based on work presented by Hale [Hale, 1980]. Initially, the transmitters are arranged in some specific sequence and then first transmitter is allocated the frequency one. The next transmitter is carefully chosen from the sequence (which differ from the initial sequence). At the end, the selected transmitter is allocated a particular frequency.

2.7.3 Simulated Annealing

Simulated annealing is a local search technique motivated by the process of simulating the physical cooling process. Simulated annealing has been introduced for general optimization by Mathar and Mattfeldt, [Mathar & Mattfeldt, 1993]. SA starts with an initial solution, repetitively produces a neighbor of the present solution and transfers it, according to some strategy, with the aim of improving the objective function value. The method itself has a direct analogy with thermodynamics, specifically with the way the liquids freeze and crystallize, metal cools and anneal. For the SA algorithms, the energy function is the objective function (to be minimized). SA begins with an initial solution and iteratively computes this solution in the hope of eventually finding a solution of lower energy. The variance of this transition is the function of a temperature parameter T, and is large for high temperatures and much smaller for lower temperatures.

2.7.4 Tabu Search

Glover [Glover, 1989] suggested Tabu Search (TS) independently in 1986, to solve a combinatorial problem. It is a meta-heuristic method that monitors local heuristic search techniques to discover the solution space away from a local optimality. The basic idea is to prevent certain moves that would return to newly visited solutions, by rendering them tabu. To go beyond a local optimum, TS allows a worsening solution. Given a starting feasible solution, TS computes the neighborhood solutions, but selects the solution with the finest objective function value within the neighborhood, even it’s worse than the best
solution obtained so far. Tabu search was implemented by Castelino et.al. [Castelino et. al., 1996] to find an assignment with minimum and weighted interference for cases of graph of 726 vertices and compare the performance with a genetic algorithm and a steepest descent heuristic.

2.7.5 Genetic Algorithm

Genetic Algorithms (GAs) can be defined as adaptive experiential search algorithms based on the evolutionary ideas of genetics and ordinary selection. The fundamental idea of GAs is planned to simulate processes in natural system necessary for evolution. The Genetic Algorithms have been widely studied, experimented and applied in many fields of the engineering world after it has been first initiated by John Holland in the 1960s. Many of the involved real world problems for finding optimal parameters, which might have proved difficult for traditional methods, have been found to be ideal for GAs. In 1996 Kim [Kim et. al., 1996] applied a genetic algorithm to obtain interference free assignments.

2.8 GRAPH THEORETICAL APPROACH

In graph theory, researchers have developed many approaches for solving frequency allocation problems. One of the interesting approaches is graph coloring. Graph coloring is a natural model for solving frequency allocation problem in a mobile network. We use this graph theoretical approach for frequency allocation. Independent sets approach and graph coloring approach are related to each other. Independent sets are reduced for graph coloring.

2.9 DISTRIBUTED ALGORITHM

Distributed algorithm was used to refer to algorithms that were designed to run on many processors “distributed” over a large geographical area. The distributed algorithm plays an important role for frequency allocation applications in the mobile network.
Distributed algorithm arises in many applications, including telecommunication, distributed information processing, scientific computing and the real-time process control. For e.g., airline reservation, telephone services, global information, banking, aircraft, nuclear power plant control and weather prediction systems all are based on distributed algorithms. Therefore, it is vital for the algorithms to run correctly and efficiently. The design of distributed algorithm can be an extremely difficult task because of the complicated settings in which they execute.

As the area covered by transmitters is increasing day by day, the problem of frequency allocation also becomes distributed in nature.

The term distributed algorithm [Lynch, 1996] was originally used to refer to an algorithm, designed to run on many processors “distributed” over a large geographical area. But over the years, the usage of this term has been broadened, so that it now includes algorithms that run on local area networks and even algorithms for shared memory multiprocessors. This has happened because it has been recognized that the algorithms used in these various settings have a great deal in common. The hardware consisting of many interconnected processors are the ones on which distributed algorithms run. Sections of a distributed algorithm run simultaneously and individually, each with only a partial amount of information. In case if the individual processors and communication channels operate at different speed and if some of the components fail then also the algorithms work concurrently.

Some of the attributes by which the different types of distributed algorithms differ are:

- **Inter-process communication (IPC) method**
  Distributed algorithms execute on a set of processors, which need to communicate with each other. Some common methods of communication include accessing shared memory, sending point to point or broadcast messages (either over a long distance or local area network), and executing remote procedure calls. An important problem in the distributed setting is the requirement of communication among various entities contributing in the activities of the system. This aspect does not exist in centralized computing. It is because of this that there is a requirement of characterizing, developing and
evaluating the methods for exchange of information. A fundamental point contained in the above statement is that communication has certain costs associated with it and does not come for free. Besides, there may be limits to the speed and the amounts of information that can be transmitted. Hence, communication should be considered as a computational resource and one should make use of it judiciously.

- **Timing model**

Several different assumptions can be made about the timing of events in the system, reflecting the different types of timing information that might be used by algorithms. At one extreme, processors can be completely synchronous, performing communication and computation in perfect lock step synchrony. At the other extreme, they can be completely asynchronous, taking steps at arbitrary speeds and in arbitrary orders. In between, there is a wide range of possible assumptions that can be grouped together under the designation partially synchronous in all of these cases, processors have partial information about the timing of events. For example, processors might have bounds on their relative speeds or might have access to approximately synchronized clocks.

- **Synchronous model:**

In the fully synchronous network, it is assumed that all link delays are bounded. More precisely, each processor keeps a local clock, whose pulses must satisfy the following properties: A message sent from a processor \( v \) to its neighbor \( u \) at pulse \( p \) of \( v \) must arrive at \( u \) before pulse \( p+1 \) of \( u \). Thus in effect, one can think about the entire system as driven by one global clock.

Following three steps are involved in machine cycle of each processor:

1. **Sending messages to neighbors**
2. **Reception of messages from neighbors**
3. **Perform some local computation**
Negligible time is taken for local computation as compared to transmission of message. Hence, virtually the entire cycle is spent by each processor on waiting to receive the messages sent to it by its neighbors at the start of the cycle.

- **Asynchronous model:**

  In an asynchronous model, algorithms are event driven, i.e., processors cannot access a global clock in order to decide on their action. Messages sent from a processor to its neighbors arrive within some finite but unpredictable time.

Advantages of Distributed Algorithm

1. Distributed algorithmic approach provides better fault tolerance. Since the vertices communicate only with their adjacent neighbors, the total network traffic produced is considerably less and the tradeoff said above is no more a serious concern.
2. A distributed solution is greater composed in developing and preserving the locality inherent in the problem.
3. In distributed algorithm, since algorithm runs parallels on all nodes, it is possible to perform simultaneous communication sessions. That minimized computation and communication overhead for frequency selection.

- **Complexity Measures**

There are three measures of complexity generally used for computing the performance of distributed algorithms: time complexity and space complexity and message complexity.

*Time complexity*

The time complexity depends on the system that either system is synchronous or asynchronous. The system is synchronous when the execution of an algorithm can be partitioned into rounds: in every round, each processor can send messages; the messages are delivered, and can execute local computation on the basis of messages received.

*Space complexity*

Space complexity is having a main concern with the total memory utilization by the algorithm parameter.
Message complexity

The total number of messages sent over all the possible execution of the algorithm is message or communication complexity of an algorithm.

- Randomization

Instead of requiring the processors to be deterministic, it is sometimes useful to allow them to make random choices, based on some given probability distribution. Since the basic synchronous model does not permit this, we augment the model by introducing a new random function in addition to the message-generation and transition function, to represent the random choice steps. Formally, we add a \( \text{random}_i \) component to the automation description for each node \( i \); for each state \( s \), \( \text{random}_i(s) \) is a probability distribution over some subset of \( \text{states}_i \). Now in each round of execution, the random function \( \text{random}_i \) is first used to pick new states, and the \( \text{messages}_i \) and \( \text{transition}_i \) functions are then applied as usual. The formal notation of execution used in a randomized algorithm now includes not only state assignments and message assignments but also information about random functions. Especially, an execution of the system is defined to be an infinite sequence i.e.

\[ C_0, D_1, M_1, N_1, C_1, D_2, M_2, N_2, C_2, \ldots \], where \( C_r \) and \( D_r \) is a state assignment and each \( M_r \) and \( N_r \) is a message assignment. \( D_r \) Represents the new process states after the round \( r \) random choices.

Claims about what is computed by a randomized system are usually probabilistic, asserting that certain results are achieved with at least a certain probability. When such a claim is made, the intension is general that it is supposed to hold for all inputs and, in the case of systems with failures, for all failure patterns. To model the inputs and failure patterns, a fictitious entity called an adversary is usually assumed to control the choices of inputs and occurrence of failures and the probabilistic claim asserts that the system behaves well in competition with any allowable adversary.

Here we have considered graph model of a mobile network for frequency allocation problem by taking into consideration the important issues. The interference constraints between cells of a network and frequency reuse issue are satisfied as much as possible.
Here are two ways in which we can consider graph model of a network. First way describes that whole graph is known to every vertex in the graph. Second-way only information of neighbors is accessible to vertices in the graph, this is also termed as partial interference. When vertices have information about their neighbors only, in that case, in such case distributed algorithm provides the best solution strategy.

The method of randomization is used frequently in distributed algorithms. The use of randomization in distributed algorithms is an active research area; the two surveys [Motwani & Raghvan, 1995] and [Mitzenmacher & Upfal, 2005] are devoted to this subject only. The use of randomization for contention resolution is common in many systems and networking applications.

**Channel assignment and Distributed coloring**

There have been attempts to solve the problem in a distributed manner. In 1996 Garg et.al. [Garg et. al., 1996] modeled channel assignment as a generalized list coloring problem and provided two distributed solutions synchronous mechanism and randomized solution. In 2003 Boukerche et. al. [Boukerche et. al., 2003] have presented an efficient distributed algorithm for dynamic channel allocation based upon mutual exclusion model, where the channels are grouped by the number of cells in a cluster and each group of channels cannot be shared concurrently within the cluster. In 1995, Prakash et. al. [Prakash et. al., 1995] analyzed the problem as a multiple mutual exclusion problems.