UNIT 1: MULTIPLE ACCESS TECHNIQUES AND CELLULAR CONCEPT

1.1. Introduction:

The radio channel is fundamentally a broadcast medium, therefore signals transmitted by one user can potentially received by all other users within the range of the transmitter. However in wireless communication systems it requires stringent access control to avoid or at least limit the interference between transmissions.

The objective of wireless communication system is to provide communication channels on demand between a portable radio station and a radio portor base station that connects the user to the fixed network infrastructure. Design criteria for such systems include capacity, cost of implementation and quality of service.

All of these measures are influenced by the method used for providing multiple access capabilities. Multiple access in wireless systems is based on insulating signals used in different connections from each other. The support of parallel transmissions on the uplink and downlink is called multiple access, whereas the exchange of information in both direction of a connection is referred to as duplexing. Hence multiple access and duplexing are the methods that facilitate the sharing of the broadcast communication medium. The necessary insulation is achieved by assigning to each transmission different components of the domains that contain the signals. The signal domains most commonly used to provide multiple access capabilities include the following.

Spatial Domain:

All wireless communication systems exploit the fact that radio signals experience rapid attenuation during propagation. As the signal strength decays far away transmitters introduce interference that is negligible compared to the strength of the desired signal. Directional antennas can be used to enhance the insulation between the signals.

Frequency Domain:

Signals that occupy non-overlapping frequency bands can be easily separated using appropriate band pass filters. Hence signals can be transmitted without interfering with each other. This method of providing multiple access is called as frequency division multiple access (FDMA).

Time Domain:

Signals can be transmitted in non overlapping time slots in a round-robin fashion. Thus signals occupy the same frequency band but are separated by their time of arrival. This multiple access method is called as time division multiple access.
Figure: 1 Multiple access methods for wireless communication systems.

**Code Domain:**

In code-division multiple access (CDMA) different users employ signals that have very small cross correlation. Thus correlators can be used to extract individual signals from a mixture of signals even though they are transmitted simultaneously in the same frequency band. The term code-division multiple access technique is used to...
denote this form of channel sharing. Two forms of CDMA are widely employed, frequency hopping (FH) and direct sequence (DS).

The principal idea in all these access methods is to employ signals that are orthogonal or nearly orthogonal. Then correlators that project the received signal into the subspace of the desired signal can be employed to extract a signal without interference from other transmissions.

Preference of one access method over another depends largely on the system characteristic. No single access method is universally preferable. Before going into the detailed description of the different access methods we discuss briefly the salient features of some wireless communication systems. This allows us to assess the relative merits of the access methods in different scenarios.

1.2. Wireless communication system characteristic:

Morden wireless radio systems range from relatively simple cordless telephones to mobile cellular systems and PCSs. It is useful to consider such diverse systems as cordless telephones and mobile cellular radio to illustrate some of the fundamental characteristics of wireless communication systems. The table below illustrates the relevant parameters and characteristics for cordless and cellular radio.

<table>
<thead>
<tr>
<th>Characteristic or Parameter</th>
<th>Cordless Telephone</th>
<th>Cellular Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech quality</td>
<td>Toll quality</td>
<td>Varying with channel quality, Possibly decreased by speech pause exploitation</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>less than 100 m</td>
<td>100 m to 30 Km</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>Mill watts</td>
<td>Approximately 1W</td>
</tr>
<tr>
<td>Base station antenna height</td>
<td>Approximately 1m</td>
<td>Tens of meters</td>
</tr>
<tr>
<td>Delay spread</td>
<td>Approximately 1µs</td>
<td>Approximately 10µs</td>
</tr>
<tr>
<td>Complexity of base station</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Complexity</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 1: Summary of relevant characteristic of cordless telephone and cellular mobile radio.

As seen from the above table the fundamental differences between the two systems are speech quality and the area covered by a base station. The high speech quality requirement in cordless telephone application is the consequence of the availability of tethered access in home and office and the resulting direct competition with wire-line telephone services. In mobile cellular application, the user has no alternative to the wireless access and may be satisfied with lower but still acceptable quality of service.
In cordless applications, the transmission ranges is short because the base station can be simply moved to a conveniently located wire-line access point to provide wireless network access where desired. In contrast the mobile cellular base station must provide access for users throughout a large geographical area of approximately 30 km around the base station. This large coverage is necessary to economically meet the promise of uninterrupted service to roaming users.

1.3. FREQUENCY DIVISION MULTIPLE ACCESS:

In FDMA, non overlapping frequency bands are allocated to different users on a continuous time basis. Hence signals assigned to different users are clearly orthogonal, at least ideally. Practically out of band spectral components cannot be completely suppressed which leaves signals not quite orthogonal. This necessitates the use of guard bands between frequency bands to reduce adjacent channel interference.

It is advantageous to use FDMA with time-division duplexing (TDD) to avoid simultaneous reception and transmission that would require insulation between receive and transmit antennas. In this scenario, the base station and portable take turns using the same frequency band for transmission.

![Figure 2: FDMA where different channels are assigned different frequency bands](image)

Nevertheless, combining FDMA and frequency –division duplexing (FDD) is possible in principle, as is evident from the analog systems based on frequency modulation (FM) deployed throughout the world since from the early days.

Frequency division multiple access (FDMA) assigns individual channels to individual users. It can be seen from the above figure that each user is allocated a unique frequency band or channel. These channels are assigned on demand to users.
who request service. During the period of the call, no other user can share the same frequency band.

In FDD systems, the users are assigned a channel, as a pair of frequencies, one frequency is used for the forward channel and the other is used for the reverse channel.

The features of FDMA are as follows.

- The FDMA channel carries one phone circuit at a time.
- If an FDMA channel is not in use, then it remains idle and it cannot be used by other users to increase or share capacity. This feature is essentially a wasted resource.
- After the assignment of a voice channel, the base station and the mobile transmit simultaneously and continuously.
- The bandwidths of FDMA are relatively narrow as each channel supports one circuit per carrier. This means that FDMA is usually implemented in narrowband systems.
- The symbol time is large as compared to the delay spread. Thus ISI is low and it requires less or no equalization.
- The complexity is less as compared to TDMA systems.
- Since FDMA is a continuous transmission scheme, fewer bits are needed for overhead purposes as compared to TDMA.
- FDMA systems are costly to implement as it requires band pass filters to eliminate spurious radiation at the base station.
- FDMA requires tight RF filtering to minimize adjacent channel interference.

1.3.1. Influence of antenna height:

In the cellular mobile environment, base station antennas are raised considerably to increase the coverage area. Antennas mounted on towers and rooftops are common sight, and antenna heights of 50 m above ground are no exceptions.

Besides increasing the coverage area, this has the effect that frequently there exists a better propagation path between two base station antennas than between a mobile and a base station.

Assuming that FDMA is used in conjunction with TDD, then base stations and mobiles transmit on the same frequency. Unless there is tight synchronization between all base stations, signals from other base stations interfere with the reception of signals from portables at the base station.

To keep the interference at acceptable levels, it is necessary to increase the reuse distance. In other words we can say that sufficient insulation in the spatial domain must be provided to facilitate the separation of signals. These comments apply to both co-channel and adjacent channel interference.
Figure 3: High base station antennas lead to stronger propagation paths between base stations than between a user set and its base stations.

This problem does not arise in cordless applications. Base station antennas are of the same height as user sets. Hence interference created by base station is subject to the same propagation conditions as signals from user sets.

Furthermore in cordless telephone applications there are frequently attenuating obstacles, such as walls, between base stations, that reduce intracell interference further. To overcome intracell interference adaptive channel management strategies based on sensing interference levels can be employed.

The number of channels that can be simultaneously supported in a FDMA system is given by

\[ N = B_t - 2B_{\text{guard}} / B_c \] ................................ (1)

Where \( B_t \) is the total spectrum allocation and \( B_{\text{guard}} \) is the guard band allocated at the edge of the allocated spectrum and \( B_c \) is the channel bandwidth.

1.4. TIME DIVISION MULTIPLE ACCESS:

Time division multiple access (TDMA) systems divide the radio spectrum into time slots and in each slot only one user is allowed to either transmit or receive.

As shown in the figure above, each user occupies a cyclically repeating time slot, so a channel may be thought of as particular time slot that reoccurs every frame, where \( N \) time slots compromise a frame.

TDMA systems transmit data in a buffer-and-burst method, thus the transmission for any user is non-continuous. Digital data and digital modulation must be used with TDMA. The transmission from various users is interlaced into a repeating frame structure as shown in the figure. It can be seen that a frame consists of a number of slots. Each frame is made up of a preamble, an information message, and tail bits. In TDMA/TDD, half of the time slots in the frame information message would be used for the forward link channels, and the other half would be used for reverse link channels.
Figure 4: TDMA scheme where each channel occupies a cyclically repeating time slots

In TDMA/FDD systems, an identical or similar frame structure would be used solely for either forward or reverse transmission, but the carrier frequencies would be different for the forward and reverse links.

In general TDMA/FDD systems intentionally induce several time slots of delay between the forward and reverse time slots of a particular user, so that duplexers are not required in the subscriber unit.

In a TDMA frame, the preamble contains the address and synchronization information that both the base station and the subscribers use to identify each other. Guard times are utilized to allow synchronization of the receivers between different slots and frames.

The features of TDMA are as follows:

- TDMA shares a single carrier frequency with several users, where every user makes use of non-overlapping time slots
- The number of time slots per frame depends on several factors, such as modulation technique, available bandwidth etc.
Data transmission for users of a TDMA system is not continuous, but occurs in bursts. This results in low battery consumption, since the subscriber transmitter can be turned off when not in use.

The handoff process in a TDMA system is simpler for a subscriber unit, since it is able to listen for other base stations during idle time slots.

Here duplexers are not required.

Adaptive equalizers are usually necessary in TDMA systems, since the transmission rates are generally very high as compared to FDMA channels.

The guard time should be minimized. If the transmitted signal at the edges of a time slot are suppressed sharply inorder to shorten the guard time, the transmitted spectrum will expand and cause interference to adjacent channels.

High synchronization overhead is required in TDMA systems because of burst transmissions. TDMA transmissions are slotted, and this requires the receivers to be synchronized for each data burst.

TDMA systems have an advantage in that it is possible to allocate different number of time slots per frame to different users. Thus bandwidth can be supplied on demand to different users by concatenating or reassigning time slots based on priority.

1.4.1. Efficiency of TDMA:

It is a measure of the percentage of the percentage of transmitted data that contains information as opposed to providing overhead for the access scheme. The frame efficiency \( \eta_f \) is the percentage of bits per frame which contains transmitted data.

The frame efficiency can be found as follows. The number of overhead bits per frame is

\[
b_{OH} = N_r b_r + N_t b_p + N_t b_g + N_r b_g \tag{2}
\]

Where \( N_r \) is the number of reference burst per frame, \( N_t \) is the number of traffic bursts per frame, \( b_r \) is the number of overhead bits per reference burst, \( b_p \) is the number of overhead bits per preamble in each slot, and \( b_g \) is the number of equivalent bits in each guard time interval. The total number of bits per frame, \( b_T \) is

\[
b_T = T_f R \tag{3}
\]

where \( T_f \) is the frame duration and \( R \) is the channel bit rate. The frame efficiency is thus given as

\[
\eta_f = (1 - \frac{b_{OH}}{b_T}) \times 100\% \tag{4}
\]

1.4.2. Number of channels in TDMA system:

The number of TDMA channel slots that can be provided in a TDMA system is found by multiplying the number of TDMA slots per channel by the number of channels available and is given by
\[ N = \frac{m \cdot (B_{\text{tot}} - 2B_{\text{guard}})}{B_c} \] .................................(5)

Where \( m \) is the maximum number of TDMA users supported on each radio channel.

1.4.3. **Propagation considerations:**

In comparison to a FDMA system supporting the same user data rate, the transmitted data rate in a TDMA system is large by a factor equal to the number of users sharing the frequency band. This factor is 8 in the pan-European Global System for Mobile Communication and 3 in the digital advanced mobile phone service (D-AMPS) system. Thus the symbol duration is reduced by the same factor, and severe ISI results, at least in the cellular environment.

To illustrate, consider the example in which each user transmits 25 thousandsymbols per second. Assuming eight users per frequency band leads to a symbol duration of 5 μs. Even in the cordless application with delay spreads of up to 1 μs, an equalizer may be useful to combat the resulting interference between adjacentsymbols. In cellular systems, however, the delay spread of up to 20 μs introduces severe intersymbol interference spanning up to five symbol periods. As the delayspread often exceeds the symbol duration, the channel can be classified as frequency selective, emphasizing the observation that the channel affects different spectralcomponents differently. The intersymbol interference in cellular TDMA systems can be so severe that linear equalizers are insufficient to overcome its negative effects. Instead, morepowerful, nonlinear decision feedback or maximum-likelihood sequence estimationequalizers must be employed.

Furthermore, all of these equalizers require some information about the channel impulse response that must be estimated from the received signal by means of an embedded training sequence. Clearly, the trainingsequence carries no user data and, thus, wastes valuable bandwidth.

In general, receivers for cellular TDMA systems will be fairly complex. On the positive side of the argument, however, the frequency selective nature of the channelprovides some built-in diversity that makes transmission more robust to channel fading. The diversity stems from the fact that the multipath components of thereceived signal can be resolved at a resolution roughly equal to the symbol duration, and the different multipath components can be combined by the equalizer during the demodulation of the signal. To further improve robustness to channel
fading, coding, and interleaving, slow frequency hopping and antenna diversity can be employed as discussed in connection with FDMA.

1.4.4. Initial Channel Assignment:

In both FDMA and TDMA systems, channels should not be assigned to a mobile on a permanent basis. A fixed assignment strategy would be either extremely wasteful of precious bandwidth or highly susceptible to co-channel interference. Instead, channels must be assigned on demand. Clearly, this implies the existence of a separate uplink channel on which mobiles can notify the base station of their need for a traffic channel. This uplink channel is referred to as the random-access channel because of the type of strategy used to regulate access to it.

The successful procedure for establishing a call that originates from the mobile station is outlined in Figure 2.3. The mobile initiates the procedure by transmitting a request on the random-access channel. Since this channel is shared by all users in range of the base station, a random-access protocol, like the ALOHA protocol, has to be employed to resolve possible collisions. Once the base station has received the mobile’s request, it responds with an immediate assignment message that directs the mobile to tune to a dedicated control channel for the ensuing call setup. On completion of the call setup negotiation, a traffic channel (i.e., a frequency in FDMA systems or a time slot in TDMA systems) is assigned by the base station, and all future communication takes place on that channel. In the case of a mobile-terminating call request, the sequence of events is preceded by a paging message alerting the base station of the call request.

![Figure: 6 Mobile originating call establishments](image-url)
1.5. CODE DIVISION MULTIPLE ACCESS:

In code division multiple access (CDMA) systems, the narrowband message signal is multiplied by a very large bandwidth signal called the spreading signal. The spreading signal is a pseudo-noise sequence that has a chip rate which is orders of magnitudes greater than the data rate of the message.

All users in a CDMA system use the same carrier frequency and may transmit simultaneously. Each user has its own pseudorandom codeword which is approximately orthogonal to all other users codewords. The receiver performs a time correlation operation to detect only the specific desired code word. All other code words appear as noise due to decorrelation.

For the detection of the message signal, the receiver needs to know the codeword used by the transmitter. Each user operates independently with no knowledge of other users. In CDMA, the power of multiple users at a receiver determines the noise floor after decorrelation. If the power of each user within a cell is not controlled such that they do not appear equal at the base station receiver, then the near-far problem occurs.

![CDMA Diagram]

**Figure 7:** CDMA in which each channel is assigned a unique PN code which is orthogonal to PN codes used by other users.

The near-far problem occurs when many mobile users share the same channel. In general, the strongest received mobile signal will capture the demodulator at the base station. In CDMA, stronger received signal levels raise the noise floor at the base
station demodulators for the weaker signals, thereby decreasing the probability that weaker signals will be received.

To combat the near-far problem, power control is usually implemented in most CDMA systems. Power control is provided by each base station in a cellular system and assures that each mobile within the base station coverage area provides the same signal to the base station receiver. This solves the problem of a nearby subscriber overpowering the base station receiver and drowning out the signals of far away subscribers.

Power control is implemented at the base station rapidly sampling the radio signal strength indicator (RSSI) levels of each mobile and then spreading a power change command over the forward radio link. Despite the use of power control within each cell, out of cell mobiles provide interference which is not under the control of the receiving base station.

The features of CDMA are given as follows.

- Many users of CDMA systems share the same frequency. Either TDD or FDD may be used.
- CDMA has a soft capacity limit. Increasing the number of users in a CDMA system raises the noise floor in linear manner. Thus there is no absolute limit on the number of users in a CDMA system.
- Multipath fading may be substantially reduced because the signal is spread over a large spectrum.
- Channel data rates are very high in CDMA systems.
- Self jamming is a problem in CDMA systems. It arises from the fact that spreading the sequences of different users are not exactly orthogonal and hence during de-spreading nonzero contributions to the receiver decision static for a desired user arise from the transmission of other users in the system.
- The near-far problem occurs at a CDMA receiver if an undesired user has a high detected power as compared to the desired user.

1.5.1. Propagation Considerations:

Spread spectrum is well suited for wireless communication systems because of its built-in frequency diversity. As discussed, in cellular systems the delay spread measures several microseconds; hence, the coherence bandwidth of the channel is smaller than 1 MHz. Spreading rates can be chosen to exceed the coherence bandwidth such that the channel becomes frequency selective; that is, different
spectral components are affected unequally by the channel, and only parts of the signal are affected by fades.

Expressing the same observation in time domain terms, multipath components are resolvable at a resolution equal to the chip period and can be combined coherently, for example, by means of a RAKE receiver. An estimate of the channel impulse response is required for the coherent combination of multipath components. This estimate can be gained from a training sequence or by means of a so-called pilot signal.

Even for cordless telephone systems, operating in environments with sub-microsecond delay spread and corresponding coherence bandwidths of a few megahertz, the spreading rate can be chosen large enough to facilitate multipath diversity. If the combination of multipath components described is deemed too complex, a simpler, but less powerful, form of diversity can be used that de-correlates only the strongest received multipath component and relies on the suppression of other path components by the matched filter.

1.5.2. Multiple-Access Interference:

If it is possible to control the relative timing of the transmitted signals, such as on the downlink, the transmitted signals can be made perfectly orthogonal, and if the channel only adds white Gaussian noise, matched filter receivers are optimal for extracting a signal from the superposition of waveforms. If the channel is dispersive because of multipath, the signals arriving at the receiver will no longer be orthogonal and will introduce some multiple-access interference, that is, signal components from other signals that are not rejected by the matched filter. On the uplink, extremely tight synchronization between users to within a fraction of a chip period, which is defined as the inverse of the spreading rate, is generally not possible, and measures to control the impact of multiple-access interference must be taken. Otherwise, the near-far problem (i.e., the problem of very strong undesired users’ signals overwhelming the weaker signal of the desired user) can severely decrease performance. Two approaches are proposed to overcome the near-far problem: power control with soft handovers and multiuser detection.

Power control attempts to ensure that signals from all mobiles in a cell arrive at the base station with approximately equal power levels. To be effective, power control must be accurate to within about 1 dB and fast enough to compensate for channel fading. For a mobile moving at 55 mph and transmitting at 1 GHz, the Doppler
bandwidth is approximately 100 Hz. Hence, the channel changes its characteristic drastically about 100 times per second, and on the order of 1000 bps must be sent from base station to mobile for power control purposes.

As different mobiles may be subject to vastly different fading and shadowing conditions, a large dynamic range of about 80 dB must be covered by power control. Notice that power control on the downlink is really only necessary for mobiles that are about equidistant from two base stations, and even then neither the update rate nor the dynamic range of the uplink is required.

The interference problem that arises at the cell boundaries where mobiles are within range of two or more base stations can be turned into an advantage through the idea of soft handover. On the downlink, all base stations within range can transmit to the mobile, which in turn can combine the received signals to achieve some gain from the antenna diversity. On the uplink, a similar effect can be obtained by selecting the strongest received signal from all base stations that receive a user’s signal.

The base station that receives the strongest signal will also issue power control commands to minimize the transmit power of the mobile. Note, however, that soft handover requires fairly tight synchronization between base stations, and one of the advantages of CDMA over TDMA is lost.

Multiuser detection is still an emerging technique. It is probably best used in conjunction with power control. The fundamental idea behind this technique is to model multiple-access interference explicitly and devise receivers that reject or cancel the undesired signals. A variety of techniques has been proposed, ranging from optimum maximum likelihood sequence estimation via multistage schemes, reminiscent of decision feedback algorithms, to linear de-correlating receivers.

1.6. SPREAD SPECTRUM MULTIPLE ACCESS:

Spread spectrum multiple access (SSMA) uses signals which have a transmission bandwidth that is several orders of magnitude greater than the minimum required RF bandwidth. A pseudo-noise sequence converts a narrow band signal to a wide band noise like signal before transmission.

SSMA also provides immunity to multipath interference and robust multiple access capability. SSMA is not very bandwidth efficient when used by a single user. It
becomes bandwidth efficient when many users share the same spread spectrum bandwidth

There are two main types of spread spectrum multiple access techniques; frequency hopped multiple access (FH) and direct sequence multiple access (DH)

1.6.1. Frequency hopped multiple access:

Frequency hopped multiple access (FHMA) is a digital multiple access system in which the carrier frequencies of the individual users are varied in pseudo-random fashion within a wide band channel. The digital data is broken into uniform sized bursts which are transmitted on different carrier frequencies.

The instantaneous bandwidth of any one transmission burst is much smaller than the total spread bandwidth. The pseudo-random change of the carrier frequencies of the user randomizes the occupancy of the specific channel at any given time, thereby allowing for multiple access over a wide range of frequencies.

In the FH receiver a locally generated PN code is used to synchronize the receivers instantaneous frequency with that of the transmitter. At any given point in time a frequency hopped signal occupies only a single, relatively narrow channel since narrow band FM or FSK is used.

The difference between FHMA and traditional FDMA system is that the frequency hopped signal changes channels at rapid intervals. If the rate of change the carrier frequency is greater than the symbol rate then the system is referred to as fast frequency hopping system. If a channel changes at a rate less than or equal to the symbol rate then the system is referred to as a slow frequency hopping.

A fast frequency hopper may thus be thought of as an FDMA system which employs frequency diversity. FHMA systems often employ energy efficient constant envelope modulation.

A frequency hopped system provides a level of security, especially when a large number of channels are used, since an unintended receiver that does not know the pseudorandom sequence of frequency slots must retune rapidly to search for the signal it wishes to intercept.

In addition the FH signal is somewhat immune to fading, since error control coding and interleaving can be used to protect the frequency hopped signal against deep fades which may occasionally occur during the hopping sequence. Error control coding and interleaving can also be combined to guard against erasures which can occur when two or more users transmit on the same channel at the same time.
1.7. CELLULAR CONCEPT:

The design objective of early mobile radio systems was to achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower. While this approach achieved very good coverage, it also meant that it was impossible to reuse those same frequencies throughout the system, since any attempt to achieve frequency reuse would result in interference.

Owing to the very limited frequency bands, a mobile radio network only has a relatively small number of speech channels available. For example, the GSM system has an allocation of 25MHz bandwidth in the 900 MHz frequency range, which amounts to a maximum of 125 frequency channels each carrier with a carrier bandwidth of 200 KHz.

The cellular concept was a major breakthrough in solving the problem of spectral congestion and user capacity. If offered very high capacity in a limited spectrum allocation without any major technological challenges.

The cellular concept is a system level idea which calls for replacing a single high power transmitter with many low power transmitters each providing coverage to only a small portion of the total number of channels available to the entire system, and nearby base stations are assigned different group of channels so that the available channels are assigned to a relatively small number of neighbouring base stations. Neighbouring base stations are assigned different groups of channels so that the interference between base stations is minimized.

By systematically spacing base stations and their channel groups throughout a market, the available channels are distributed throughout the geographic region and may be re-used as many times as necessary, so long as the interference between co-channel stations is kept below acceptable levels.
Figure 8: Model of a cellular network with frequency reuse

As the demand for services increases, the number of base stations may be increased, thereby providing additional radio capacity with no additional increase in radio spectrum. This fundamental principle is the foundation for all modern wireless communication systems, since it enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region.

Furthermore, the cellular concept allows every piece of subscriber equipment within a country or continent to be manufactured with the same set of channels, so that any mobile may be used anywhere within the region.

1.7.1. Definitions:

The spatial frequency reuse concept led to the development of the cellular principle, which allowed a significant improvement in the economic use of frequencies. The essential characteristics of the cellular network principle are as follows.

- The area to be covered is subdivided into cells. These cells are often modelled in a simplified way as hexagons. The base station is located at the centre of each cell.
To each cell $i$ a subset of the frequencies $S_i$ is assigned from the total set (bundle) which is assigned to the respective mobile radio network. In the GSM system, the set $S_i$ of frequencies assigned to a cell is called the Cell Allocation (CA). Two neighbouring cells must never use the same frequencies, since this would lead to severe co-channel interference from the adjacent cells.

- Only at distance $D$ (the frequency reuse distance) can a frequency from the set $S_i$ be reused (Figure 2.13), i.e. cells with distance $D$ to cell $i$ can be assigned one or all of the frequencies from the set $S_i$ belonging to cell $i$. When designing a mobile radio network, $D$ must be chosen sufficiently large, such that the co-channel interference remains small enough not to affect speech quality.

- When a mobile station moves from one cell to another during an ongoing conversation, an automatic channel/frequency change occurs (handover), which maintains an active speech connection over cell boundaries.

The spatial repetition of frequencies is done in a regular systematic way, i.e. each cell with the cell allocation $S_i$ sees its neighbours with the same frequencies again at a distance $D$ (Figure 8). Therefore, there exist exactly six such next neighbour cells. Independent of form and size of the cells – not only in the hexagon model – the first ring in the frequency set contains six co-channel cells (Figure 9).

### 1.8. FREQUENCY REUSE:

**Figure:9 Frequency reuse and cluster information**
Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region. Each cellular base station is allocated a group of radio channels to be used within a small geographical area called a cell.

Base stations in adjacent cells are assigned channel groups which contain completely different channel than neighbouring cells. The base station antennas are designed to achieve the desired coverage within the particular cell. By limiting the coverage area, to within the boundaries of a cell, the same group of channels may be used to cover different cells that are separated from one another by distances large enough to keep interference levels within tolerable limits.

The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called frequency reuse or frequency planning.

The below figure shows the concept of cellular frequency reuse, where cells labelled with the same letter use the same group of channels. The hexagonal cell shape shown in the above figure is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system. The actual radio coverage of a cell is known as the footprint and is determined from field measurements or propagation prediction models.

![Cellular Frequency Reuse Diagram]

**Figure 10: Illustration of the cellular frequency reuse concept**

When considering geometric shapes which cover an entire region without overlap and with equal area, there are three sensible choices: a square; an equilateral
triangle; and a hexagon. A cell must be designed to serve the weakest mobiles within the footprint and these are typically located at the edge of a cell. For a given distance between the centre of a polygon and its farthest perimeter points, the hexagon has the largest area of the three. Thus by using the hexagon geometry, the fewest number of cells can cover a geographic region, and the hexagon closely approximates a circular radiation pattern which could occur for an omni-directional base station antenna and free space propagation. Of course, the actual cellular footprint is determined by the contour in which the given transmitter serves the mobiles successfully.

When using hexagons to model coverage areas, base station transmitters are depicted as either being in the centre of the cell (centre excited cells) or on three of the six cell vertices (edge-excited cells). Normally omni-directional antennas are used in centre-excited cells and sectored directional antennas are used in corner-excited cells.

Practical considerations usually do not allow base stations to be placed exactly as they appear in the hexagonal layout. Most system designs permit a base station to be positioned up to one-fourth the cell radius away from the ideal location.

To understand the frequency reuse concept, consider a cellular system which has a total of $S$ duplex channels available for use. If each cell is allocated a group of $k$ channels ($k<S$), and if the $S$ channels are divided among $N$ cells into unique and disjoint channel groups which each have the same number of channels, the total number of available radio channels can be expressed as

$$S = kN \text{ .................................................(6)}$$

The $N$ cells which collectively use the complete set of available frequencies is called a cluster. If a cluster is replicated $M$ times within the system, the total number of duplex channels, $C$ can be used as a measure of capacity and is given

$$C = MkN = MS \text{ .................................................(7)}$$

As seen from the above equation the capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area. The factor $N$ is called the cluster size and is typically equal to 4, 7 or 12. If the cluster size $N$ is reduced while the cell size is kept constant, more clusters are required to cover a given area and hence more capacity is achieved.

A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is large. Conversely, a small cluster size indicates
that co-channel cells are located much closer together. The value for \( N \) is a function of how much interference a mobile or base station can tolerate while maintaining a sufficient quality of communications.

From a design viewpoint, the smallest possible value of \( N \) is desirable inorder to maximize capacity over a given coverage area.

The frequency reuse factor of a cellular system is given by \( 1/N \) since each cell within a cluster is only assigned \( 1/N \) of the total available channels in the system. Due to the fact that the hexagonal geometry has exactly six equidistant neighbours are separated by multiples of 60 degrees, there are only certain cluster sizes and cell layouts which are possible.

Inorder to tessellate to connect without gaps between adjacent cells the geometry of hexagons is such that the number of cells per cluster \( N \) can only have values which satisfy equation

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

where \( i \) and \( j \) are non-negative integers. To find the nearest co-channel neighbours of a particular cell we must do the following:

Move \( i \) cells along any chain of hexagons and then turn 60 degrees counter-clockwise and move \( j \) cells. This is shown in figure below for \( i=3 \) and \( j=2 \).
1.9. CHANNEL ASSIGNMENT STRATEGIES:

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required. A variety of channel assignment strategies have been developed to achieve these objectives. Channel assignment strategies can be classified as either fixed or dynamic. The choice of channel assignment strategy impacts the performance of the system.

In a fixed channel assignment strategy each cell is allocated a predetermined set of voice channels. Any call attempt with the cell can only be served by the unused channels in that particular cell. If all the channels in that cell are occupied, the call is blocked and the subscribers do not receive service. Several variations of fixed channel strategies exist. In the first approach called the borrowing strategy. A cell is allowed to borrow channels from a neighbouring cell if all of its own channels are already occupied. The mobile switching centre (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disturb or interfere with any of the calls in progress in the donor cell.

In a dynamic channel assignment strategy voice channels are not allocated to different cells permanently. Instead of that each time when a call request is made, the serving base station requires a channel from the MSC. The switch then allocates a channel to the requested cell following an algorithm that takes into account the likelihood of future blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel and other cost functions.

Accordingly, the MSC only allocates a given frequency if that frequency is not presently in use in the cell or any other cell which falls within the minimum restricted distance of frequency reuse to avoid co-channel interference. Dynamic channel assignment reduce the chance of call blocking which increases the trunking capacity of the system, since all the available channels in a market are accessible to all of the cells. Dynamic channel assignment strategies require the MSC to collect real time data on channel occupancy, traffic distribution and radio signal strength indicators (RSSI) of all channels on a continuous basis. This increases the storage and computational load on the system but provides the advantage of increased channel utilization and decreased probability of a blocked call.
1.10. HANDOFF STRATEGY:

When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station. This handoff operation not only involves identifying a new base station, but also requires that the voice and control signals be allocated to channels associated with the new base station.

Processing handoffs is an important task in any cellular radio system. Many handoff strategies prioritize handoff requests over call initiation requests when allocating unused channels in a cell site. Handoffs must be performed successfully and as infrequently as possible, and be imperceptible to the users.

In order to meet these requirements, system designers must specify an optimum signal level at which to initiate a handoff. Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver, a slightly stronger signal is used as a threshold at which a handoff is made. This margin given by $\Delta = P_{r\text{handoff}} - P_{r\text{minimum usable}}$, cannot be too large or too small. If $\Delta$ is too large, unnecessary handoffs which burden the MSC may occur and if $\Delta$ is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions.
Therefore $\Delta$ is chosen carefully to meet these conflicting requirements. The figure 12 illustrates a handoff situation. The figure 12(a) demonstrates the case where a handoff is not made and the signal drops below the minimum acceptable level to keep the channel active. This dropped call event can happen when there is an excessive delay by the MSC in assigning a handoff or when the threshold $\Delta$ is set too small for the handoff time in the system.

Excessive delays may occur during high traffic conditions due to computational loading at the MSC or due to the fact that no channels are available on any of the nearby base stations.

In deciding when to handoff, it is important to ensure that the drop in the measured signal level is not due to momentary fading and that mobile is actually moving away from the serving base station. In order to ensure this, the base station monitors the signal level for a certain period of time before a handoff is initiated. This running average measurement of signal strength should be optimized so that...
unnecessary handoffs are avoided, while ensuring that necessary handoffs are completed before a call is terminated due to poor signal level.

The length of time needed to decide if a handoff is necessary depends on the speed at which the vehicle is moving. If slope of the short-term average received signal level in a given time interval is steep, the handoff should be made quickly. Information about the vehicle speed which can be useful in handoff decisions can also be computed from the statistics of the received short time fading signal at the base station.

The time over which a call may be maintained within a cell, without a handoff is called the dwell time. The dwell time of a particular user is governed by a number of factors which include propagation, interference, distance between the subscriber and the base station and other time varying effects.

1.10.1. Network –Controlled Handoff:

In network-controlled handoff, each base station monitors the signal strength received from mobiles in their cells and makes periodic measurements of the received signal from mobiles in their neighbouring cells. The MSC then initiates and completes the handoff of a mobile as and when it decides. The decision is based on the received signal strength at the base station serving the mobiles and base stations in neighbouring cells. Because of its centralized nature, the collection of these measurements generates large network traffic. This could be reduced to an extent by making measurements less frequently and by not requiring the neighbouring base station to send the measurements continually. However, this reduces accuracy. The execution of handoff by this method takes a few seconds, and for this reason the method is not preferred by microcellular systems where a quick handoff is desirable.

1.10.2. Mobile-Controlled Handoff:

Mobile-controlled handoff is a highly decentralized method and does not need any assistance from the MSC. In this scheme, a mobile monitors signal strength on its current channel and measures signals received from the neighbouring base stations. It receives BER and signal strength information about uplink channels from its serving base stations. Based on all this information, it initiates the handoff process by requesting the neighbouring base for allocation of a low-interference channel. The method has a handoff execution time on the order of 100 ms and is suitable for microcell systems.

1.10.3. Mobile-Assisted Handoff:
In MAHO methods, as the name suggests, a mobile helps the network in the handoff decision making by monitoring the signal strength of its neighbouring base stations and passing the results to the MSC via its serving base station. The handoff is initiated and completed by the network. The execution time is on the order of 1 s.

1.10.4. Hard Handoff and Soft Handoff:

Handoff may be classified into hard handoff and soft handoff. During hard handoff, the mobile can communicate only with one base station. The communication link gets broken with the current base station before the new one is established, and there is normally a small gap in communication during the transition. In the process of soft handoff, the mobile is able to communicate with more than one base station. It receives signals from more than one base station, and the received signals are combined after appropriate delay adjustment. Similarly, more than one station receives signals from mobiles, and the network combines different signals. This scheme is also known as macroscopic diversity and is mostly employed by CDMA systems. Hard handoff, on the other hand, is more appropriate for TDMA and FDMA systems. It is also simple to implement compared with soft handoff.

However it may lead to unnecessary handoff back and forth between two base stations when the signals from two base stations fluctuate. The situation may arise when a mobile, currently being served, for example, by base 1 receives a stronger signal from, say, base 2 and is handed over to base 2. Immediately after that, it receives a stronger signal from base 1 compared to what it receives from base 2, causing a handoff. This phenomenon, known as the ping-pong effect, may continue for some time and is undesirable because every handoff has a cost associated with it, requiring network signalling of varying amount for authentication, database updates, and circuit switching, and so on. This is avoided by using a hysteresis margin such that the handoff is not initiated until the difference between the signals received from the two base stations is more than the margin. For example, if the margin is $\Delta dB$, then the handoff is initiated when the signal received by the mobile from base 2 is $\Delta dB$ more than that from base 1.

1.11. INTERFERENCE AND SYSTEM CAPACITY:

Interference is the major limiting factor in the performance of cellular radio systems. The various sources of interference include another mobile in the same cell, a call in progress in a neighbouring cell, other base stations operating in the same
frequency band, or any non-cellular system which involuntarily leaks energy into the cellular frequency band.

Interference results in cross talks. On control channels interference leads to missed and blocked calls due to errors in digital signalling. Interference has become a blockage in increasing the capacity and is often responsible for dropped calls. The two major types of system generated interference are co-channel interference and adjacent channel interference. Even though the interference are generated within the cellular system they are very difficult to control in practice due to random propagation effects. Practically out of band interference results due to the close proximity of base stations to provide comparable coverage to customers.

1.11.1 Co-channel interference and system capacity:

Co-channels are the cells that use the same set of frequencies in a given coverage area and the interference resulting from these cells are called as co-channel interference. Co-channel interference cannot be combated by increasing the carrier power of the transmitter. Increasing the transmitter power induces interference in the neighbouring cells. To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation.

When the size of each cell is approximately the same, and the base stations transmit the same power, the co-channel interference ratio is independent of the transmitted power and becomes a function of the radius of the cell (R) and the distance between the centres of the nearest co-channel cells (D). By increasing the ratio D/R, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased. Thus interference is reduced from improved isolation of RF energy from the co-channel cell. The parameter called the co-channel reuse ratio (Q) is related to the cluster size. For a hexagonal geometry

\[ Q = \frac{D}{R} = \sqrt{3}N \] ................................(9)

A small value of Q provides larger capacity since the cluster size N is small, whereas a large value of Q improves the transmission quality due to a smaller level of co-channel interference. A trade-off must be made between these two objectives in actual cellular design.

<table>
<thead>
<tr>
<th>i=1, j=1</th>
<th>CLUSTER SIZE (N)</th>
<th>CO-CHANNEL REUSE RATIO (Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>i=1, j=2</td>
<td>7</td>
<td>4.58</td>
</tr>
</tbody>
</table>
Table 2: Co-channel reuse ratio for some values of N

<table>
<thead>
<tr>
<th>i, j</th>
<th>12</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,3</td>
<td>13</td>
<td>6.24</td>
</tr>
</tbody>
</table>

Let $i_0$ be the number of co-channel interfering cells. Then the signal to interference ratio (S/I or SIR) for a mobile receiver which monitors a forward channel can be expressed as

$$S/I = S/\sum_{i=1}^{i_0} I_i$$  \hspace{1cm} (10)

where $S$ is the desired signal power from the desired base station and $I_i$ is the interference power caused by the $i$th interfering co-channel cell base station. If the signal levels of co-channel cells are known then the S/I ratio for the forward link can be found using the above equation.

Propagation measurements in a mobile radio channel slow the average received signal strength at any point decays as a power law of the distance of separation between a transmitter and a receiver. The average received power $P_r$ at a distance $d$ from the transmitting antenna is approximated by

$$P_r = P_o (d/d_0)^{-n}$$  \hspace{1cm} (11)

Or

$$P_r (dBm) = P_o (dBm) - 10 n \log (d/d_0)$$  \hspace{1cm} (12)

where $P_o$ is the power received at a close in-reference point in the far field region of the antenna at a small distance $d_0$ from the transmitting antenna, and $n$ is the path loss exponent.

When the transmit power of each base station is equal and the path loss exponent is the same throughout the coverage region, S/I for a mobile can be approximated as

$$S/I = R^{-n}/\sum_{i=1}^{i_0} (D_i)^{-n}$$  \hspace{1cm} (13)

Considering only the first layer of interfering cells, if all the interfering base stations are equidistant from the desired base station and if the distance is equal to the distance $D$ between cell centres the above equation simplifies to

$$S/I = (D/R)^n/i_0 = (\sqrt{3N})^n/i_0$$  \hspace{1cm} (14)

The above equation relates S/I to the cluster size $N$, which in turn determines the overall capacity of the system from equation (7).

1.11.2. Adjacent channel interference:

Interference resulting from signals which are adjacent in frequency to the desired signal is called adjacent channel interference. Adjacent channel interference
results from imperfect receiver filters which allow nearby frequencies to leak into the passband.

The problem can be particularly serious if an adjacent channel user is transmitting in very close range to a subscriber’s receiver, while the receiver attempts to receive a base station on the desired channel. This is referred to as the near-far effect, where a near-by transmitter captures the receiver of the subscriber.

Alternatively, the near-far effect occurs when a mobile close to a base station transmits on a channel close to one being used by a weak mobile. The base station may have difficulty in discriminating the desired mobile user from the bleedover caused by the close adjacent mobile.

Adjacent channel interference can be minimized through careful filtering and channel assignments. Since each cell is given only a fraction of the available channels, a cell need not be assigned channels which are all adjacent in frequency. By keeping the frequency separation between each channel in a given cell as large as possible, the adjacent channel interference may be reduced considerably. Thus instead of assigning channels which form a contiguous band of frequencies within a particular cell, channels are allocated such that the frequency separation between channels in a given cell is maximized.

By sequencing assigning successive channels in the frequency band to different cells, many channel allocation schemes are able to separate adjacent channels in a cell by as many as N channel bandwidths, where N is the cluster size.

If the frequency reuse factor is small, the separation between adjacent channels may not be sufficient to keep the adjacent channel interference level within tolerable limits.

For example if a mobile is 20 times as close to the base station as another mobile and has energy spill out of its pass band, the signal to interference ratio for the weak mobile is approximately

\[ S/I = (20)^{-n} \] ........................................ (15)

For a path loss exponent \( n=4 \), this is equal to -52 dB. If the intermediate frequency (IF) filter of the base station receiver has a slope of 20 dB/octave, then an adjacent channel interference must be displaced by at least six times the pass band bandwidth from the centre of the receiver frequency passband to achieve 52 dB attenuation. Here a separation of approximately six channel bandwidth is required for typical filters inorder to provide 0dB SIR from a close-in adjacent channel user.
This implies that a channel separation greater than six is needed to bring the adjacent channel interference to an acceptable level, or tighter base station filters are needed when close-in and distant users share the same cell. In practice, each base station receiver is preceded by a high Q cavity filter inorder to reject adjacent channel interference.

1.11.3. Power control for reducing interference:

In practical radio systems the power level transmitted by every subscriber unit are under constant control by the serving base stations. This is done to ensure that each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel.

Power control not only helps prolong battery life for the subscriber unit but also dramatically reduces the reverse channel S/I in the system

1.12. TRUNKING AND GRADE OF SERVICE:

Cellular radio systems rely on trunking to accommodate a large number of users in a limited radio spectrum. The concept of trunking allows a large number of users to share the relatively small number of channels in a cell by providing access to each user, on demand from a pool of available channels.

In a trunked radio system, each user is allocated a channel on a per call basis, and upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels.

Trunking exploits the statistical behaviour of users so that a fixed number of channels or circuits may accommodate a large random user community. The trunking theory is used to determine the number of telephone circuits that needed to be allocated for office buildings with hundreds of telephones, and the same principle is used in designing cellular radio systems.

There is a trade-off between the number of available telephone circuits and the likelihood of a particular user finding that no circuits are available during the peak calling time. As the number of phone line decreases, it becomes more likely that all circuits will be busy for a particular user.

In a trunked mobile radio system when a particular user request service and all of the radio channels are already in use, or the user is blocked, or denied access to the system. In some systems a queue may be used to hold the requesting users until a channel becomes available.
To design trunked radio systems that can handle a specific capacity at a specific grade of service is essential to understand trunking theory and queuing theory. The fundamentals of trunking theory were explained by Erlang. Today the measure of the traffic intensity bears his name.

On Erlang represents the amount of traffic intensity carried by a channel that is completely occupied. For example a radio channel that is continuously occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic.

The grade of service (GOS) is the measure of the ability of a user to access a trunked system during the busiest hour during a week, month or year. The grade of service is a bench mark used to define the desired performance of a particular trunked system by specifying a desired likelihood of a user obtaining channel access given a specific number of channels available in the system. GOS is typically given as the likelihood that a call is blocked or the likelihood of a call experiencing a delay greater than a certain queuing time.

A number of definitions are listed below are used in trunking theory to make capacity estimates in trunked systems.

**Set-up time**: the time required to allocate a trunked radio channel to a requesting user

**Blocked call**: Call which cannot be completed at time of request, due to congestion. Also referred to as lost call.

**Holding time**: average duration of a typical call and is denoted by \( H \) in seconds.

**Traffic intensity**: Measure of channel time utilization, which is average channel occupancy measured in Erlangs. This is a dimensionless quantity and may be used to measure the time utilization of single or multiple channels and is denoted by \( A \).

**Load**: Traffic intensity across the entire trunked radio system, measured in Erlangs.

**Grade of service**: a measure of congestion which is specified as the probability of a call being blocked, or the probability of a call being delayed beyond a certain amount of time.

**Request rate**: The average number of call requests per unit time and is denoted by \( \lambda \) seconds\(^{-1}\)

The traffic intensity offered by each user is equal to the call request rate multiplied by the holding time. That is each user generates a traffic intensity of \( Au \) Erlangs given by

\[
Au = \lambda H \quad \text{.................................................. (16)}
\]
where $H$ is the average duration of a call and $\lambda$ is the average number of call request per time. For a system containing $U$ users and an unspecified number of channels, the total offered traffic intensity $A$ is given as

$$A = UAu \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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The second type of trunked system is one in which a queue is provided to hold calls which are blocked. If a channel is not available immediately, the call request may be delayed until a channel becomes available. This type of trunking is called blocked calls delayed and its measure of GOS is defined as the probability that after a call is blocked after waiting a specific length of time in queue. To find the GOS, it is first necessary to find the likelihood that a call is initially delayed access to the system.

The likelihood of a call not having immediate access to a channel is determined by the Erlang C formula given by

\[ Pr[\text{delay}>0] = \frac{A^C}{A^C+C!(1-\frac{A}{C})\sum_{k=0}^{C-1} \frac{A^k}{k!}} \] ...........................(20)

If no channels are immediately available the call is delayed, and the probability that a delayed call is forced to wait more than t seconds is given by the probability that a call is delayed, multiplied by the conditional probability that the delay is greater than t seconds. The GOS of a trunked system where blocked calls are delayed is hence given by

\[ Pr[\text{delay}>t] = Pr[\text{delay}>0] Pr[\text{delay}>t/\text{delay}>0]......(21) \]

\[ = Pr[\text{delay}>0]\exp(-(C-A)t/H) \]

The average delay D for all calls in a queued system is given by

\[ D = Pr[\text{delay}>0] = \frac{H}{C-A} \] .................................(22)

where the average delay for those calls which are queued is given by \( \frac{H}{C-A} \)

**1.13. IMPROVING CAPACITY IN CELLULAR SYSTEMS:**

As the demand for wireless service increases, the number of channels assigned to a cell eventually becomes insufficient to support the required number of users. At this point, cellular design techniques are needed to provide more channels per unit coverage area.

Techniques such as cell splitting, sectoring and coverage zone approaches are used in practice to expand the capacity of cellular systems. Cell splitting allows an orderly growth of the cellular system. Sectoring uses directional antennas further to control the interference and frequency reuse of channels. The zone microcell concept distributes the coverage of a cell and extends the cell boundary to hard-to-reach places. While cell splitting increases the number of base stations in order to increase capacity, sectoring and zone microcells rely on base station antenna placements to
improve capacity by reducing co-channel interference. Cell splitting and zone microcell techniques do not suffer the trunking inefficiencies experienced by sectored cells, and enable the base station to oversee all handoff chores related to the microcells, thus reducing the computational load at MSC.

1.13.1. Cell splitting:
Cell splitting is the process of subdividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna height and transmitter power.

Cell splitting increases the capacity of a cellular system since it increases the number of times that channels are reused. By defining new cells which have a smaller radius than the original cells and by installing these smaller cells between the existing cells, capacity increases due to the additional number of channels per unit area.

In order to cover the entire service area with smaller cells, approximately four times as many cells would be required. This can be easily shown by considering a circle with radius R. The area covered by such a circle is four times as large as the area covered by a circle with radius R/2. The increased number of cells would increase the number of clusters over the coverage region, which in turn would increase the number of channels and thus capacity in the coverage area. Cell splitting allows a system to grow by replacing large cells with smaller cells, while not upsetting the channel allocation scheme required to maintain a minimum co-channel reuse ratio Q between co-channel cells.

An example of cell splitting is shown in figure below. Here the base stations are placed at the corners of the cells, and the area served by the base station A is assumed to be saturated with traffic. New base stations are therefore needed on the region to increase the number of channels in the area and to reduce the area served by the single base station.

In the figure given below, the original base station A has been surrounded by six new microcell base stations. The smaller cells were added in such a way as to preserve the frequency reuse plan of the system.

For example the microcell base station labelled G was placed halfway between two large base stations utilizing the same channel set G. This is also the case for other microcells. Cell splitting merely scales the geometry of the cluster. In this case, the radius of each new microcell is half that of the original cell.
For the new cells to be smaller in size, the transmit power of these cells must be reduced. The transmit power of the new cells with radius half that of the original cells can be found by examining the received power $Pr$ at the new and old cell boundaries and setting them equal to each other. This is necessary to ensure that the frequency reuse plan for the new microcells behaves exactly as for the original cells.

From the above figure,

$$Pr \text{ [at old cell boundary ] } \propto P_{t1} R^{-n} \text{.................................. (23)}$$

and

$$Pr \text{ [at new cell boundary ] } \propto P_{t2}(R/2)^{-n} \text{..................(24)}$$

where $P_{t1}$ and $P_{t2}$ are the transmit powers of the larger and smaller cell base stations, respectively and $n$ is the path loss exponent. If we take $n=4$ and set the received powers equal to each other, then

$$P_{t2} = \frac{P_{t1}}{16} \text{.................................................................(25)}$$
In other words the transmit power must be reduced by 12 dB inorder to fill in the original coverage area with microcells while maintaining S/I requirement.

In practice not all cells are split at the same time. The two channel group sizes depend on the stage of the splitting process. At the beginning of the cell splitting process there will be fewer channels in the small power groups. However as demand grows more channels will be required, and thus the smaller groups will require more channels.

Figure 14: Illustration of cell splitting within a 3 km by 3 km square centered around base station A

The splitting process continues until all the channels in an area are used in the lower power group, at which point cell splitting is complete within the region, and the entire system is rescaled to have a smaller radius per cell.

Antenna downtilting, which deliberately focuses radiated energy from the base station towards the ground is often used to limit the radio coverage of newly formed microcells.

1.13.2. Cell sectoring:
Cell splitting achieves capacity improvement by essentially rescaling the system. By decreasing the cell radius $R$ and keeping the co-channel reuse ratio $d/R$ unchanged, cell splitting increases the number of channels per unit area.

However another way to improve capacity is to keep the cell radius unchanged and seek the methods to decrease the $D/R$ ratio. In this approach capacity improvement is achieved by reducing the number of cells in a cluster and thus increasing the frequency reuse. In order to do this it is necessary to reduce the relative interference without decreasing the transmit power.

The co-channel interference in a cellular system may be decreased by replacing a single omni-directional antenna at the base station by several directional antennas each radiating within a specific sector. By using directional antennas, a given cell will receive interference and transmit with only a fraction of the available co-channel cells. The technique for decreasing co-channel interference and thus increasing system capacity by using directional antennas is called sectoring. The factor by which the co-channel interference is reduced depends on the amount of sectoring used. A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in figure 15 (a) and (b).
When sectoring is employed, the channels used in a particular cell are broken down into sectored groups and are used only within a particular sector as shown in figure above. Assuming 7-cell reuse, for the case of 120° sectors, the number of interferers in the first tire is reduced from 6 to 2. This is because only 6 of the two co-channel cells receive interference with a particular sectored channel group.
Figure 16: Illustration of how 120° sectoring reduces interference from co-channel cells.

Referring to the above figure consider the interference experienced by a mobile located in the right most sector in the centre cell labelled 5. There are three co-channel cell sectors labelled 5 to the right of the centre cell and 3 to the left of the centre cell. Out of these 6 co-channel cells only 2 cells have sectors with antenna patterns which radiate into the centre cell, and hence a mobile in the centre cell will experience interference on the forward link from only these two sectors. The resulting S/I for this case can be found using equation (13) to be 24.2 dB, which is a significant improvement in the omni-directional case.

In practical systems, further improvement in S/I is achieved by downtilting the sectored antennas such as the radiation pattern in the vertical plane has a notch at the nearest co-channel cell distance. The improvement in S/I implies that with
120° sectoring the minimum required S/I of 18 dB can be easily achieved with 7-cell reuse as compared to 12-cell reuse for the worst possible situation in the un-sectored case. Thus sectoring reduces interference, which amounts to an increase in capacity by a factor of 12/7 or 1.714.

In practice the reduction in interference offered by sectoring enable planners to reduce the cluster size $N$, and provides an additional degree of freedom in assigning channels. The penalty for improved S/I and the resulting capacity improvement is an increased number of antennas at each base station, and a decrease in trunking efficiency due to channel sectoring at the base station.

Since sectoring reduces the coverage area, of a particular group of channels, the number of handoffs increases, as well.

A novel microcell zone concept:

The increased number of handoffs required when sectoring is employed results in an increased load on the switching and control link elements of the mobile system. A solution for this problem is proposed based on a microcell concept for 7-cell reuse as shown in figure below.

![Figure 17: The microcell concept](image)

In this scheme each of three zone sites are connected to a single base station and share the same radio equipment. These zones are connected by co-axial cables,
optical fibre or microwave link to the base station. Multiple zones and a single base station make up a cell. As the mobile travels within the cell, it is served by the zone with the strongest signal. This approach is superior to sectoring since antennas are placed at the outer edges of the cell, and any base station channel may be assigned to any zone by the base station.

As a mobile travels from one zone to another within a cell, it retains the same channel. Thus unlike in sectoring, a handoff is not required at the MSC when the mobile travels between zones within the cell. The base station simply switches the channel to a different zone site. In this way a given channel is active only in the particular zone in which the mobile is travelling and hence the base station radiation is localized and interference is reduced. The channels are distributed in time and space by all three zones and are also reused in co-channel cells in normal fashion. This technique is used particularly used along highways or urban traffic corridors.

The advantage of cell zone technique is that while the cell maintains a particular coverage radius, the co-channel interference in the cellular system is reduced since a large central base station is replaced by several low powered transmitters on the edges of the cell.

Decreased co-channel interference improves the signal quality and also leads to an increase in capacity, without the degradation in trunking efficiency caused by sectoring. With respect to the zone microcell system, since transmission at any instant is restricted to a particular zone, this implies that a $\frac{D_z}{R_z}$ can achieve the link performance.

Dz – Minimum distance between active co-channel zones.
Rz – Zone radius.