UNIT II

CELLULAR ARCHITECTURE

Multiple Access techniques -FDMA, TDMA, CDMA –Capacity calculations–Cellular concept-Frequency reuse -channel assignment-hand off-interference & system capacity-trunking & grade of service –Coverage and capacity improvement.

Fundamentals of Cellular Systems

- **Subscriber** – Mobile or portable user.
- **Base stations** – Link mobiles through a backbone network.
- **Simplex** – Communication is possible only in one direction, (e.g., paging systems).
- **Half Duplex** – Two way communication, but uses the same radio channel for both transmission and reception. (User can only transmit or receive information. Eg: Walkie-talkies)
- **Full Duplex** – Simultaneous two-way radio transmission and reception between subscriber and base station. (Eg: Cellphones and cordless phones)

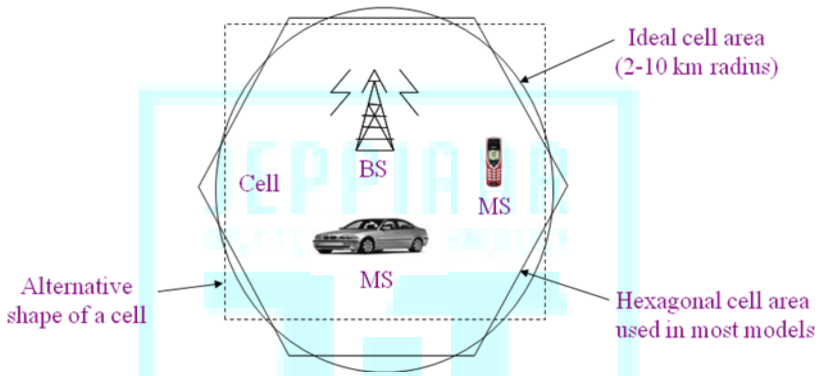


Illustration of a Cell with a Mobile Station and a Base Station

Base Station (BS):

A network element that interconnects the mobile station (or Mobile unit (MU)) to the network via the air interface. Each cell in the network has a BS associated with it. The primary function of a BS is to maintain the air interface, or medium, for communication to any mobile unit within its cell. Other functions of BS are call processing, signaling, maintenance, and diagnostics.

Mobile Units (MU):

Also called Mobile Systems (MS) or Mobile Hosts (MH). It consists of three components: (a) transceiver, (b) antenna, and (c) user interface. The user interface exists only at MU, which consists of a display, a keypad for entering information, and an audio interface for speaking and hearing voice conversation. This can be a laptop, a palmtop, or a cell phone, or any other mobile device. A MU also stores (a) Mobile Identification Number (MIN), (b) Electronic Serial Number (EIN), and (C) Station Class Mark (SCM). These are transmitted upon power on, cell initiated sampling, and cell origination.

Functions of Cellular System

- Provides wireless connection to the PSTN for any user location within the radio range of the system.
- High capacity is achieved:

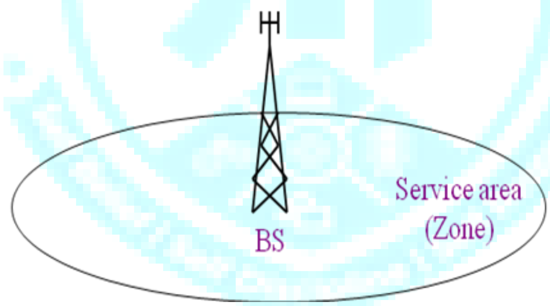
- By limiting the coverage of each base station transmitter to a small geographical area called a cell, and
- By reusing the same radio channels in another base station located some distance away – Frequency reuse.
- Switching system, called handoff, enables call to proceed uninterrupted when the user moves from one cell to another.
- Typical MSC handles 100,000 cellular users and 5,000 simultaneous conversations at a time.

Why 800 MHz frequency is selected for mobiles?

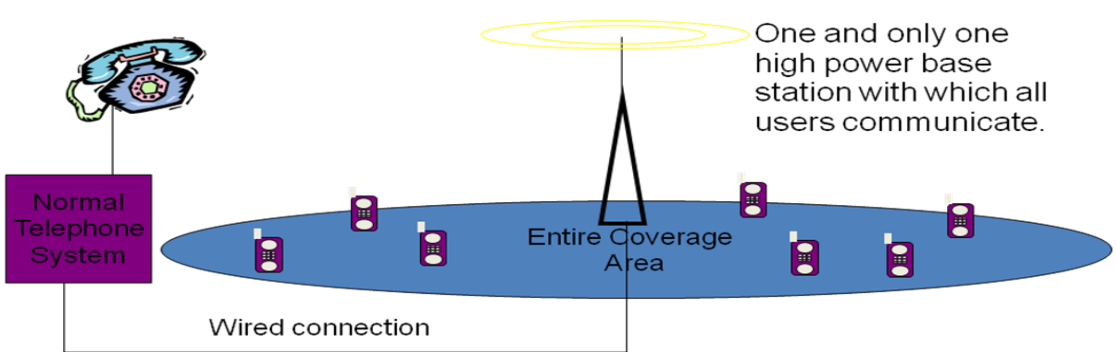
Fixed Station Services	-	30 MHz to 100 MHz
Television Broadcasting	-	41 MHz to 960 MHz
FM Broadcasting	-	100 MHz
Air to Ground system	-	118 MHz to 136 MHz
Maritime mobile services	-	160 MHz
Military Aircraft use	-	225 MHz to 400 MHz

Frequency bands between 30 MHz to 400 MHz is crowded with large number of services and above 10 GHz is not used due to propagation path loss, multipath fading and improper medium due to rain activity. So 800 MHz is chosen for mobile communication
First Mobile Telephone System

Cellular System Infrastructure



Early wireless system: Large zone



Problem with Original Design

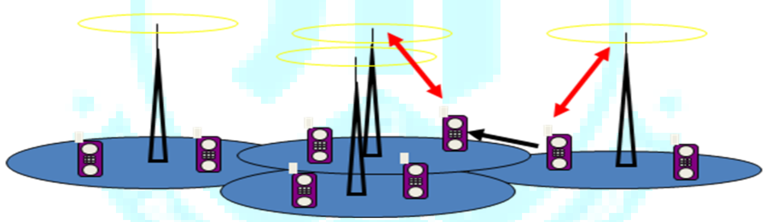
- Original mobile telephone system could only support a handful of users at a time…over an entire city!
- With only one high power base station, user's phones also needed to be able to transmit at high powers (to reliably transmit signals to the distant base station).
- Car phones were therefore much more feasible than handheld phones, e.g., police car phones.

Improved Design

- Over the next few decades, researchers at AT&T Bell Labs developed the core ideas for today's cellular systems.
- Although these core ideas existed since the 60's, it was not until the 80's that electronic equipment become available to realize a cellular system.
- In the mid 80's the first generation of cellular systems was developed and deployed.

The Core Idea: Cellular Concept

- The core idea that led to today's system was the cellular concept.
- The cellular concept: multiple lower-power base stations that service mobile users within their coverage area and handoff users to neighboring base stations as users move. Together base stations tessellate the system coverage area.



Cellular Concept

- Thus, instead of one base station covering an entire city, the city was broken up into cells, or smaller coverage areas.
- Each of these smaller coverage areas had its own lower-power base station.
- User phones in one cell communicate with the base station in that cell.

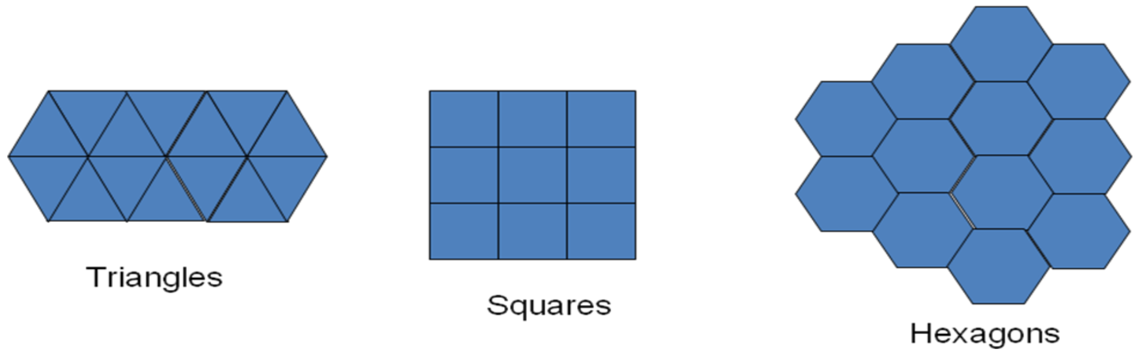
3 Core Principles

- Small cells tessellate overall coverage area.
- User's handoff as they move from one cell to another.
- Frequency reuse.

Tessellation

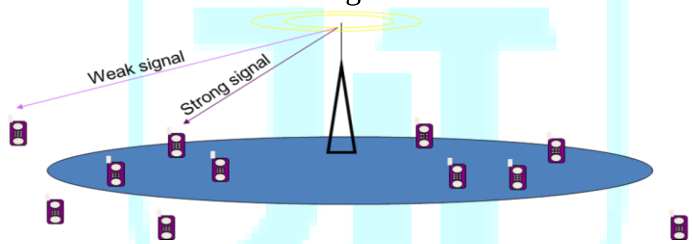
- Some groups of small regions tessellate a large region if they over the large region without any gaps or overlaps.
- There are only three regular polygons that tessellate any given region.
- Three regular polygons that always tessellate:

- Equilateral triangle
- Square
- Regular Hexagon



Circular Coverage Areas

- Original cellular system was developed assuming base station antennas are omnidirectional, i.e., they transmit in all directions equally.
- Users located outside some distance to the base station receive weak signals.
- Result: base station has circular coverage area.

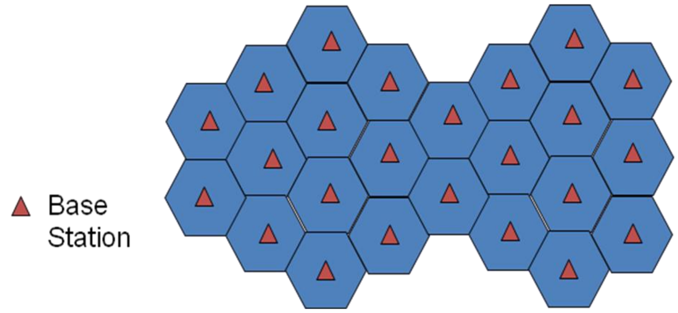


Circles Don't Tessellate

- Thus, ideally base stations have identical, circular coverage areas.
  Problem: Circles do not tessellate.
- The most circular of the regular polygons that tessellate is the hexagon.
- Thus, early researchers started using hexagons to represent the coverage area of a base station, i.e., a cell.

Thus the Name Cellular

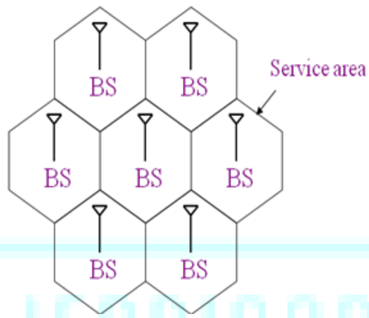
- With hexagonal coverage area, a cellular network is drawn as:
- Since the network resembles cells from a honeycomb, the name cellular was used to describe the resulting mobile telephone network.



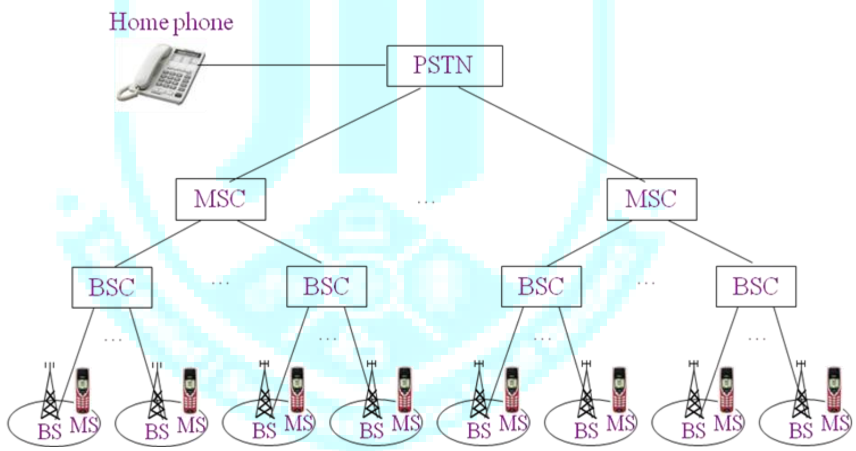
Choices of Hexagonal Cell Factors:

- Equal area
- No overlap between cells

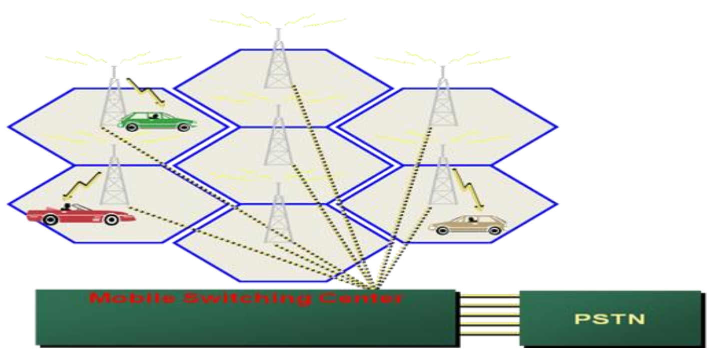
Cellular System: Small Zone



MS, BS, BSC, MSC, and PSTN



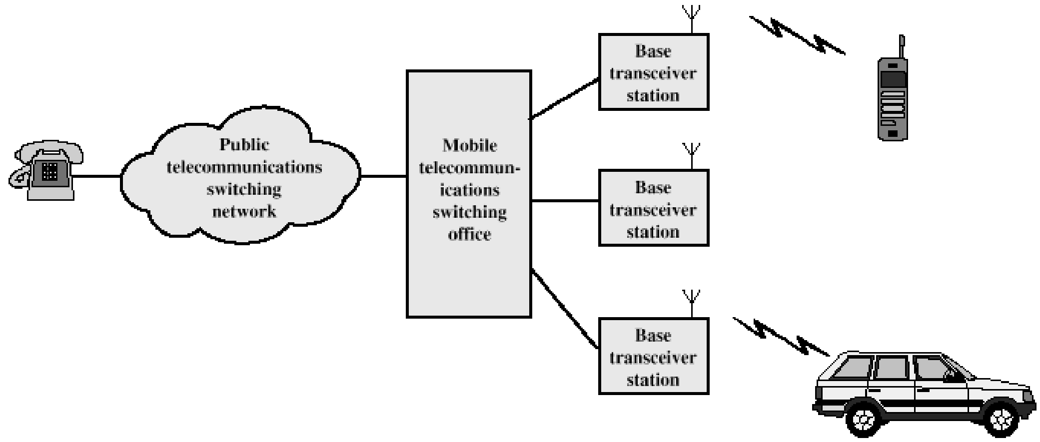
Cellular System

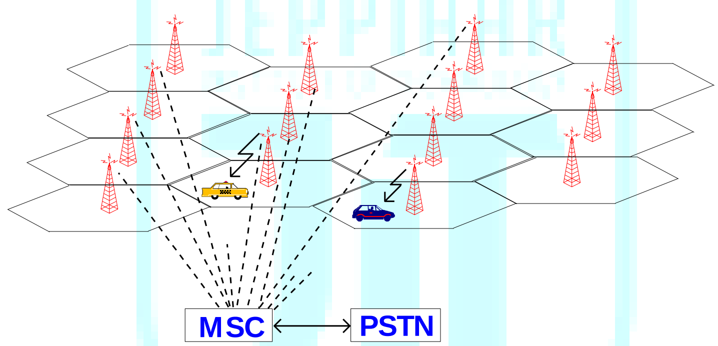


Base stations (towers) provide radio access between mobile users and MSC.

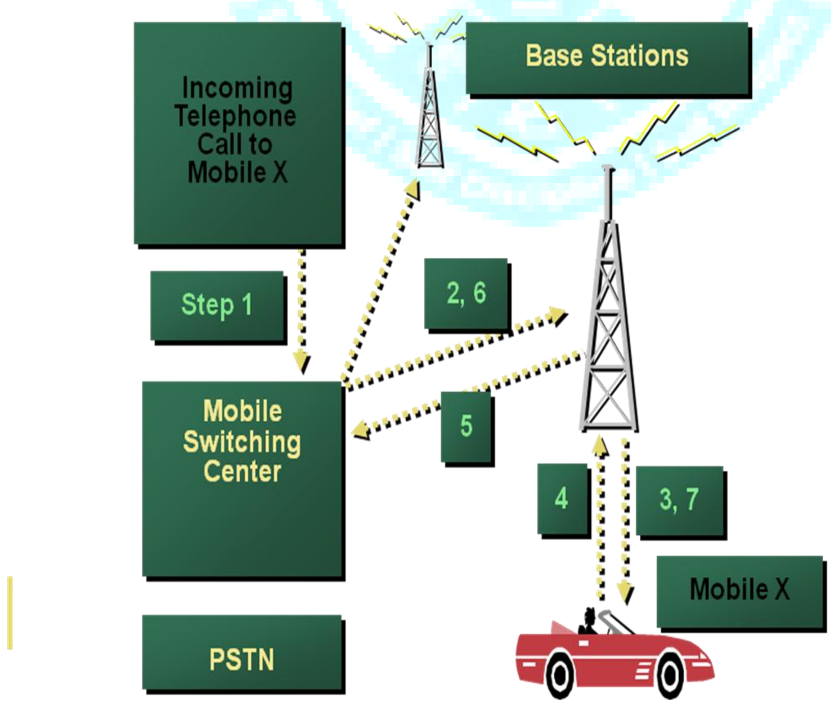
Mobile cells

The entire coverage area is a group of a number of cells. The size of cell depends upon the power of the base stations.





Telephone Call Made To Mobile User



Brief Outline of Cellular Process: Telephone Call Placed to a Mobile User

Step 1: The incoming telephone call to Mobile X is received at the MSC.

Step 2: The MSC dispatches the request to all base stations in the cellular system.

Step 3: The base stations broadcast the Mobile Identification Number (MIN), telephone number of Mobile X, as a paging message over the FCC throughout the cellular system.

Step 4: The mobile receives the paging message sent by the base station it monitors and responds by identifying itself over the reverse control channel (RCC).

Step 5: The base station relays the acknowledgement sent by the mobile and informs the MSC of the handshake.

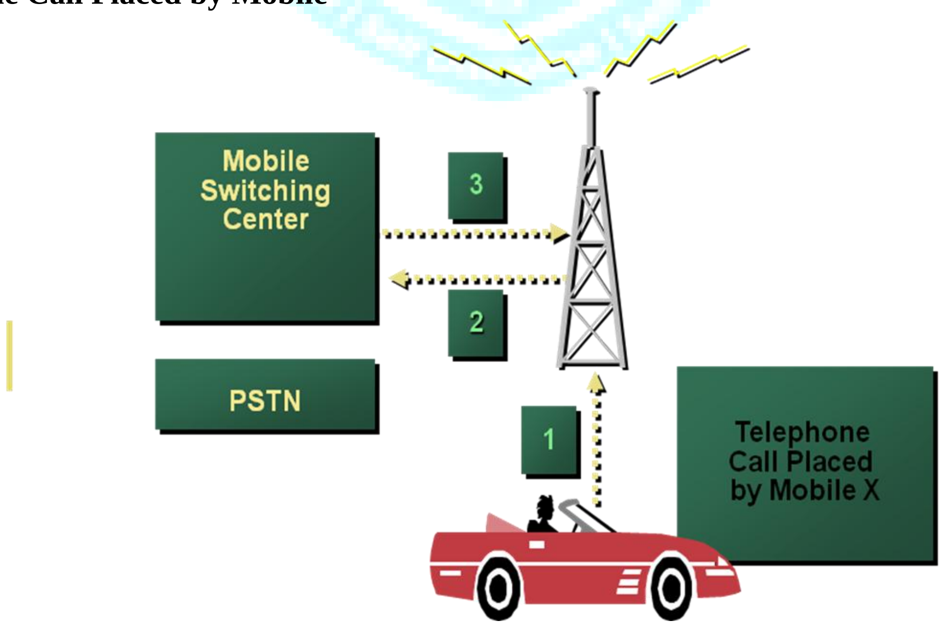
Step 6: The MSC instructs the base station to move the call to an available voice channel within the cell.

Step 7: The base station signals the mobile to change frequencies to an unused forward and reverse voice channel pair.

At the point another data message (alert) is transmitted over the forward voice channel (FVC) to instruct the mobile to ring.

Now the call is in progress. The MSC adjusts the transmitted power of the mobile and changes the channel of the mobile end and base stations in order to maintain call quality. This is called handoff.

Telephone Call Placed by Mobile



Step 1: When a mobile originates a call, it sends the base station its telephone number (MIN), electronic serial number (ESN), and telephone number of called party. It also transmits a station class mark (SCM) which indicates what the maximum power level is for the particular user.

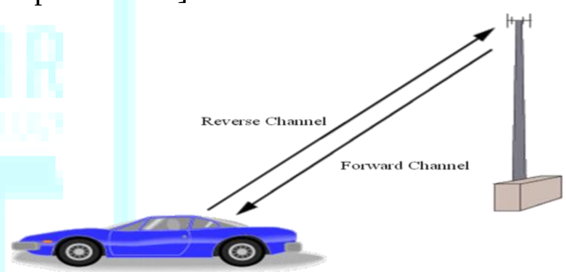
Step 2: The cell base station receives the data and sends it to the MSC.

Step 3: The MSC validates the request, makes connection to the called party through the PSTN and validates the base station and mobile user to move to an unused forward and reverse channel pair to allow the conversation to begin.

Common Air Interface (CAI)

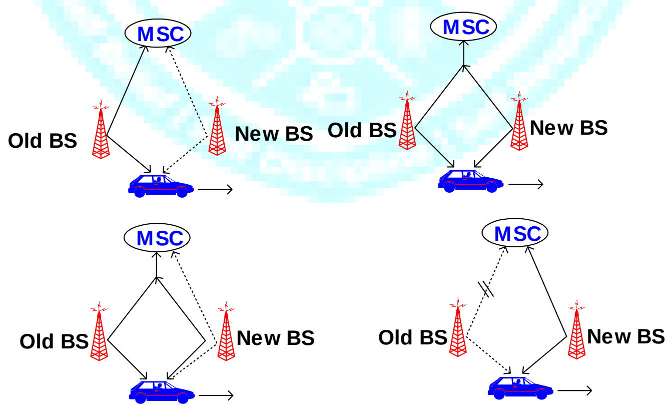
A Standard that defines Communication between a Base Station and Mobile.
Specifies Four Channels [Voice Channels and Control / Setup Channels]

- FVC: Forward Voice Channel
- RVC: Reverse Voice Channel
- FCC: Forward Control Channel
- RCC: Reverse Control Channel

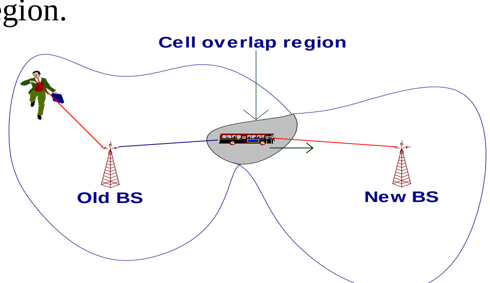


Handoff

A process, which allows users to remain in touch, even while breaking the connection with one BS and establishing connection with another BS.



To keep the conversation going, the Handoff procedure should be completed while the MS (the bus) is in the overlap region.



Handoff Issues

- ❖ Handoff detection
- ❖ Channel assignment
- ❖ Radio link transfer

Handoff detection strategies

- ❖ Mobile-Controlled handoff (MCHO)
- ❖ Network-Controlled handoff (NCHO)
- ❖ Mobile-Assisted handoff (MAHO)

Mobile-Controlled Handoff (MCHO)

In this strategy, the MS continuously monitors the radio signal strength and quality of the surrounding BSs. When predefined criteria are met, then the MS checks for the best candidate BS for an available traffic channel and requests the handoff to occur.

Network-Controlled Handoff (NCHO)

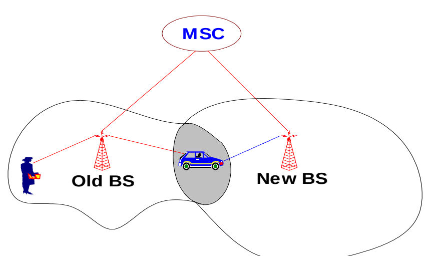
In this strategy, the surrounding BSs, the MSC or both monitor the radio signal. When the signal's strength and quality deteriorate below a predefined threshold, the network arranges for a handoff to another channel.

Mobile-Assisted Handoff (MAHO)

It is a variant of NCHO strategy. In this strategy, the network directs the MS to measure the signal from the surrounding BSs and to report those measurements back to the network. The network then uses these measurements to determine where a handoff is required and to which channel. MACHO is used in GSM and IS-95 CDMA.

Handoff types with reference to the network

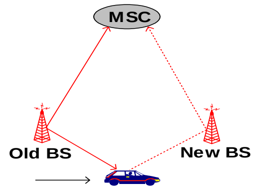
❖ Intra-system handoff or Inter-BS handoff
The new and the old BSs are connected to the same MSC.



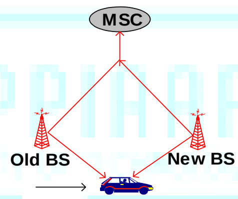
Intra-system handoff or Inter-BS handoff

Steps

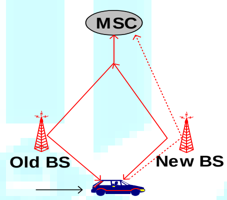
1. The MU (MS) momentarily suspends conversation and initiates the handoff procedure by signaling on an idle (currently free) channel in the new BS. Then it resumes the conversation on the old BS.



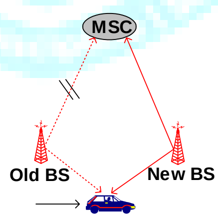
2. Upon receipt of the signal, the MSC transfers the encryption information to the selected idle channel of the new BS and sets up the new conversation path to the MS through that channel. The switch bridges the new path with the old path and informs the MS to transfer from the old channel to the new channel.



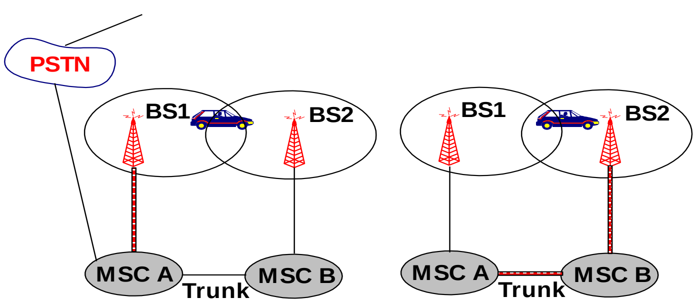
3. After the MS has been transferred to the new BS, it signals the network and resumes conversation using the new channel.

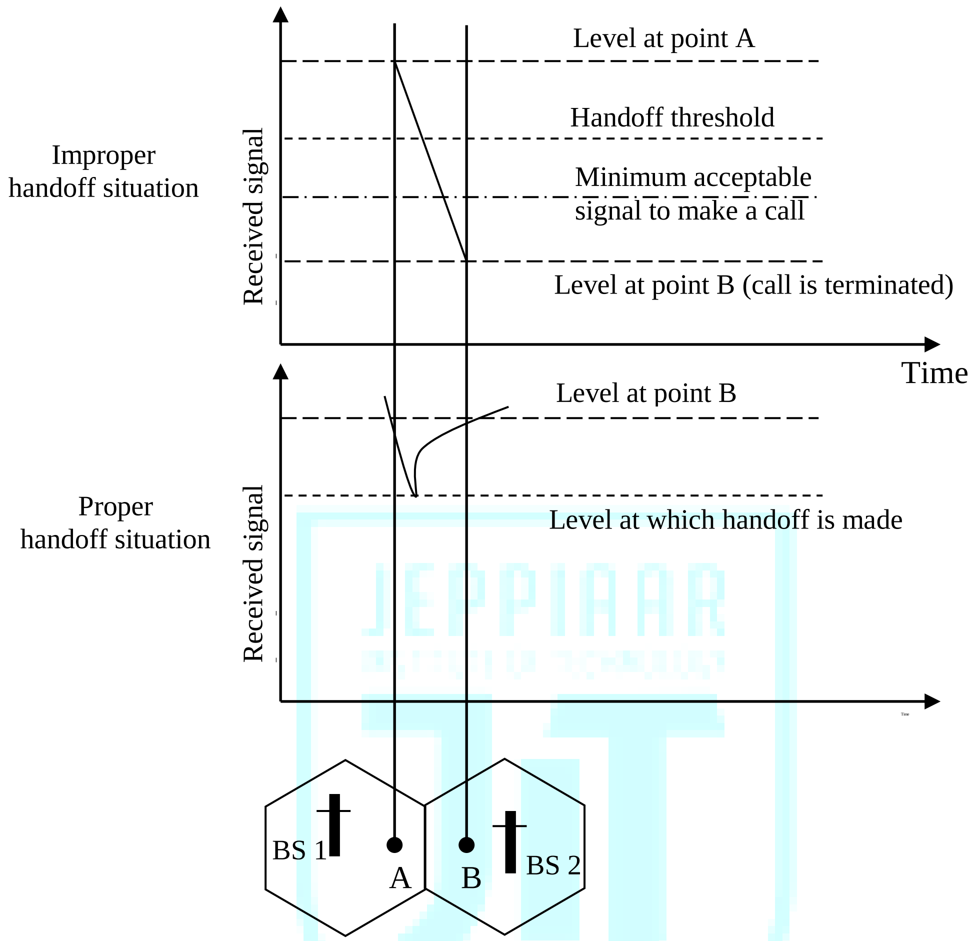


4. Upon the receipt of the handoff completion signal, the network removes the bridge from the path and releases resources associated with the old channel.



❖ Intersystem handoff or Inter-MSC handoff
The new and the old BSs are connected to different MSCs.





Handoff types with reference to link transfer

❖ **Hard handoff**

Channelized wireless systems assign different radio channels during a handoff. This is called a **hard handoff**.

Eg: The MS connects with only one BS at a time, and there is usually some interruption in the conversation during the link transition.

❖ **Soft handoff**

Spread spectrum mobiles share the same channel in every cell. A different base station handles the radio communication task. The ability to select between the instantaneous received signals from a variety of base stations is called **soft handoff**.

Eg: The two BSs are briefly simultaneously connected to the MU while crossing the cell boundary. As soon as the mobile's link with the new BS is acceptable, the initial BS disengages from the MU

Roaming

All cellular systems provide a service called roaming. This allows subscribers to operate in service areas other than the one from which service is subscribed.

When a mobile enters a city or geographic area that is different from its home service area, it is registered as a roamer in the new service area.

Periodically, the MSC issues a global command over each FCC in the system, asking for all mobiles which are previously unregistered to report their MIN and ESN over the RCC for billing purposes.

If a particular mobile user has roaming authorization for billing purposes, MSC registers the subscriber as a valid roamer.

Roaming is a facility, which allows a subscriber to enjoy uninterrupted communication from anywhere in the entire coverage space.

A mobile network coverage space may be managed by a number of different service providers. They must cooperate with each other to provide roaming facility.

Roaming can be provided only if some administrative and technical constraints are met.

Administrative constraints

- Billing.
- Subscription agreement.
- Call transfer charges.
- User profile and database sharing.
- Any other policy constraints.

Technical constraints

Bandwidth mismatch:

For example, European 900MHz band may not be available in other parts of the world. This may preclude some mobile equipment for roaming.

- ❖ Service providers must be able to communicate with each other. Needs some standard.
- ❖ Mobile station constraints.
- ❖ Integration of a new service provider into the network. A roaming subscriber must be able to detect this new provider.

- Service providers must be able to communicate with each other. Needs some standard.
- Quick MU response to a service provider's availability.
- Limited battery life.

Two basic operations in roaming management are

- Registration (Location update): The process of informing the presence or arrival of a MU to a cell.
- Location tracking: the process of locating the desired MU.

Registration (Location update)

There are six different types of registration.

Power-down registration:
Done by the MU when it intends to switch itself off.

Power-up registration:
Opposite to power-down registration. When an MU is switched on, it registers.

Deregistration:
A MU decides to acquire control channel service on a different type of network (public, private, or residential).

New system/Location area registration:
When the location area of the MU changes, it sends a registration message.

Periodic registration:
A MU may be instructed to periodically register with the network.

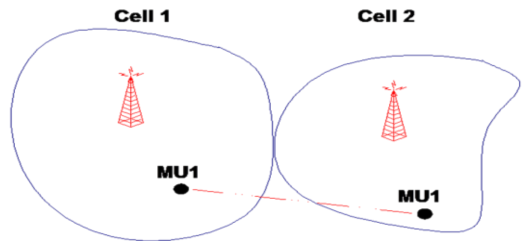
Forced registration:
A network may, under certain circumstances, force all MUs to register.

Two-Tier Scheme

HLR: Home Location Register
A HLR stores user profile and the geographical location.

VLR: Visitor Location Register
A VLR stores user profile and the current location who is a visitor to a different cell that its home cell.

Two-Tier Scheme steps. MU1 moves to cell 2.



Location tracking

Steps

- ❖ VLR of cell 2 is searched for MU1's profile.
- ❖ If it is not found, then HLR is searched.
- ❖ Once the location of MU1 is found, then the information is sent to the base station of cell 1.
- ❖ Cell 1 establishes the communication.

Cordless Telephone Systems

Cordless telephone systems are full duplex communication systems that use radio to connect a portable handset to a dedicated base station, which is then connected to dedicated telephone line with a specific telephone number on the public switched telephone network (PSTN). In first generation cordless telephone systems (manufactured in 1980's), the portable unit communicates only to the dedicated base unit and only over distances of few ten of meters. Early cordless telephone operate solely as extension telephones to a transceiver connected to a subscriber line on the PSTN and are primarily for in home use.

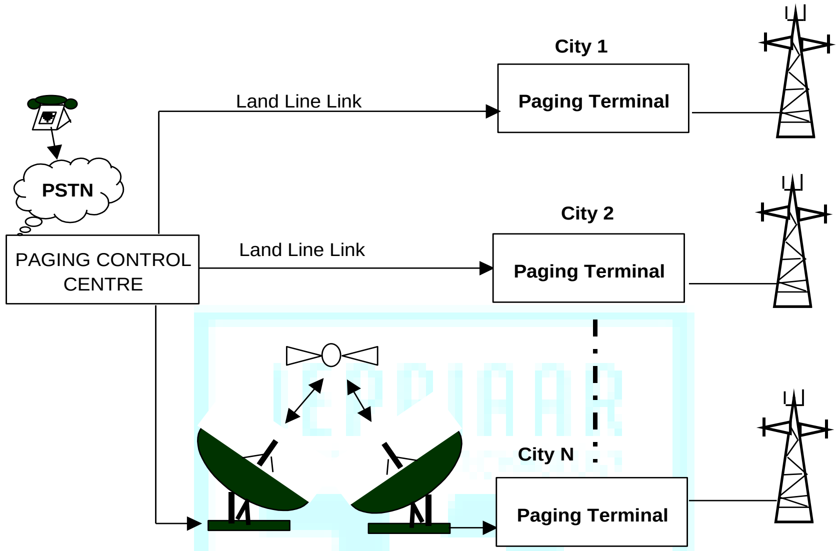
Second generation cordless telephones have recently been introduced which allow subscriber to use their handsets at many outdoor locations within urban centers such as London or hong kong.

Modern cordless telephones are sometimes combined with paging receivers so that a subscriber may first be paged and then respond to the page using the cordless telephone. Cordless telephone systems provide the user with limited range and mobility, as it is usually not possible to maintain a call if the user travel outside the range of the base station. Typical second generation base station provide coverage ranges up to a few hundred meters.

Paging Systems

Wide Area System

The paging control center dispatches pages received from the PSTN throughout several cities at the same time.



Paging System:

Paging systems are communication systems that send brief messages to a subscriber. Depending on the type of service, the message may be a numeric message, an Alpha-numeric message, or a Voice message. Paging systems are typically used to notify a subscriber of the need to call a particular telephone number or travel to a known location to receive further instructions. In modern paging systems, news headlines, stock quotations, and faxes may be sent. A message is send to a paging subscribe via the paging system access number with a telephone keypad or modem. The issued message is called a page. The paging system then transmits the page throughout the service area using base stations which broadcast the page on a radio carrier.

Paging systems vary widely in their complexity and coverage area. While simple paging system may cover a limited range of 2 to 5 km, or may even be confined to within individual buildings, wide area paging systems can provide worldwide coverage. Through paging receivers are simple and inexpensive; the transmission system required is quite sophisticated. Wide area paging system consist of a network of telephone lines, many base station transmitters, and large radio towers that simultaneously broadcast a page from each base station (this is simulcasting). Simulcast transmitter may be located within the same service area or in different cities or countries, paging system are designed to provide reliable communication to subscribers wherever they are: whether inside a building, driving on a highway, or flying in an airplane. This necessitates large transmitter powers (on the order of kilowatts) and low data rates (a couple of thousand bits per second) for maximum coverage from each base station.

Problems with cellular structure

How to maintain continuous communication between two parties in the presence of mobility?

Solution: Handoff

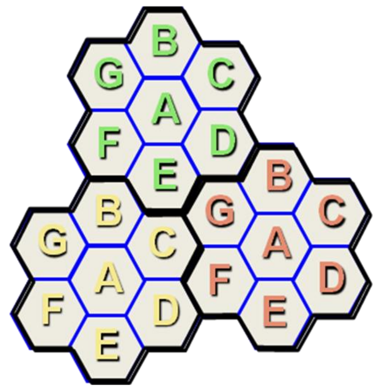
How to maintain continuous communication between two parties in the presence of mobility?
Solution: Roaming

How to locate of a mobile unit in the entire coverage area?
Solution: Location management

Frequency Reuse

Each cellular base station is allocated a group of radio channels. Base stations in adjacent cells are assigned channel groups which contain different channels than neighboring cells.

Cellular Frequency Reuse Concept

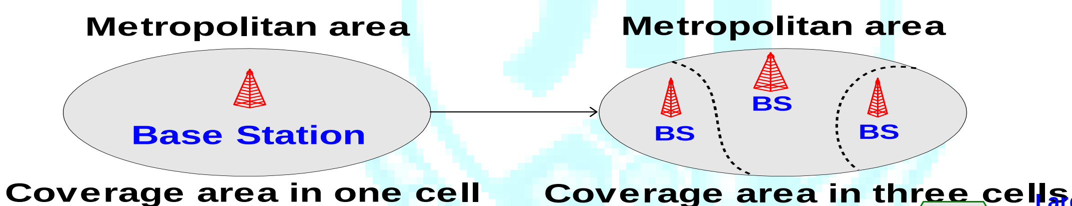


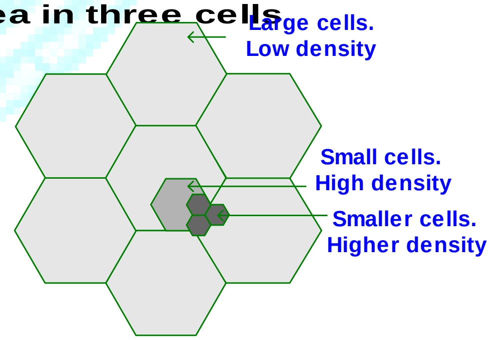
Cells with the same letter use the same set of frequencies.

A cell cluster is outlined in bold, and replicated over the coverage area.

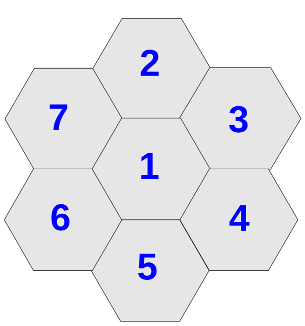
In this example, the cluster size, N, is equal to 7; and the frequency reuse factor is 1/7, since each cell contains 1/7 of the total number of available channels.

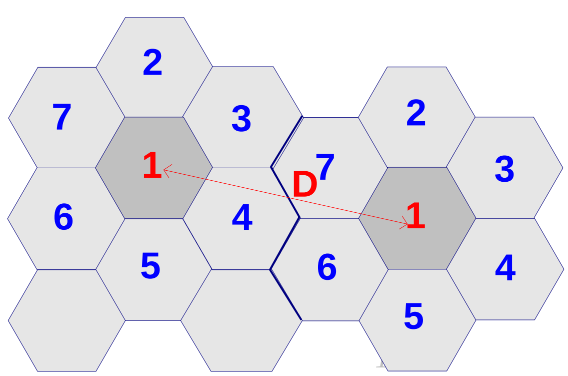
Mobile cells

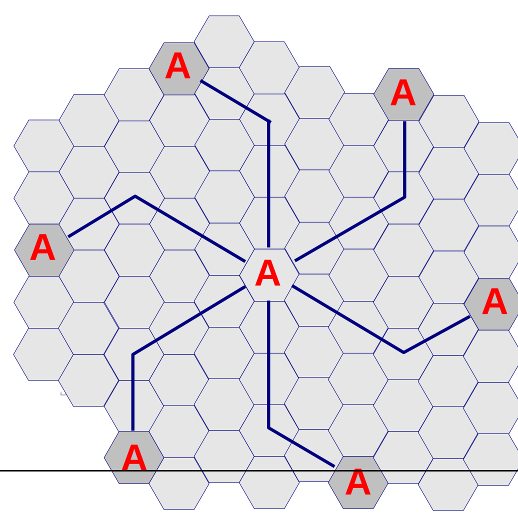




Frequency reuse







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

D = distance between cells using the same frequency
R = cell radius
N = reuse pattern (the cluster size, which is 7).

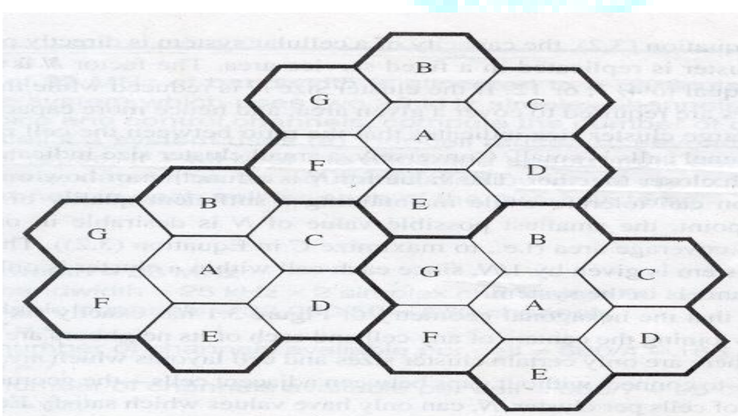
Thus, for a 7-cell group with cell radius R = 3 miles, the frequency reuse distance D is 13.74 miles.

Frequency Reuse

Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a cell. The powers of base station antennas are limited to cover designated cell area only to avoid interference with other cells. The design process of selecting and allocating channels groups for all of the cellular base stations within a system is called frequency reuse or frequency planning

For the ease of covering the entire region without gaps, hexagonal shape is selected. Also, the base station transmitter is normally kept either at the center or at the corner. Omni directional antennas are used in case of center location and sectored directional antennas are used in case corner location.

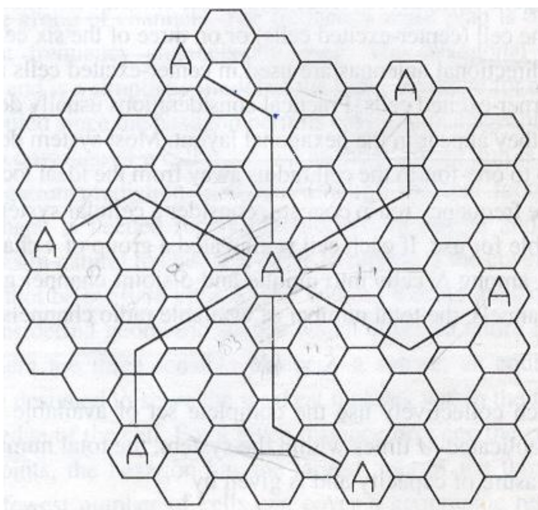
Consider a cellular system has a total of S duplex channels available for use. Let each cell is allocated a group of k channels and if the S channels are divided among N cells into unique and disjoint channel groups, which each have the same number of channels, the total number of available ratio channels can be expressed as S=kN. 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 as C = MkN = MS.



A cell cluster is outlined in bold and replicated over the coverage area.

As can be seen, 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 cluster size and it is estimated for hexagonal shape as $N=i^2 + ij + j^2$. In this case for i= 1 and j = 1, N is 3; for i=1 and j=2, N is 7; for i=2 and j=2, N = 12 and so on. If the cell area is kept and constant and the value of N is reduced, more clusters are required to cover the entire area. This gives rise to higher capacity to the system. However, small value of N gives rise to co channels repeated at closer distance compared with that of larger clusters. The frequency re use factor of a cellular system is given by 1/N, as each cell in a cell is assigned only 1/N of available channels.

To find the nearest co channel neighbors of a particular cell one must do the following: Move i cells along any chain of hexagon and then turn 60 degrees counter clockwise and move j cells. This is illustrated in the following figure for i=3 and j=2.



Method of locating a co channel in cell system

EXAMPLE:

If a particular FDD cellular telephone system has a total bandwidth of 33mhz and if the phone system uses two 25khz simplex channel to provide the no/- of channels per cell if n=4,7,12

Total bandwidth = 33 MHz

Channel bandwidth = 25 KHz x 2 = 50 KHz

Total available channels = 33 MHz / 50 KHz = 660

N = 4 Channel per cell = 660 / 4 = 165 channels

N = 7 Channel per cell = 660 / 7 = 95 channels

N = 12 Channel per cell = 660 / 12 = 55 channels

Channel Assignment strategies

Channel assignment strategies can be classified as Static and Dynamic. When fixed numbers of channels are assigned to a cell, it is called fixed channel assignment. Sometimes, this may result in traffic in some cells getting overloaded while in others under loaded. Hence, it is not a method to manage traffic efficiently. Other variation is, a cell is allowed to borrow channels from neighboring cells if its channels are filled up. The mobile switching center supervises such activity.

In case of dynamic channel assignment, voice channels are assigned by MSC based on request from the Base stations. However, before the MSC need to keep a strict account on frequency use in candidate cell, the reuse distance of the channel and other cost functions etc. Although this method likely to avoid blocking of the channels and provides efficient use, the MSC need to tack a lot of data like, channel occupancy, traffic distribution, RSSI (Radio Signal Strength Indications 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.

Interference and System Capacity:
Interference is the major limiting factor in the performance of cellular radio systems. Two major types of system generated interference are co channel interference and adjacent channel interference.

Co-Channel interference and system capacity: Frequency reuse implies that in a given coverage area that there are several cell that use the same set of frequencies. These cells are called co channels cells and the interference form these cells called co channel interference. This cannot be controlled by increasing the transmitted signal power as it increases the interference in the co channel cells. When the size of the each cell is approximately same and the base stations transmit the same power, the co channel interference ratio is independent of transmitted power and becomes a function of the cell radius R and the distance between centers of the nearest co channel cell D. By increasing the ratio D / R, the spatial separation between co channel cells relative to the coverage distance of a cell is increased. The parameter Q, called the co channel reuse ration is related to the cluster size. For a hexagonal geometry

$$Q = D / R = \sqrt{3N}. \qquad (1)$$

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 tradeoff must be made between these two objectives in actual cellular design. Following table gives the co channel reuse ratio for some values of N

i	J	Cluster size N	Co channel reuse ratio
`1	1	3	3
1	2	7	4.583
2	2	12	6
1	3	13	6.24

The relationship between co channel signal to interference ratio and the cluster size is evaluated as follows. Let i_o the number of co channels interfering with the main signal. Then the signal to interference ration S / R or SIR for a mobile which monitors a forward channel is expressed as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i=io} Ii} \quad (2)$$

Where S is the desired signal power and Ii 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 show that the average received signal strength at any point decays as a power of law of the distance of separation between a transmitter and receiver. That is the average power Pr at a distance d from the transmitter antenna is approximately equal to

$$Pr \ \alpha \ \frac{1}{r^n}$$

Where n is the path loss exponent which varies between 2 to 4 in urban area..

Consider the forward link where the desired signal is the serving base station and where the interference is due to co channel base station. If Di is the distance of the i^{th} interferer from the mobile, the received power at a given mobile due to the i^{th} interfering cell will be proportional to $(Di)^{-n}$. When the transmit power of each base station is equal and the path loss exponent is the same throughout the coverage area, S / I for a mobile can be approximated as

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i=io} Di^{-n}} \quad (3)$$

Considering only the first layer of interfering cells, if all the interfering base stations are equidistance from the desired base station and if this distance is equal to the distance D between cell centers, then the equations simplifies to

$$\frac{S}{I} = \frac{(D/R)^n}{io} = \frac{\sqrt{3N}^n}{io} \quad (4)$$

This equation relates S / I to the cluster size N, which in turn determines the overall capacity of the system. Let us we assume six closest cells are close enough to create significant interference and that all are approximately equidistance from the desired base station. I generation experiment indicates that good voice can be provided when S /I is greater than 18 db. Using the first equation, it can be shown that in order to meet this requirement, the cluster size N should be 6. 49, assuming a path loss exponent of n = 4. Thus minimum cluster size of seven is required to meet an S/ I ratio requirement of 18 db.

Example:

If a signal to interference ratio of 15 db is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size should be used for maximum capacity if the path loss exponent is a) n = 4 and b.) n=3. Assume that there are six co channel cells in the first tier and all of them are at the same distance from the mobile. . Use suitable assumption.

a) n= 4

First lest us consider a seven cell reuse pattern.
Using the table the co channel re use ratio is D / R = 4.583.
Using the equation (4), the signal to noise ratio is given as

$$S / I = (1 / 6) * (4.583)^4 = 75.3 = 18.66 \text{ db}$$

Since this is greater than the minimum required S / I, N = 7 can be used.

b) n = 3

First consider the seven cells re use pattern.
Using the equation (4), the signal to noise ratio is given as

$$S / I = (1 / 6) * (4.583)^3 = 16.04 = 12.06 \text{ db}$$

Since this is less than the minimum required S / I , we need to use a larger N.

Using the N = 12, D/ R becomes 6.0
Using the equation (4), the signal to noise ratio is given as

$$S / I = (1 / 6) * (6)^3 = 36 = 15.56 \text{ db}$$

Since this is greater than the minimum required S / I, N = 12 is used.

Adjacent Channel Interference:

Interference resulting from signals which are adjusted in frequency to the desired signal is called adjacent channel interference. This results from imperfect receiver filters which allow nearby frequencies to leak into the pass band. The problem is very 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 as near – far effect.

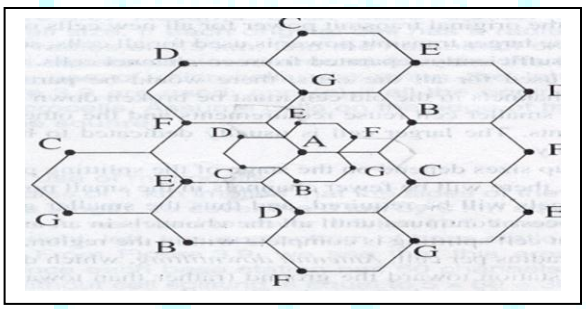
Adjacent channel interference can be minimized through careful filtering and channel assignment. As a cell is given only a fraction of available channel, a cell need not be given frequencies that are adjacent to each other. By keeping the frequency separation between each channel as large as possible adjacent interference can be reduced considerably.

Improving the coverage and the capacity of in cellular systems:

In order to enhance the capacity of the cellular system, certain techniques are followed. These are cell splitting, sectoring and zone microcell approaches etc. Cell splitting allows the orderly growth of the cellular system. Sectoring uses directional antennas to further control the interference and frequency reuse of channel. The micro cell zone concepts distribute the coverage of a cell and extend the cell boundary to hard and reach places. While cell splitting increases the number of base stations, sectoring and zone micro cells rely on base stations antenna placements to improve capacity by reducing co channel interferences.

Cell Splitting:

It 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. It increases the capacity of the system as the number of times the channels are reused. BY defining new cells which have a smaller radius and by installing these smaller cells between existing cells, capacity increases due to the additional number of channels per unit area. Cell splitting is shown below:



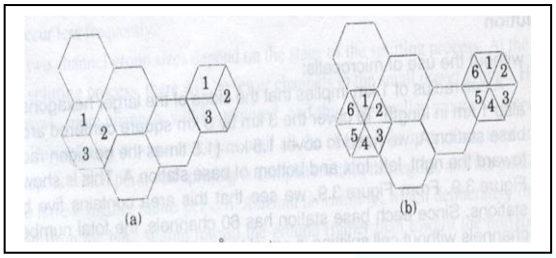
If every cell were reduced such that the radius of every cell is reduced to half, then it will require approximately four smaller cells to cover the same area. The increased number of cells would increase the number of clusters over the coverage region, which in turn would increase the number of channels and thus capacity in the coverage area. While allocating the channels, frequency reuse plan is preserved.

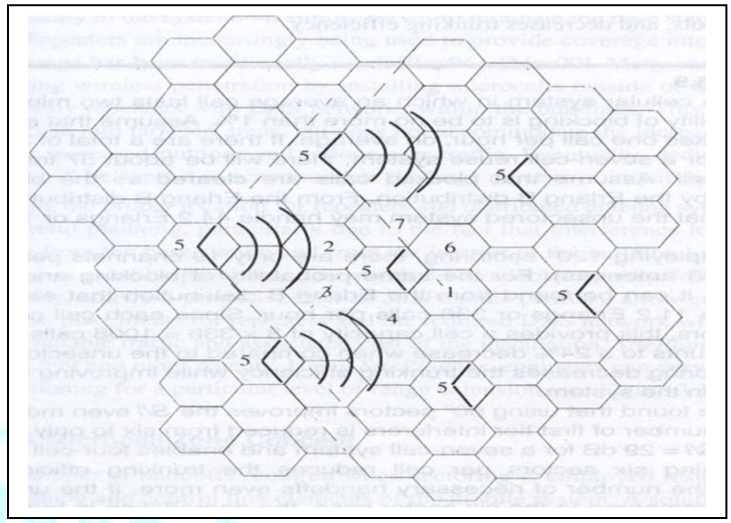
As can be seen in the figure, microcell base station labeled G was placed half way between two larger stations utilizing the same channel as G. Similar method is followed while allocating channels to other micro cells. In this case each cell is allowed to transmit only a power that is equal to 1/ 16^{th} that of original transmitter power so as to cover the smaller area.

Essentially, cell splitting achieves capacity improvement by essentially rescaling the system. That is by decreasing the cell radius R and keeping the co channel reuse ration D / R unchanged, cell splitting increases the number of channels per unit area.

Sectoring:

In this, the cell radius is kept unchanged, but methods are used to decrease the Ratio D / R. In this, sectoring improves the SIR so that the cluster size may be reduced. It replaces the omni directional antenna at the center or directional antennas at the corner with three directional antenna at the center if the cell is divided into three sectors. Each of the directional antennas covers a sector of 120 degrees as shown in the following figure





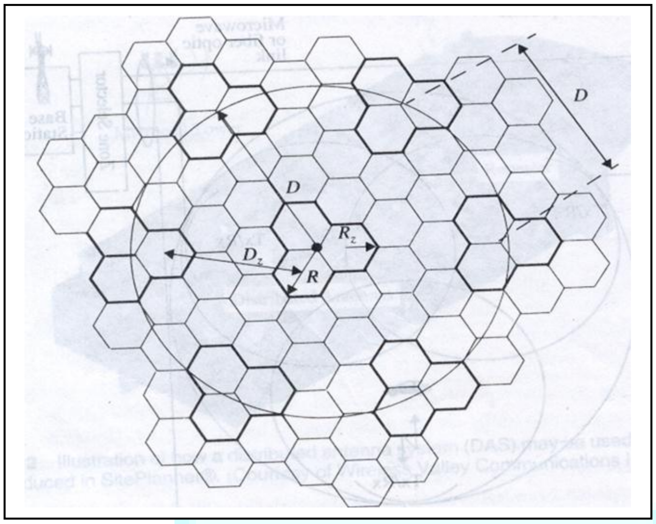
When sectoring is employed, the channels used in particular cell are broken down into sectored groups and are used only within a particular sector. Assuming a seven cell reuse, for the case of 120 deg sectors, the number of interferers in the first tier is reduced from six to two. This is because only two of the six channels cells receive interference with a particular sectored channel group. With this, the resulting SIR is found to be 24.2 db instead of 17 db.

This enhancement in the SIR, allows one to decrease the cluster size N in order to improve the frequency reuse and thus the capacity of the system
In particular system, further improvement in SIR is achieved by down tilting the sector antennas such that the radiation pattern in the vertical plane has a notch at the nearest co channels cell distance. BY going in for 7 cell reuse pattern instead of 12 cell pattern gives rise to an increase in capacity of 12 / 7 = 1.714 times.

However, the penalty for improved S/I and the resulting capacity improvement from the shrinking cluster size is an increased number of antennas at each base station. Also as the sectoring reduces the coverage areas of a particular group of channels, the number of hand off increases. This increases the load on the switching and control link elements of the mobile system.

Microcell Zone:

In this each of the three zone sites are connected to a single base station and share the same radio requirement. The zones are connected by coaxial cable, fiber optic cable or microwave link to the base station. As the mobile travels within the cell, it retains the same channel thus avoiding the handoff and associated complexity. The base station simply switches the channels to a different zone site. The advantage of the zone cell technique is that while the cell maintains a particular coverage radius, the co channel interference in the cellular system is reduced such a large central base station is replaced by several lower powered transmitters on the edges of the cell.



Decreased co channel interferences improve the signal quality and also lead to an increase in capacity without the degradation in trucking efficiency caused by the sectoring. For satisfactory performance, and SIR of 18 db is required. For a system with N= 7, a D/ R of 4.6 was shown to achieve this. With respect to Zone microcell, since the transmission is confined to a particular zone, this implies that the D / R ratio, can be improved as the R value is now equal to the radius of the cell and is equal to the twice the length of the hexagon radius. Thus, instead of D / R ratio of 4.6 for cluster size of 7, the D / R ratio becomes 3 with the microcell concept. This facilitates the cluster size to be reduced from 7 to 3, thereby increasing the capacity 7 / 3 = 2.33 times. Hence for the same SIR requirement of 18 db, the system provides significant increase in capacity over conventional cellular planning.

Other Methods to Improve System capacity

1. **Increasing the amount of spectrum used:** It is very expensive, as spectrum is a scarce resource.

2. **More efficient modulation formats and coding:** Use modulation formats that require less bandwidth (higher order modulation) and/or are more resistant to interference.
   - Higher order modulation allows an increase in data rate for each user. But they are more sensitive to noise and interference.
   - The introduction of turbo codes and low-density parity check codes is another way of achieving better immunity to interference, and thus increases system capacity.

3. **Better source coding:** Depending on required speech quality, current speech coders need data rates between 32 kbit/s and 4 kbit/s. Better models for the properties of speech allow the data rate to be decreased without decreasing quality

4. **DISCONTINUOUS VOICE TRANSMISSION DTX:** During a phone conversation each participant talks only 50% of the time. A TDMA system can thus set up more calls than there are available timeslots. During the call, the users that are actively talking at the moment are multiplexed onto the available timeslots, while quiet users do not get assigned any radio resources.

5. **MULTIUSER DETECTION:** Multiuser detection reduces the effect of interference, and thus allows more users per cell for CDMA systems or smaller reuse distances for FDMA systems.

6. **ADAPTIVE MODULATION AND CODING:** Chooses the modulation format and coding rate that are suitable for the current link situation. This approach makes better use of available power, and, among other effects, reduces interference.

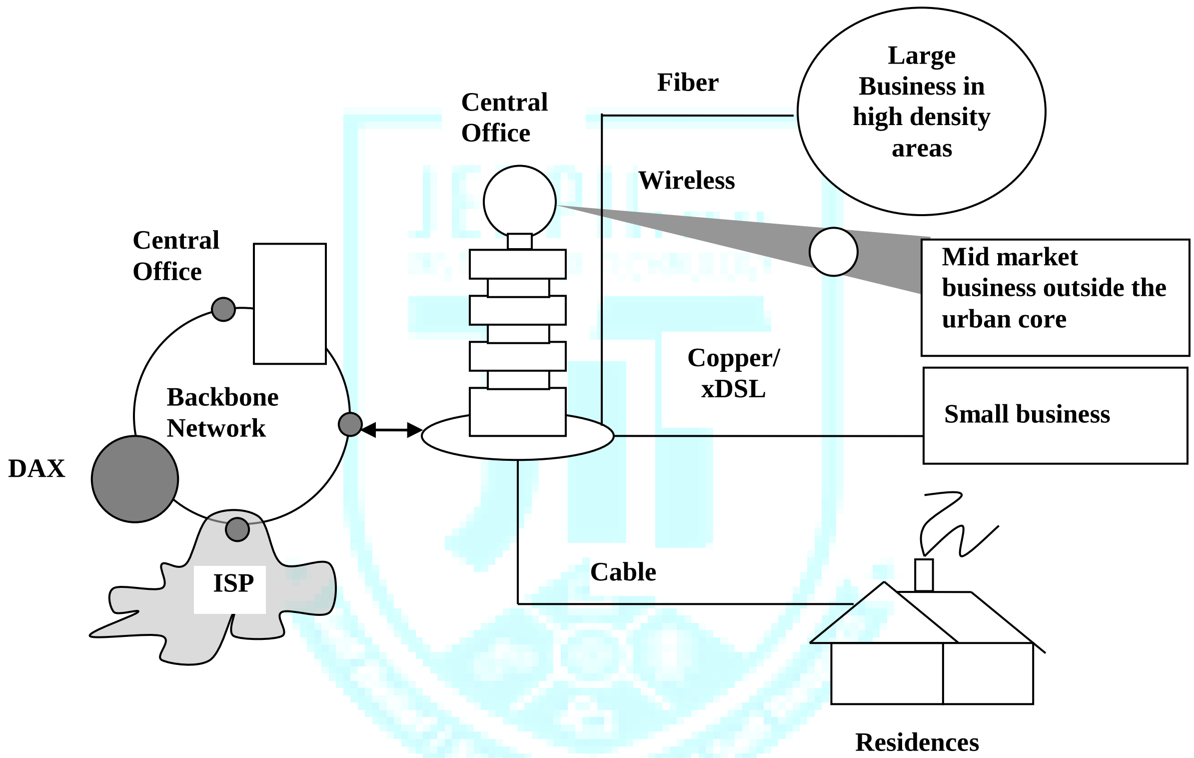
7. **MULTIPLE ANTENNAS:** Multiple antennas can be used to enhance capacity by:
   a. diversity increases the quality of the received signal, which can be exploited to increase capacity – e.g., by use of higher order modulation formats, or reduction of the reuse distance
   b. multiple-input multiple-output systems increase the capacity of each link
   c. space division multiple access allows several users in the same frequency channel in the same cell to be served

8. **FRACTIONAL LOADING:** This system uses a small reuse distance, but uses only a small percentage of the available timeslots in each cell.

Wireless Local loop

The rapid growth of Internet has created a concurrent demand for Broadband Internet and computer access from business and homes throughout the world. Particularly in developing nations where there is inadequate telecommunication backbone infrastructure, there is a tremendous need for inexpensive, reliable, rapidly deployable broadband connectivity that can bring individuals and enterprises into the information age. In fact, as voice over Internet protocols (VoIP) become prevalent, it is quite conceivable that a single broadband Internet connection could someday provide all of the needed telecommunication services, including telephone service, television, radio, fax, and internet, for a home or Business customer. Fixed wireless equipment is extremely well suited for rapidly deploying a broadband connection in many instances, and this approach is steadily becoming more popular for providing "last mile" broadband local loop access, as well as for emergency or redundant point-to-point or Point-to-Multipoint private networks.

Unlike Mobile Cellular telephone systems, fixed wireless communication systems are able to take advantage of the very well defined, time-invariant nature of the propagation channel between the fixed transmitter and fixed receiver. Furthermore, modern fixed wireless systems are usually assigned microwave or millimeter radio frequencies in the 28 GHz band and higher, which is greater than ten times the carrier frequency of 3G terrestrial cellular telephone networks. At these higher frequencies, the wavelengths are extremely small, which in turn allows very high gain directional antennas to be fabricated in small physical form factors. At Higher frequencies, too, more bandwidth can be easily used. High gain antennas have spatial filter properties that can reject multipath signals that arrive from directions other than the desired line of sight, and this in turn support the transmission of very wide bandwidth signals without distortion. Also, since the carrier frequencies of these fixed wireless access terminals are so high, the radio channel behaves much like optical channels. Thus, fixed wireless network at very high microwave frequencies are only viable where there are no obstructions, such as in a relatively flat sub-urban or rural setting. Microwave wireless links can be used to create a wireless local loop (WLL) such as the one shown in the figure below.



Example of the emerging applications and markets for broadband services

The local loop can be thought of as the "last mile" of the telecommunication network that resides between the central office (CO) and the individual homes and businesses in close proximity to the CO. In developed countries, copper or fiber optic cable has been installed to residences and businesses. However in many developing nations, cable is too expensive or can take months or years to install. Wireless equipment, on the other hand, can easily be deployed in just in couple of hours.

An additional benefit of WLL technology is that once the wireless equipment is paid for, there are no additional costs for transport between the CO and the customer premises Equipment (CPE), whereas buried cables often must be leased from a service provider or utility company on a monthly basis. It s possible that WLL systems could compete copper wire based Digital Subscriber loops (DSL) technologies that are rapidly proliferating.

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 behavior of users so that a fixed number of channels or circuits may accommodate a large, random user community. The telephone company uses trunking theory to determine the number of telephone circuits that need to be allocated for office buildings with hundreds of telephones, and this 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 lines 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 requests service and all of the radio channels are already in use, 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,” it is essential to understand trunking theory and queuing theory. The fundamentals of trunking theory were developed by Erlang, a Danish mathematician who, in the late 19th century, embarked on the study of how a large population could be accommodated by a limited number of servers. Today, the measure of traffic intensity bears his name. One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. one call-hour per hour or one call-minute per minute). For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic.

The grade of service (GOS) is a measure of the ability of a user to access a trunked system during the busiest hour. The busy hour is based upon customer demand at the busiest hour during a week, month, or year. The busy hours for cellular radio systems typically occur during rush hours, between 4 p.m. and 6 p.m. on a Thursday or Friday evening. The grade of service is a benchmark 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. It is the wireless designer’s job to estimate the maximum required capacity and to allocate the proper number of channels in order to meet the GOS. 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.

The following definitions 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 a lost call.

Holding Time:

Average duration of a typical call. Denoted by H (in seconds).

Traffic Intensity:

Measure of channel time utilization, which is the 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. Denoted by A.

Load:

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

Grade of Service (GOS):

A measure of congestion which is specified as the probability of a call being blocked (for Erlang B), or the probability of a call being delayed beyond a certain amount of time (for Erlang C).

Request Rate:

The average number of call requests per unit time. Denoted by λ 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

$$A_u = \lambda H$$

Where H is the average duration of a call and λ is the average number of call requests per unit time for each user. For a system containing U users and an unspecified number of channels, the total offered traffic intensity A, is given as

$$A = U A_u$$

Furthermore, in a C channel trunked system, if the traffic is equally distributed among the channels, then the traffic intensity per channel, Ac, is given as

$$A_c = UA_u / C$$

Note that the offered traffic is not necessarily the traffic which is carried by the trunked system, only that which is offered to the trunked system. When the offered traffic exceeds the maximum capacity of the system, the carried traffic becomes limited due to the limited capacity (i.e. limited number of channels). The maximum possible carried traffic is the total number of channels, C, in Erlangs. The AMPS cellular system is designed for a GOS of 2% blocking. This implies that the channel allocations for cell sites are designed so that 2 out of 100 calls will be blocked due to channel occupancy during the busiest hour.

There are two types of trunked systems which are commonly used. The first type offers no queuing for call requests. That is, for every user who requests service, it is assumed there is no setup time and the user is given immediate access to a channel if one is available. If no channels are available, the requesting user is blocked without access and is free to try again later. This type of trunking is called blocked calls cleared and assumes that calls arrive as determined by a Poisson distribution. Furthermore, it is assumed that there are an infinite number of users as well as the following: (a) there are memoryless arrivals of requests, implying that all users, including blocked users, may request a channel at any time; (b) the probability of a user occupying a channel is exponentially distributed, so that longer calls are less likely to occur as described by an exponential distribution; and (c) there are a finite number of channels available in the trunking pool. This is known as an M/M/m/m queue, and leads to the derivation of the Erlang B formula (also known as the blocked calls cleared formula). The Erlang B formula determines the probability that a call is blocked and is a measure of the GOS for a trunked system which provides no queuing for blocked calls. The Erlang B formula is given by

$$Pr[blocking] = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}} = GOS$$

Where C is the number of trunked channels offered by a trunked radio system and A is the total offered traffic.

While it is possible to model trunked systems with finite users, the resulting expressions are much more complicated than the Erlang B result, and the added complexity is not warranted for typical trunked systems which have users that outnumber available channels by orders of magnitude. Furthermore, the Erlang B formula provides a conservative estimate of the GOS, as the finite user results always predict a smaller likelihood of blocking. The capacity of a trunked radio system where blocked calls are lost is tabulated for various values of GOS and numbers of channels in the following Table

Number of Channels *C*	Capacity (Erlangs) for GOS = 0.01	= 0.005	= 0.002	= 0.001
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

The second kind 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 a call is blocked after waiting a specific length of time in the queue. To find the GOS, it is first necessary to find the likelihood that a call is initially denied access to the system. The likelihood of a call not having immediate access to a channel is determined by the Erlang C formula

$$Pr[delay > 0] = \frac{A^C}{A^C + C!\left(1 - \frac{A}{C}\right)\sum_{k=0}^{C-1}\frac{A^k}{k!}}$$

If no channels are immediately available the call is delayed, and the probability that the 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

$$\begin{aligned} Pr[delay > t] &= Pr[delay > 0]Pr[delay > t | delay > 0] \\ &= Pr[delay > 0]\exp(-(C-A)t/H) \end{aligned}$$

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

$$D = Pr[delay > 0]\frac{H}{C-A}$$

Where the average delay for those calls which are queued is given by $H/(C-A)$.

EXAMPLE:

An urban area has a population of two million residents. Three competing trunked mobile networks (systems A, B, and C) provide cellular service in this area. System A has 394 cells with 19 channels each, system B has 98 cells with 57 channels each, and system C has 49 cells, each with 100 channels. Find the number of users that can be supported at 2% blocking if each user averages two calls per hour at average call duration of three minutes. Assuming that all three trunked systems are operated at maximum capacity, compute the percentage market penetration of each cellular provider.

Solution

System A

Given:
Probability of blocking = 2% = 0.02
Number of channels per cell used in the system, C = 19

Traffic intensity per user, Au = λH = 2 × (3/60) = 0.1 Erlangs

For GOS = 0.02 and C = 19, from the Erlang B chart, the total carried traffic, A, is obtained as 12 Erlangs.

Therefore, the number of users that can be supported per cell is
U = A/Au = 12/0.1 = 120

Since there are 394 cells, the total number of subscribers that can be supported by System A is equal to 120 × 394 = 47280

System B

Given:
Probability of blocking = 2% = 0.02
Number of channels per cell used in the system, C = 57

Traffic intensity per user, Au = λH = 2 × (3/60) = 0.1 Erlangs

For GOS = 0.02 and C = 57, from the Erlang B chart, the total carried traffic, A, is obtained as 45 Erlangs.

Therefore, the number of users that can be supported per cell is
U = A/Au = 45/0.1 = 450

Since there are 98 cells, the total number of subscribers that can be supported by System B is equal to 450 × 98 = 44,100

System C

Given:
Probability of blocking = 2% = 0.02
Number of channels per cell used in the system, C = 100

Traffic intensity per user, Au = λH = 2 × (3/60) = 0.1 Erlangs

For GOS = 0.02 and C = 100, from the Erlang B chart, the total carried traffic, A, is obtained as 88 Erlangs.

Therefore, the number of users that can be supported per cell is
U = A/Au = 88/0.1 = 880

Since there are 49 cells, the total number of subscribers that can be supported by System C is equal to 880 × 49 = 43,120

Therefore, total numbers of cellular subscribers that can be supported by these three systems are 47,280 + 44,100 + 43,120 = 134,500 users.

Since there are two million residents in the given urban area and the total number of cellular subscribers in System A is equal to 47280, the percentage market penetration is equal to

47,280/2,000,000 = 2.36%

Similarly, market penetration of System B is equal to
44,100/2,000,000 = 2.205%

and the market penetration of System C is equal to
43,120/2,000,000 = 2.156%

The market penetration of the three systems combined is equal to

134,500/2,000,000 = 6.725%

MULTIPLE ACCESS SCHEMES

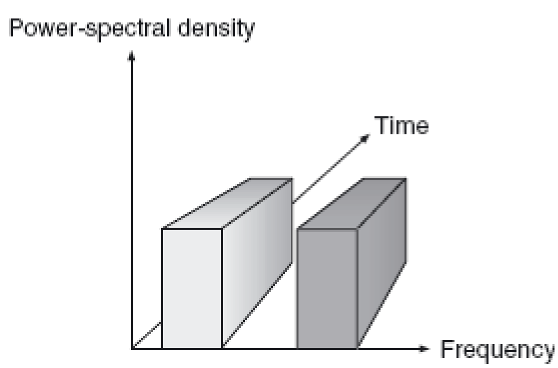
Multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum.
Various multiple access schemes are:

- **Frequency Division Multiple Access:** Different frequencies are assigned to different users.
- **Time Division Multiple Access:** Different timeslots are assigned to different users.
- **Code Division Multiple Access:** Each user is assigned a different code.
- **Packet Radio:** A form of TDMA, where the assignment of timeslots to users is adaptive.

The goal of all multiple access methods is to maximize spectral efficiency – i.e., to maximize the number of users per unit bandwidth.

Frequency Division Multiple Access (FDMA)

Frequency division multiple access (FDMA) assigns individual channels to individual users. The 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.



Features of FDMA

- The FDMA channel carries only one phone circuit at a time.
- If an FDMA channel is not in use, then it cannot be used by other users to increase capacity.
- After the assignment of a channel, the BS and the mobile transmit simultaneously and continuously.
- Since FDMA is a continuous transmission scheme, fewer bits are needed for overhead purposes.
- FDMA is usually implemented in narrowband systems.
- The amount of inter-symbol interference is low. So little or no equalization is required in FDMA narrowband systems.
- The FDMA mobile unit uses duplexers.
- FDMA requires tight RF filtering to minimize adjacent channel interference.

Advantages

1. The transmitter (TX) and receiver (RX) require little digital signal processing.
2. (Temporal) synchronization is simple. Once synchronization has been established during the call setup, it is easy to maintain it by means of a simple tracking algorithm, as transmission occurs continuously.

Disadvantages

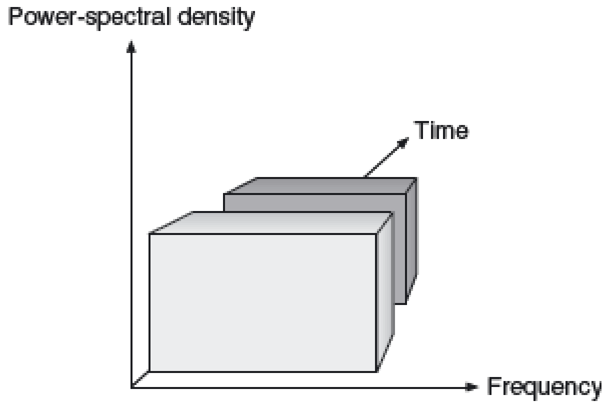
1. Frequency synchronization and stability are difficult
2. Sensitivity to fading
3. Sensitivity to random Frequency Modulation (FM)
4. Intermodulation

Nonlinear effects in FDMA

In a FDMA system, many channels share the same antenna at the base station. The power amplifiers or the power combiners are nonlinear. The nonlinearities cause signal spreading in the frequency domain and generate intermodulation (IM) frequencies. IM is undesired RF radiation which can interfere with other channels in the FDMA systems. Spreading of the spectrum results in adjacent-channel interference. **Intermodulation** is the generation of undesirable harmonics.

Time Division Multiple Access (TDMA)

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.
A time unit is subdivided into N timeslots of fixed duration, and each user is assigned one such timeslot. During the assigned timeslot, the user can transmit with a high data rate. Then, it remains silent for the next $N - 1$ timeslots, when other users take their turn. This process is then repeated periodically.



TDMA systems transmit data in a buffer-and-burst method, thus the transmission for any user is non-continuous. So, unlike in FDMA systems which accommodate analog FM, digital data and digital modulation must be used with TDMA.

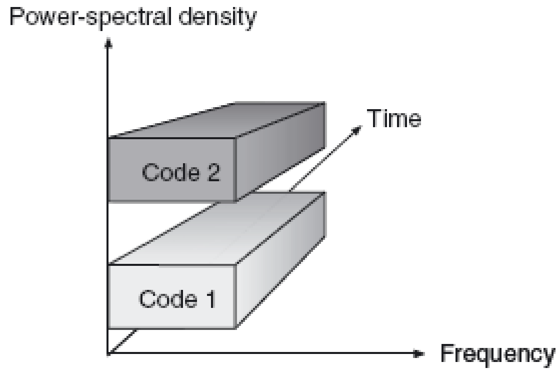
Features of TDMA

- TDMA shares a single carrier frequency with several users, where each user makes use of non-overlapping time slots.
- Data transmission for users of a TDMA system is not continuous, but occurs in bursts. This results in low battery consumption.
- Because of discontinuous transmissions in TDMA, the handoff process is much simpler for a subscriber unit
- TDMA uses different time slots for transmission and reception, thus duplexers are not required.
- Adaptive equalization is usually necessary in TDMA systems, since the transmission rates are generally very high as compared to FDMA 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. In addition, guard slots are necessary to separate users. So the TDMA systems having larger overheads as compared to FDMA.

Code Division Multiple Access (CDMA)

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 code sequence** that has a chip rate which is orders of magnitudes greater than the data rate of the message. Each user has its own **pseudorandom code word** which is approximately orthogonal to all other code words.
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 detection of the message signal, the receiver needs to know the code word used by the transmitter.



Features of CDMA

- Many users of a CDMA system share the same frequency. Either TDD or FDD may be used.
- Unlike TDMA or FDMA, CDMA has a soft capacity limit. The system performance gradually degrades for all users as the number of users is increased, and improves as the number of users is decreased.
- Frequency-dependent transmission impairments (such as noise bursts and selective fading) have less effect on the signal.
- Multipath fading may be substantially reduced because the signal is spread over a large spectrum.
- Channel data rates are very high in CDMA systems.
- Since CDMA uses co-channel cells, it can use macroscopic spatial diversity to provide soft handoff.
- The near-far problem occurs at a CDMA receiver if an undesired user has a high detected power as compared to the desired user.

	FDMA	*TDMA*	*CDMA*
Modulation	▪ Relies on bandwidth-efficient modulation	▪ Relies on bandwidth-efficient modulation	▪ Simple modulation
Diversity	▪ Requires multiple transmitters or receivers	▪ Requires multiple transmitters or receivers ▪ Can be frequency-hopped	▪ Includes frequency diversity when implemented with a RAKE receiver
User terminal complexity	▪ simple	▪ Medium complexity	▪ More complex
Handover	▪ hard	▪ hard	▪ Soft
System complexity	▪ Large number of simple components	▪ Reduced number of channel units	▪ Large number of complex interacting components

Multiple-Access interference	▪ Limited by system planning	▪ Limited by system planning	▪ Dynamic power control
Fading	▪ Flat-fading ▪ No diversity ▪ Simple to track	▪ May be frequency-selective ▪ May need equalizer	▪ Frequency-selective diversity via RAKE receiver

Packet Radio

In packet radio (PR) access techniques, many subscribers attempt to access a single channel in an uncoordinated (or minimally coordinated) manner. Transmission is done by using bursts of data. Packet radio access schemes break data down into packets, and each of the packets is transmitted over the medium independently.

Packet radio shows two main differences from TDMA and FDMA:

1. Each packet has to fight for its own resources. The most common methods for resource allocation are ALOHA systems, Carrier Sense Multiple Access (CSMA), and packet reservation (polling).
2. Each packet can be routed to the RX in different ways – i.e., via different relay stations.

ALOHA

Pure ALOHA: The pure ALOHA protocol is a random access protocol used for data transfer. A user accesses a channel as soon as a message is ready to be transmitted. After a transmission, the user waits for an acknowledgment on either the same channel or a separate feedback channel. In case of collisions the terminal waits for a random period of time and retransmits the message.

Slotted ALOHA: In slotted ALOHA, time is divided into equal time slots of length greater than the packet duration. The subscribers each have synchronized clocks and transmit a message only at the beginning of a new time slot, thus resulting in a discrete distribution of packets.

Carrier Sense Multiple Access

A TX can determine (*sense*) whether the channel is currently occupied by another user (*carrier*). This knowledge can be used to increase the efficiency of a packet-switched system. If one user is transmitting, no other user is allowed to send a signal. Such a method is called **CSMA**.