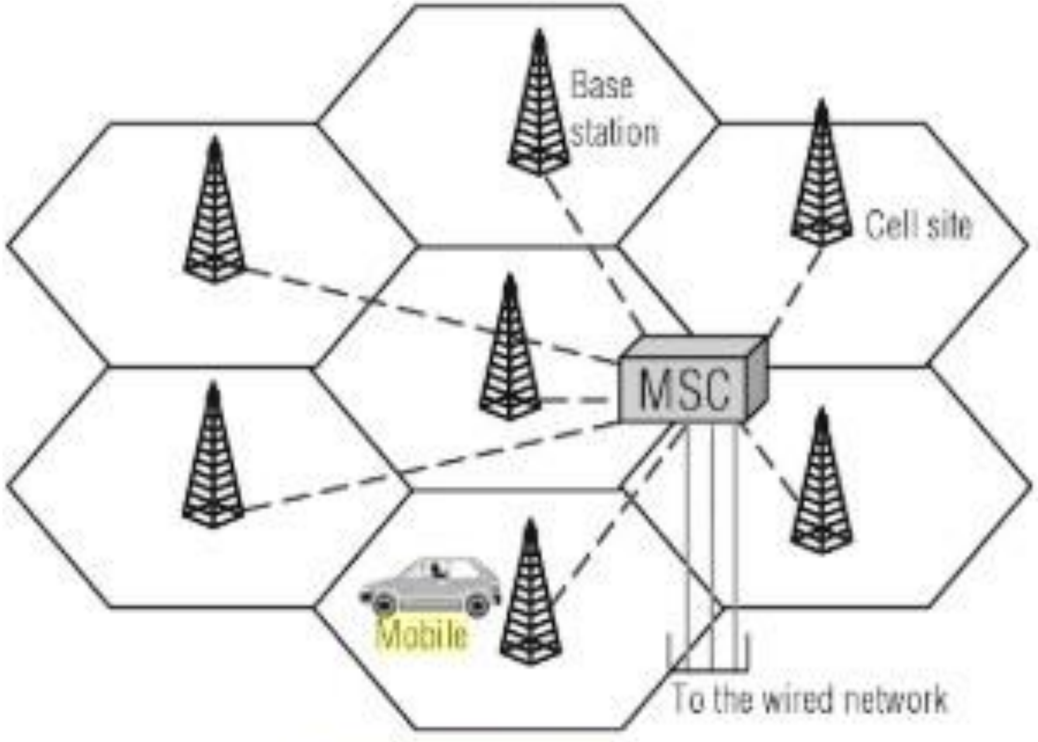
Introduction

- Around the globe, billions of subscribers are using mobile phones and this number is increasing rapidly. So mobile communications need to offer efficiency in the use of available frequency spectrum without any mutual interference.
- For eg., each channel in the analog cellular system needs 25 kHz bandwidth that includes guard bands between adjacent channels to ensure no co-channel interference and also to offer sufficient voice quality.
- If the available frequency spectrum is 1MHz wide, then we can accommodate only 40 users.
- Even if the spectrum increases to 100 MHz, only 4000 users could still be accommodated.

- The main objective of cellular system design is to handle as many calls as possible in a given bandwidth in the most efficient way with reliability and quality of service.
- To achieve this objective, the cellular system employs two crucial features known as Frequency reuse and Cell splitting.
- Frequency reuse refers to the usage of the same frequency carrier in different geographical locations that are distant enough so that the interference caused by using the same carrier is not a problem. The reason for the application of frequency reuse is to increase the number of simultaneous calls.
- Cell splitting refers to the reconfiguration of a cell into smaller cells. This allows the system to adjust to an increase in the traffic demand in certain areas or in the whole network without any increase in the spectrum allocation.

- The geographical areas covered by cellular radio antennas are called cells. The cell site antenna is located at a point within the cell.
- The cellular concept is a system-level idea which calls for replacing a single, high power transmitter (large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of the service area.
- Each base station is allocated a portion of the total number of channels available to the entire system, and nearby base stations are assigned different groups of channels so that all 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.
- As the demand for service increases the number of base stations may be increased thereby providing additional radio capacity with no additional increase in radio spectrum.

- **In mobile communication ‘cells’ represent a small geographic area which is why the technology is referred to as ‘cellularphone’.**
- **Users are called Mobile stations (MS) which receive and transmit calls while moving in a cellular network.**
- **Each cell has a Base station(BS) that supplies frequency channels to MS s. BS is also referred to as cell sites.**
- **The Base stations are linked to a mobile switching centre (MSC) which is responsible for controlling the calls and acting as gateway to other networks.**

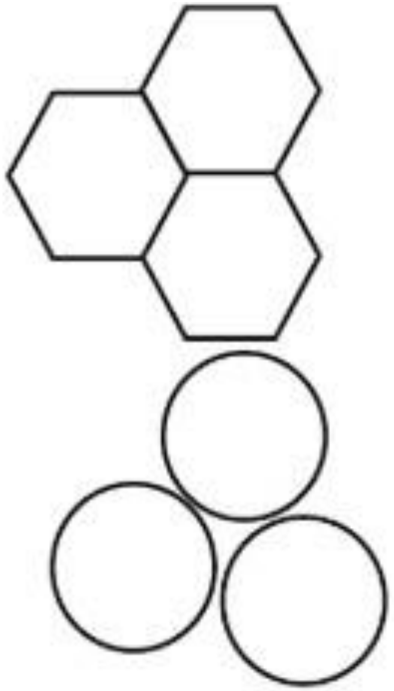


Mobile cellular system architecture

Cellular geometry

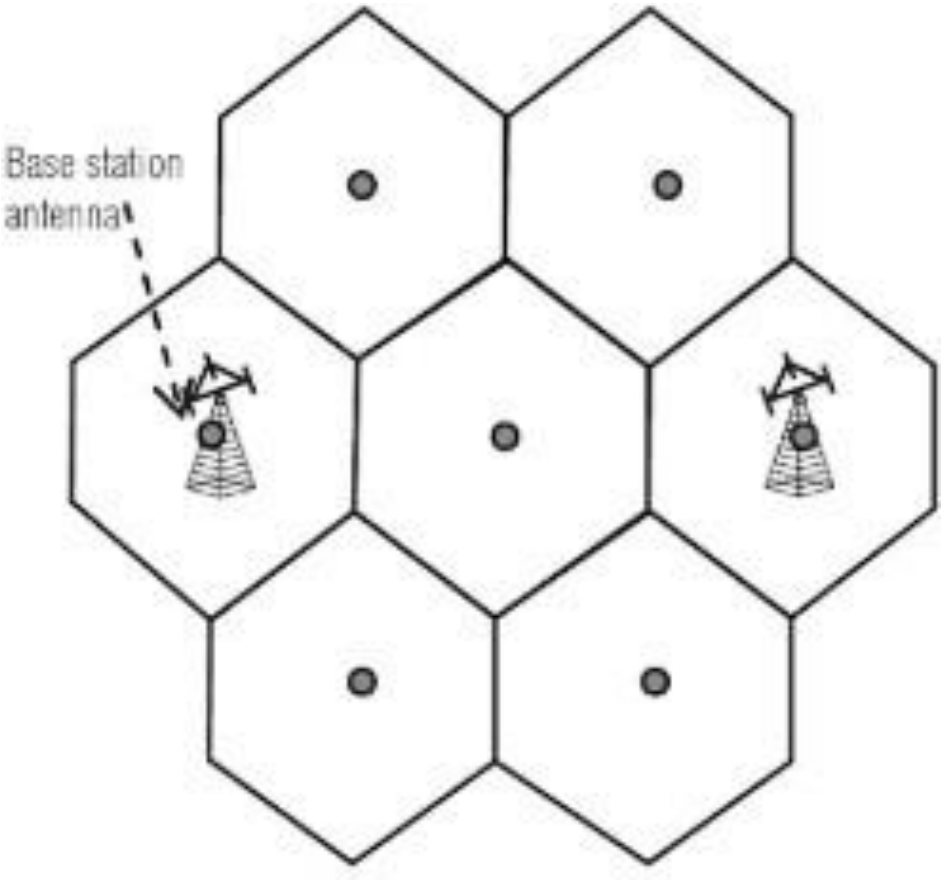
- Cells are assumed to have a regular hexagonal shape.
- The reasons for choosing this geometry are explained here.
- When considering geometric shapes which cover an entire region without overlap and with equal area, there are three sensible choices—a square, an equilateral triangle, and a hexagon.
- A circle also may be chosen naturally to represent the coverage area of a base station. However adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions.
- For a given distance between the center of a polygon and its farthest perimeter points, the hexagon has the largest area of the three.

Different cell shapes



Gaps in the circular cells

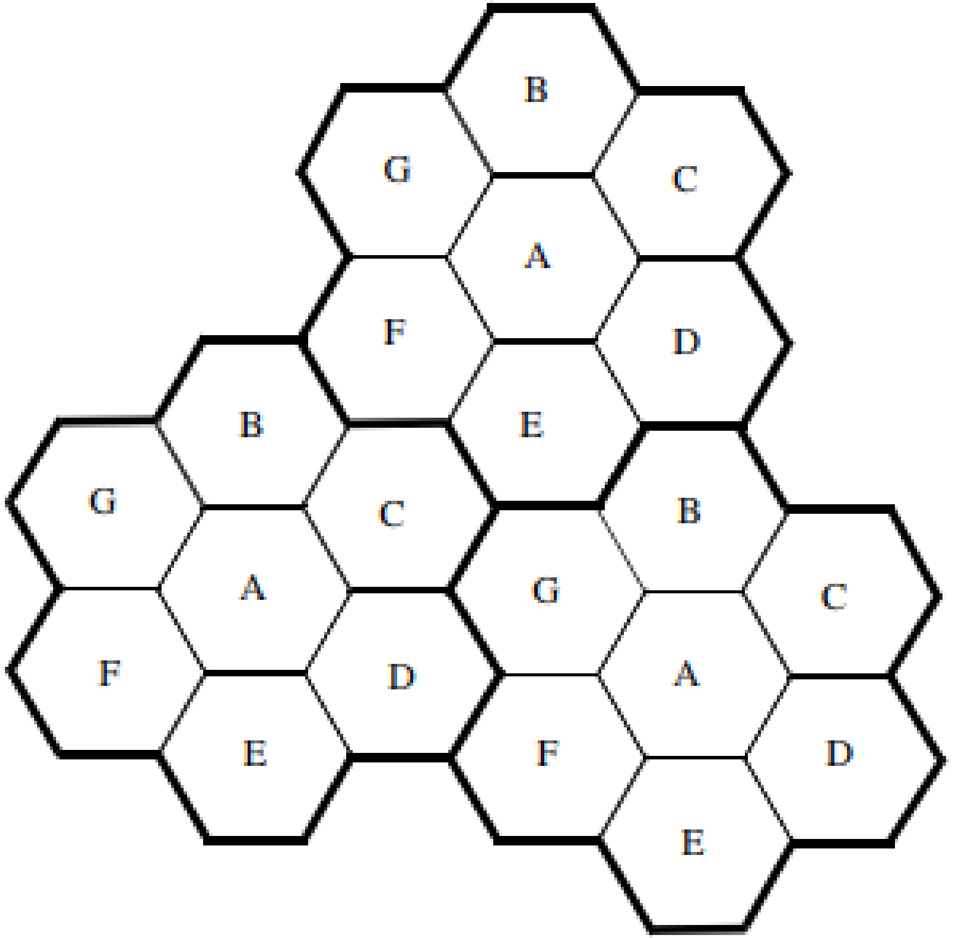
- By using the hexagon geometry, the fewest number of cells can cover a geographic region, and the hexagon closely approximates a circular radiation pattern which would occur for an omnidirectional base station antenna and free space propagation.
- The actual radio coverage of a cell is known as the footprint and is determined from field measurements or propagation prediction models. A cell must be designed to serve the weakest mobiles within the footprint, and these are typically located at the edge of the cell.
- When using hexagons to model coverage areas, base station transmitters are depicted as either being in the center of the cell (center-excited cells) or on three of the six cell vertices (edge-excited cells). Normally, omnidirectional antennas are used in center-excited cells and sectored directional antennas are used in corner-excited cells.



Antenna positioning

Frequency Reuse

- Base stations in adjacent cells are assigned channel groups which contain completely different channels 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.
- Figure illustrates the concept of cellular frequency reuse,
- Cells labelled with the same letter use the same group of channels.
- A cell cluster is outlined in bold and replicated over the coverage area.
- The cluster size is 7 and the frequency reuse factor is 1/7 since each cell contains 1/7 of the total number of available channels.`



- Consider a cellular system which has a total of S duplex channels available for use.
- Each cell is allocated a group of k channels ($k < S$)
- The S channels are divided among N cells into unique and disjoint channel groups which each having the same number of channels.
- Then the total number of available radio 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 by

$$C=MkN=MS$$

- Thus 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 (a larger value of C) is achieved.
- A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is small. Conversely, a small cluster size indicates that co-channel cells are located much closer together.

- The smallest possible value of N is desirable in order to maximize capacity over a given coverage area (i.e., to maximize C .
- 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.
- The hexagonal geometry has exactly six equidistant neighbours and the lines joining the centres of any cell and each of its neighbours are separated by multiples of 60 degrees.
- Hence to connect without gaps between adjacent cell, the geometry of hexagons is such that the number of cells per cluster, N, can only have values which satisfy the 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, one must
- 1.move i cells along any chain of hexagons and then
- 2. turn 60 degrees counter-clockwise and move j cells.

- **Example:**
- **A total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system. It uses two 25 kHz simplex channels to provide full duplex voice and control channels.**
- **Compute the number of channels available per cell if a system uses**
- **(a) four-cell reuse,**
- **(b) seven-cell reuse, and**
- **(c) 12-cell reuse.**
- **If 1MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control channels and voice channels in each cell for each of the three systems.**

Solution:

Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz × 2 simplex channels = 50 kHz/duplex channel

Total available channels = 33,000/50 = 660 channels

(a) For N = 4,

Total number of channels available per cell = 660/4 ≈ 165 channels.

(b) For N = 7,

Total number of channels available per cell = 660/7 ≈ 95 channels.

(c) For N = 12,

Total number of channels available per cell = 660/12 ≈ 55 channels

Solution:

- 1 MHz spectrum for control channels means there are 1000/50 =20 control channels out of the 660 channels available.
- To evenly distribute the control and voice channels allocate the same number of voice channels in each cell wherever possible. Thus the 660 channels must be evenly distributed to each cell within the cluster. In practice, only the 640 voice channels would be allocated, since the control channels are allocated separately as 1 per cell.
- (a) For N = 4, we can have five control channels and 160 voice channels per cell.
- (b) For N = 7, four cells with three control channels and 92 voice channels, two cells with three control channels and 90 voice channels, and one cell with two control channels and 92 voice channels could be allocated.
- (c) For N = 12, we can have eight cells with two control channels and 53 voice channels, and four cells with one control channel and 54 voice channels each.

Channel assignment strategies can be classified as

- Fixed or
- Dynamic.

The choice of channel assignment strategy determines the performance of the system, particularly as to how calls are managed when a mobile user is handed off from one cell to another .

- Fixed channel assignment strategy: Each cell is allocated a predetermined set of voice channels. Any call attempt within 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 subscriber does not receive service. Several variations of the fixed assignment strategy exist. In one approach, called the borrowing strategy, a cell is allowed to borrow channels from a neighboring cell if all of its own channels are already occupied. The mobile switching center (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell.

- **Dynamic channel assignment strategy: Voice channels are not allocated to different cells permanently. Instead, each time a call request is made, the serving base station requests 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 likelihood of 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 indications (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.**

Handoff Strategies

- 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.
- Handoffs must be performed successfully and as infrequently as possible.
- System designers must specify an optimum signal level at which to initiate a handoff.
- A particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver.
- A slightly stronger signal level is used as a threshold at which a handoff is made.
- This margin, given by $\Delta = P_{r\ handoff} - P_{r\ minimum\ usable}$, cannot be too large or too small.
- If Δ is too large, unnecessary handoffs which burden the MSC may occur, and if Δ is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions.
- Handoffs are broadly of two categories: Hard Handoff and Soft Handoff
- Hard handoff is break-before –make. The connection to the old BS is broken before a connection to the new BS is made. Hard handoff is further divided into intercellular and intracellular types.
- Soft handoff is make-before-break. The connection to the old BS is not broken until connection to the new BS is made.

- **Figure illustrates a handoff situation**
- **Fig(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 Δ is set too small for the handoff time in the system.**
- **Fig (b) shows a situation where the handoff is carried out properly.**

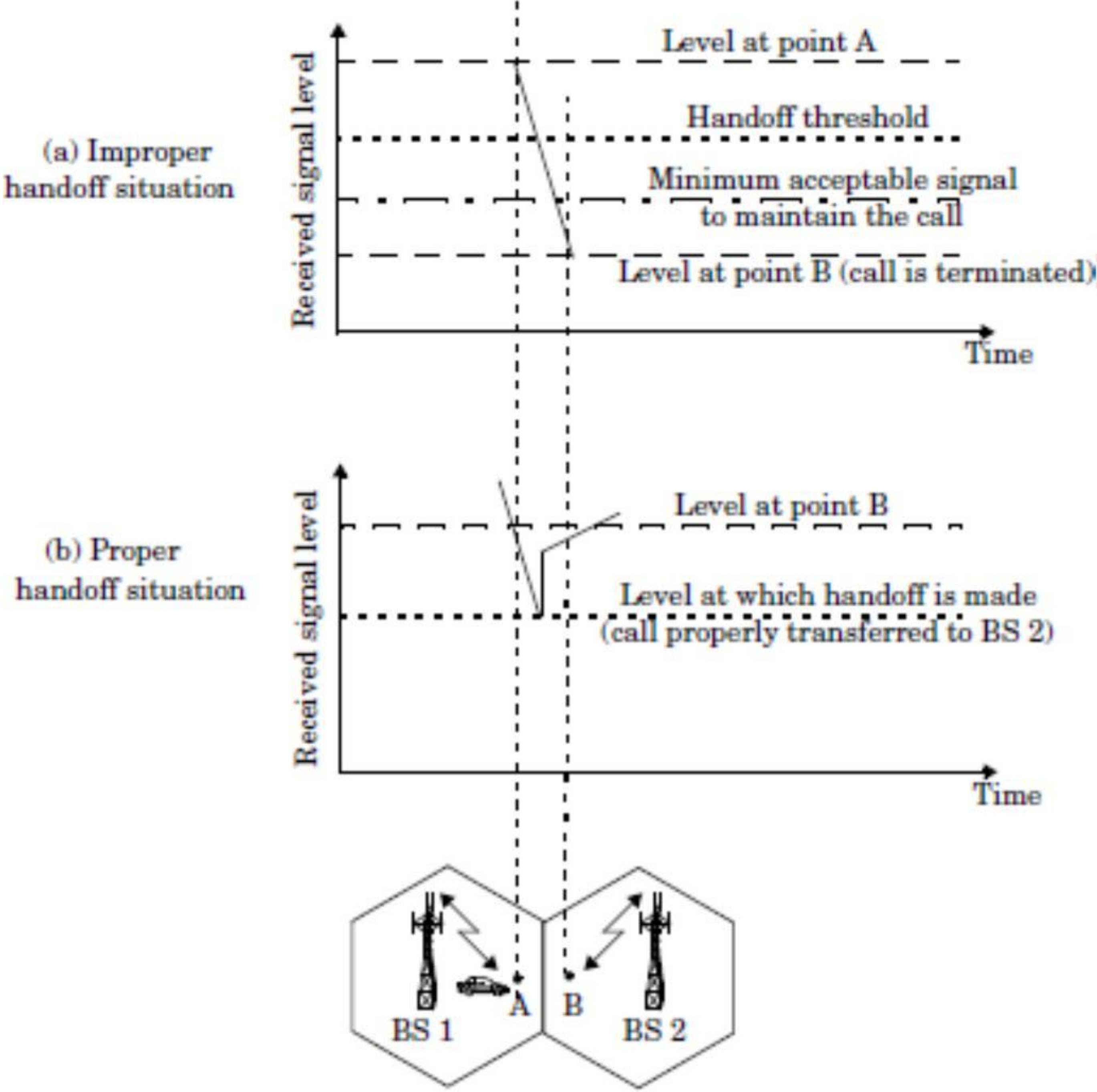


Illustration of a handoff scenario at cell boundary.

- The time over which a call may be maintained within a cell, without handoff, is called the dwell time.
- Mobile assisted Handoff (MAHO): In today's second generation systems, handoff decisions are mobile assisted. In mobile assisted handoff (MAHO), every mobile station measures the received power from surrounding base stations and continually reports the results of these measurements to the serving base station. A handoff is initiated when the power received from the base station of a neighboring cell begins to exceed the power received from the current base station by a certain level or for a certain period of time. The MAHO method enables the call to be handed over between base stations at a much faster rate than in first generation analog systems since the handoff measurements are made by each mobile, and the MSC no longer constantly monitors signal strengths. MAHO is particularly suited for microcellular environments where handoffs are more frequent.
- Intersystem Handoff: During the course of a call, if a mobile moves from one cellular system to a different cellular system controlled by a different MSC, an intersystem handoff becomes necessary. An MSC engages in an intersystem handoff when a mobile signal becomes weak in a given cell and the MSC cannot find another cell within its system to which it can transfer the call in progress.

Interference and System Capacity

- Interference is the major limiting factor in the performance of cellular radio systems.
- Sources of interference include

❑ Another mobile in the same cell,

❑ A call in progress in a neighboring cell,

❑ Other base stations operating in the same frequency band,

❑ Any noncellular system which accidentally leaks energy into the cellular frequency band

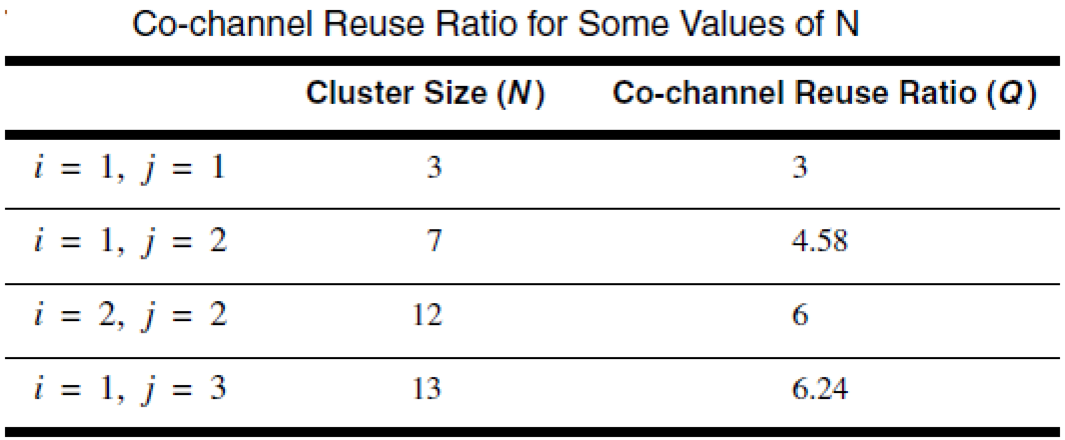
- Interference on voice channels causes cross talk, where the subscriber hears interference in the background due to an undesired transmission.
- On control channels, interference leads to missed and blocked calls due to errors in the digital signaling.
- Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls.
- The two major types of system-generated cellular interference are

❑ Co-channel interference (CCI) and

❑ Adjacent channel interference (ACI)

- **Co-channel Interference(CCI): Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called co-channel cells, and the interference between signals from these cells is called co-channel interference. The distance between co-channel cells is known as co-channel distance or frequency reuse cells**
- **To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation.**
- **In a cellular system of equal cell size, the CCI is a function of frequency reuse factor Q. the frequency reuse factor Q is defined as the ratio of the distance between centers of the nearest co-channel cells (D) and the cell radius (R) of the cell and is known as the D/R ratio.**

- **For a hexagonal geometry $Q = \frac{D}{R} = \sqrt{3N}$ where N is the cluster size.**
- **Also from cell geometry of hexagon $N = i^2 + ij + j^2$**



Co-channel Reuse Ratio for Some Values of N

	Cluster Size (N)	Co-channel Reuse Ratio (Q)
$i = 1, j = 1$	3	3
$i = 1, j = 2$	7	4.58
$i = 2, j = 2$	12	6
$i = 1, j = 3$	13	6.24

- **If i_0 is the number of co-channel interfering cells, the signal-to-interference ratio is** $$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$
- **If path loss in propagation is considered , the S/I ratio modifies to** $$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

Where n is the path loss exponent which typically ranges between two and four in urban cellular systems

- Adjacent Channel Interference(ACI): 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.
- 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.
- By sequentially 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.
- In practice, base station receivers are preceded by a high Q cavity filter in order to reject adjacent channel interference.

Trunking and Grade of Service

- Trunking is used by cellular radio systems to accommodate a large number of users in a limited radio spectrum. Trunking allows a large number of users to share the relatively small number of channels in a cell.
- Each user is provided access on demand, from a pool of available channels.
- Each user is allocated a channel on a per call basis. 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 fundamentals of trunking theory were developed by **Erlang,** a Danish mathematician who demonstrated how a large population could be accommodated by a limited number of servers. 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 GOS 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.
- 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.
- Trunking efficiency is a measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels.
- The ERLANG FORMULA is used to estimate the GOS for two types of trunking known as i. Blocked calls cleared and ii. Blocked calls delayed
- Thus the Erlang B formula applies to Blocked calls cleared and the Erlang C formula applies to the Blocked call delayed type of trunking.

- 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.
- Erlang B formula is also known as the blocked calls cleared formula and is given as

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

C is the number of trunked channels offered by a trunked radio system

A is the total offered traffic.

- The Erlang C formula states the likelihood of a call not having immediate access to a channel. It is given by,

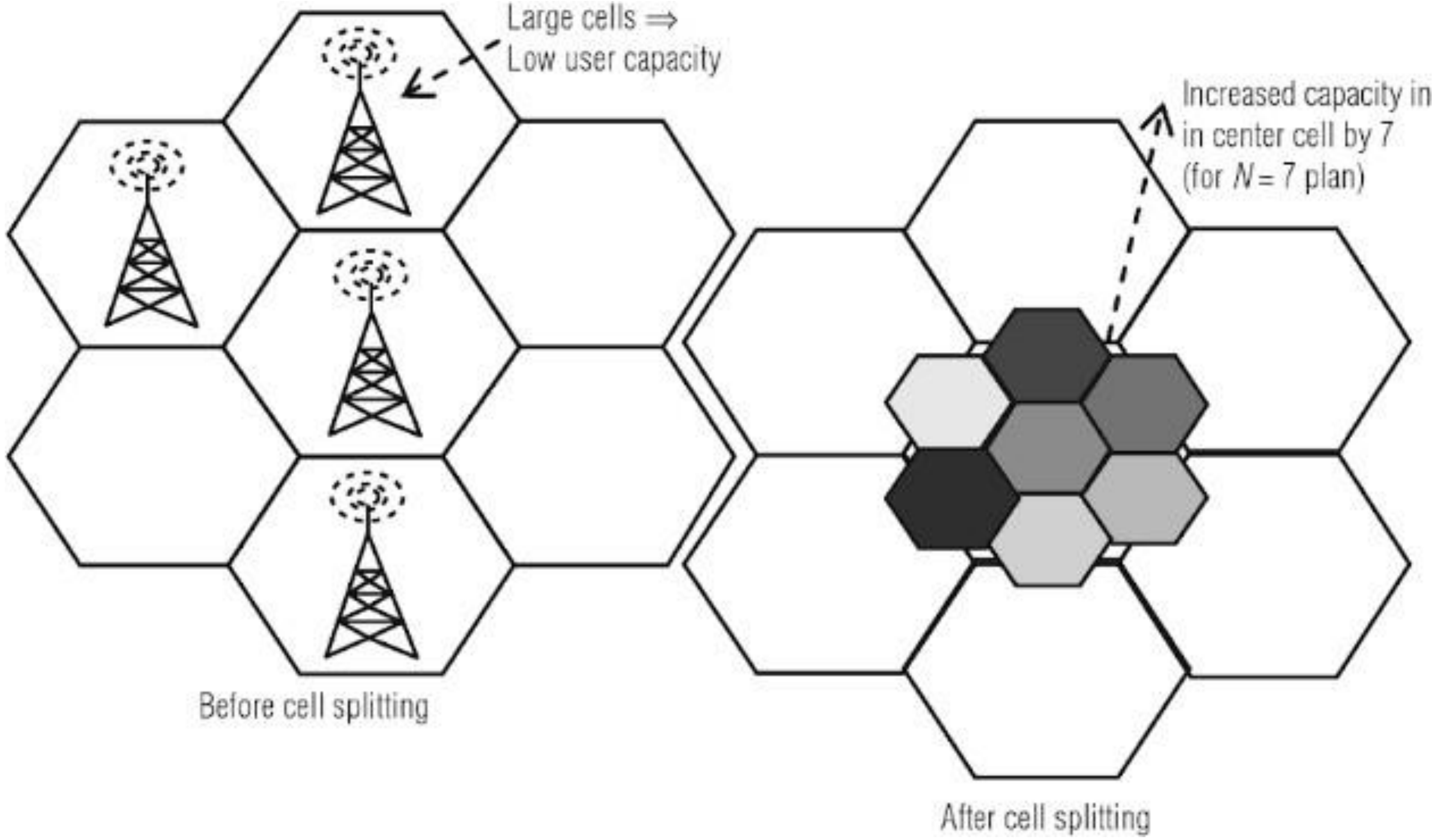
$$Pr[delay > 0] = \frac{A^C}{A^C + C!\left(1 - \frac{A}{C}\right)\sum_{k=0}^{C-1} \frac{A^k}{k!}}$$

Improving Coverage and Capacity in Cellular Systems

- As the demand for wireless service increases, the number of channels assigned to a cell becomes insufficient to support the required number of users. Hence design techniques that provide more channels per unit coverage area are required.
- 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 where capacity is increased by increasing the number of base stations.
- Sectoring uses placement of directional antennas to further control the co-channel 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.
- Cell splitting and zone microcell techniques do not suffer the trunking inefficiencies experienced by sectored cells. The base station takes care of handoff of microcells. Thus the computational load at the MSC is reduced.

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 (called microcells) between the existing cells, capacity increases due to the additional number of channels per unit area.



- The base stations are placed at corners of the cells, and the area served by base station A is assumed to be saturated with traffic.
- New base stations are therefore needed in the region to increase the number of channels in the area and to reduce the area served by the single base station.
- Thus smaller cells are added in such a way as to preserve the frequency reuse plan of the system.
- The cell A is split into several cells called Microcells
- The area of a cell is proportional to R^2. Thus splitting reduces the new cell radius to one-half of its original value. This means that the area of cell reduces to one quarter of its original value. Theoretically 4 quarter-size cells can fit into one full size hexagonal cell.

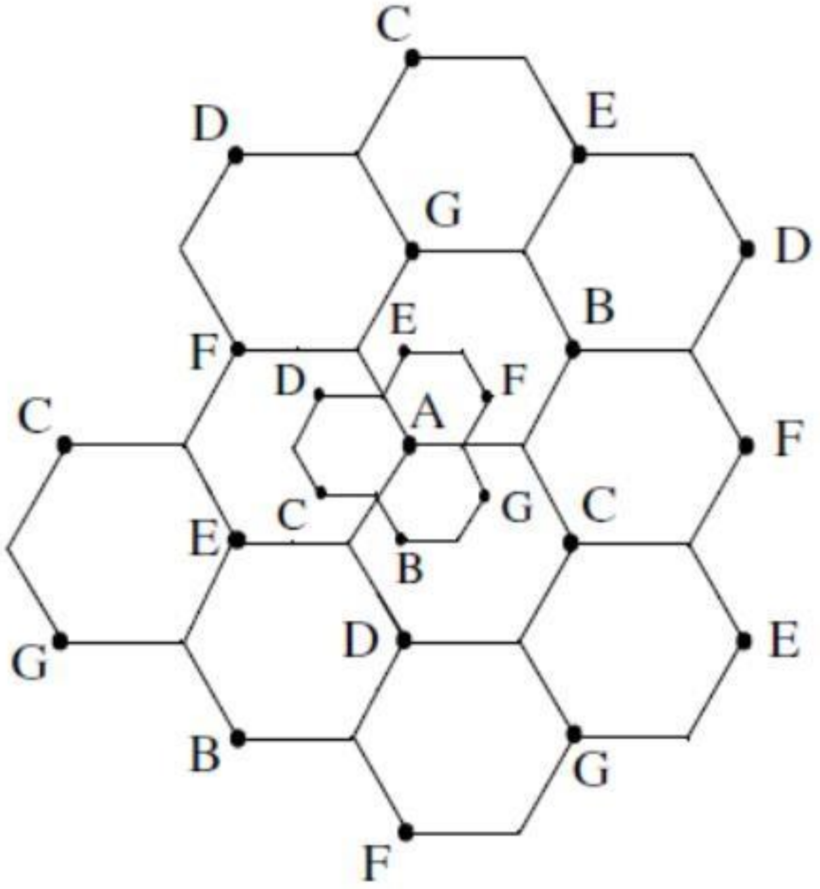
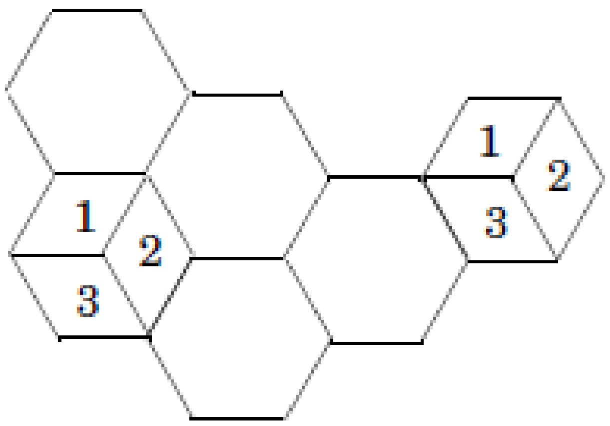


Illustration of cell splitting.

- 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 smaller new cells the transmit power must be reduced.
- This an be found by examining the received power P_r at the new and old cell boundaries and setting them equal to each other. This ensures that the frequency reuse plan remains unchanged for the new cells.
- P_r[at old cell boundary] $\propto P_{t1}R^{-n}$ and P_r[at new cell boundary] $\propto P_{t2}R^{-n}$
- 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 $P_{t2} = \frac{P_{t1}}{16}$
- In other words, the transmit power must be reduced by 12 dB in order to fill in the original coverage area with microcells, while maintaining the S/I requirement

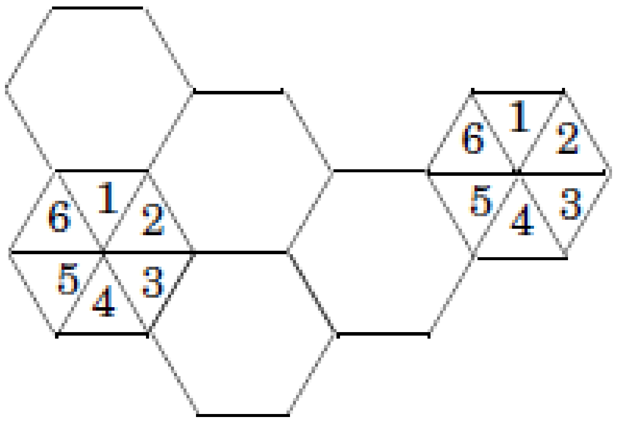
Sectoring

- Sectoring consists of increasing capacity by using directional antennas and decrease the co-channel interference.
- Sectoring increases SIR so that the cluster size may be reduced.
- First the Signal to interference ratio (SIR) is reduced by using directional antennas
- Then the number of cells are decreased thereby increasing frequency reuse and capacity.
- The co-channel interference in a cellular system may be decreased by replacing a single omnidirectional antenna at the base station by several directional antennas, each radiating within a specified sector.
- By using directional antennas, a given cell will receive interference and transmit with only a fraction of the available co-channel cells.
- 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



(a)

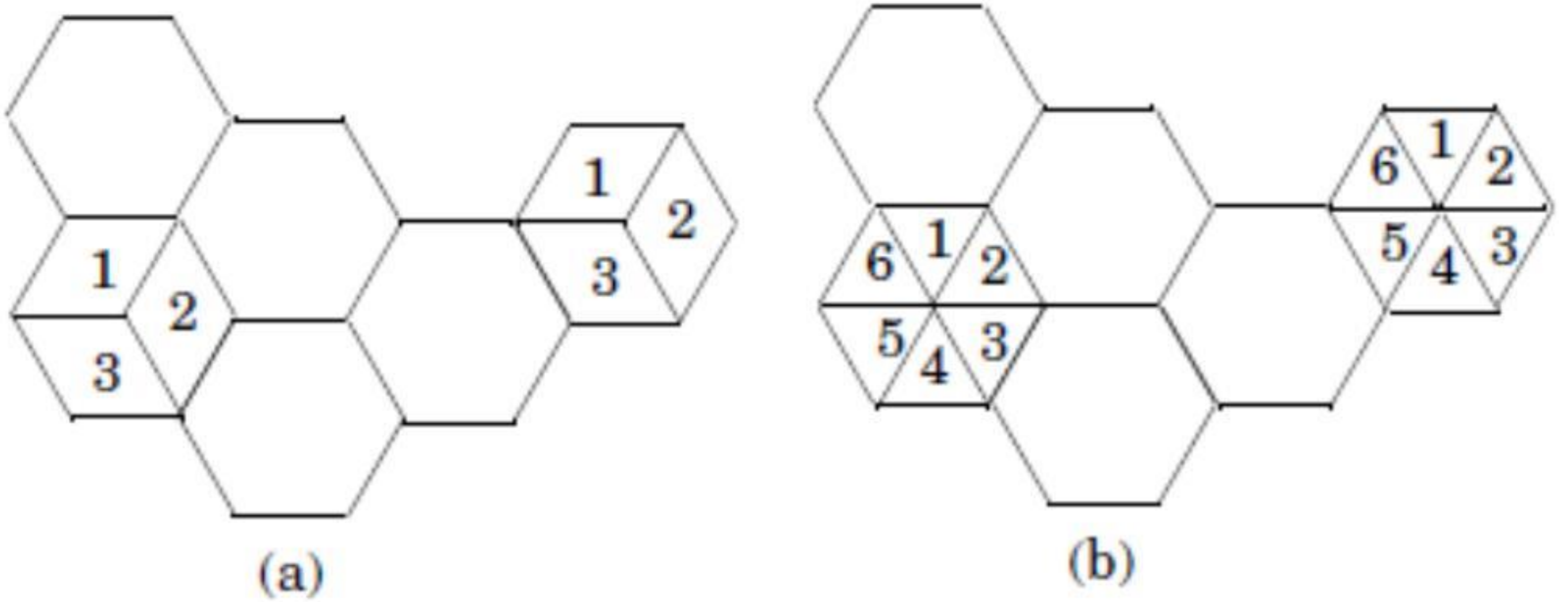
(a) 120° sectoring;



(b)

(b) 60° sectoring.

- 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.
- Assuming seven-cell reuse, for the case of 120° sectors, the number of interferers in the first tier is reduced from six to two. This is because only two of the six co-channel cells receive interference with a particular sectored channel group.
- Sectoring reduces the coverage area of a particular group of channels, thus the number of handoffs also increases.



(a) 120° sectoring; (b) 60° sectoring.

Repeaters for Range Extension

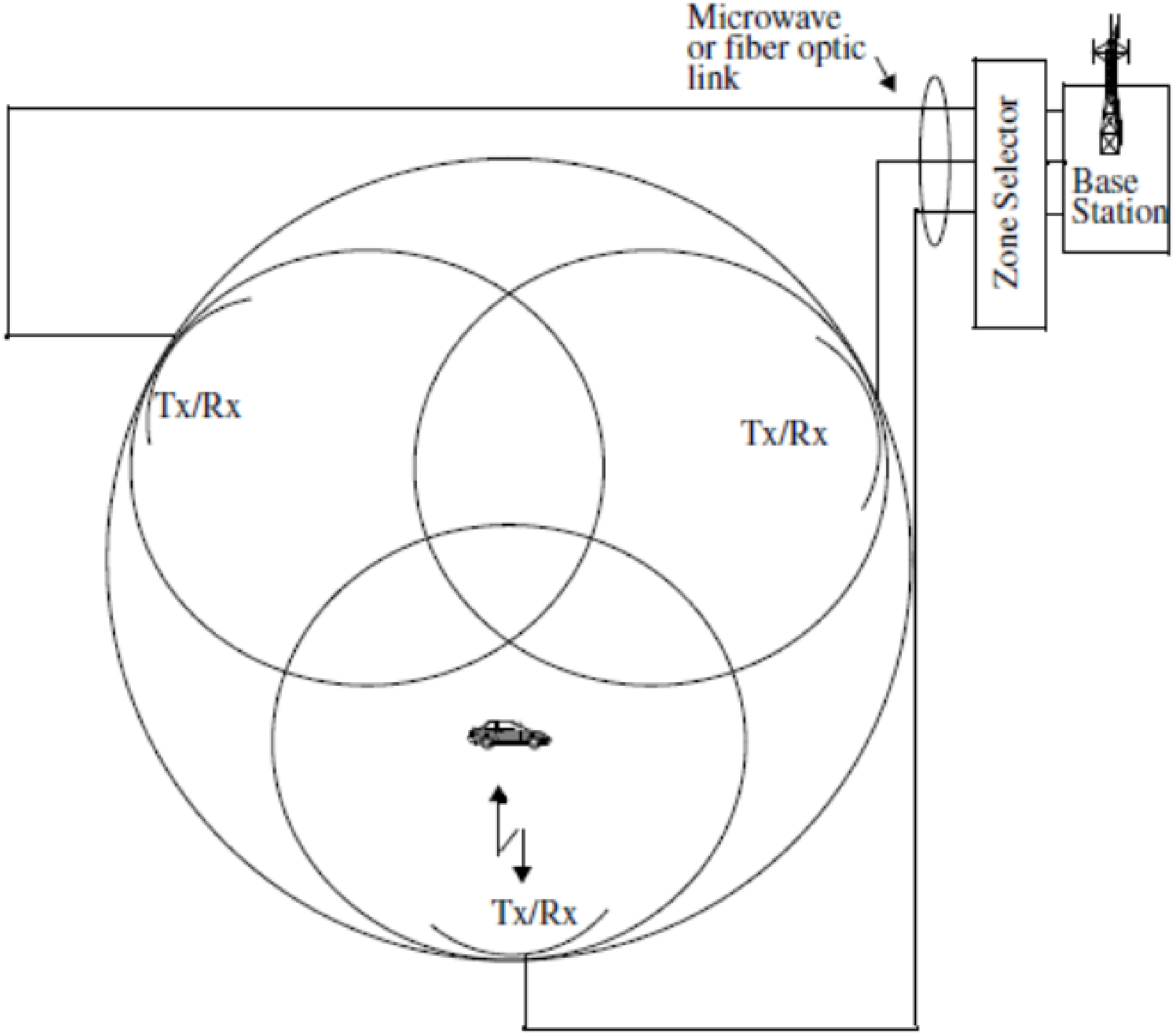
- To provide dedicated coverage for hard-to-reach areas, thereby extending the range, radio retransmitters, known as repeaters, are often used.
- Repeaters are bidirectional in nature, and simultaneously send signals to and receive signals from a serving base station.
- Repeaters work using over-the-air signals, so they may be installed anywhere and are capable of repeating an entire cellular or PCS band.
- Upon receiving signals from a base station forward link, the repeater amplifies and reradiates the base station signals to the specific coverage region.
- Unfortunately, the received noise and interference is also reradiated by the repeater on both the forward and reverse link, so care must be taken to properly place the repeaters, and to adjust the various forward and reverse link amplifier levels and antenna patterns.
- In practice, directional antennas or distributed antenna systems (DAS) are connected to the inputs or outputs of repeaters for localized spot coverage, particularly in tunnels or buildings

Microcell Zone

- Sectoring increases the load on the switching and control link elements of the mobile system due to the increased number of handoffs required.
- A solution to this problem is based on a microcell concept for seven cell reuse.
- In this scheme, each of the three or more zone sites are connected to a single base station and share the same radio equipment. The zones are connected by coaxial cable, fiber optic cable, or microwave link to the base station.
- Multiple zones and a single base station make up a cell. As a mobile travels within the cell, it is served by the zone with the strongest signal.
- As a mobile travels from one zone to another within the 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 traveling, and hence the base station radiation is localized and interference is reduced.

Advantages of microcell zone

- A given channel is active only in the particular zone. Thus, interference is reduced and capacity is increased.
- While the cell maintains a particular coverage radius, the co-channel interference in the cellular system is reduced.
- Decreased co-channel interference improves the signal quality
- Degradation of trunking efficiency is eliminated.
- Handoff are reduced.



The microcell concept

Radio wave propagation models

The mechanisms behind radio wave propagation can be generaaly attributed to

- Reflection
- Diffraction
- Scattering
- Most cellular radio systems operate in urban areas where there is no direct line-of-sight path between the transmitter and the receiver.
- Due to multiple reflections from various objects, the electromagnetic waves travel along different paths of varying lengths.
- The interaction between these waves causes multipath fading at a specific location, and the strengths of the waves decrease as the distance between the transmitter and receiver increases.
- Propagation models have traditionally focused on predicting the average received signal strength at a given distance from the transmitter, as well as the variability of the signal strength in close spatial proximity to a particular loca tion.

- **Propagation models focus on predicting the average received signal strength at a given distance from the transmitter, and the variability of the signal strength in close spatial proximity to a particular location.**
- **Two types of models:**
- **Large-scale Propagation models: Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver (T-R) separation distance are useful in estimating the radio coverage area of a transmitter. They characterize signal strength over large T-R separation distances (several hundreds or thousands of meters). As the mobile moves away from the transmitter over much larger distances, the local average received signal will gradually decrease, and it is this local average signal level that is predicted by large-scale propagation models.**
- **Small-scale or Fading models: Propagation models that characterize the rapid fluctuations of the received signal strength over very short travel distances (a few wavelengths) or short time durations (on the order of seconds). As a mobile moves over very small distances, the instantaneous received signal strength may fluctuate rapidly giving rise to small-scale fading.**

Free space propagation model

- The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them.
- Satellite communication systems and microwave line-of-sight radio links typically undergo free space propagation.
- The free space model predicts that received power decays as a function of the T-R separation distance raised to some power (i.e. a power law function).
- Friis transmission equation gives the received power at a distance d from the transmitter as

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

P_t is the transmitted power,

$P_r(d)$ is the received power which is a function of the T-R separation,

G_t is the transmitter antenna gain,

G_r is the receiver antenna gain,

d is the T-R separation distance in meters,

L is the system loss factor not related to propagation ($L \geq I$),

λ is the wavelength in meters

- **The gain of an antenna is related to its effective aperture, by**

$$G = \frac{4\pi A_e}{\lambda^2}$$

- **The effective aperture A_e is related to the physical size of the antenna, and λ is related to the carrier frequency by**

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c}$$

- **The values for P_t and P_r must be expressed in the same units**
- **G_t and G_r, are dimensionless quantities.**
- **The miscellaneous losses L ($L \geq 1$) are usually due to transmission line attenuation, filter losses, and antenna losses in the communication system.**
- **A value of L = I indicates no loss in the system hardware.**
- **The Friis free space equation shows that the received power decreases as the square of the T-R separation distance. This implies that the received power decays with distance at a rate of 20 dB/decade.**

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- **The path loss, which represents signal attenuation as a positive quantity measured in dB,**
- **Path loss is defined as the difference (in dB) between the effective transmitted power and the received power, and may or may not include the effect of the antenna gains. The path loss for the free space model when antenna gains are included is given by**

$$PL\,(\mathrm{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

- **When antenna gains are excluded, the antennas are assumed to have unity gain, and path loss is given by**

$$PL\,(\mathrm{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right]$$

- **The Friis free space model is only a valid predictor for P_r for values of d which are in the far-field of the 'transmitting antenna.**

- The far-field, or Fraunhofer region, of a transmitting antenna is defined as the region beyond the far field distance d_f, which is related to the largest linear dimension of the transmitter antenna aperture and the carrier wavelength.
- The Fraunhofer distance is given by

$$d_f = \frac{2D^2}{\lambda}$$

where D is the largest physical linear dimension of the antenna.

- To be in the far-field region, d_f must satisfy

$$d_f \gg D \quad \text{and} \quad d_f \gg \lambda$$

- If d_0 is the power reference point where $d_0 \geq d_f$,

then the received power at a distance greater than d_0 is

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0 \geq d_f$$

- If P_r is in dBm,

$$P_r(d)\ \text{dBm} = 10\log\left[\frac{P_r(d_0)}{0.001\ \text{W}}\right] + 20\log\left(\frac{d_0}{d}\right)$$

- **Example:**

Find the far-field distance for an antenna with maximum dimension of 1m and operating frequency of 900 MHz.

Solution: Largest dimension of antenna, D = 1m

Operating frequency f = 900 MHz $\lambda = \frac{c}{f} = \frac{3x10^8}{900x10^6} = 0.33m$

Using equation $d_f = \frac{2D^2}{\lambda}$

The far-field distance is obtained as $d_f = \frac{2x1^2}{0.33} = 6\mathrm{m}$

- **Example:**

If a transmitter produces 50 watts of power, express the transmit power in units of (a) dBm, and (b) dBW. (c) If 50 watts is applied to a unity gain antenna with a 900 MHz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna.

Solution:

Given P_t=50 W f_c= 900 MHz

(a) Using the dBm equation for Pt,

$$P_t(dBm) = 10\log\left[\frac{P_t(mW)}{1mW}\right] = 10\log[50000] = 46dBm$$

(b)Using dBW equation,

$$P_t(dBW) = 10\log\left[\frac{P_t(W)}{1W}\right] = 10\log[50] = 17dBW$$

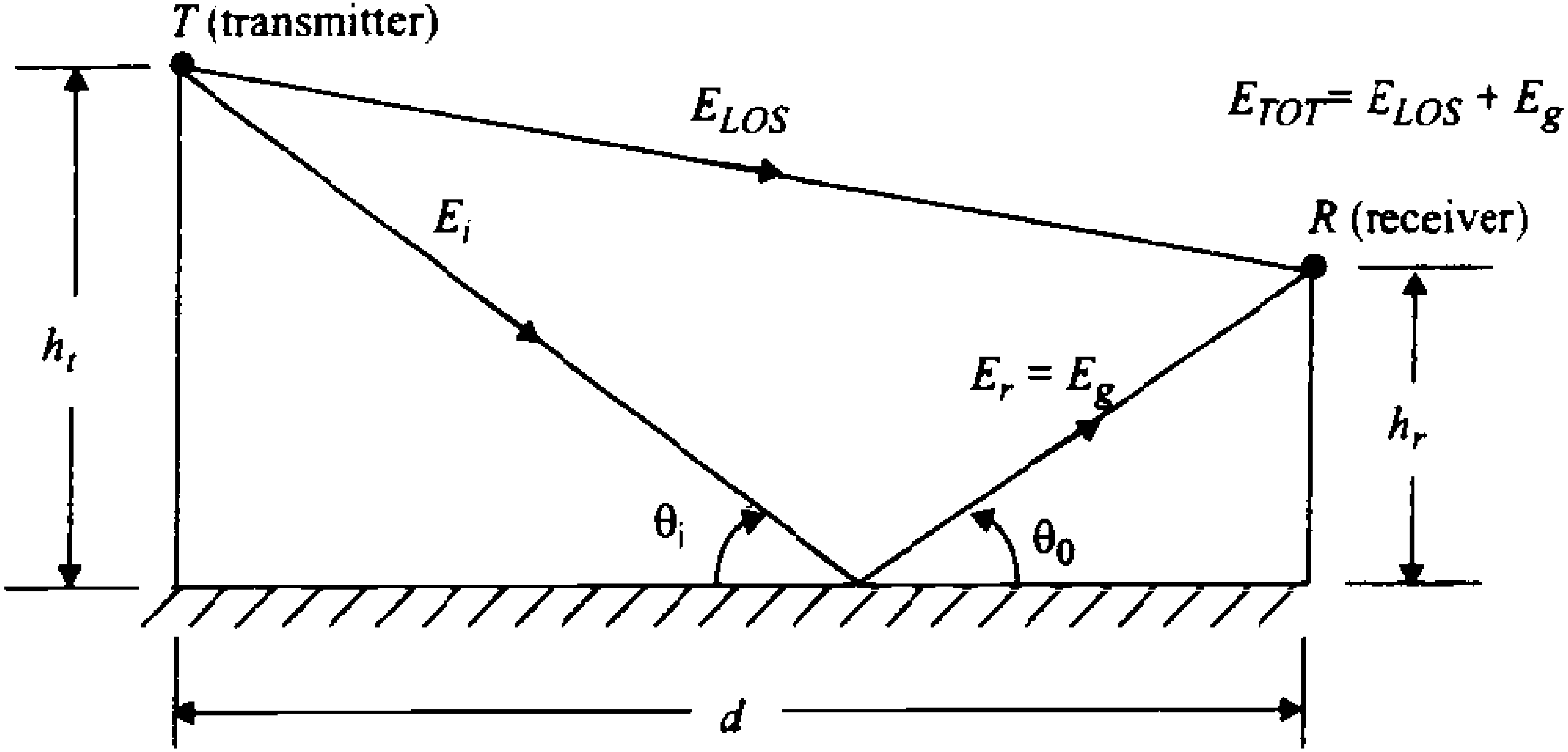
(c) Using $P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$

Received power at d=100m, $P_r(d) = \frac{50x1x1x0.33^2}{(4\pi)^2 x100^2 x1} = 3.5x10^{-3}mW$

$$P_r(dBm) = 10\log P_r(mW) = 10\log(3.5x10^{-3}mW) = -24.5dBm$$

Ground Reflection model

- In a mobile radio channel, a single direct path between the base station and a mobile is not the only physical means for propagation,
- Hence the free space propagation model is in most cases inaccurate when used alone.
- The 2-ray ground reflection model shown below is a useful propagation model that is based on geometric optics, and considers both the direct path and a ground reflected propagation path between transmitter and receiver.



- In most mobile communication systems, the maximum T-R separation distance is at most only a few tens of kilometers, and the earth may be assumed to be flat.
- The total received E-field, E_{TOT}, is then a result of two components
  - The direct line-of-sight component, E_{LOS} , and
  - The ground reflected component, E_g
- h_t is the height of the transmitter and h_r is the height of the receiver.
- E_0 is the free space E-field (in units of V/m) at a reference distance d_0 from the transmitter
- Two propagating waves arrive at the receiver: the direct wave that travels a distance d' and the reflected wave that travels a distance d''

- Derivation of path loss using the ground reflection model.
- The path loss for the 2-ray model (with antenna gains) can be expressed in dB as

$$PL(\mathrm{dB}) = 40\log d - (10\log G_t + 10\log G_r + 20\log h_t + 20\log h_r)$$

Path Loss derivation for Ground Reflection model

Draw the figure for 2-ray ground reflection model.

E-field due to LOS component at receiver is

$$E_{LOS}(d',t) = \frac{E_0 d_0}{d'} \cos\left(\omega_c\left(t-\frac{d'}{c}\right)\right) \quad ① \text{ due to distance } d'$$

E field due to ground-reflected wave

$$E_g(d'',t) = \Gamma \frac{E_0 d_0}{d''} \cos\left[\omega_c\left(t-\frac{d''}{c}\right)\right] \quad ② \text{ due to distance } d''$$

According to law of reflection

$\theta_i = \theta_r$. Γ - reflection coefft.

$E_g = \Gamma E_i$

$E_t = (1+\Gamma) E_i$

For small values of θ_i, $E_i = E_g$.

Resultant total E field $E_{TOT} = |E_{LOS} + E_g|$

E_{TOT} = Sum of ① + ② . $\Rightarrow$ ③

Using method of images, the path difference

$$\Delta = d' - d'' = \sqrt{(h_t+h_r)^2+d^2} - \sqrt{(h_t-h_r)^2+d^2}$$

When $d \gg h_t + h_r$

$$\Delta = d' - d'' \approx \frac{2h_t h_r}{d} \quad ④$$

Phase difference θ_Δ between the two E field components is

$$\theta_\Delta = \frac{2\pi\Delta}{\lambda} = \frac{\Delta\omega_c}{c} \quad ⑤$$

The time delay between the arrival of the two components is

$$\tau_d = \frac{\Delta}{c} = \frac{\theta_\Delta}{2\pi f_c} \quad ⑥$$

As d is large, the diff between d' & d'' become small. So the amplitudes of E_{LOS} and E_g are almost equal and differ in phase.

$$\therefore \left|\frac{E_0 d_0}{d}\right| = \left|\frac{E_0 d_0}{d'}\right| = \left|\frac{E_0 d_0}{d''}\right| \quad ⑦$$

From eqn ③ at $t = \frac{d''}{c}$

$$E_{TOT}\left(d, t=\frac{d''}{c}\right) = \frac{E_0 d_0}{d'} \cos\left\{\omega_c\left(\frac{d''-d'}{c}\right)\right] - \frac{E_0 d_0}{d''}\cos$$

$$= \frac{E_0 d_0}{d'} \cos\theta_\Delta - \frac{E_0 d_0}{d''} = \frac{E_0 d_0}{d}\left\{\cos\theta_\Delta -\right.$$

d- is the distance over a flat earth between the bases of the Tx & the Rx.

$$|E_{TOT}(d)| = \sqrt{\left(\frac{E_0 d_0}{d}\right)^2 \cos(\theta_\Delta - 1)^2 + \left(\frac{E_0 d_0}{d}\right)^2 \sin^2\theta_\Delta}$$

$$= \frac{E_0 d_0}{d}\sqrt{2 - 2\cos\theta_\Delta}$$

Using trigonometric identity

$$|E_{TOT}(d)| = \frac{2E_0 d_0}{d}\sin\left(\frac{\theta_\Delta}{2}\right)$$

when θ_Δ is very small $\sin\frac{\theta_\Delta}{2} \approx \frac{\theta_\Delta}{2}$ $(\theta_\Delta < 0.3\text{rad})$

∴ Using ④, ⑤

$$\frac{\theta_\Delta}{2} = \frac{2\pi}{2} \times \frac{2h_t h_r}{d\lambda} \approx \frac{2\pi h_t h_r}{\lambda d} < 0.3\text{rad}$$

$$\therefore d > \frac{20\pi h_t h_r}{3\lambda} \approx \frac{20 h_t h_r}{\lambda}$$

$$\therefore E_{TOT}(d) \approx \frac{2E_0 d_0}{d} \times \frac{2\pi h_t h_r}{\lambda d} \approx \frac{k}{d^2}\ \text{V/m}$$

where k is a Constant. ⑧

$$G = \frac{4\pi A_e}{\lambda^2}$$ where G is gain and A_e - Effective aperture

Using this equation, along with the Friis equation

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \quad ⑨$$

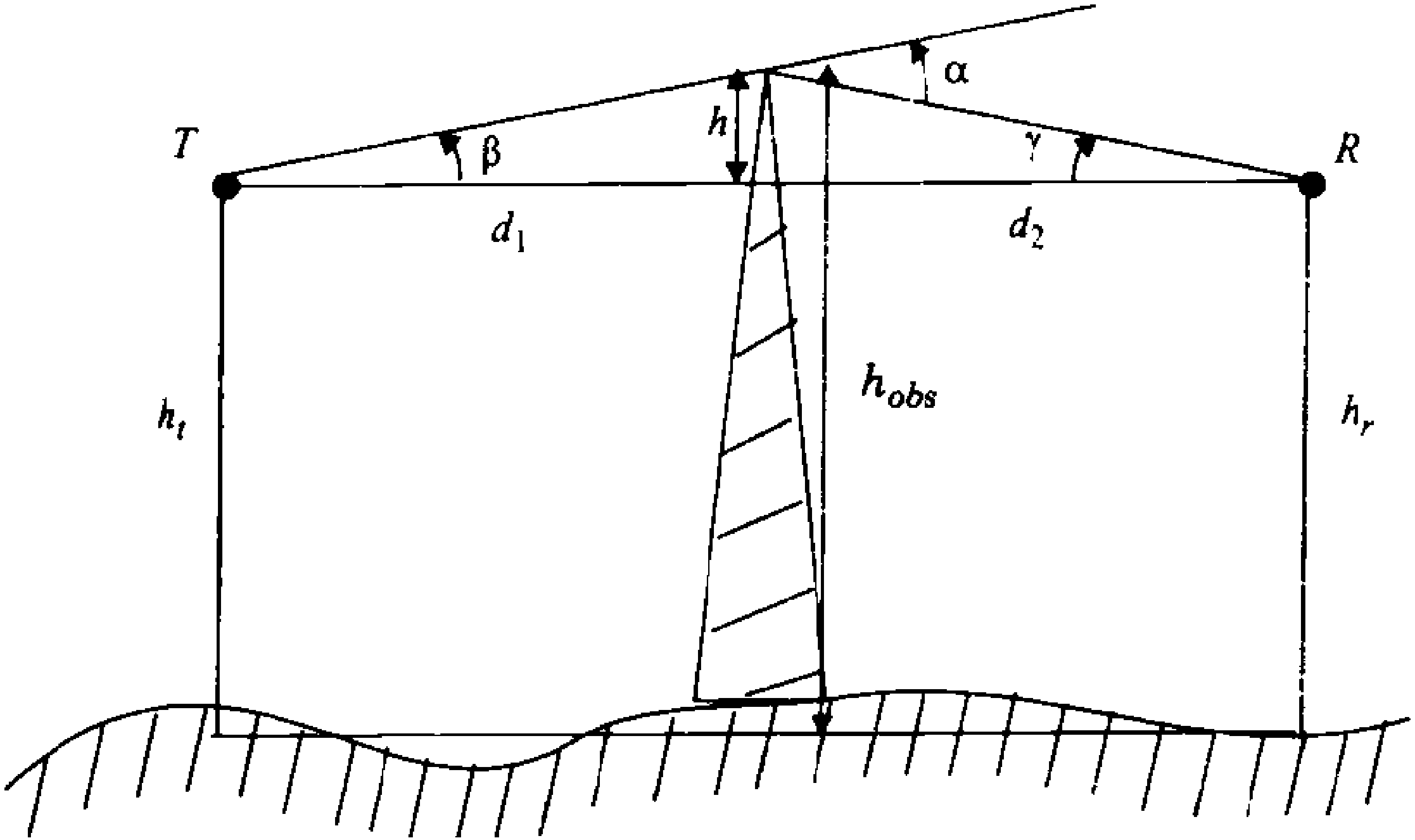
At large distances the P_r falls off with distance to the power of four, ie at a rate of 40 dB/decade.

Thus the Path loss for the 2-ray model is expressed as

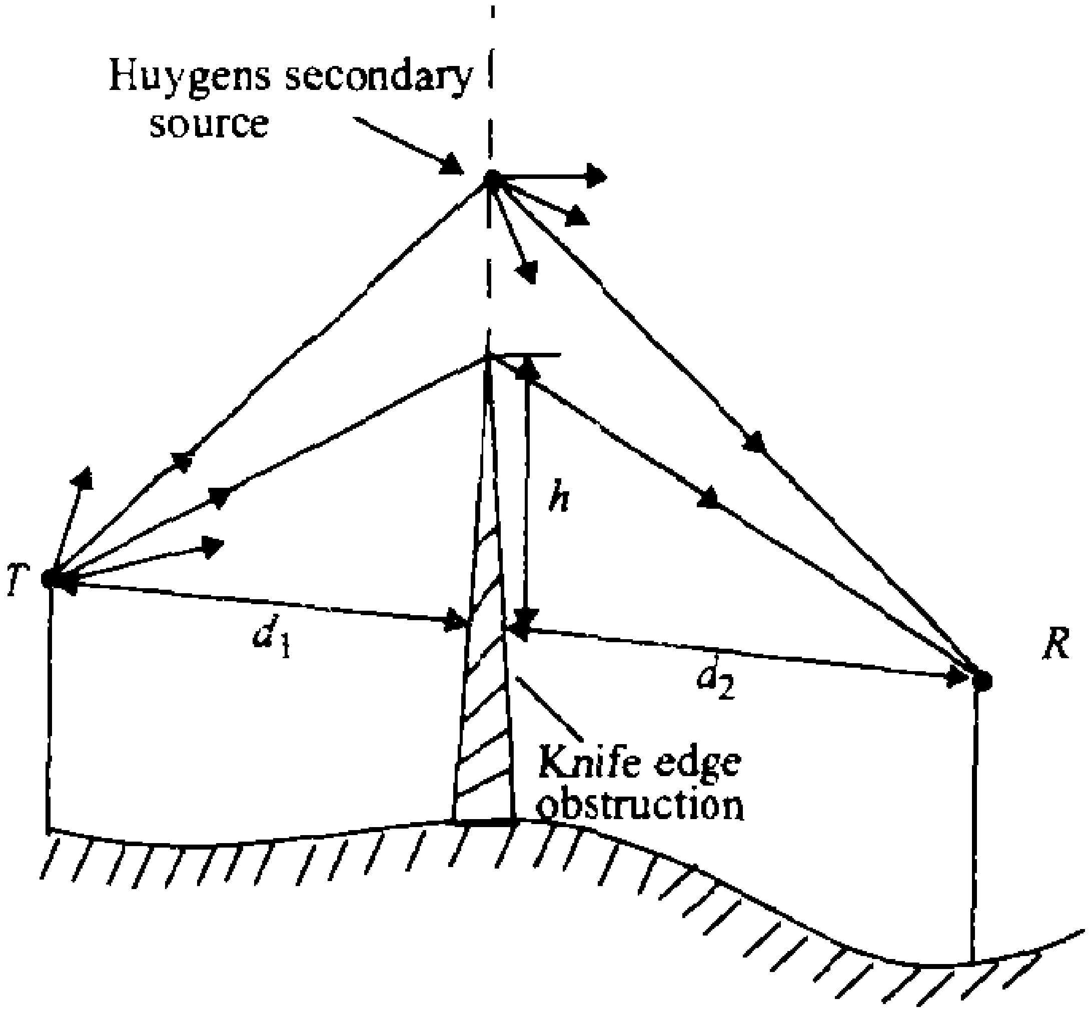
$$\boxed{PL(dB) = 40\log d - (10\log G_t + 10\log G_r + 20\log h_t + 20\log h_r)}$$

Knife-edge Diffraction model

- **Consider a transmitter and receiver separated in free space as shown**
- **Let an obstructing screen of effective height h with infinite width be placed between them at a distance d1 from the transmitter and d2 from the receiver.**
- **This obstructing screen is called a knife edge obstructing screen due to its shape.**
- **The wave gets diffracted by the knife edge screen.**
- **It is apparent that the wave propagating from the transmitter to the receiver via the top of the screen travels a longer distance than if a direct line-of-sight path.**



- **When shadowing is caused by a single object such as a hill or mountain, the attenuation caused by diffraction can be estimated by treating the obstruction as a diffracting knife edge. This is the simplest of diffraction models, and the diffraction loss in this case can be readily estimated using the classical Fresnel solution for the field behind a knife edge.**
- **Consider a receiver at point R, located in the shadowed region (also called the diffraction zone). The field strength at point R in Figure is a vector sum of the fields due to all of the secondary Huygen's sources in the plane above the knife edge.**



- **The electric field strength, E_d of a knife-edge diffracted wave is given by**

$$\frac{E_d}{E_o} = F(v) = \frac{(1+j)}{2}\int_{v}^{\infty} \exp\left((-j\pi t^2)/2\right) dt$$

- **where E_0 is the free space field strength in the absence of both the ground and the knife edge,**
- **F (v) is the complex Fresnel integral. The Fresnel integral, F(v), is a function of the Fresnel-Kirchoff diffraction parameter v is commonly evaluated using tables or graphs for given values of u.**
- **The diffraction gain due to the presence of a knife edge, as compared to the free space E-field, is given by**

$$G_d(\mathrm{dB}) = 20\log|F(v)|$$

MIMO -Multiple Input Multiple Output

A channel may be affected by fading and this will impact the signal to noise ratio. In turn this will impact the error rate, assuming digital data is being transmitted. The principle of diversity is to provide the receiver with multiple versions of the same signal. If these can be made to be affected in different ways by the signal path, the probability that they will all be affected at the same time is considerably reduced. Accordingly, diversity helps to stabilize a link and improves performance, reducing error rate.

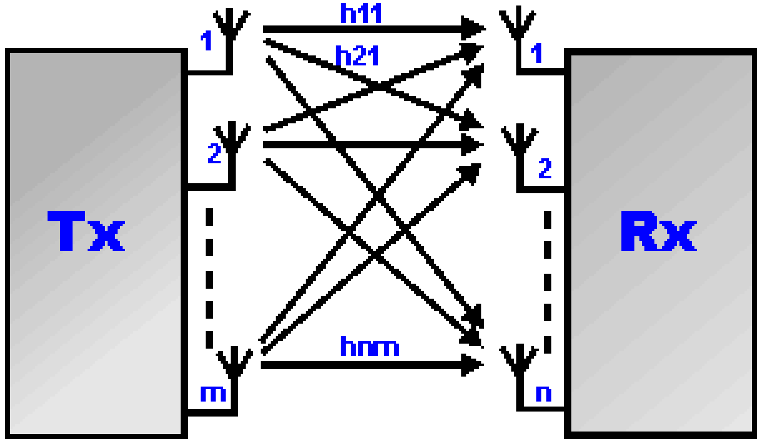
Several different diversity modes are available and provide a number of advantages:

- ***Time diversity:*** **Using time diversity, a message may be transmitted at different times, e.g. using different timeslots and channel coding.**

- ***Frequency diversity:*** **This form of diversity uses different frequencies. It may be in the form of using different channels, or technologies such as spread spectrum / OFDM.**

- ***Space diversity :*** **Space diversity used in the broadest sense of the definition is used as the basis for MIMO. It uses antennas located in different positions to take advantage of the different radio paths that exist in a typical terrestrial environment.**

MIMO is effectively a radio antenna technology as it uses multiple antennas at the transmitter and receiver to enable a variety of signal paths to carry the data, choosing separate paths for each antenna to enable multiple signal paths to be used.



It is found between a transmitter and a receiver, the signal can take many paths. By using MIMO, these additional paths can be used to advantage. They can be used to provide additional robustness to the radio link by improving the signal to noise ratio, or by increasing the link data capacity.

The two main formats for MIMO are given below:

- ***Spatial diversity:*** Spatial diversity used in this narrower sense often refers to transmit and receive diversity. These two methodologies are used to provide improvements in the signal to noise ratio and they are characterized by improving the reliability of the system with respect to the various forms of fading.

- ***Spatial multiplexing :*** This form of MIMO is used to provide additional data capacity by utilizing the different paths to carry additional traffic, i.e. increasing the data throughput capability.

By increasing the number of receive and transmit antennas it is possible to linearly increase the throughput of the channel with every pair of antennas added to the system. This makes MIMO wireless technology one of the most important wireless techniques to be employed in recent years.

As spectral bandwidth is becoming an ever more valuable commodity for radio communications systems, techniques are needed to use the available bandwidth more effectively. MIMO wireless technology is one of these techniques

There are a number of different MIMO configurations or formats that can be used. These are termed SISO, SIMO, MISO and MIMO. These different MIMO formats require different numbers of antennas as well as having different levels of complexity. Also dependent upon the format, processing may be needed at one end of the link or the other - this can have an impact on any decisions made.

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- SISO - Single Input Single Output
- SIMO - Single Input Multiple output
- MISO - Multiple Input Single Output
- MIMO - Multiple Input multiple Output

MIMO – SISO

The simplest form of radio link can be defined in MIMO terms as SISO - Single Input Single Output. This is effectively a standard radio channel - this transmitter operates with one antenna as does the receiver. There is no diversity and no additional processing required.

The advantage of a SISO system is its simplicity. SISO requires no processing in terms of the various forms of diversity that may be used. However the SISO channel is limited in its performance. Interference and fading will impact the system more than a MIMO system using some form of diversity, and the channel bandwidth is limited by Shannon's law - the throughput being dependent upon the channel bandwidth and the signal to noise ratio.

There are two forms of SIMO that can be used:

- •Switched diversity SIMO: This form of SIMO looks for the strongest signal and switches to that antenna.
- •Maximum ratio combining SIMO**:** This form of SIMO takes both signals and sums them to give the a combination. In this way, the signals from both antennas contribute to the overall signal

MIMO – MISO

MISO is also termed transmit diversity. In this case, the same data is transmitted redundantly from the two transmitter antennas. The receiver is then able to receive the optimum signal which it can then use to receive extract the required data.

MIMO - SIMO

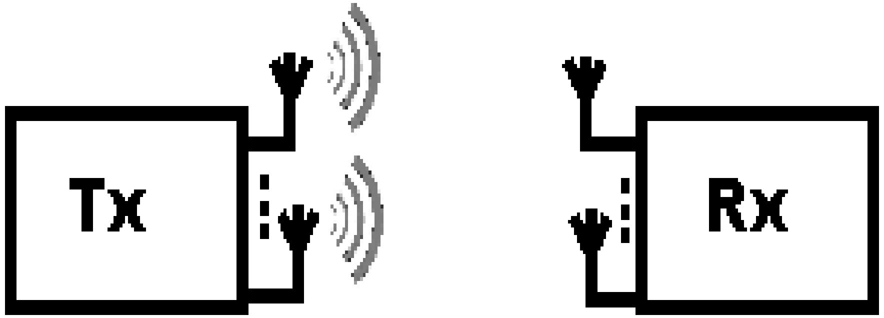
The SIMO or Single Input Multiple Output version of MIMO occurs where the transmitter has a single antenna and the receiver has multiple antennas. This is also known as receive diversity. It is often used to enable a receiver system that receives signals from a number of independent sources to combat the effects of fading. It has been used for many years with short wave listening / receiving stations to combat the effects of ionospheric fading and interference.

SIMO has the advantage that it is relatively easy to implement although it does have some disadvantages in that the processing is required in the receiver. The use of SIMO may be quite acceptable in many applications, but where the receiver is located in a mobile device such as a cellphone handset, the levels of processing may be limited by size, cost and battery drain.

The advantage of using MISO is that the multiple antennas and the redundancy coding / processing is moved from the receiver to the transmitter. This can be a significant advantage in terms of space for the antennas and reducing the level of processing required in the receiver for the redundancy coding. This has a positive impact on size, cost and battery life as the lower level of processing requires less battery consumption.

MIMO

Where there are more than one antenna at either end of the radio link, this is termed MIMO - Multiple Input Multiple Output. MIMO can be used to provide improvements in both channel robustness as well as channel throughput.



In order to be able to benefit from MIMO fully it is necessary to utilise coding on the channels to separate the data from the different paths. This requires processing, but provides additional channel robustness / data throughput capacity.