Chapter 2 :

The Cellular Concept-System Design

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قسم هندسة تقنيات الحاسوب

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2.1 Cellular Mobile Systems

GSM is a PLMN (Public Land Mobile Network)

- several providers setup mobile networks following the GSM standard within each country
- components
  - MS (mobile station)
  - BS (base station)
  - MSC (mobile switching center)
  - LR (location register)
- subsystems
  - RSS (radio subsystem): covers all radio aspects
  - NSS (network and switching subsystem): call forwarding, handover, switching
  - OSS (operation subsystem): management of the network

NSS is the main component of the public mobile network GSM

1- switching, mobility management, interconnection to other networks, system control

2- Components

a. Mobile Services Switching Center (MSC) – high performance digital ISDN switches.

controls all connections via a separated network to/from a mobile terminal within the domain of the MSC - several BSC can belong to a MSC

b. Databases (important: scalability, high capacity, low delay)

i. Home Location Register (HLR)

central master database containing user data, permanent and semi-permanent data of all subscribers assigned to the HLR (one provider can have several HLRs)

ii. Visitor Location Register (VLR)

local database for a subset of user data, including data about all user currently in the domain of the VLR

The MSC (mobile switching center) plays a central role in GSM

- switching functions
- additional functions for mobility support
- management of network resources
- interworking functions via Gateway MSC (GMSC)
- integration of several databases

Functions of a MSC

1- Assigns the voice channel to each call.
2- Performs handoffs.
3- Monitors the call for billing information

Communication between the base station and the mobiles is defined by a standard common air interface (CAI) that specifies four different channels (2) voice channels, 2 control channels.

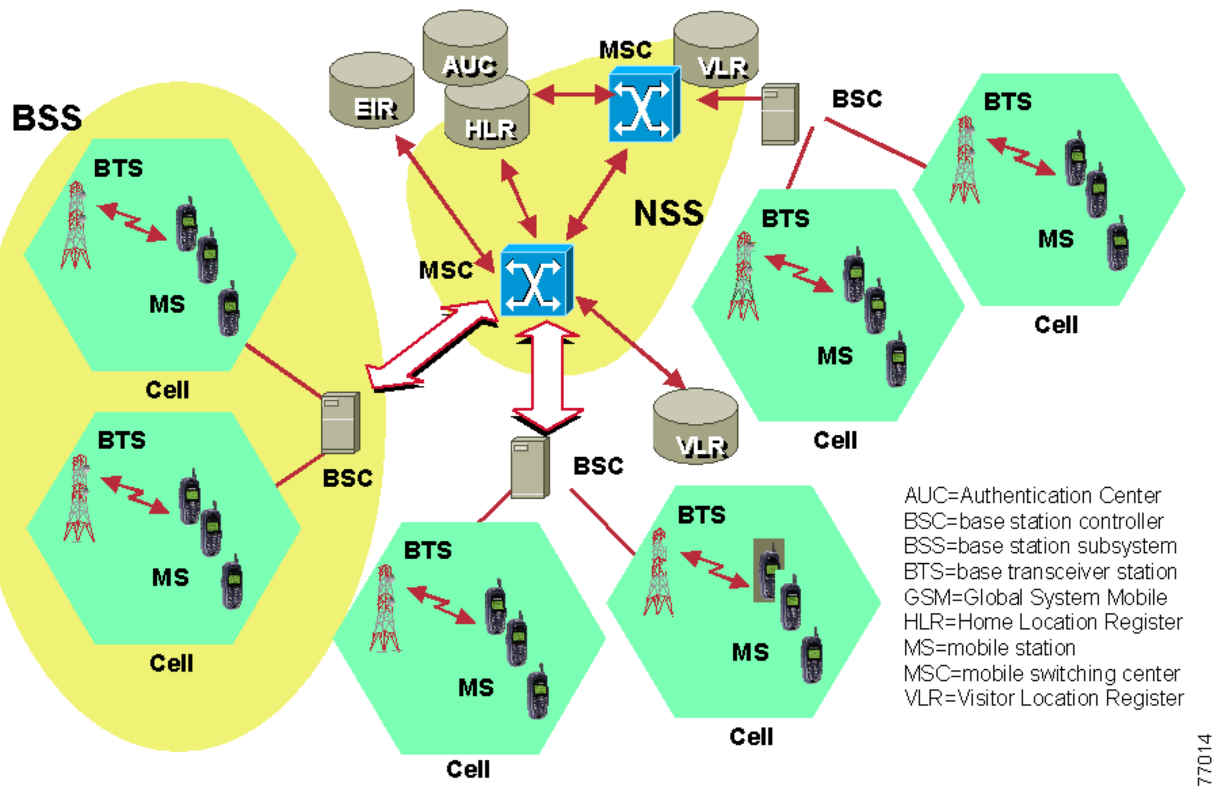
a. *Voice channels (Traffic channels):*

The channels used for voice transmission from the base station to mobiles are called forward voice channels (FVC), and the channels used for voice transmission from mobiles to the base station are called reverse voice channels (RVC).

b. *Control channels (setup channels)*

The two channels responsible for initiating mobile calls are the forward control channels (FCC) and reverse control channels (RCC). Control channels transmit and receive data messages that carry call initiation and service requests, and are monitored by mobiles when they do not have a call in progress.

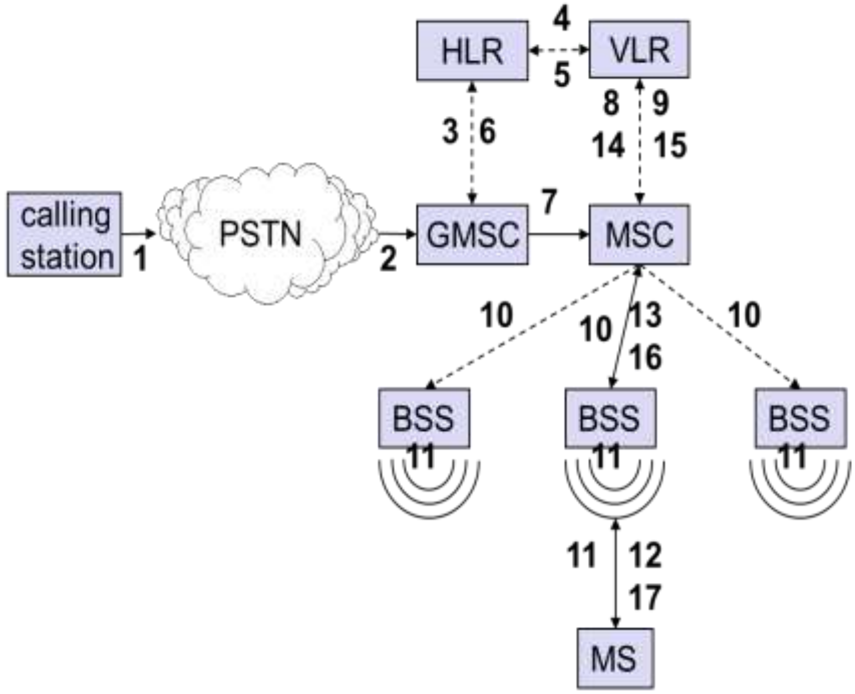
2.2 Cellular system operation



According to the diagram above, it can be understood simply by:

- Mobile device is connected to BTS (Antenna).
- BTS is connected to the Switching system called BSC.
- BSC is connected to the main switching system called MSC.
- MSC contains its own VLR (VLR: is a temporary database which stores the information of the visitors under its coverage area. VLR stands for Visitor Location register. When you roam in a different place VLR stores your user information.).
- MSC's are connected to GMSC which is connected to HLR. (HLR stands for Home location register, it is the main database where the documents or information of user is stored. all the documents that you give during purchase of a SIM card is stored in this HLR.
- VLR Takes your information from HLR when you Roam in other state or region.).
- HLR also provides authentication by AuC. AuC is connected with HLR. If you initiate a call HLR and AuC will see if you are a genuine Mobile user with valid IMEI number and Plan.and then the call is set up from source to the destination device.

Mobile Terminated Call



1: calling a GSM subscriber

2: forwarding call to GMSC

3: signal call setup to HLR

4, 5: request MSRN from VLR

6: forward responsible
MSC to GMSC

7: forward call to

current MSC

8, 9: get current status of MS

10, 11: paging of MS

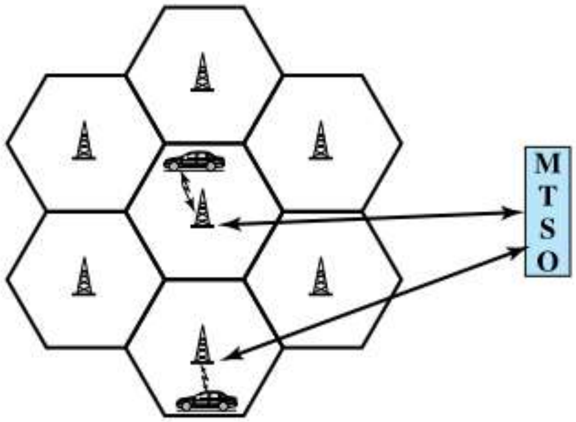
12, 13: MS answers

14, 15: security checks

16, 17: set up connection

<u>Other functions performed by the system include the following:</u>

- **Handoff (Handover):** If a mobile unit moves out of range of one cell and into the range of another during a connection, the traffic channel has to change to one assigned to the BS in the new cell. The system makes this change without either interrupting the call or alerting the user.



- **Call blocking:** During the mobile-initiated call stage, if all the traffic channels assigned to the nearest BS are busy, then the mobile unit makes a preconfigured number of repeated attempts. After a certain number of failed tries, a busy tone is returned to the user.
- **Call termination:** When one of the two users hangs up, the MTSO is informed and the traffic channels at the two BSs are released.
- **Call drop:** During a connection, because of interference or weak signal spots in certain areas, if the BS cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the MTSO is informed.
- **Calls to/from fixed and remote mobile subscriber:** The MTSO connects to the public switched telephone network (PSTN). Thus, the MTSO can set up a connection between a mobile user in its area and a fixed subscriber via the telephone network.

2.3 RF Planning

RF Planning is the process of assigning frequencies, transmitter locations and parameters of a wireless communications system to provide sufficient coverage and capacity for the services required. The RF plan of a cellular communication system has two objectives: coverage and capacity.

a. Coverage relates to the geographical footprint within the system that has sufficient RF signal strength to provide for a call/data session.
b. Capacity relates to the capability of the system to sustain a given number of subscribers. Capacity and coverage are interrelated.

To improve coverage, capacity has to be sacrificed, while to improve capacity, coverage will have to be sacrificed. **It is necessary to restructure radiotelephone system to achieve high capacity with limited spectrum.**

1- **Increase the capacity of the system**: by using lower-power systems with shorter radius and to use numerous transmitters/receivers (Base stations). Thereby providing additional radio capacity with no additional increase in radio spectrum.

2- **Distributing the available channels throughout geographic region**: by systematically spacing base stations and their channel groups. The available channels can be reused as long as the interference between co-channel stations is kept below acceptable level.

2.4 Cell types

- Macro cell – their coverage is large (aprox. 6 miles in diameter); used in remote areas, high-power transmitters and receivers are used
- Micro cell – their coverage is small (half a mile in diameter) and are used in urban zones; low-powered transmitters and receivers are used to avoid interference with cells in another clusters

- Pico cell –is a small cellular system typically covering a small area, such as in-building (offices, shopping malls, train stations) . In cellular networks, picocells are typically used to extend coverage to indoor areas where outdoor signals do not reach well.

- Selective cells . located at the entrances of tunnels where a coverage of 360 degrees is not needed this case, a selective cell with a coverage of 120 degrees is used.

Decreasing the cell size gives:

- Increased user capacity
- Increased number of handovers per call
- Increased complexity in locating the subscriber
- Lower power consumption in mobile terminal: so it gives longer talk time, safer operation

2.5 Cellular Network Coverage

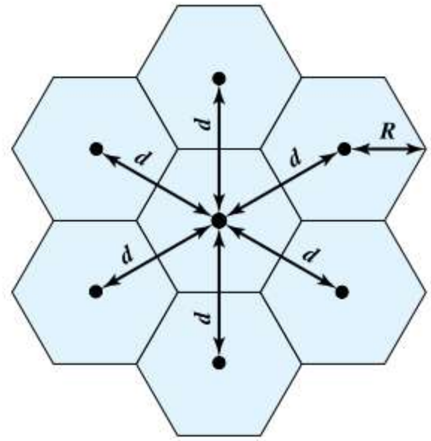
The essence of a cellular network is the use of multiple low-power transmitters, on the order of 100 W or less. Because the range of such a transmitter is small, an area can be divided into cells, each one served by its own antenna.

A- Each cell is allocated a band of frequencies and is served by a base station (consisting of transmitter, receiver, and control unit).

B- Adjacent cells are assigned different frequencies to avoid interference or crosstalk. However, cells sufficiently distant from each other can use the same frequency band.

While it might seem natural to choose a circle to represent the coverage area of a base station, adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions.

<u>The hexagon has:</u>



- No gaps or overlapping
- The largest area compared with square and triangle.
- Fewest number of cells can cover a geographic region,
- Closely approximates a circular radiation pattern which would occur for an omnidirectional base station antenna and free space propagation.
- A hexagonal pattern provides for equidistant antennas.
- When using hexagons to model coverage areas, base station transmitters are depicted as either:
  - In the center of the cell (center-excited cells): omnidirectional antennas are used in center-excited cells.
  - On three of the six cell vertices (edge-excited cells): sectored directional antennas are used in corner-excited cells.

The radius of a hexagon is defined to be the radius of the circle that circumscribes it (equivalently, the distance from the center to each vertex; also equal to the length of a side of a hexagon).

For a cell radius R, the distance between the cell center and each adjacent cell center is

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

Therefore the area of the hexagon is

$$Area = \frac{3\sqrt{3}}{2}R^2$$

- In practice, a precise hexagonal pattern is not used. Variations from the ideal are due to:
  - Topographical limitations.
  - Local signal propagation conditions.
  - Practical limitation on siting antennas.

$A_{tri} = 1.3R^2$ $A_{sq} = 2.0R^2$ $A_{hex} = 2.6R^2$

2.6 Frequency Reuse

In a cellular system, each cell has a base transceiver. The transmission power is carefully controlled

1-To allow communication within the cell using a given frequency

2-To limit the power at that frequency that escapes the cell into adjacent ones.

- The objective is to use the same frequency in other nearby cells, thus allowing the frequency to be used for multiple simultaneous conversations.
- Generally, 10 to 50 frequencies are assigned to each cell, depending on the traffic expected.
- The essential issue is to determine how many cells must intervene between two cells using the same frequency so that the two cells do not interfere with each other. Various patterns of frequency reuse are possible.

Frequency reuse (frequency planning): is the design process of selecting and allocating channel groups for all of the cellular base stations within a system.

If the pattern consists of N cells and each cell is assigned the same number of frequencies, each cell can have ***K/N*** frequencies, where K is the total number of frequencies allotted to the system.

- For Advanced Mobile Phone System (AMPS), K = 395, and N = 7 is the smallest pattern that can provide sufficient isolation between two uses of the same frequency. This implies that there can be at most 57 frequencies per cell on average.

- In characterizing frequency reuse, the following parameters are commonly used:

D = minimum distance between centers of cells that use the same frequency band (called co-channels)

R = radius of a cell

d = distance between centers of adjacent cells $\mathbf{d} = \sqrt{3}R$

N = number of cells in a pattern (Cluster size)

(Each cell in the pattern uses a unique set of frequency bands), termed the ***reuse factor***

In a hexagonal cell pattern: in order to tessellate (to connect without gaps between adjacent cells), only the following values of N are possible:

$$N = I^2 + J^2 + (I \times J) \qquad I, J = 0, 1, 2, 3, \ldots$$

Hence, possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on.

Choice of N (assuming constant cell size)

Small N:

•More cluster are required to cover the service area

•More capacity

•Higher probability of co-channel interference

Large N:

•Less cluster are required to cover the service area

•Less capacity

•Less probability of co-channel interference

The following relationship holds:

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

Where q is the reuse ratio.

This can also be expressed as

$$\frac{D}{d} = \sqrt{N}$$

Consider a cellular system which has a total of K duplex channels available for use. If each cell is allocated a group of C channels ($C < K$), and if the K channels are divided among N cells into channel groups which each have the same number of channels, the total number of available radio channels can be expressed as

$$K = C\,N$$

where

$$K = \frac{Spectrum\,bandwidth\,(or\,Total\,bandwidth)}{Channel\,bandwidth}$$

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, can be used as a measure of capacity and is given

$$Capacity = MCN = MK\_$$

The capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area.

The cluster size (N) is typically equal to 4, 7, or 12.

If N is reduced while the cell size is kept constant, more clusters are required to cover a given area and hence more capacity is achieved.

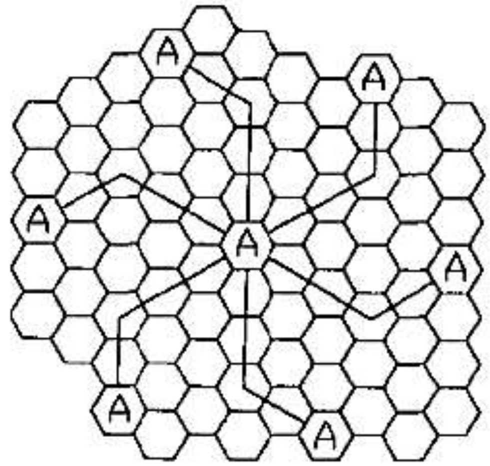
- A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is large.
- A small cluster size indicates that co-channel cells are located much closer together.

From a design viewpoint, the smallest possible value of N is desirable in order to maximize capacity over a given coverage area.

To find the nearest co-channel neighbors of a particular cell, one must do the following:

i. Move i cells along any chain of hexagons and then

ii. Turn 60 degrees counter-clockwise and move j cells. This is illustrated in Figure below for $i = 3$ and $j = 2$ (example, $N = 19$).

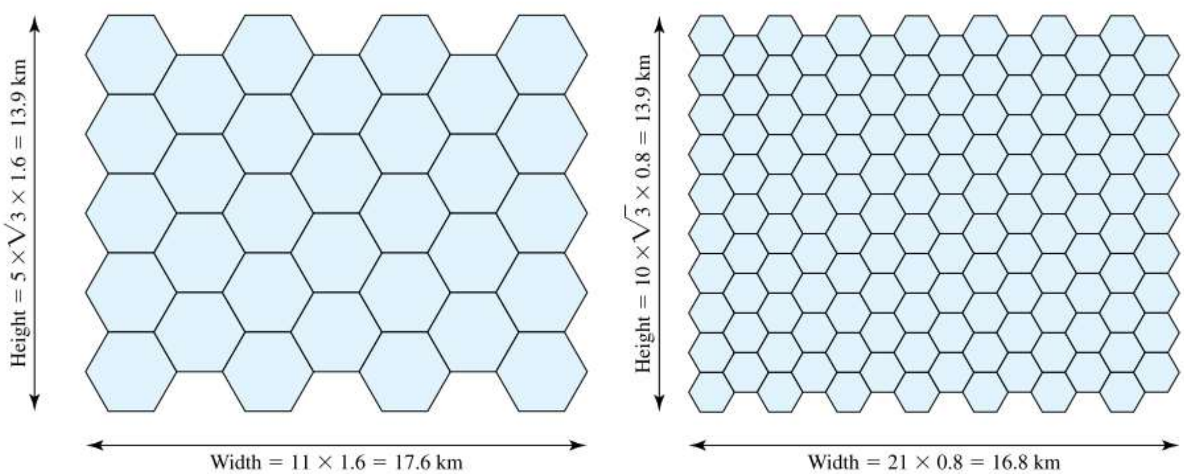


Example 1

Assume a system of 32 cells with a cell radius of 1.6 km, a total of 32 cells, a total frequency bandwidth that supports 336 traffic channels, and a reuse factor of $N = 7$.

(a) If there are 32 total cells, what geographic area is covered, how many channels are there per cell, and what is the total number of concurrent calls that can be handled?

(b) Repeat for a cell radius of 0.8 km and 128 cells.



(a) Cell radius = 1.6 km **(b) Cell radius = 0.8 km**

Solution:

(a)

The area of a hexagon of radius R is

$$Area_a = \frac{3\sqrt{3}}{2}R^2 = \frac{3\sqrt{3}}{2}(1.6)^2 = 6.65\,\text{km}^2$$

The total area covered is $6.65 \times 32 = 213$ km^2.

For $N = 7$, the number of channels per cell is $K/N = 336/7 = 48$,

Total number of concurrent calls that can be handled is

$$Capacity = 48 \times 32 = 1536 \text{ channels}$$

(b)

The area of a hexagon of radius R is

$$Area_b = \frac{3\sqrt{3}}{2}R^2 = \frac{3\sqrt{3}}{2}(0.8)^2 = 1.66\,\text{km}^2$$

The area covered is $1.66 \times 128 = 213$ km^2.

The number of channels per cell is $K/N = 336/7 = 48$,

Total number of concurrent calls is

$$Capacity = 48 \times 128 = 6144 \text{ calls}$$

Example 2

Consider a cellular system in which total available voice channels to handle the traffic are 960. The area of each cell is 6 km^2 and the total coverage area of the system is 2000 km^2. Calculate:

(a) The system capacity if the cluster size N is 4

(b) The system capacity if the cluster size is 7.

- How many times would a cluster of size 4 have to be replicated to cover the entire cellular area? Does decreasing N increase the system capacity? Explain.

Solution

Total available channels =960 , Cell area = 6 km^2

Total coverage area = 2000 km^2

(a) $N = 4$

Area of a cluster = 4 × 6 = 24 km^2

Number of clusters for covering total area = 2000/24 = 83.33 ~ 83

Number of channels per cell = 960/4 = 240

System capacity = 83 × 960 = 79, 680 channels

(b) $N = 7$

Area of cluster = 7 × 6 = 42 km^2

Number of clusters for covering total area = 2000/42 = 47.62 ~ 48

Number of channels per cell = 960/7 = 137.15 ~ 137

System capacity = 48 × 960 = 46,080 channels

It is evident when we decrease the value of N from 7 to 4, we increase the system capacity from 46,080 to 79,680 channels. Thus, decreasing N increases the system capacity.

2.7 Channel Assignment Strategies

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required. A variety of channel assignment strategies have been developed to achieve these objectives.

Channel assignment strategies can be classified as either fixed or dynamic. The choice of channel assignment strategy impacts the performance of the system, particularly as to how calls are managed when a mobile user is handed off from one cell to another.

a) **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.
   - ***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.

b) **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,
     - 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.

***Advantage*:**

- Dynamic channel assignment reduces 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.
- Increases the channel utilization and decreases probability of a blocked call.

***Disadvantage*:**

- 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.

2.8 Co-channel Interference

The *S/I* ratio at the desired mobile receiver is given as:

$$\frac{S}{I} = \frac{S}{\sum_{k=1}^{N_I} I_k}$$

where:

I_k = the interference due to the *k*th interferer

N_I = the number of interfering cells in the first tier.

In a fully equipped hexagonal-shaped cellular system, there are always six co-channel interfering cells in the first tier (i.e., $N_I = 6$).

- Most of the co-channel interference results from the first tier.

- Interference from second and higher tiers amounts to less than 1% of the total interference (ignored).
- Co-channel interference can be experienced both at the cell site and the mobile stations in the center cell.
- In a small cell system, interference will be the dominating factor and thermal noise can be neglected. Thus the *S/I* ratio can be given as:

$$\frac{S}{I} = \frac{1}{\sum_{k=1}^{6} \left(\frac{D_k}{R}\right)^{-\gamma}}$$

where:

$2 \leq \gamma \leq 5$: the propagation path loss, and γ depends upon the terrain environment.

D_k : the distance between mobile and *k*th interfering cell

R : the cell radius

If we assume D_k is the same for the six interfering cells for simplification, or $D = D_k$, then Equation above becomes:

$$\frac{S}{I} = \frac{1}{6(q)^{-\gamma}} = \frac{q^{\gamma}}{6}$$

Therefore

$$\therefore q = \left[6\left(\frac{S}{I}\right)\right]^{1/\gamma}$$

Since $q = \sqrt{3N}$, therefore

$$N = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{\gamma}}$$

Example 3

Consider the advanced mobile phone system (AMPS) in which an *S/I* ratio of 18 dB is required for the accepted voice quality. Assume $\gamma = 4$.

(a) What should be the reuse factor for the system?

(b) What will be the reuse factor of the Global System of Mobile (GSM) system in which an *S/I* of 12 dB is required?

Solution

$$N = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{\gamma}}$$

$$N_{AMPS} = \frac{1}{3}\left[6\left(10^{\frac{18}{10}}\right)\right]^{\frac{2}{4}} = 6.486 \approx 7$$

(b)

$$N_{GSM} = \frac{1}{3}\left[6\left(10^{\frac{12}{10}}\right)\right]^{\frac{2}{4}} = 3.251 \approx 4$$

Example 4

Consider a cellular system with 395 total allocated voice channel frequencies. Calculate the mean *S/I* ratio for cell reuse factor equal to 4, 7, and 12. Assume omnidirectional antennas with six interferers in the first tier and a slope for path loss of 40 dB/decade ($\gamma = 4$). Discuss the results.

Solution

For a reuse factor $N = 4$, the number of voice channels per cell site = K/N = 395/4 = 99.

$$N = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{\gamma}}$$

$$4 = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{4}}$$

$$\frac{S}{I} = 24\ (13.8\,dB)$$

The results for N = 7 and N = 12 are given in Table below.

N	**Voice channels per cell**	**Mean *S/I* (dB)**
4	99	13.8
7	56	18.7
12	33	23.3

It is evident from the results that, by increasing the reuse factor from N = 4 to N = 12, the mean S/I ratio is improved from 13.8 to 23.3 dB.

2.9 Co-channel Interference Reduction

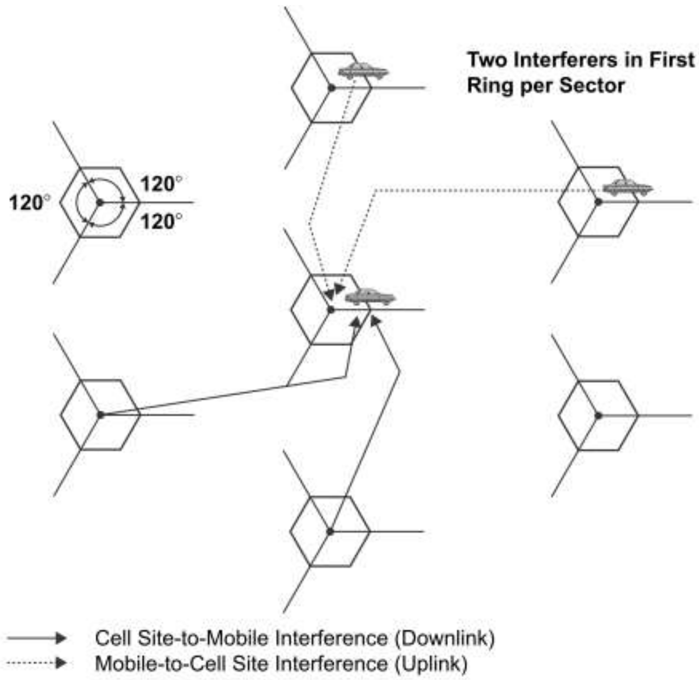
In the case of increased call traffic, the frequency spectrum should be used efficiently. We should avoid increasing the number of cells N in a frequency reuse pattern. As N increases, the number of frequency channels assigned to a cell is reduced, thereby decreasing the call capacity of the cell.

Instead of increasing N, we either

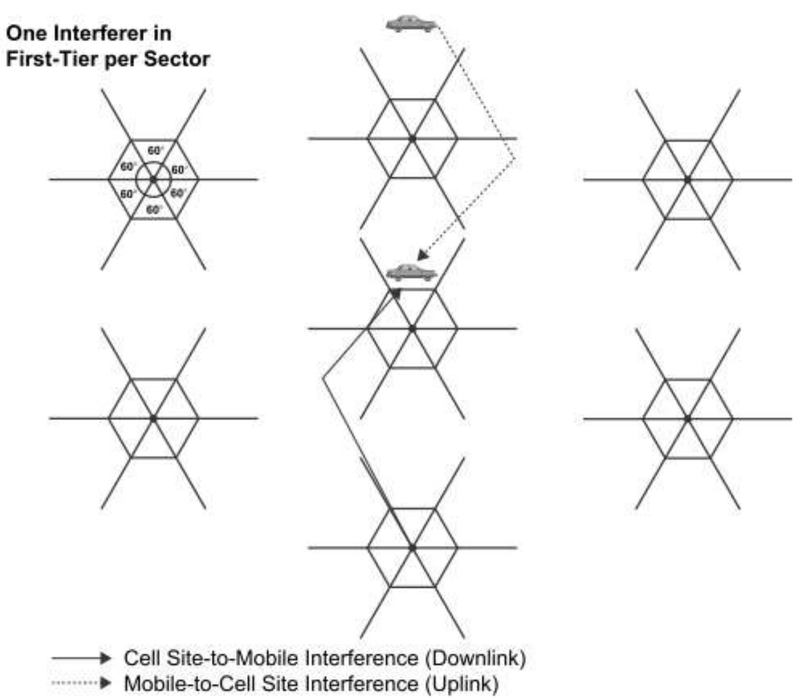
a. Perform cell splitting to subdivide a congested cell into smaller cells.

Or

b. Use a directional antenna arrangement (sectorization) to reduce co-channel interference. In this case, each cell is divided into three or six sectors and uses three or six directional antennas at the base station to reduce the number of co-channel interferers



Co-channel interference with 120° sectorized cells.



Co-channel interference with 60° sectorized cells.

Each sector is assigned a set of channels (frequencies) (either 1/3 or 1/6 of the frequencies of the omnidirectional cell).

2.10 Adjacent Channel Interference (ACI)

Signals which are adjacent in frequency to the desired signal cause adjacent channel interference. ACI is brought about primarily because of imperfect receiver filters which allow nearby frequencies to move into the pass band, and nonlinearity of the amplifiers.

The ACI can be reduced by:

(1) Using modulation schemes which have low out-of-band radiation.

(2) Carefully designing the band-pass filter (BPF) at the receiver front end.

(3) Assigning adjacent channels to different cells in order to keep the frequency separation between each channel in a given cell as large as possible.

The effects of ACI can also be reduced using advanced signal processing techniques that employ equalizers.

Review

We developed a relationship between the reuse ratio (q) and cell cluster size (N) for the hexagonal geometry. Co-channel interference ratios for the omnidirectional and sectorized cell were derived. A numerical example was given to demonstrate that, for a given cluster size, sectorization yields a higher S/I ratio, but reduces spectral efficiency. However, it is possible to achieve a higher spectral efficiency by reducing the cluster size in a sectorized system without lowering the S/I ratio below the minimum requirement.

2.11 Handoff (Handover) 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.

The Handoff decision is made depending on:

a. Power
b. Traffic
c. Channel quality
d. Distance
e. Administration

The handoff operation involves:

1. Identifying a new base station,
2. Allocate the voice and control signals to channels associated with the new base station.

Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver (normally taken as between -90 dBm and -100 dBm), a slightly stronger signal level is used as a threshold at which a handoff is made. This margin (cannot be too large or too small) is given by

$$A = P_{r_{Handoff}} - P_{r_{Minimum\ usable}}$$

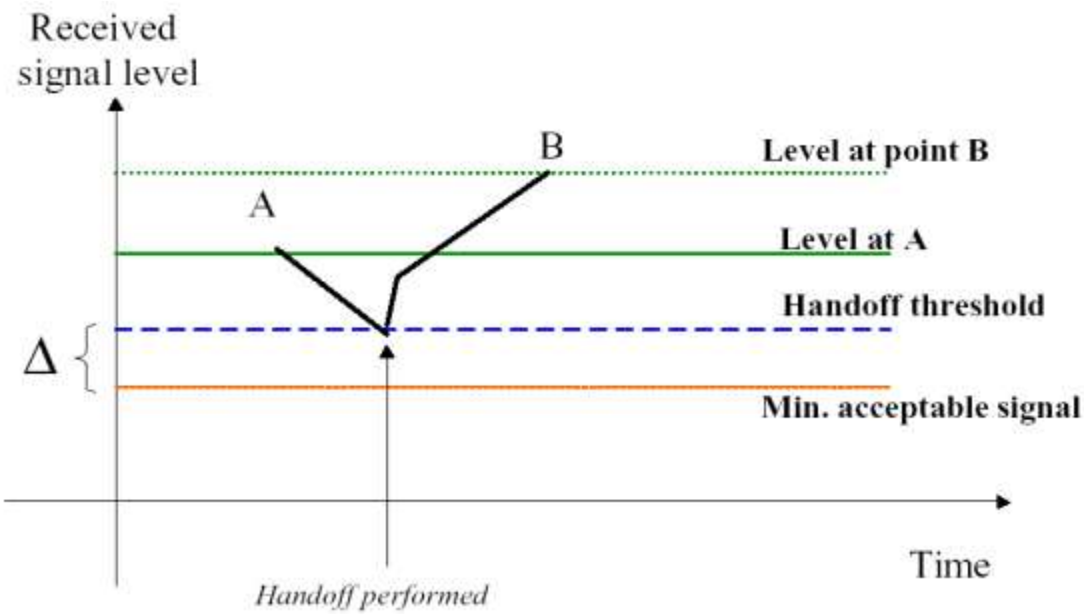
- If A is too large, unnecessary handoffs which burden the MSC may occur.
- If A is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions.

Therefore, A is chosen carefully to meet these conflicting requirements.

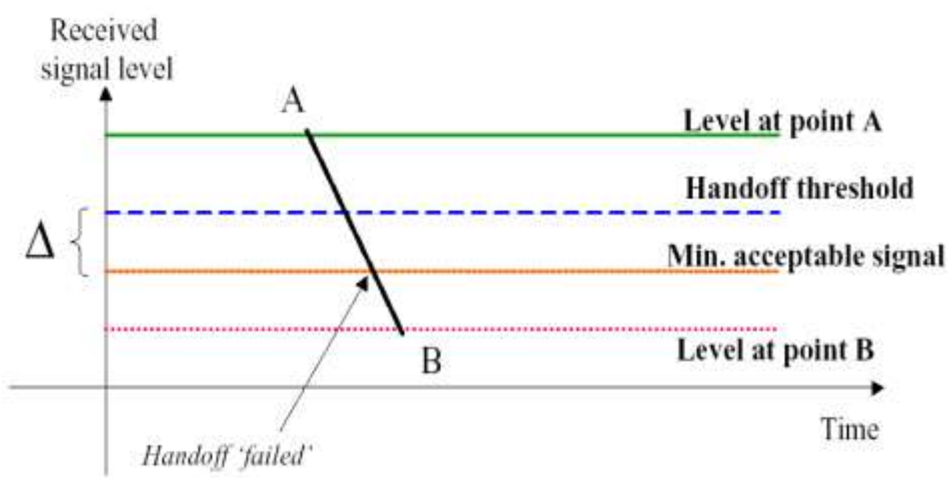
Figure below demonstrates the case where a handoff is not made and the signal drops below the minimum acceptable level to keep the channel active. This dropped call event can happen when there is an excessive delay by the MSC in assigning a handoff, or when the threshold A is set too small for the handoff time in the system. ***The length of time needed to decide if a handoff is necessary depends on the speed at which the vehicle is moving***

Excessive delays may occur during high traffic conditions due to

- Either computational loading at the MSC
- Or no channels are available on any of the nearby base stations



Value of delta is large enough. When the $P_{Handoff}$ is reached, the MSC initiates the handoff.



In this case, the MSC was unable to perform the handoff before the signal level dropped below the minimum usable level, and so the call was lost.

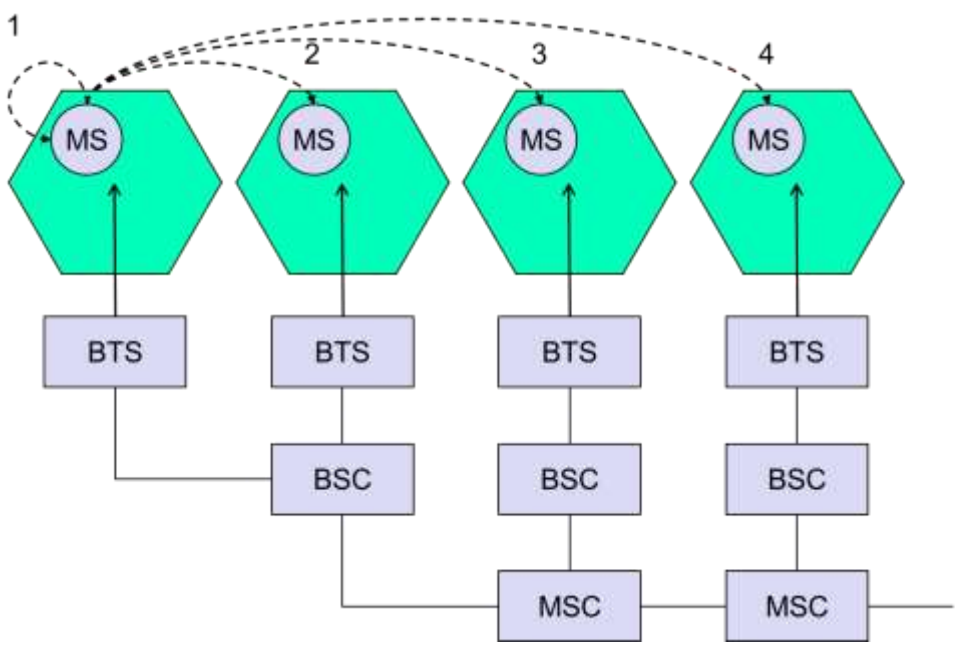
2.12 Handoff Types

Handoff can be categorized as hard handoff, soft handoff, and softer handoff.

If the hand-off is needed between two cells (BTS) controlled by the same Base Station Controller (BSC), the MSC is not needed as the BSC does it all.

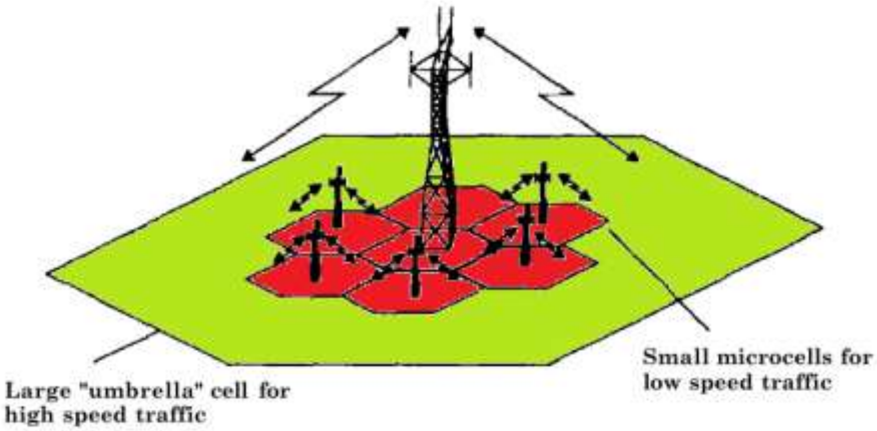
Types of hand-off are:

1. INTRA-CELL, within a cell, narrow-band interferences could make transmission at a certain frequency impossible. The BSC decides to change the carrier frequency.
2. INTRA BSS, between cells controlled by the same BSC. The BSC performs the handover, assigns a new radio channel in the new cell and releases the old one
3. INTER BSS, between cells controlled by different BSCs, and the MSc is involved.
4. INTER MSC-from region to region where more than one MSC is involved. Between two cells belonging to different MSCs. Both MSCs perform the handover together



2.13 Umbrella cell approach

- By using different antenna heights (often on the same building or tower) and different power levels, it is possible to provide "large" and "small" cells which are co-located at a single location. This technique is called the umbrella cell approach
- Used to provide large area coverage to high speed users while providing small area coverage to users traveling at low speeds.



- The umbrella cell approach ensures that the number of handoffs is minimized for high speed users and provides additional microcell channels for pedestrian users.
- The speed of each user may be estimated by the base station or MSC by evaluating how rapidly the short term average signal strength on the RVC changes over time, or more sophisticated algorithms may be used to evaluate and partition users.
- If a high speed user in the large umbrella cell is approaching the base station, and its velocity is rapidly decreasing, the base station may decide to hand the user into the co-located microcell, without MSC intervention.
- **When the speed of the mobile is too high**, the mobile is handed off to the umbrella cell. The mobile will then stay longer in the same cell (in this case the umbrella cell).

- large cell → high speed traffic → fewer handoffs
- small cell → low speed traffic