Fundamentals of Cellular communications

- The design objective of early mobile radio systems was to achieve a **large coverage area by using a single, high powered transmitter** with an antenna mounted on a tall tower.
- While this approach achieved very good coverage, it also meant that it was impossible to **reuse** those same frequencies throughout the system, since any attempts to achieve frequency reuse would result in **interference**.
- For example, the Bell mobile system in New York City in the 1970s could only support a **maximum of twelve simultaneous calls over a thousand square miles**.

- Faced with the fact that government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services, it became imperative to restructure the radio telephone system to achieve high capacity with limited radio spectrum, while at the same time covering very large areas.

The cellular concept

- 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 neighboring base stations.

- Neighboring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users under their control) is **minimized**.
- By systematically spacing base stations and their channel groups throughout a market, the available channels are distributed throughout the geographic region and may be reused as many times as necessary, so long as the interfeerence between co-channel stations is kept below acceptable levels.
- As the demand for service increases (i.e., as more channels are needed within a particular market), the number of base stations may be increased (along with a corresponding decrease in transmitter power to avoid added interference), thereby providing additional radio capacity with no additional increase in radio spectrum.
- This fundamental principle is the foundation for all modern wireless communication systems, since it enables a fixed number of channels to

serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region.

Frequency Reuse

- Each cellular base station is **allocated a group of radio channels** to be used within a small geographic area called a **cell**.
- Base stations in adjacent cells are assigned channel groups which contain completely **different** channels than neighboring 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
- Illustration of the cellular frequency reuse concept is shown in Figure 4. 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 seven**, and the **frequency reuse factor is 1/7** since each cell contains **one-seventh** of the total number of available channels.

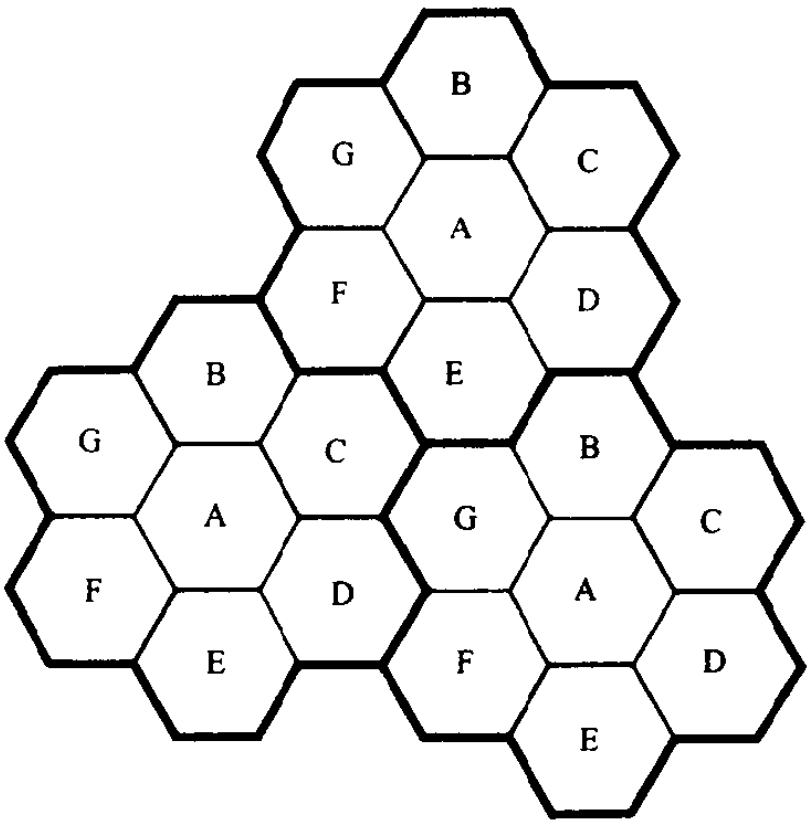


Figure 4: Illustration of the cellular frequency reuse concept.

- The frequency reuse plan is overlaid upon a map to indicate where different frequency channels are used. The hexagonal cell shape is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system.

- The actual radio coverage of a cell is known as the **footprint** and is determined from field measurements or propagation prediction models.
- Although the real footprint is amorphous in nature, a regular cell shape is needed for systematic system design and adaptation for future growth.
- 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, **omni-directional antennas** are used in center-excited cells and **sectored directional** antennas are used in corner-excited cells.
- Practical considerations usually do not allow base stations to be placed exactly as they appear in the hexagonal layout. Most system designs

permit a base station to be positioned up to **one-fourth the cell radius away** from the ideal location.

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

$$S = kN \tag{1}$$

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

$$C = MkN = MS \tag{2}$$

- As seen from equation(2), 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 large.
- Conversely, a **small cluster size** indicates that co-channel cells are located much **closer together**.
- The value for N is a function of how much interference a mobile or base station can tolerate while maintaining a sufficient quality of communications.

- From a design viewpoint, the smallest possible value of N is desirable in order to maximize capacity over a given coverage area (i.e., to maximize C in equation (2). The **frequency reuse factor** of a cellular system is given by 1/N, since each cell within a cluster is only assigned 1/N of the total available channels in the system.
- Due to the fact that the hexagonal geometry of Figure 4 has exactly six equidistant neighbors and that the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees, there are only certain cluster sizes and cell layouts which are possible.
- In order to connect without gaps between adjacent cells - the geometry of hexagons is such that the number of cells per cluster, N, can only have values which satisfy equation

$$N = i^2 + ij + j^2 \qquad (3)$$

- where i and j are non-negative integers.

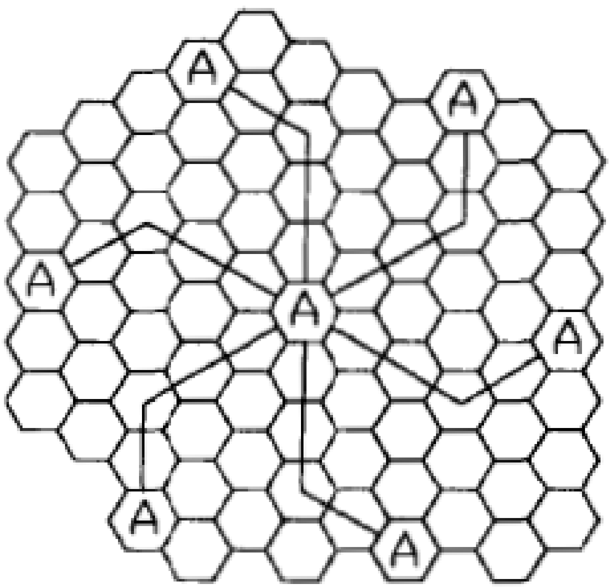
- To find the **nearest co-channel neighbors** of a particular cell, one must do the following:
- (1) move i cells along any chain of hexagons and then
- (2) turn 60 degrees counter-clockwise and move j cells.
- This is illustrated in Figure 5 for i = 3 and j = 2 (example, N = 19).
- 

Figure 5: Method of locating co-channel cells in a cellular system.

Example

4. *If a total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system which uses two 25 kHz simplex channels to provide full duplex if a system uses*

   a. *4-cell reuse,*

   b. *7-cell reuse*

   c. *12-cell reuse.*

   If 1 MHz 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

Given: 'Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz x 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::1 SS channels.

- A 1 MHz spectrum for control channels implies that there are 1000/50 = 20 control channels out of the 660 channels available. To evenly distribute the control and voice channels, simply allocate the same number of channels in each cell wherever possible.
- Here, 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 5 control channels and 160 voice channels per cell. In practice, however, each cell only needs a single control channel (the control channels have a greater reuse distance than the voice channels}. Thus, one control channel and 160 voice channels would be assigned to each cell.
- (b) For N = 7, 4 cells with 3 control channels and 92 voice channels, 2 cells with 3 control channels and 90 voice channels, and 1 cell with 2 control channels and 92 voice channels could be allocated. In practice,

however, each cell would have one control channel, four cells-would have 91 voice channels, and three cells would have 92 voice channels.

- (c) For N = 12, we can have 8 cells with 2 control channels and 53 voice channels, and 4 cells with 1 control channel and 54 voice channels each. In an actual system, each cell would have 1 control channel, 8 cells would have 53 voice channels, and 4 cells would have 54 voice channels.

Example 2

Find the relationship between any two nearest co-channel cell distance D and the cluster size N.

Solution

For hexagonal cells, it can be shown that the distance between two adjacent cell centers $=\sqrt{3}R$, where R is the radius of any cell. The normalized co-channel cell distance D_n can be calculated by traveling '*i*' cells in one direction and then traveling '*j*' cells in **anticlockwise** 120° of the primary direction. Using law of vector addition

$$D_n^2 = j^2 \cos^2\left(30^o\right) + \left(i + j \sin\left(30^o\right)\right)^2 \qquad (4)$$

which turns out to be

$$D = \sqrt{i^2 + ij + j^2} = \sqrt{N} \qquad (5)$$

Multiplying the actual distance $\sqrt{3}R$ between two adjacent cells with it, we get

$$D = D_n \sqrt{3}R = \sqrt{3N}R \qquad (6)$$

Example 3

Find out the surface area of a regular hexagon with radius R, the surface area of a large hexagon with radius D, and hence compute the total number of cells in this large hexagon.

Hint: In general, this large hexagon with radius D encompasses the center cluster of N cells and one-third of the cells associated with six other peripheral large hexagons.

Thus, the answer must be $N + 6\left(N3\right) = 3N$

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.
- In 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.

- 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.
- In a **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.

- **Hybrid channel assignment strategy** is a combination of fixed and dynamic channel allocation schemes, with the channels divided into fixed and dynamic sets. This means that each cell is given a fixed number of channels that is exclusively used by the cell. Request for a channel from the dynamic set is initiated only when a cell has exhausted using all its channels in the fixed set.

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 hand off 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, and be **imperceptible** to the users. In order to meet these requirements, system designers must specify an **optimum signal** level at which to initiate a handoff.
- Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver (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, 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. Therefore, Δ is chosen carefully to meet these conflicting requirements.

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

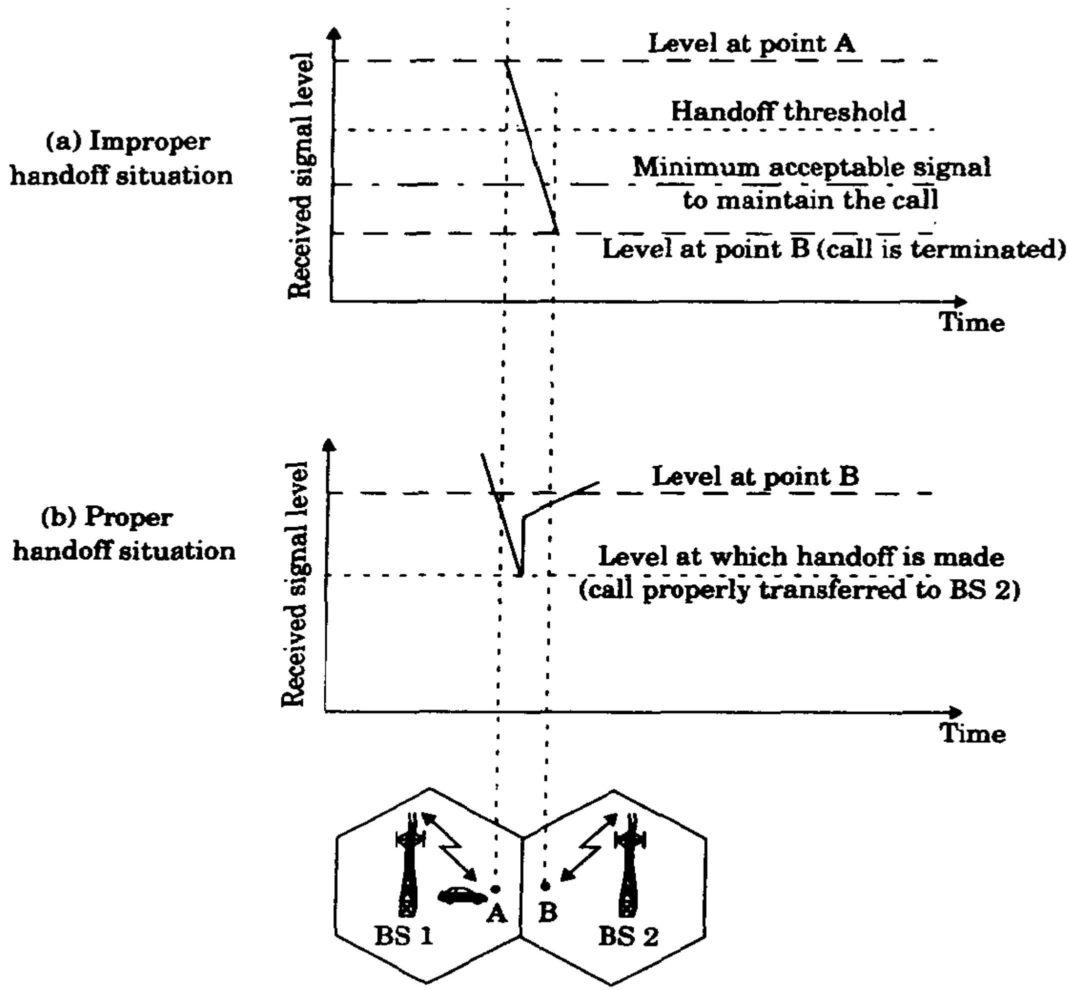


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Figure 6: Illustration of a handoff scenario at cell boundary.

To do task

1. *Discuss at least three challenges encountered when designing and/or implementing handoff process in practical cellular systems*

2. *Discuss different handoff strategies employed to achieve the objects of handoff process such as soft handoff, mobile assisted handoff, intersystem handoff etc*

3. *Using appropriate diagrams, define four different and practical types of handoffs*

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, or any noncellular system which inadvertently 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 is more severe in urban areas, due to the greater RF noise floor and the large number of base stations and mobiles. 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** and **adjacent channel interference**.