EEEN 474
Wireless Communication

Spring 2020

The Cellular Concept

System Design Fundamentals

The motivation behind the cellular concept

- Design objective of **early** mobile radio systems: To achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower

  (+) Good coverage

  (-) Impossible to reuse frequencies (because of interference)

e.g. Bell mobile system in NYC in the 1970s: max 12 simultaneous channels over a 1000 miles^2

The motivation behind the cellular concept

- Government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services, had to restructure the radio telephone system to
  - achieve high capacity with limited radio spectrum
  - while at the same time covering very large areas

Cellular Technology

- Solves the problem of spectral congestion and user capacity without any major technological changes
- A system-level idea
  - Replace a single high-power transmitter (large cell) with many low power transmitters (small cells)
  - Each base station is allocated a portion of channels available to the system and provides coverage to a small area (for frequency reuse)
  - Neighboring base stations are assigned different groups of channels to minimize interference

Cellular Technology

- As more channels are needed
  - The number of base stations may be increased
  - Along with a corresponding decrease in transmitter power to avoid added interference

This fundamental principle is the foundation for all modern wireless communication systems

(Fixed number of channels and arbitrarily large number of subscribers, by reusing the channels)

Frequency Reuse

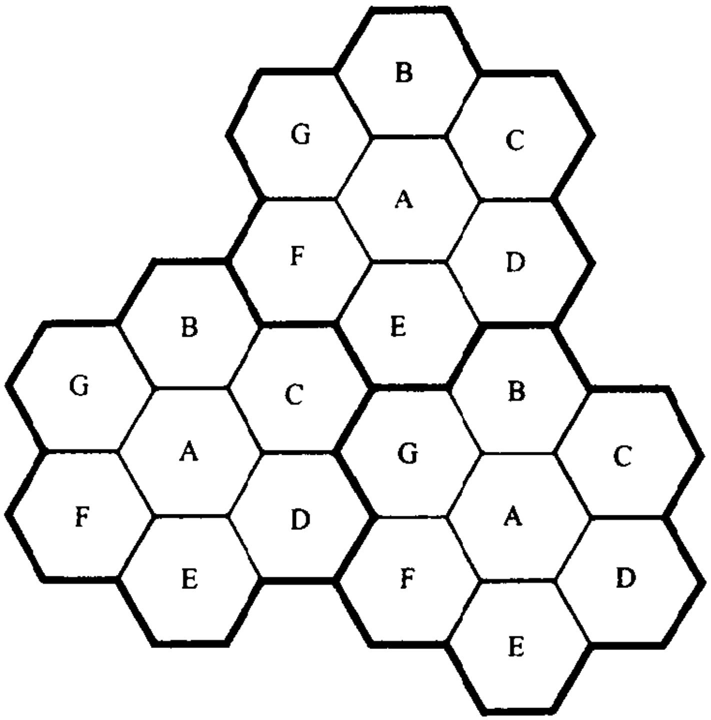


Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, N, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

Hexagonal cell shape is a conceptual and simplistic model of the radio coverage for each base station, however is universally adopted since it permits easy and manageable analysis of a cellular system.

The actual radio coverage is known as the footprint and is determined from field measurements or propagation prediction models.

Cluster size: N (here N=7) Frequency reuse factor: 1/N (here 1/7)

Why Hexagon?

- Circle: gaps between adjacent cells, or overlapping regions.
- Shapes to cover the entire region w/o gap or overlap, and with equal area: square, equilateral triangle, hexagon
  - A cell must be designed to serve the weakest mobiles (those located at the perimeter)
  - For a given distance between the center of a polygon and its farthest perimeter points, the hexagon has the largest area of the three

Placement of Base Stations

- Center-excited cells (omni-directional antennas are used)
- Edge-excited (or corner-excited) cells (sectored directional antennas are used)
- 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

Frequency Reuse

- 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

    (N unique and disjoint channel groups, each having the same number of channels)

    N is the size of the cluster, or, the number of cells in a cluster
  - Then the total number of available radio channels can be expressed as

$$S = kN$$

Frequency Reuse

- If a cluster is replicated M times within the system, the total number of duplex channels, C, can be used as a capacity and is given by

$$C = MkN = MS$$

The Capacity

In summary:

$$C = MkN = MS$$

k: the number of distinct channels within a cell

N: number of cells within a cluster

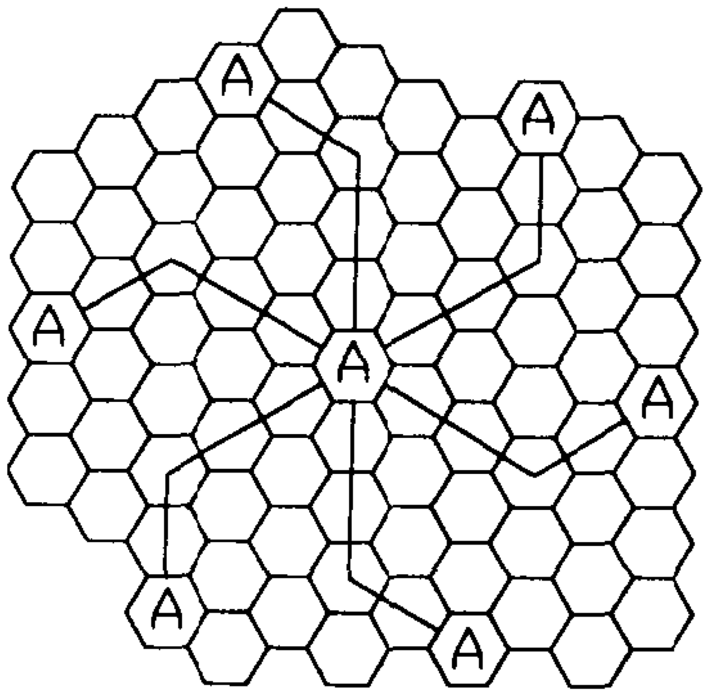
S: total number of duplex channels available in a cellular system

M: the number of clusters

C: the capacity

- Smallest possible N is the best for maximum capacity (WHY?)
- Limitation: Interference

Method of locating co-channel cells



Method of locating co-channel cells in a cellular system. In this example, $N = 19$ (i.e., $i = 3, j = 2$). [Adapted from [Oet83] © IEEE].

$$N = i^2 + ij + j^2$$

i and *j* are non-negative integers

a) Move *i* cells along any chain of hexagons

b) Turn 60 degrees counter-clockwise and move *j* cells

Example 1

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 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 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 × 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.

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 voice 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 five 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 $N = 7$, 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. 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 eight cells with two control channels and 53 voice channels, and four cells with one control channel and 54 voice channels each. In an actual system, each cell would have one control channel, eight cells would have 53 voice channels, and four cells would have 54 voice channels.

Channel Assignment Strategies

- For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of
  - increasing the capacity
  - minimizing the interference

  is required
- A variety of channel assignment strategies have been developed to achieve these objectives
- Channel assignment strategies
  - Fixed
  - Dynamic

The choice effects the performance, especially in handoff

Channel Assignment Strategies

- Fixed: Voice channels are allocated to different cells permanently

  (-) If all channels in the cell are occupied, a new call is *blocked*

  Several strategies to prevent blocking, e.g., *borrowing strategy:* Borrowing channels from neighboring cell. MSC supervises the procedure.

- Dynamic: Voice channels are not allocated to different cells permanently. Each time a call request is made, base station requests a channel from MSC.

  MSC allocates the channel by taking into account:
  - The likelihood of future blocking
  - The frequency of use of the candidate channel
  - The reuse distance of the channel
  - Other cost functions

  (+) Reduces the likelihood of blocking, increases channel utilization

  (-) Requires the MSC to collect real-time data on channel occupancy, traffic distribution, and *radio signal strength indications* (RSII) of all channels continuously. This increases the storage and computational load

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 → **handoff**
  - Involves identifying a new base station
  - Also requires that the voice and control signals be allocated to channels associated with the new base station

Handoff Strategies

- Many handoff strategies prioritize handoff requests over call initiation requests when allocating unused channels in a cell site
- Handoff must be
  - performed successfully
  - performed as infrequently as possible
  - imperceptible to users
- → system designers must specify an optimum signal level at which to initiate a handoff

Handoff Strategies

- Specify a particular signal level as the minimum usable signal for acceptable voice quality at the base station receiver
  - Normally between -90 dBm and -100 dBm

dBm: $10\log_{10}$(<power_in_milliwatts>)

Power in dBm = Power in dB + 30 dBm

- Use a slightly stronger signal level as the threshold at which a handoff is made

Handoff Strategies

- The margin

$$\Delta = P_{r\ handoff} - P_{r\ minimum\ usable}$$

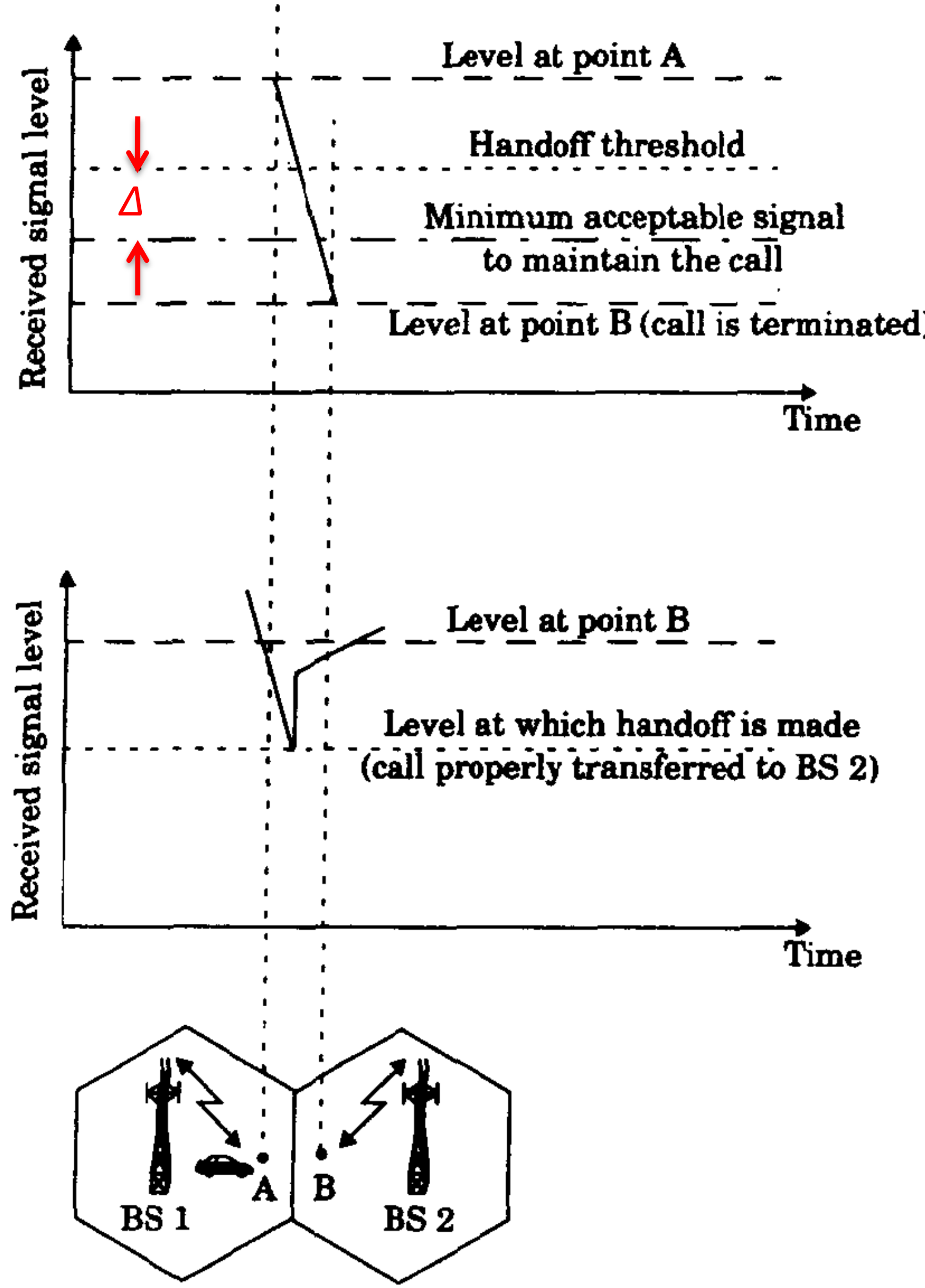
- Δ Cannot be too large or too small
  - If too large→ unnecessary handoffs (which burden MSC)
  - If too small → there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions

→ choose Δ carefully

May happen if
-There is delay by the MSC
-Δ is too small

(a) Improper handoff situation

(b) Proper handoff situation



Handoff Strategies

- MSC should make sure that the drop in the signal level is not due to momentary fading and that the mobile is actually moving away from the serving base station

→ the base station monitors the signal level for a certain period of time before a handoff is initiated

Tradeoff: Avoiding unnecessary handoff & avoiding termination of the call

An important factor: Speed of the vehicle (can be computed from the statistics)

Dwell Time

- The time over which a call may be maintained within a cell, without handoff, is called the *dwell time*
- Governed by a number of factors
  - Speed of the user
  - Propagation
  - Interference
  - Distance between the subscriber and the base station
  - Other time varying effects
- Even when a mobile user is stationary, ambient motion in the vicinity of the base station and the mobile can produce fading (i.e., even a stationary subscriber can have a random and finite dwell time)
- Analysis shows that dwell time statistics vary greatly, depending on the speed of the user & the type of radio coverage
  - Around highways, has a distribution concentrated around the mean
  - In dense, cluttered environments, has a distribution with a large variation around the mean (and dwell time is usually shorter than assumed)

- Some systems handle handoff requests in the same way they handle originating calls
  - The probability that a handoff request will not be served by a new base station is equal to the blocking probability of incoming calls
- However, from the user’s point of view, having a call abruptly terminated while in the middle of a conversation is more annoying than being blocked occasionally on a new call attempt
- To improve the quality of the service as perceived by the users, there are various methods to prioritize handoff requests over a call initiation requests (when allocating voice channels)

Prioritizing Handoffs

- Guard channel concept
  - A fraction of the total available channels in a cell is reserved exclusively for handoff requests

  (-) reduces the total carried traffic

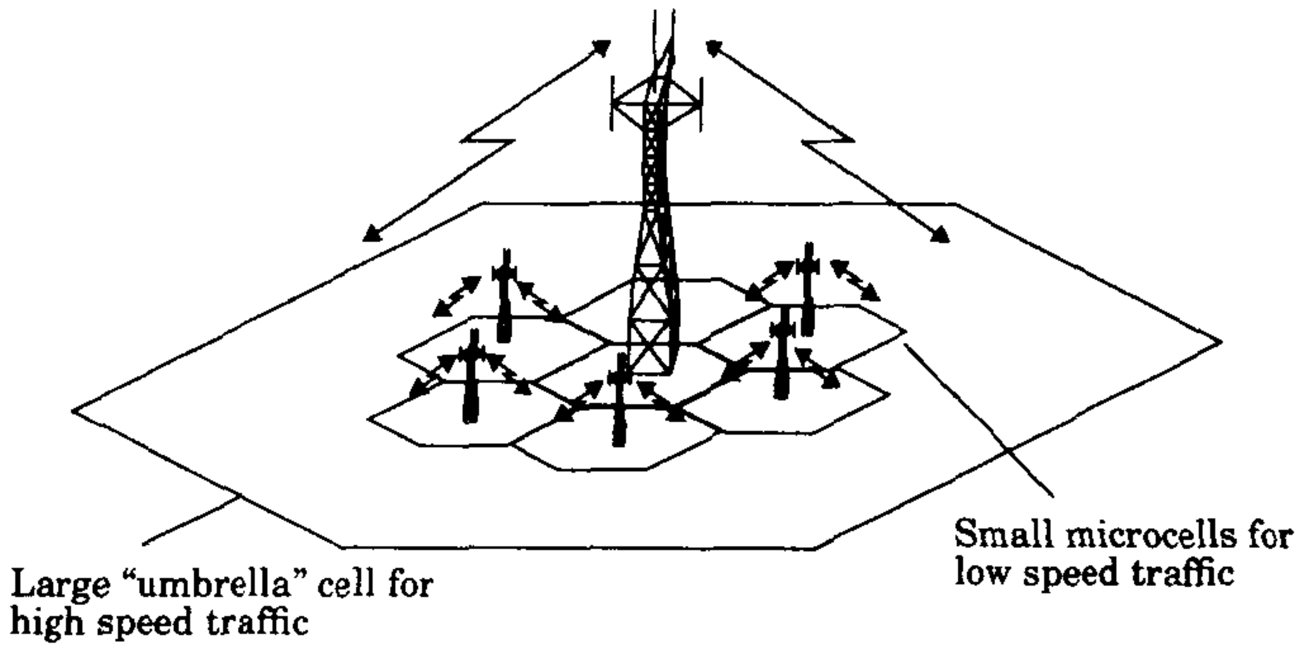
  (+) efficient spectrum utilization when dynamic channel assignment strategies are used
- Queuing of handoff requests to decrease the probability of forced termination of a call

  (-) time delay may cause forced termination

  (+) if the time interval between signal level drop and termination is sufficient for the size of queue (depends on the traffic pattern of the particular service area), it works

Practical Handoff Considerations

- High speed vehicles versus pedestrian users
- Solution:



The umbrella cell approach

Practical Handoff Considerations

- A pedestrian user that provide a very strong signal to the base station (e.g. in urban areas, when there is a line-of-sight (LOS) radio path between the subscriber and the base station)
- This is called *cell dragging*
- Creates a potential interference and traffic management problem

Solution: Adjusting handoff thresholds and radio coverage parameters carefully

Interference and System Capacity

- Sources of interference
  - Another mobile in the same cell
  - A call in progress in the neighboring cell
  - Other base stations operating in the same frequency band
  - Any noncellular system which inadvertently leaks energy into the cellular frequency band
- Effects:
  - On voice channels → crosstalk
  - On control channels → missed and blocked calls due to errors
- More severe in urban areas

Interference and System Capacity

- The two major types of system-generated cellular interference
  - Co-channel interference
  - Adjacent channel interference

Co-channel interference and system capacity

- Cells that use the same set of frequencies → co-channel cells
- Interference between signals from these cells: Co-channel interference
- Cannot be combated by simply increasing the carrier power of a transmitter
- Co-channel cells must be physically separated by a minimum distance to provide sufficient isolation

Co-channel Reuse Ratio

- The co-channel reuse ratio is independent of the transmitted power when
  - the size of each cell is approximately the same, and
  - the base stations transmit the same power

  and it becomes a function of the radius of the cell (R) and the distance between centers of the nearest co-channel cells (D)

$$Q = \frac{D}{R} = \sqrt{3N}$$ *co-channel reuse ratio*

- Tradeoff:
  - Small *Q* provides larger capacity since *N* is small
  - Large *Q* improves transmission quality (smaller level of co-channel interference)

	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

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

co-channel reuse ratio

Signal-to-Interference Ratio

- Considering only the first layer of interfering cells,
- If all the interfering base stations are equidistant from the desired base station and if this distance is equal to the distance *D* between cell centers
- The signal-to-interference ratio (S/I or SIR) for a mobile receiver which monitors a forward channel is:

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

- *R*: radius of the cell
- *D*: the distance between the centers of the nearest co-channel cells
- *n*: path loss exponent
- i_0: number of co-channel interfering cells

Example 2

If a signal to interference ratio of 15 dB is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) $n = 4$, (b) $n = 3$? Assume that there are 6 co-channels cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution

	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

(a) $n = 4$

First, let us consider a 7-cell reuse pattern.

Using equation (2.4), the co-channel reuse ratio $D/R = 4.583$.

Using equation (2.9), the signal-to-noise interference ratio is given by

$$S/I = (1/6)\times(4.583)^4 = 75.3 = 18.66 \text{ dB}.$$

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

b) $n = 3$

First, let us consider a 7-cell reuse pattern.

Using equation (2.9), the signal-to-interference ratio is given by

$$S/I = (1/6)\times(4.583)^3 = 16.04 = 12.05 \text{ dB}.$$

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

Using equation (2.3), the next possible value of N is 12, ($i = j = 2$).

The corresponding co-channel ratio is given by equation (2.4) as

$$D/R = 6.0.$$

Using equation (2.3) the signal-to-interference ratio is given by

$$S/I = (1/6)\times(6)^3 = 36 = 15.56 \text{ dB}.$$

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

Adjacent Channel Interference

- Interference resulting from signals which are adjacent in frequency to the desired signal → adjacent channel interference
- Results from
  - Imperfect receiver filters which allow nearby frequencies to leak into the pass band
- Can be minimized through
  - careful filtering
  - careful channel assignments

    (by not assigning adjacent channels to a cell, by making the frequency separation as large as possible)
- May occur when *N* is small

Power Control for Reducing Interference

- Base stations keep under constant control the power levels transmitted by every subscriber unit, to ensure that each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel
- Helps prolong the battery life