The Cellular Concept
2.1 Introduction to Cellular Systems

- Solves the problem of spectral congestion and user capacity.
- Offer very high capacity in a limited spectrum without major technological changes.
- Reuse of radio channel in different cells.
- Enable a fix number of channels to serve an arbitrarily large number of users by reusing the channel throughout the coverage region.
2.2 Frequency Reuse

- Each cellular base station is allocated a group of radio channels within a small geographic area called a *cell*.
- Neighboring cells are assigned different channel groups.
- By limiting the coverage area to within the boundary of the cell, the channel groups may be reused to cover different cells.
- Keep interference levels within tolerable limits.
- Frequency reuse or frequency planning
  - seven groups of channel from A to G
  - footprint of a cell - actual radio coverage
  - omni-directional antenna v.s. directional antenna
Consider a cellular system which has a total of \( S \) duplex channels.

Each cell is allocated a group of \( k \) channels, \( k < S \).

The \( S \) channels are divided among \( N \) cells.

The total number of available radio channels

\[
S = kN
\]

The \( N \) cells which use the complete set of channels is called *cluster*.

The cluster can be repeated \( M \) times within the system. The total number of channels, \( C \), is used as a measure of capacity

\[
C = MkN = MS
\]

The capacity is directly proportional to the number of replication \( M \).

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

Small \( N \) is desirable to maximize capacity.

The frequency reuse factor is given by \( 1/N \).
• Hexagonal geometry has
  – exactly six equidistance neighbors
  – the lines joining the centers of any cell and each of its neighbors are
    separated by multiples of 60 degrees.
• Only certain cluster sizes and cell layout are possible.
• The number of cells per cluster, $N$, can only have values which satisfy
  \[ N = i^2 + ij + j^2 \]
• Co-channel neighbors of a particular cell, ex, $i=3$ and $j=2$. 
2.3 Channel Assignment Strategies

- Frequency reuse scheme
  - increases capacity
  - minimize interference

- Channel assignment strategy
  - fixed channel assignment
  - dynamic channel assignment

- Fixed channel assignment
  - each cell is allocated a predetermined set of voice channels
  - any new call attempt can only be served by the unused channels
  - the call will be *blocked* if all channels in that cell are occupied

- Dynamic channel assignment
  - channels are not allocated to cells permanently
  - allocate channels based on request
  - reduce the likelihood of blocking, increase capacity
2.4 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 operation
  – identifying a new base station
  – re-allocating the voice and control channels with the new base station.

• Handoff Threshold
  – Minimum usable signal for acceptable voice quality (-90dBm to -100dBm)
  – Handoff margin \( \Delta = P_{r,\text{handoff}} - P_{r,\text{minimum usable}} \) cannot be too large or too small.
  – If \( \Delta \) is too large, unnecessary handoffs burden the MSC
  – If \( \Delta \) is too small, there may be insufficient time to complete handoff before a call is lost.
(a) Improper handoff situation

Level at point A
Handoff threshold
Minimum acceptable signal to maintain the call
Level at point B (call is terminated)

(b) Proper handoff situation

Level at point B
Level at which handoff is made (call properly transferred to BS 2)

BS 1

BS 2
• Handoff must ensure that the drop in the measured signal is not due to momentary fading and that the mobile is actually moving away from the serving base station.

• Running average measurement of signal strength should be optimized so that unnecessary handoffs are avoided.
  – Depends on the speed at which the vehicle is moving.
  – Steep short term average -> the hand off should be made quickly
  – The speed can be estimated from the statistics of the received short-term fading signal at the base station

• Dwell time: the time over which a call may be maintained within a cell without handoff.

• Dwell time depends on
  – propagation
  – interference
  – distance
  – speed
• **Handoff measurement**
  – In first generation analog cellular systems, signal strength measurements are made by the base station and supervised by the MSC.
  – In second generation systems (TDMA), handoff decisions are mobile assisted, called mobile assisted handoff (MAHO)

• **Intersystem handoff**: If a mobile moves from one cellular system to a different cellular system controlled by a different MSC.

• **Handoff requests is much important than handling a new call.**
Practical Handoff Consideration

- Different type of users
  - High speed users need frequent handoff during a call.
  - Low speed users may never need a handoff during a call.
- Microcells to provide capacity, the MSC can become burdened if high speed users are constantly being passed between very small cells.
- Minimize handoff intervention
  - handle the simultaneous traffic of high speed and low speed users.
- Large and small cells can be located at a single location (umbrella cell)
  - different antenna height
  - different power level
- Cell dragging problem: pedestrian users provide a very strong signal to the base station
  - The user may travel deep within a neighboring cell
Large “umbrella” cell for high speed traffic

Small microcells for low speed traffic
• Handoff for first generation analog cellular systems
  – 10 secs handoff time
  – \( \Delta \) is in the order of 6 dB to 12 dB
• Handoff for second generation cellular systems, e.g., GSM
  – 1 to 2 seconds handoff time
  – mobile assists handoff
  – \( \Delta \) is in the order of 0 dB to 6 dB
  – Handoff decisions based on signal strength, co-channel interference, and adjacent channel interference.
• IS-95 CDMA spread spectrum cellular system
  – Mobiles share the channel in every cell.
  – No physical change of channel during handoff
  – MSC decides the base station with the best receiving signal as the service station
2.5 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
  – noncellular system leaks energy into the cellular frequency band

• Two major cellular interference
  – co-channel interference
  – adjacent channel interference
2.5.1 Co-channel Interference and System Capacity

- Frequency reuse - there are several cells that use the same set of frequencies
  - co-channel cells
  - co-channel interference
- To reduce co-channel interference, co-channel cell must be separated by a minimum distance.
- When the size of the cell is approximately the same
  - co-channel interference is independent of the transmitted power
  - co-channel interference is a function of
    - $R$: Radius of the cell
    - $D$: distance to the center of the nearest co-channel cell
- Increasing the ratio $Q = D/R$, the interference is reduced.
- $Q$ is called the co-channel reuse ratio
• For a hexagonal geometry

\[ Q = \frac{D}{R} = \sqrt{3N} \]

• A small value of Q provides large capacity
• A large value of Q improves the transmission quality - smaller level of co-channel interference
• A tradeoff must be made between these two objectives

<table>
<thead>
<tr>
<th>Table 2.1 Co-channel Reuse Ratio for Some Values of N</th>
</tr>
</thead>
<tbody>
<tr>
<td>i = 1, j = 1</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>i = 1, j = 1</td>
</tr>
<tr>
<td>i = 1, j = 2</td>
</tr>
<tr>
<td>i = 2, j = 2</td>
</tr>
<tr>
<td>i = 1, j = 3</td>
</tr>
</tbody>
</table>
• Let $i_0$ be the number of co-channel interfering cells. The signal-to-interference ratio (SIR) for a mobile receiver can be expressed as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

$S$: the desired signal power

$I_i$: interference power caused by the $i$th interfering co-channel cell base station

• The average received power at a distance $d$ from the transmitting antenna is approximated by

$$P_r = P_0 \left( \frac{d}{d_0} \right)^{-n}$$

or

$$P_r(\text{dBm}) = P_0(\text{dBm}) - 10n \log \left( \frac{d}{d_0} \right)$$

$n$ is the path loss exponent which ranges between 2 and 4.
• When the transmission power of each base station is equal, SIR for a mobile can be approximated as

\[
\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}}
\]

• Consider only the first layer of interfering cells

\[
\frac{S}{I} = \frac{(D/R)^n}{i_0} = \left(\sqrt[3]{3N}\right)^n
\]

• Example: AMPS requires that SIR be greater than 18dB
  – \( N \) should be at least 6.49 for \( n=4 \).
  – Minimum cluster size is 7
• For hexagonal geometry with 7-cell cluster, with the mobile unit being at the cell boundary, the signal-to-interference ratio for the worst case can be approximated as

\[
\frac{S}{I} = \frac{R^{-4}}{2(D - R)^{-4} + (D - R/2)^{-4} + (D + R/2)^{-4} + (D + R)^{-4} + D^{-4}}
\]
2.5.2 Adjacent Channel Interference

- Adjacent channel interference: interference from adjacent in frequency to the desired signal.
  - Imperfect receiver filters allow nearby frequencies to leak into the passband
  - Performance degrade seriously due to *near-far* effect.
• Adjacent channel interference can be minimized through careful filtering and *channel assignment*.
• Keep the frequency separation between each channel in a given cell as large as possible
• A channel separation greater than six is needed to bring the adjacent channel interference to an acceptable level.
2.5.3 Power Control for Reducing Interference

- Ensure each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel
  - long battery life
  - increase SIR
  - solve the near-far problem
2.6 Trunking and Grade of Service

- **Erlangs**: One Erlang represents the amount of traffic density carried by a channel that is completely occupied.
  - Ex: A radio channel that is occupied for 30 minutes during an hour carries 0.5 Erlangs of traffic.

- **Grade of Service (GOS)**: The likelihood that a call is blocked.

- Each user generates a traffic intensity of \( A_u \) Erlangs given by
  \[
  A_u = \mu H
  \]
  where:
  - \( H \): average duration of a call.
  - \( \mu \): average number of call requests per unit time

- For a system containing \( U \) users and an unspecified number of channels, the total offered traffic intensity \( A \), is given by
  \[
  A = UA_u
  \]

- For \( C \) channel trunking system, the traffic intensity, \( A_c \), is given as
  \[
  A_c = UA_u / C
  \]
2.7 Improving Capacity in Cellular Systems

• Methods for improving capacity in cellular systems
  – Cell Splitting: subdividing a congested cell into smaller cells.
  – Sectoring: directional antennas to control the interference and frequency reuse.
  – Coverage zone: Distributing the coverage of a cell and extends the cell boundary to hard-to-reach place.
2.7.1 Cell Splitting

- Split congested cell into smaller cells.
  - Preserve frequency reuse plan.
  - Reduce transmission power.

Reduce $R$ to $R/2$
Illustration of cell splitting within a 3 km by 3 km square
• Transmission power reduction from $P_{t1}$ to $P_{t2}$
• Examining the receiving power at the new and old cell boundary

$$P_r[\text{at old cell boundary}] \propto P_{t1} R^{-n}$$
$$P_r[\text{at new cell boundary}] \propto P_{t2} (R/2)^{-n}$$

• If we take $n = 4$ and set the received power equal to each other

$$P_{t2} = \frac{P_{t1}}{16}$$

• The transmit power must be reduced by 12 dB in order to fill in the original coverage area.
• Problem: if only part of the cells are split
  – Different cell sizes will exist simultaneously
• Handoff issues - high speed and low speed traffic can be simultaneously accommodated
2.7.2 Sectoring

- Decrease the *co-channel interference* and keep the cell radius $R$ unchanged
  - Replacing single omni-directional antenna by several directional antennas
  - Radiating within a specified sector
• Interference Reduction
2.7.3 Microcell Zone Concept

- Antennas are placed at the outer edges of the cell
- Any channel may be assigned to any zone by the base station
- Mobile is served by the zone with the strongest signal.

- Handoff within a cell
  - No channel re-assignment
  - Switch the channel to a different zone site

- Reduce interference
  - Low power transmitters are employed