EC 551
Telecommunication System Engineering

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# Syllabus

- Tentatively

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Terminologies: BS, MS, Cell, Sector

- **Base station (BS)**
  - Access point (AP)
- **Mobile station (MS)**
  - SS (Subscriber station)
  - MT (mobile terminal)
  - MN (mobile node)
- **Downlink**
  - Forward link
  - BS→MS
- **Uplink**
  - Reverse link
  - MS→BS
- **Cell**
  - Coverage area of a BS
- **Sector**
  - Partial area of a cell that is served by a directional antenna
Abstract model for a cellular system

- **Components**
  - Gateway to the wireline system (backhaul)
  - Base station (BS)
  - Database
  - Security
  - Air interface
  - Cellular phone
Basic Cellular Concept

• “Cell”
  - Typically, cells are hexagonal
  - In practice, it depends on available cell sites and radio propagation conditions

• Spectrum reuse
  - Reuse the same EM spectrum in other geographical location
  - Frequency reuse factor
Frequency Reuse

- **Cluster**
  - A group of cells

- **Frequency reuse factor**
  - \( \frac{\text{Total # of channels in a cluster}}{\text{Total # of channels in a cell}} \)
Clusters:

- Number of BSs comprised in a circle of diameter $D$
- Number of BSs whose inter-distance is lower than $D$
Coverage for a terrestrial zone

Signal OK if $P_{rx} > -X \text{ dBm}$

$P_{rx} = c \ P_{tx} \ d^{-4}$

greater $P_{tx} \rightarrow$ greater $d$

1 Base Station
N=12 channels
• (e.g. 1 channel = 1 frequency)

↓

N=12 simultaneous calls
Cellular coverage

target: cover the same area with a larger number of BSs

19 Base Station
12 frequencies
4 frequencies/cell

Worst case:
4 calls (all users in same cell)

Best case:
76 calls (4 users per cell)

Average case >> 12
Low transmit power

Key advantages:
• Increased capacity (freq. reuse)
• Decreased tx power
Cellular coverage (microcells)

- Many BS
- Very low power!!
- Unlimited capacity!!
- Usage of same spectrum
  - (12 frequencies)
  - (4 freq/cell)
- Disadvantage:
  - Mobility management
Cellular Geometries

(a) Square pattern

(b) Hexagonal pattern
A frequency reuse example

- Example
  - Frequency reuse factor = 7
  - Cluster size = 7

- Question
  - What are other possible frequency reuse patterns?
Cluster

• The hexagon is an ideal choice for macrocellular coverage areas, because it closely approximates a circle and offers a wide range of tessellating reuse cluster sizes.

• A cluster of size N can be constructed if,
  - \( N = i^2 + ij + j^2 \).
  - \( i, j \) are positive integer

• Allowable cluster sizes are
  - \( N = 1,3,4,7,9,12,... \)
\[ N = I^2 + IQ + J^2 \]
\[ N = (2)^2 + (2)(1) + (1)^2 = 7 \]

For \( N = 3 \) we have:

\[ N = I^2 + IQ + J^2 \]
\[ N = (1)^2 + (1)(1) + (1)^2 = 3 \]
Example: $N=7$

- Frequency reuse factor $N=7$
  - $N = i^2 + ij + j^2$
  - $(i,j) = (1,2)$ or $(2,1)$

- Other commonly used patterns
  - $N=3$
    - $(1,1)$
  - $N=4$
    - $(2,0)$; $(0,2)$

- $N=1$ is possible
  - CDMA
Reuse distance

- **Notations**
  - $D$: Reuse distance
  - $r$: Cell radius
  - $N$: Frequency reuse factor

- **Relationship between $D$ and $r$**
  - $D/r = (3N)^{0.5}$
  - $N = i^2 + ij + j^2$
For a hexagon we can define both an inner radius and an outer radius. Both are useful.

\[ R_i = R_o \cos \phi = R_o \cos \frac{2\pi}{12} = R_o \frac{\sqrt{3}}{2} \]

Note that a hexagon has 6 faces or, equivalently, 12 “half-faces.”
In this case: \( j=2, \ i=1 \)

\[
D^2 = (L \cdot i)^2 + (L \cdot j)^2 - 2(L \cdot i)(L \cdot j) \cos(2\pi / 3)
\]

\[
D^2 = L^2 \cdot i^2 + L^2 \cdot j^2 - 2L^2 \cdot i \cdot j \cdot (-0.5)
\]

\[
D^2 = L^2 (i^2 + j^2 + ij)
\]

\[
D / r = \sqrt{3(i^2 + j^2 + ij)} = \sqrt{3N}
\]

Compute \( D \) based on “law of cosine”
Reuse distance

- General formula: $D = R \sqrt{3K}$
- Valid for hexagonal geometry
- $D = $ reuse distance
- $R = $ cell radius
- $q = D/R = $ frequency reuse factor

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<thead>
<tr>
<th>K</th>
<th>q = D/R</th>
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<tbody>
<tr>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>3.46</td>
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<tr>
<td>7</td>
<td>4.58</td>
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<td>9</td>
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<tr>
<td>12</td>
<td>6.00</td>
</tr>
<tr>
<td>13</td>
<td>6.24</td>
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Possible clusters
all integer i,j values

<table>
<thead>
<tr>
<th>i</th>
<th>j</th>
<th>K=ii+jj+ij</th>
<th>q=D/R</th>
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<tr>
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Determine frequency reuse pattern

• Co-channel interference [CCI]
  - one of the major factors that limits cellular system capacity
  - CCI arises when the same carrier frequency is used in different cells.

• Determine frequency reuse factor
  - Propagation model
  - Sensitivity to CCI
Compute total system capacity

- Example
  - Total coverage area = 100 mile$^2$ = 262.4 km$^2$
  - Total 1000, 1256 duplex channels
  - Cell radius = 1km , 0.5km
  - N=4 or N=7

- What’s the total system capacity for N=4 and N=7?

\[ A = \frac{3\sqrt{3}}{2} r^2 = 2.6r^2 \]
Compute total system capacity

• # of cells = 262.4/2.6=100 cells

• # of usable duplex channels/cell
  - \( S = (\# \text{ of channels})/(\text{reuse factor}) \)
  - \( S_4 = 1000/4 = 250 \)
  - \( S_7 = 1000/7 = 142 \)

• Total system capacity (# of users could be accommodated simultaneously)
  - \( C = S \times (\# \text{ of cells}) \)
  - \( C_4 = 250 \times 100 = 25000 \)
  - \( C_7 = 142 \times 100 = 14200 \)
Cellular concepts

• $W$ - total available spectrum, $B$ - bandwidth per user, $N$ is the frequency reuse factor, $m$ - number of cells, number of simultaneous users is given by $n = (m/B)*(W/N)$

• # of users can be increased by
  - Increasing $m$ (cells)
  - Decreasing cluster size ($N$)

• A small cell size
  - Results in longer battery life
  - Reduces handset size
  - Increases handoffs
  - Increases signaling load
  - Increases the complexity of design and network deployment
Practical deployment issues

• Location to setup antenna
  - Antenna towers are expensive
  - Local people do not like BSs
    • Antenna/BS does not look like antenna/BS

• Antenna
  - Omni-directional
  - Directional antenna
Worst-Case CCI on the Forward Channel

- Co channel interference [CCI] is one of the prime limitations on system capacity. We use the propagation model to calculate CCI.

- There are six first-tier, co-channel BSs, two each at (approximate) distances of D-R, D, and R+D and the worst case (average) Carrier-to-(Co-Channel) Interference [CCI] is

\[ \Lambda = \frac{1}{2} \frac{R^{-\beta}}{(D - R)^{-\beta} + D^{-\beta} + (D + R)^{-\beta}} \]

Worst case CCI on the forward channel

R= cell radius
Cell splitting

- Smaller cells have greater system capacity
  - Better spatial reuse
- As traffic load grows, larger cells could split into smaller cells
Cell splitting is the technique of splitting a congested cell into smaller cells.

- New (smaller cells) have their own base stations with reduced antenna height and reduced power.
- Cell splitting increases capacity since frequency reuse can be increased.
- Cell splitting preserves the geometry of the architecture and therefore simply scales the geometry of the architecture.
- In the following figure the cell radius has been reduced by half.
the simple propagation model

\[ P_R = P_o \left( \frac{d}{d_o} \right)^{-n} \]

At the cell boundary the distance \( d \) is \( R \), the unsplit cell radius. Consider both an unsplit and a split scenario. For the unsplit case

\[ P_{r(\text{unsplit})} = P_{t,\text{unsplit}} R^{-n} \]

For the split case

\[ P_{r(\text{split})} = P_{t,\text{split}} \left( \frac{R}{2} \right)^{-n} \]

or

\[ P_{r,\text{split}} = P_{t,\text{split}} R^{-n} 2^n \]
For the received signal powers to be equal we must have

\[ P_{t, \text{unsplit}} R^{-n} = P_{t, \text{split}} R^{-n} 2^n \]

The ratio of transmitted powers is important. Consider the following:

\[ \frac{P_{t, \text{split}}}{P_{t, \text{unsplit}}} = 2^{-n} \]

Note the role of the path loss exponent. For \( n = 4 \), the transmitted can be reduced by a factor of 16 and still provide equal received signal powers.