EL 675
UHF Propagation for Modern Wireless Systems

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Context for Discussing Wireless Channel Characteristics

• Frequencies above ~ 300 MHz ($\lambda < 1 \text{ m}$)
• Radio links in man-made environments
  – At least one end is among the buildings
  – Link lengths
    • Macrocells ($20 \text{ km} > R > 1 \text{ km}$)
    • Microcells ($2 \text{ km} > R > 100 \text{ m}$)
    • Picocells/indoor ($R < 100 \text{ m}$)
  – Presence of many objects with sizes from 10 cm to 100 m
  – Wave interactions described by scattering and shadowing, rather than resonances
Need to Bridge Electromagnetics (EM) and Communications (Com)

- **Electromagnetics**
  - Deals with deterministic physical environment - seek precise solution
  - Field quantities are prediction output

- **Communications**
  - Deals with random processes - seek statistical solutions
  - Required inputs that are statistical measures of received signal properties

- **Must phrase the electromagnetic solutions in ways that can be used by communication community**
  - Understand and predict channel characteristics
Complimentary View Points

• Electromagnetic view point
  – Objects cause a rich set of ray paths connecting transmitter and receiver (multipath)

• Communications view point
  – Received signal is the sum of delayed versions of the transmitted signal (multipath)

• Interpreting the ray description of electromagnetic fields provides the channel characteristics
  – EM propagation governs the channel characteristics, but signal processing governs what is observed
  – Interpret ray results to predict observed statistics
Communication Systems Drive Descriptions of the Radio Channel

• How to characterize channel depends on the radio system and link geometry
  – All require knowledge of the power level

• Different measures of multipath interference
  – Narrowband -- pulsed -- multi-frequency systems
  – Fast fading -- delay spread -- coherence bandwidth
  – Coherence distance -- angle spread -- ?

• Macrocells, microcells and indoor picocells
  – Different considerations of multipath interference
  – Slow fading statistics and range dependence vs. deterministic variations power level
EM Effects That Need to Be Considered

- Propagation of waves through space
- Reflection, transmission and diffraction
  - Mechanisms by which fields get to locations not visible to the transmitter
- Radiation and reception by antennas
- Ray description of radiation
Basic Concepts

• Operation of individual radio systems is dependent on specific channel parameters -- all systems depend on received power and interference.
• Frequency re-use as a basis for increased system capacity
Pre 1980 Vehicular Mobile Telephone System

- Single high base station served entire metropolitan area with $N_c$ frequency channels
- Frequency channels reused in other metropolitan areas
- Because of physical separation, desired signal $S$ much larger than the interfering signal $I$
Cellular Mobile Radio: Frequency Re-use Within a Metropolitan Area

- Advanced Mobile Phone System (AMPS) has 395 two-way channels in two 25 MHz bands centered at 850 MHz.
- Re-using frequency channels in $N$ sub-regions allows for $395N$ simultaneous phone calls.
Dividing Sub-Regions Into $N_R$ Cells Allows Spatial Separation of Cells Using Same Frequency

$N_R = 7$ frequency re-use pattern for hexagonal cells in each sub-region

MTSO assigns channels to mobile and connects to telephone network.
Cell Splitting to Increase Capacity

Cell have same number of channels \((N_C / N_R)\) no matter what size.

Small cells accommodate higher subscriber density.
Number of Cells Needed in Each Sub Region

Determined by:

I. Propagation characteristics of the environment
   
   Simplest form of propagation dependence
   
   \[ P = P_T A / R^n \]
   
   \( P \) = Received power
   
   \( P_T \) = Transmitted power
   
   \( A, n \) = Amplitude and range index dependent on frequency, antenna height, buildings

II. Minimum signal to interference ratio for adequate reception by radio system.

   For AMPS systems \( P/I \geq 50 \) (10log \( P/I \) > 17dB).
Example of Linear Cells Along a Highway

Signal Power for mobile at the cell boundary from base station of Cell 1, Region 1:

\[ P = \frac{P_T A}{R_C^n} \]

Interference from base station of Cell 1, Region 2:

\[ I = \frac{P_T A}{(2N_R - 1) R_C^n} \]

\( N_R = 3 \)

Reuse Factor
\( N_R \) for Linear Cells for Different Range Index \( n \)

Accounting for interference only from the nearest co-channel cell

\[
\left( \frac{P}{I} \right)_{\text{min}} \leq \frac{P}{I} = \left( \frac{(2N_R - 1)R_C}{R_C^n} \right)^n = (2N_R - 1)^n
\]

or

\[
N_R \geq \frac{1}{2} \left[ 1 + \sqrt[n]{(P/I)_{\text{min}}} \right]
\]

For \( (P/I)_{\text{min}} = 50 \)

<table>
<thead>
<tr>
<th>Condition</th>
<th>( n )</th>
<th>( N_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Flat earth</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
Symmetric patterns based on hexagonal cells have all co-channel cells located on circles. There are six cells on the smallest circle of radius $D$, where

$$D = R_C \sqrt{3N_R}.$$ 

For symmetric reuse patterns

$$N_R = m_1^2 + m_1k_1 + k_1^2$$

where $m_1, k_1$ are any integers. Lowest values are

$N_R = 3, 4, 7, 9, 12, 13, 19, 21, 25, 27, 31, 39$. 

Co-channel cells in the first tier
Frequency Re-Use for \( S = A/R^n \) Signal Variation

Signal Power from base stations to mobile at the cell edge

\[
P = P_T A / (R_C)^n
\]

Interference power from co-channel base stations in the first tier

\[
I = P_T A \left[ \frac{2}{(D - R_C)^n} + \frac{2}{D^n} + \frac{2}{(D + R_C)^n} \right]
\]
**NR for Symmetric Pattern of Hexagonal Cell**

\[
\left(\frac{P}{I}\right)_{\text{min}} \leq \left(\frac{P}{I}\right) = \left(\frac{R_C}{D-R_C}\right)^n + \left(\frac{R_C}{D}\right)^n + \left(\frac{R_C}{D+R_C}\right)^n
\]

\[
= \frac{0.5}{\left(\frac{1}{(D/R_C)-1}\right)^n + \left(\frac{1}{D/R_C}\right)^n + \left(\frac{1}{(D/R_C)+1}\right)^n}
\]

If \((P/I)_{\text{min}} = 50\), and since \(D = R_c \sqrt{3N_R}\), then

\[
50 \leq \frac{0.5}{\left(\frac{1}{\sqrt{3N_R}-1}\right)^n + \left(\frac{1}{\sqrt{3N_R}}\right)^n + \left(\frac{1}{\sqrt{3N_R}+1}\right)^n}
\]

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<th>(N_R)</th>
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</thead>
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<tr>
<td>Free space</td>
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<td>4</td>
<td>7</td>
</tr>
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Interference Limited Cellular Systems

- System design is dependent on the propagation characteristics
  For signal dependence: \( S = \frac{A}{R^n} \)
    
    Free space propagation:
    \[ n = 2 \text{ and } N_R \text{ will be large } (N_R = 101) \]
    Propagation over flat earth:
    \[ n = 4 \text{ and } N_R = 7 \]
    For Cellular Mobile Radio, \( N_C \sim 400 \)

<table>
<thead>
<tr>
<th>( n )</th>
<th>Channels / cell</th>
<th>Base Station/1,000 Calls</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>~ 4</td>
<td>~250</td>
</tr>
<tr>
<td>4</td>
<td>~ 60</td>
<td>~16</td>
</tr>
</tbody>
</table>
Use Sectored Cells to Account for Realistic Propagation Laws

- Range index $n$ is between 3 and 4 for elevated base station antenna
- Additional random fading of the signal exists
- Use sectored cells to achieve $P/I > 50$
- Three sectors per cell is variation of $N_R=21$ frequency re-use pattern.

Patterns for cell sectorization using directive antennas. Single base station serves three sectors.
Effect of Range Index $n$ on Down Link System Capacity for CDMA System

- Same frequency used to communicate to subscribers in all cells.
- Different code used for each subscriber.
- Signals to subscribers in other cells act as interference.
- Subscribers in same cells have orthogonal codes, but multipath interference results in some interference.
- Subscriber can receive same signal from up to three base stations.
- For adequate reception, $I \leq FP$, where the value of $F > 1$ depends on processing gain, voice activity factor, etc.
$P / I$ for Subscriber at Junction of 3 Cells for $A / R_C^n$ Propagation Dependence

Power received from 3 nearest base stations: 

$$P = 3P_T A / R_C^n$$

Multipath interference due signals sent to other subscribers in cells A, B, C:

$$I_0 = 3\gamma(N_S - 1)P_T A / R_C^n$$

where $0 < \gamma < 1$

Interference due to signals sent to subscribers in cells I, II, III:

$$I_\alpha = 3N_S P_T A / (2R_C)^n$$

Interference due to signals to subscribers in cells 1, 2, L, 6:

$$I_\beta = 6N_S P_T A / (\sqrt{7}R_C)^n$$

$N_S$ active subscribers in each cell
Interference Power Received From Base Stations Outside of the Closest 12

Smear out base stations over an infinite disk with a hole of radius $R_1$ to achieve a transmitted power density

$$P_D = \frac{N_s P_T}{\text{area of a cell}}.$$  

Area of cell = \frac{3\sqrt{3}}{2} R_C^2  

so that

$$P_D = \frac{2}{3\sqrt{3}} \frac{N_s P_T}{R_C^2}$$

To find the radius of the hole, set the area of the hole $\pi R_c^2$ equal to the area of the 12 cells. Thus

$$R_1 = 3 \sqrt{\frac{2\sqrt{3}}{\pi}} R_C = 3.150 R_C$$
Interference Received From Smeared Out Base Stations on the Infinite Disk

Interference power \( I_D = \iint (\text{Tx power density}) \left( \frac{A}{R^n} \right) (\text{area element}) \)

For circular symmetry

\[
I_D = \int_{R_1}^{\infty} \left( \frac{2}{3\sqrt{3}} \frac{N_SP_T}{R_C^2} \right) \left( \frac{A}{R^n} \right) (2\pi R dR) = \frac{4\pi}{3\sqrt{3}} N_S P_T \frac{A}{R_C^2} \int_{R_1}^{\infty} \frac{dR}{R^{n-1}}
\]

If \( n \leq 2 \), then \( I_D = \infty \)

If \( n > 2 \), then

\[
I_D = \frac{4\pi}{3\sqrt{3}} N_S P_T \frac{A}{R_C^2} \frac{1}{(n-2)R_1^{n-2}} = \frac{4\pi}{3\sqrt{3}} N_S P_T \frac{A}{(n-2)} (3.15)^{(n-2)} R_1^n
\]

\[
= \frac{2.418}{(n-2)(3.15)^{(n-2)}} N_S P_T \frac{A}{R_C^n}
\]
P/I Requirement and Capacity $N_s$

Total interference $I = I_o + I_\alpha + I_\beta + I_D$. For adequate reception

$$I \leq F(\text{Signal Power}) = F \frac{3P_T A}{R_C^n}$$

For $n \leq 2$:

$$I_D = \infty \quad \text{so that capacity} \quad N_s = 0$$

For $n > 2$:

$$I = P_T \frac{A}{R_C^n} \left[ 3\gamma(N_s - 1) + 3 \frac{N_s}{2^n} + \frac{2N_s}{(\sqrt{7})^n} + \frac{2.418}{(n-2)(3.15)^{(n-2)}} N_s \right]$$

Reception requirement gives

$$N_s \left[ \gamma + \frac{1}{2^n} + \frac{2}{(\sqrt{7})^n} + \frac{2.418}{3(n-2)(3.15)^{(n-2)}} \right] \leq F + \gamma$$

To see the role of $n$, recall that $F > 1$ and suppose that $\gamma = 0.1$

If $n = 4$:

$$N_s \leq (F + 0.1) / 0.224 = 4.47(F + 0.1)$$

If $n = 3$:

$$N_s \leq 1.70(F + 0.1)$$
Conclusions

Modern systems employ frequency re-use to increase capacity

Wireless systems employing frequency re-use are interference limited
   It is necessary to balance coverage and interference

Design of Systems to accommodate a given number of subscribers
   is dependent on the propagation characteristics

Higher values of range index $n$ allow for less base stations to cover
   a given area

Other channel characteristics will influence system design
   Random spatial fading
   Doppler spread, time delay spread