EEC173B/ECS152C, Spring 2009

Fundamentals of Wireless Communications
- #4: Spread Spectrum
- #5: Multiplexing
- #6: Frequency Reuse (Cellular Concept)

Case Study: Wireless cellular networks
- #7: Handoff

Acknowledgment: Selected slides from Prof. Schiller

How do we overcome limitations imposed by the radio channel?

- Flat fading countermeasures
  - Fade Margin
  - Diversity
  - Coding and Interleaving
  - Adaptive Techniques
- Delay Spread Countermeasures
  - Equalization
  - Multicarrier
  - Spread Spectrum
  - Antenna Solutions
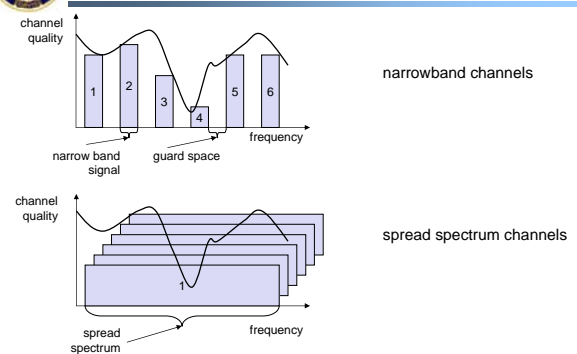
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#4: Spread Spectrum Technology

- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
- Protection against narrow band interference

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Spreading and frequency selective fading

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Spread Spectrum

- Spread spectrum increases the transmit signal bandwidth to reduce the effects of flat fading, ISI and interference.
- SS is used in all wireless LAN products in the ISM band
  - Required for operation with reasonable power
  - Minimal performance impact on other systems
  - IEEE 802.11 standard
- There are two SS methods: direct sequence and frequency hopping
  - Direct sequence multiplies the data sequence by a faster chip sequence.
  - Frequency hopping varies the carrier frequency by the same chip sequence
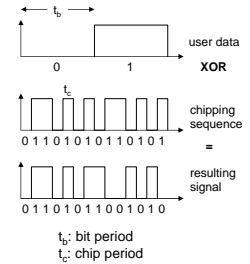
Direct Sequence Spread Spectrum (DSSS)

- XOR of the signal with pseudo-random number (chipping sequence)
  - Many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - Reduces frequency selective fading
  - In cellular networks
    - Base stations can use the same frequency range
    - Several base stations can detect and recover the signal
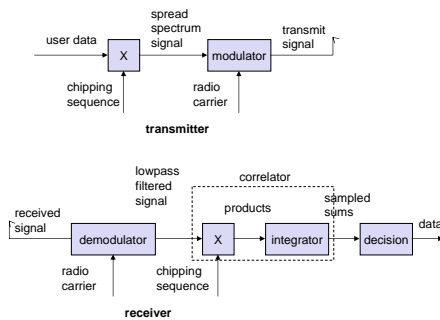   - Soft handover
- Disadvantages
  - Precise power control necessary

t_b

user data

0   1   **XOR**

t_c

chipping sequence

0 1 1 0 1 0 1 0 1 1 0 1 0 1

=

resulting signal

0 1 1 0 1 0 1 1 0 0 1 0 1 0

t_b: bit period
t_c: chip period

DSSS

spread spectrum signal

user data → X → modulator → transmit signal

chipping sequence   radio carrier

transmitter

lowpass filtered signal   correlator

products   sampled sums

received signal → demodulator → X → integrator → decision → data
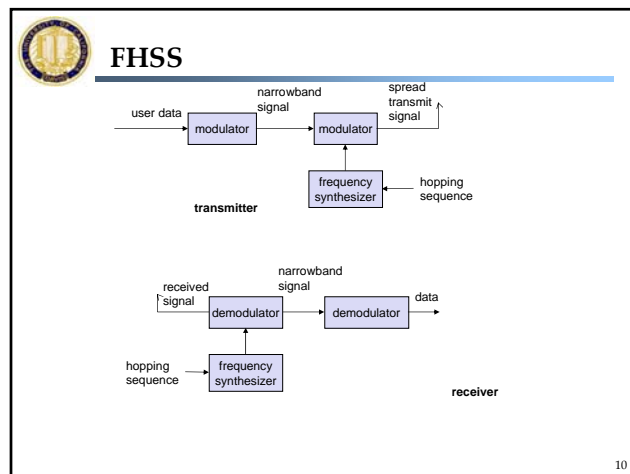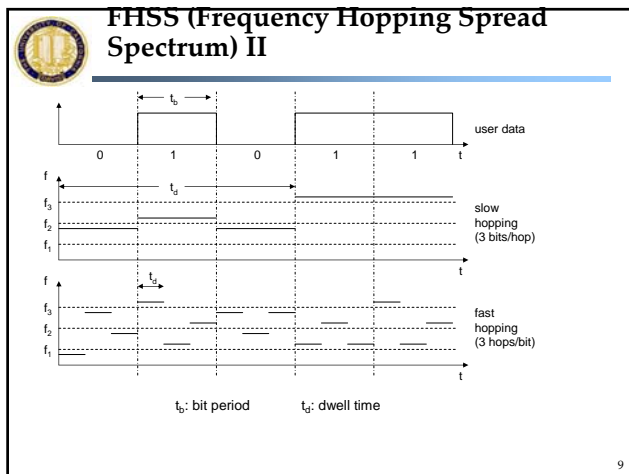
radio carrier   chipping sequence

receiver

Frequency Hopping Spread Spectrum (FHSS)

- Discrete changes of carrier frequency
  - Sequence of frequency changes determined via pseudo random number sequence
- Two versions
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency
- Advantages
  - Frequency selective fading and interference limited to short period
  - Simple implementation
  - Uses only small portion of spectrum at any time
- Disadvantages
  - Not as robust as DSSS
  - Simpler to detect

FHSS (Frequency Hopping Spread Spectrum) II

t_b

user data

0 1 0 1 1 t

f

t_d

f_3
f_2
f_1

slow hopping
(3 bits/hop)

t

f

t_d

f_3
f_2
f_1

fast hopping
(3 hops/bit)

t

t_b: bit period t_d: dwell time

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FHSS

user data → modulator → narrowband signal → modulator → spread transmit signal

frequency synthesizer ← hopping sequence

transmitter

received signal → demodulator → narrowband signal → demodulator → data

hopping sequence → frequency synthesizer

receiver

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Fundamentals of Wireless Communications
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#5: Multiple Access

Single shared (broadcast) wireless communication channel
- Only one can send successfully at a time
- Two or more simultaneous transmissions
  - Interference
- How to share the wireless media?
- Design goals
  - Fairness among users
  - High efficiency
  - Low delay
  - Fault tolerance
- Design choice
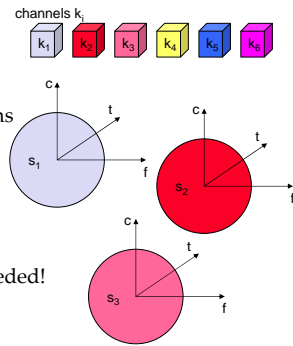 - Fully centralized (controlled) vs. decentralized

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Multiplexing

- Goal: multiple use of a shared medium

channels k_i

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)

- Important: guard spaces needed!

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Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands and allocate to different users
- A channel gets a certain band of the spectrum for the whole time
- Advantages:
  - No dynamic coordination necessary
  - Works also for analog signals
- Disadvantages:
  - Waste of bandwidth if the traffic is distributed unevenly
  - Inflexible
  - Guard spaces
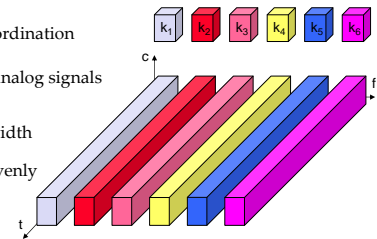
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Time multiplex

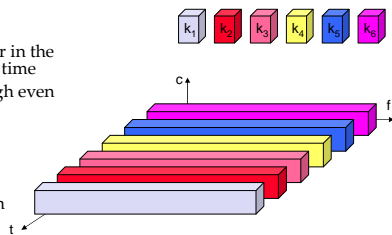- A channel gets the whole spectrum for a certain amount of time
  - Time is divided into slots which are allocated to different users

- Advantages:
  - Only one carrier in the medium at any time
  - Throughput high even for many users

- Disadvantages:
  - Precise synchronization necessary

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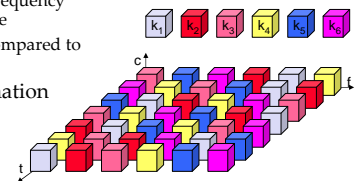## Time and frequency multiplex

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM
- Advantages:
  - Better protection against tapping
  - Protection against frequency selective interference
  - Higher data rates compared to code multiplex
- But: precise coordination required


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Code multiplex

- Time and bandwidth are used simultaneously by different users
- Each channel has a unique code
  - Signal modulated by orthogonal or semi-orthogonal codes (e.g., spread spectrum)
- Advantages:
  - Bandwidth efficient
  - No coordination and synchronization necessary
  - Good protection against interference and tapping
- Disadvantages:
  - Lower user data rates
  - More complex signal regeneration
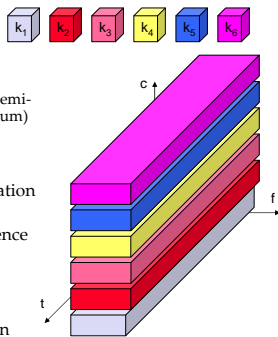
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#6: Frequency Reuse
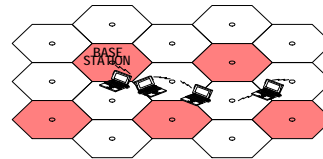
- Frequencies (or time slots or codes) are reused at spatially-separated locations.
- Introduces interference => system capacity is interference-limited.
- Mainly designed for circuit-switched communications, e.g., cellular network

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Cell structure

- Implements space division multiplex: base station covers a certain transmission area (cell)
- Mobile stations communicate only via the base station
- Cell sizes from some 100 m in cities to, e.g., 35 km on the country side (GSM) - even less for higher frequencies
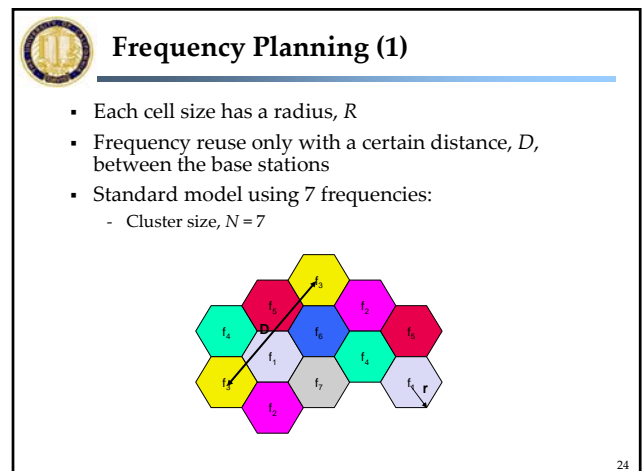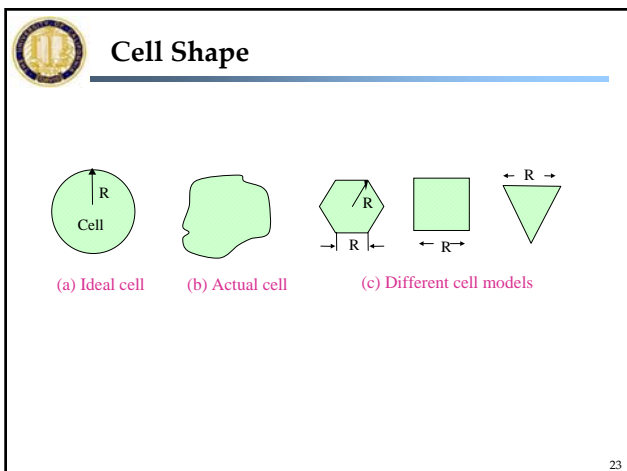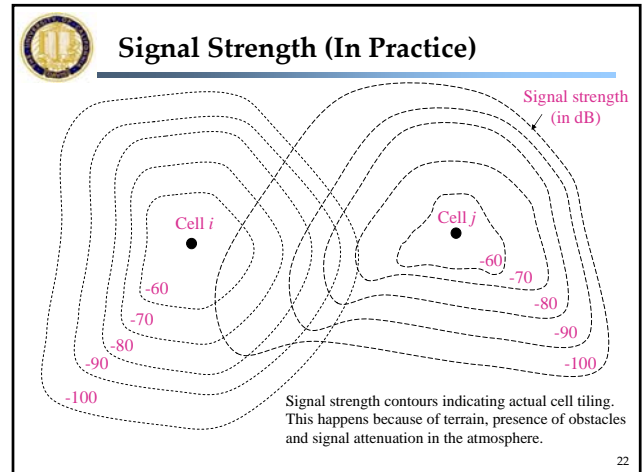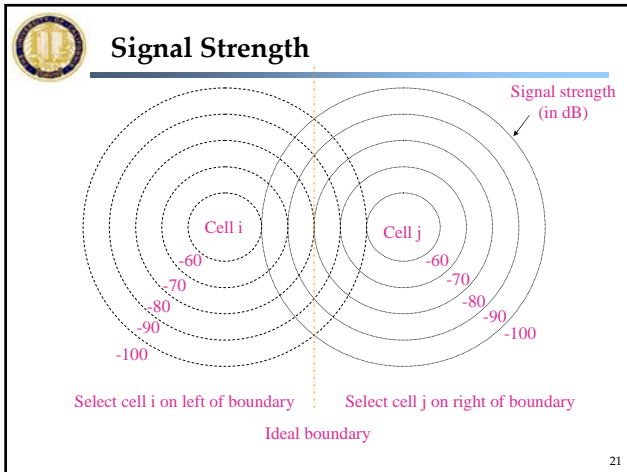
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Cellular Concept

- Advantages of cell structures:
  - Higher capacity, higher number of users
  - Less transmission power needed
  - More robust, decentralized
  - Base station deals with interference, transmission area etc, locally
  - Base stations perform centralized control functions. (call setup, handoff, routing, etc.)

- Problems:
  - Fixed network needed for the base stations
  - Handover (changing from one cell to another) necessary
  - Interference with other cells

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Signal Strength

Signal strength (in dB)

Cell i
-60
-70
-80
-90
-100

Cell j
-60
-70
-80
-90
-100

Select cell i on left of boundary

Select cell j on right of boundary

Ideal boundary

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Signal Strength (In Practice)

Signal strength (in dB)

Cell i
-60
-70
-80
-90
-100

Cell j
-60
-70
-80
-90
-100

Signal strength contours indicating actual cell tiling. This happens because of terrain, presence of obstacles and signal attenuation in the atmosphere.

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Cell Shape

R
Cell

R

← R →

→ R ←   ← R →

(a) Ideal cell   (b) Actual cell   (c) Different cell models

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Frequency Planning (1)

- Each cell size has a radius, R
- Frequency reuse only with a certain distance, D, between the base stations
- Standard model using 7 frequencies:
  - Cluster size, $N = 7$

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Design Considerations

- Reuse distance (D)
  - Distance between two cells using the same frequency (time slot/code)
  - Smaller reuse distance packs more users into a given area, but also increases their co-channel interference
- Cell Radius (R)
  - Decreases the cell size increases the system capacity, but complicates network functions of handoff and routing
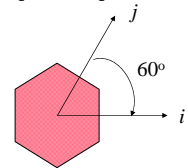
Frequency Planning (2)

- N cannot be just any number!
- The cluster size (or the number of cells per cluster, or the total number of frequencies per cluster) is given by

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

where i and j are integers.

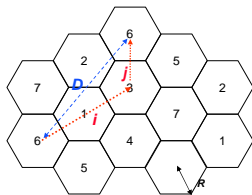N = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 28, …, etc.

The popular value of N being 4 and 7.

Illustration

- i and j are positive integers. To find the nearest co-channel neighbor of a particular cell, you have to (1) move i cells along any chain of hexagons and then (2) turn 60 degrees counter-clockwise and move j cells.
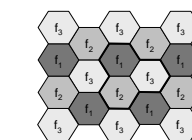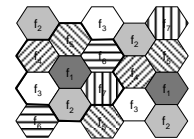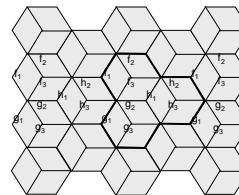
- For N = 7, i=2, j=1

Illustration

3 cell cluster

7 cell cluster

3 cell cluster with 3 sector antennas

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Reuse Distance

R Cluster

F7 F2
F6 F1 F3
F5 F4 F7 F2
F6 F1 F3
F5 F4

Reuse distance D

• For hexagonal cells, the reuse distance is given by

$$D = \sqrt{3N}\,R$$

where R is cell radius and N is the reuse pattern (the cluster size or the number of cells per cluster).

• Reuse factor is

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

Co-Channel Interference

Second tier cochannel Base Station

First tier cochannel Base Station

D_5 D_6 R

D_4 D_1

D_2 Mobile Station

D_3

Serving Base Station

Worst Case Co-channel interference

- Worst-case co-channel interference happens when a user is at a cell boundary
- Example: $N=7$

Serving Base Station

R

Mobile Station

Co-channel Base Station

Estimating Co-Channel Interference

Carrier or signal to interference ratio (C/I) is given by:

$$C/I = \frac{Carrier}{Interference} = \frac{C}{\sum_{k=1}^{M} I_k}$$

where I is co-channel interference and M is the maximum number of co-channel interfering cells.

For M = 6, C/I is given by

$$\frac{C}{I} = \frac{R^{-\alpha}}{\sum_{k=1}^{6}(D_k)^{-\alpha}}$$

where α is the propagation path loss exponent.

C/I or SIR

(Cont'd) Assuming $D_i = D$ for $i = 1, 2, \ldots 6$

$$\frac{C}{I} = \frac{R^{-\alpha}}{6D^{-\alpha}} = \frac{\left(D/R\right)^{\alpha}}{6}$$

▪ General approximation for SIR (in dB), considering only 1st ring of interferers:

$$SIR = 10\log\frac{\left(D/R\right)^{\alpha}}{M}$$

where M = number of interferers (depending on antenna used, etc.)

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Example

- If a carrier-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) $\alpha=4$, and (b) $\alpha=3$? Assume that there are six co-channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximation.
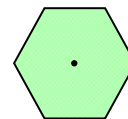
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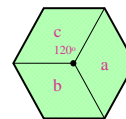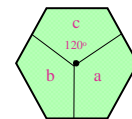## Solution

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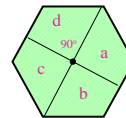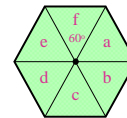## Cell Sectoring by Antenna Design

(a). Omni   (b). 120º sector   (c). 120º sector (alternate)

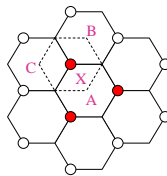(d). 90º sector   (e). 60º sector

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Cell Sectoring by Antenna Design
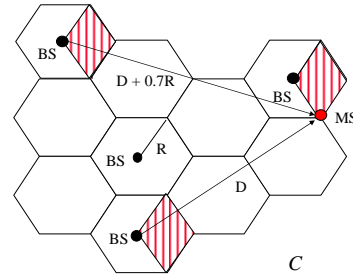
- Placing directional transmitters at corners where three adjacent cells meet

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$$\frac{C}{I} = \frac{C}{q^{-\gamma} + (q+0.7)^{-\gamma}}$$

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Frequency Assignment

- Fixed frequency (channel) assignment – FCA
  - Each cell is assigned a fixed number of channels (frequencies)
  - Channels used for both handoffs and new calls
  - Problem: different traffic load in different cells
- Reservation channels with FCA
  - Each cell reserves some channels for handoff cells
- Channel borrowing
  - A cell may borrow free channels from neighboring cells
- Dynamic frequency (channel) assignment – DCA
  - Base station chooses frequencies depending on the frequencies already used in neighbor cells
  - More capacity in cells with more traffic
  - Assignment can also be based on interference measurements

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Cell Breathing

- CDM systems: cell size depends on current load
- Additional traffic appears as noise to other users
- If the noise level is too high users drop out of cells
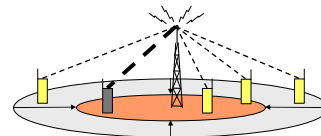
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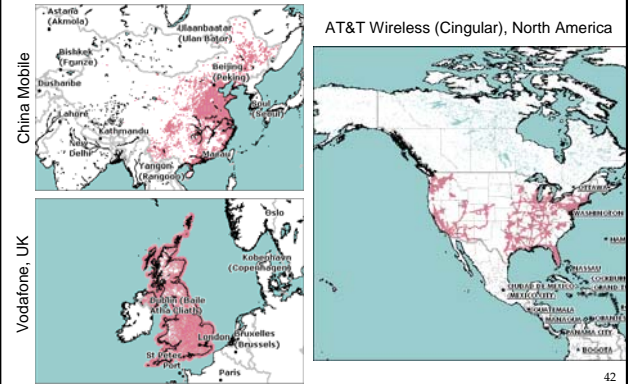Case Study: GSM Wireless cellular networks
- #7: Handoff

Example coverage of GSM networks (www.gsmworld.com)

China Mobile

Vodafone, UK

AT&T Wireless (Cingular), North America

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GSM Cellular network

Segmentation of the area into cells

Possible radio coverage of the cell

Idealized shape of the cell
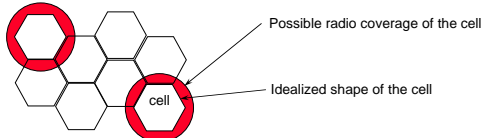
cell

- Use of several carrier frequencies
- Not the same frequency in adjoining cells
- Cell sizes vary from some 100 m up to 35 km depending on user density, geography, transceiver power etc.
- Hexagonal shape of cells is idealized (cells overlap, shapes depend on geography)
- If a mobile user changes cells
  - handover of the connection to the neighbor cell

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#7: Handoffs (or Handover)

- Required to support mobility when the user moves into a different cell
- Involves
  - Identifying a new BS in new cell
  - Find uplink/downlink channel pair from new cell to carry on the call
  - Drop the link from the old BS

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Handoffs: Design Issues (1)

- Optimal BS selection:
  - BS nearest to MT may not necessarily be the best in terms of signal strength, especially new the cell boundaries
- Ping-pong Effect
  - Call gets bounced back and forth between two BS (a series of handoffs)
- Data loss
  - Interruption due to handoff may cause a loss in data
  - Delay in relinquishing channel in old cell and resume in new call may be acceptable for voice, but cause data loss

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Handoff: Design Issues (2)

- Detection of handoff requirement
  - Mobile-initiated: MT monitors signal strength from BS and requests a handoff when signal drops below a threshold)
  - Network-initiated: BS forces a handoff when signals from an MT weaken, queries neighboring BS about signal strength from the MT and deduce which BS to handoff too
  - Mobile-assisted scheme: combination of mobile- and network-initiated schemes. MT evaluates signal strength, but final handoff decision is made by BS

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Handover Decision

Receive level BTS_{old}

Receive level BTS_{old}

HO_MARGIN

MS

MS

BTS_{old}

BTS_{new}
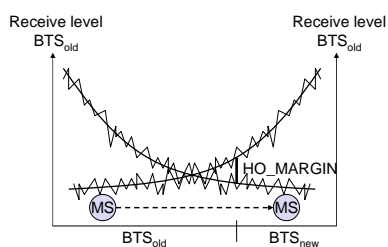
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Handoff Quality

- Handoff delay:
  - Signaling during a handoff causes delay in transfer
  - If delay is too large, SINR may fall below minimum threshold, causing call to be dropped
- Duration of interruption
  - Hard handoff: channel pair from old BS cancel and then channel pair from next BS is used to continue the call
- Handoff success: probability of successful handoffs
  - Depends on number of available channel pairs, capacity to switch before SINR falls below threshold
- Probability of unnecessary handoff
  - E.g., Ping-Pong effect
  - Increase signaling overhead, leading to unwanted delays and interruptions

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Questions?

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