

**18-452/18-750**  
**Wireless Networks and Applications**  
**Lecture 15:**  
**Cellular - Principles**

**Peter Steenkiste**

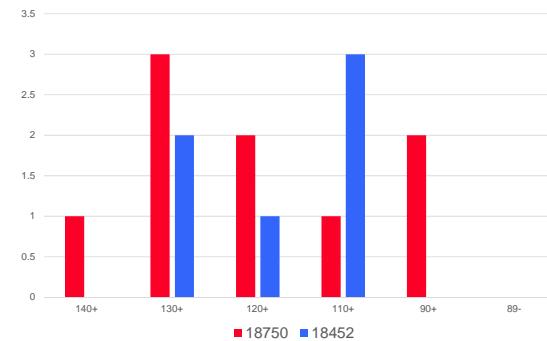
**Spring Semester 2018**

<http://www.cs.cmu.edu/~prs/wirelessS18/>

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## Midterm Grades



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## Projects

- An interesting set of projects proposals!
- Equipment requirements sometimes vague
  - » Need to identify specific devices, software
- Project plan:
  - » Who will do what?
- A few projects have some gaps
  - » Minimal or no references to previous work
  - » More interesting easy, early result
  - » Mismatch between the project and earlier work

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## Surveys

- Check topic and dates
- Please submit draft of slides according to the schedule in the handout
- It is fine to propose alternative papers
- Papers with a checkmark are part of the syllabus
  - ✓ Required reading for everyone

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## Overview

- **Cellular principles**
  - » Cellular design
  - » Elements of a (generic) cellular network
  - » How does a mobile phone call take place?
  - » Handoff
  - » Frequency Allocation, Traffic Engineering
- **Early cellular generations: 1G, 2G, 3G**
- **Today's cellular: LTE**

Some slides based on material from  
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## Cellular versus WiFi

Cellular WiFi

Spectrum

Service model

MAC services

- Implications for level of service (SLAs), cost, nature of protocols, ...?

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## The Advent of Cellular Networks

- “Mobile radio telephone system” was a predecessor of today's cellular systems
  - » High power transmitter/receivers
  - » Could support about 25 channels
  - » in a radius of 80 Km
- To increase network capacity:
  - » Multiple lower power transmitters (100W or less)
  - » Smaller transmission radius -> area split in cells
  - » Each cell with its own frequencies and base station
  - » Adjacent cells use different frequencies
  - » The same frequency can be reused at sufficient distance
- These trends are continuing ...

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## The Cellular Idea

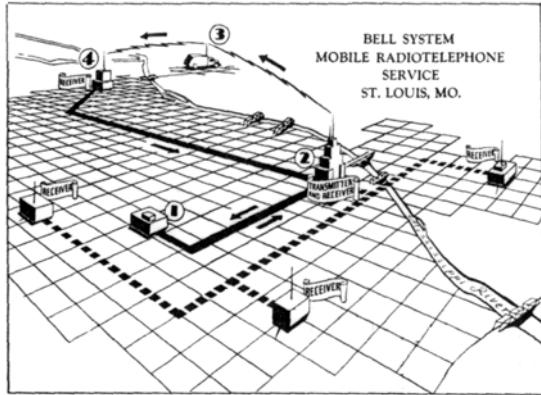
- In December 1947 Donald H. Ring outlined the idea in a Bell labs memo
- Split an area into cells, each with their own low power towers
- Each cell would use its own frequency
- Did not take off due to “extreme-at-the-time” processing needs
  - » Handoff for thousands of users
  - » Rapid switching infeasible – maintain call while changing frequency
  - » Technology not ready

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## The MTS network

<http://www.privateline.com/PCS/images/Saintlouis2.gif>



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## The Early Mobile Phones

- First mobile phones bulky, expensive and hardly portable, let alone mobile
  - » Phones weighed 40 Kg~
  - » Some early prototypes were much bulkier than shown in the pictures (think: large backpack)
- Operator assisted with 250 maximum users



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## ... the Remaining Components

- In December 1947 the transistor was invented by William Shockley, John Bardeen, and Walter Brattain
- Why no portable phones at that time?
- A mobile phone needs to send a signal – not just receive and amplify
- The energy required for a mobile phone transmission still too high for the high power/high tower approach – could only be done with a car battery

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## ... and the Regulatory Bodies

The FCC commissioner Robert E. Lee said that mobile phones were a status symbol and worried that every family might someday believe that its car had to have one. Lee called this a case of people "frivolously using spectrum" simply because they could afford to.

From The Cell-Phone Revolution,  
AmericanHeritage.com

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## DynaTAC8000X: the First Cell Phone

The “brick”:

- weighed 2 pounds,
- offered 30 mins of talk time for every recharging and
- sold for \$3,995!

It took 10 years to develop (1973-1983) and cost \$100 million! (delay due to infrastructure)

Size primarily determined by the size of batteries, antennas, keypads, etc.

Today size determined by the UI!

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Dr. Martin Cooper of Motorola, made the first US analogue mobile phone call on a larger prototype model in 1973

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## How To Design a Cellular Network?

- Need to get good coverage everywhere
- Must be able to plan network based on demand



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## Overview

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- **Early cellular generations: 1G, 2G, 3G**

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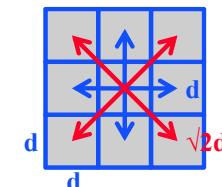
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## Cellular Network Design Options

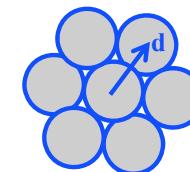
- **Simplest layout**

- » Does not match any propagation model
- » Adjacent antennas not equidistant – how do you handle users at the edge of the cell?



- **“Ideal” layout**

- » Based on a naïve propagation model – bad approximation but better than squares
- » Does not cover entire area!

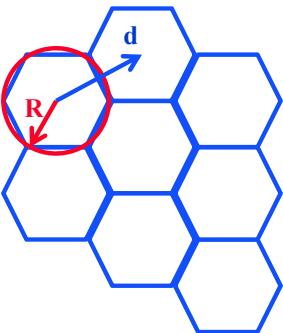


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## The Hexagonal Pattern

- A hexagon pattern can provide equidistant access to neighboring cell towers
- $d = \sqrt{3}R$
- In practice, variations from ideal due to topological reasons
  - » Signal propagation
  - » Tower placement



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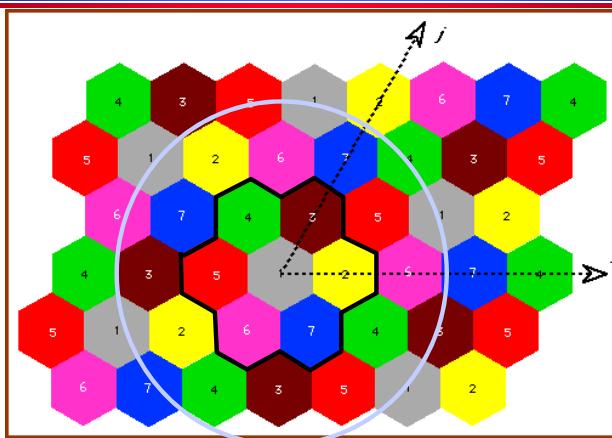
## Frequency reuse

- Each cell features one base transceiver
- Through power control the tower covers the cell area while limiting the power leaking to other co-frequency cells
- The number of frequency bands assigned to a cell dependent on its traffic
  - » 10 to 50 frequencies assigned to each cell (early systems)
- How do we determine how many cells must separate two cells using the same frequency?
  - » Need to control the “power to interference” ratio

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## Minimum separation?



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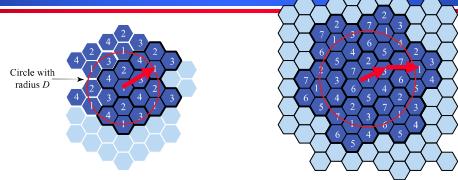
## Frequency reuse characterization

- $D = \text{minimum distance between centers of co-channel cells}$
- $R = \text{radius of cell}$
- $d = \text{distance between centers of adjacent cells}$
- $N = \text{number of cells in a repetitious pattern, i.e. reuse factor}$
- Hexagonal pattern only possible for certain  $N$ :
 
$$N = I^2 + J^2 + (I \times J), \quad I, J = 0, 1, 2, 3, \dots$$
- The following relationship hold
 
$$\frac{D}{R} = \sqrt{3N} \quad \text{or} \quad \frac{D}{d} = \sqrt{N}$$

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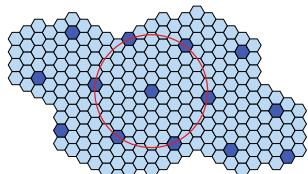
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## Frequency Reuse Pattern Examples



(a) Frequency reuse pattern for  $N = 4$

(b) Frequency reuse pattern for  $N = 7$



(c) Black cells indicate a frequency reuse for  $N = 19$

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## Capacity and Interference

- $S =$  Total # of duplex channels available for use
- $k =$  Total # of duplex channels per cell
- $N =$  Size of cluster, i.e., cells that collectively use the complete set of available frequencies

$$\frac{S}{k} = N \quad \Rightarrow \quad S = kN$$

- If a cluster is replicated  $M$  times within the system, the total # of duplex channels  $C$  can be used as a measure of capacity

$$\Rightarrow \quad C = MkN = MS$$

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$$C = MkN = MS$$

## Tradeoffs

- If  $N \downarrow \Rightarrow k \uparrow$  since  $S$  is a constant  
 $\therefore M \uparrow$  for a fixed geographical area if the same cell radius is maintained  
 $\Rightarrow$  Capacity increases as cluster size goes down
- Reuse distance:  $\frac{D}{R} \downarrow \Rightarrow$  Co-channel interference  $\uparrow$
- NOTE: To reduce co-channel interference  
 $\frac{D}{R} \uparrow \Leftrightarrow N \uparrow \Rightarrow M \downarrow \therefore$  Capacity  $\downarrow$  since  $kN = S = \text{fixed}$
- There is a trade-off between capacity and interference reduction

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## Approaches to Cope with Increasing Capacity

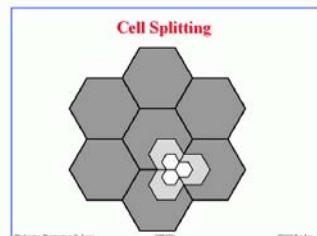
- Adding new channels
- Frequency borrowing – frequencies are taken from adjacent cells by congested cells
- Cell splitting – cells in areas of high usage can be split into smaller cells
- Cell sectoring – cells are divided into wedge-shaped sectors, each with their own set of channels
- Network densification – more cells and frequency reuse
  - » Microcells – antennas move to buildings, hills, and lamp posts
  - » Femtocells – antennas to create small cells in buildings

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## Cell splitting

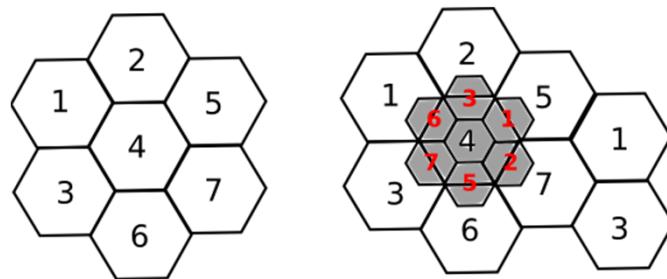
- Cell size ~ 6.5-13Km, Minimum ~ 1.5Km
  - » Again, for early systems
- Requires careful power control and possibly more frequent handoffs for mobile stations
- A radius reduction by  $F$  reduces the coverage area and increases the number of base stations by  $F^2$



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## Cell splitting



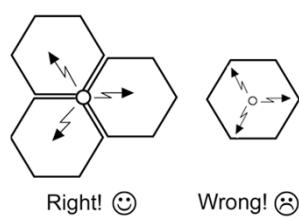
Radius of small cell half that of the original

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## Cell sectoring

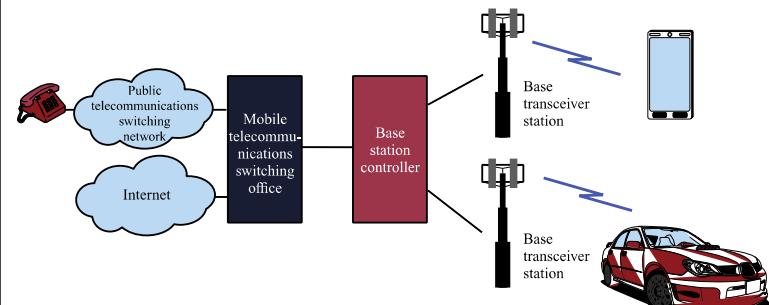
- Cell divided into wedge shaped sectors
- 3-6 sectors per cell, each with own channel set
- Subset of cell's channel, use of directional antennas



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## Overview of Cellular System



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## Elements of a cellular system

- Base Station (BS): includes antenna, a controller, and a number of transceivers for communicating on the channels assigned to that cell
- Controller handles the call process between the mobile unit and the rest of the network
- MTSO: Mobile Telecommunications Switching Office, serving multiple BSs. Connects calls between mobiles and to the PSTN. Assigns the voice channel, performs handoffs, billing

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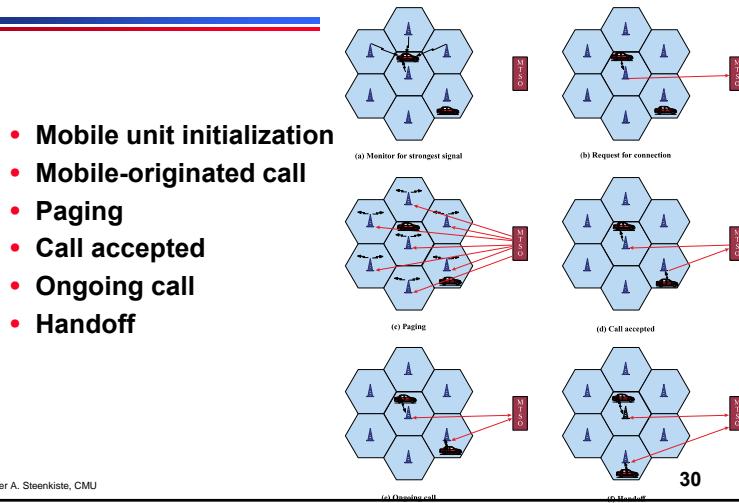
## Paging

- Broadcast mechanism to locate a target mobile unit
- Normally, there is knowledge on a limited number of cells where the mobile may be (Location Area in GSM, Routing Area if data packet sessions)
- GSM: neighbor cells grouped in Location Area and subscriber only updates when moving across. Paging restricted to the Location Area itself.
  - » How do we assign cells to LAs?

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## MTSO Sets up Call between Mobile Users



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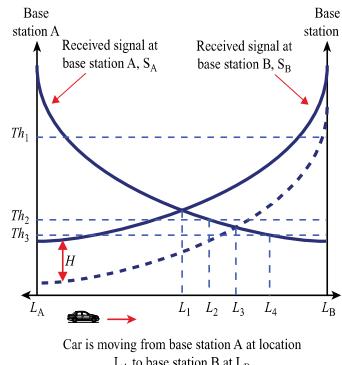
## Handoff Strategies Used to Determine Instant of Handoff

- Metrics related to handoff:
  - » Call blocking probability: probability of a new call being blocked
  - » Call dropping probability: probability that a call is terminated due to a handoff
- Possible strategies for scheduling handoffs:
  - » Relative signal strength –  $L_1$
  - » Relative signal strength with threshold  $Th_2 - L_2$
  - » Relative signal strength with hysteresis  $H - L_3$
  - » Relative signal strength with hysteresis and threshold  $Th_1$  or  $Th_2 - L_3; Th_3 - L_4$
  - » Prediction techniques

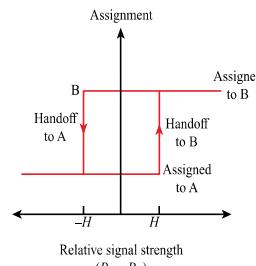
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## Example of Handoff



(a) Handoff decision as a function of handoff scheme



(b) Hysteresis mechanism

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## Handoff implementations

- **GSM/W-CDMA**
  - » Inter-frequency handovers will measure the target channel before moving over
  - » Once the channel is confirmed OK, the network will command the mobile to move and start bi-directional communication there
- **CDMA2000/W-CDMA(same)**
  - » Both channels are used at the same time – **soft** handover
- **IS-95 (inter-frequency)**
  - » Impossible to measure channel directly while communicating. Need to use pilot beacons. Almost always a brief disruption.

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## Mobile Radio Propagation Effects

- **Signal strength**
  - » Must be strong enough to maintain signal quality at the receiver
  - » Must not be so strong as to create too much co-channel interference with channels in another cell using the same frequency band
  - » Fading may distort the signal and cause errors
- **Mobile transmission power minimized to avoid co-channel interference, alleviate health concerns and save battery power**
- **In systems using CDMA, need to equalize power from all mobiles at the BS**

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## Open and Closed Loop Power Control

- **Open loop power control: BS sends pilot**
  - » Used by mobile to acquire timing and phase reference, and to assess channel attenuation
  - » Mobile adjust power accordingly
    - Assume up and down channels are similar
  - » Can adjust quickly but not very accurate
- **Closed loop power control: power is adjust based on explicit feedback from receiver**
  - » Reverse signal power level, received signal-to-noise ratio, or received bit error rate
  - » Mobile to BS: BS base station sends power adjustment command to mobile based on observed signal
  - » BS to mobile: BS adjust power based on information provided by mobile

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## Fixed Channel Assignment (FCA)

- Each cell is allocated a predetermined set of voice channels.
- Any call attempt within the cell can only be served by the unused channels in that cell
- If all the channels in that cell are being used the call is blocked → user does not get service
- A variation of FCA: the cell whose channels are all being used is allowed to borrow channels from the next cell. MTSO supervises this operation.

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## Dynamic Channel Assignment (DCA)

- Channels are not permanently assigned to cells. Instead, for each request the BS requests a channel from the MTSO.
- MTSO allocates a channel using an algorithm that takes many factors into account
  - » The likelihood of future blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel, and other cost functions.
  - » MTSO only allocates a channel if it is not being used in the restricted distance for co-channel interference
- DCA can use channels more effectively but incurs measurement, communication, and computer overhead

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## Traffic Engineering

- If the cell has  $L$  subscribers..
- ... and can support  $N$  simultaneous users.
- If  $L \leq N$ , **nonblocking** system
- If  $L > N$ , **blocking** system
- Questions operator cares about:
  - » What is the probability of a call being blocked?
  - » What  $N$  do I need to upper bound this probability?
  - » If blocked calls are queued, what is the average delay?
  - » What capacity is needed to achieve a certain average delay?
- **Difficult problem but important**

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