# 18-452/18-750
# Wireless Networks and Applications
## Lecture 14: Cellular Introduction

**Peter Steenkiste**

**Spring Semester 2020**

**http://www.cs.cmu.edu/~prs/wirelessS20/**



## Overview

- **Cellular principles – "classic" view**
  - » A bit of history
  - » Cellular design
  - » How does a mobile phone call take place?
  - » Handoff
  - » Frequency Allocation, Traffic Engineering
- **Early cellular generations: 1G, 2G, 3G**
- **Today's cellular: 4G – LTE**
- **Emerging: 5G widely advertised**

Some slides based on material from
"Wireless Communication Networks and Systems"




## Cellular versus WiFi

| | Cellular | WiFi |
|---|---|---|
| Spectrum | | |
| Service model | | |
| MAC services | | |

- Implications for Service Level Agreements (SLAs), cost, nature of protocols, …



## 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
- Over time, 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 …

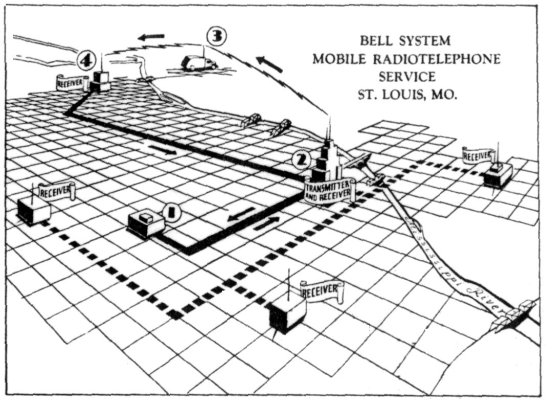
## The Cellular Idea

- 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



## The MTS network

http://www.privateline.com/PCS/images/SaintLouis2.gif






## 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 maximum 250 users



## ... 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

## … 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.

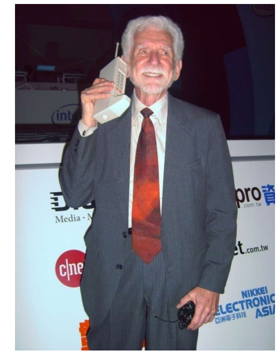
Lee called this a case of people "frivolously using spectrum" simply because they could afford to.

From The Cell-Phone Revolution, AmericanHeritage.com



## DynaTAC8000X: the First Cell Phone

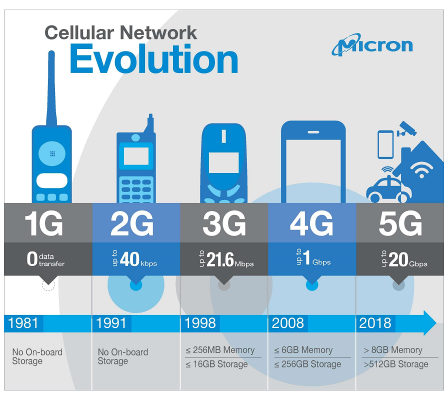
- The "brick":
  - Weighed 2 pounds
  - Offered 30 mins of talk time
  - Sold for $3,995!
- It took 10 years to develop (1973-1983) at a cost of $100 million!
  - Size determined by size of batteries, antennas, keypad, etc.
  - Today size determined by the UI!
- First commercial service in early 80s
  - FCC allocated spectrum in 70s



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



## Cellular Generations

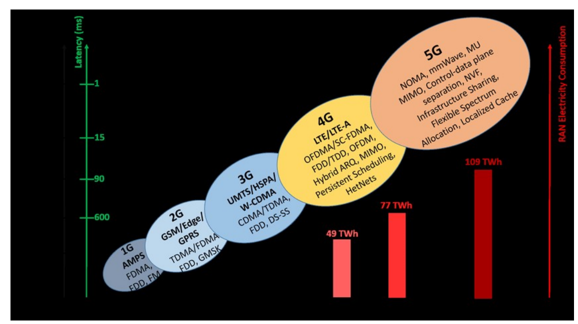



*eetimes.com*

- Roughly one generation every 10 years
- Spectrum allocation for mobile broadband has increased significantly
  - Shift to higher frequencies



## Technologies Used




- We have already seen many of these technologies!
- Terminology for 5G is a bit different – How?

## Standardization Process

- Standardization takes as much as 10 years
  - » Setting goals, identifying technologies
  - » Standardization: many releases
  - » Product development and trials




## Overview

- Cellular principles – "classic" view
  - » A bit of history
  - » Cellular design
  - » How does a mobile phone call take place?
  - » Handoff
  - » Frequency Allocation, Traffic Engineering
- Early cellular generations: 1G, 2G, 3G
- Today's cellular: 4G – LTE
- Emerging: 5G widely advertised

Some slides based on material from
"Wireless Communication Networks and Systems"



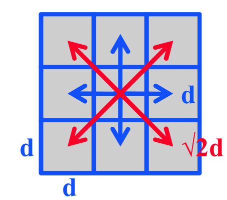

## How To Design a Cellular Network?

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

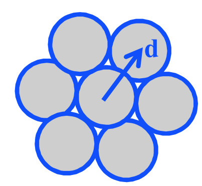


## Cellular Network Design Options

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

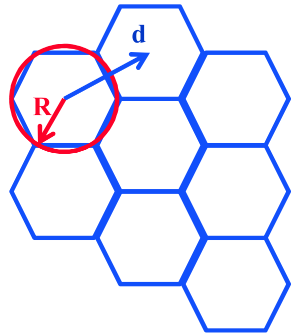



- "Ideal" layout
  - » Based on a naïve propagation model – bad approximation but better than squares
  - » Does not cover entire area!



## The Hexagonal Pattern

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



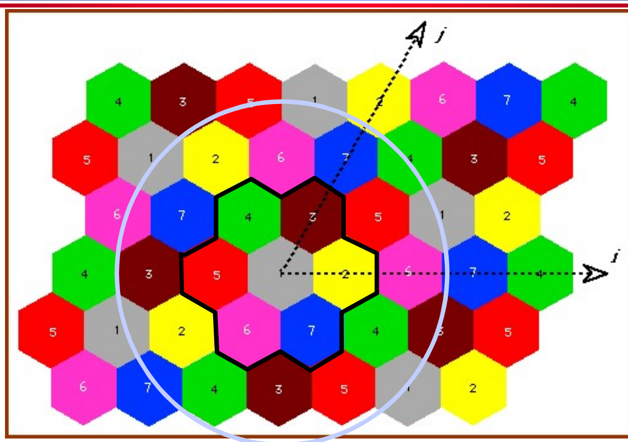



## Frequency reuse

- 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



## Minimum separation?






## Frequency reuse characterization

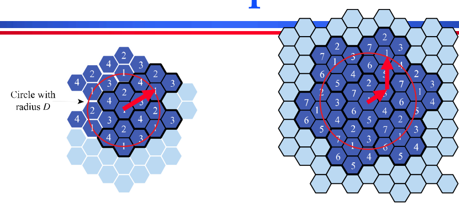
- D = minimum distance between centers of co-channel cells
- R = radius of cell
- d = distance between centers of adjacent cells
- N = number of cells in a repetitious pattern, i.e. reuse factor
- Hexagonal pattern only possible for certain N:

$$N = I^2 + J^2 + (I \times J), \quad I, J = 0, 1, 2, 3, \ldots$$

- The following relationship hold

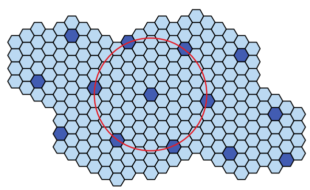
$$\frac{D}{R} = \sqrt{3N} \quad \text{or} \quad \frac{D}{d} = \sqrt{N}$$

## 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 $N = 19$



## 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

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

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

$$\Rightarrow \qquad C = MkN = MS$$



## Tradeoffs

$C = MkN = MS$

- 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: $\frac{D}{R}\downarrow \quad \Rightarrow$ Co-channel interference $\uparrow$
- NOTE: To reduce co-channel interference

$$\frac{D}{R}\uparrow \quad \Leftrightarrow N\uparrow \quad \Rightarrow M\downarrow \quad \therefore \text{Capacity}\downarrow \text{ since kN = S = fixed}$$

- There is a trade-off between capacity and interference reduction

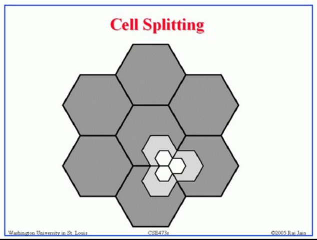


## Approaches to Cope with Increasing Capacity

- 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

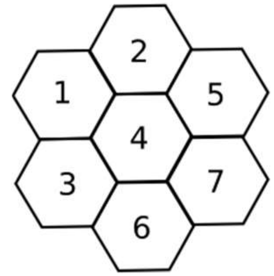
# Cell splitting

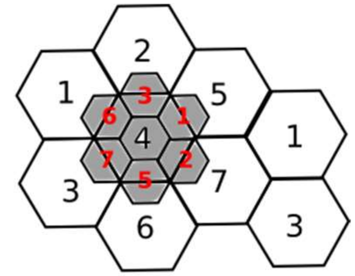
- Cell size ~ 6.5-13Km, Minimum ~ 1.5Km
  - » Again, for early systems
- Requires careful power control and possibly more frequent handoffs for mobile stations
- A radius reduction by F reduces the coverage area and increases the number of base stations by $F^2$






# Cell splitting



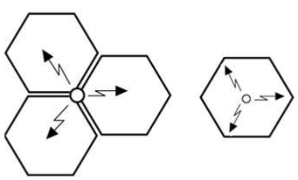




Radius of small cell half that of the original



# 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



Right! ☺ Wrong! ☹

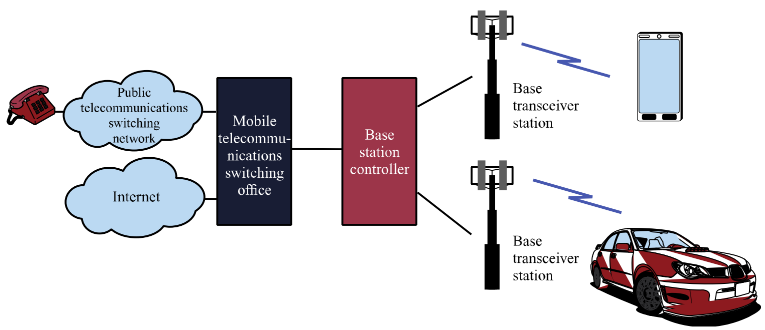


# Overview

- Cellular principles – "classic" view
  - » A bit of history
  - » Cellular design
  - » How does a mobile phone call take place?
  - » Handoff
  - » Frequency Allocation, Traffic Engineering
- Early cellular generations: 1G, 2G, 3G
- Today's cellular: 4G – LTE
- Emerging: 5G widely advertised

Some slides based on material from
"Wireless Communication Networks and Systems"

# Overview of Cellular System





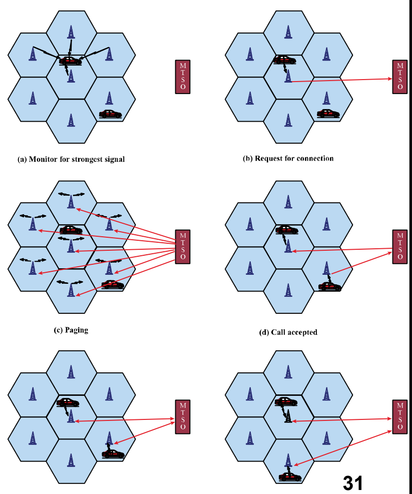

# Elements of a cellular system

- 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



# MTSO Sets up Call between Mobile Users

- Mobile unit initialization
- Mobile-originated call
- Paging
- Call accepted
- Ongoing call
- Handoff






# Paging

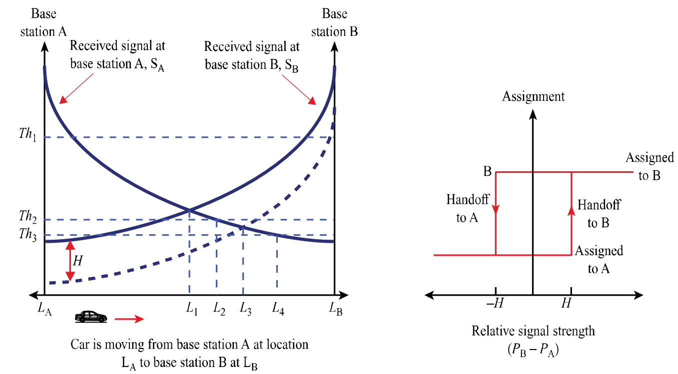
- Broadcast mechanism to locate a target mobile unit
- Normally, there is knowledge on a limited number of cells where the mobile may be (Location Area in GSM, Routing Area if data packet sessions)
- GSM: neighbor cells grouped in Location Area and subscriber only updates when moving across. Paging restricted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

# 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



# Example of Handoff




(a) Handoff decision as a function of handoff scheme

(b) Hysteresis mechanism



# 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.



# 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**

## 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



## 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.



## 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



## Traffic Engineering

- If the cell has L subscribers..
- … and can support N simultaneous users.
- If L<=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