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

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- 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

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

- 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

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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

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

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 \( N \):
  \[ N = I^2 + J^2 + (I \times J), \quad I,J = 0,1,2,3,... \]
- The following relationship hold
  \[ \frac{D}{R} = \sqrt{3N} \quad \text{or} \quad \frac{D}{d} = \sqrt{N} \]
Frequency Reuse Pattern Examples

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

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

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

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

  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 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

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 \( T_{h2} \) – \( L_2 \)
  - Relative signal strength with hysteresis \( H \) – \( L_3 \)
  - Relative signal strength with hysteresis and threshold \( T_{h1} \) or \( T_{h3} \) – \( L_4 \)
  - Prediction techniques

Example of Handoff

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

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.
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