18-452/18-750
Wireless Networks and Applications
Lecture 13: Cellular Introduction

Peter Steenkiste

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http://www.cs.cmu.edu/~prs/wirelessS24/

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	Licensed	Unlicensed
Service model	Provisioned "for pay"	Unprovisioned "free"
MAC services	Fixed bandwidth SLAs	Best effort no SLAs

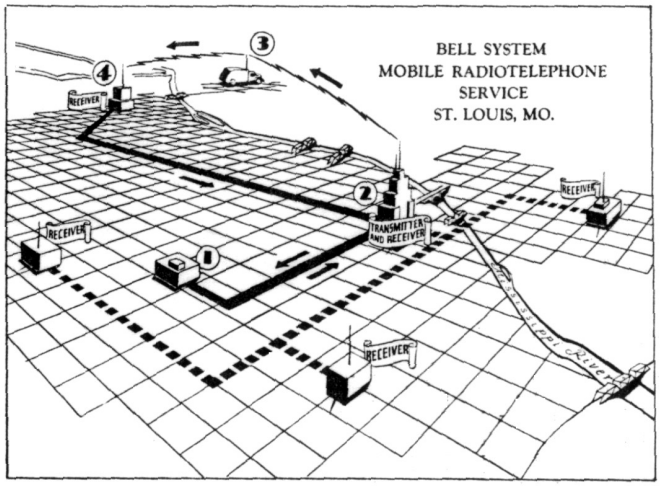
- Implications for Service Level Agreements (SLAs), cost, nature of protocols, …

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.

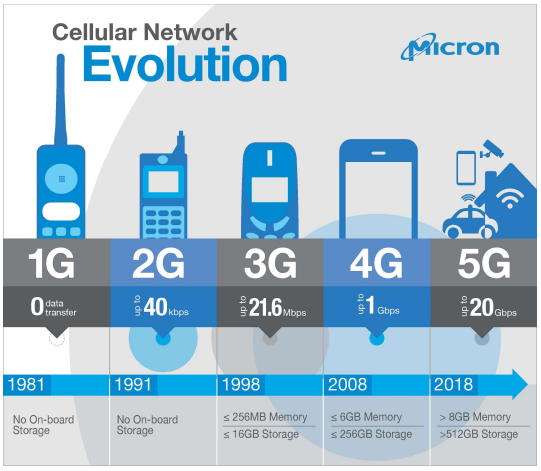
From The Cell-Phone Revolution, AmericanHeritage.com

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

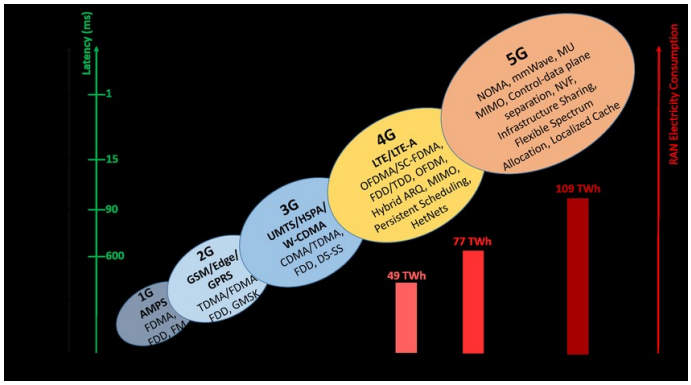
Cellular Generations



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

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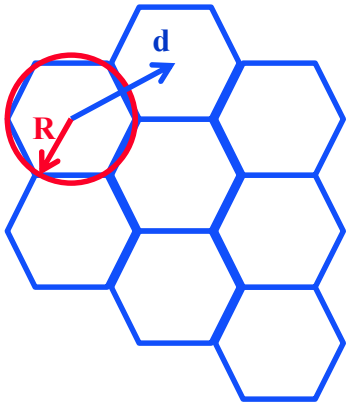
How To Design a Cellular Network?

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

The Hexagonal Pattern

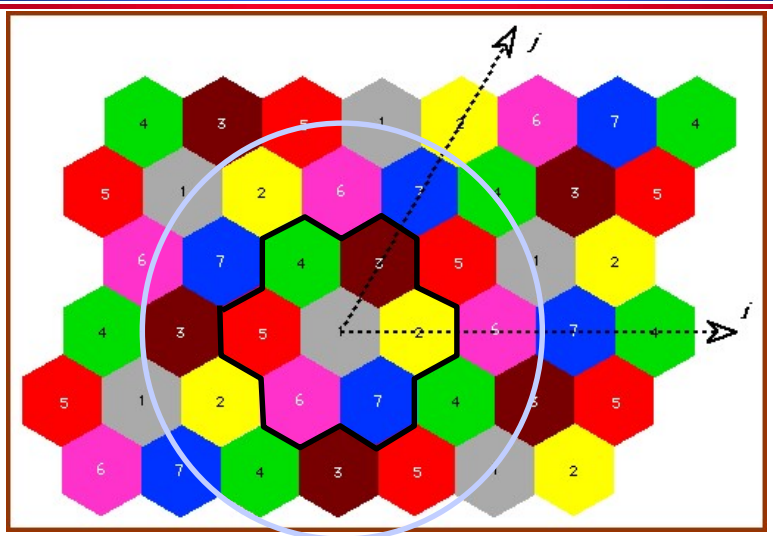
- Network consists of cells each served by a cell tower
  - » Transmit range few kilometers
- Each cell is modeled as a hexagon
  - » d = √3R
  - » Hexagons fit to cover a region
  - » Convenient for capacity planning
- In practice, variations from ideal due to topological constraints
  - » Signal propagation
  - » Tower placement, …



Frequency reuse

- Each cell features one cell tower
- 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 noise and interference" ratio

Minimum separation?

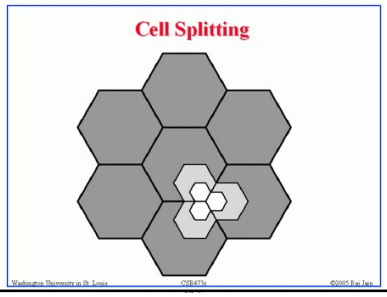


Approaches to Cope with Increasing Capacity

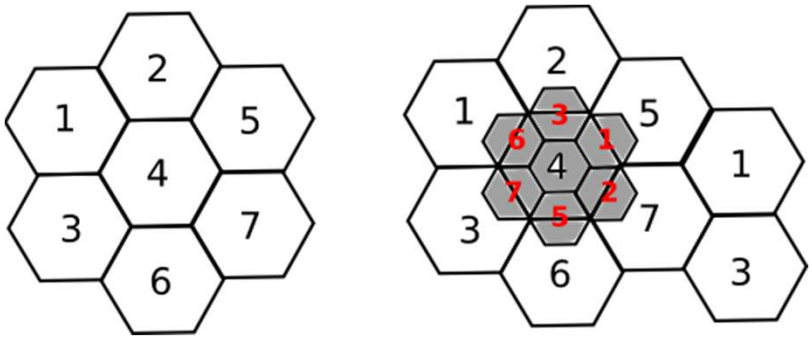
- Adding new channels
- Frequency borrowing – frequencies are taken from adjacent cells by congested cells
- Cell splitting – cells in areas of high usage can be split into smaller cells
- Cell sectoring – cells are divided into wedge-shaped sectors, each with their own set of channels
- Network densification – 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



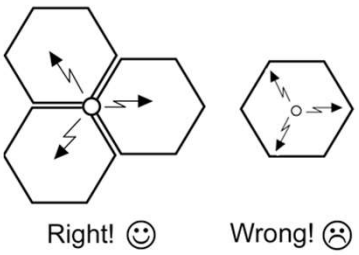
Cell splitting



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



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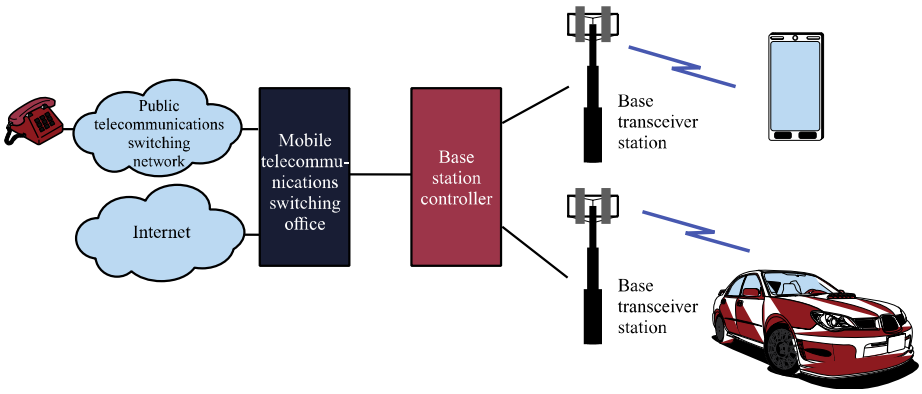
General Model of a Cellular System



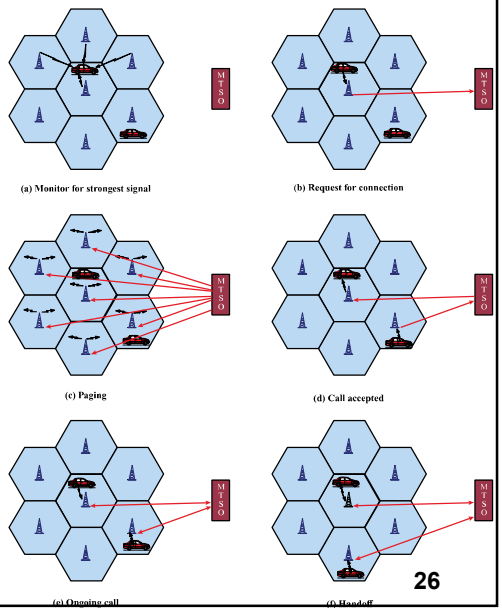
Old terminology
Every generation introduces new names

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.**
  - **The management and control infrastructure**
  - **The name is different in each generation**
- **MTSO connects calls between mobiles and to the PSTN. Assigns the voice channel, performs handoffs, billing**

Steps in Placing Calls

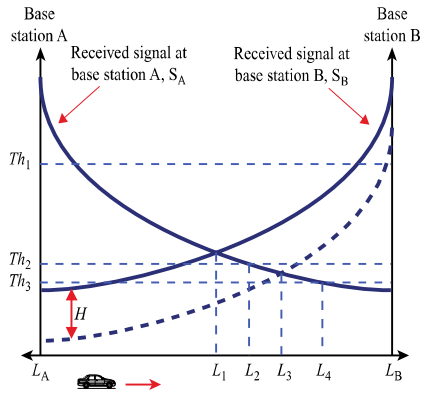
- Mobile unit initialization
- Mobile-originated call
- Paging
- Call accepted
- Ongoing call
- Handoff



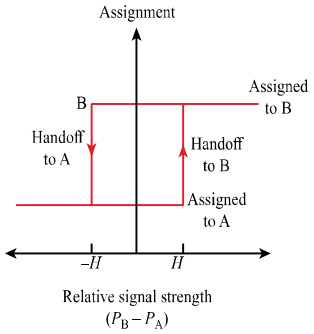
Handoff Strategies Used to Determine Instant of Handoff

- Metrics related to handoff:
  - » Call blocking probability: probability of a new call being blocked (specific to early systems)
  - » 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
- Details are different across the generations

Example of Handoff



(a) Handoff decision as a function of handoff scheme



(b) Hysteresis mechanism

https://media.pearsoncmg.com/ph/esm/ecs_stallingsbeard_wcns_1/animations/13_7_handoff_between_two_cells/index.html

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**

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

Overview

- Cellular principles – "classic" view
- Early cellular generations: 1G, 2G, 3G
  - » 1G: AMPS
  - » 2G: GSM
  - » 2.5G: EDGE, CDMA
  - » 3G: WCDMA
- Today's cellular: 4G – LTE
- Emerging: 5G widely advertised

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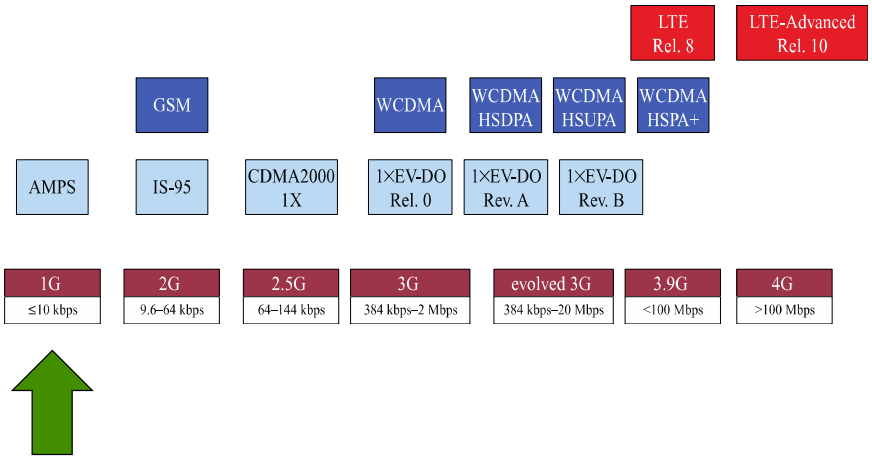
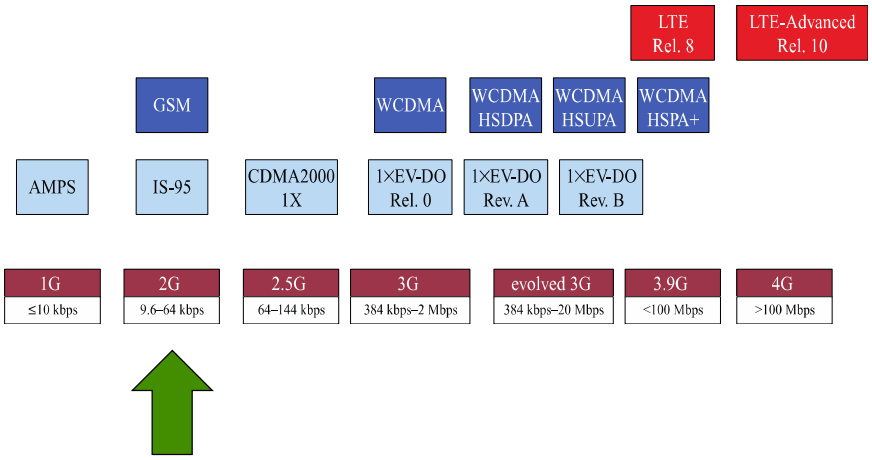
Evolution of Cellular Wireless Systems



Advanced Mobile Phone Service (AMPS)

- In North America, two 25-MHz bands were allocated (DL: 869-894 MHz, UP: 824-849 MHz)
  - » Deployed since early 80's by two providers
- Channels are spaced by 30 KHz, allowing for 416 channels (21 control, 395 for voice calls)
  - » Control channels are full duplex data channels at 10 Kbps
  - » Includes preamble, word sync, and Digital Color Code identifying the base station
  - » Can send urgent control in data channels
- Voice calls carried in analog using frequency modulation
  - » Effectively extends analog telephone over wireless
- Cell size = 2-20Km, frequency reuse is exploited

Evolution of Cellular Wireless Systems



Differences Between First and Second Generation Systems

- **Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital**
  - » **This offers several benefits both to users and operators**
- **Encryption: second generation systems use encryption to prevent eavesdropping**
- **Error detection and correction: digital encoding allows for error detection and correction, giving clear voice reception**

Switch from Analog to Digital Operator Benefits

- Channels can be dynamically shared by a number of users
  - 1G systems had two dedicated one-way channels
  - But at least one of them was idle most of the time!
  - Digital transmission allows multiple users to share a channel (TDMA)
- Digital data can be compressed
  - Makes the network more efficient – can support more simultaneous calls

Global System for Mobile communication (GSM)

- GSM is a set of ETSI standards specifying the infrastructure for a digital cellular service
  - European Telecommunications Standards Institute
  - Developed to provide a common second-generation technology for Europe
- The standard was used in approx. 109 countries around the world including Europe, Japan and Australia
  - Order 44 million subscribers
  - 1G systems were often operator specific
- Process: define a set of requirements, and then develop technologies to meet them

Design Requirements for 2G Systems

- Degree of multiplexing: at least 8
  - » Not worth adding TDMA complexity otherwise
- Maximum cell radius: ~35km
  - » Needed for rural areas
- Frequency: around 900 MHz
- Maximum speed: 250 km/hr – high-speed train
- Maximum coding delay: 20 msec
  - » Do not want to add too much to network delay (voice!)
- Maximum delay spread: ~10 μsec
  - » Multi-path property: ~3.3 km
- Bandwidth: up to 200 KHz, ~25 kHz/channel

GSM Features

- Hybrid FDMA/TDMA approach
- Mobile station communicates across the air interface with base station in the same cell as mobile unit
- Mobile equipment (ME) – physical terminal, e.g., a telephone or "personal communication system"
  - » ME includes radio transceiver, digital signal processors and subscriber identity module (SIM)
- GSM subscriber units are generic until a SIM is inserted
  - » SIMs roam since they are based on single standard
  - » Not necessarily the case for subscriber devices – may use different versions of the protocol

GSM SIM

- Users have a Subscriber Identity Module (SIM) – a smart card
- The user identity is associated with a mobile device through the SIM card
- The SIM is portable and transferable
- All cryptographic algorithms (for authentication and data encryption) can be realized in the SIM
- May also store short messages, charging info, ..
- SIM implications:
  - » Equipment mobility and user mobility are not the same
  - » International roaming independent of the equipment and network technology