15-441/641: Cellular Networks and Mobility

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https://computer-networks.github.io/fa19/

Carnegie Mellon University

Overview

- Cellular networks
  - How different from WiFi?
  - Overview of technologies
- Mobility
  - The Internet
  - Cellular

Cellular versus WiFi

	Cellular	WiFi
Spectrum	Licensed	Unlicensed
Service model	Provisioned "for pay"	Unprovisioned "free" – no SLA
MAC services	Fixed bandwidth SLAs	Best effort no SLAs

Implications WiFi

	WiFi	Implication
Spectrum	Unlicensed	No control – open, diverse access
Service model	Unprovisioned "free"	No guarantees maximize throughput, fairness
MAC services	Best effort no SLAs	FCC rules to avoid collapse

Implications Cellular

	Cellular	Implication
Spectrum	**Licensed**	**Provider has control over interference**
Service model	**Provisioned "for pay"**	**Can and must charge + make commitments**
MAC services	**Fixed bandwidth SLAs**	**TDMA, FDMA, CDMA; access control**

But There are Many Similarities

- Cellular and WiFi face the same fundamental physical layer challenges
  - Interference, attenuation, multi-path, …
- Spatial frequency reuse based on "cells"
  - Adjacent cells use different frequencies
- Over time, they use similar modulation schemes
  - Each generation uses the best technology available at that time
- Rapid improvements in throughputs
  - Better modulation and coding, increasingly aggressive MIMO, …

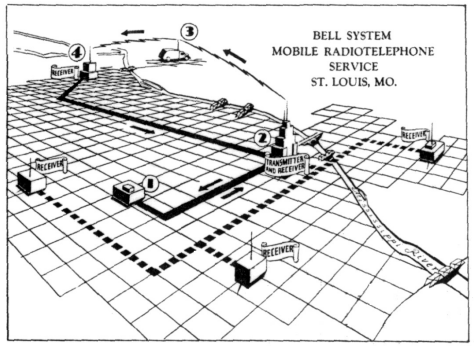
The Cellular Idea

- 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 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

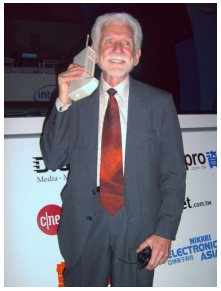
DynaTAC8000X: the First Cell Phone

The "brick":
- weighed 2 pounds,
- offered 30 mins of talk time 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!



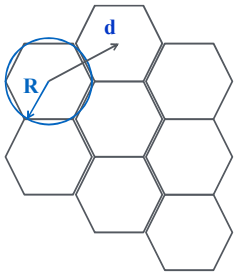
Dr. Martin Cooper of Motorola, made the first US analogue mobile phone call on a larger prototype model in 1973

How To Design a Cellular Network?

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

The Hexagonal Pattern

- Used in early cellular networks as an abstraction of corverage of a cell tower
- A hexagon pattern can provide equidistant access to neighboring cell towers
- In practice, big variations from ideal due to topological reasons
  - Signal propagation
  - Tower placement



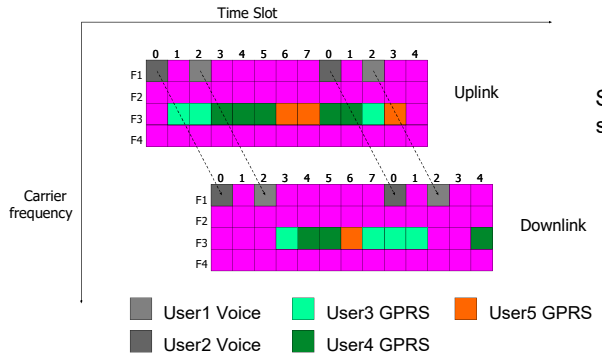
Early Cellular Networks

- Mobile radio telephone system was based on:
  - High power transmitter/receivers
  - Could support about 25 channels
  - in a radius of 80 Km
- To increase network capacity:
  - Multiple low-power transmitters (100W or less)
  - Small 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

Early Cellular Standards

- 1G systems: analog voice
  - Not unlike a wired voice line (without the wire)
  - Pure FDMA: each voice channel gets two frequencies (up, down)
- 2G systems: digital voice
  - Big step forward!
    - Allows for: Error correction, compression, encryption
- 2G example: GSM, most widely deployed, 200 countries, a billion people
  - Uses a combination of TDMA and FDMA
  - Version 2.5 also supported data using General Packet Radio Service (GPRS)

GPRS Radio Interface



Slots centrally scheduled by cell tower - Control slots

Next Generation Cellular Standards

- 3G: voice (circuit-switched) and data (packet-switched)
  - Several standards
  - Most use Code Division Multiple Access (CDMA)
- 4G: 10 Mbps and up, seamless mobility between different cellular technologies
  - LTE the dominating technology
  - Completely packet switched, voice sent as packets
  - Uses Orthogonal Frequency Division Multiplexing (OFDM) for increased robustness wrt. frequency selective fading and mobility

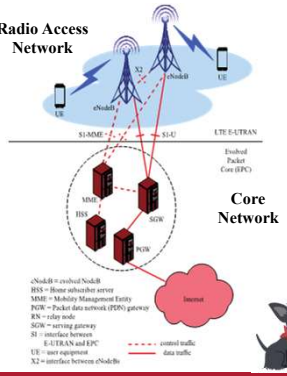
High Level Features LTE

- Provides an IP-based data network
  - No longer supports circuit-based voice support
  - Voice layers on top of data backbone using "Voice of LTE"
- Still uses FDMA/TDMA based resource allocation - guarantees

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

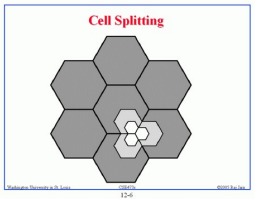
LTE Architecture

- Separates Radio Access Network from Core Network – can evolve independently
- Core uses OFDM instead of CDMA
- evolved NodeB (eNodeB)
  - Most devices connect into the network through the eNodeB
- Has its own control functionality
  - Dropped the Radio Network Controller
  - eNodeB supports radio resource control, admission control, and mobility management (handover)
  - Was originally the responsibility of the RNC



How to Increase Capacity?

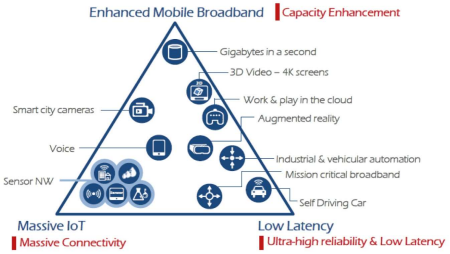
- Adding new channels
  - More spectrum – spectrum auctions
- Frequency borrowing
  - More flexible sharing of channels across cells
- Sectoring antennas
  - Split cell into smaller cells using directional antennas – 3-6 per cell
- Microcells, picocells, …
  - Antennas on top of buildings, lamp posts
  - Form micro cells with reduced power
  - Good for city streets, roads and inside buildings



Trends

- Cloud RAN optimizes spectrum use
  - Goal is to reuse frequencies very aggressively
  - Leverage cloud technology to centralize the processing for many cells
- Standards are complex and rigid and must support several generations
  - E.g., switch seamlessly from 4G to 3G
  - Still need to support 2G (legacy phones, voice)
- Scalability of signaling infrastructure is a growing concern
  - Hardware cannot keep up with changes in usage
- Wide-spread use of custom hardware
  - Move to commodity, programmable equipment

5G Vision ITU IMT
International Mobile Telecommunications



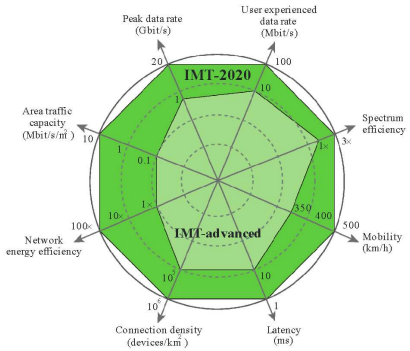
Faster 4G

Growing application domains

(Source: ETRI graphic, from ITU-R IMT 2020 requirements)

https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

Performance Goals ITU



5G technology

- Goal is 10+ fold increase in bandwidth over 4G
  - Combination of more spectrum and more aggressive use of 4G technologies
- Very aggressive use of MIMO
  - Tens to hundred antennas
  - Very fine grain beamforming and MU-MIMO
- More spectrum: use of millimeter bands
  - Challenging but a lot of spectrum available
  - Bands between 26 and 60 GHz
  - Beamforming extends range
- Also new lower frequency bands
  - Low-band and mid-band 5G: 600 MHz to 6 GHz

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How about Link Layer Mobility?

- Link layer mobility is easier
- Learning bridges can handle mobility → this is how it is handled at CMU
- Wireless LAN (802.11) also provides some help to reduce impact of handoff
  - The two access points coordinate to reduce latency, packet loss
- Problem is with inter-network mobility, i.e. Changing IP addresses
  - Want host to always have the same IP address

Routing to Mobile Nodes

- Obvious solution: have mobile nodes advertise route to mobile address/32
  - Should work!!!
- Why is this bad?
  - Consider forwarding tables on backbone routers
    - Would have an entry for each mobile host
    - Not very scalable
- What are some possible solutions?

How to Handle Addressing for Mobile Nodes?

- Simple existing solution: Dynamic Host Configuration (DHCP)
- Host gets new IP address in new locations
  - No impact on Internet routing
- Problems for the mobile host
  1. Finding the host: Host does not have constant address → how do other devices contact the host?
  2. Maintaining a connection while mobile: Transport connections are tied to src/dest IP addresses → What happens to active connections when a host moves?

How to Handle Transport Connections for Mobile Nodes?

- Hosts use a 4 tuple to identify a TCP connection
  - <Src Addr, Src port, Dst addr, Dst port>
  - Change your IP address breaks the connection – hard to fix
- Best approach: add a level of indirection using two IP addresses
  - A "identifier" IP address that identifies the connection on end-points
  - A "locator" IP address that is used in the packets and can change
  - Host does a mapping
- Security issue: Can someone easily hijack connection?
- Difficult to deploy → both ends must support mobility
- Even better approach: keep the same IP address!

First Contact: Fix Naming Problem

- Use DNS and update name-address mapping whenever host changes address
  - An awkward solution, at best
  - Increases "write" load on DNS
  - What about caching?
  - Also raises security issues
- Alternative: mobile IP

Mobile IP Goals

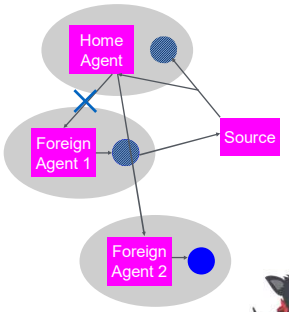
- Communicate with mobile hosts using their "home" IP address
  - Target is "nomadic" devices: do not move while communicating, i.e., laptop, not cellphone
  - Allows any host to contact mobile host using its "usual" IP address, as if it where in its "normal" location
- Mobility should be transparent to applications and higher level protocols
  - No need to modify the software
- Minimize changes to host and router software
  - No changes to communicating host
- Security should not get worse

Mobile IP Overview

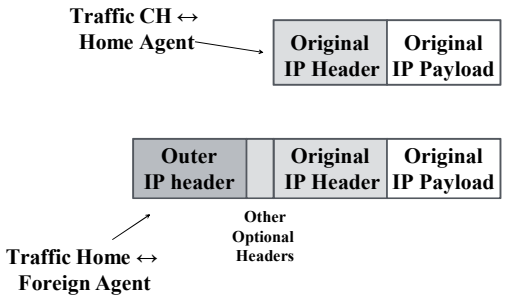
- Home network has a home agent that is responsible for intercepting packets and forwarding them to the mobile host.
  - E.g., router at the edge of the home network
  - Forwarding is done using tunneling
- Remote network has a foreign agent that manages communication with mobile host.
  - Point of contact for the mobile host
- Binding ties IP address of mobile host to a "care of" address in the foreign network.
  - binding = (IP address, foreign agent address)
  - binding includes time stamp

Mobile IP Operation

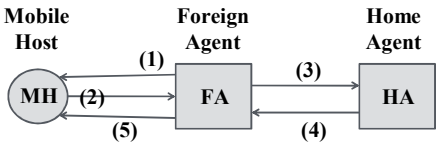
- Agents advertise their presence.
  - Using ICMP or mobile IP control messages
  - Mobile host can solicit agent information
  - Mobile host can determine where it is
- Registration process: mobile host registers with home and foreign agent.
  - Set up binding valid for *registration lifetime*
- Tunneling
  - forward packets to foreign agent
  - foreign agent forwards packets to mobile host
- Supporting mobility
  - invalidating old caches in a lazy fashion



Tunneling
IP-in-IP Encapsulation



Registration via Foreign Agent

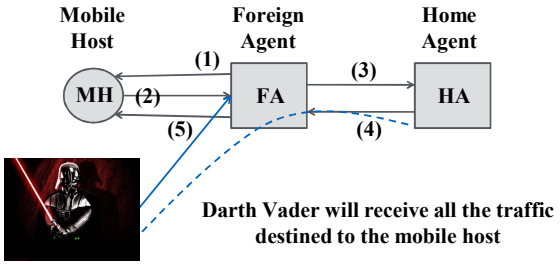


1. FA advertizes service
2. MH requests service
3. FA relays request to HA
4. HA accepts (or denies) request and replies
5. FA relays reply to MH

Optimizations

- Mobile host can be its own the foreign agent.
  - Mobile host acquires local IP address using DHCP
  - Performs tasks of the mobile agent
- Short circuit the home location by going directly to the foreign agent.
  - Routers in the network store cache bindings and intercept and tunnel packets before they the mobile host's home network
  - Need a protocol to update/invalidate caches
  - Raises many security questions and is not in the standard

Authentication



Solution: Registration messages between a mobile host and its home agent must be authenticated

Discussion

- Mobile IP not used in practice
- Not designed for truly mobile users
  - Designed for nomadic users, e.g. visitors to a remote site
  - Only solves the initial contact problem, but …
- Mobile devices are typically clients, not servers, i.e., they initiate connections
  - Problem Mobile IP solves not common in practice
- IETF defined solutions that are more efficient
  - But they are move heavy weight: effectively creates overlay with tunnels and special "routers"
- Ultimately all solutions are similar: need a "relay" that knows location of the device

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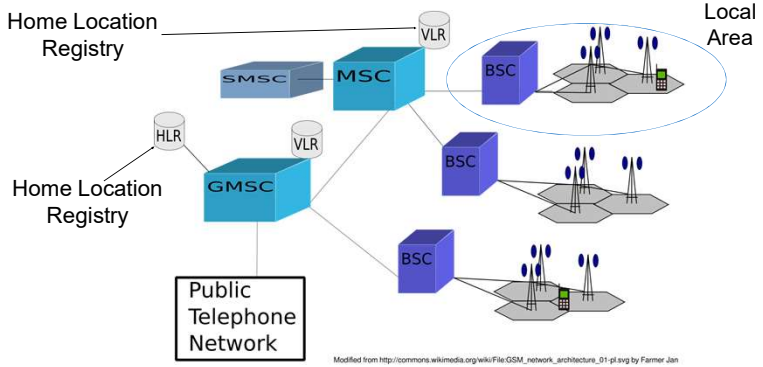
GSM Core Architecture



Mobility with GSM

- Mobile Station – MS
  - A device connecting to the cellular network
- Base Station Controller - BSC
  - In charge of a group of cells
  - Sometimes called a Location Area (LA)
- Mobile Switching center – MSC
  - In charge of several clusters of cells
- Gateway Mobile Switching center – GMSC
  - Connects to the wired telephone networks
- Location registries
  - Home Location Registry (HLR)
  - Visitor Location Registry (VLR)

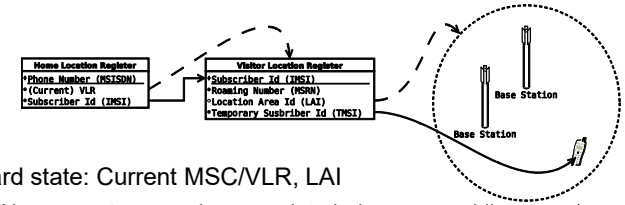
Home Location Register

- One per separately managed network
  - E.g., Pittsburgh region for operator X
- Contains entries for every subscriber and every mobile ISDN number that is homed in the respective network
- Permanent subscriber data and relevant temporary information
- Current location of the mobile station
  - Either in this network, or in a remote network (e.g., Chicago)
- All administrative activities of the subscriber happen here!

Visitor Location Register

- Stores data on all mobile stations that are currently in the administrative area of the MSC
  - Roughly a large region
- A MS is registered in the VLR of its home network when local
- It is registered with VLR of the foreign network when roaming
  - Its location is also passed on to its home network (MLR)
- MS registers upon entering a Local Area. The MSC passes the identities of the MS and Local Area to VLR

GSM Address Lookup (“registers”)



- Hard state: Current MSC/VLR, LAI
  - (Necessary to page phone, updated whenever mobile moves)
- Soft-ish state:
  - MSRN, cell ID, TMSI
- Not all that different from mobile IP!

Grossly simplified for your safety and sanity!

GSM Addressing Hierarchy

- Device
  - IMEI (International Mobile Equipment Identifier)
- User
  - IMSI (International Mobile Subscriber Identifier)
  - MSISDN (Mobile Subscriber IDSN Number)
    - "Real phone number"
  - MSRN (Mobile Station Roaming Number)
  - TMSI (Temporary Mobile Subscriber Identity
  - LMSI (Local Mobile Subscriber Identity)
- Other
  - LAI (Location Area Identity)
  - CI (Cell Identity)

Just for your entertainment – do not memorize