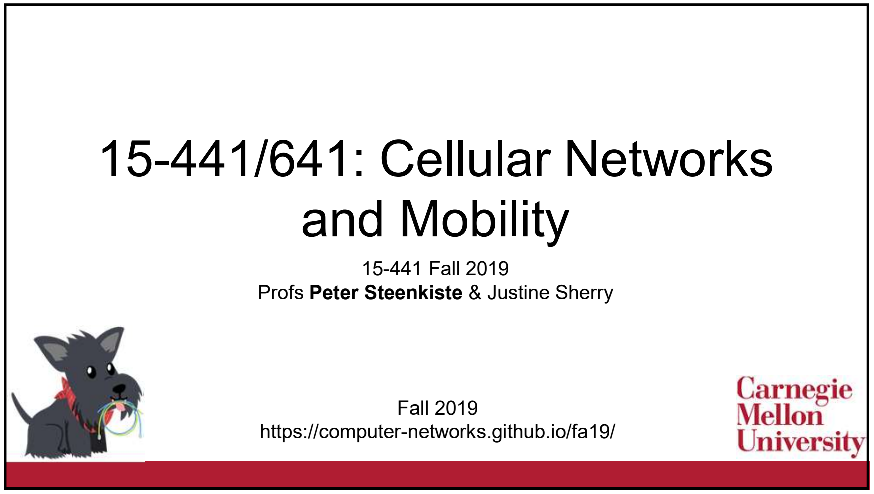
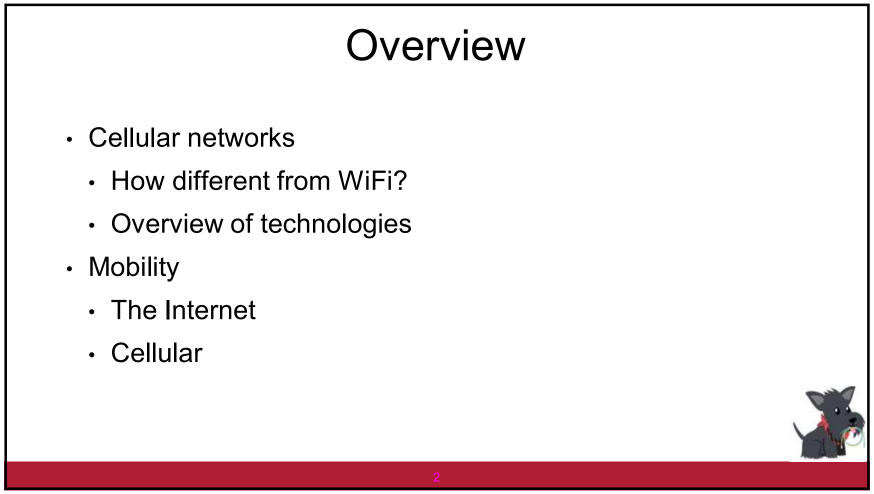


15-441/641: Cellular Networks and Mobility

15-441 Fall 2019
Profs **Peter Steenkiste** & Justine Sherry

Fall 2019
https://computer-networks.github.io/fa19/

Carnegie Mellon University



Overview

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

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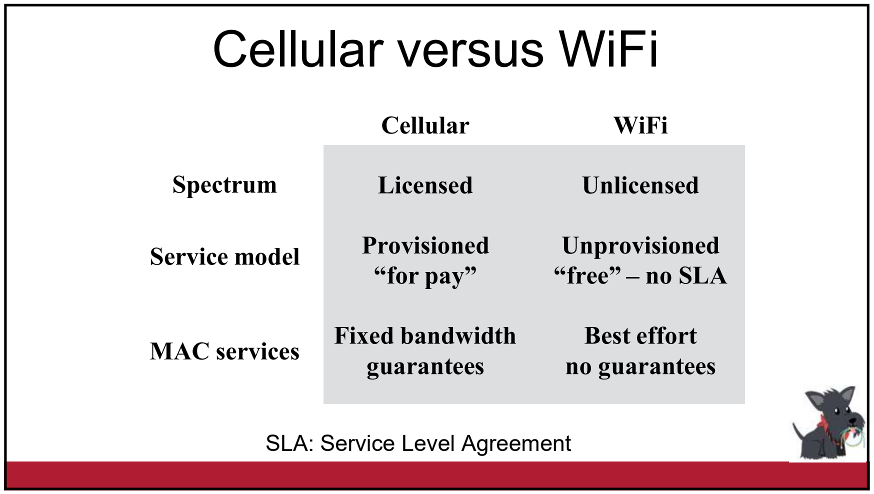
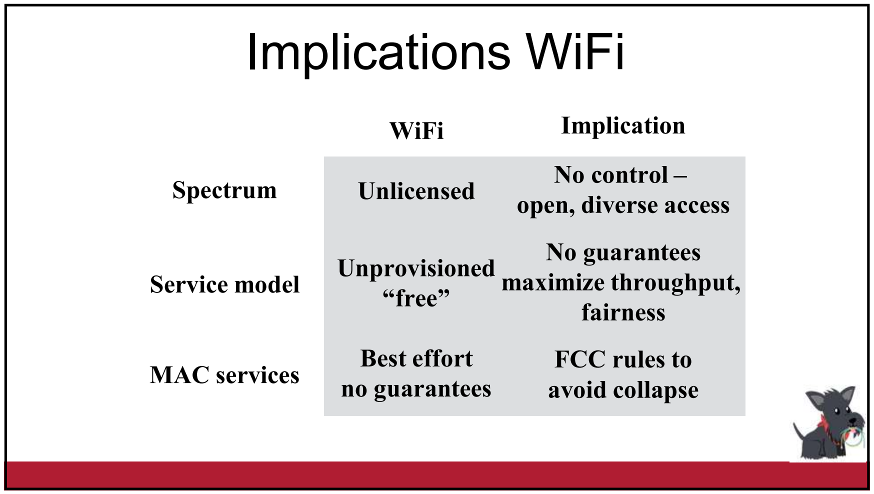


Cellular versus WiFi

	Cellular	WiFi
Spectrum	**Licensed**	**Unlicensed**
Service model	**Provisioned “for pay”**	**Unprovisioned “free” – no SLA**
MAC services	**Fixed bandwidth guarantees**	**Best effort no guarantees**

SLA: Service Level Agreement



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 guarantees**	**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, …

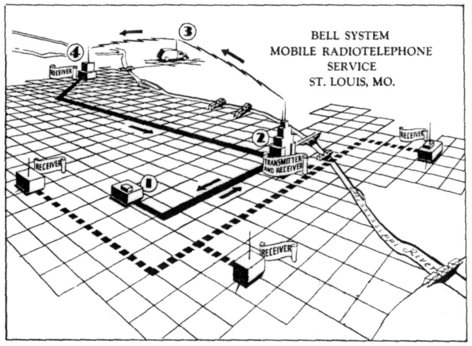
The Cellular Idea

- 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

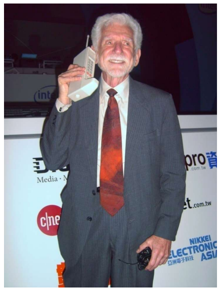
DynaTAC8000X: the First Cell Phone

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!

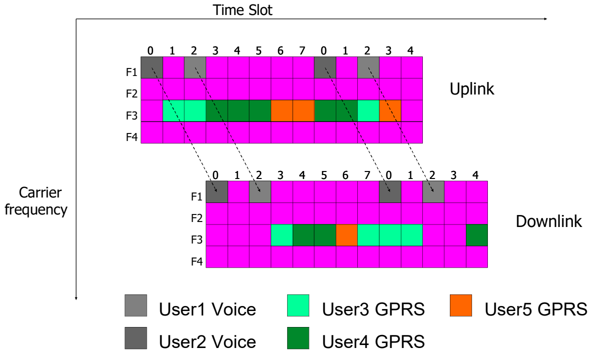


Dr. Martin Cooper of Motorola, made the first US analogue mobile phone call on a larger prototype model in 1973

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

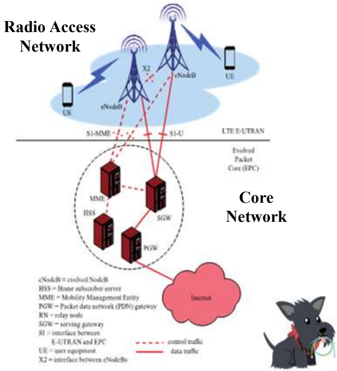
High Level Features LTE

- 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

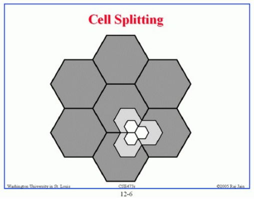
LTE Architecture

- 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

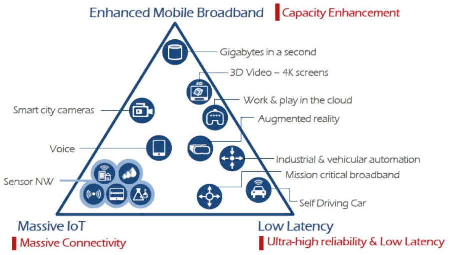


Cell Splitting

Washington University in St. Louis CSE473s ©2005 Raj Jain

12-6

5G Vision ITU IMT International Mobile Telecommunications



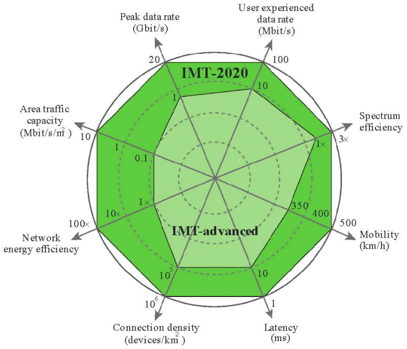
Faster 4G

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

Network Mobility: Two Simple Solutions

- Routing: mobile nodes keep “home” IP address and advertise route to mobile address as /32 in BGP
  - Leverages LPM semantics - should work!!
  - Bad idea: scalability
- DNS: mobile nodes get “local” IP address and update name-address binding in DNS
  - DNS allows updates of the address – should work!!
  - Bad idea: results in a lot of write traffic to DNS
  - DNS is not designed for this and reduces caching benefit

More Practical Way to Support Mobility

- Host gets new IP address in new “foreign” network
  - Simple: use Dynamic Host Configuration (DHCP)
  - No impact on Internet routing
- Raises two challenges:
  1. Maintaining a TCP connection while mobile: Transport connections are tied to src/dest IP addresses → What happens to active connections when a host moves?
  2. Finding the host: Host does not have constant address → how do other devices contact the host?

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!

Finding Mobile Hosts: Mobile IP

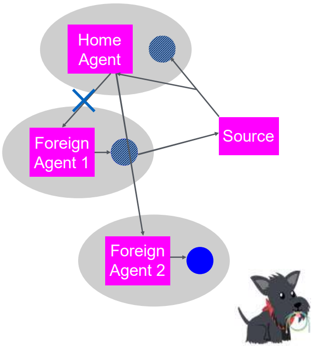
- Communicate with mobile hosts using their “home” IP address
  - Target is “nomadic” devices: do not move while communicating, i.e., laptop, not cellphone
  - Allows any host to contact mobile host using its “usual” IP address, as if it where in its “normal” location
- Mobility should be transparent 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

Finding Mobile Hosts: Mobile IP

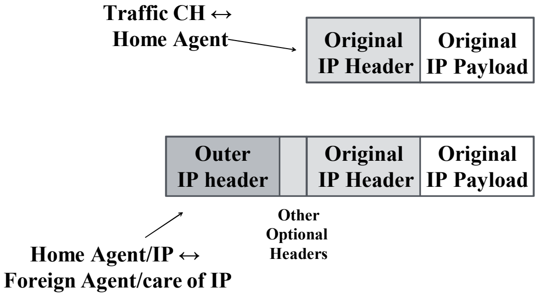
- Any host can contact mobile host using its usual “home” IP address
  - Target is “nomadic” devices: do not move while communicating, i.e., laptop
- Home network has a home agent that is responsible for intercepting packets and forwarding them to the mobile host.
  - E.g., router at the edge of the home network
  - Forwarding is done using tunneling
- Remote network has a foreign agent that manages communication with mobile host.
  - Module that runs on mobile and the point of contact for the mobile host
- Binding ties home IP address of mobile host to a “care of” address in the foreign network.
  - binding = (home IP address, foreign IP addess)

Mobile IP Operation

- Registration process: mobile host registers with home agent.
  - Home agents needs to know that it should intercept packet and forward them
- In foreign network, foreign agent gets local “care of” address and notifies home agent
  - Home agent knows where to forward packets
- Tunneling
  - Home agent forward packets to foreign agent
  - Return packets are tunneled in the reverse direction
- Supporting mobility
  - Update binding in home and foreign agents.



Tunneling IP-in-IP Encapsulation



Traffic CH ↔ Home Agent

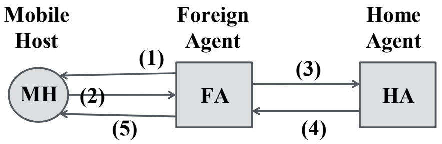
Original IP Header	Original IP Payload

Outer IP header		Original IP Header	Original IP Payload

Other Optional Headers

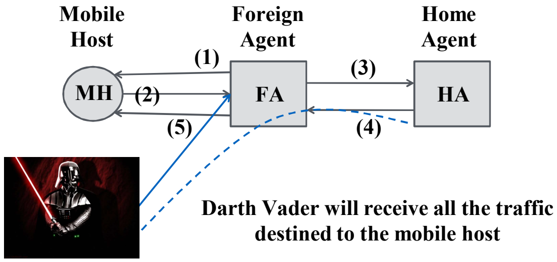
Home Agent/IP ↔ Foreign Agent/care of IP

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

Authentication



Darth Vader will receive all the traffic destined to the mobile host

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

Discussion

- Obvious optimization: mobile host send return packet directly to communicating host – not through home agent
  - Problem: may look like spoofed traffic to the foreign network
- Mobile IP not used in practice
- Mobile devices are typically clients, not servers, i.e., they initiate connections
  - The problem Mobile IP solves rare in practice
- Mobile IP is not designed for truly mobile users
  - Designed for nomadic users, e.g. visitors to a remote site
- IETF defined several solutions that are more efficient
  - Also more heavy weight: creates overlay with tunnels and special "routers"
- All solutions are similar: need a "relay" that knows location of the device

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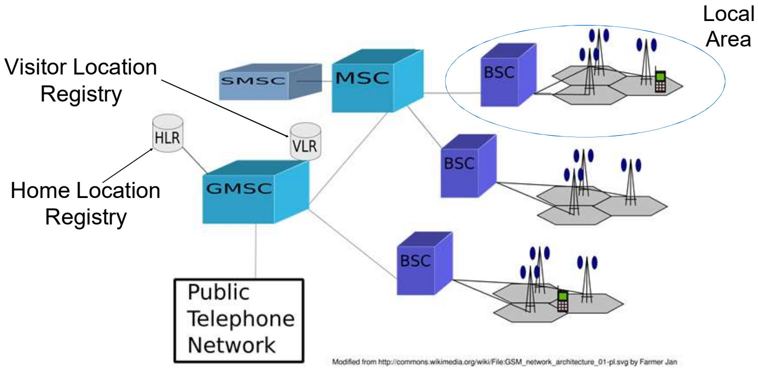
GSM Core Architecture



Modified from http://commons.wikimedia.org/wiki/File:GSM_network_architecture_01-pl.svg by Farmer Jan

List of Acronyms

- 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
  - SMSC: Short Message Switching Center (SMS)
- Gateway Mobile Switching center – GMSC
  - Connects to the wired telephone networks
- Location registries
  - Home Location Registry (HLR)
  - Visitor Location Registry (VLR)

Supports Mobility

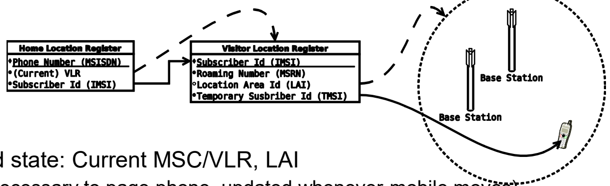
Home Location Register

- 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 that network
- Permanent subscriber data and relevant temporary information
  - All administrative activities of the subscriber happen here!
- Includes the current location of the mobile station
  - Either in this network, or in a remote network (e.g., Chicago)

Visitor Location Register

- Stores data on all mobile stations that are currently in the administrative area of the MSC
  - Roughly a large region, e.g., Pittsburgh 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
  - Home network stored this in its HLR
- 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!
  - HLR and VLR roughty map to home and foreign agent