Computer Networks

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Notes derived from "*Computer Networking: A Top Down Approach*", by Jim Kurose and Keith Ross, Addison-Wesley.

The slides are adapted and modified based on slides from the book's companion Web site, as well as modified slides by Anirban Mahanti and Carey Williamson.

What is Wireless Networking?

- The use of infra-red (IR) or radio frequency (RF) signals to share information and resources between devices
- Promises *anytime*, *anywhere* connectivity
  - Laptops, palmtops, PDAs, Internet-enabled phone promise anytime *untethered* Internet access
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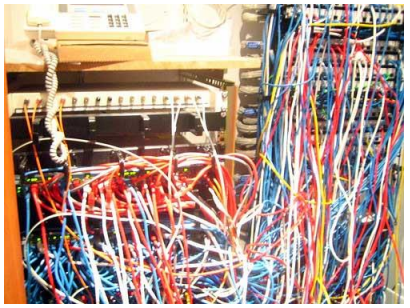

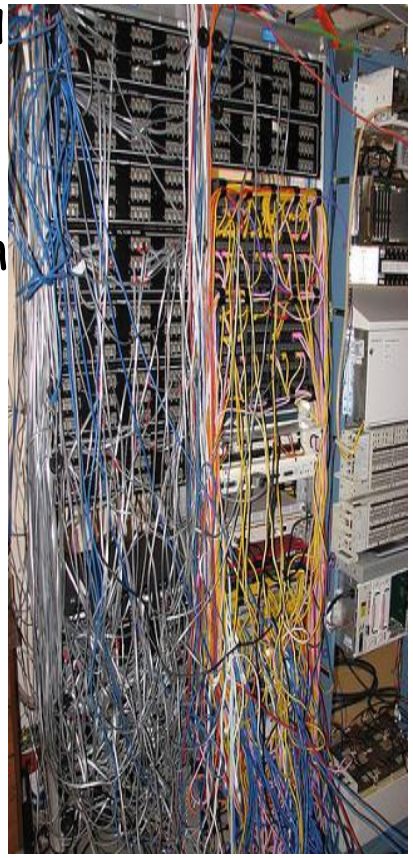

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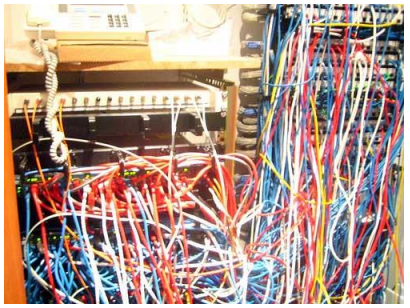

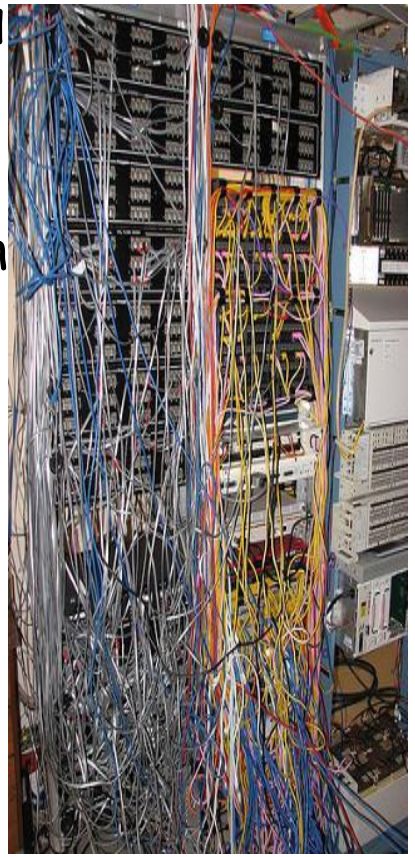

- Lots of media buzzwords!
  - Mobile Internet, Pervasive Computing, Nomadic Computing, M-Commerce, Ubiquitous Computing …
  - … and acronyms; e.g., CSMA, WiFi, 802.11, …

Two important (but different!) challenges

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- Communication over wireless link

- Handling mobile user who changes point of attachment to network

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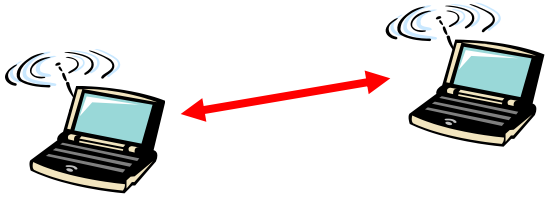

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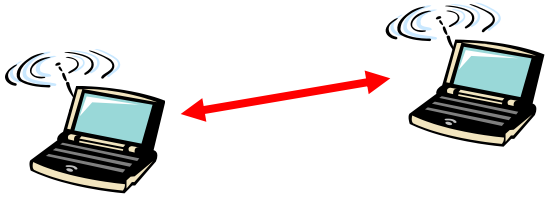
- Communication over wireless link



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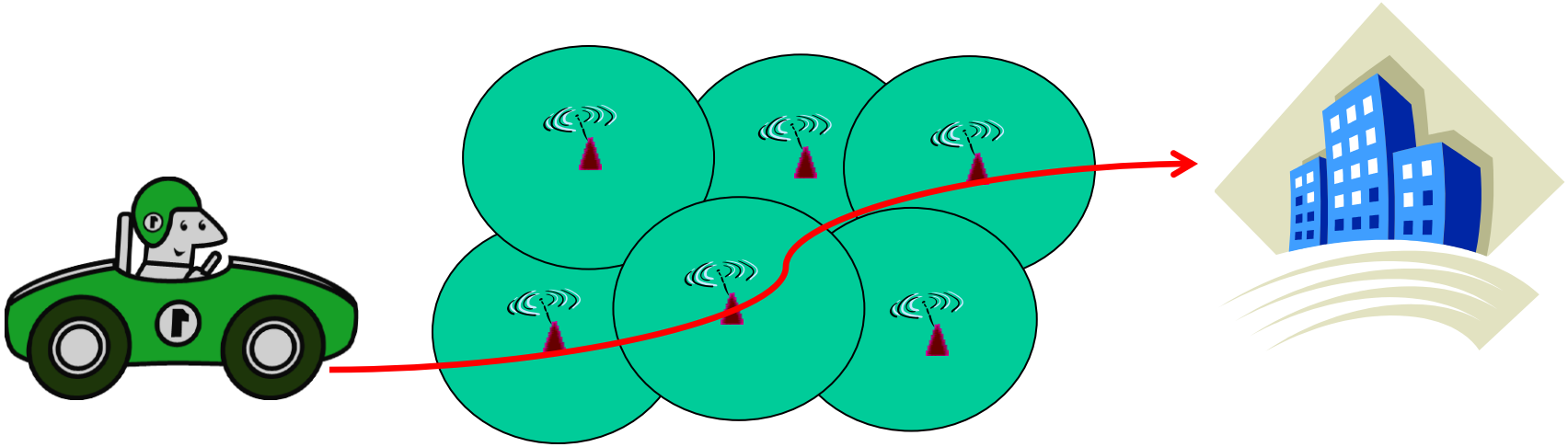


Wireless Link Characteristics

Differences from wired link ….

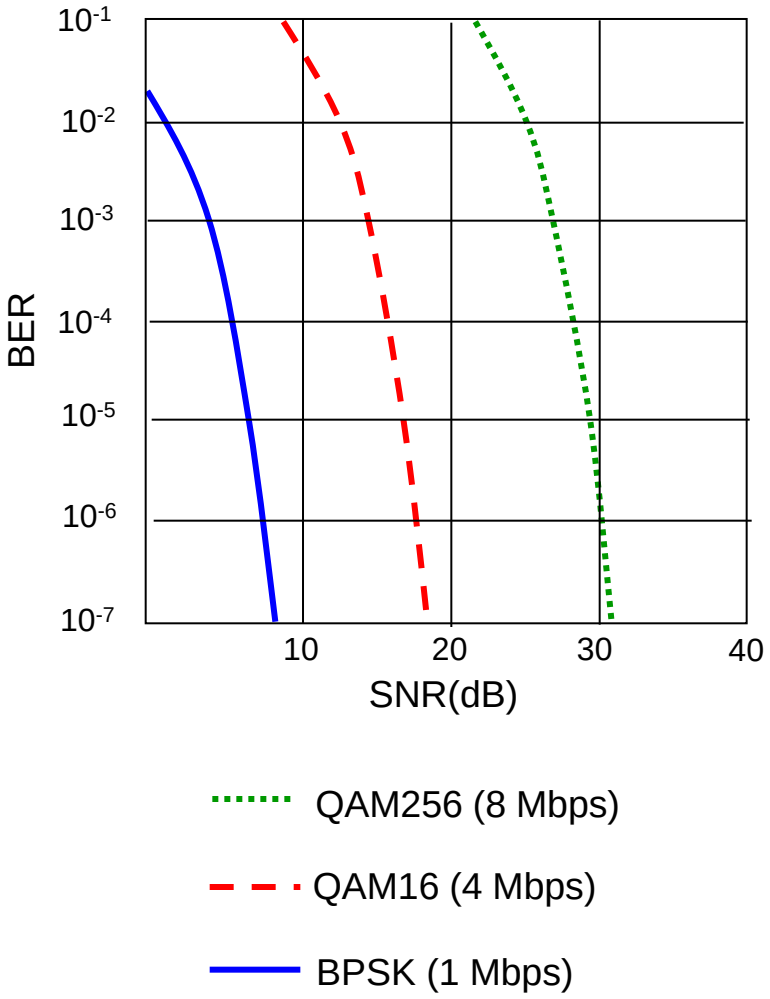
- Decreasing signal strength: radio signal attenuates as it propagates through matter (path loss)
- Interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- Multi-path propagation: radio signal reflects off objects ground, arriving at destination at slightly different times

…. make communication across (even a point to point) wireless link much more "difficult"

- Higher error rates; lower bandwidths; non-uniform transmission characteristics; increased usage costs; and increased susceptibility to interference and eavesdropping

Wireless Link Characteristics

- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a "good thing")
- *SNR versus BER tradeoffs*
  - *given physical layer:* increase power -> increase SNR ->decrease BER
  - *given SNR:* choose physical layer that meets BER requirement, giving highest throughput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



Technology and Example Standards

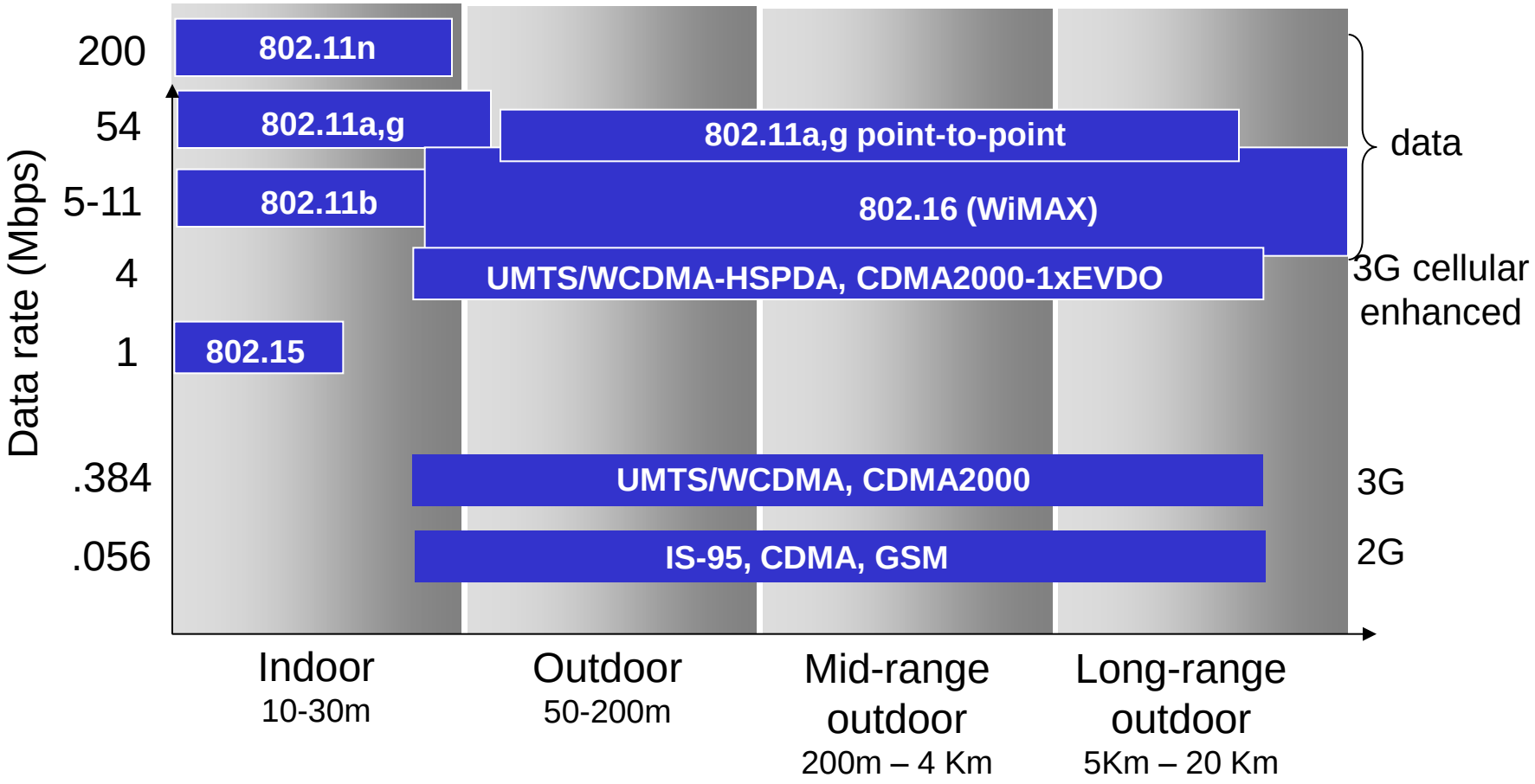
- The right technology/standard for the problem/environment??

A Classification of Networks

- Wide Area Network (WAN)
- Metropolitan Area Network (MAN)
- Local Area Network (LAN)

- Wireless LAN (WLAN)
- Home Networks
- Personal Area Network (PAN)
- Body Area Network (BAN)
- Also … Ad hoc and sensor networks …

Characteristics of selected wireless link standards



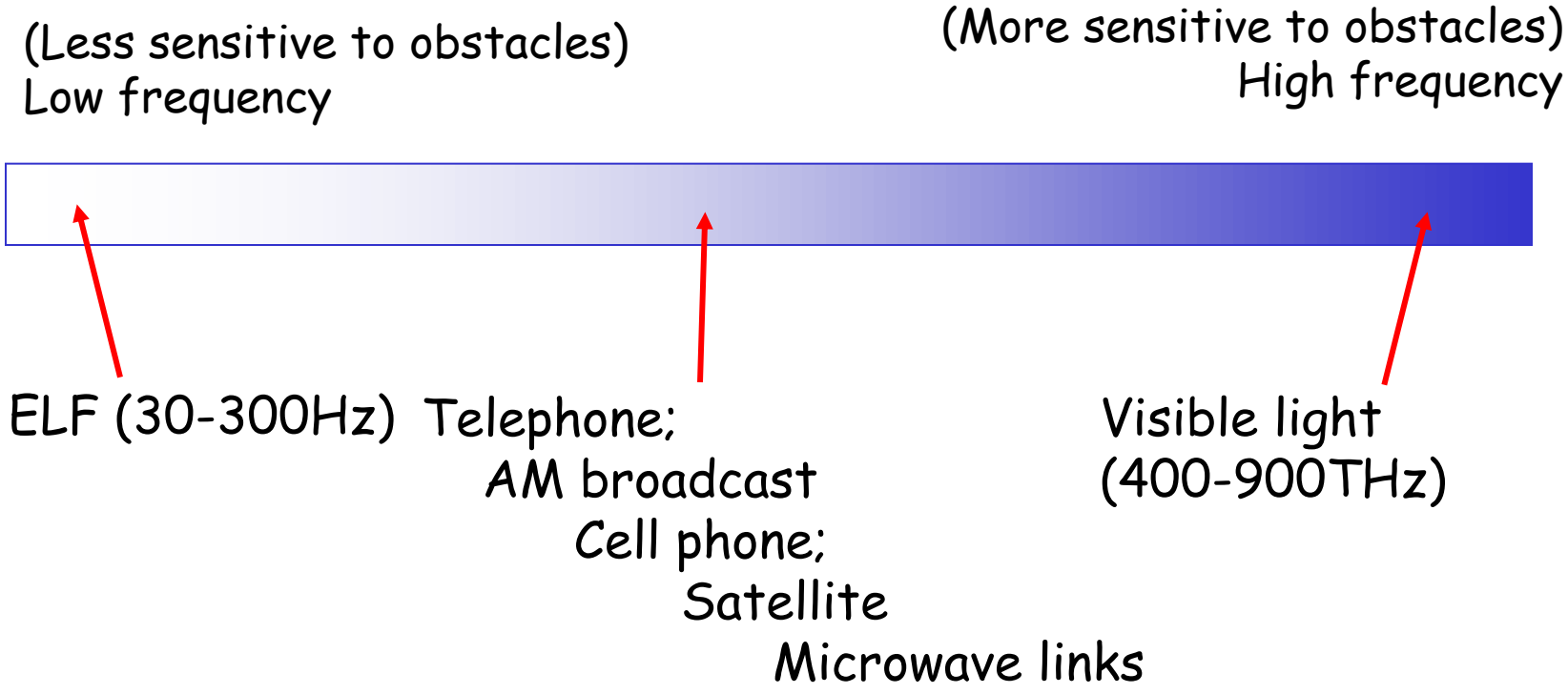
Differences in "per hop bandwidths" primarily from ...

- Physical layer
  - Spectrum allocation (wave length)
  - Frequency; channel width; time multiplexing
  - Signal-to-Noise; BER; Error correction; etc.

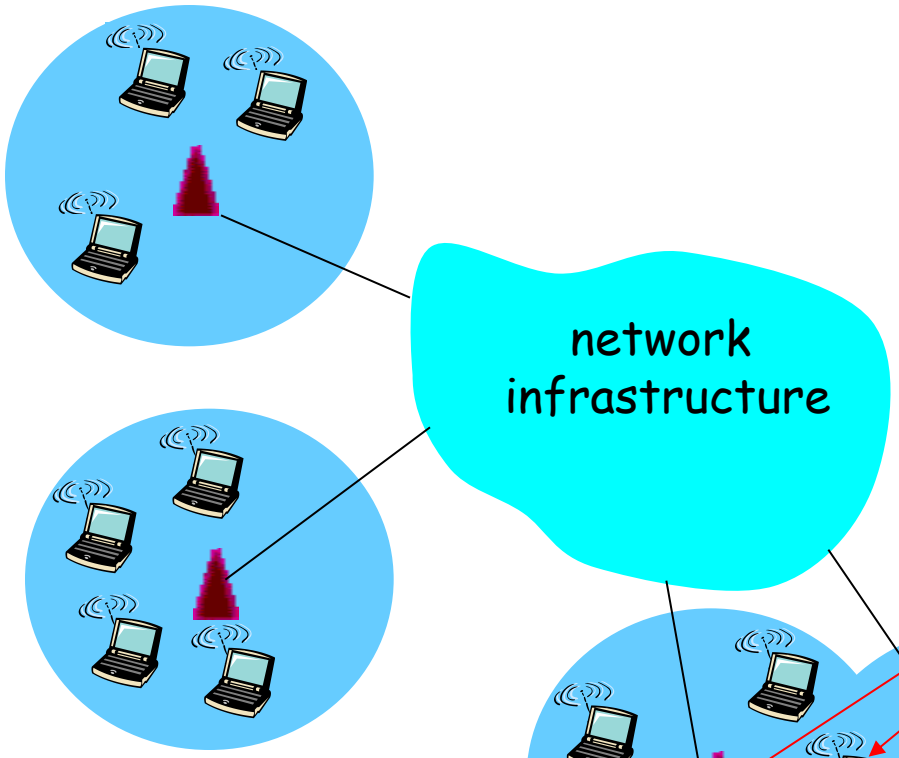
- MAC layer (sub-layer in data link layer)
  - Multiple access techniques
  - E.g., FDMA, TDMA, CDMA, SDMA, CSMA

Frequency band spectrum

- spectrum allocated by global and national agencies



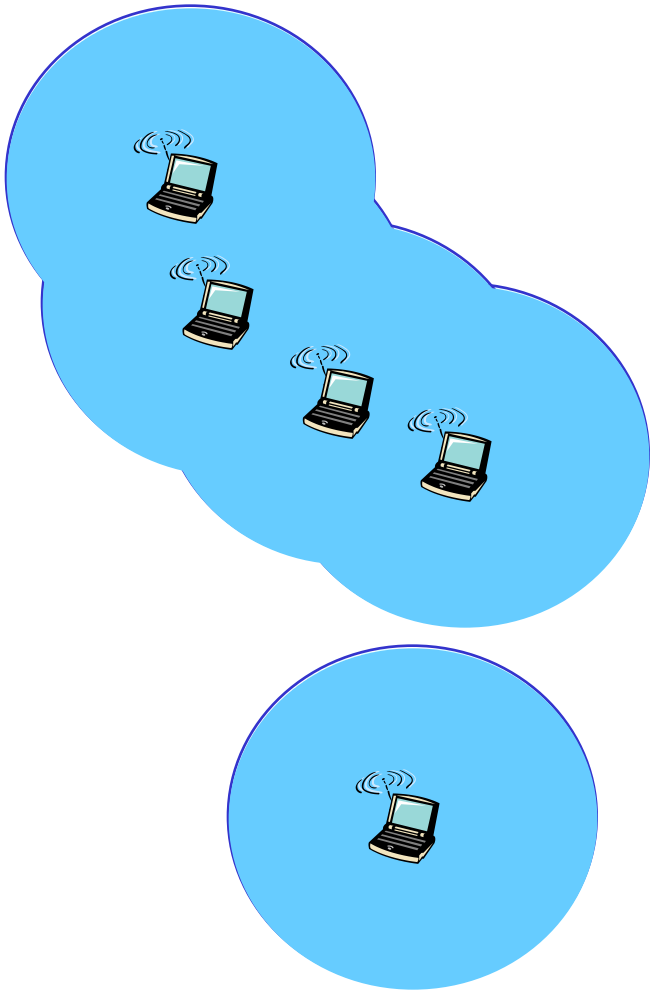
Infrastructure Mode



Infrastructure mode

- base station connects mobiles into wired network
- handoff: mobile changes base station providing connection into wired network

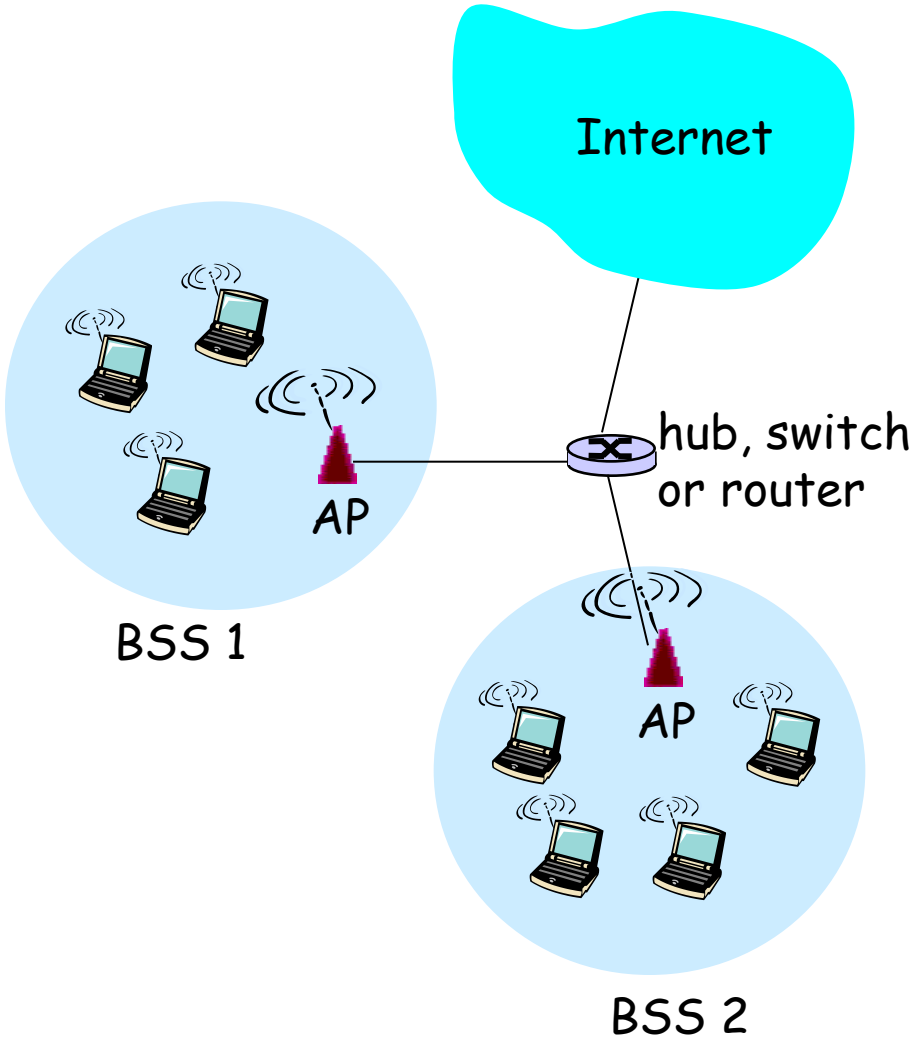
Ad hoc Mode



Ad hoc mode

- no base stations
- nodes can only transmit to other nodes within link coverage
- nodes organize themselves into a network: route among themselves

802.11 LAN architecture

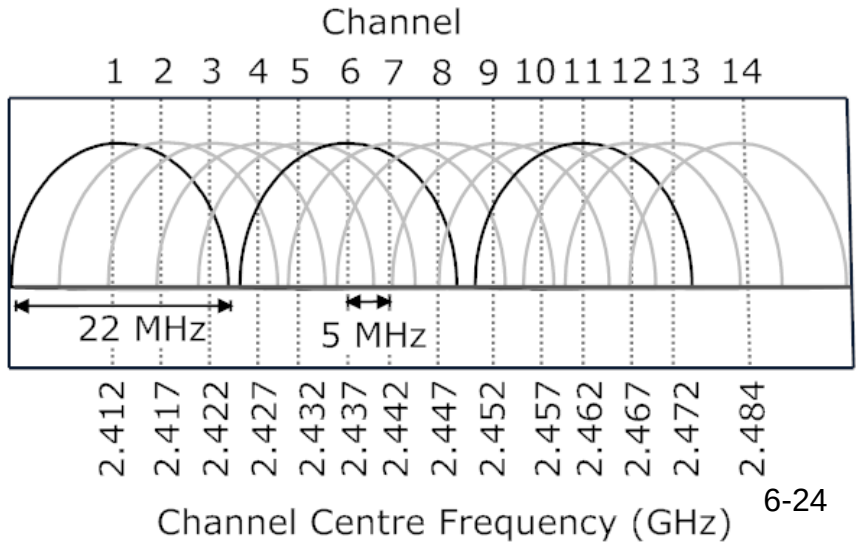


- Wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - wireless hosts
  - access point (AP)
  - ad hoc mode: hosts only

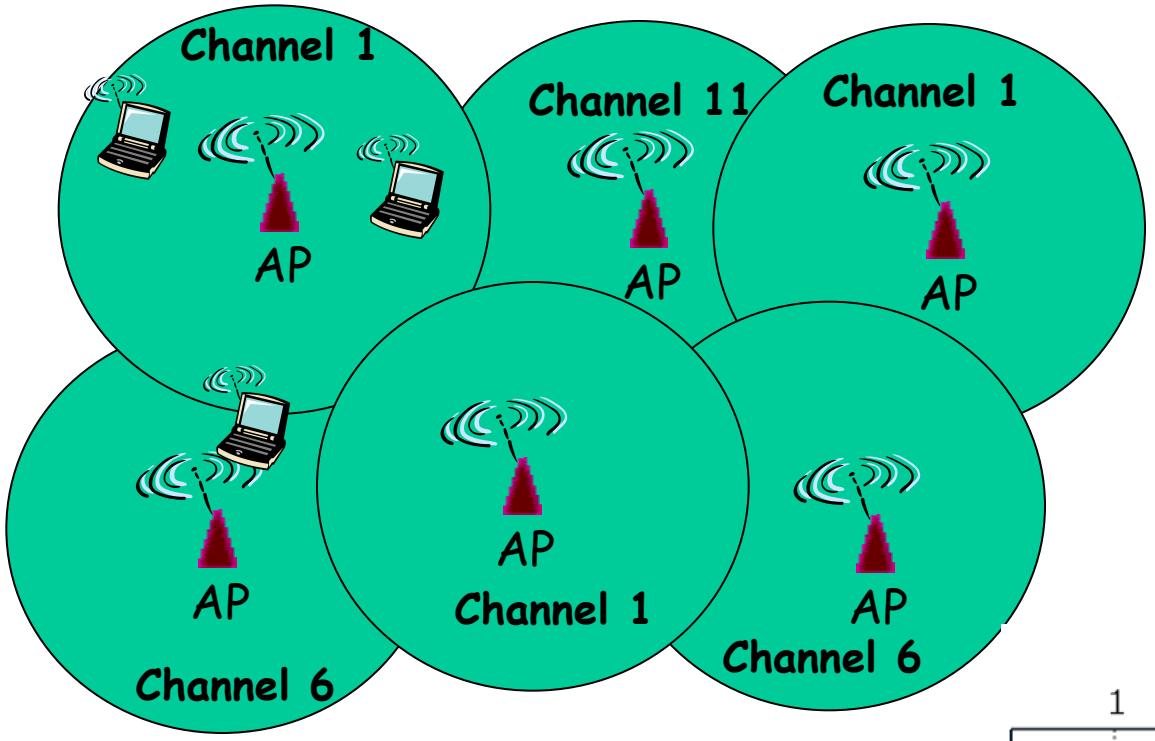
Wireless Cells

- 802.11b has 11 channels
- Channels 1, 6, and 11 are non-overlapping

- Admin chooses frequency for AP

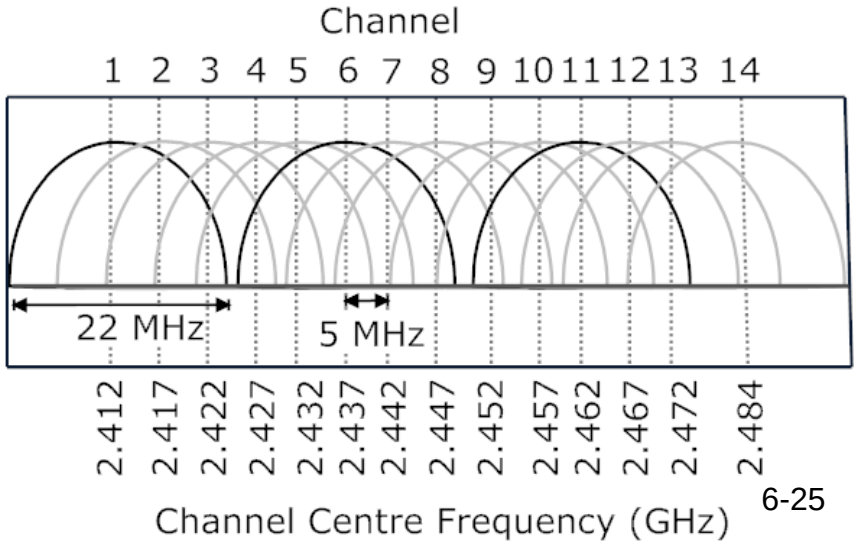


Wireless Cells



- 802.11b has 11 channels
- Channels 1, 6, and 11 are non-overlapping
- Each AP coverage area is called a "cell"
- Wireless nodes can roam between cells

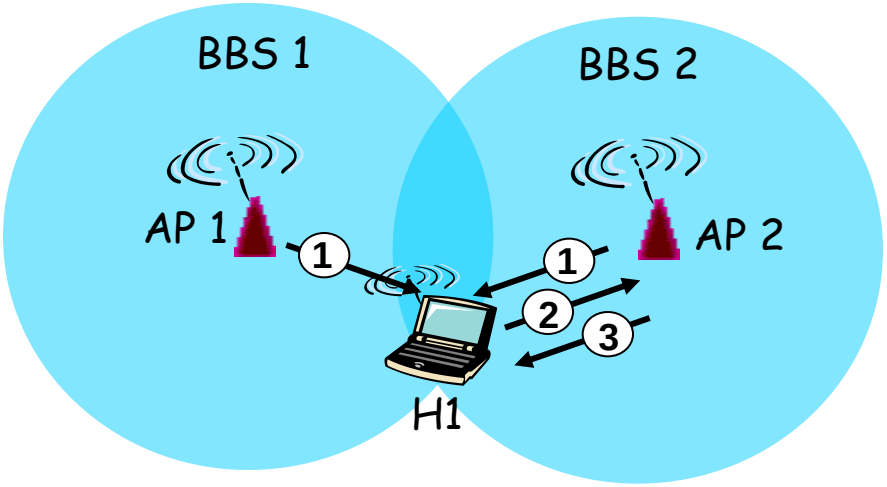
- Admin chooses frequency for AP
- Interference possible: channel can be same as that chosen by neighboring AP!

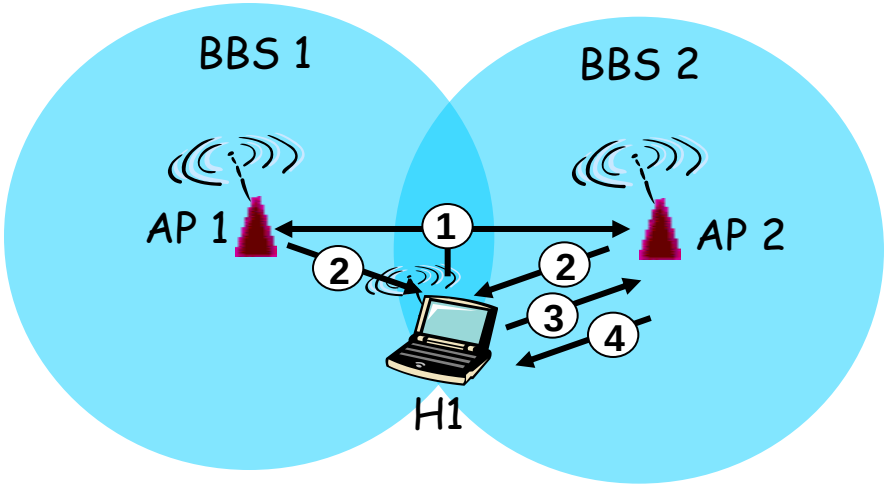


802.11: Channels, association

- host: must *associate* with an AP
  - scans channels, listening for *beacon frames* containing AP's name (SSID) and MAC address
  - selects AP to associate with
  - may perform authentication
  - will typically run DHCP to get IP address in AP's subnet

802.11: passive/active scanning





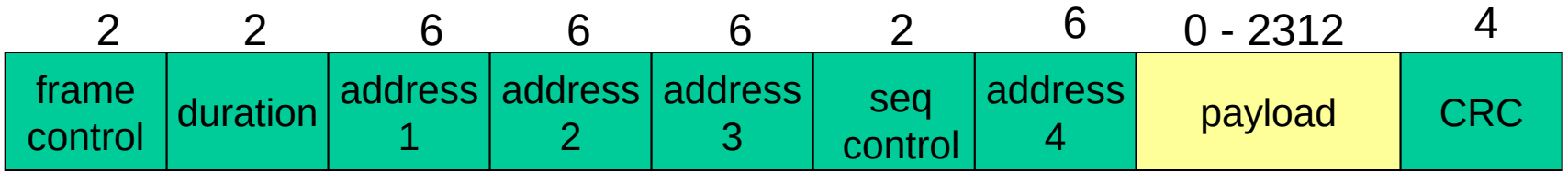
Passive Scanning:

(1) **Beacon** frames sent from APs
(2) **Association Request** frame sent: H1 to selected AP
(3) **Association Response** frame sent: H1 to selected AP

Active Scanning:

(1) **Probe Request** frame broadcast from H1
(2) **Probes Response** frame sent from APs
(3) **Association Request** frame sent: H1 to selected AP
(4) **Association Response** frame sent: H1 to selected AP

802.11 frame: addressing



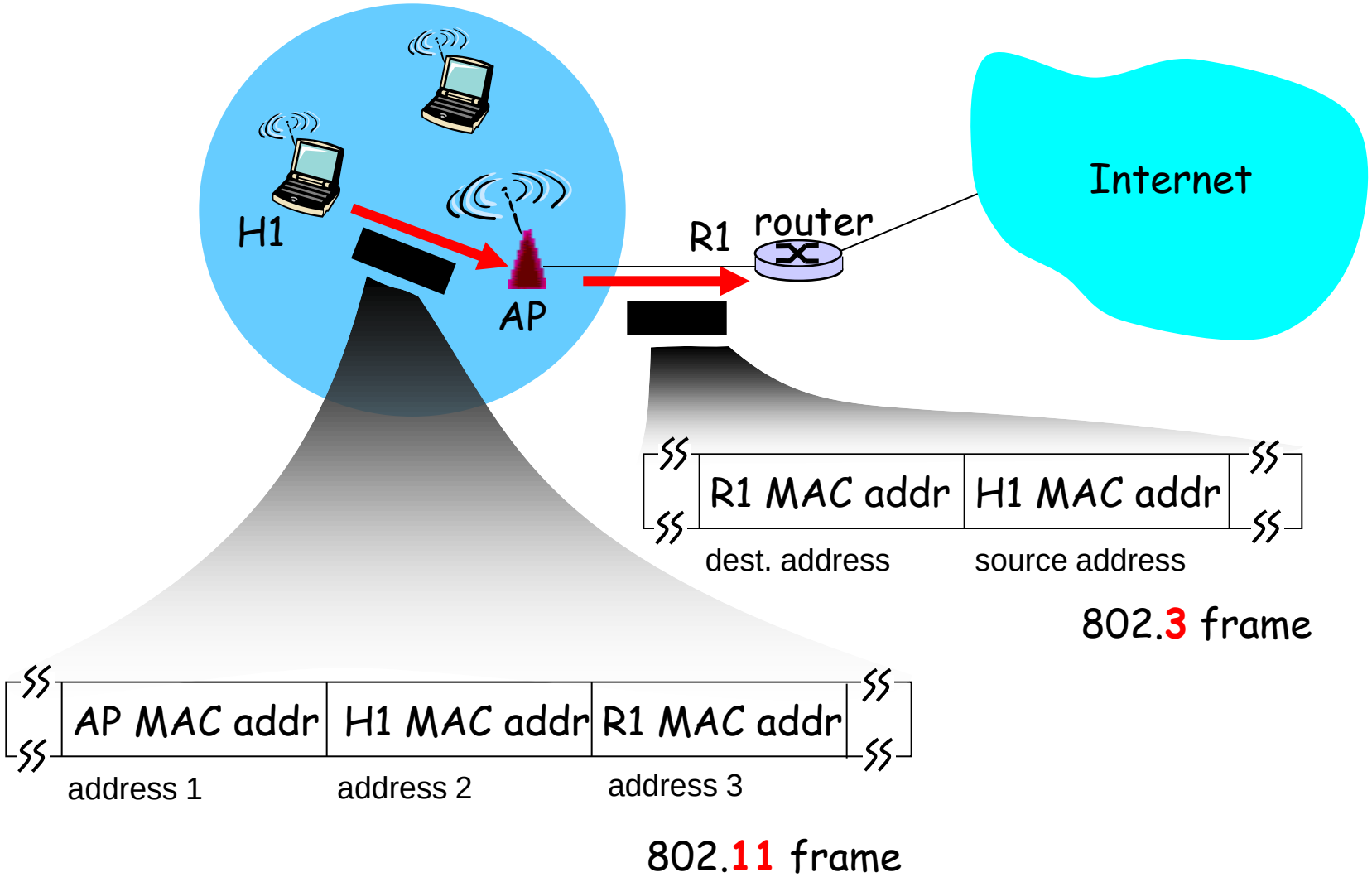
Address 1: MAC address of wireless host or AP to receive this frame

Address 2: MAC address of wireless host or AP transmitting this frame

Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

802.11 frame: addressing



IEEE 802.11: multiple access

- avoid collisions: 2^+ nodes transmitting at same time
- 802.11: *CSMA* - sense before transmitting
  - don't collide with ongoing transmission by other node
- 802.11: *no* collision detection!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/C(ollision)A(voidance)

IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS** then

transmit entire frame (no CD)

2 if sense channel busy then

start random backoff time

timer counts down while channel idle

transmit when timer expires

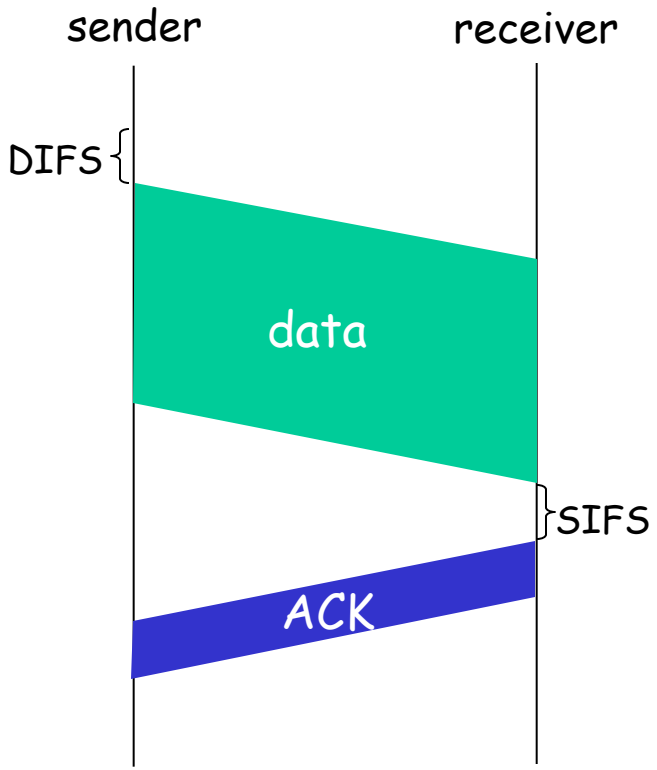
3 if no ACK then increase random backoff interval, repeat step 2

802.11 receiver

- if frame received OK

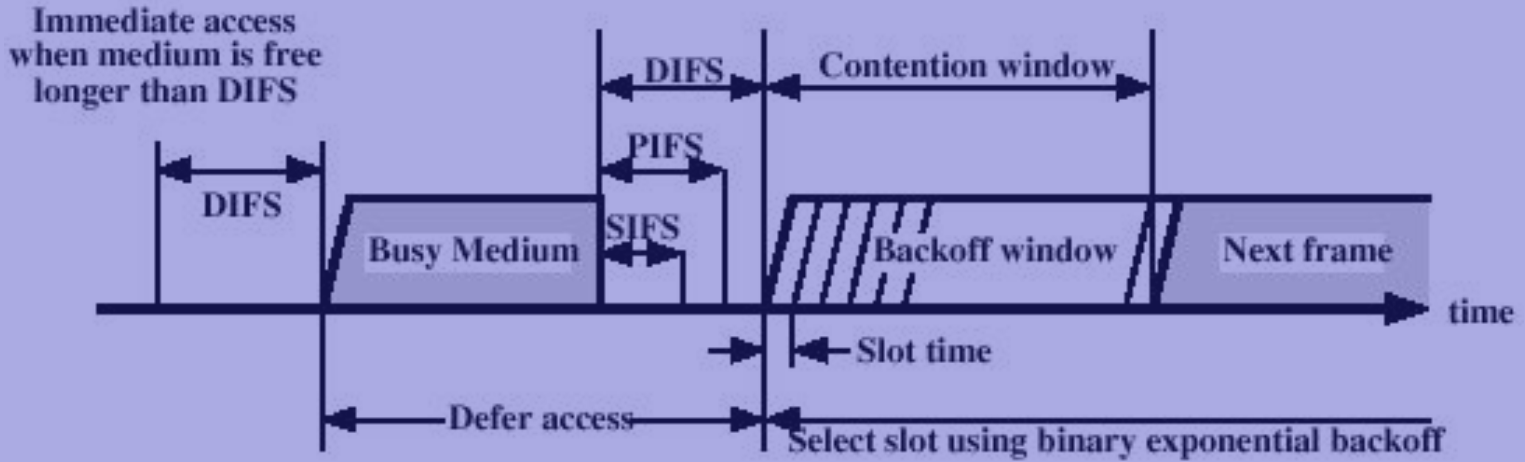
return ACK after **SIFS**

(service model is connectionless, acked)



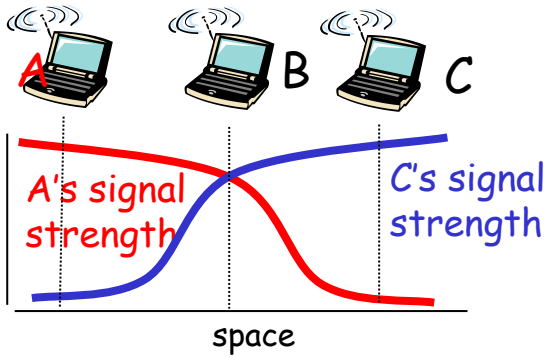
IEEE 802.11 MAC: DCF, cont'd

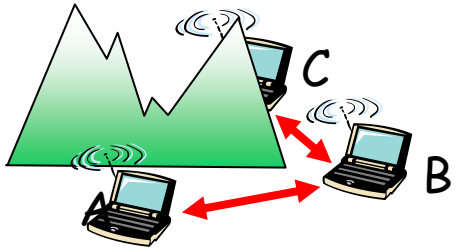
- Priority-based scheme - use 3 values for IFS:
- SIFS (short IFS): shortest IFS used for immediate responses such as ACK, CTS, poll response
- PIFS (point coordination function IFS): middle length IFS used for issuing polls by a centralized controller
- DIFS (distributed coordination function IFS): longest IFS used for regular asynchronous frames



Hidden Terminal Problem

Hidden terminal problem (ad-hoc and WLAN)





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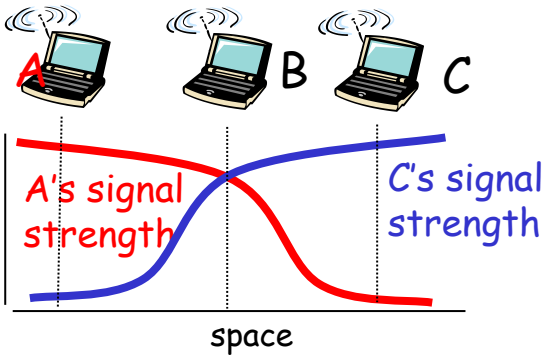
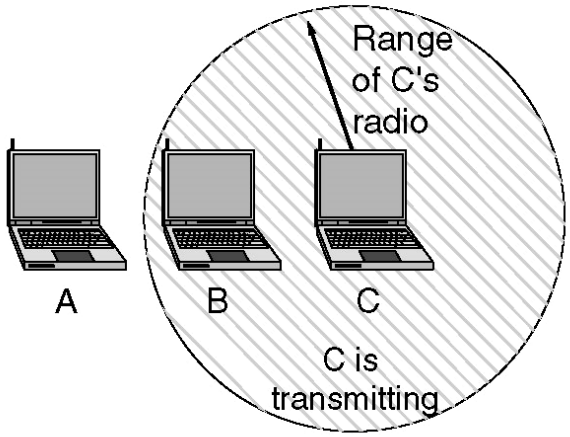
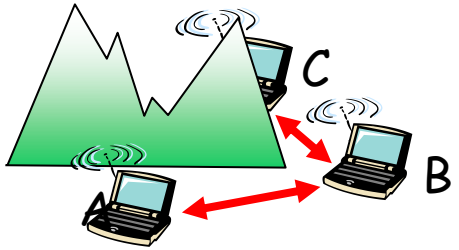


A wants to send to B but cannot hear that B is busy





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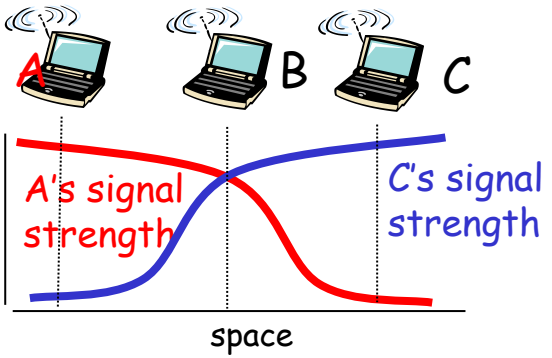
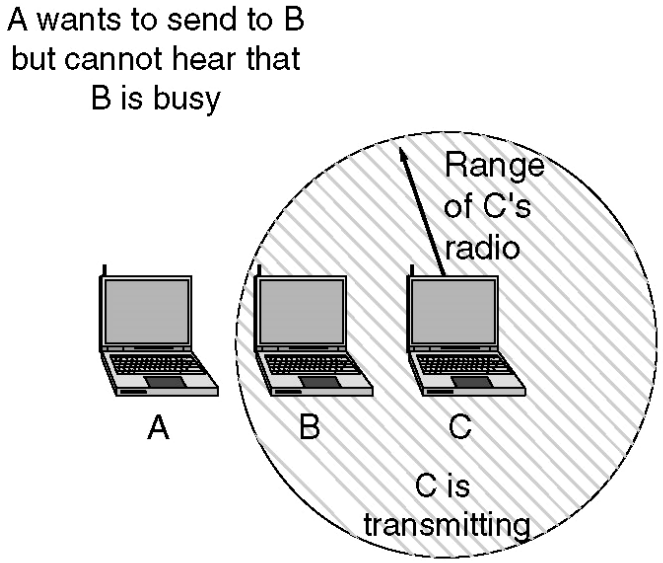
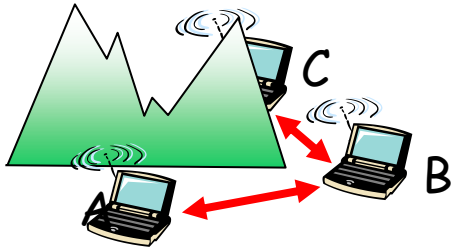
Hidden terminal problem (ad-hoc and WLAN)
- medium free near the transmitter
- medium not free near the receiver

=> Packet collision







Hidden Terminal Problem

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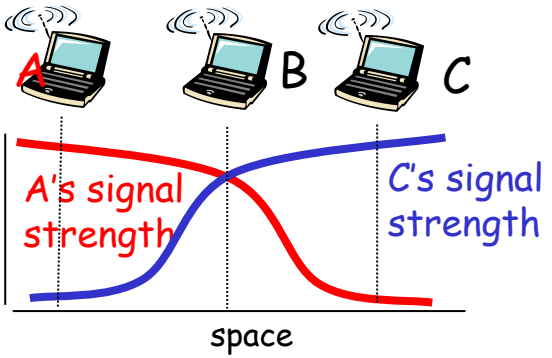
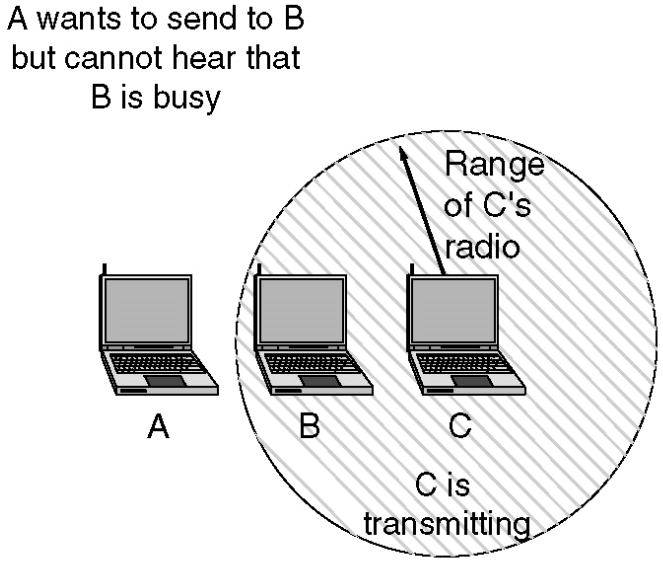
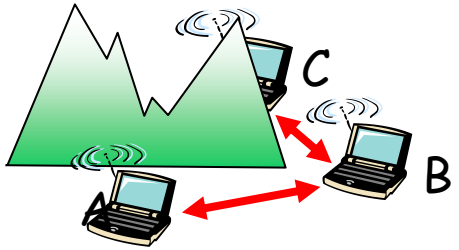
=> Packet collision

Possible solution:

- MAC scheme using RTS-CTS scheme







Avoiding collisions (more)

idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

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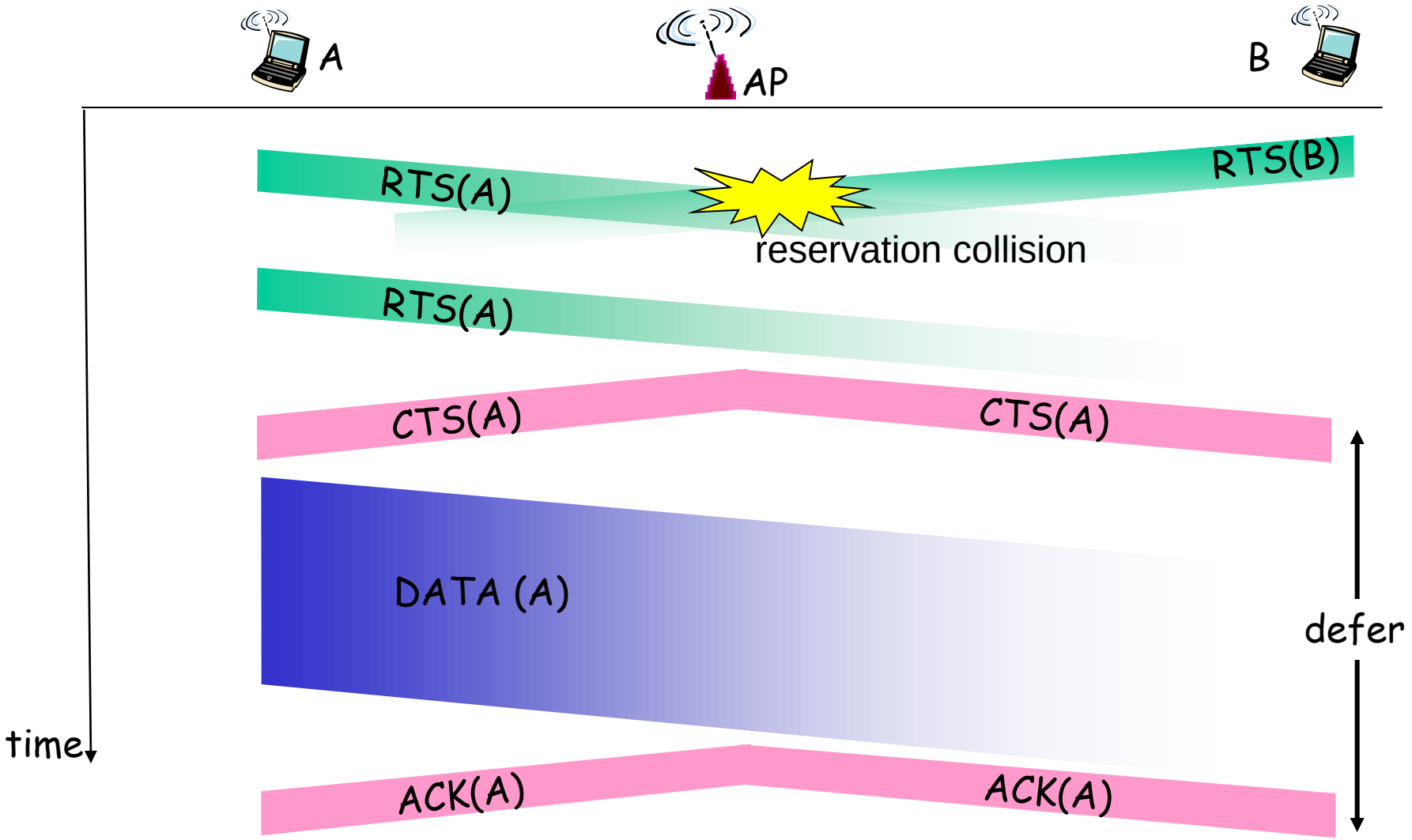
idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

- sender first transmits *small* request-to-send (RTS) packets to base station using CSMA
  - RTS may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS to host in response to RTS
- RTS heard by all nodes because of broadcast property
  - sender transmits (large) data frame
  - other stations defer transmissions until it is done

Avoid data frame collisions completely using small reservation packets!

Collision Avoidance: RTS-CTS exchange



Exposed Terminal Problems

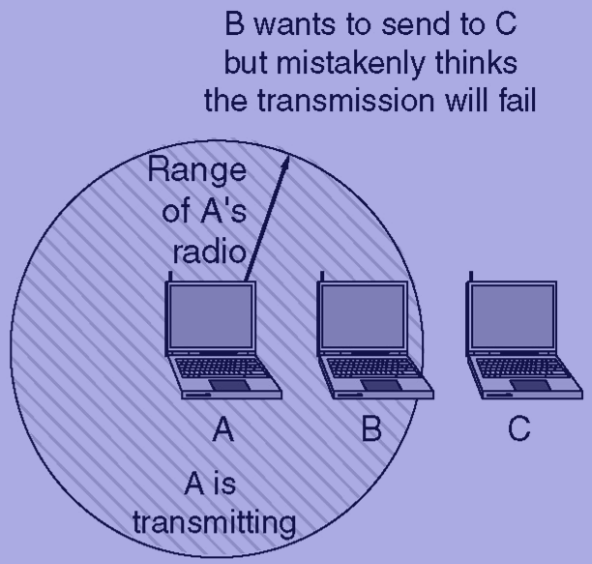
Exposed terminal problem - ad-hoc and WLAN

- medium free near the receiver
- medium busy near the transmitter

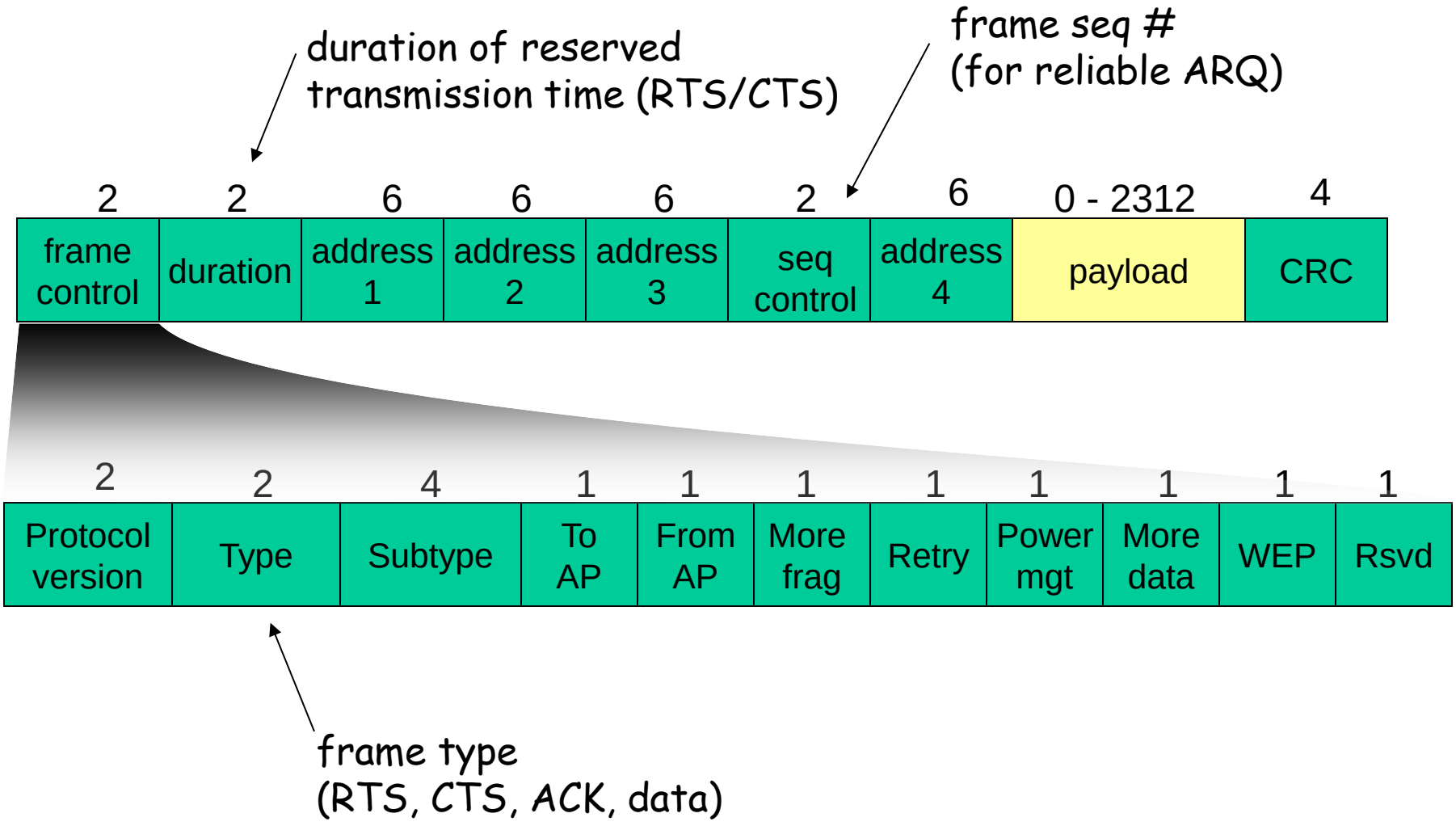
=> Waist of bandwidth

Possible solutions:

- directional antennas
- separate channels for control and data



802.11 frame: more



802.11: advanced capabilities

Power Management

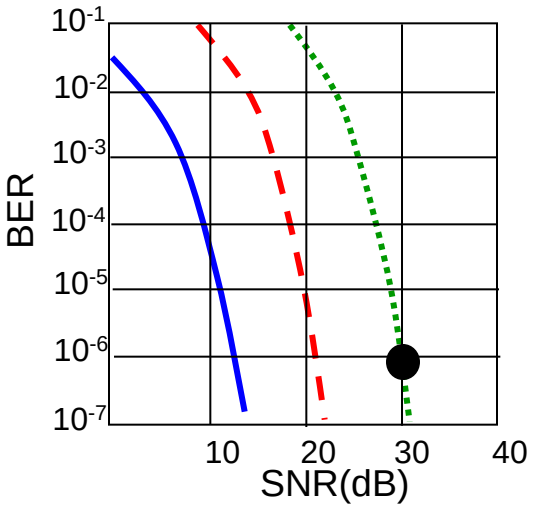
- node-to-AP: "I am going to sleep until next beacon frame"
  - AP knows not to transmit frames to this node
  - node wakes up before next beacon frame
- beacon frame: contains list of mobiles with AP-to-mobile frames waiting to be sent
  - Every 100ms (250μs wakeup time)
  - node will stay awake if AP-to-mobile frames to be sent; otherwise sleep again until next beacon frame
  - Explicit pull request

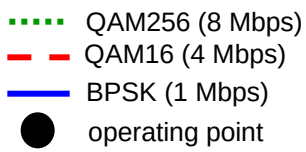
Note: Nodes with nothing to send/receive can save 99% of energy

802.11: advanced capabilities

Rate Adaptation

- base station, mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies



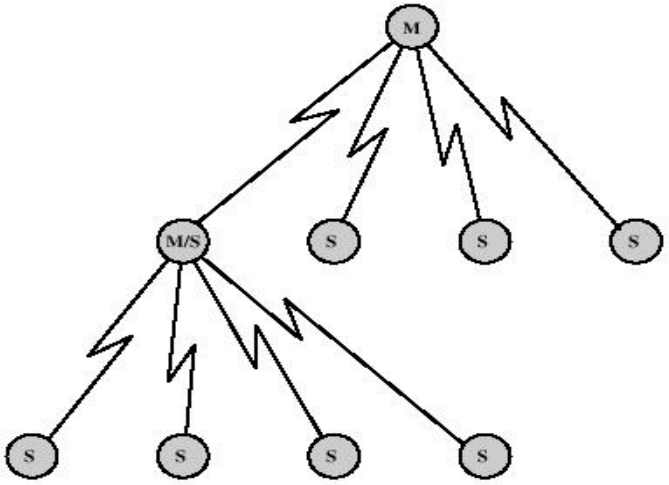


1. SNR decreases, BER increase as node moves away from base station

2. When BER becomes too high, switch to lower transmission rate but with lower BER

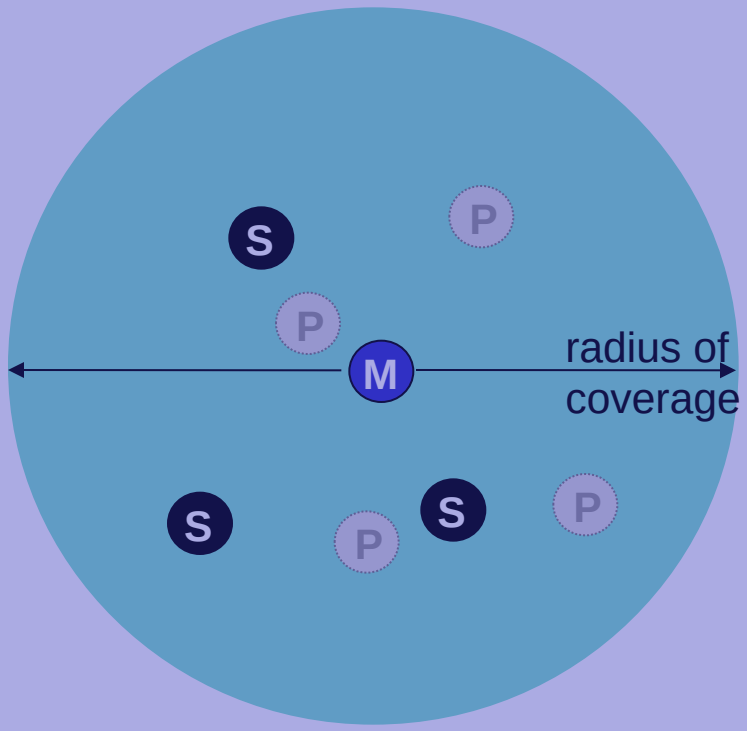
Bluetooth Networking: Piconets and Scatternets

- Bluetooth devices are organized in ***piconets***
  - Up to eight devices can be part of a piconet
- Devices are divided in ***master*** and ***slaves***
  - Master controls the utilization of the radio channel (e.g. frequency-hopping sequence and timing)
  - Slaves may communicate only with the master and when allowed by the master
- Several connected piconets is called a ***scatternet***
  - A device may belong to different piconets, and may be both a master and a slave in two different piconets



802.15: personal area network (PAN)

- less than 10 m diameter
- replacement for cables (mouse, keyboard, headphones)
- ad hoc: no infrastructure
- master/slaves:
  - slaves request permission to send (to master)
  - master grants requests
- 802.15: evolved from Bluetooth specification
  - 2.4-2.5 GHz radio band
  - up to 721 kbps



M Master device

S Slave device

P Parked device (inactive)

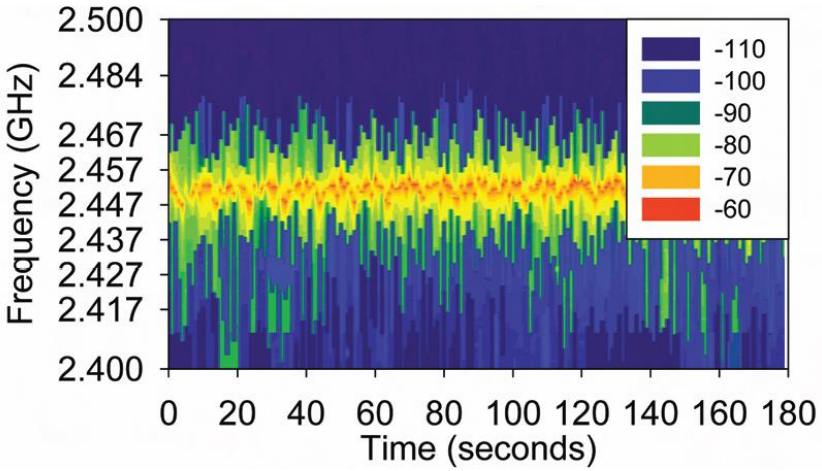
Two Popular 2.4 GHz Standards:

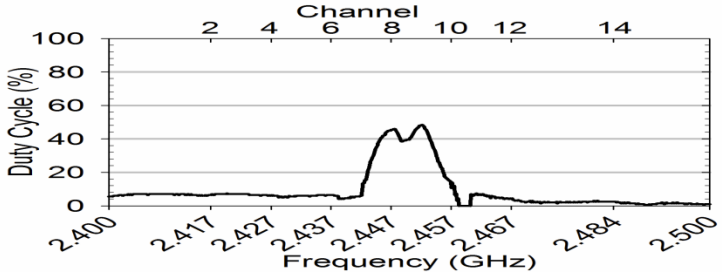
- IEEE 802.11 (WiFi)
  - Fast (11 Mbps)
  - High power
  - Long range
  - Single-purpose
  - Typically channel 1, 6, or 11
  - Ethernet replacement
  - Easily available
- Bluetooth
  - Slow (1 Mbps)
  - Low power
  - Short range
  - Flexible
  - Frequency hopping
  - Cable replacement (e.g., device-to-device)

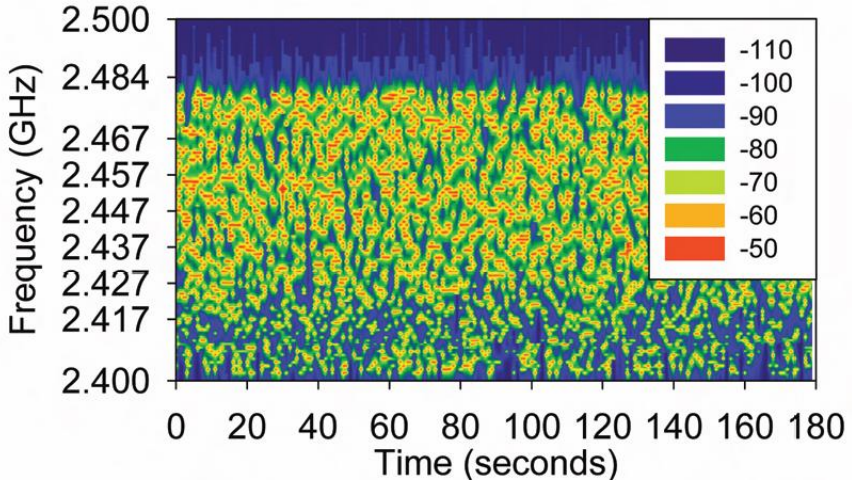
Interference example

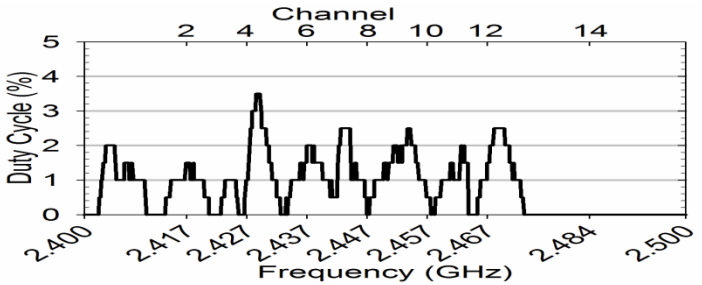
Measurements (Mahanti et al. 2010)

- Many devices and technologies sharing the medium



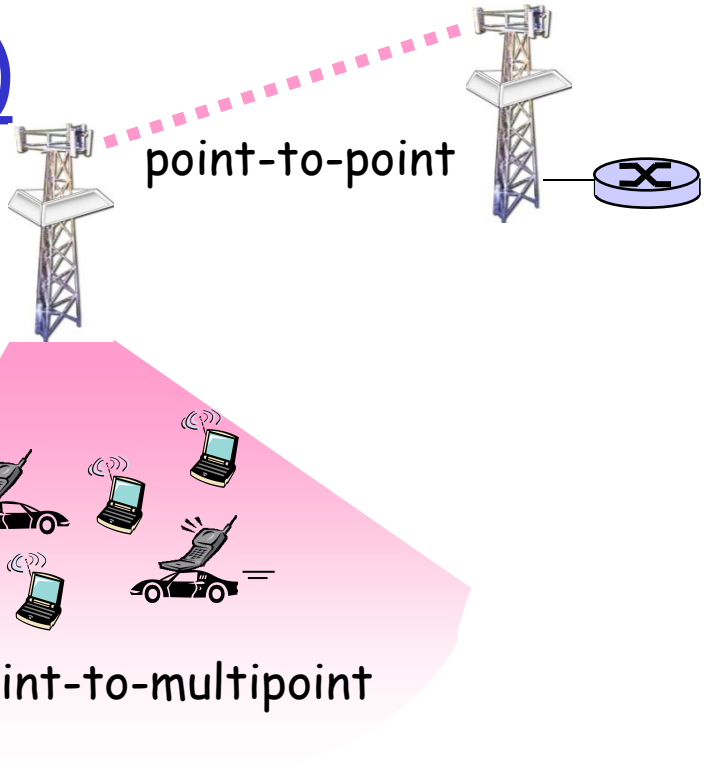


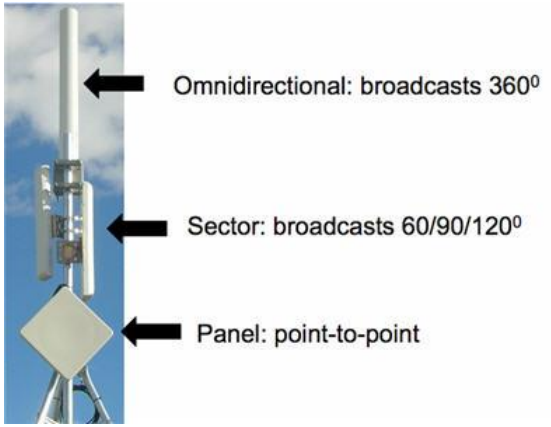




802.16: WiMAX (MAN)

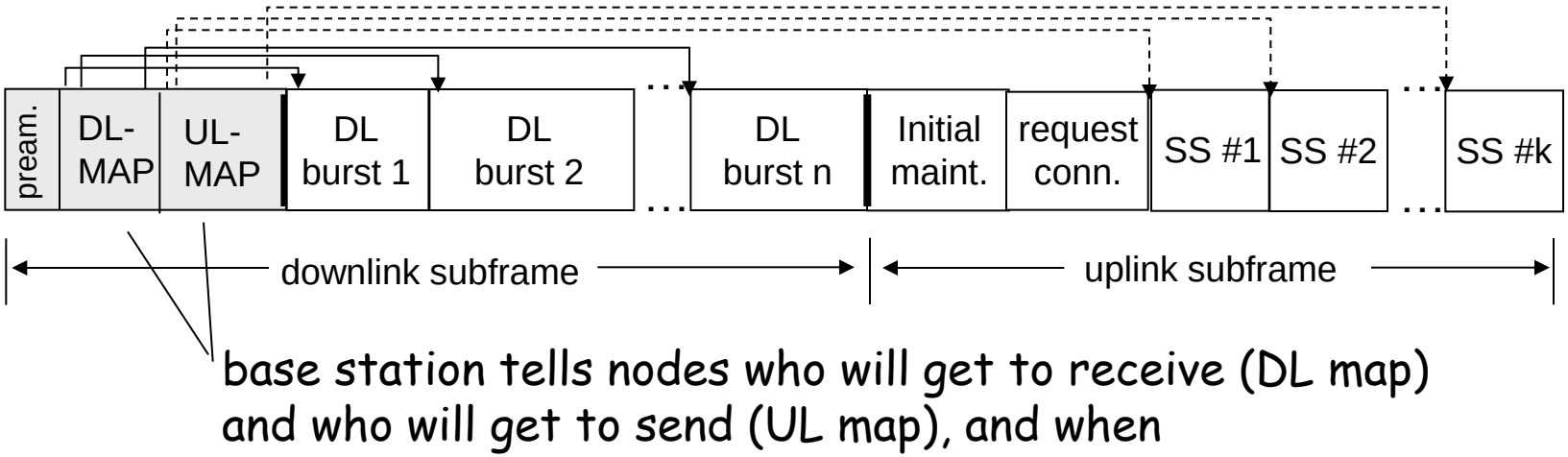
- like 802.11 & cellular: base station model
  - transmissions to/from base station by hosts with omnidirectional antenna
  - base station-to-base station backhaul with point-to-point antenna
- unlike 802.11:
  - range ~ 6 miles ("city rather than coffee shop")
  - ~14 Mbps





802.16: WiMAX: downlink, uplink scheduling

- transmission frame
  - down-link subframe: base station to node
  - uplink subframe: node to base station



- WiMAX standard provide mechanism for scheduling, but not scheduling algorithm

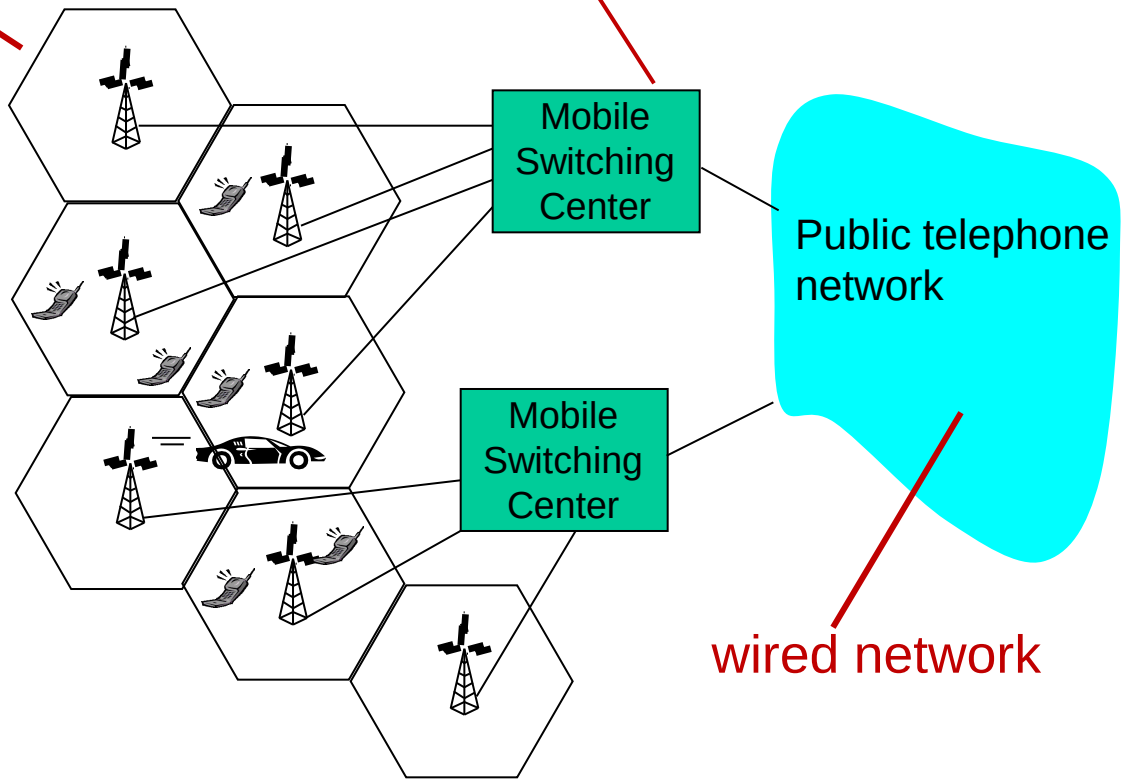
Background: Cellular network technology

- Overview
  - 1G: Analog voice (no global standard …)
  - 2G: Digital voice (again … GSM vs. CDMA)
  - 3G: Digital voice and data
    - Again … UMTS (WCDMA) vs. CDMA2000 (both CDMA-based)
    - and … 2.5G: EDGE (GSM-based)
  - 4G: LTE, LTE-Advanced (IP-based only) …
    - OFDM (OFDMA for downlink and SC-OFDM for uplink)
- Trends
  - More data, packet-based switching, shared channel, directional (spatial reuse), multi-antenna, etc.
  - Other goals: Seamless with other technologies, QoS for multimedia, etc.

Components of cellular network architecture

MSC
- connects cells to wired tel. net.
- manages call setup (more later!)
- handles mobility (more later!)

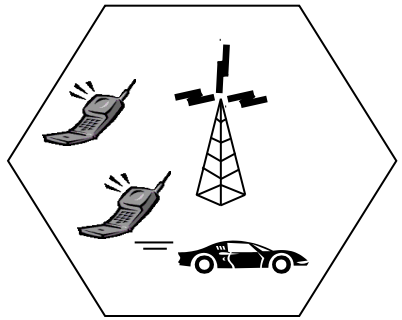
cell
- covers geographical region
- *base station* (BS) analogous to 802.11 AP
- *mobile users* attach to network through BS
- *air-interface:* physical and link layer protocol between mobile and BS

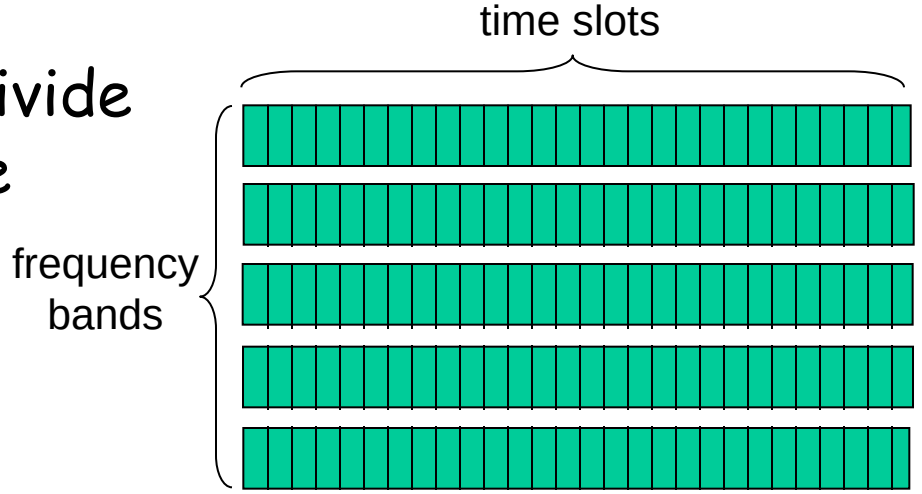


Cellular networks: the first hop

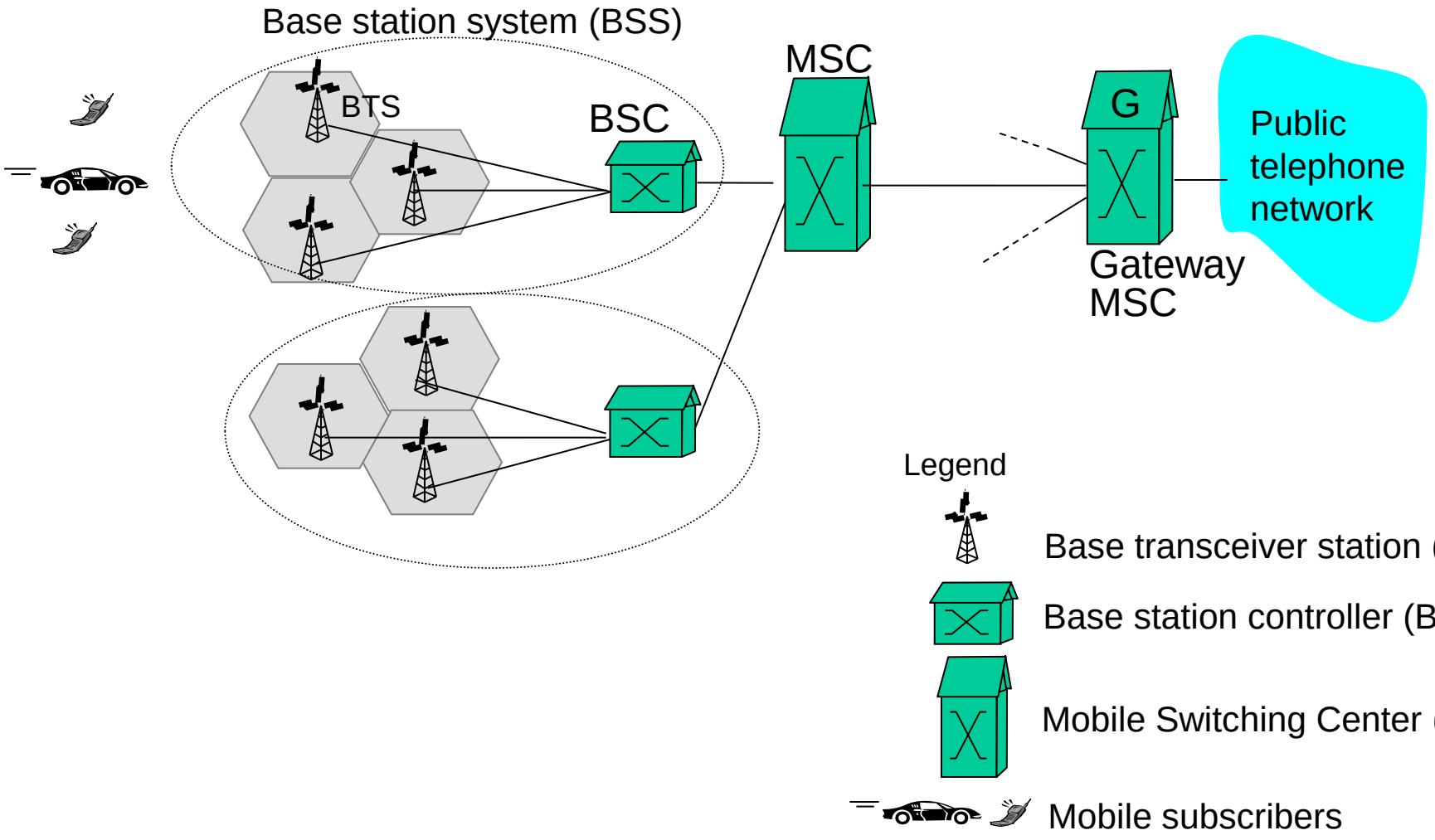
Techniques for sharing mobile-to-BS radio spectrum

- combined FDMA/TDMA: divide spectrum in frequency channels, divide each channel into time slots
- CDMA: code division multiple access
- SDMA: space division multiple access

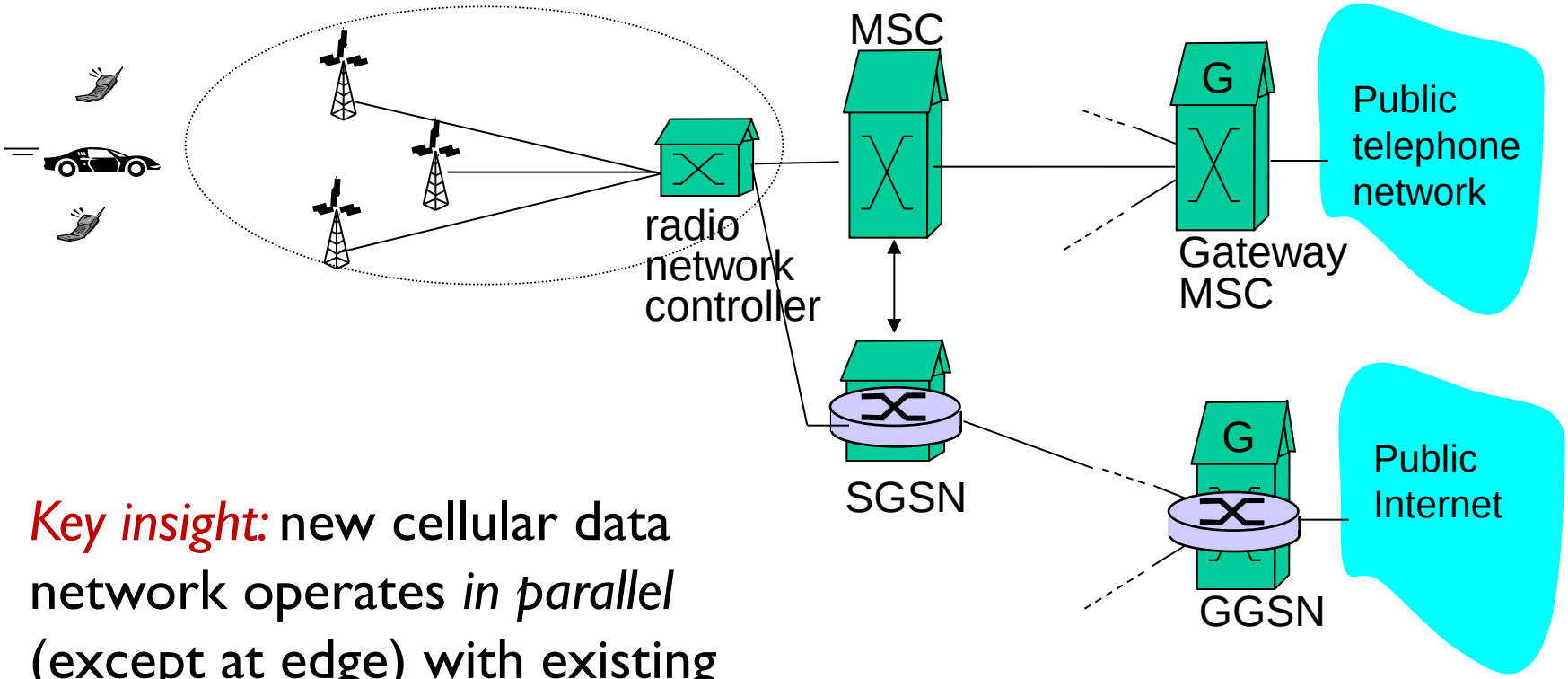




2G (voice) network architecture



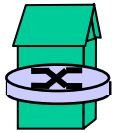
3G (voice+data) network architecture



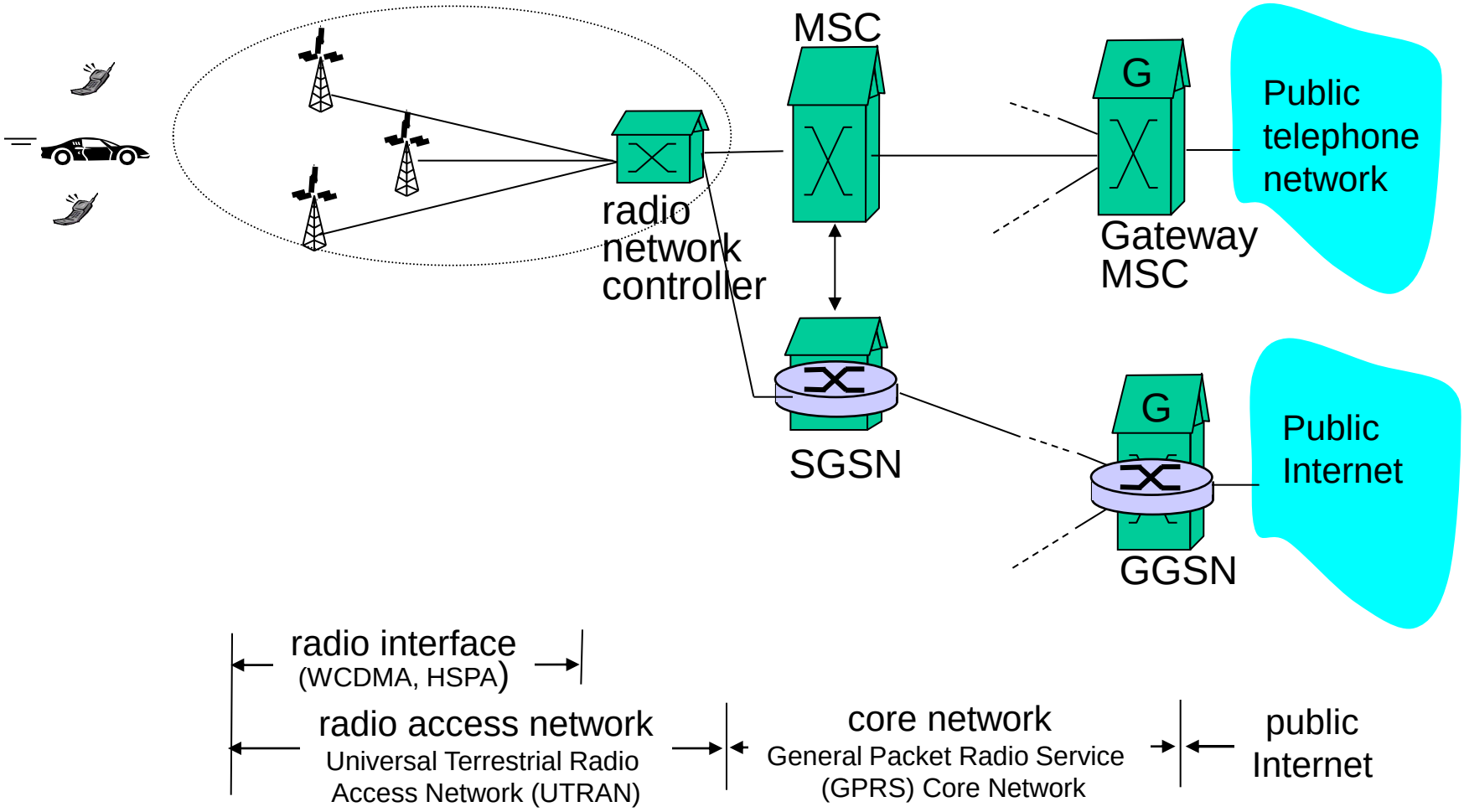
Key insight: new cellular data network operates *in parallel* (except at edge) with existing cellular voice network

- voice network unchanged in core
- data network operates in parallel

Serving GPRS Support Node (SGSN)


Gateway GPRS Support Node (GGSN)

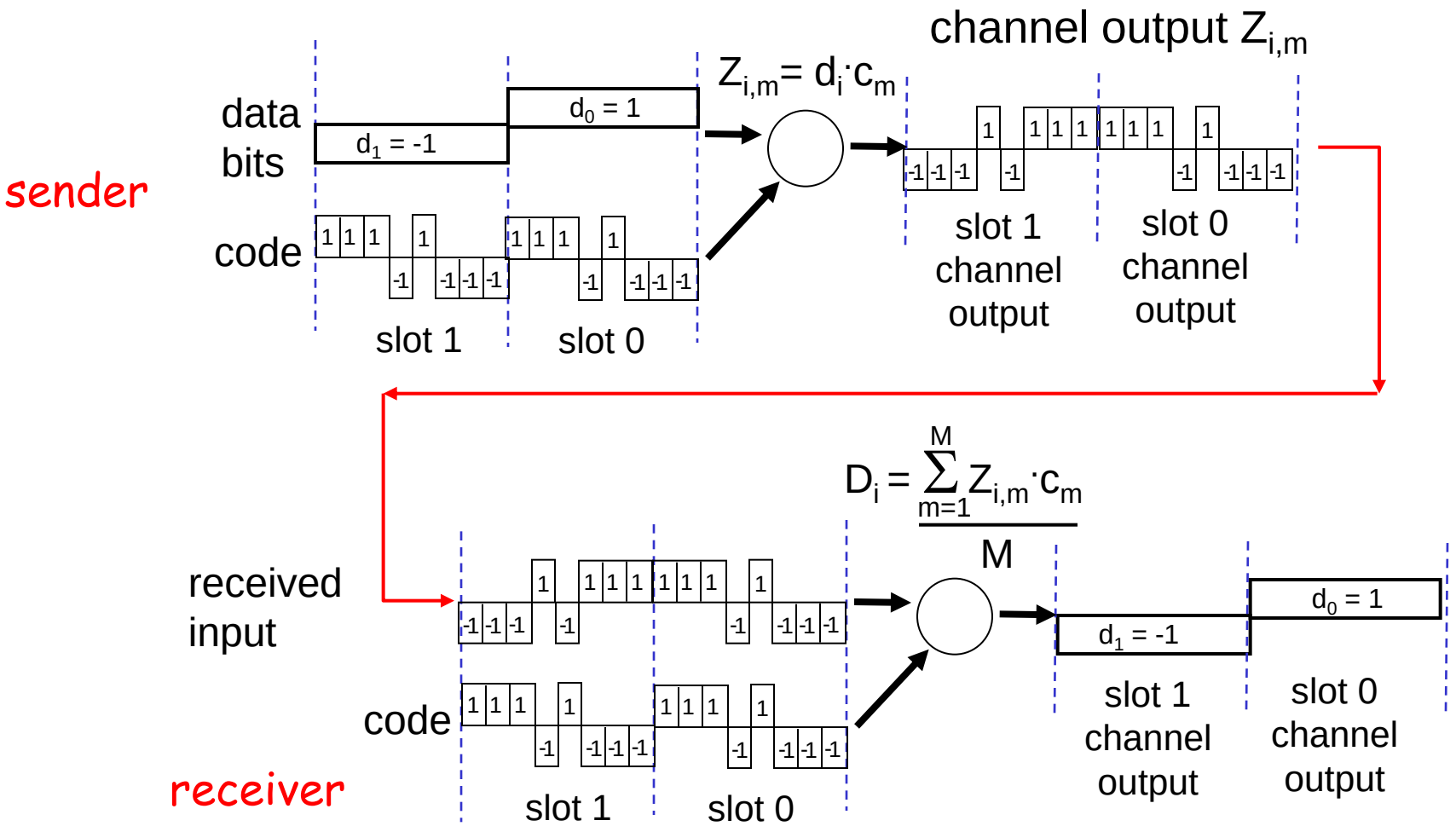
3G (voice+data) network architecture



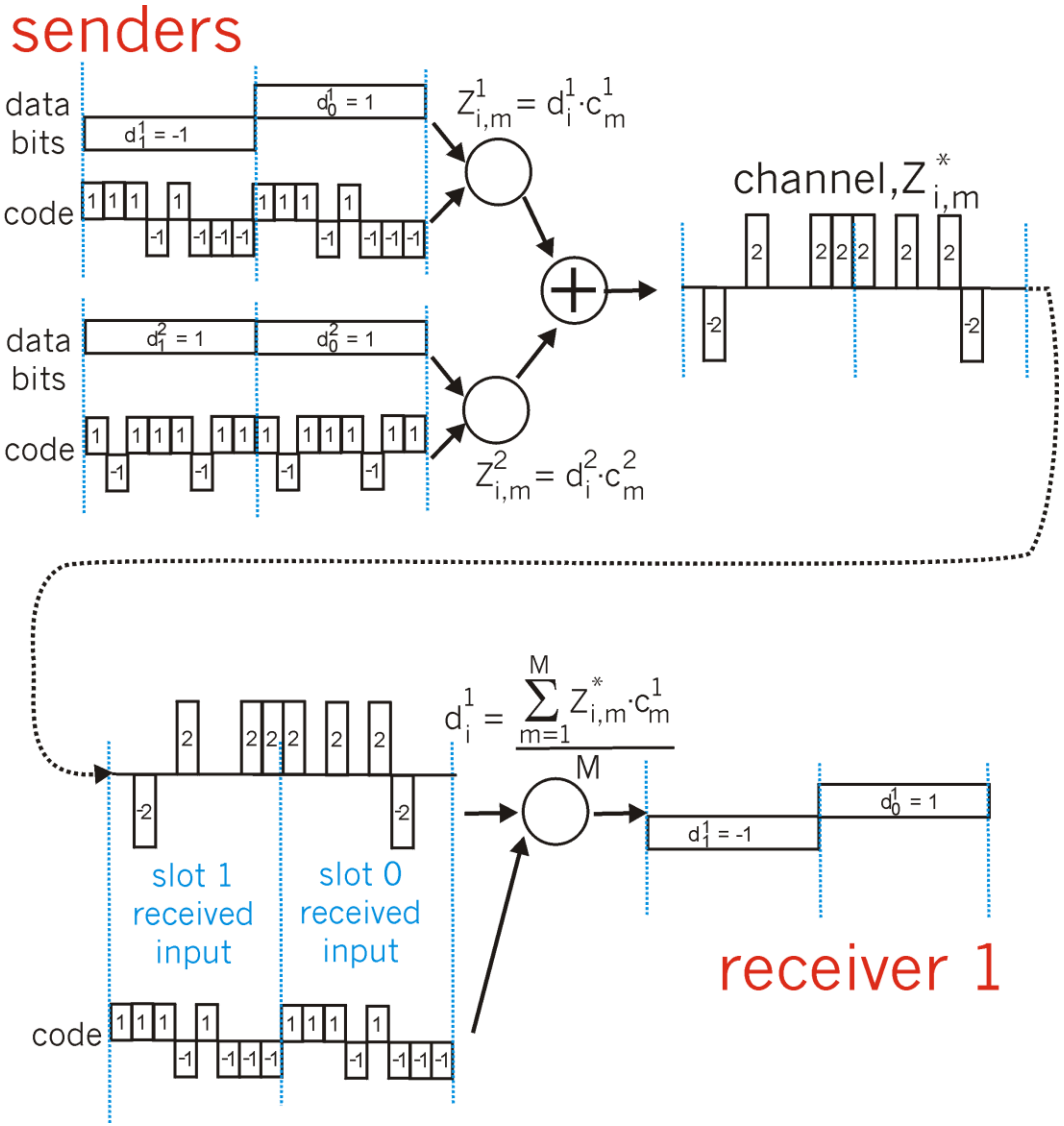
Code Division Multiple Access (CDMA)

- used in several wireless broadcast channels (cellular, satellite, etc) standards
- unique "code" assigned to each user; i.e., code set partitioning
- all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence
- allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")

CDMA Encode/Decode



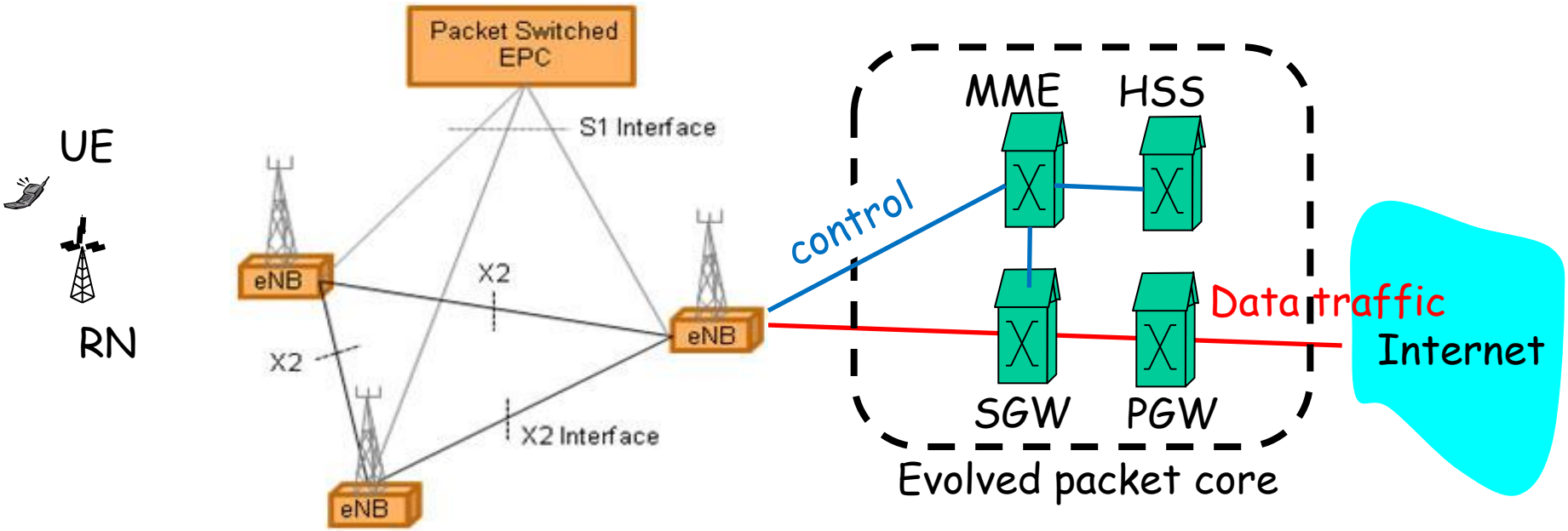
CDMA: two-sender interference



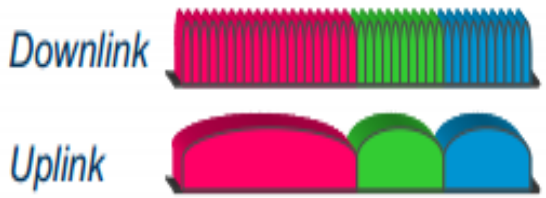
Practical chipping codes …

- Orthogonal even under offset?
  - No synchronization …
  - Random sequence; high probability low cross-correlation
- Different chip lengths?
  - different rates, take advantage of silence, more calls

LTE and LTE-Advanced



- All traffic is IP-based
  - VOLTE (or 2G/3G offloading) for voice
- Base station called enhanced NodeB, eNodeB or eNB
  - Downlink: OFDMA
  - Uplink: SC-OFDM



LTE downlink (OFDMA-based)

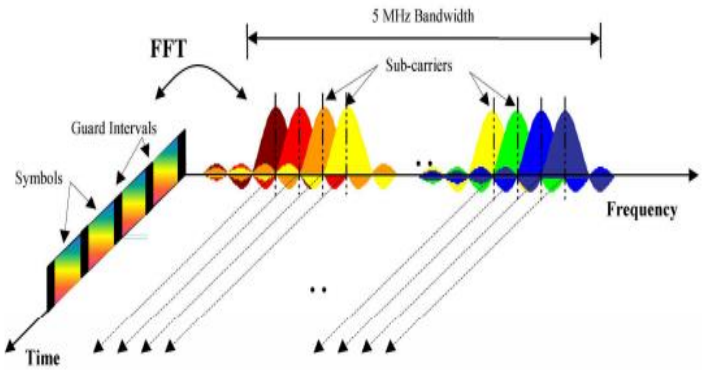
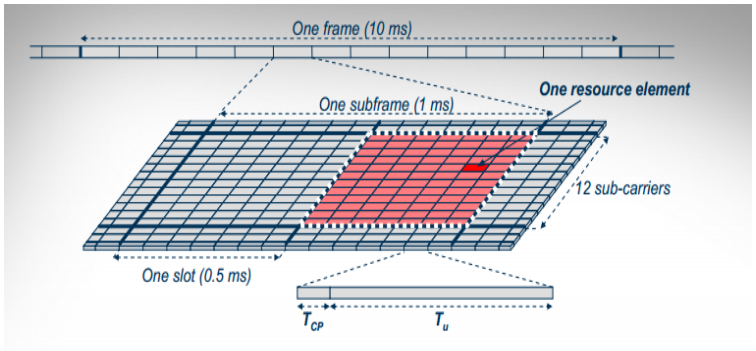
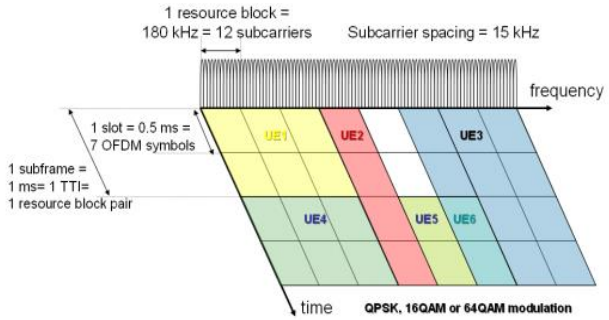


Figure from:
3GPP TR 25.892; Feasibility Study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement (Release 6)

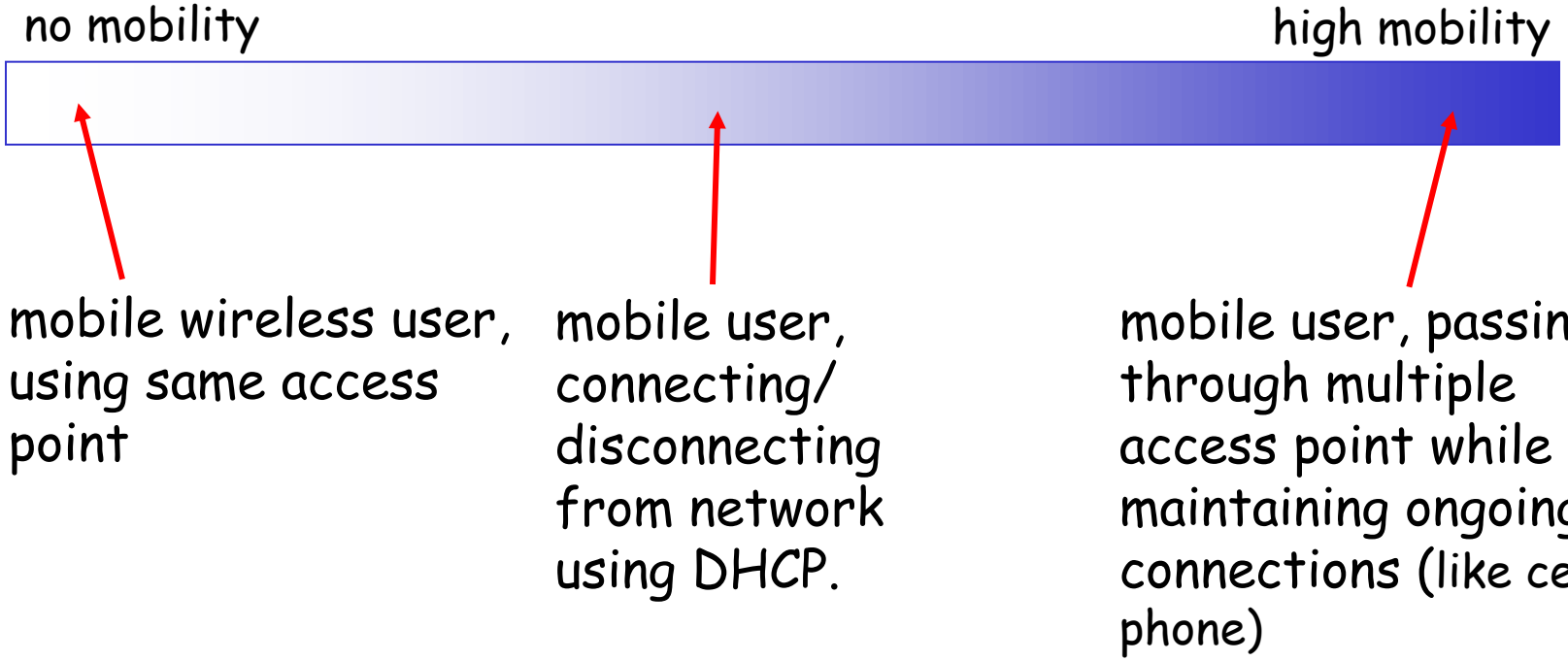




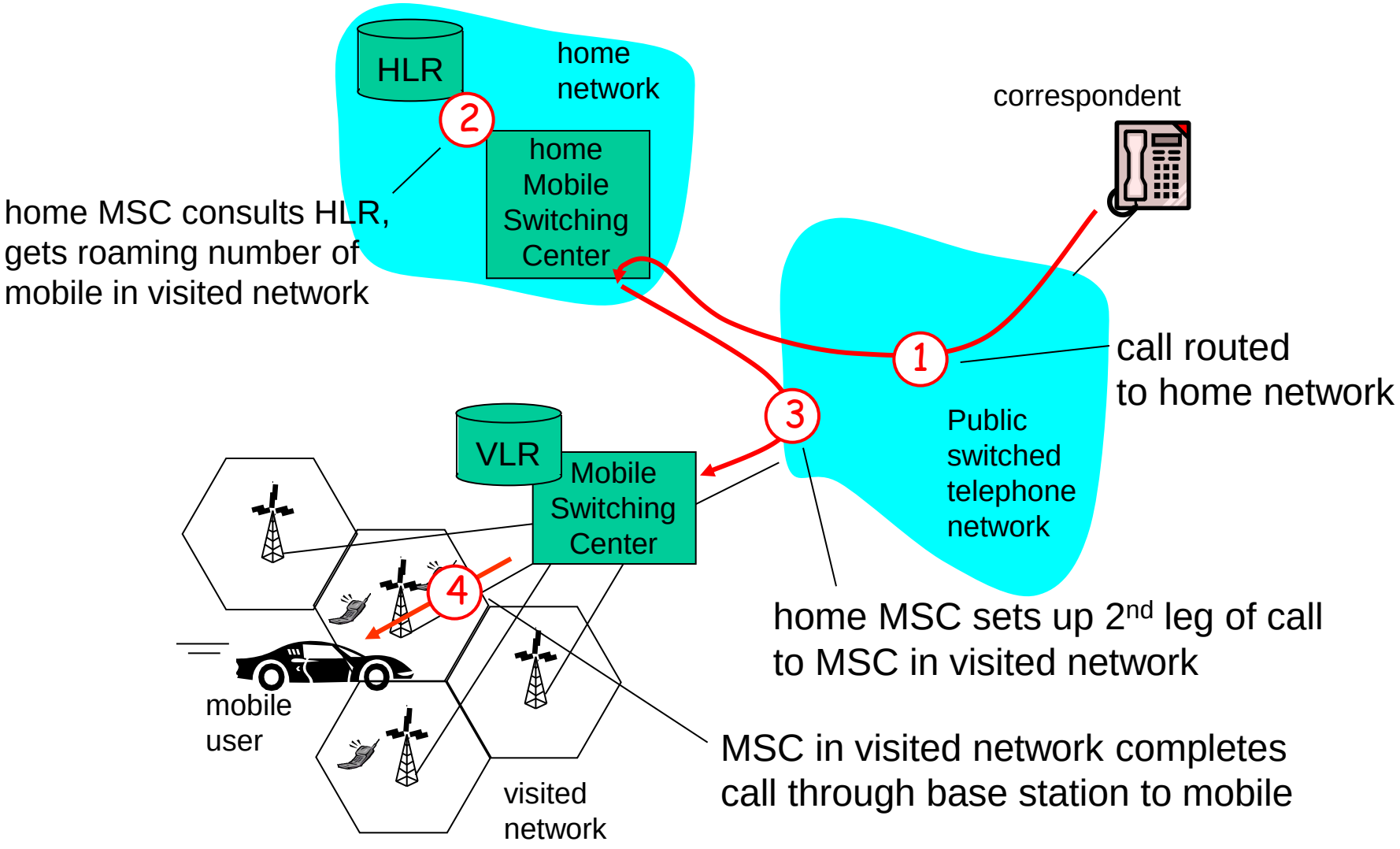
- Data symbols are independently modulated and transmitted over a high number of closely spaced orthogonal subcarriers.
- Resource block (RB): 12 subcarriers during one slot (180 kHz × 0.5 ms)
- Vendor specific scheduling decisions done in the base station, typically taking account
  - Radio link quality situation of different users
  - Overall interference situation
  - Quality of Service requirements
  - Service priorities, etc.

What is mobility?

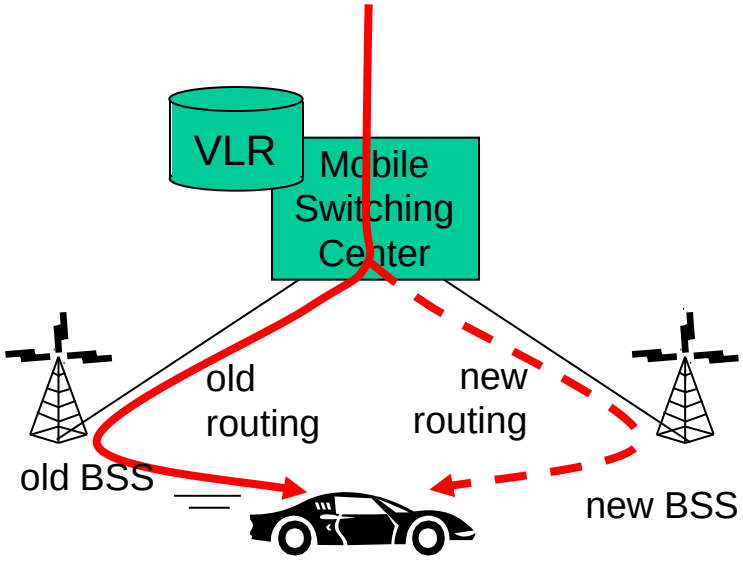
- spectrum of mobility, from the *network* perspective:



GSM: indirect routing to mobile

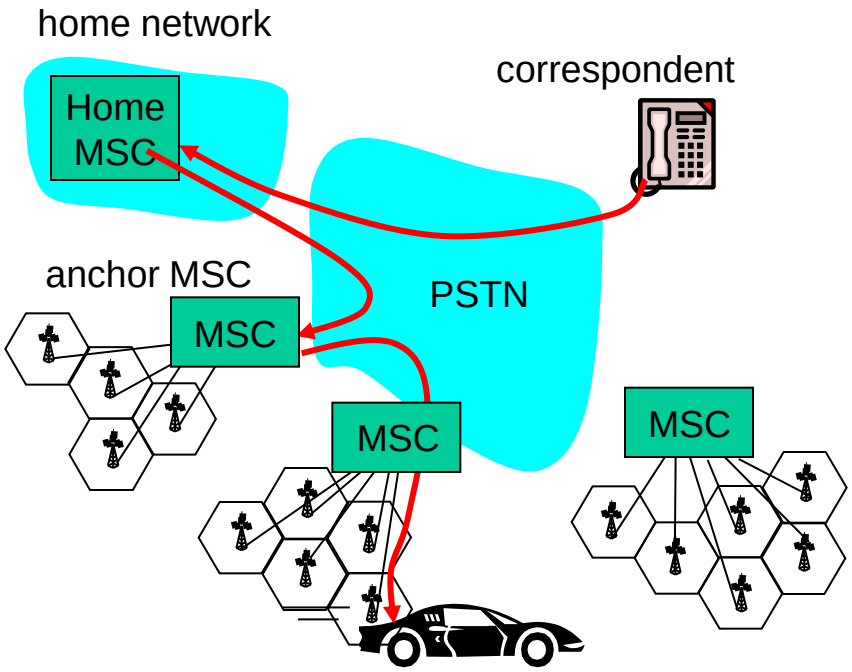


GSM: handoff with common MSC



- Handoff goal: route call via new base station (without interruption)

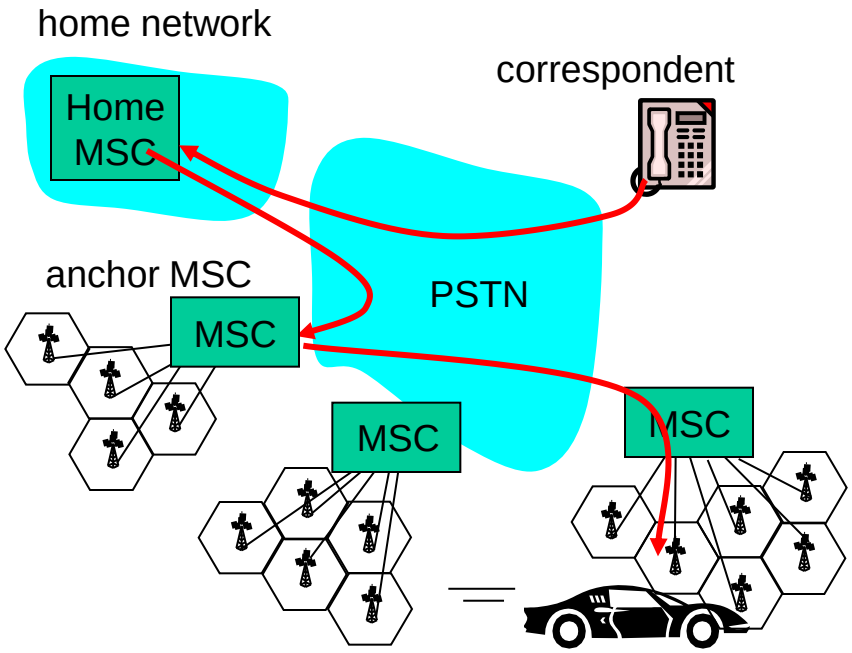
GSM: handoff between MSCs



(a) before handoff

- *anchor MSC:* first MSC visited during call
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain

GSM: handoff between MSCs



(b) after handoff

- *anchor MSC:* first MSC visited during call
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain

More slides …

Components of cellular network architecture

MSC
- connects cells to wide area net
- manages call setup (more later!)
- handles mobility (more later!)

cell
- covers geographical region
- *base station* (BS) analogous to 802.11 AP
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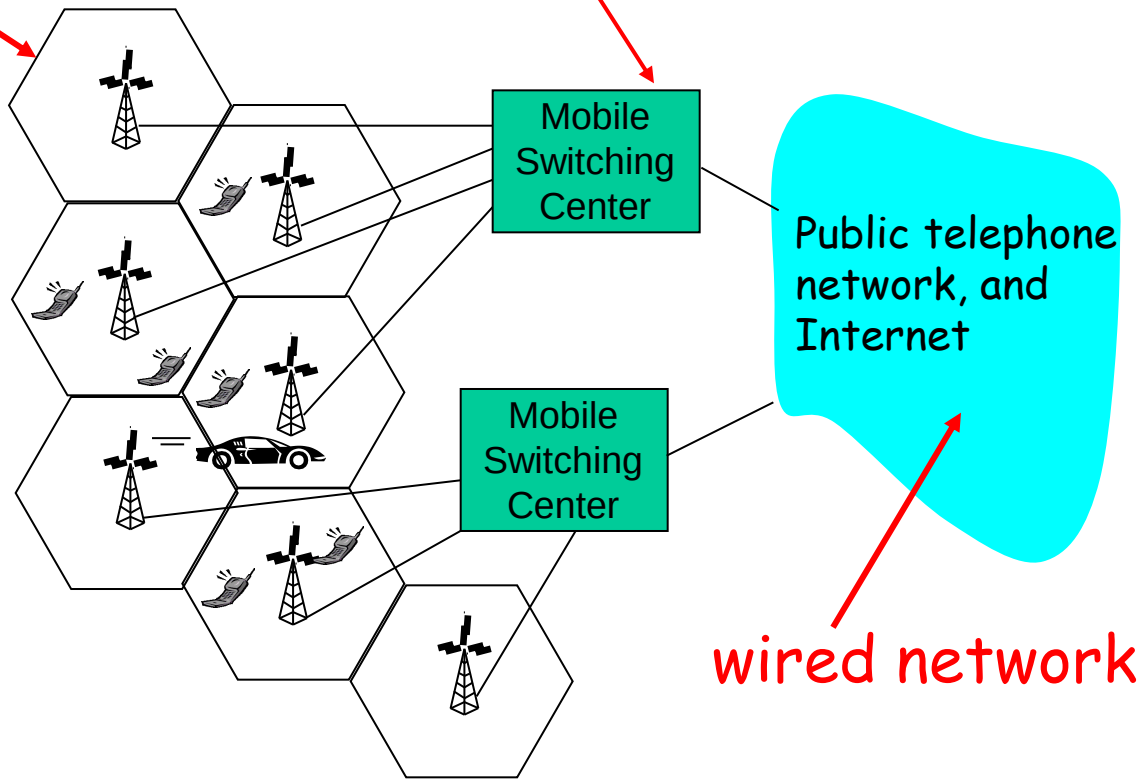
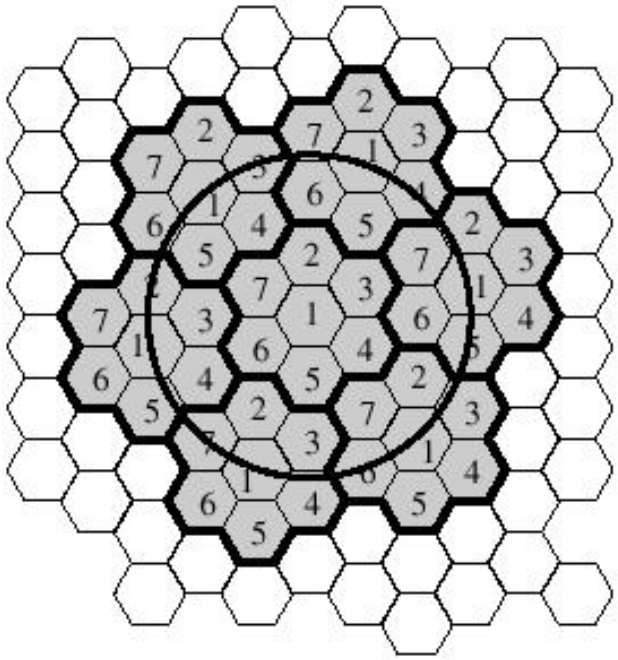


Components of cellular networks, cont'd

- Frequency reuse: use the same frequency spectrum in different set of cells
- Cells that reuse the same frequency must be distant enough for avoiding interference
- Transmission power control
- Migration of a mobile station from one cell to another with continuance of communication -> *handoff*



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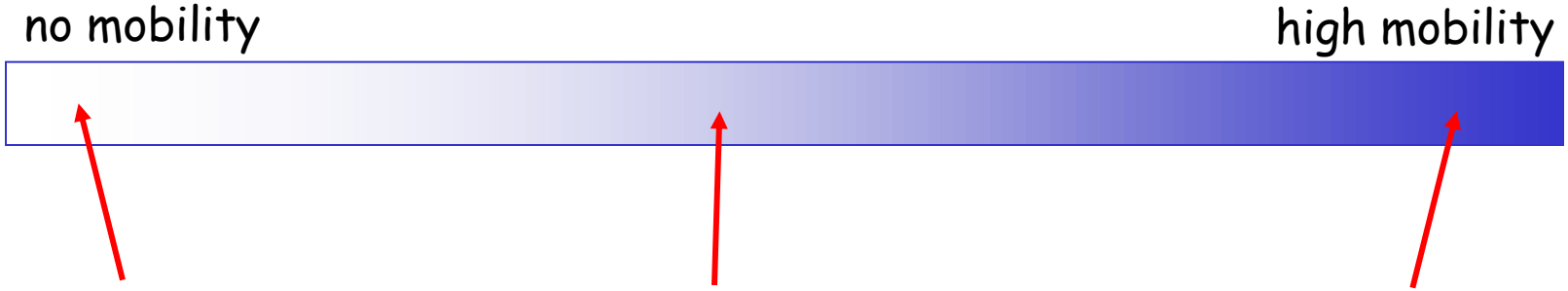


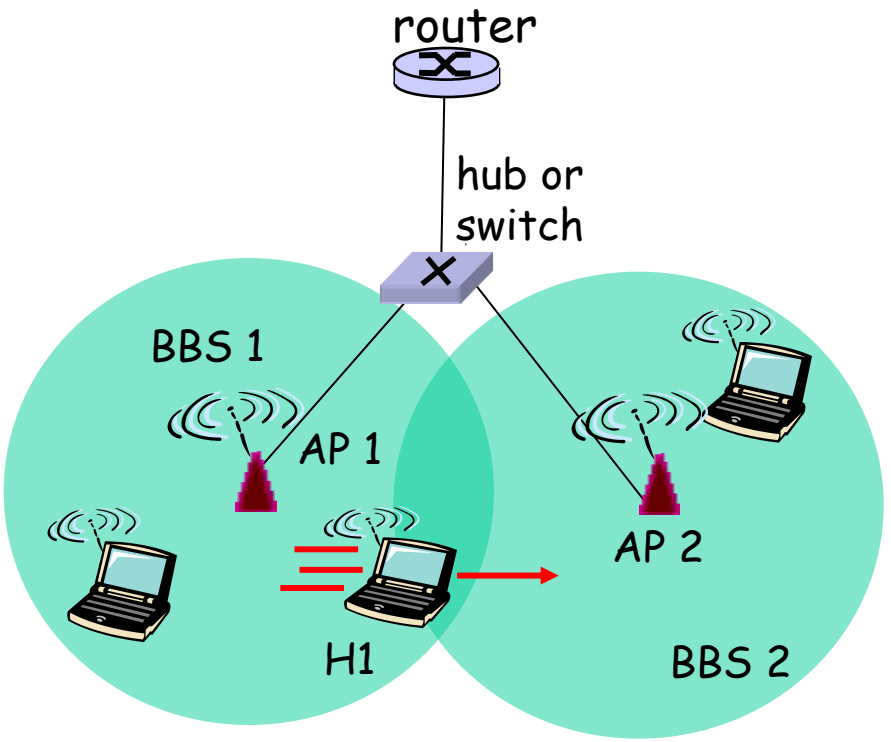
mobile wireless user, using same access point

mobile user, connecting/ disconnecting from network using DHCP.

mobile user, passing through multiple access point while maintaining ongoing connections (like cell phone)

802.11: mobility within same subnet

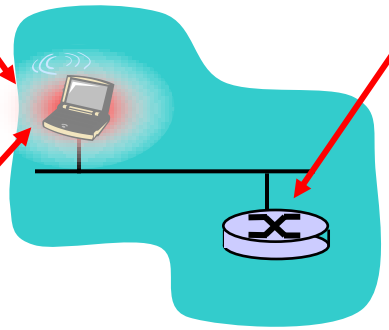
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - self-learning (Ch. 5): switch will see frame from H1 and "remember" which switch port can be used to reach H1

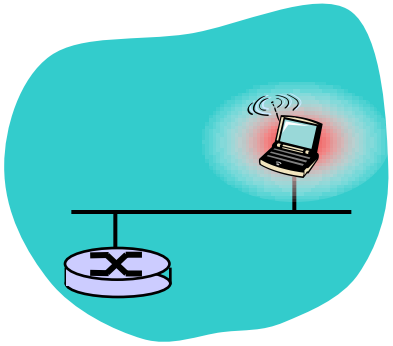


Mobility: Vocabulary

home network: permanent "home" of mobile (e.g., 128.119.40/24)

home agent: *entity that will perform mobility functions on behalf of mobile, when mobile is remote*





wide area network

permanent address: address in home network, *can always* be used to reach mobile e.g., 128.119.40.186

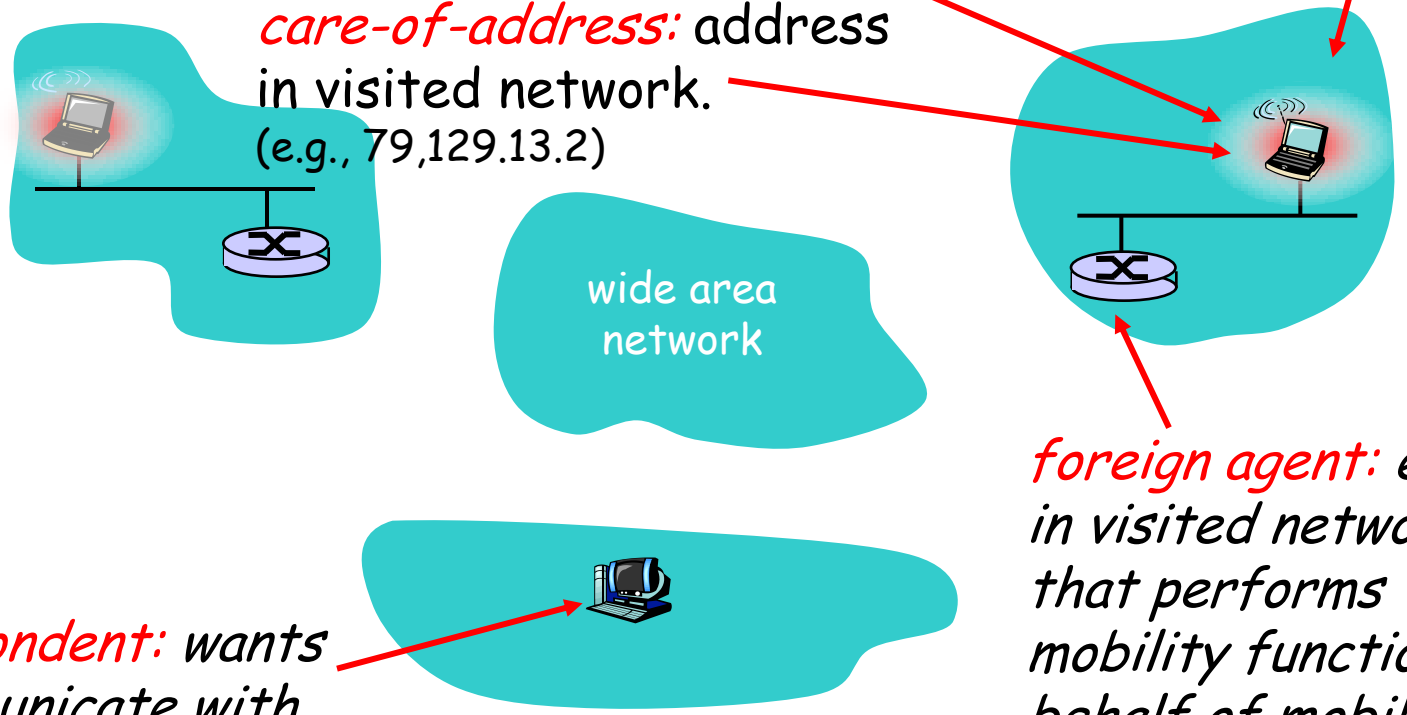
correspondent

Mobility: more vocabulary

permanent address: remains constant (e.g., 128.119.40.186)

visited network: network in which mobile currently resides (e.g., 79.129.13/24)

care-of-address: address in visited network. (e.g., 79,129.13.2)



foreign agent: *entity in visited network that performs mobility functions on behalf of mobile.*

correspondent: *wants to communicate with mobile*

How do *you* contact a mobile friend:

Consider friend frequently changing addresses, how do you find her?

- search all phone books?
- call her parents?
- expect her to let you know where he/she is?

Mobility: approaches

- *Let routing handle it:* routers advertise permanent address of mobile-nodes-in-residence via usual routing table exchange.
  - routing tables indicate where each mobile located
  - no changes to end-systems
- *Let end-systems handle it:*
  - *indirect routing:* communication from correspondent to mobile goes through home agent, then forwarded to remote
  - *direct routing:* correspondent gets foreign address of mobile, sends directly to mobile

Mobility: approaches

- *Let routing handle it:* routers advertise permanent address of mobile-nodes in visited network via usual routing table exchange.
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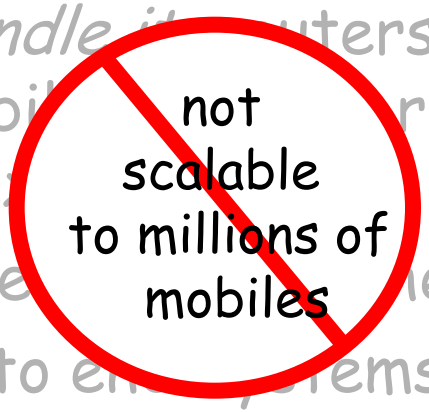

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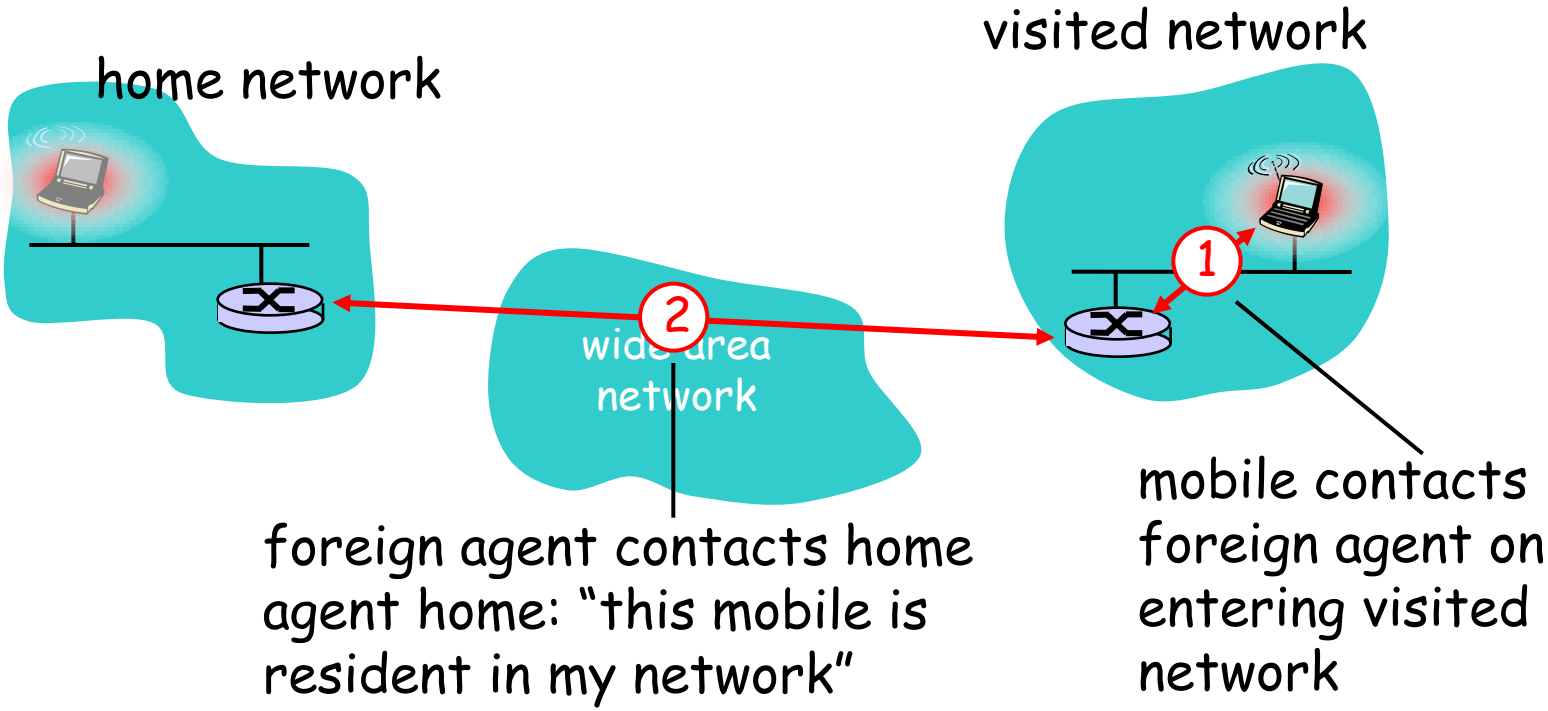
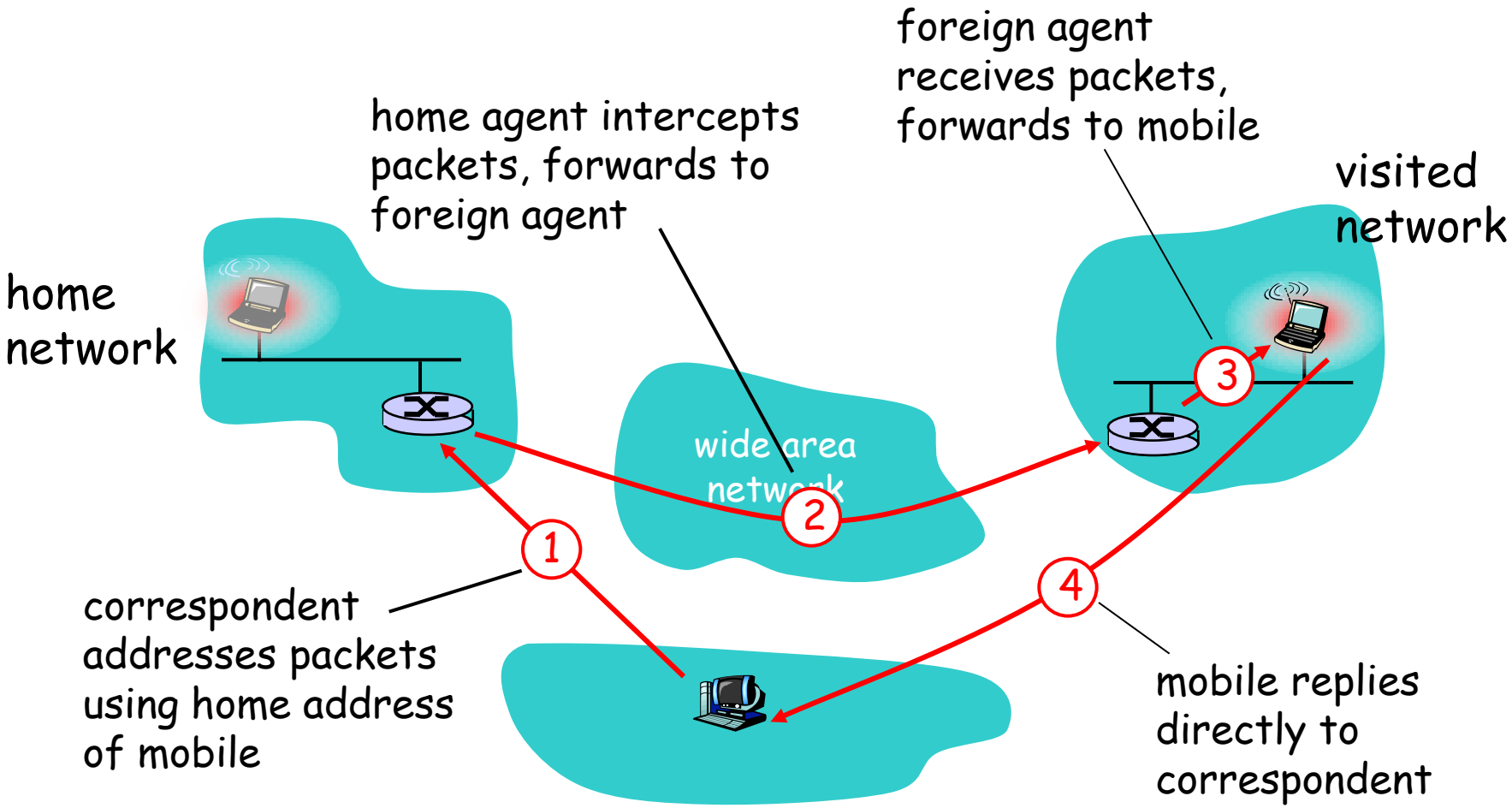
Mobility: registration



End result:

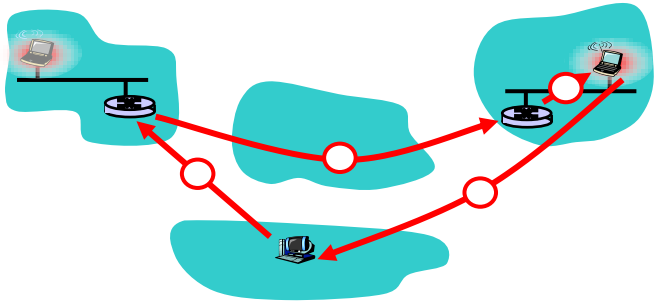
- Foreign Agent (FA) knows about mobile
- Home Agent (HA) knows location of mobile

Mobility via Indirect Routing



Indirect Routing: comments

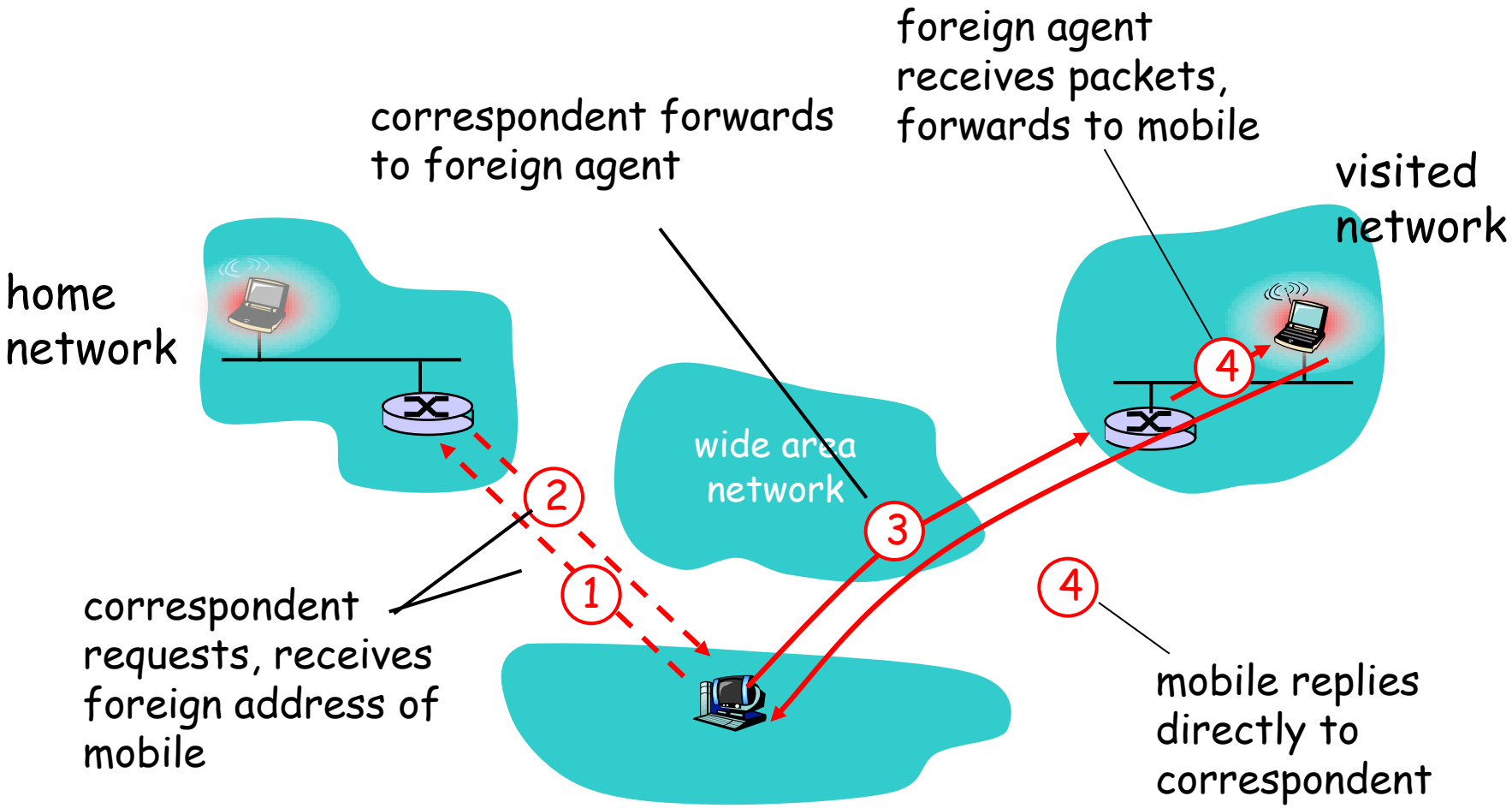
- Mobile uses two addresses:
  - permanent address: used by correspondent (hence mobile location is *transparent* to correspondent)
  - care-of-address: used by home agent to forward datagrams to mobile
- foreign agent functions may be done by mobile itself
- triangle routing: correspondent-home-network-mobile
  - inefficient when correspondent, mobile are in same network



Indirect Routing: moving between networks

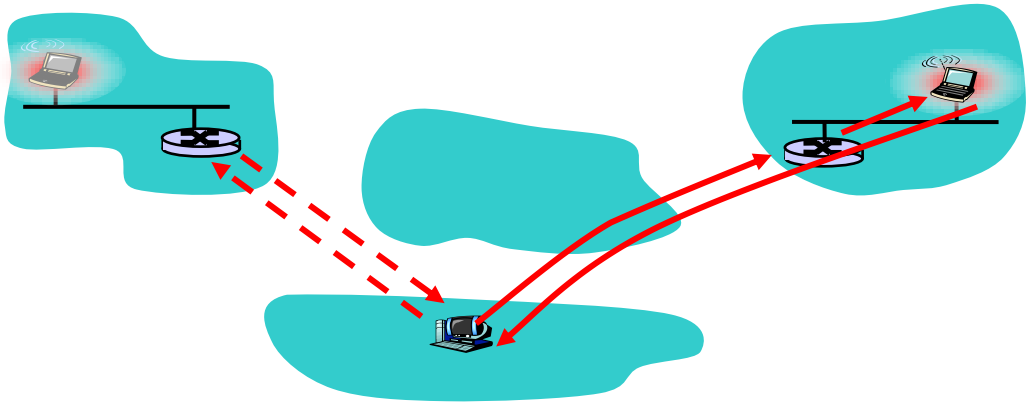
- suppose mobile user moves to another network
  - registers with new foreign agent
  - new foreign agent registers with home agent
  - home agent update care-of-address for mobile
  - packets continue to be forwarded to mobile (but with new care-of-address)
- mobility, changing foreign networks transparent: *ongoing connections can be maintained!*

Mobility via Direct Routing



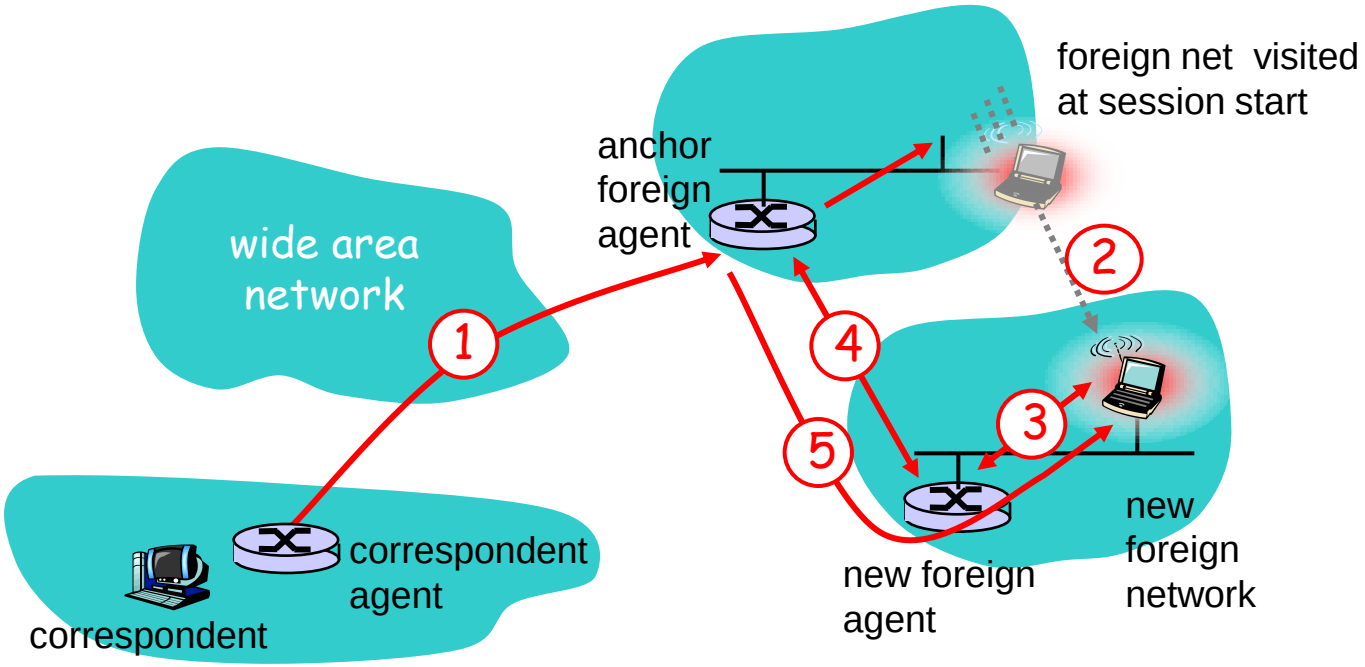
Mobility via Direct Routing: comments

- overcome triangle routing problem
- non-transparent to correspondent: correspondent must get care-of-address from home agent
  - what if mobile changes visited network?



Accommodating mobility with direct routing

- anchor foreign agent: FA in first visited network
- data always routed first to anchor FA
- when mobile moves: new FA arranges to have data forwarded from old FA (chaining)



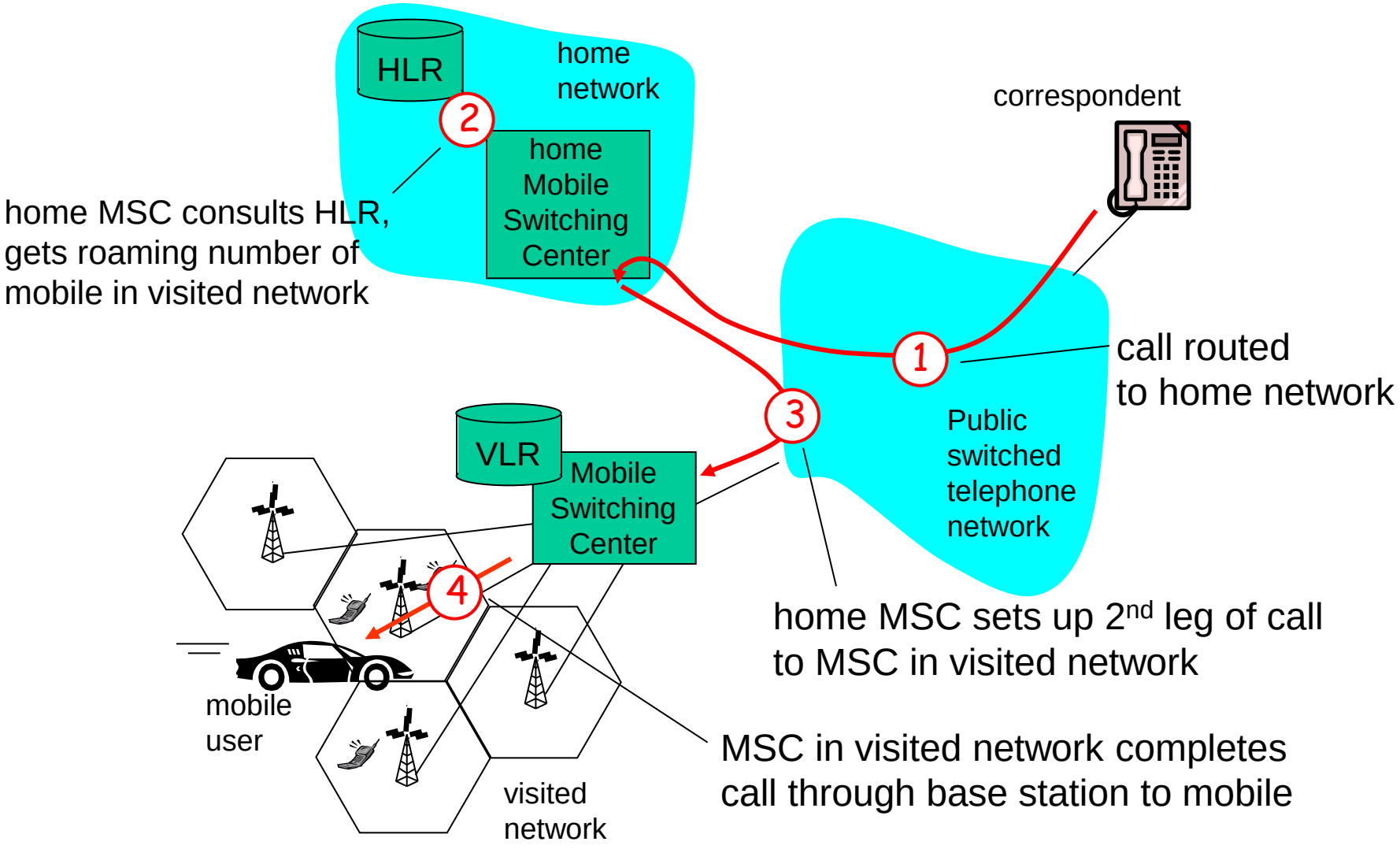
Mobile IP

- RFC 3220
- has many features we've seen:
  - home agents, foreign agents, foreign-agent registration, care-of-addresses, encapsulation (packet-within-a-packet)
- three components to standard:
  - indirect routing of datagrams
  - agent discovery
  - registration with home agent

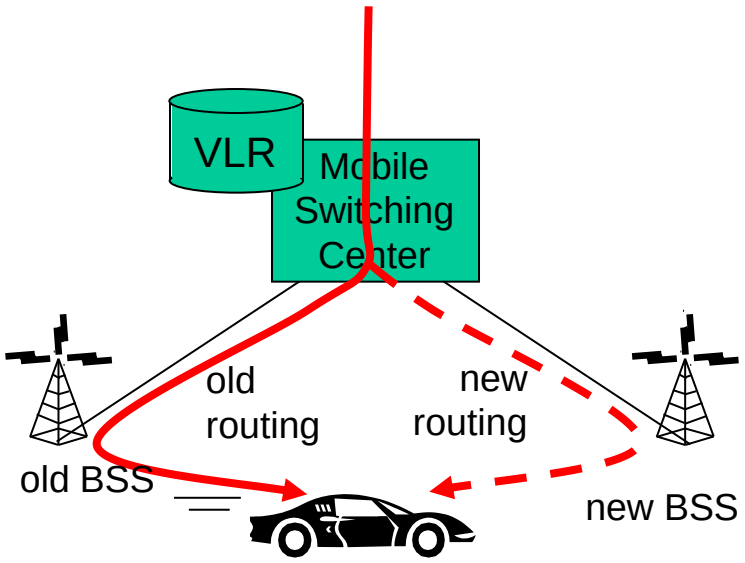
Handling mobility in cellular networks

- *home network:* network of cellular provider you subscribe to (e.g., Sprint PCS, Verizon)
  - *home location register (HLR):* database in home network containing permanent cell phone #, profile information (services, preferences, billing), information about current location (could be in another network)
- *visited network:* network in which mobile currently resides
  - *visitor location register (VLR):* database with entry for each user currently in network
  - could be home network

GSM: indirect routing to mobile

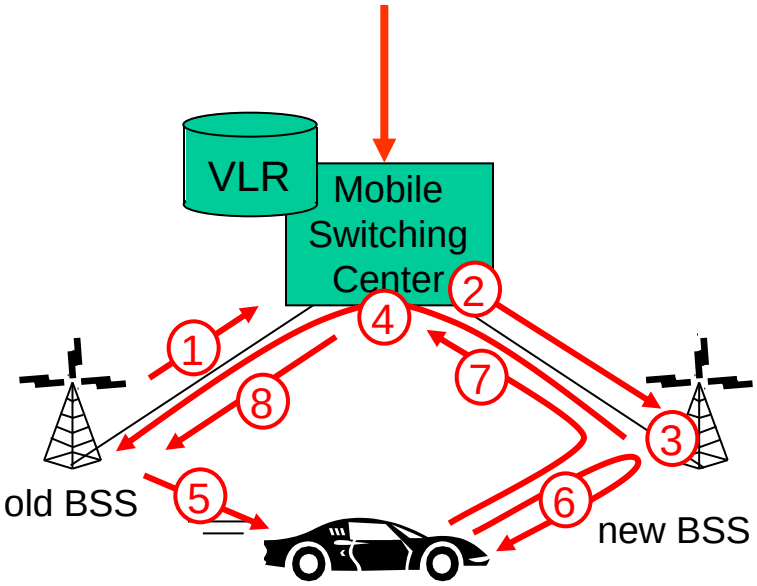


GSM: handoff with common MSC



- Handoff goal: route call via new base station (without interruption)
- reasons for handoff:
  - stronger signal to/from new BSS (continuing connectivity, less battery drain)
  - load balance: free up channel in current BSS
  - GSM doesn't mandate why to perform handoff (policy), only how (mechanism)
- handoff initiated by old BSS

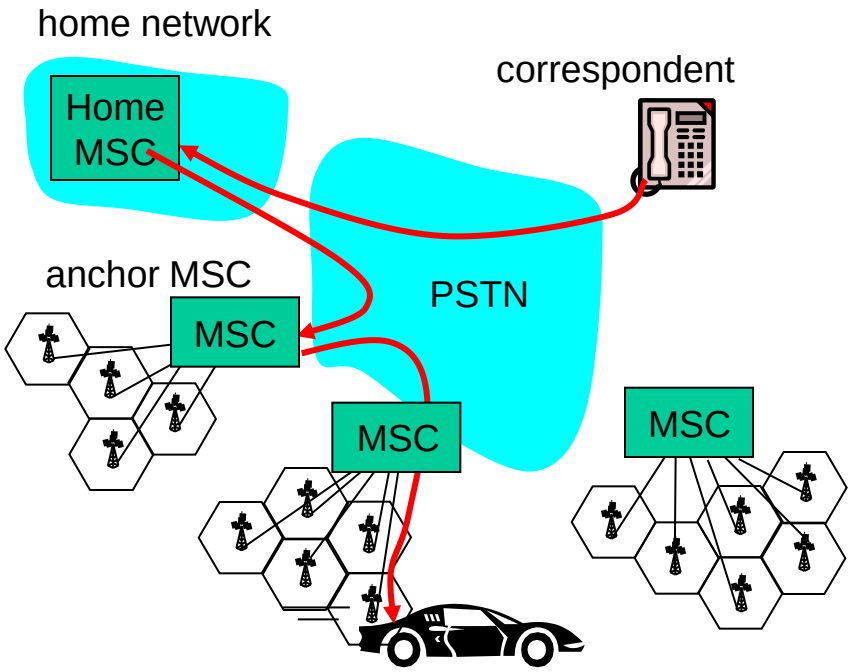
GSM: handoff with common MSC



1. old BSS informs MSC of impending handoff, provides list of 1^+ new BSSs
2. MSC sets up path (allocates resources) to new BSS
3. new BSS allocates radio channel for use by mobile
4. new BSS signals MSC, old BSS: ready
5. old BSS tells mobile: perform handoff to new BSS
6. mobile, new BSS signal to activate new channel
7. mobile signals via new BSS to MSC: handoff complete. MSC reroutes call

8 MSC-old-BSS resources released

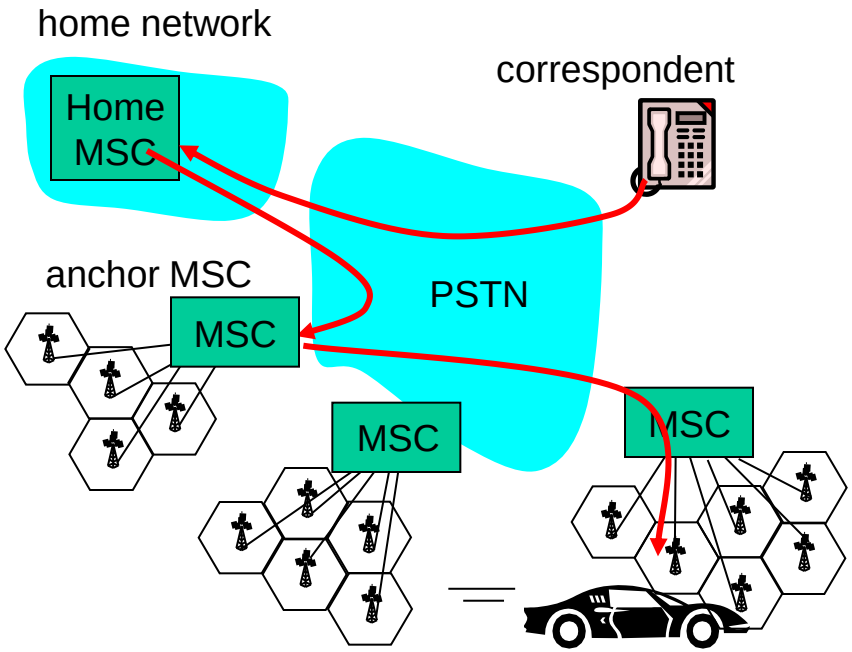
GSM: handoff between MSCs



(a) before handoff

- *anchor MSC:* first MSC visited during cal
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain

GSM: handoff between MSCs



(b) after handoff

- *anchor MSC:* first MSC visited during cal
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain

More slides …

Wireless Networking Technologies

- Mobile devices – laptop, PDA, cellular phone, wearable computer, sensors, …
- Operating modes
  - Infrastructure mode (Access Point (AP))
  - Ad hoc mode
- Access technology
  - Bluetooth (1 Mbps, up to 3m)
  - IEEE 802.11 (up to 54 Mbps, 20 – 100m)

Chapter 6: Wireless and Mobile Networks

Background:

- # wireless (mobile) phone subscribers now exceeds # wired phone subscribers!

- # wireless Internet-connected devices soon to exceed # wireline Internet-connected devices