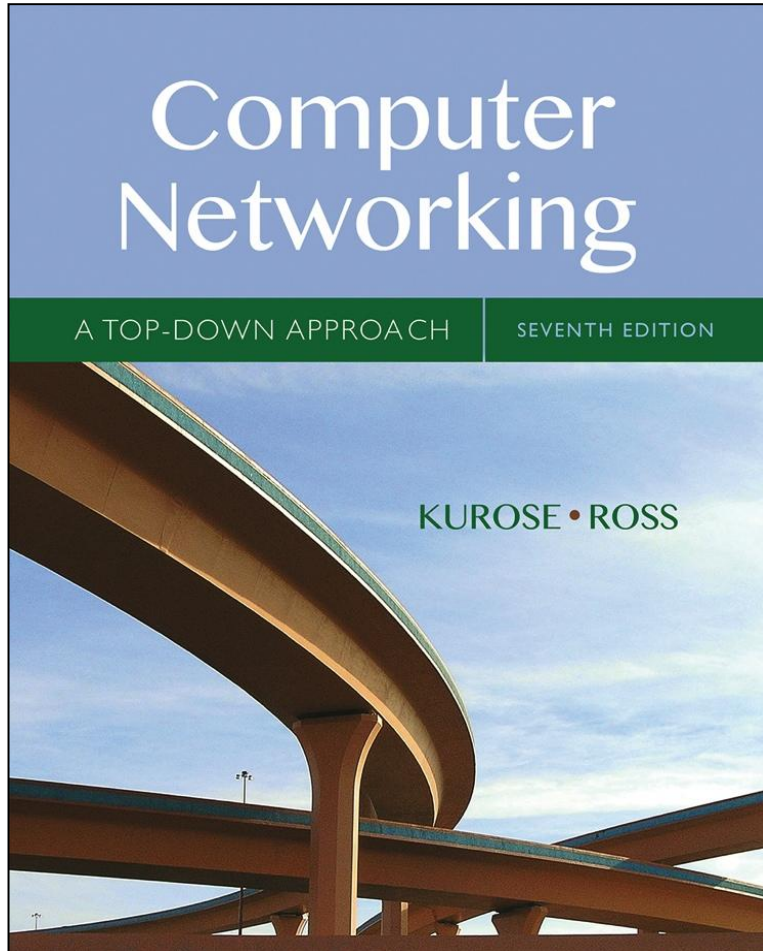# Computer Networking: A Top Down Approach

Seventh Edition

Chapter 7

Wireless and Mobile Networks

Wireless and Mobile Networks

Background:

- # wireless (mobile) phone subscribers now exceeds # wired phone subscribers (5-to-1)!

- # wireless Internet-connected devices equals # wireline Internet-connected devices
    - laptops, Internet-enabled phones promise anytime untethered Internet access

- two important (but different) challenges
    - **wireless:** communication over wireless link
    - **mobility:** handling the mobile user who changes point of attachment to network

Learning Objectives

7.1 **Introduction**

Wireless

7.2 Wireless links, characteristics

– CDMA

7.3 IEEE 802.11 wireless LANs ("Wi-Fi")

7.4 Cellular Internet Access
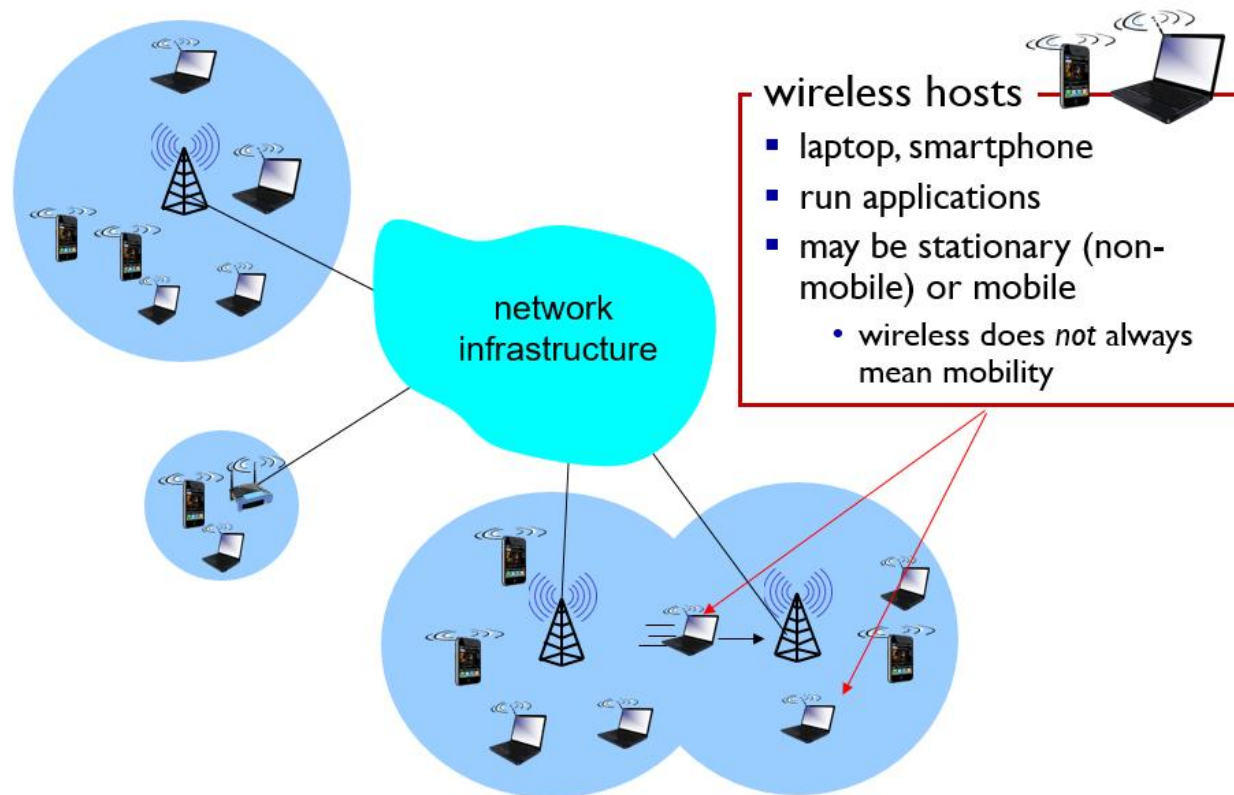
– architecture

– standards (e.g., 3G, LTE)

Mobility

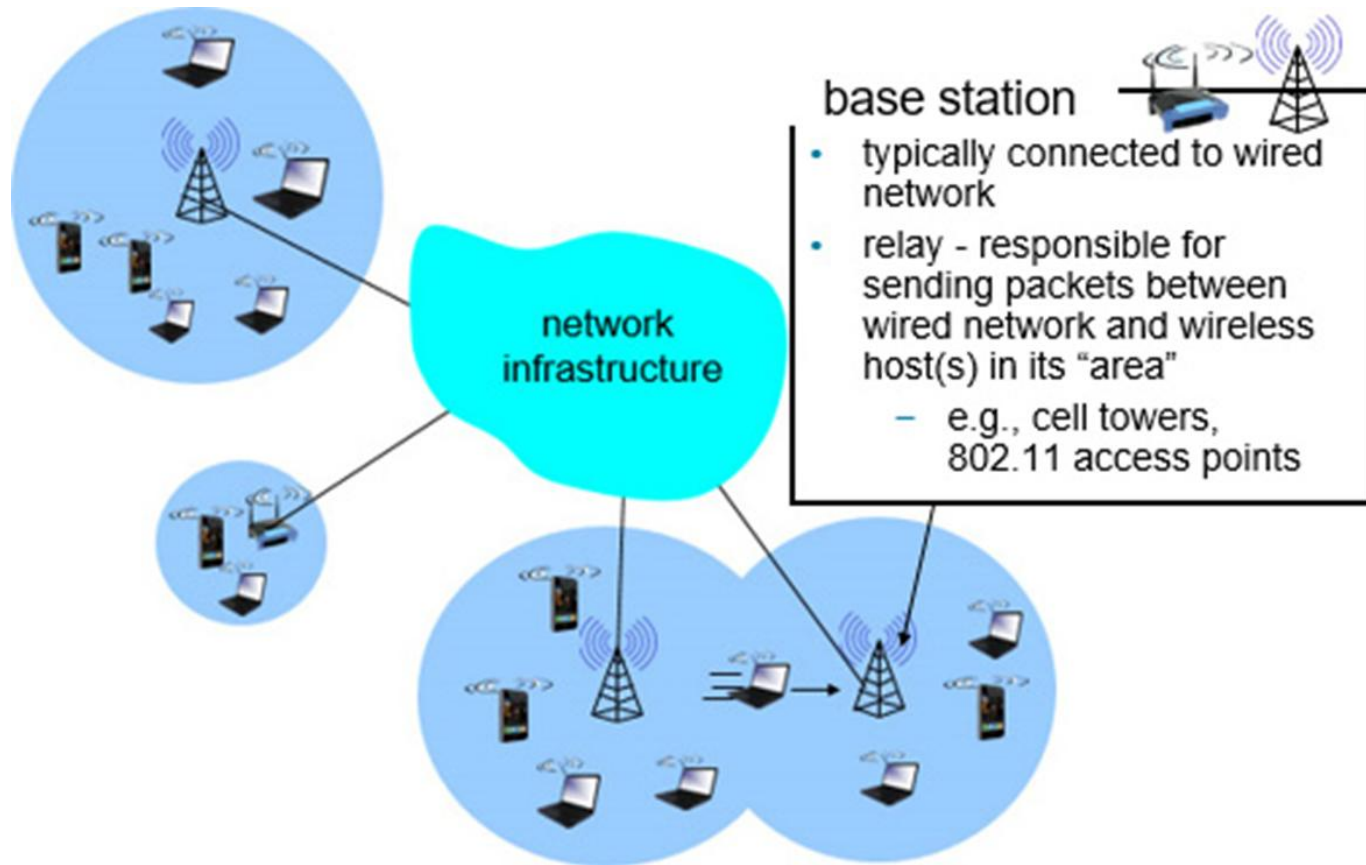**7.5** Principles: addressing and routing to mobile users

7.6 Mobile IP

7.7 Handling mobility in cellular networks

7.8 Mobility and higher-layer protocols
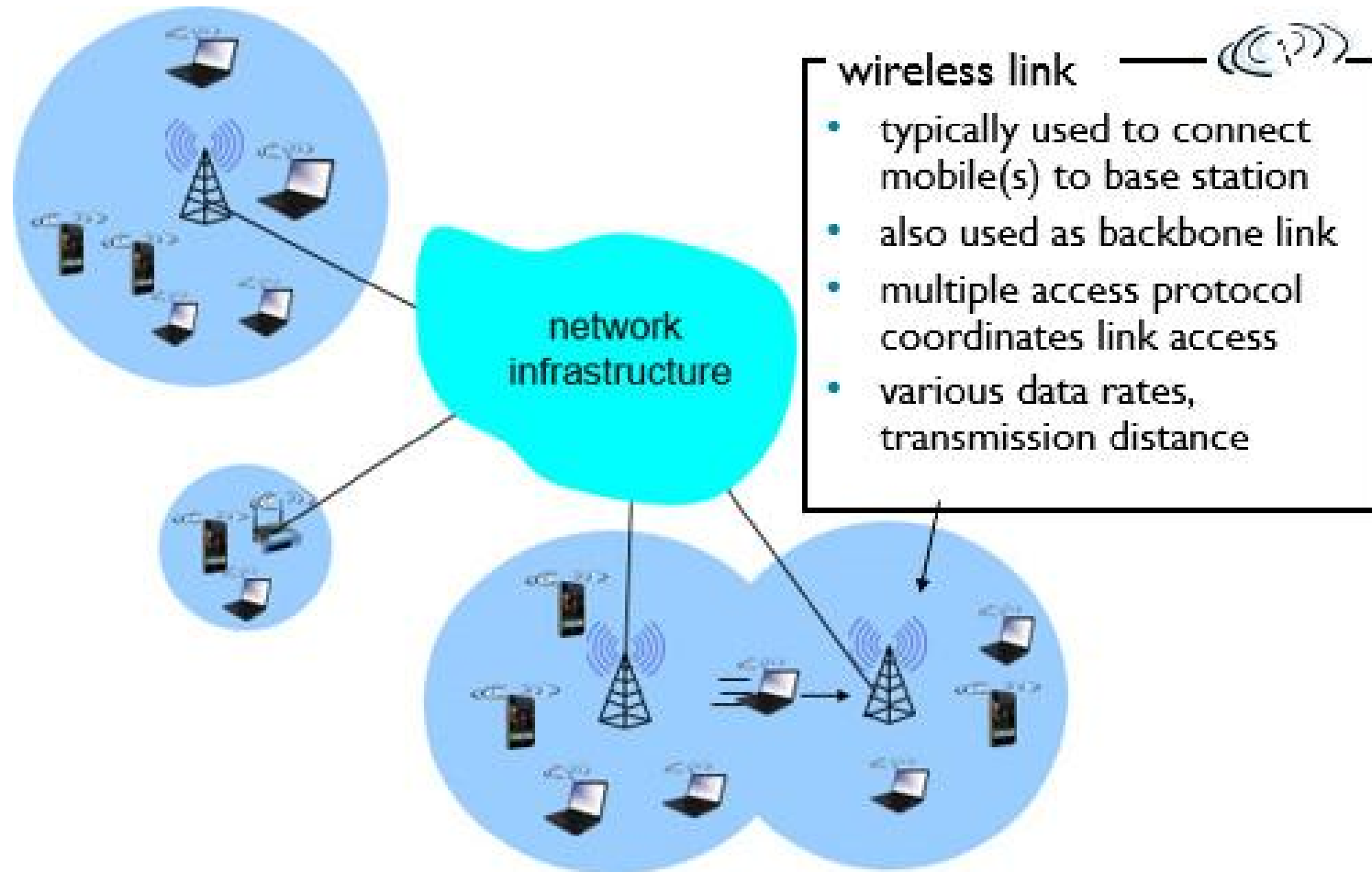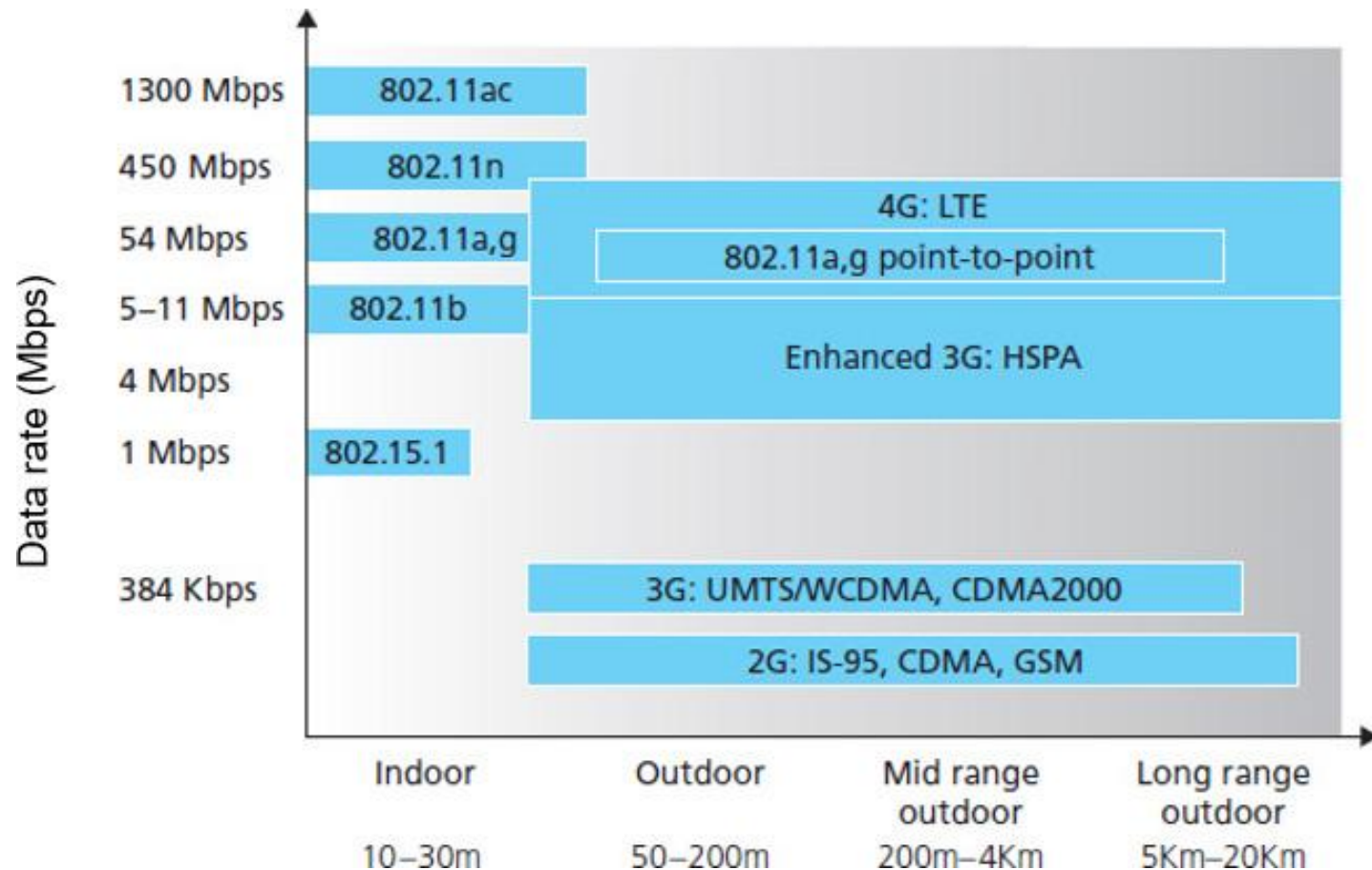
Elements of a Wireless Network (1 of 5)

wireless hosts
- laptop, smartphone
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility

network infrastructure

Elements of a Wireless Network

base station
- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers, 802.11 access points

network infrastructure

Elements of a Wireless Network

wireless link
- typically used to connect mobile(s) to base station
- also used as backbone link
- multiple access protocol coordinates link access
- various data rates, transmission distance

network infrastructure

Characteristics of Selected Wireless Links

Elements of a Wireless Network

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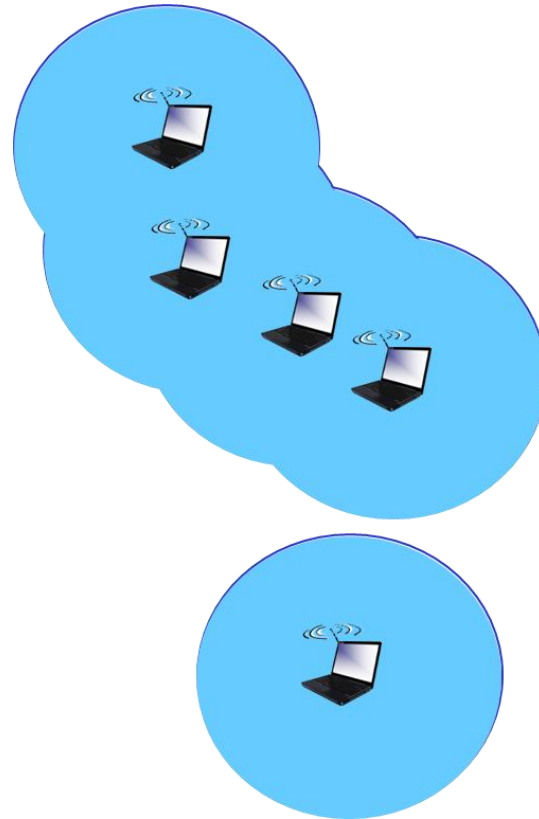- handoff: mobile changes base station providing connection into wired network

network infrastructure
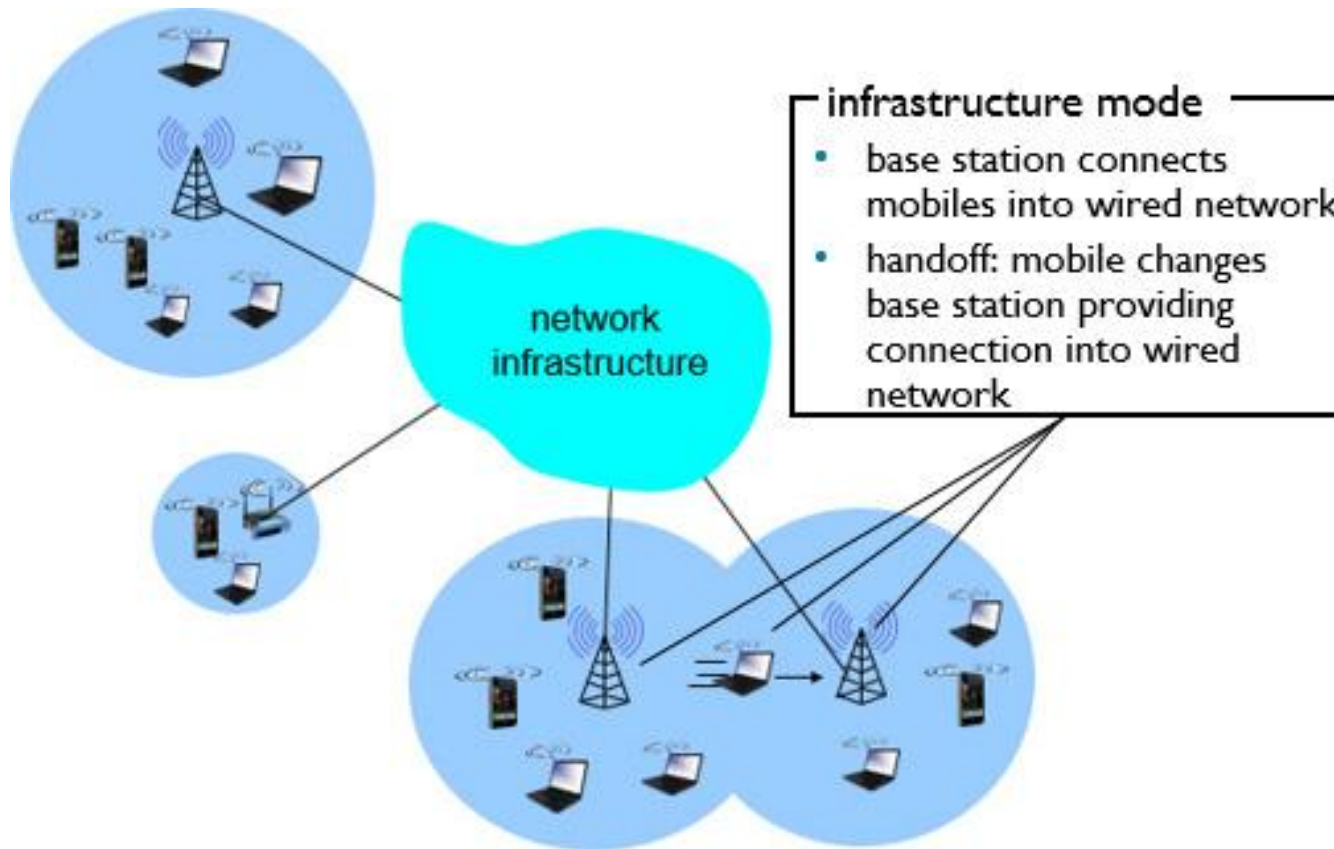
ad hoc mode

- No base stations

- Nodes can only transmit to other nodes within link coverage

- Nodes organize themselves into a network: route among themselves

Wireless Network Taxonomy

	Single hop	Multiple hops
Infrastructure (e.g.,APs)	Host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet	Host may have to relay through several wireless nodes to connect to larger Internet: **mesh net**
No infrastructure	No base station, no connection to larger Internet (Bluetooth, ad hoc nets)	No base station, no connection to larger Internet. May have to relay to reach other a given wireless node M ANET, VANET

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- **CDMA**

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7.4 Cellular Internet Access
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**7.8** Mobility and higher-layer protocols

Wireless Link Characteristics

Important differences from wired link ….

- **Decreased 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

- **Multipath propagation:** radio signal reflects off objects ground, arriving ad destination at slightly different times

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

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 thruput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)

QAM256 (8 Mbps)

QAM16 (4 Mbps)

BPSK (1 Mbps)
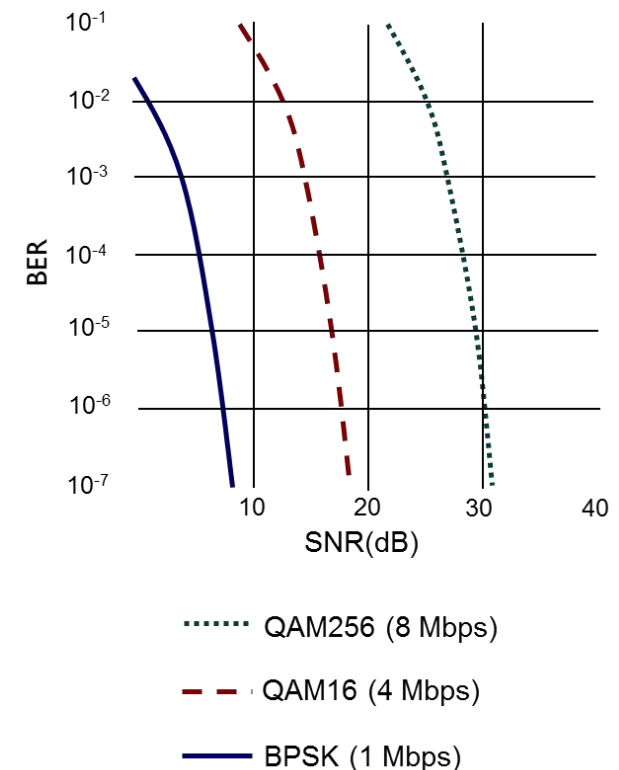
Multiple wireless senders and receivers create additional problems (beyond multiple access):
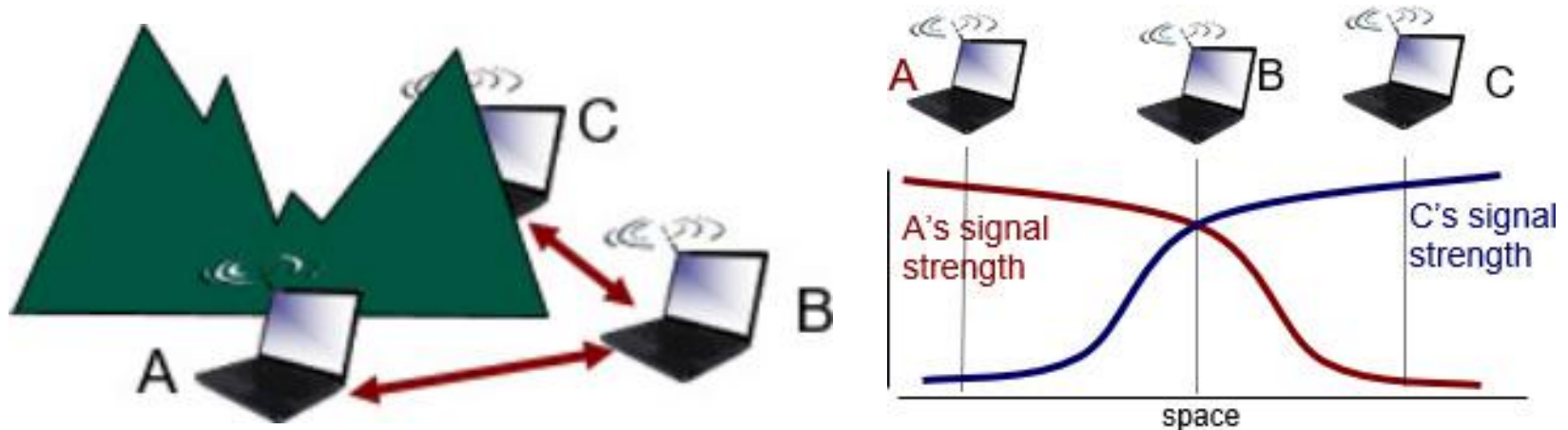
Hidden terminal problem

- B, A hear each other

- B, C hear each other

- A, C can not hear each other means A, C unaware of their interference at B

Signal attenuation:

- B, A hear each other

- B, C hear each other

- A, C can not hear each other interfering at B

Code Division Multiple Access (CDMA)

- 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
  - allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")

- **Encoded signal** = (original data) X (chipping sequence)

- **Decoding:** inner-product of encoded signal and chipping sequence

CDMA Encode/Decode
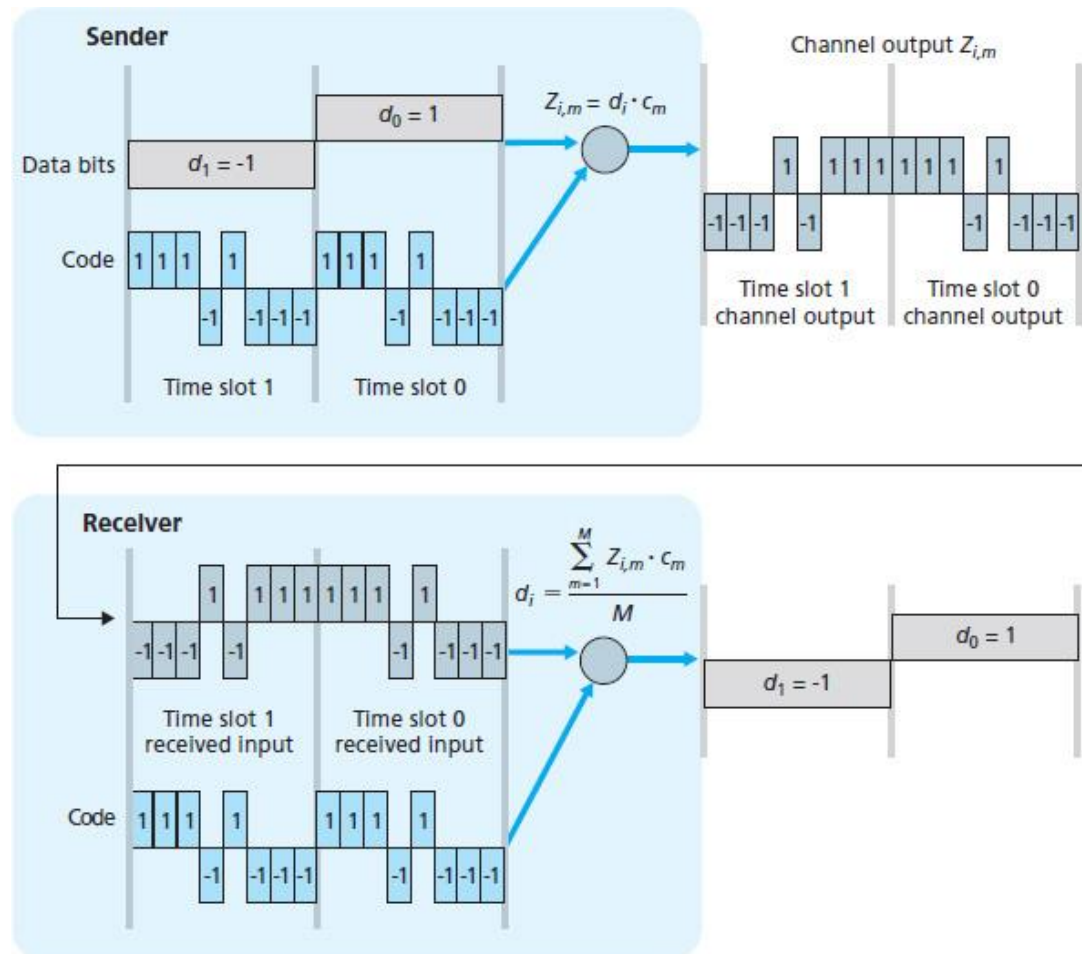
CDMA: Two-Sender Interference
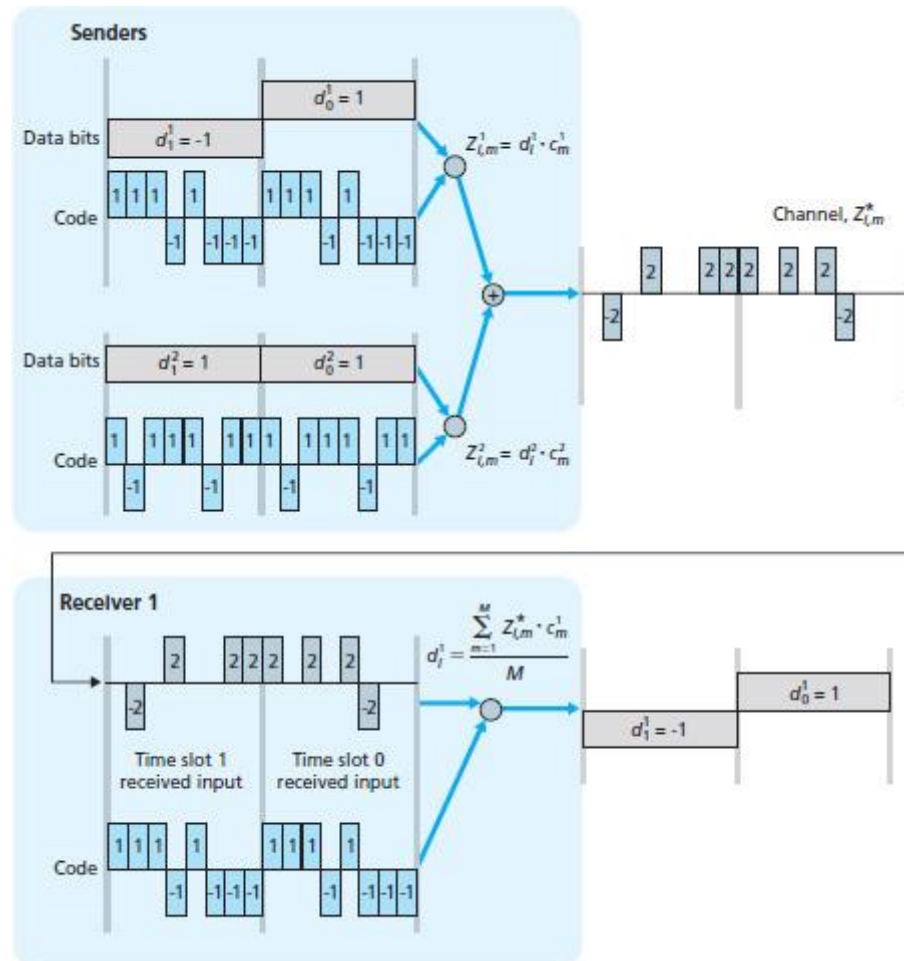
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IEEE 802.11 Wireless LAN

802.11b

- 2.4-5 GHz unlicensed spectrum

- up to 11 Mbps

- direct sequence spread spectrum (DSSS) in physical layer
  - all hosts use same chipping code

802.11a

- 5-6 GHz range

- up to 54 Mbps

802.11g

- 2.4-5 GHz range

- up to 54 Mbps

802.11n: multiple antennae

- 2.4-5 GHz range

- up to 200 Mbps

- all use CSMA/CA for multiple access

- all have base-station and ad-hoc network versions

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): base station
  - ad hoc mode: hosts only
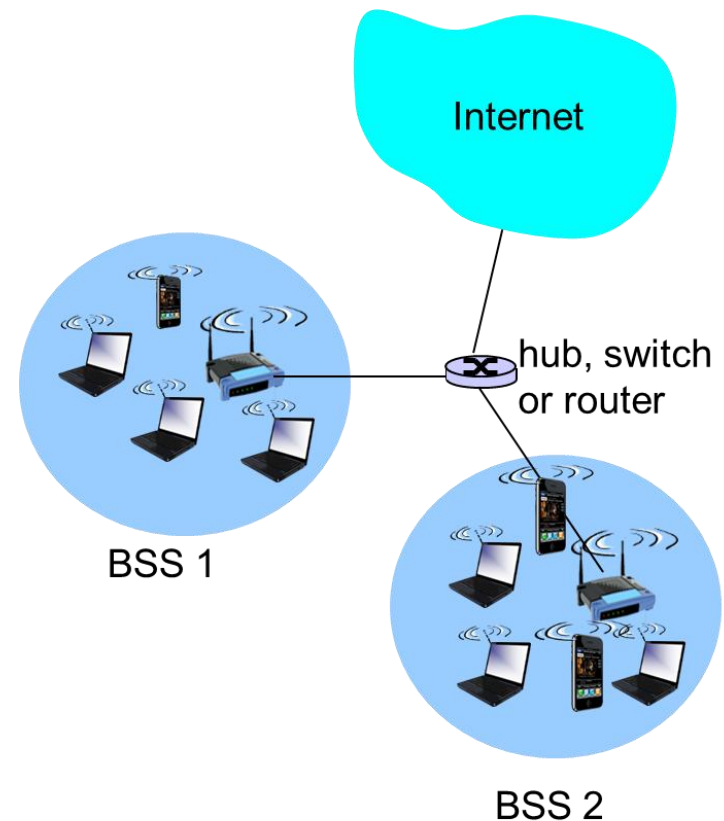
802.11: Channels, Association

- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels at different frequencies
  - AP admin chooses frequency for AP
  - Interference possible: channel can be same as that chosen by neighboring AP!

- 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 [Chapter 8]
  - will typically run DHCP to get IP address in AP's subnet

802.11: Passive/Active Scanning (1 of 2)
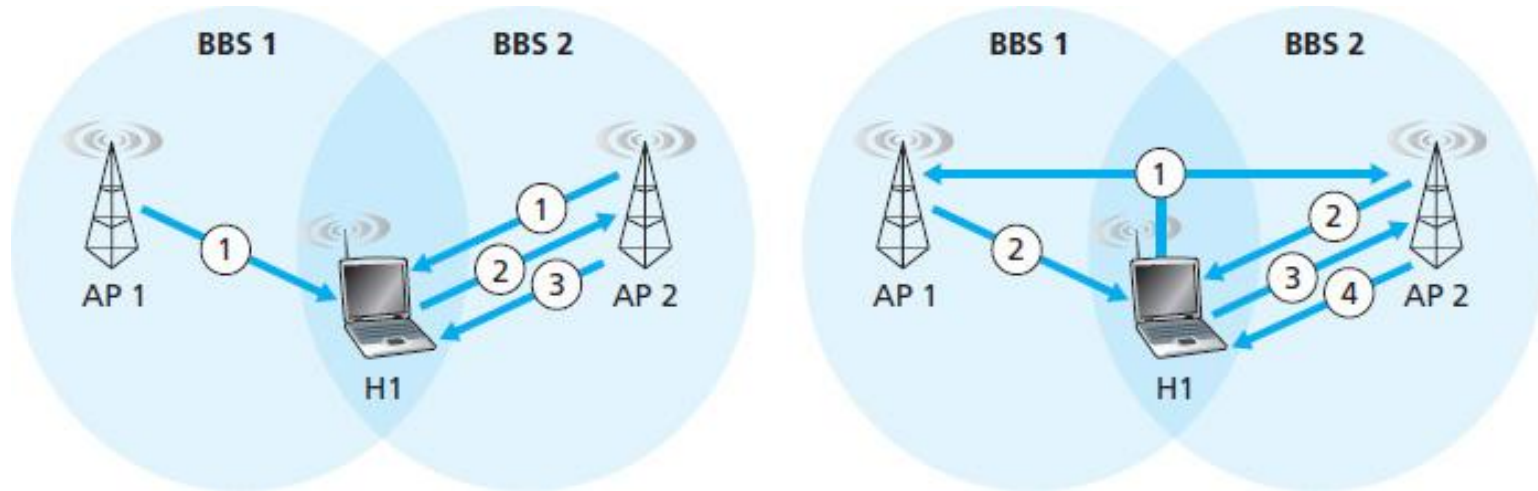
802.11: Passive/Active Scanning

Passive scanning:

(1) beacon frames sent from APs

(2) association Request frame sent: H1 to selected AP

(3) association Response frame sent from selected AP to H1

Active scanning:

(1) Probe Request frame broadcast from H1

(2) Probe Response frames sent from APs

(3) Association Request frame sent: H1 to selected AP

(4) Association Response frame sent from selected AP to H1

IEEE 802.11: Multiple Access

- avoid collisions: 2^+ nodes transmitting at same time

- 802.11: C S M A - 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)
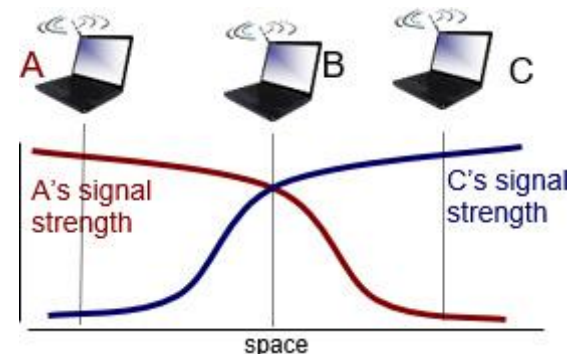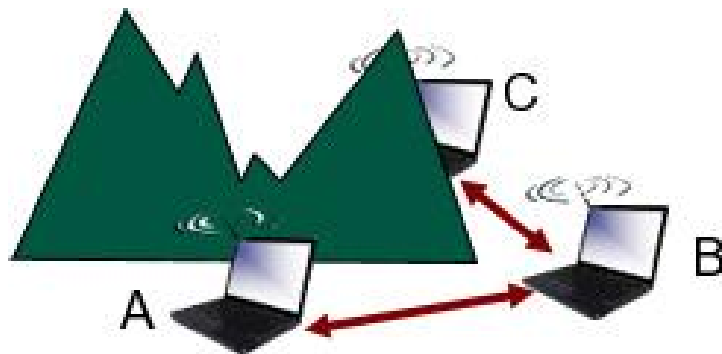
IEEE 802.11 MAC Protocol: CSMA /CA

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 if no ACK, increase random backoff interval, repeat 2

802.11 receiver

- **If frame received OK** return ACK after **SIFS** (ACK needed due to hidden terminal problem)
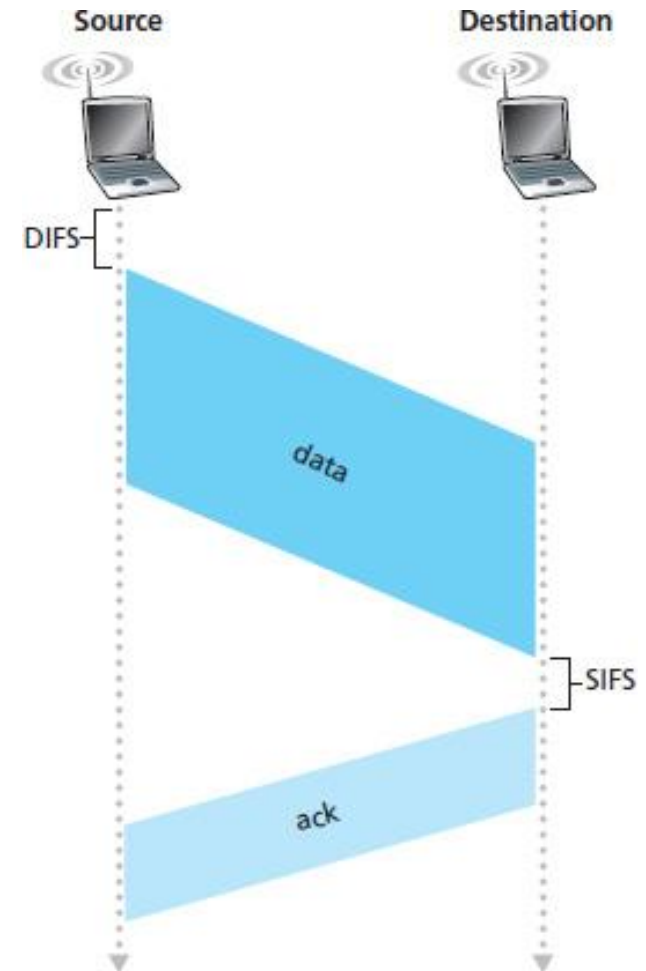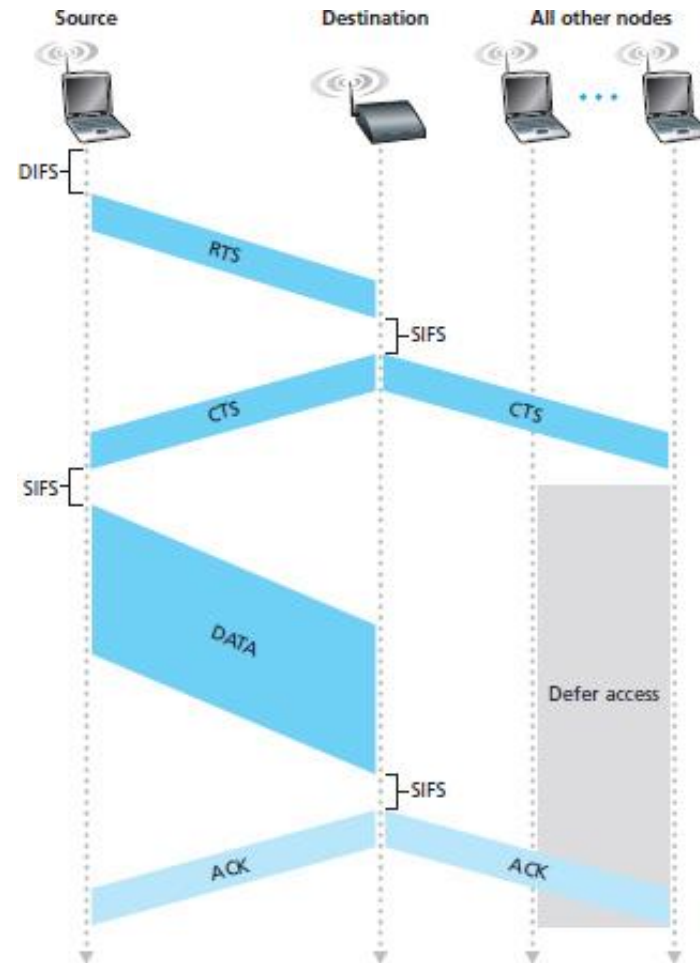
Avoiding collisions

Idea: Allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames
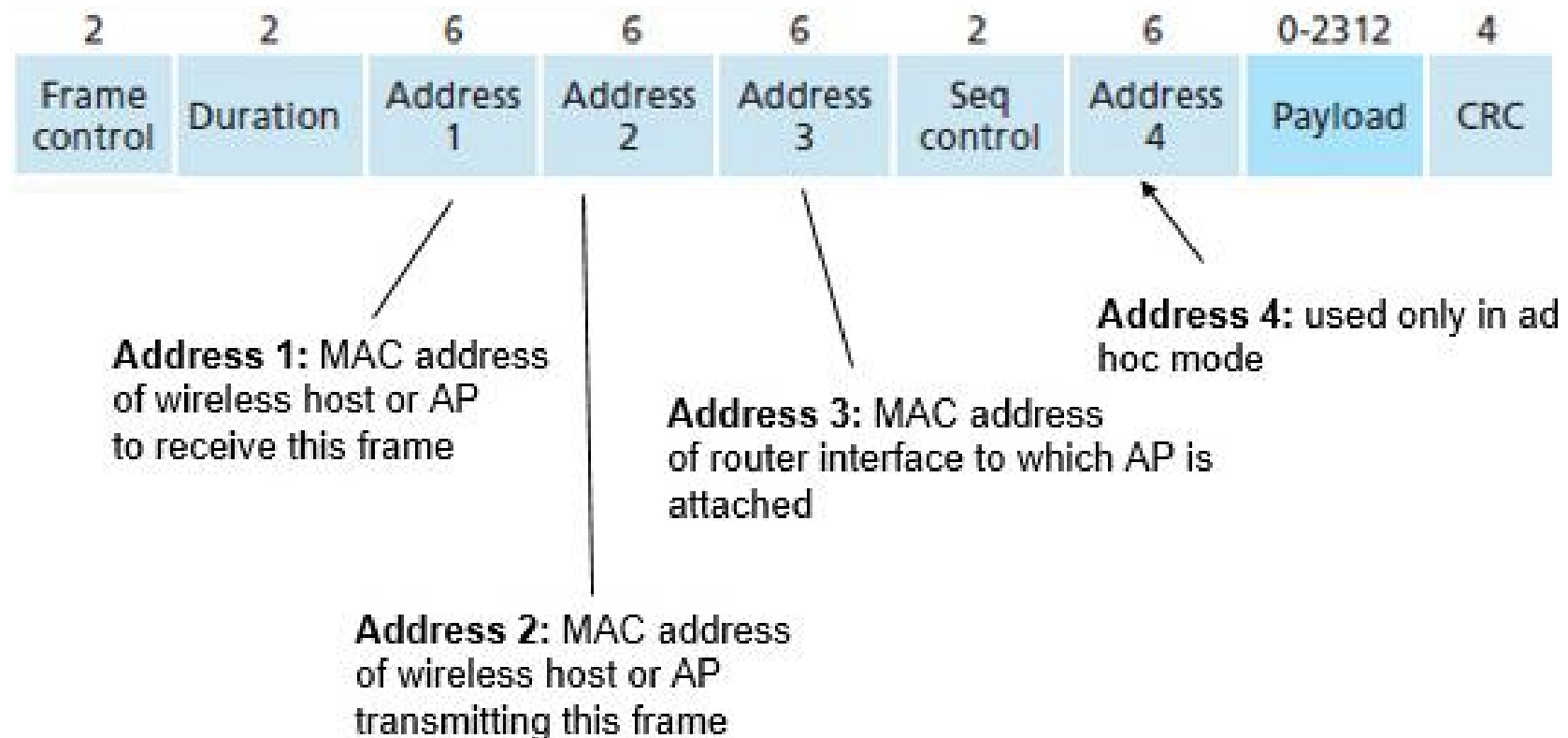
- Sender first transmits **small** request-to-send (RTS) packets to BS using CSMA
  - RTSs may still collide with each other (but they're short)

- BS broadcasts clear-to-send CTS in response to RTS

- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

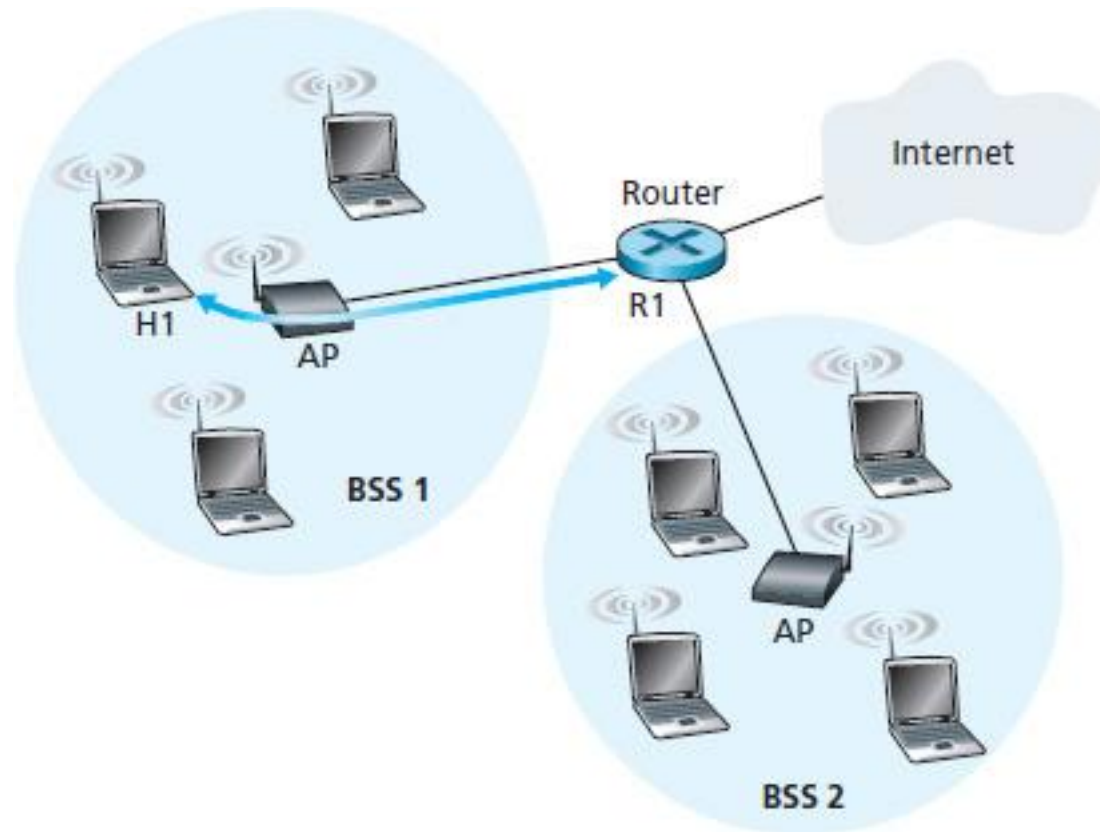**Avoid data frame collisions completely using small reservation packets!**

Collision Avoidance: RTS-CTS exchange

802.11 Frame: Addressing

2	2	6	6	6	2	6	0-2312	4
Frame control	Duration	Address 1	Address 2	Address 3	Seq control	Address 4	Payload	CRC

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: More

duration of reserved
transmission time (RTS/CTS)

frame seq #
(for RDT)

2	2	6	6	6	2	6	0-2312	4
Frame control	Duration	Address 1	Address 2	Address 3	Seq control	Address 4	Payload	CRC

2	2	4	1	1	1	1	1	1	1	1
Protocol version	Type	Subtype	To AP	From AP	More frag	Retry	Power mgt	More data	WEP	Rsvd

frame type
(RTS, CTS, ACK, data)

Pearson
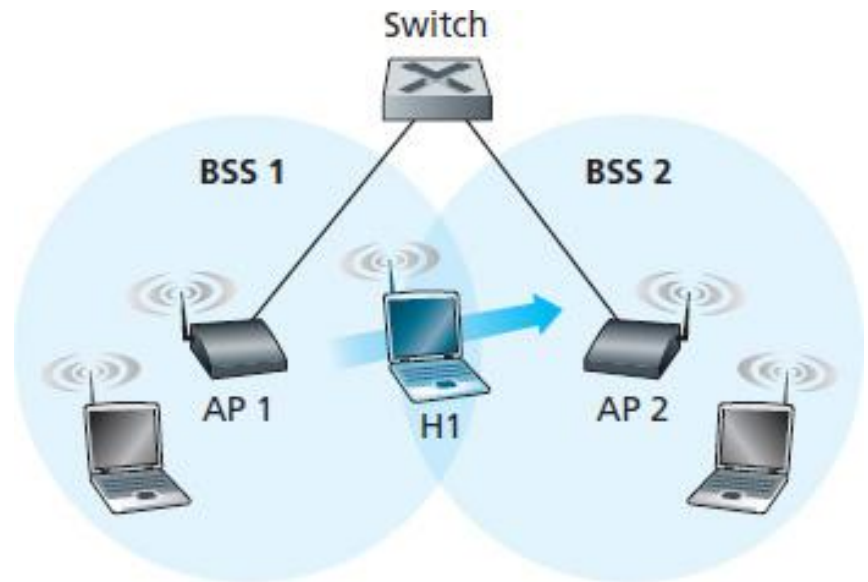
802.11: Mobility within Same Subnet

- 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
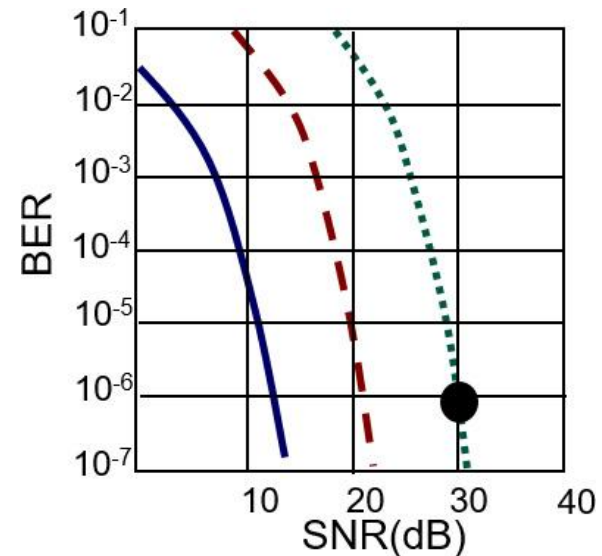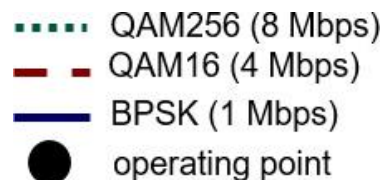
802.11: Advanced Capabilities

Rate adaptation

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

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

BER

10   20   30   40

SNR(dB)

······ QAM256 (8 Mbps)
– – – QAM16 (4 Mbps)
—— BPSK (1 Mbps)
● operating point

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

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
  - Node will stay awake if AP-to-mobile frames to be sent; otherwise sleep again until next beacon frame

802.15: Personal Area Network

- 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
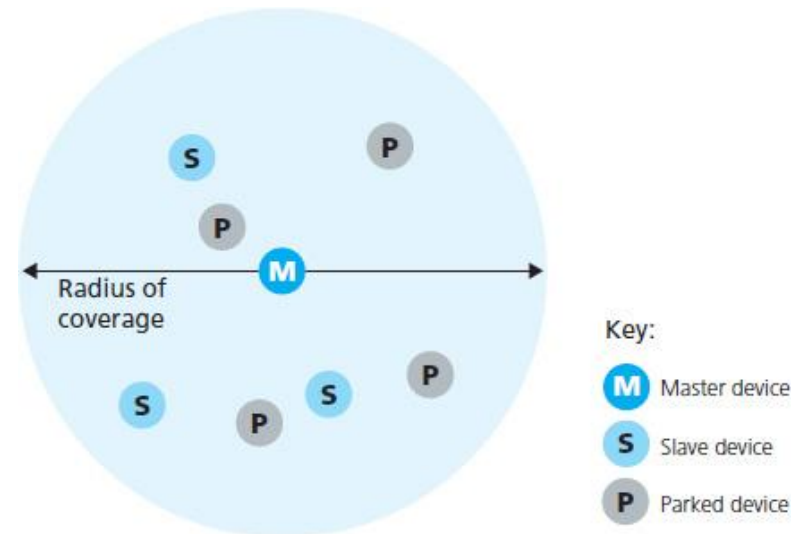
Radius of coverage

Key:
M Master device
S Slave device
P Parked device

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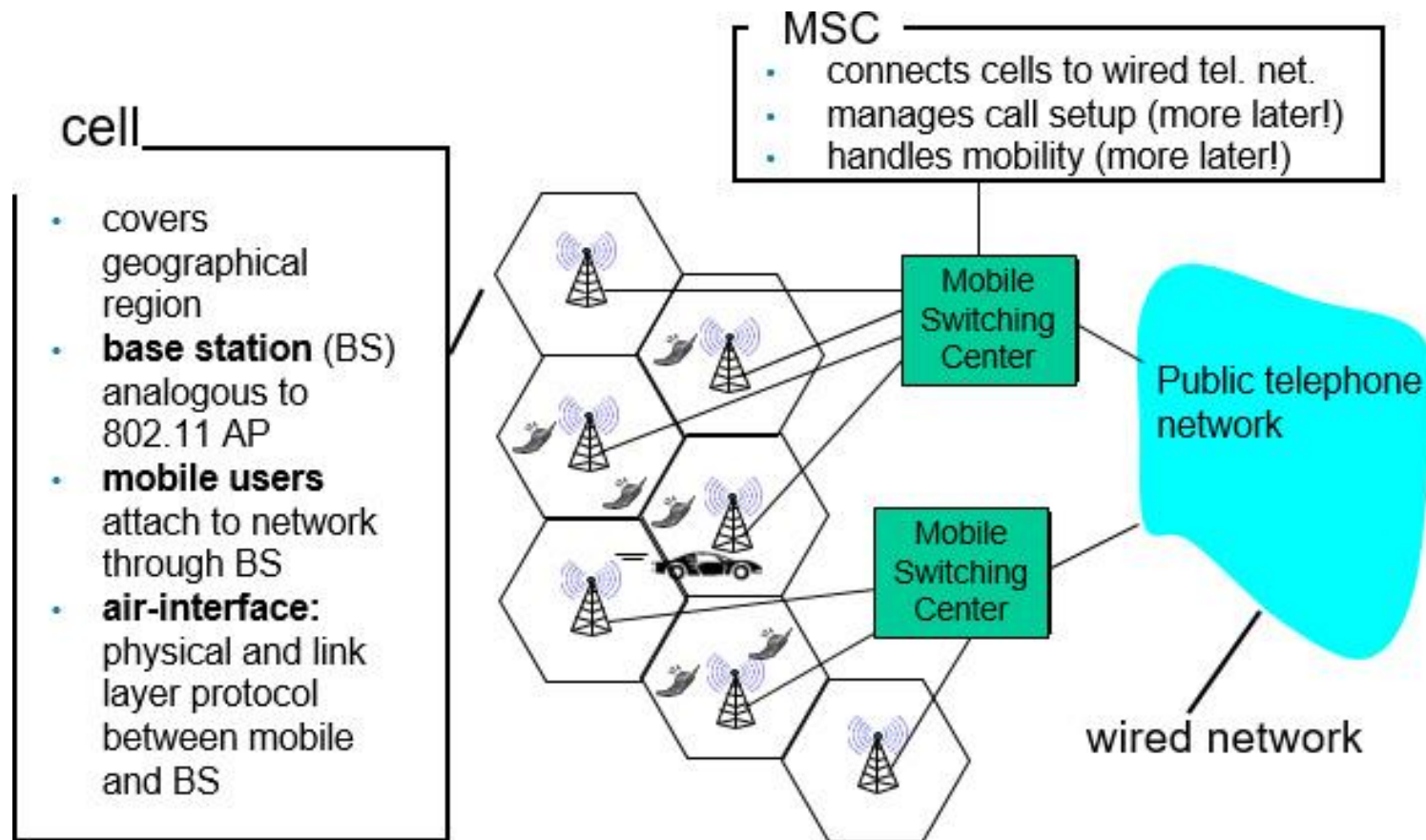- architecture
- standards (e.g., 3G, LTE)

Mobility

7.5 Principles: addressing and routing to mobile users

7.6 Mobile IP

7.7 Handling mobility in cellular networks

**7.8** Mobility and higher-layer protocols

Components of Cellular Network Architecture (1 of 2)

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

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

Mobile Switching Center

Mobile Switching Center
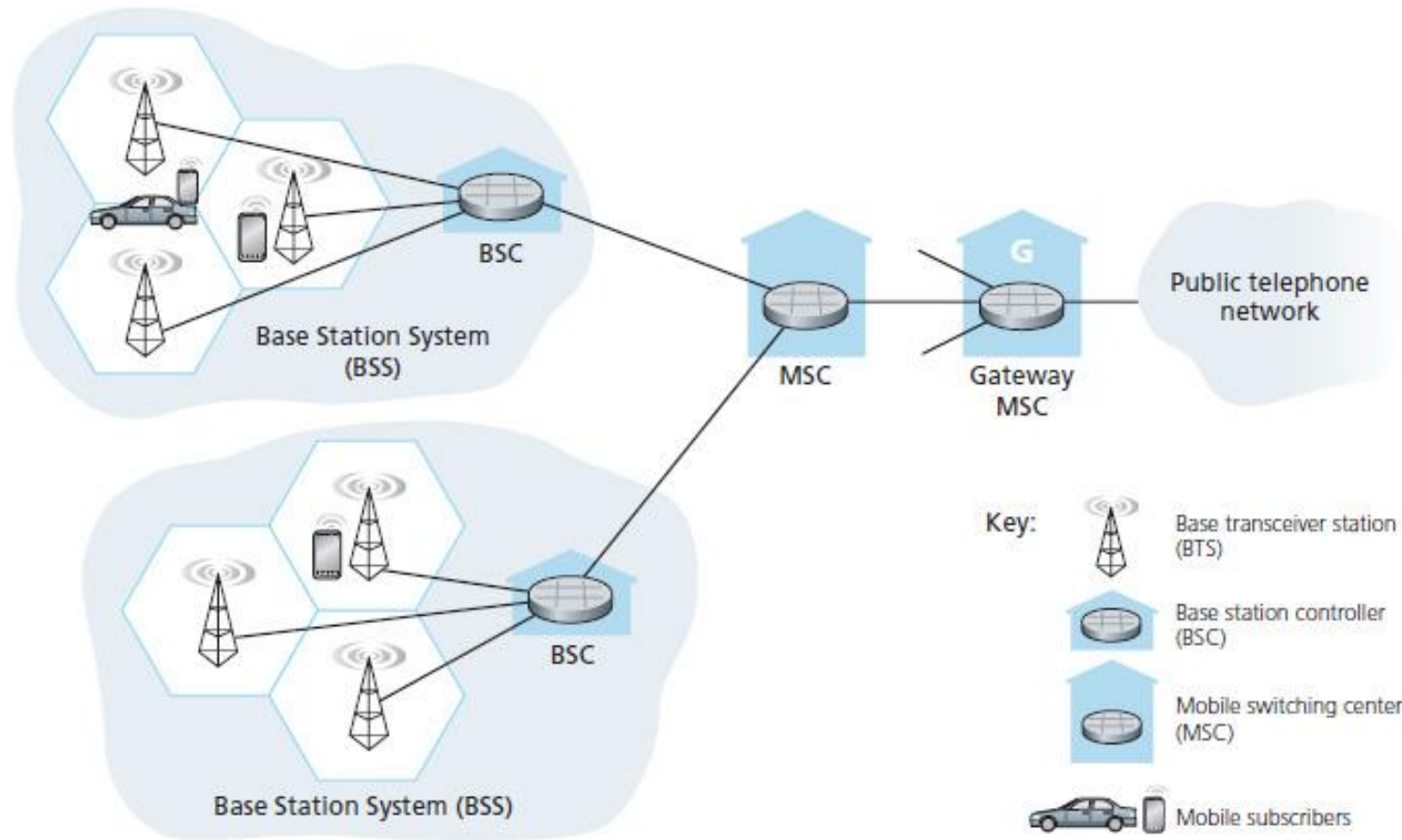
Public telephone network

wired network

Cellular Networks: The First Hop

Two techniques for sharing mobile-to-BS radio spectrum

- **Combined FDMA/TDMA:** divide spectrum in frequency channels, divide each channel into time slots

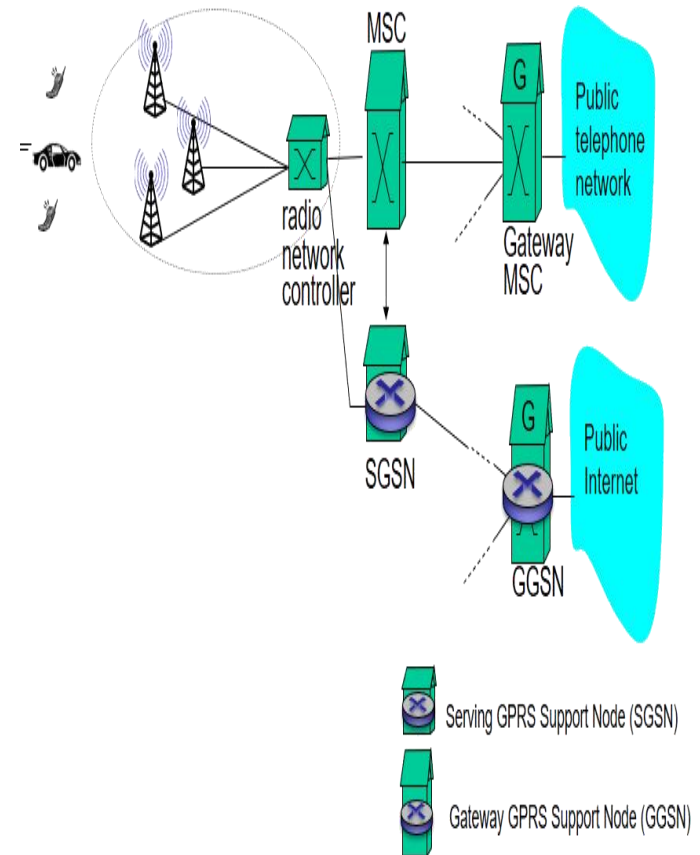- **CDMA:** code division multiple access
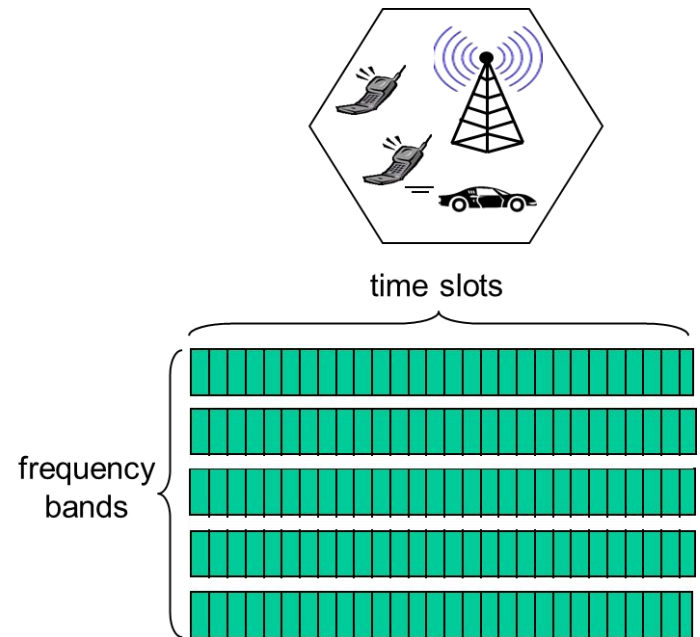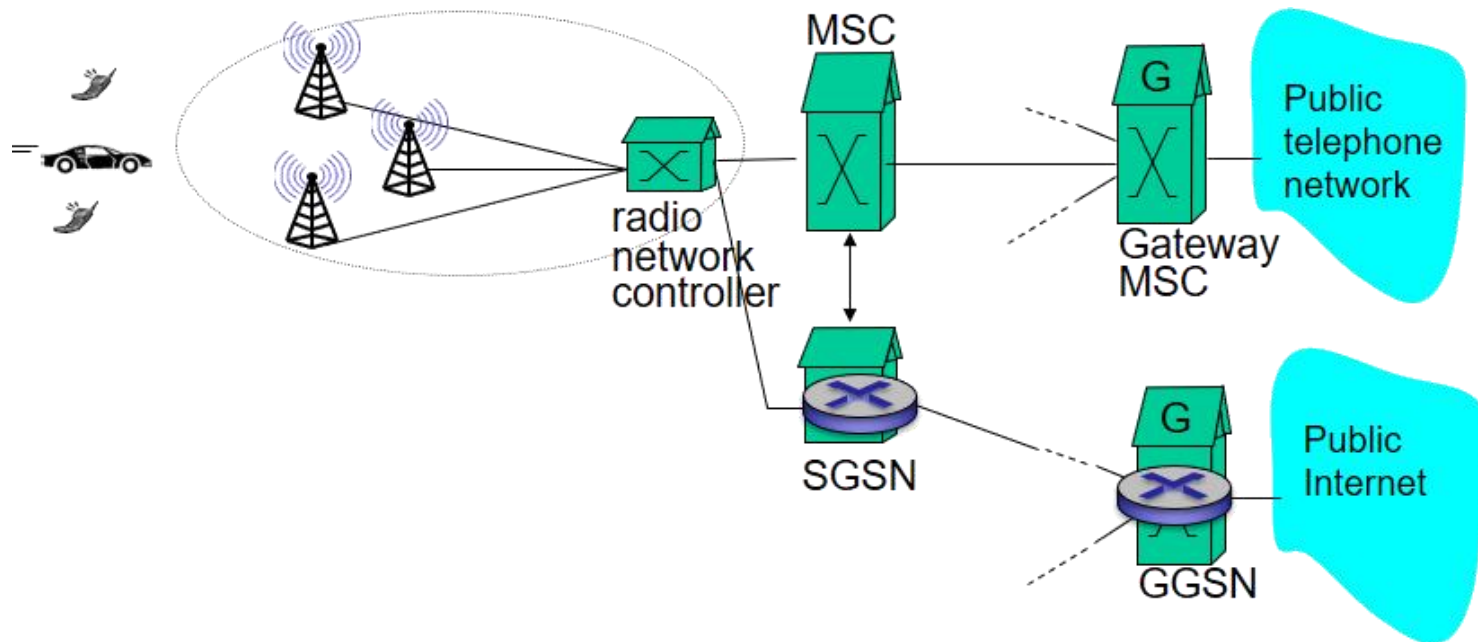
2G (voice) Network Architecture

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

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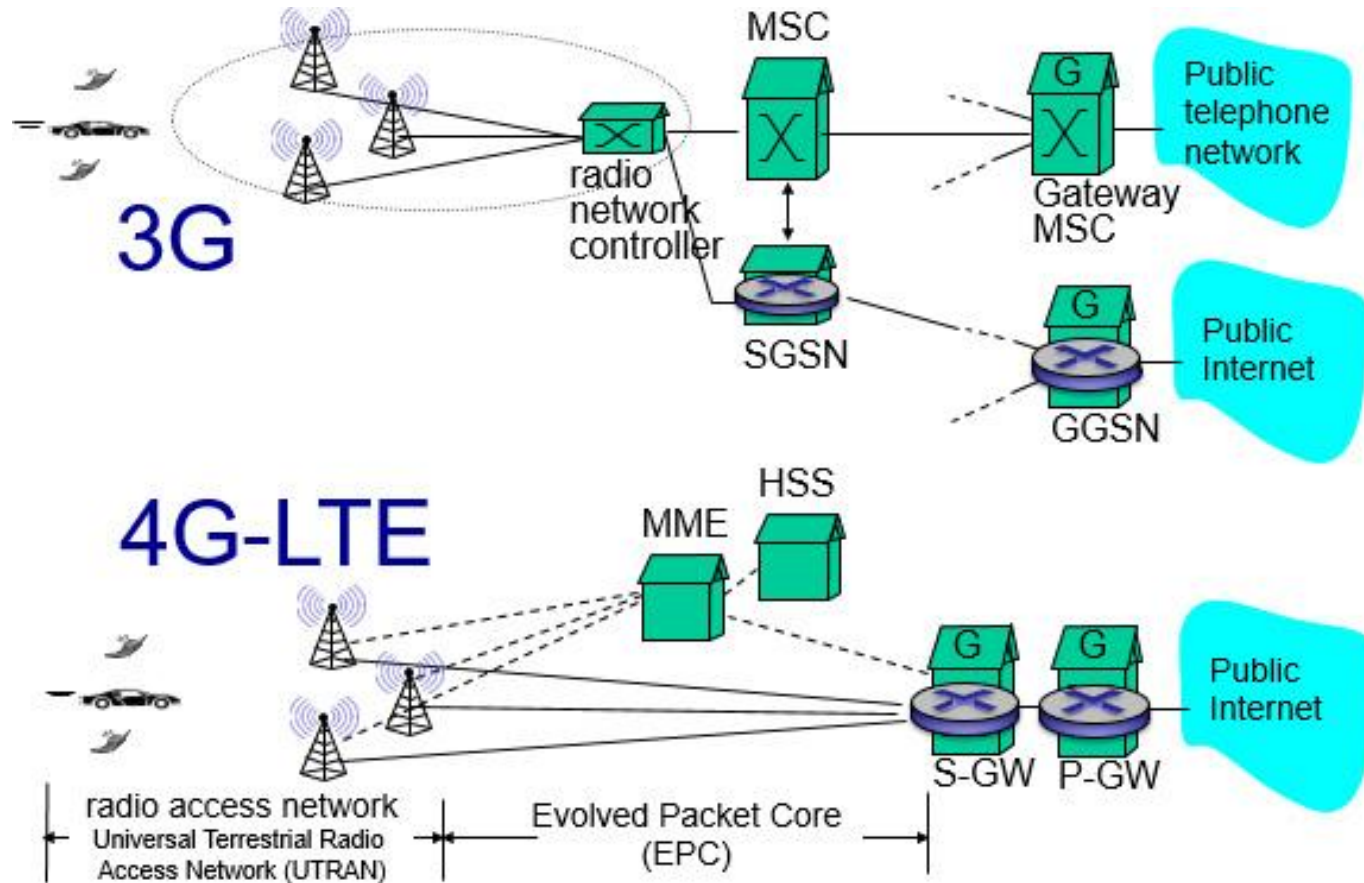 - data network operates in parallel

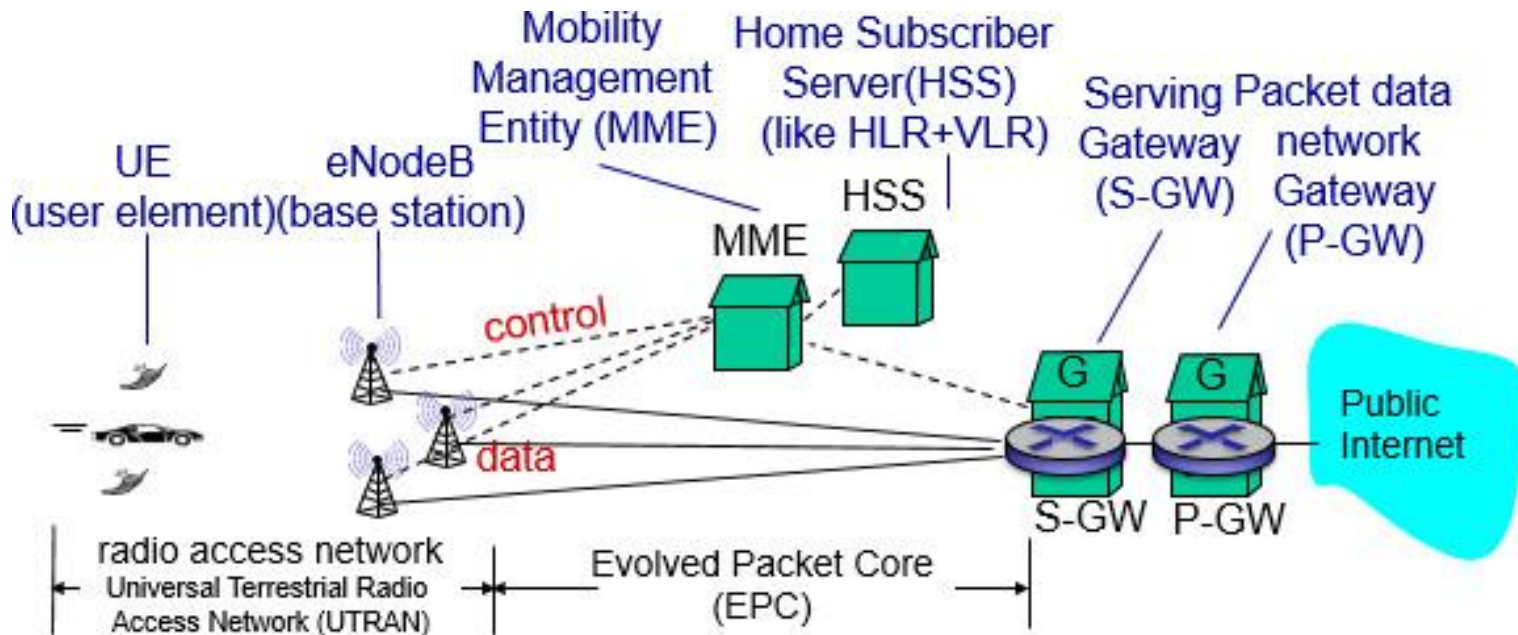# 3G (voice+data) Network Architecture (2 of 2)

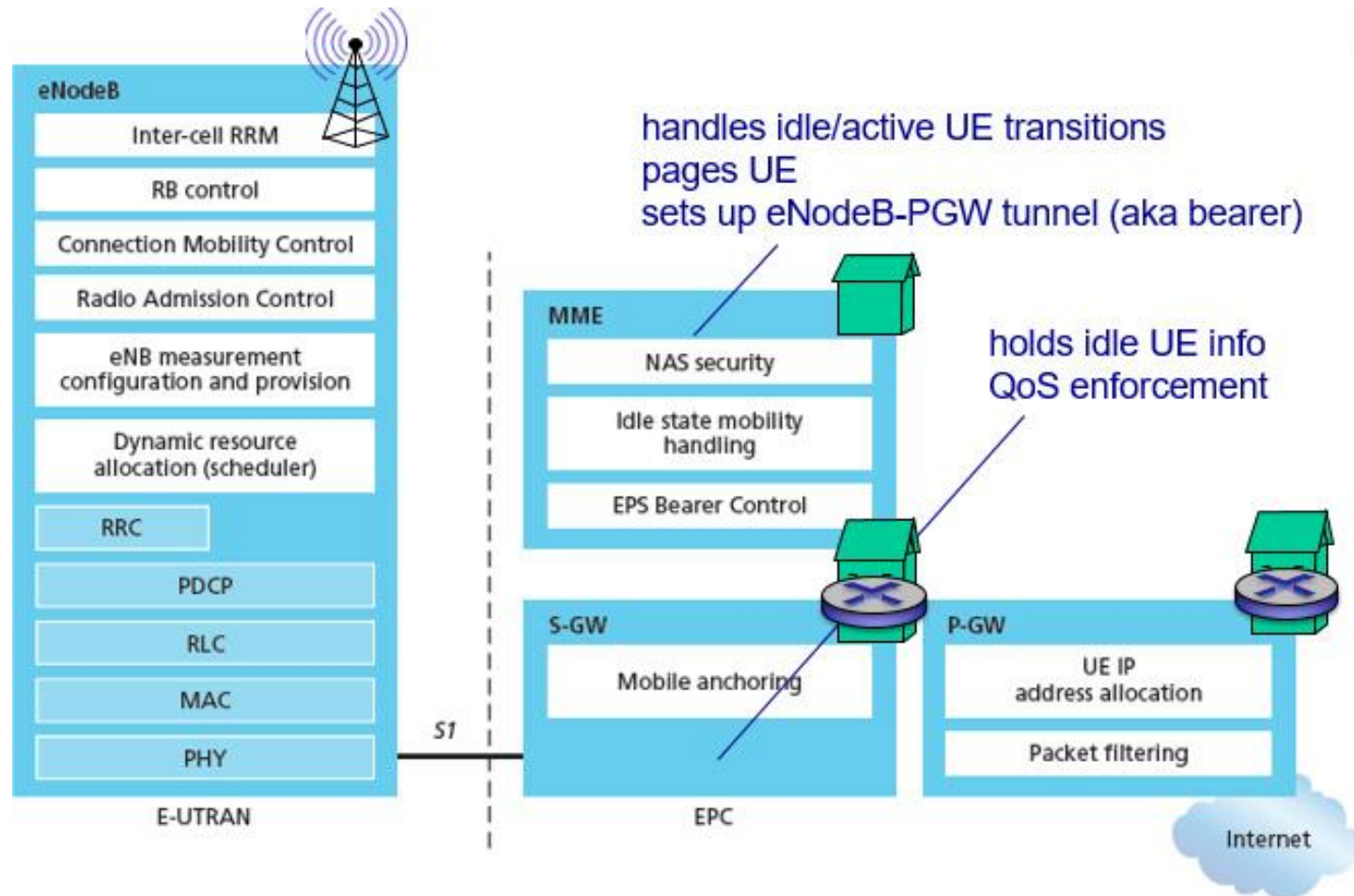# 3G versus 4G LTE Network Architecture

4G: Differences from 3G

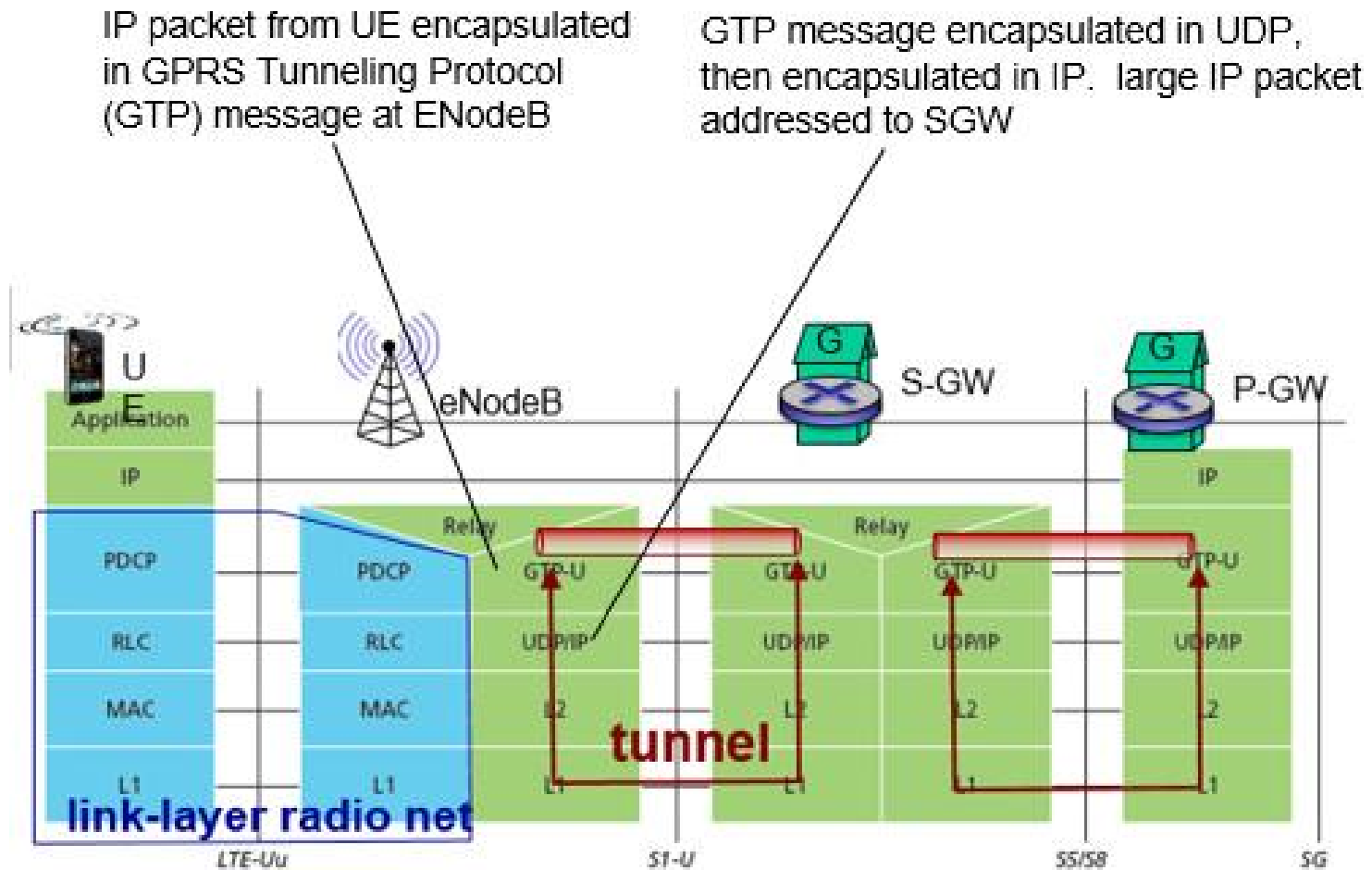- all IP core: IP packets tunneled (through core IP network) from base station to gateway

- no separation between voice and data – all traffic carried over IP core to gateway

Functional Split of Major LTE Components

Radio+Tunneling: UE – eNodeB – PGW

IP packet from UE encapsulated in GPRS Tunneling Protocol (GTP) message at ENodeB

GTP message encapsulated in UDP, then encapsulated in IP. large IP packet addressed to SGW

Quality of Service in LTE

- QoS from eNodeB to SGW: min and max guaranteed bit rate

- QoS in radio access network: one of 12 QCI values

QCI	Resource type	Priority	Packet delay Budget (ms)	Packet error loss rate	Example services
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversational video (buffer streaming)
4	GBR	3	50	10^{-3}	Real-time gaming
5	Non-GBR	1	100	10^{-6}	IMS signaling
6	Non-GBR	7	100	10^{-3}	Voice ,video (live streaming),interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffer streaming)
8	Non-GBR	8	300	10^{-6}	TCP-based (for example,WWW,e-mail),chat,FTP,p2p file sharing,Progressive video and others
9	Non-GBR	9	300	10^{-6}	

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Mobility

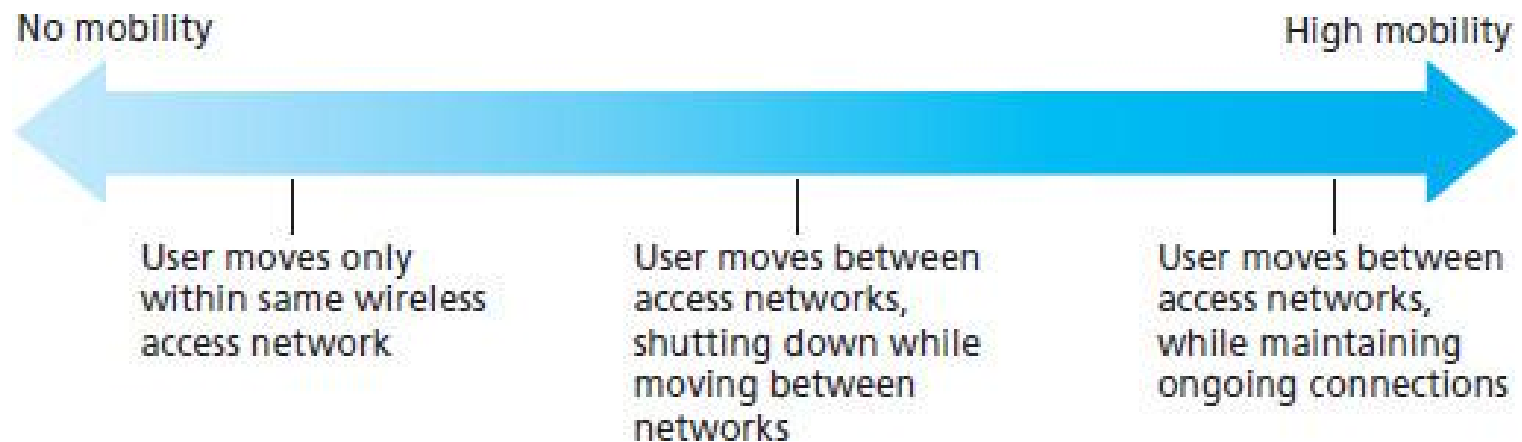**7.5 Principles: addressing and routing to mobile users**

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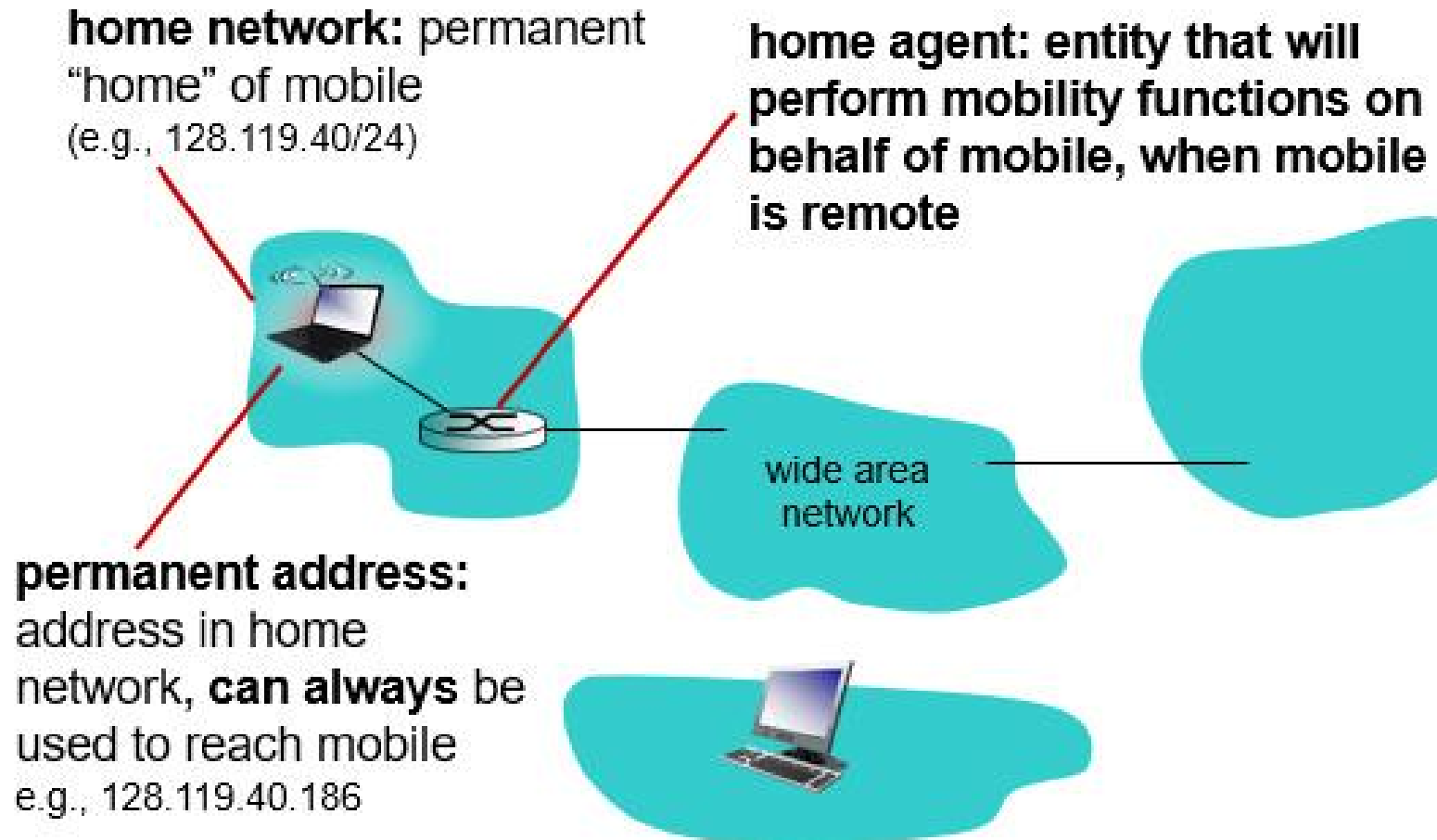
7.8 Mobility and higher-layer protocols

Pearson

What is Mobility?

- spectrum of mobility, from the **network** perspective:
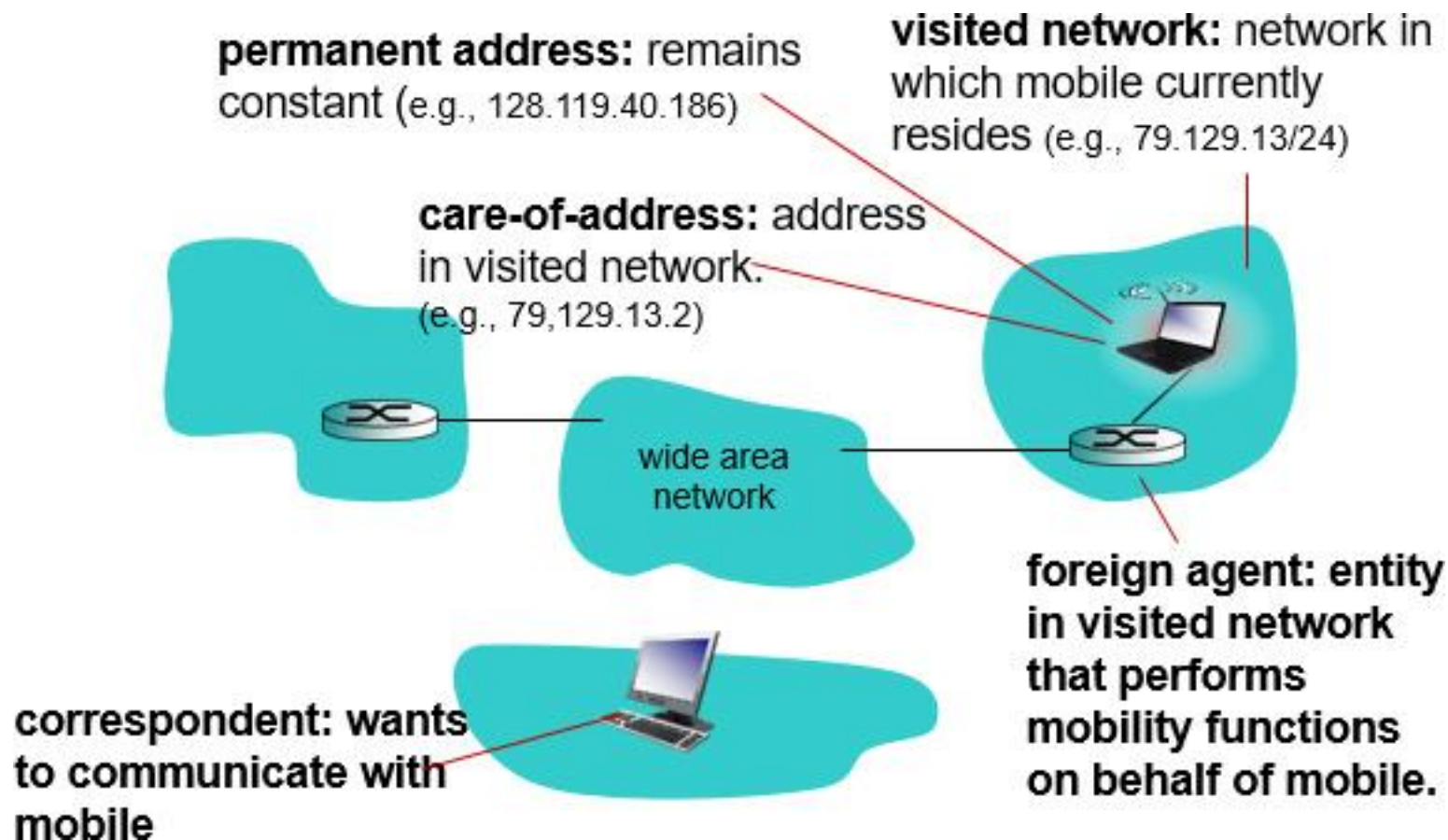
No mobility ← → High mobility

User moves only within same wireless access network

User moves between access networks, shutting down while moving between networks

User moves between access networks, while maintaining ongoing connections

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

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

wide area network

Mobility: More Vocabulary

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

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

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

wide area network

correspondent: wants to communicate with mobile

foreign agent: entity in visited network that performs mobility functions on behalf of 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?

- Facebook!

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
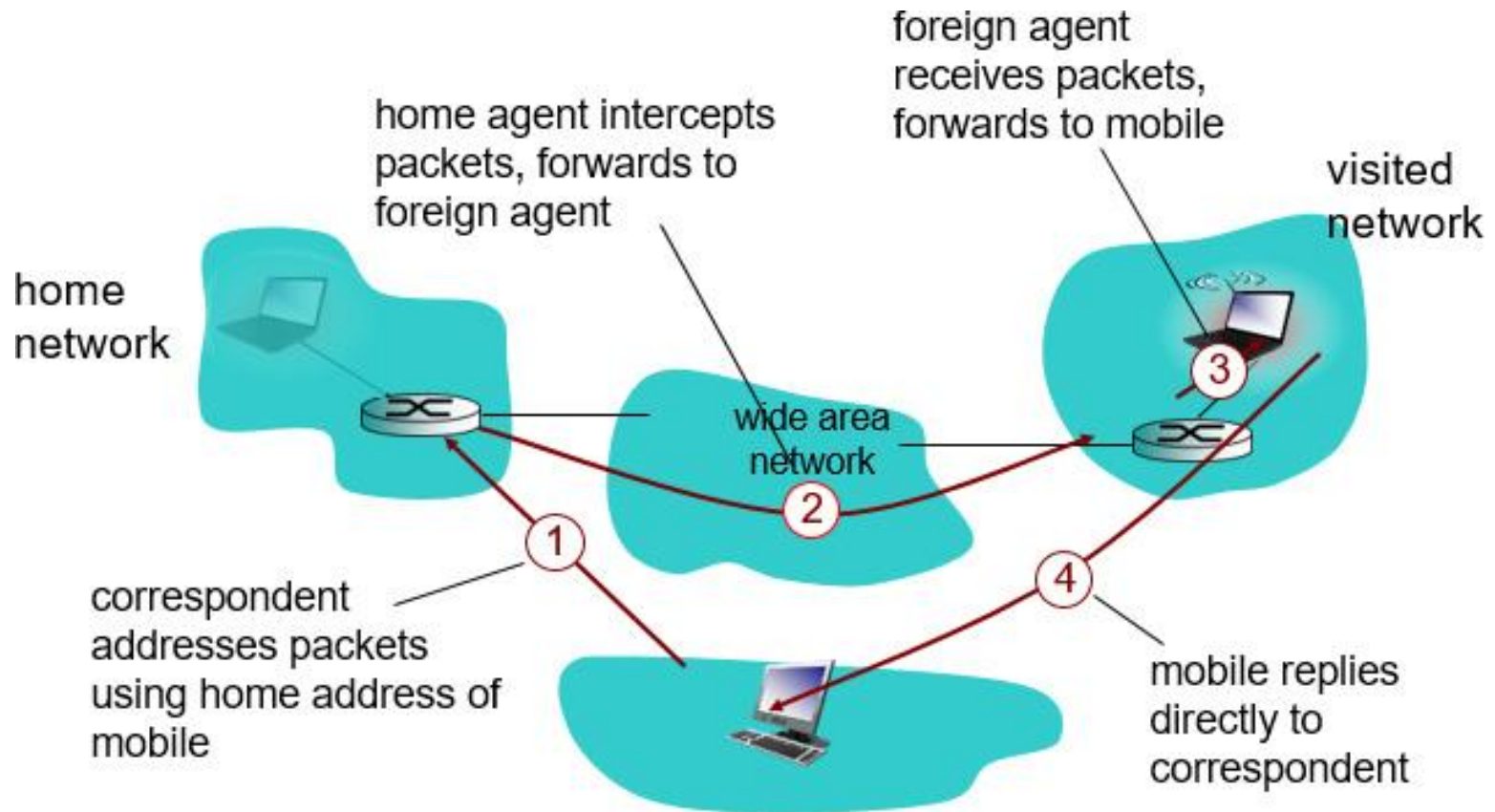
- **let routing handle it:** routers advertise permanent address of mobile-node residence via usual routing table exchange.

  (not scalable to millions of mobiles)

  - routing tables indicate 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: Registration
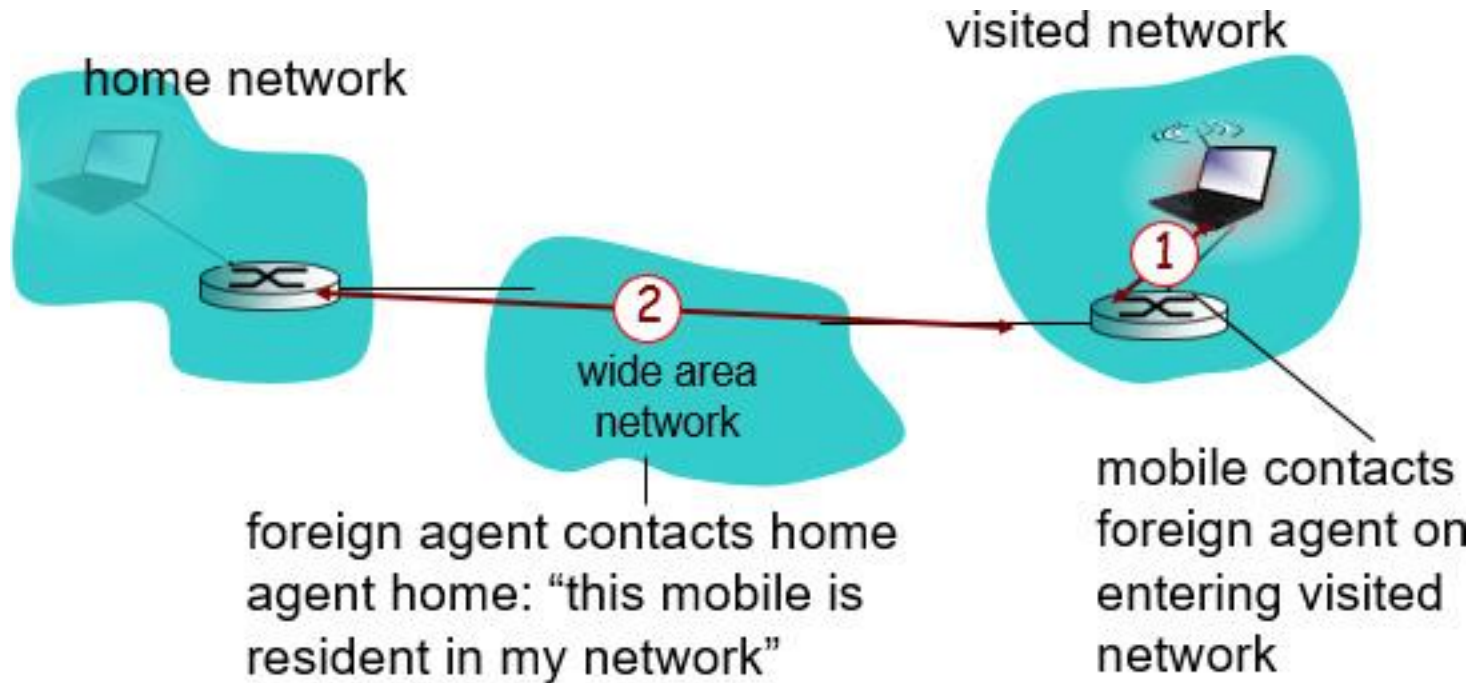
End result:

- Foreign agent knows about mobile

- Home agent knows location of mobile

Mobility via Indirect Routing

foreign agent receives packets, forwards to mobile

home agent intercepts packets, forwards to foreign agent

visited network

home network

wide area network

correspondent addresses packets using home address of mobile

mobile replies directly to correspondent

Pearson

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
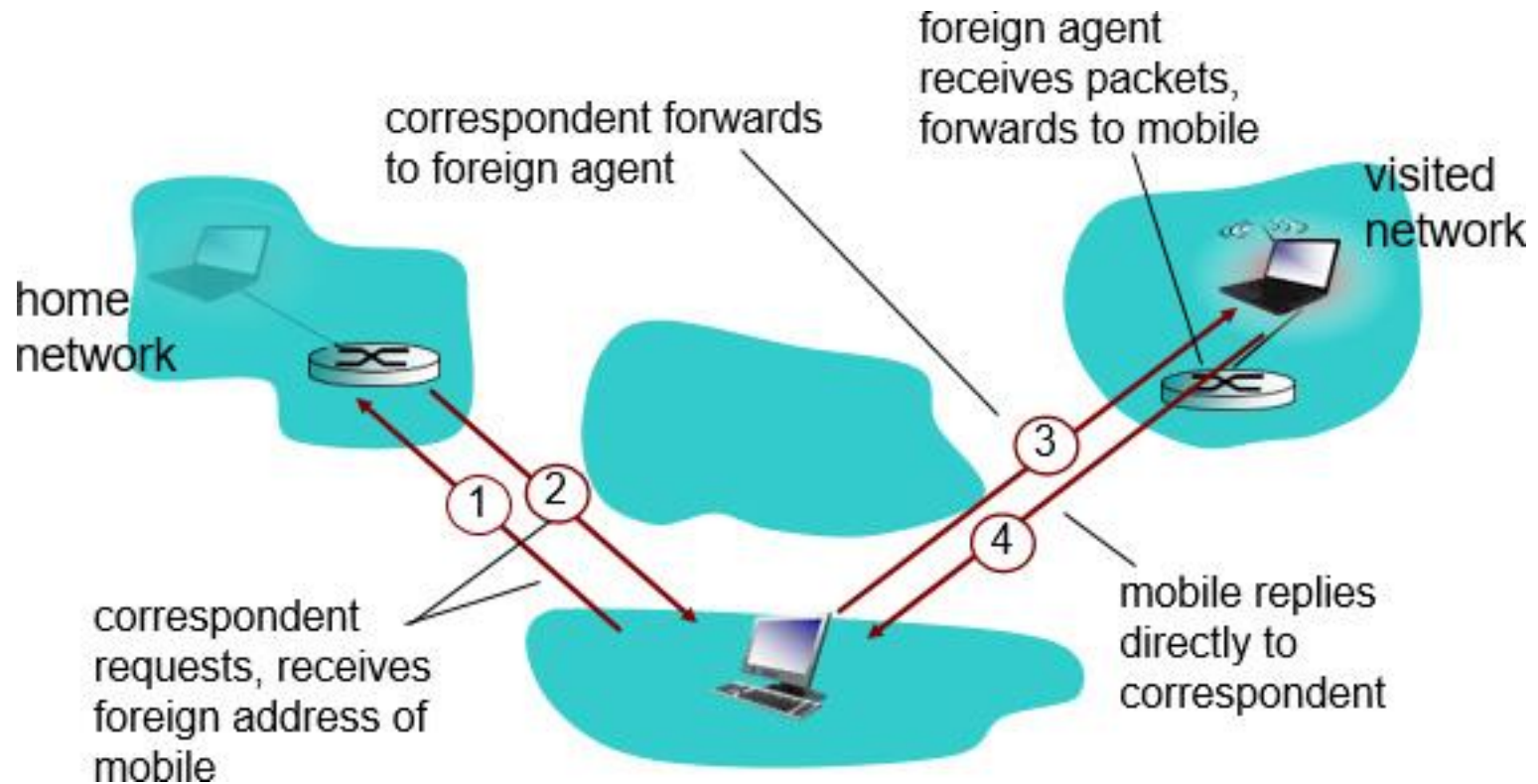 - inefficient when correspondent, mobile are in same network
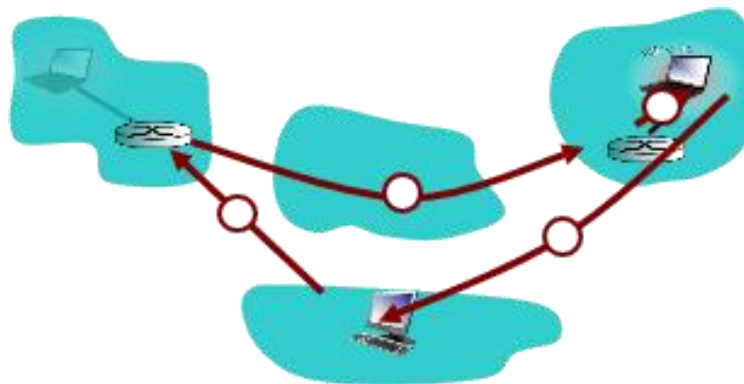
Indirect Routing: Moving Between Networks

- 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: **on going connections can be maintained!**

Mobility via Direct Routing

correspondent forwards
to foreign agent

foreign agent
receives packets,
forwards to mobile

visited
network

home
network

correspondent
requests, receives
foreign address of
mobile

① ②

③

④

mobile replies
directly to
correspondent

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?
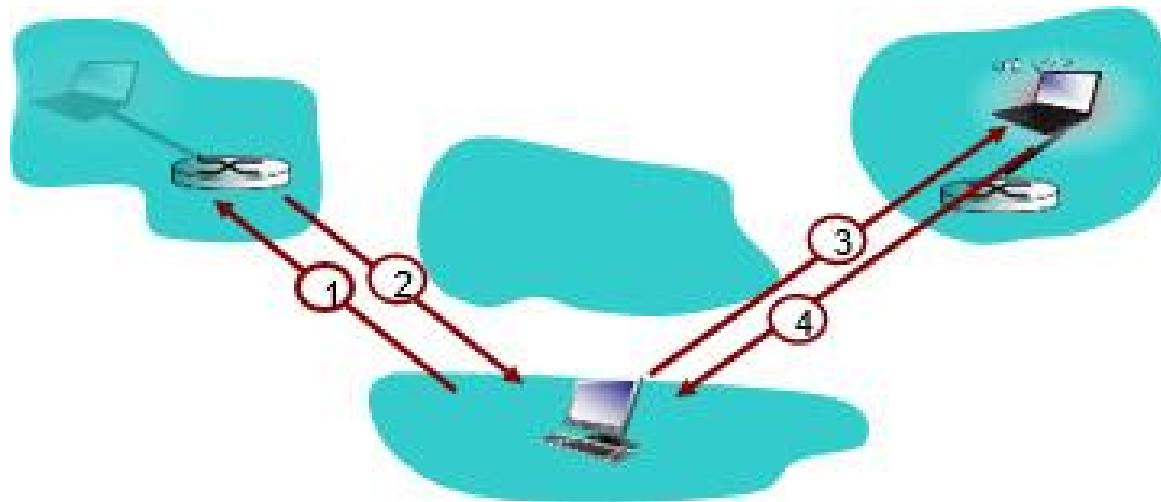
Accommodating Mobility with Direct Routing

- 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)
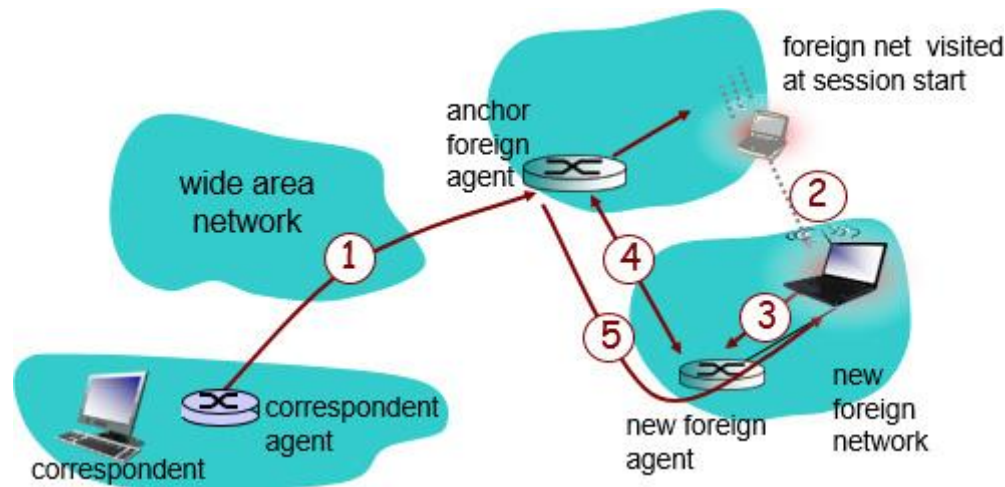
Learning Objectives

7.1 Introduction

Wireless

7.2 Wireless links, characteristics
- CDMA

7.3 IEEE 802.11 wireless LANs ("Wi-Fi")

7.4 Cellular Internet Access
- architecture
- standards (e.g., 3G, LTE)

Mobility

7.5 Principles: addressing and routing to mobile users

7.6 Mobile IP

7.7 Handling mobility in cellular networks
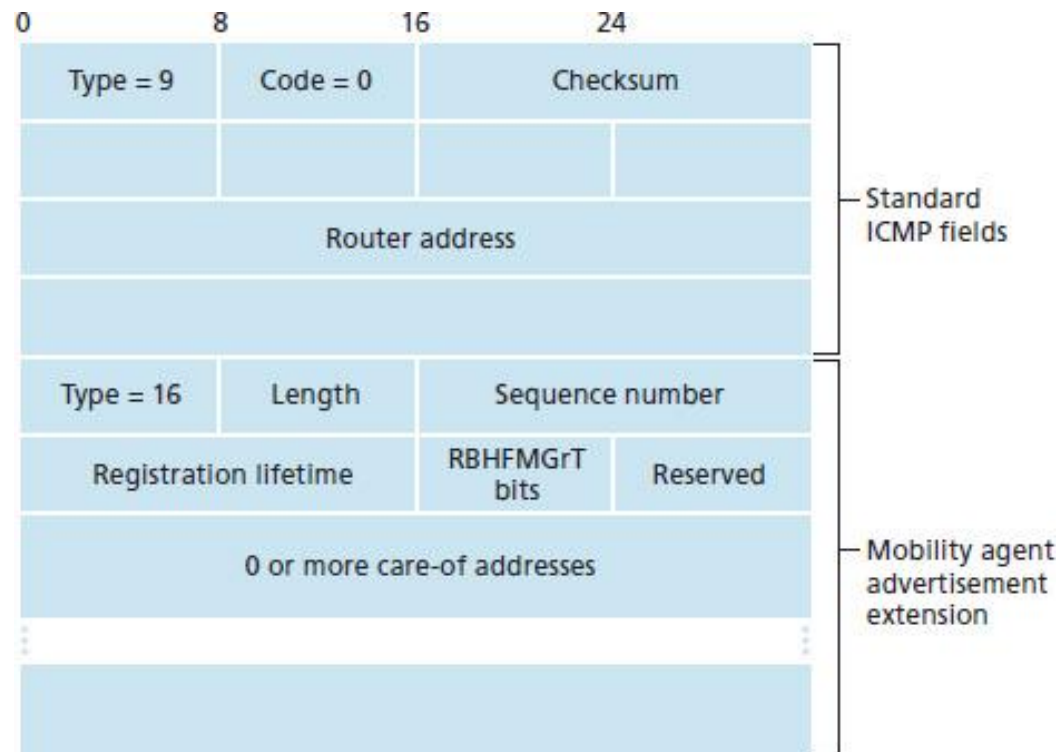
7.8 Mobility and higher-layer protocols

Mobile IP

- RFC 3344

- 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
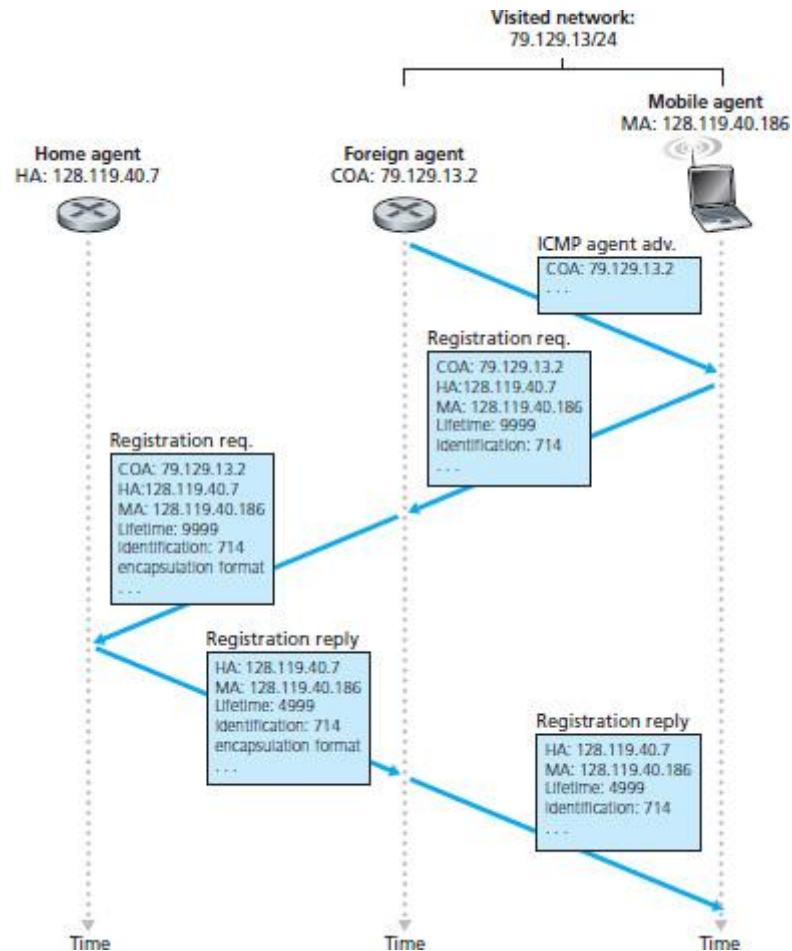
Pearson

Mobile IP: Indirect routing

foreign-agent-to-mobile packet

dest: 128.119.40.186

packet sent by home agent to foreign agent: a **packet within a packet**

dest: 79.129.13.2 | dest: 128.119.40.186

Permanent address:
128.119.40.186

Care-of address:
79.129.13.2

dest: 128.119.40.186

packet sent by correspondent

Pearson
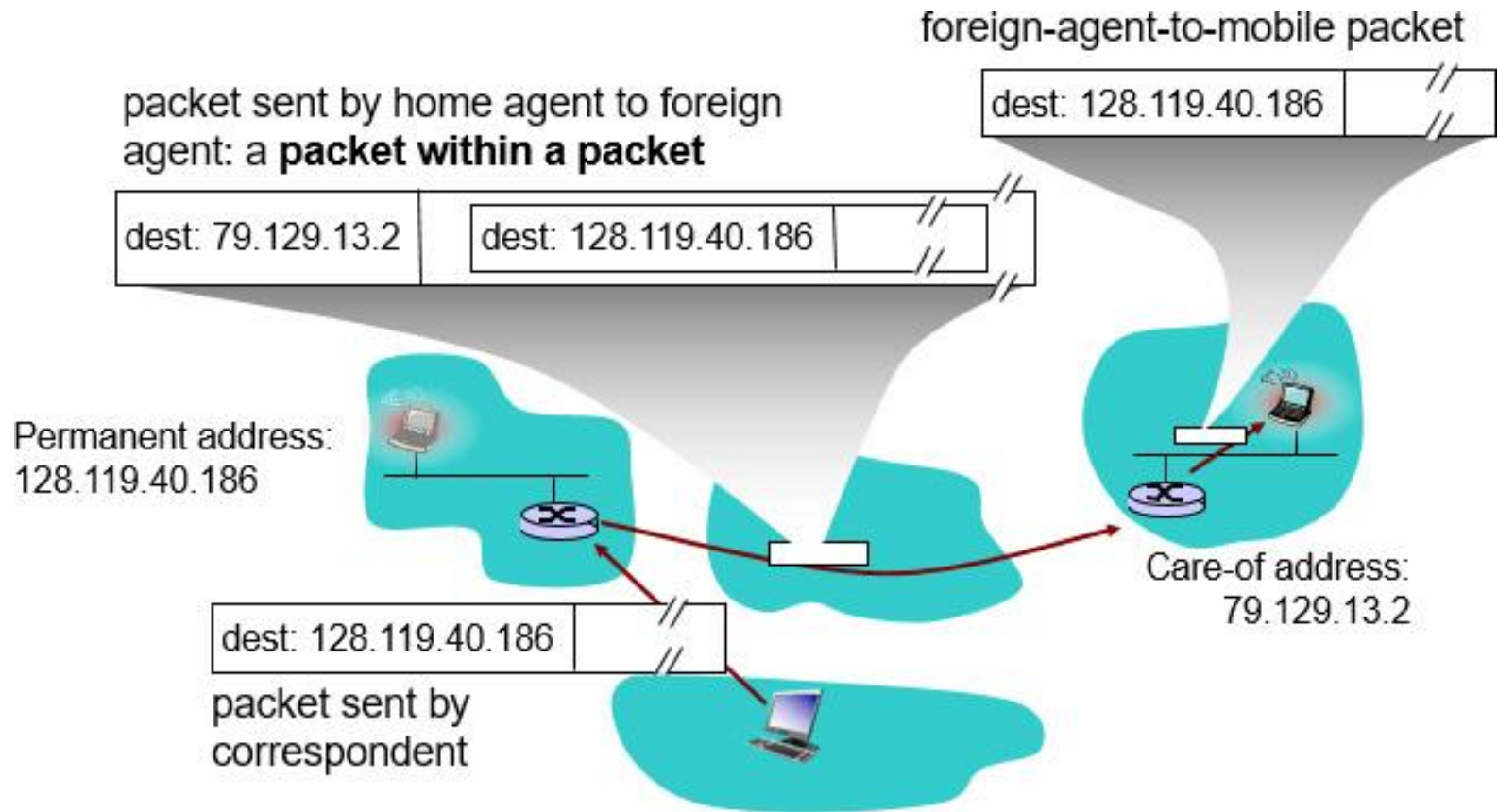
Mobile IP: Agent discovery

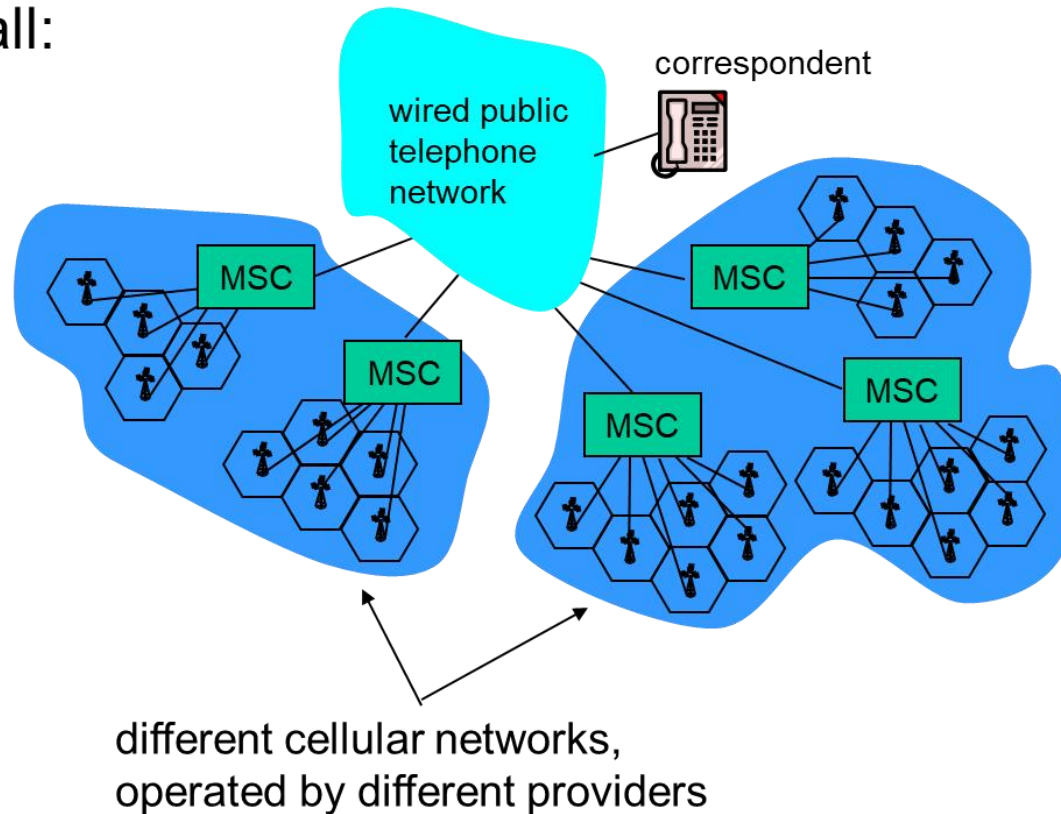- **Agent Advertisement:** Foreign/Home agents advertise service by broadcasting ICMP messages (typefield = 9)

Mobile IP: Registration Example

recall:

correspondent

wired public telephone network

MSC

MSC

MSC

MSC

MSC

different cellular networks, operated by different providers

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
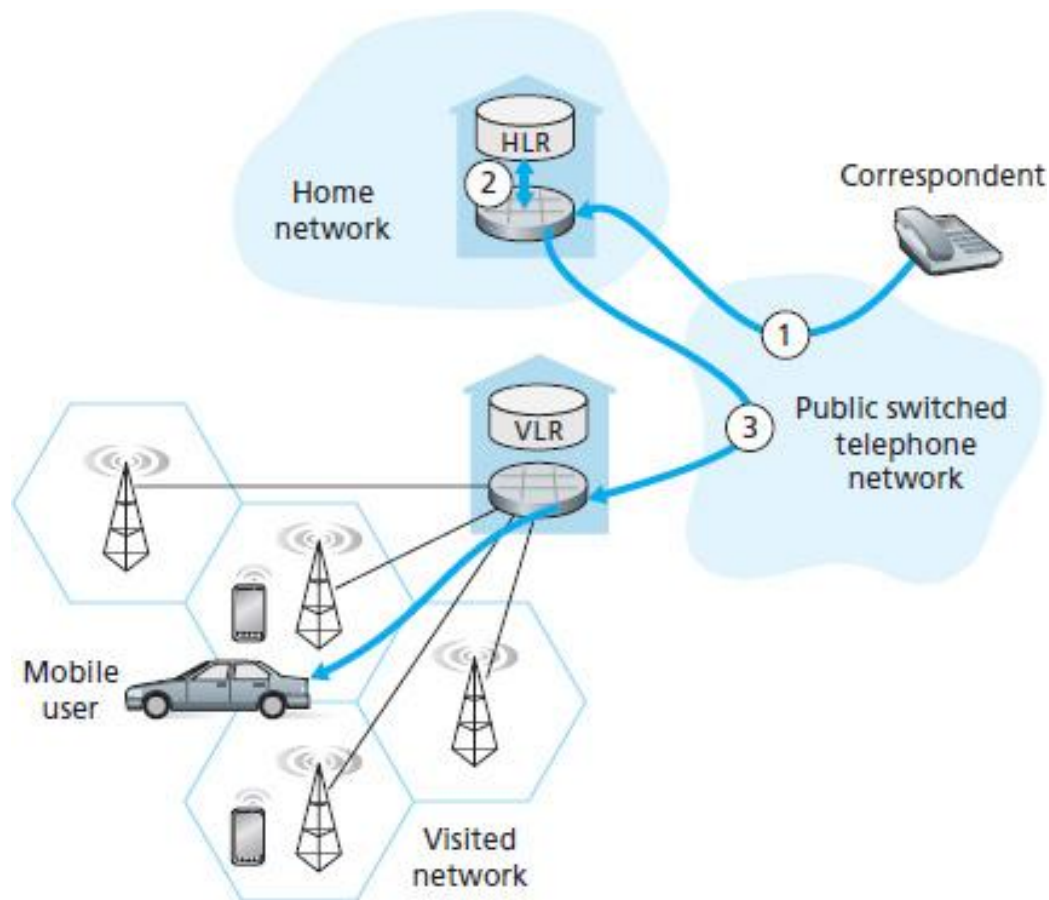
GSM: Handoff with Common MSC

- **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
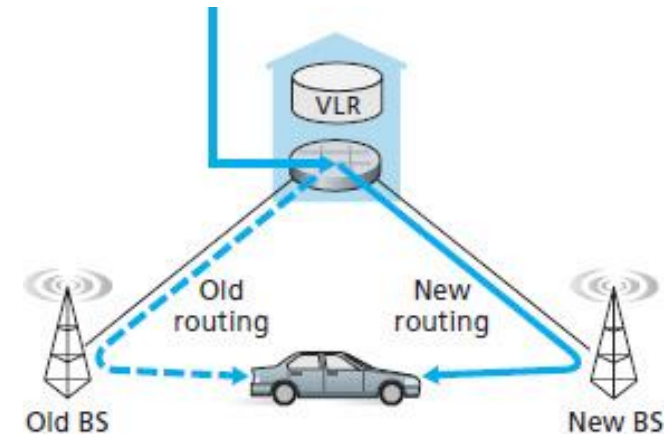
GSM: Handoff with Common MSC

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.

8. MSC reroutes call resources released
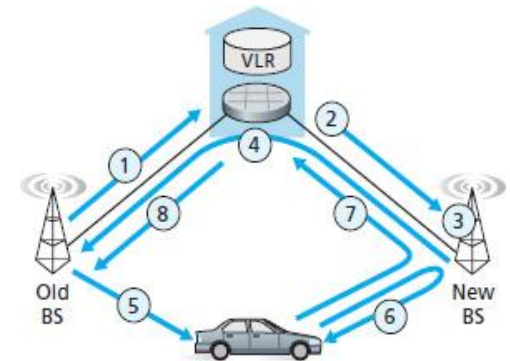
GSM: Handoff Between MSCs

- **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

- optional path minimization step to shorten multi-MSC chain
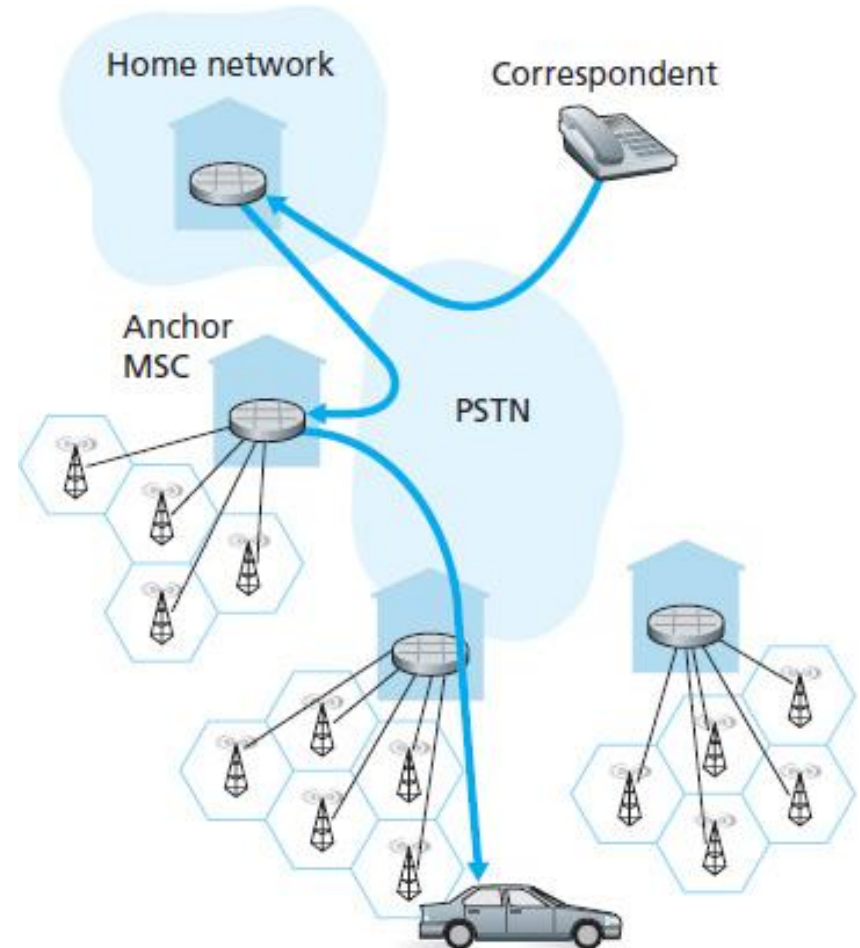
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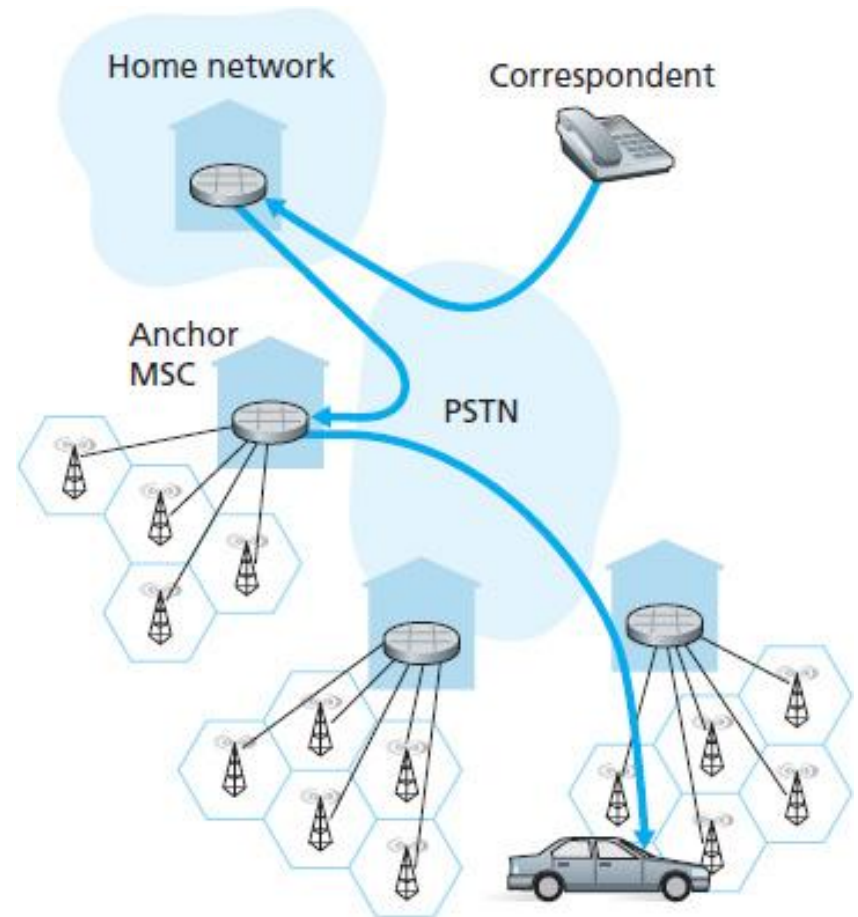
Handling Mobility in LTE

- Paging: idle UE may move from cell to cell: network does not know where the idle UE is resident

  – paging message from M ME broadcast by all eNodeB to locate UE

- Handoff: similar to 3G:

  – preparation phase

  – execution phase

  – completion phase
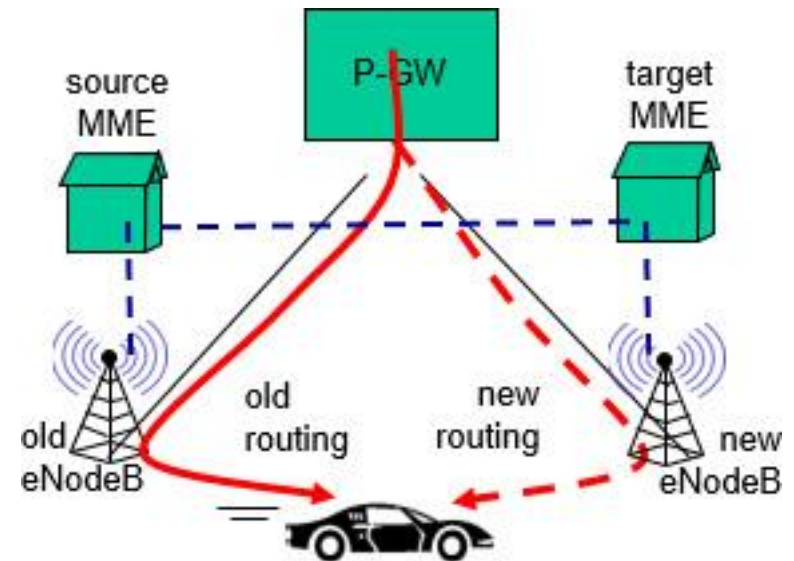
Mobility: Cellular Versus Mobile IP

Cellular element	Comment on cellular element	Mobile IP element
Home system	Network to which mobile user's permanent phone number belongs	Home network
Gateway Mobile Switching Center, or "home MSC". Home Location Register (HLR)	Home MSC: point of contact to obtain routable address of mobile user. HLR: database in home system containing permanent phone number, profile information, current location of mobile user, subscription information	Home agent
Visited System	Network other than home system where mobile user is currently residing	Visited network
Visited Mobile services Switching Center. Visitor Location Record (VLR)	Visited MSC: responsible for setting up calls to/from mobile nodes in cells associated with MSC. VLR: temporary database entry in visited system, containing subscription information for each visiting mobile user	Foreign agent
Mobile Station Roaming Number (MSRN), or "roaming number"	Routable address for telephone call segment between home MSC and visited MSC, visible to neither the mobile nor the correspondent.	Care-of-address

Wireless, Mobility: Impact on Higher Layer Protocols

- Logically, impact **should** be minimal …
    - best effort service model remains unchanged
    - TCP and UDP can (and do) run over wireless, mobile

- … but performance-wise:
    - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handoff
    - TCP interprets loss as congestion, will decrease congestion window un-necessarily
    - delay impairments for real-time traffic
    - limited bandwidth of wireless links

Chapter summary

Wireless

- wireless links:
  - – capacity, distance
  - – channel impairments
  - – CDMA

- IEEE 802.11 ("Wi-Fi")
  - – CSMA/CA reflects wireless channel characteristics

- cellular access
  - – architecture
  - – standards (e.g., 3G, 4G LTE)

Chapter summary

Mobility

- principles: addressing, routing to mobile users
  - home, visited networks
  - direct, indirect routing
  - care-of-addresses

- case studies
  - mobile IP
  - mobility in GSM, LTE

- impact on higher-layer protocols

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