

Chapter 3: roadmap

- Transport-layer services
- Multiplexing and demultiplexing
- Connectionless transport: UDP
- Principles of reliable data transfer
- Connection-oriented transport: TCP
- **Principles of congestion control**
- TCP congestion control
- Evolution of transport-layer functionality



Principles of congestion control

Congestion:

- informally: “too many sources sending too much data too fast for *network* to handle”
- manifestations:
 - long delays (queueing in router buffers)
 - packet loss (buffer overflow at routers)
- different from flow control!
- a top-10 problem!



congestion control:

too many senders,
sending too fast

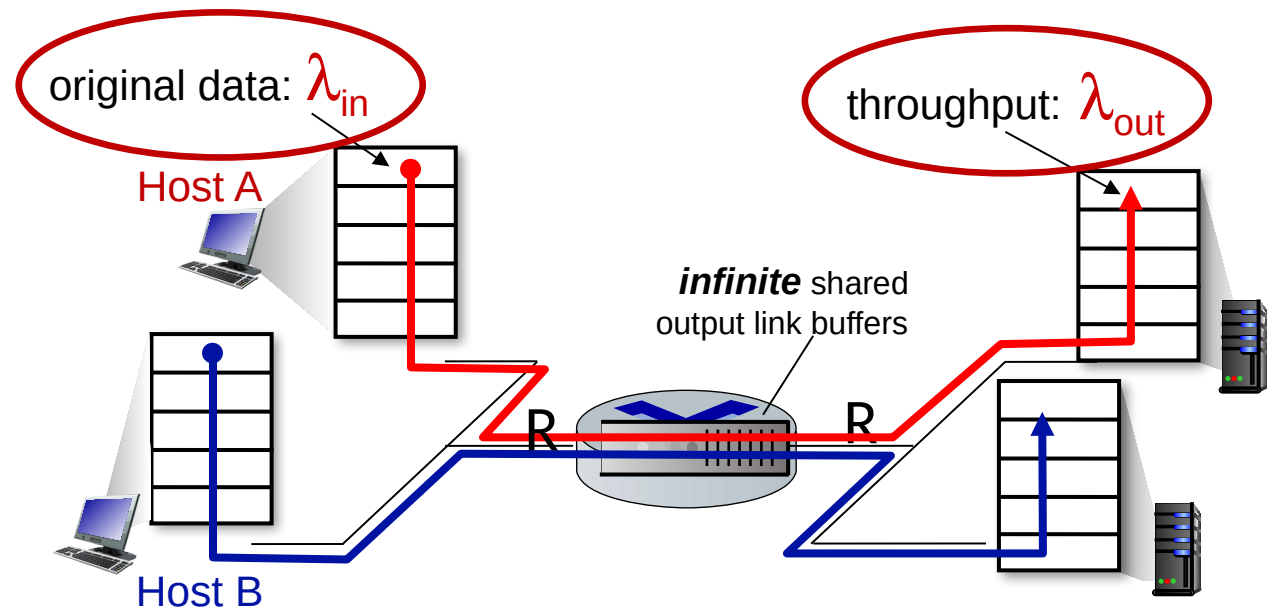


flow control: one sender
too fast for one receiver

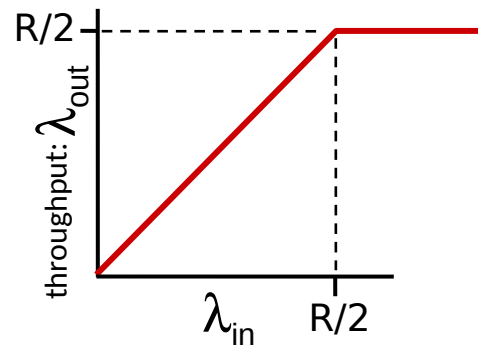
Causes/costs of congestion: scenario 1

Simplest scenario:

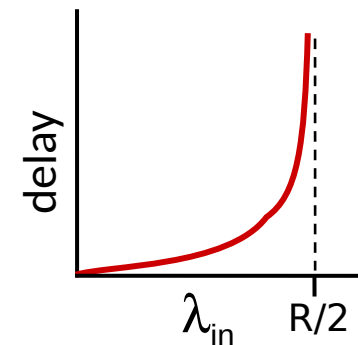
- one router, infinite buffers
- input, output link capacity: R
- two flows
- no retransmissions needed



Q: What happens as arrival rate λ_{in} approaches $R/2$?



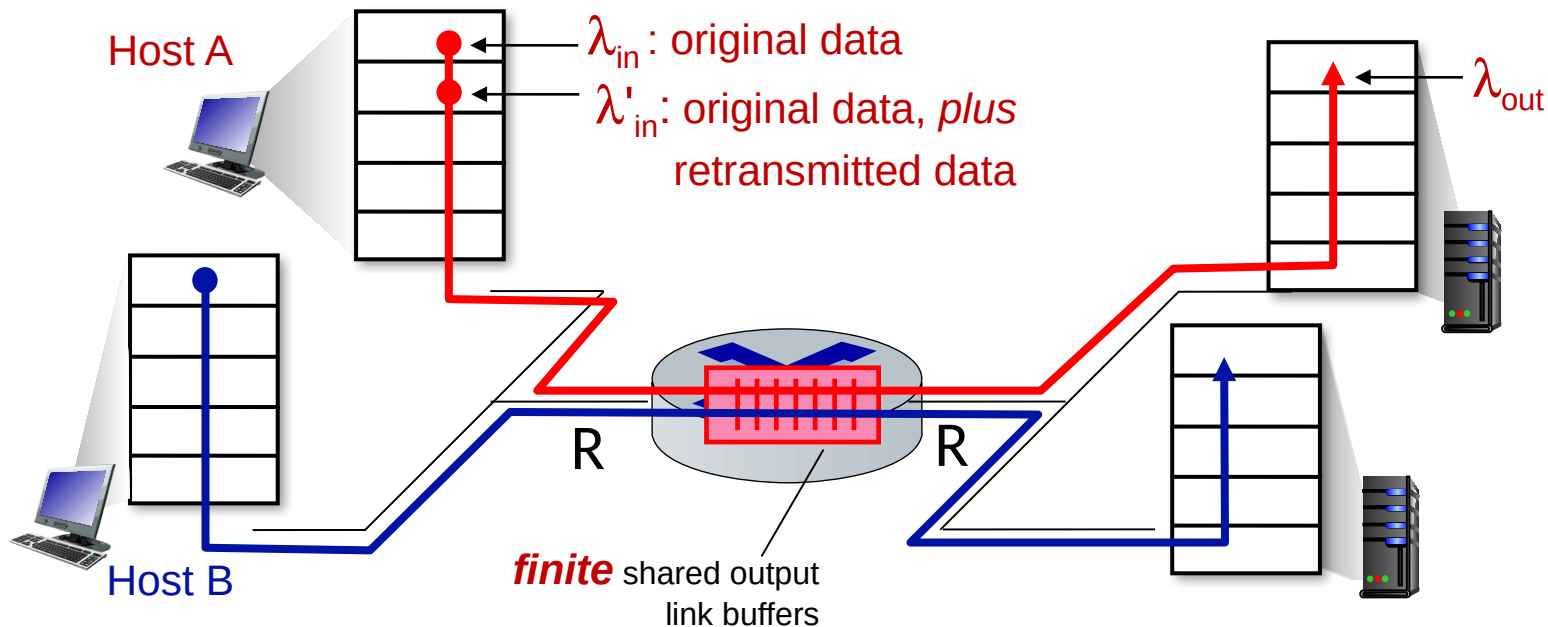
maximum per-connection throughput: $R/2$



large delays as arrival rate λ_{in} approaches capacity

Causes/costs of congestion: scenario 2

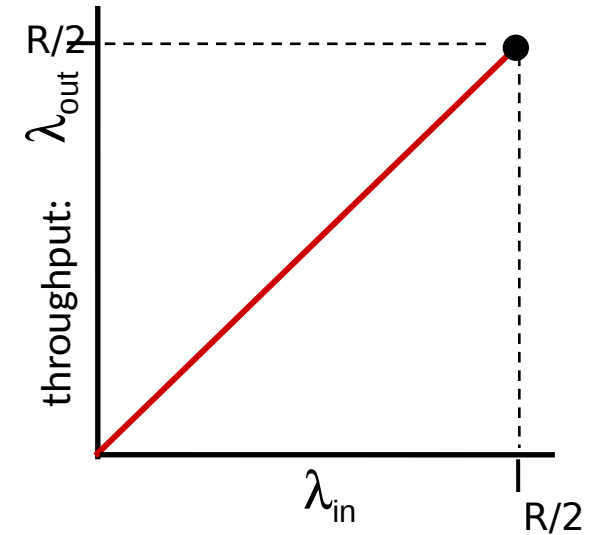
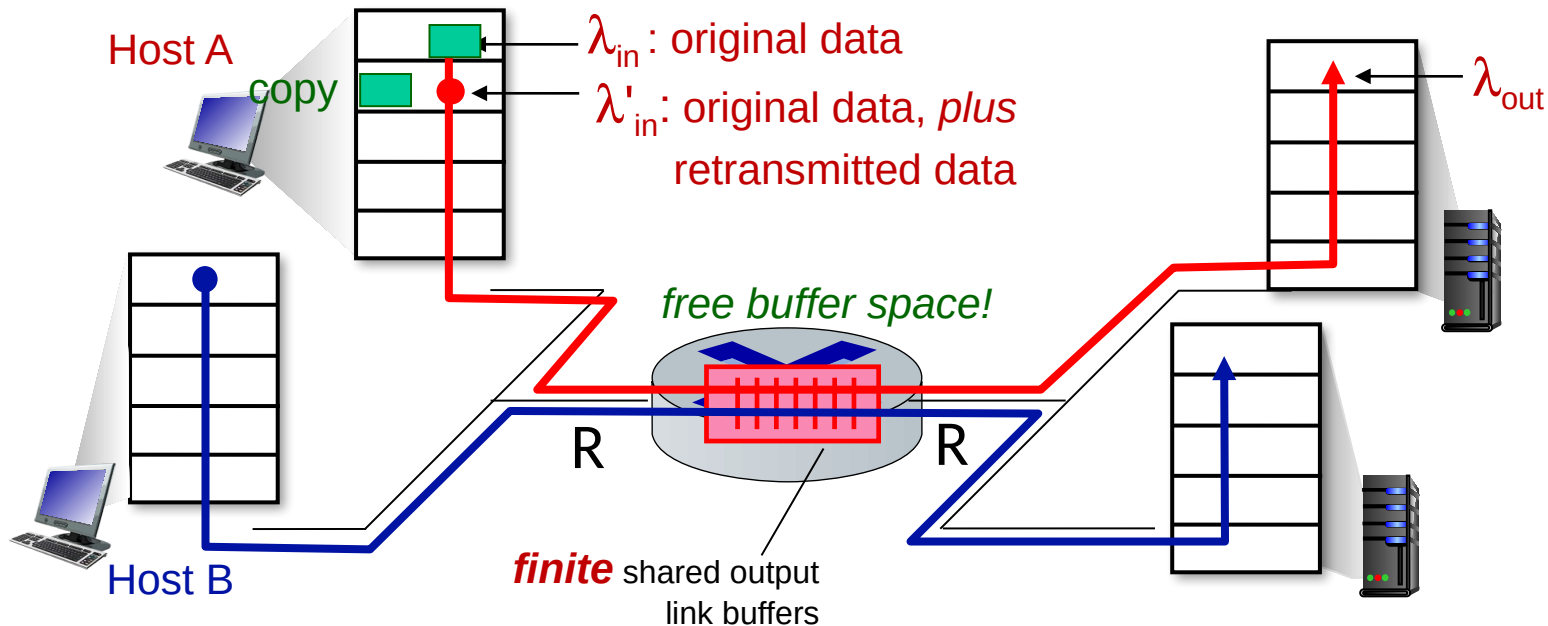
- one router, *finite* buffers
- sender retransmits lost, timed-out packet
 - application-layer input = application-layer output: $\lambda_{in} = \lambda_{out}$
 - transport-layer input includes *retransmissions* : $\lambda'_{in} \geq \lambda_{in}$



Causes/costs of congestion: scenario 2

Idealization: perfect knowledge

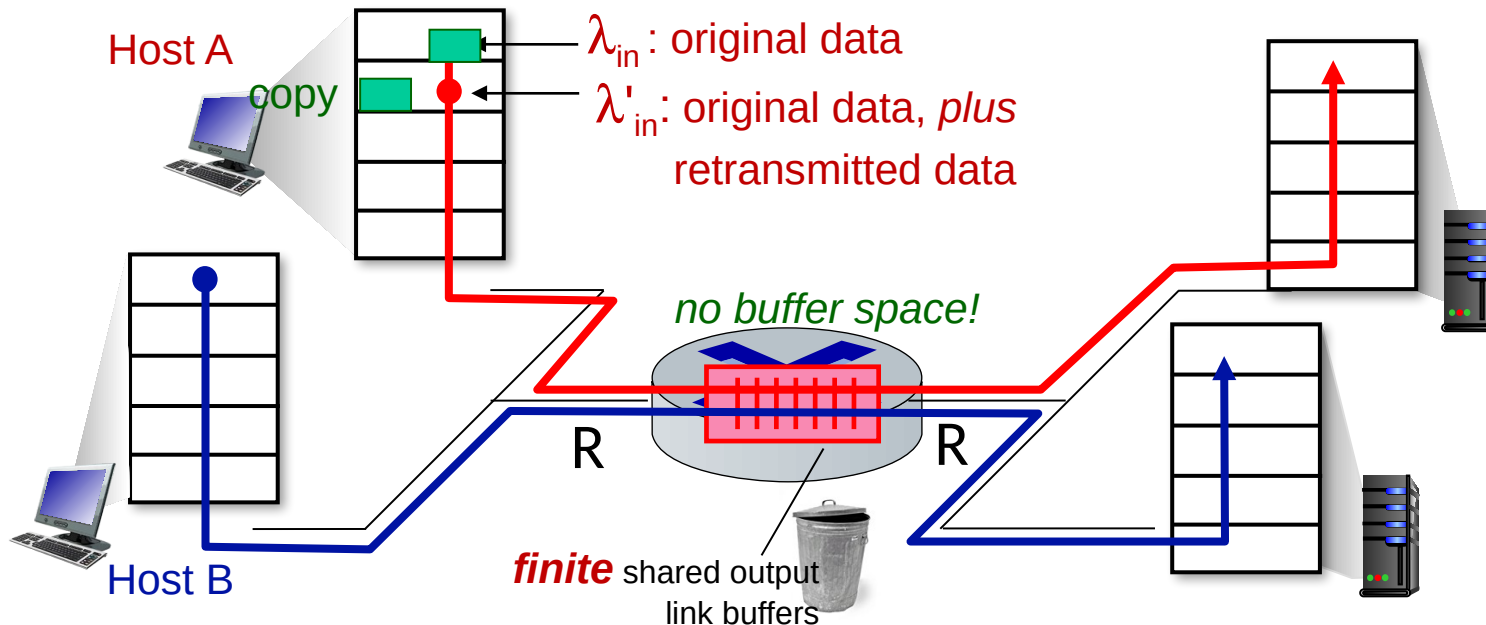
- sender sends only when router buffers available



Causes/costs of congestion: scenario 2

Idealization: *some* perfect knowledge

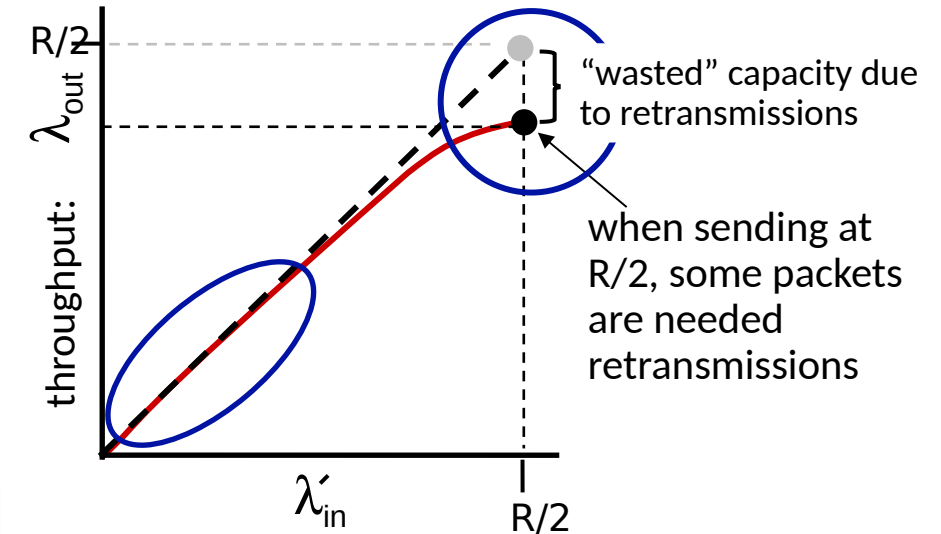
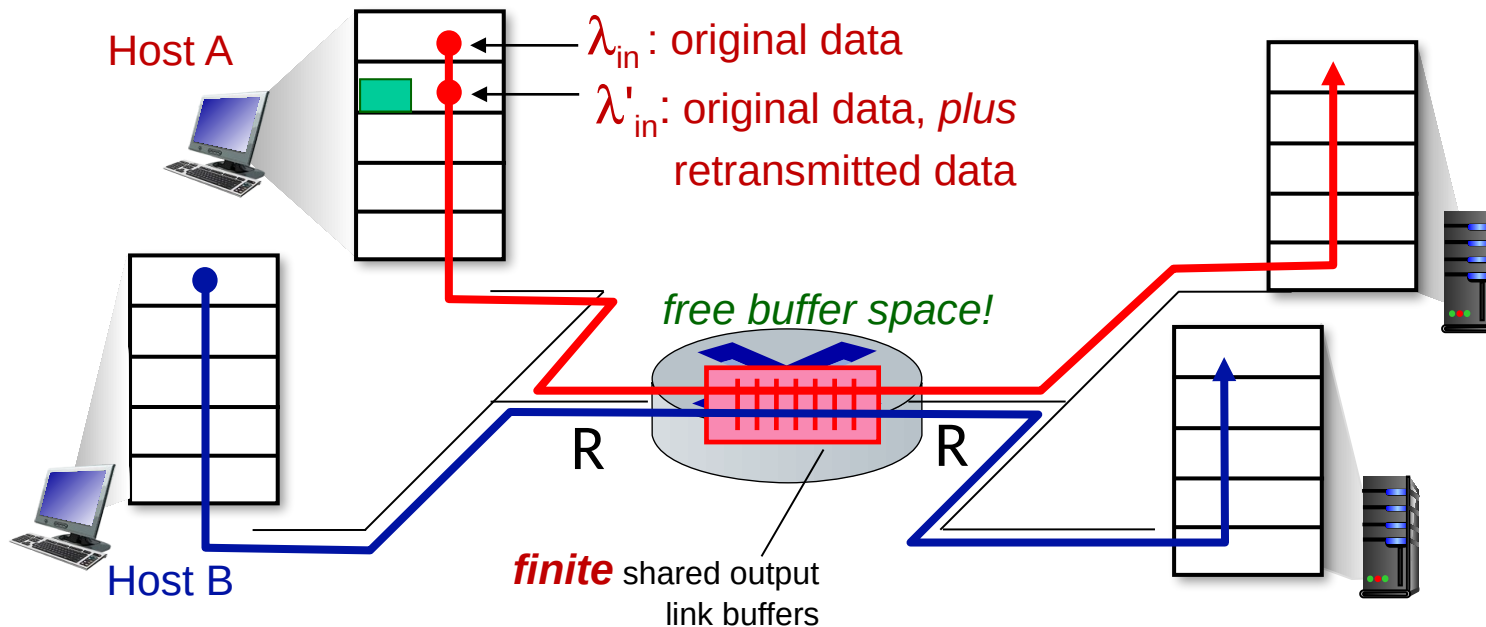
- packets can be lost (dropped at router) due to full buffers
- sender knows when packet has been dropped: only resends if packet *known* to be lost



Causes/costs of congestion: scenario 2

Idealization: *some* perfect knowledge

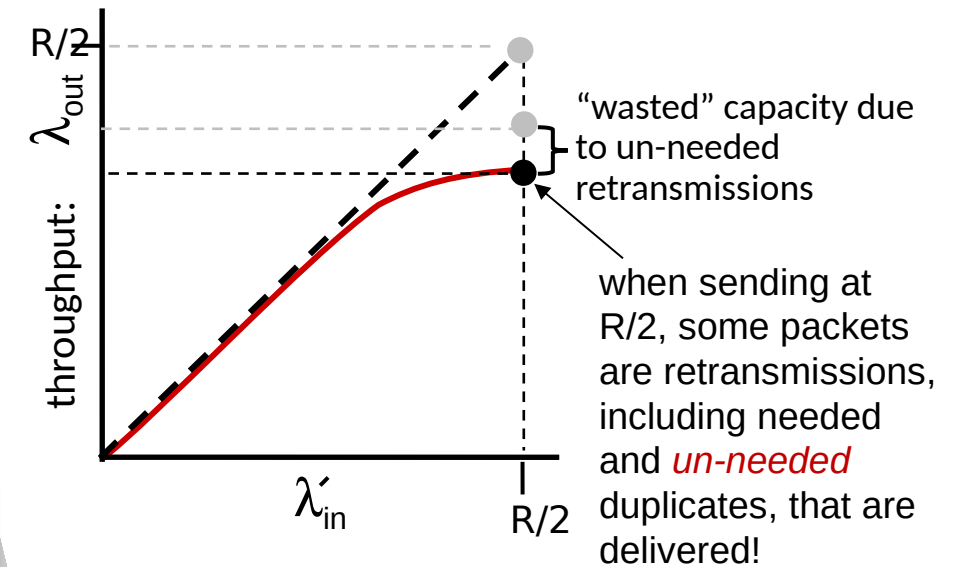
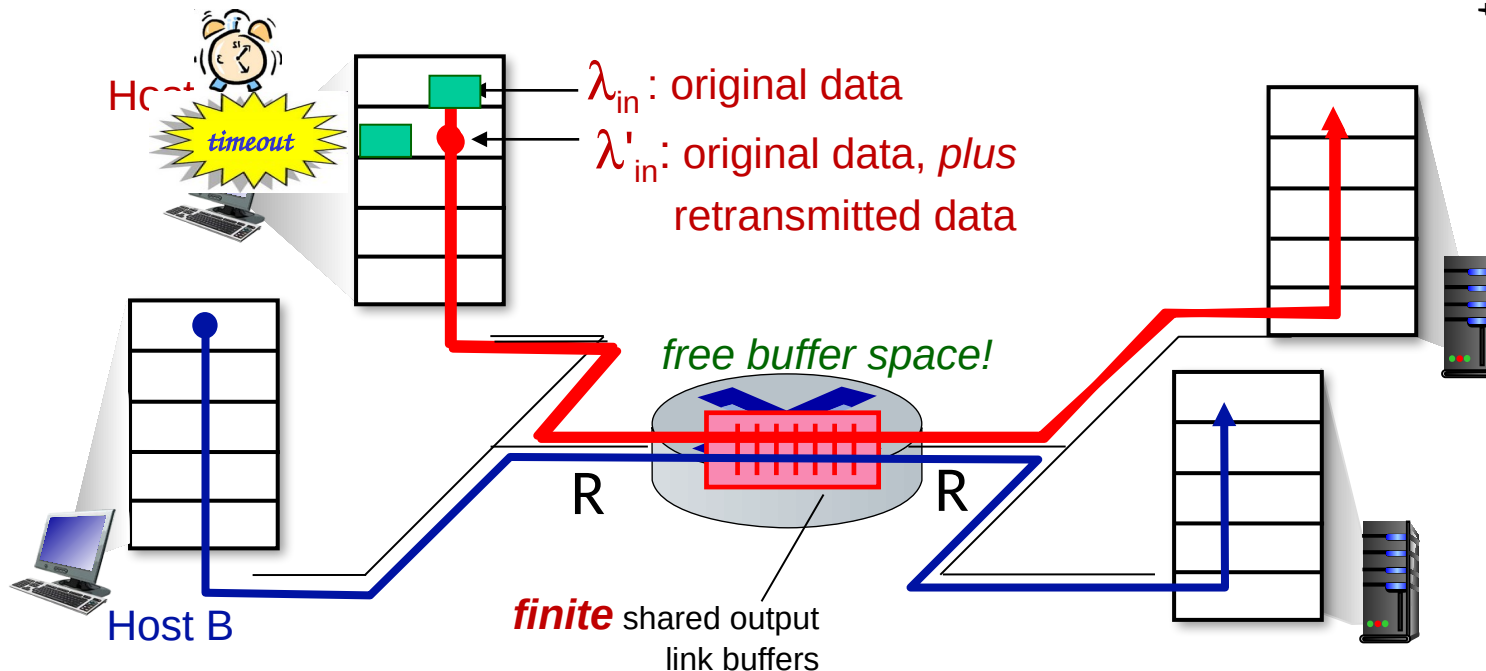
- packets can be lost (dropped at router) due to full buffers
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Causes/costs of congestion: scenario 2

Realistic scenario: *un-needed duplicates*

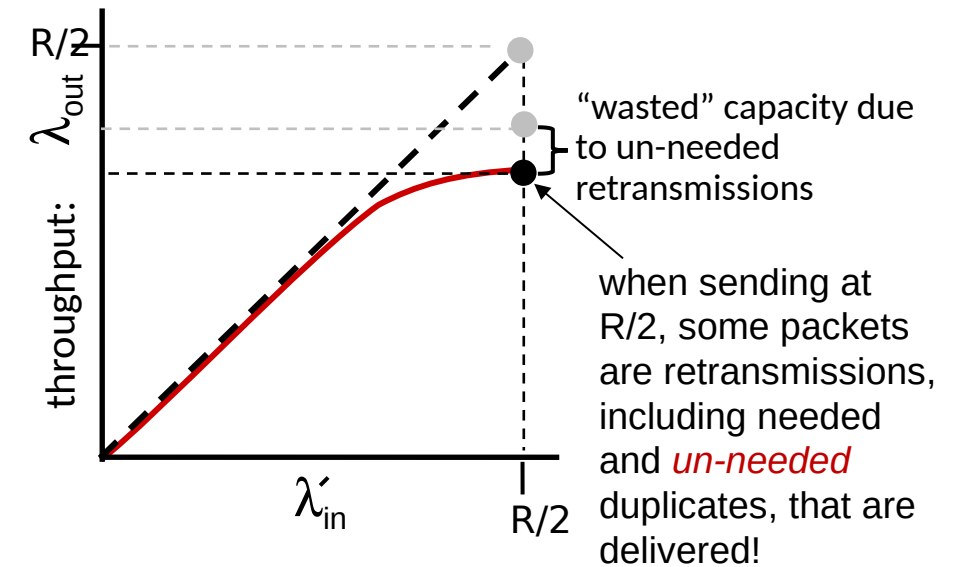
- packets can be lost, dropped at router due to full buffers – requiring retransmissions
- but sender times can time out prematurely, sending *two* copies, *both* of which are delivered



Causes/costs of congestion: scenario 2

Realistic scenario: *un-needed duplicates*

- packets can be lost, dropped at router due to full buffers – requiring retransmissions
- but sender times can time out prematurely, sending *two* copies, *both* of which are delivered



“costs” of congestion:

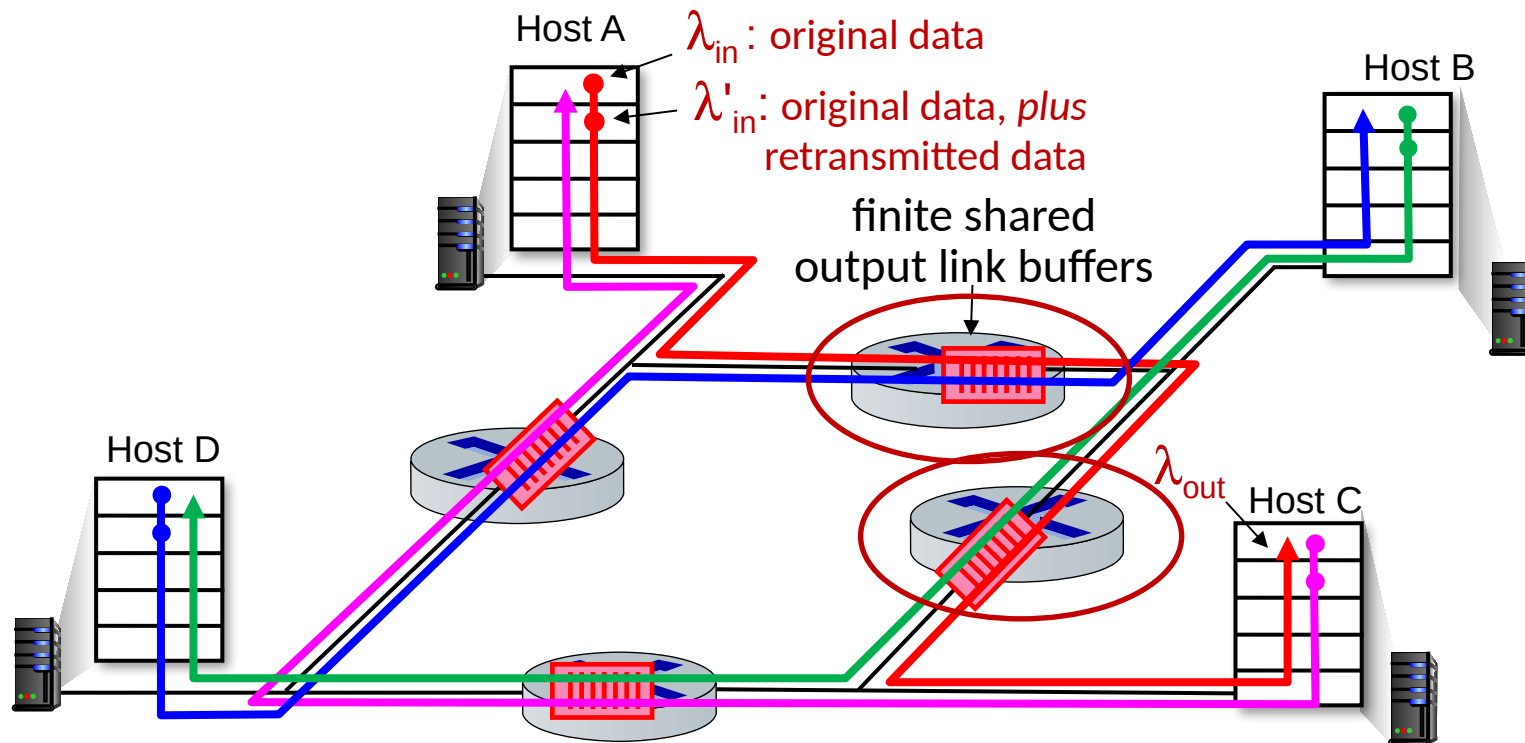
- more work (retransmission) for given receiver throughput
- unneeded retransmissions: link carries multiple copies of a packet
 - decreasing maximum achievable throughput

Causes/costs of congestion: scenario 3

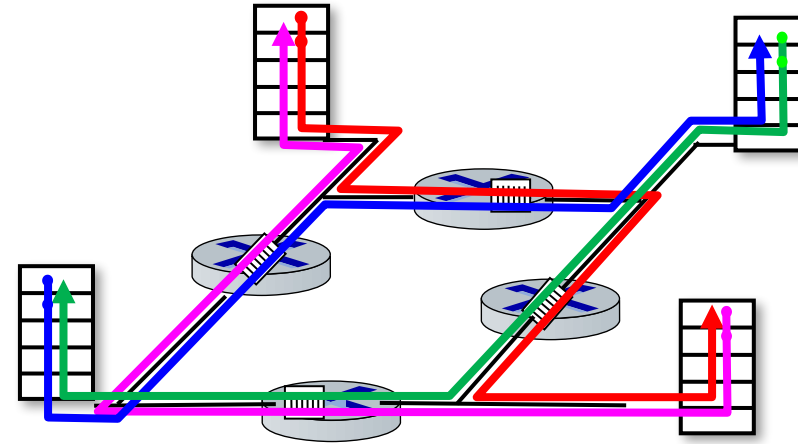
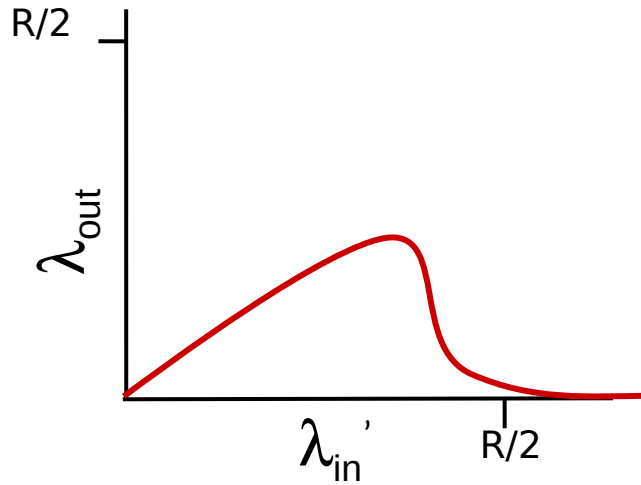
- four senders
- multi-hop paths
- timeout/retransmit

Q: what happens as λ_{in} and λ'_{in} increase ?

A: as red λ'_{in} increases, all arriving blue pkts at upper queue are dropped, blue throughput $\rightarrow 0$



Causes/costs of congestion: scenario 3

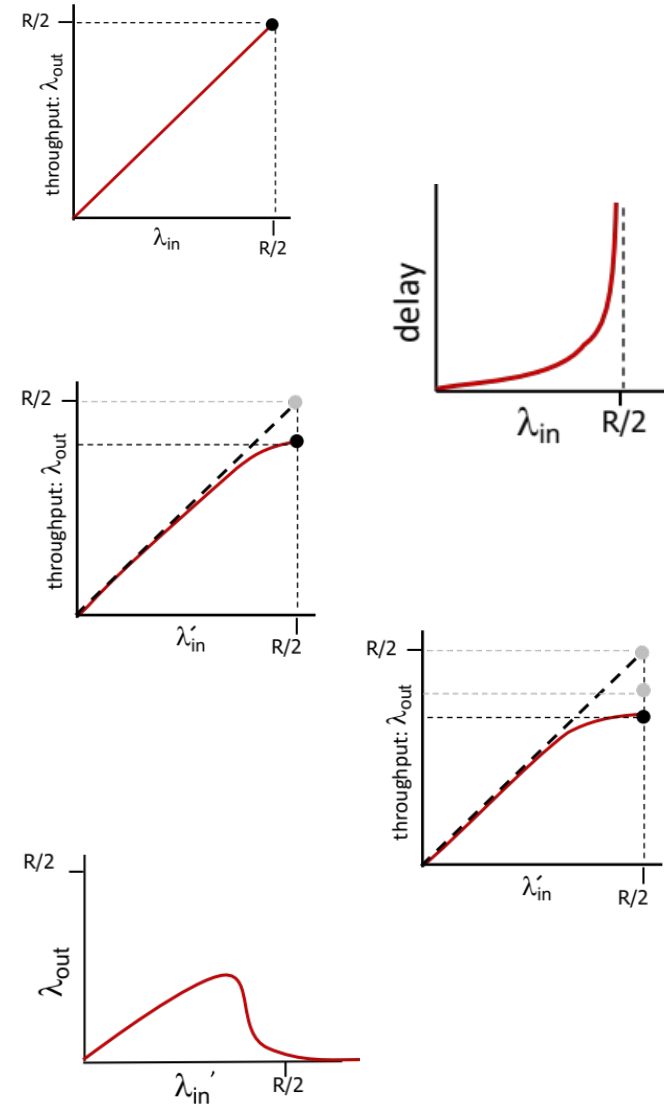


another “cost” of congestion:

- when packet dropped, any upstream transmission capacity and buffering used for that packet was wasted!

Causes/costs of congestion: insights

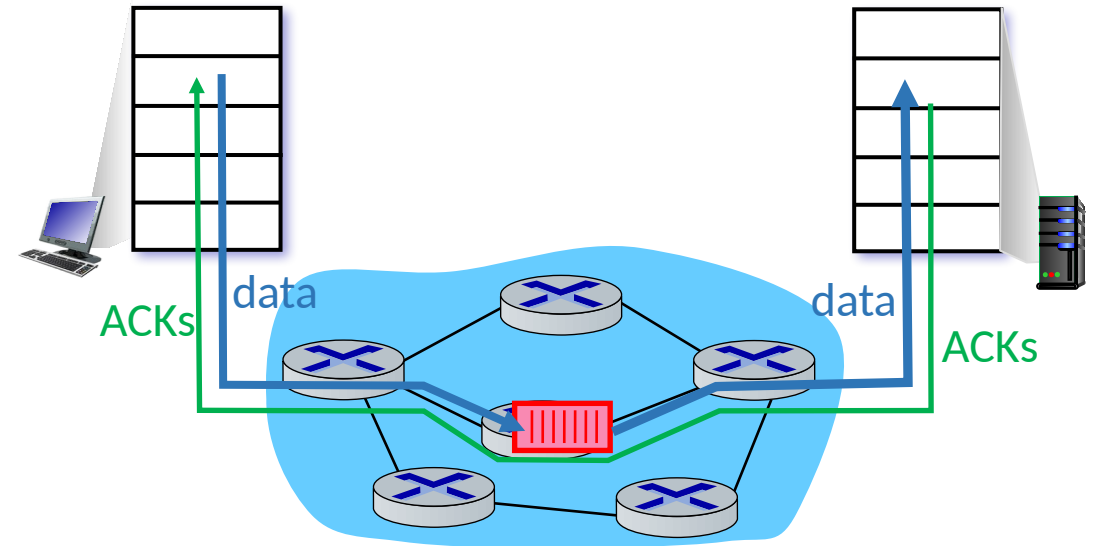
- throughput can never exceed capacity
- delay increases as capacity approached
- loss/retransmission decreases effective throughput
- un-needed duplicates further decreases effective throughput
- upstream transmission capacity / buffering wasted for packets lost downstream



Approaches towards congestion control

End-end congestion control:

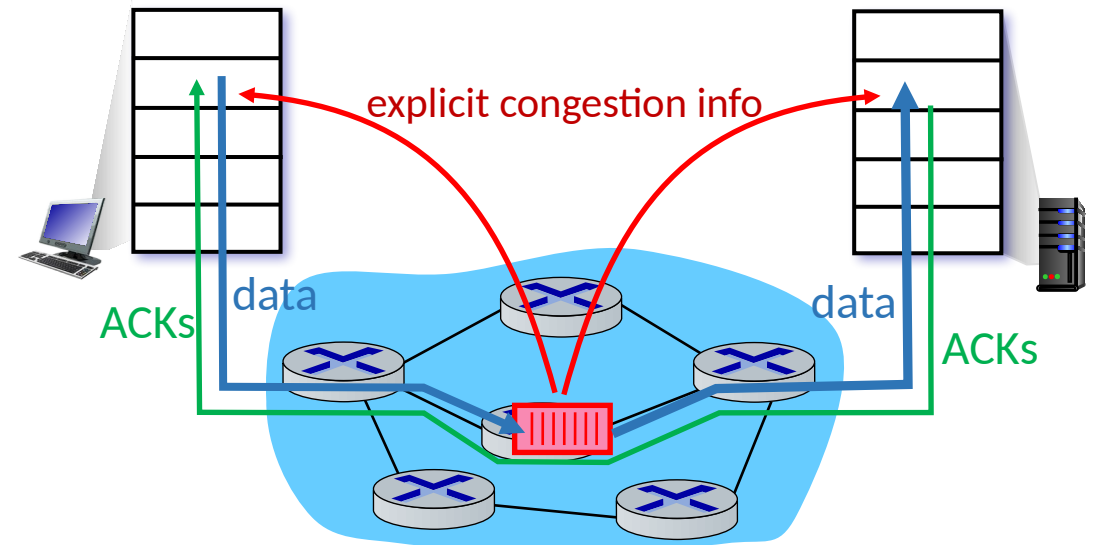
- no explicit feedback from network
- congestion *inferred* from observed loss, delay
- approach taken by TCP



Approaches towards congestion control

Network-assisted congestion control:

- routers provide *direct* feedback to sending/receiving hosts with flows passing through congested router
- may indicate congestion level or explicitly set sending rate
- TCP ECN, ATM, DECbit protocols



TCP congestion control: AIMD

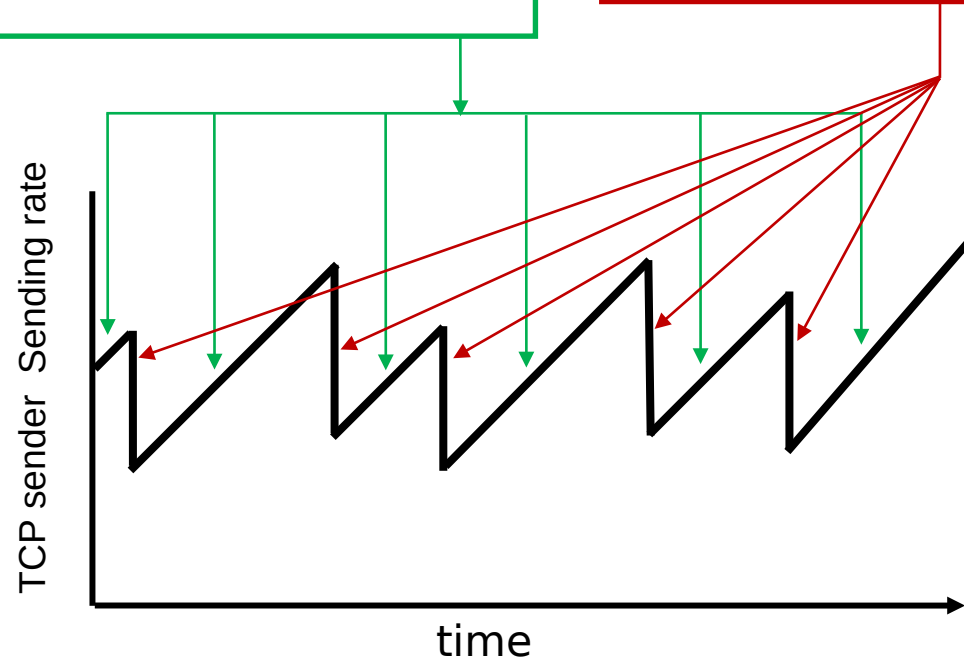
- *approach*: senders can increase sending rate until packet loss (congestion) occurs, then decrease sending rate on loss event

Additive Increase

increase sending rate by 1 maximum segment size every RTT until loss detected

Multiplicative Decrease

cut sending rate in half at each loss event



AIMD sawtooth behavior: *probing* for bandwidth

Class 8

Wireless and Mobile Networks

Context

- more wireless (mobile) phone subscribers than fixed (wired) phone subscribers (10-to-1 in 2019)!
- more mobile-broadband-connected devices than fixed-broadband-connected devices (5-1 in 2019)!
 - 4G/5G cellular networks now embracing Internet protocol stack, including SDN
- two important (but different) challenges
 - **wireless**: communication over wireless link
 - **mobility**: handling the mobile user who changes point of attachment to network

Chapter 7 outline

- Introduction

Wireless

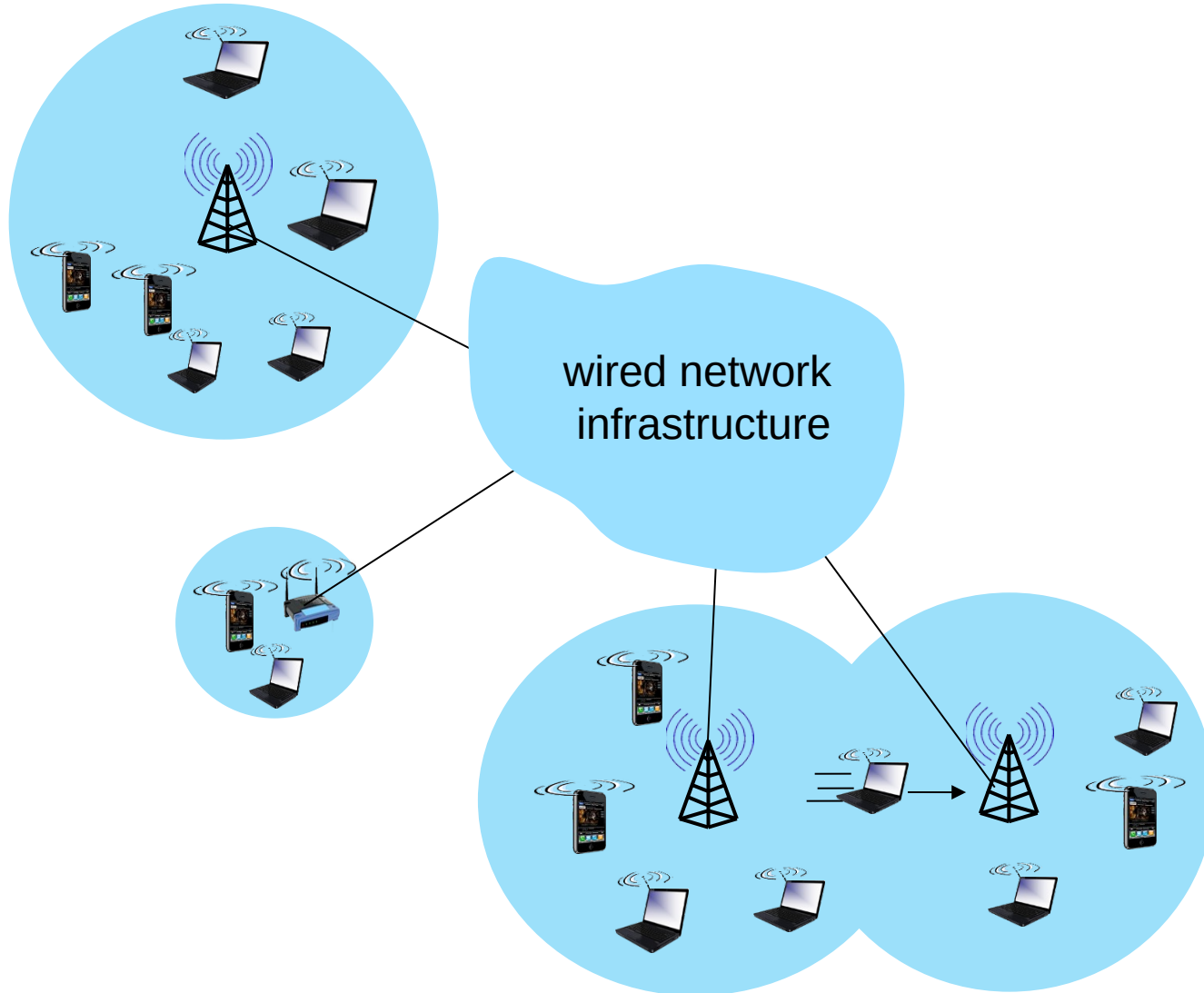
- Wireless Links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G

Mobility

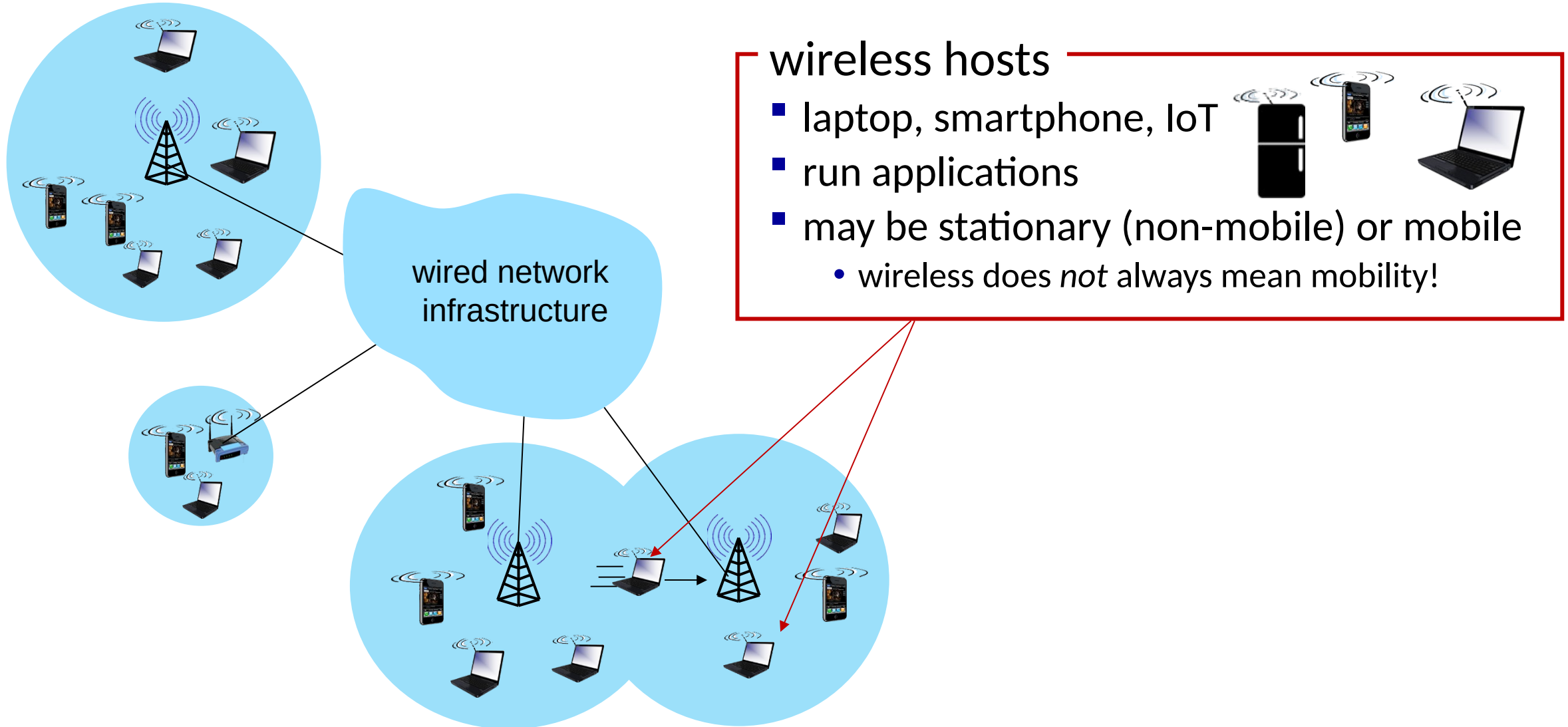
- Mobility management: principles
- Mobility management: practice
 - 4G/5G networks
 - Mobile IP
- Mobility: impact on higher-layer protocols



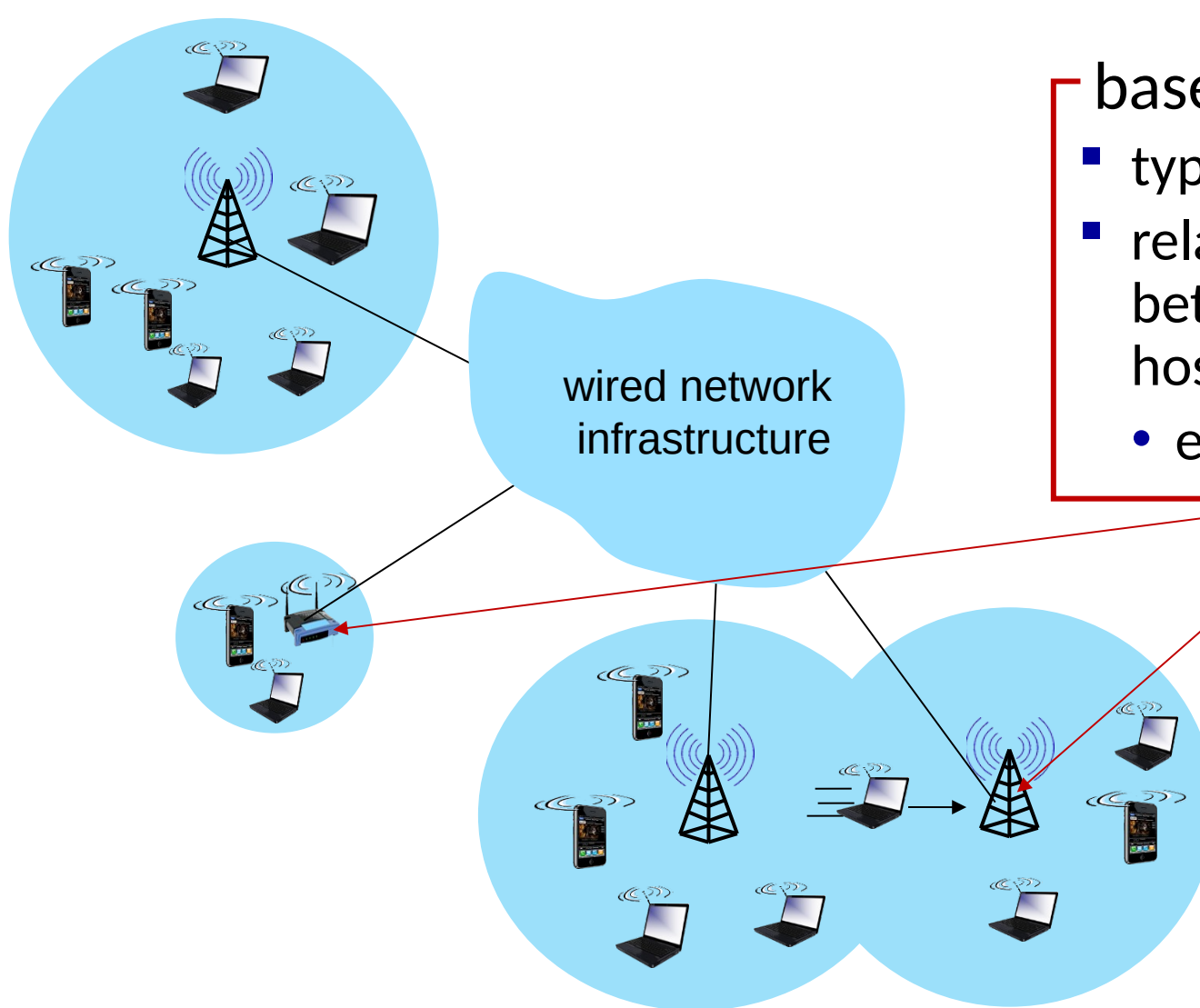
Elements of a wireless network



Elements of a wireless network



Elements of a wireless network

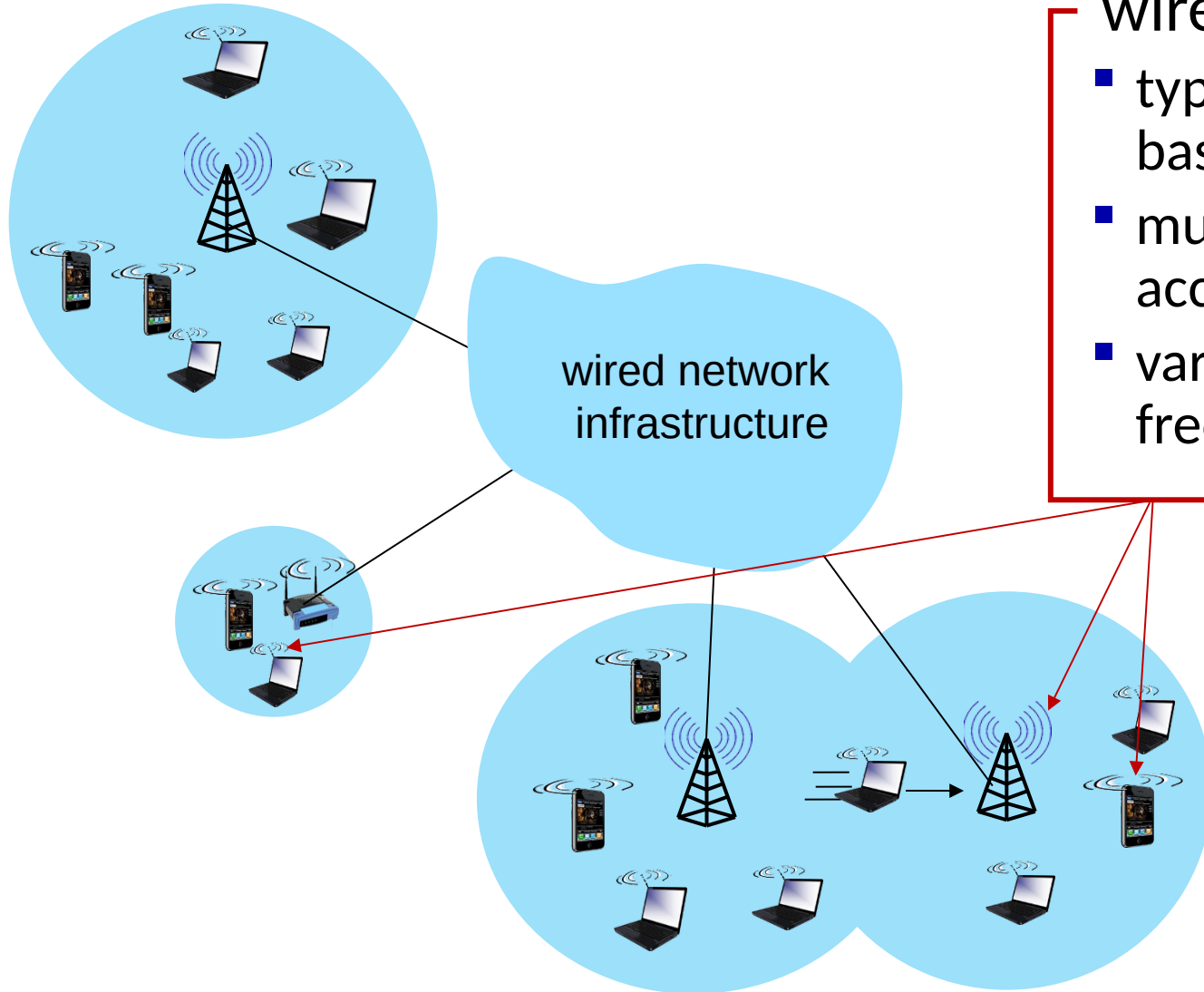


base station



- 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

Elements of a wireless network

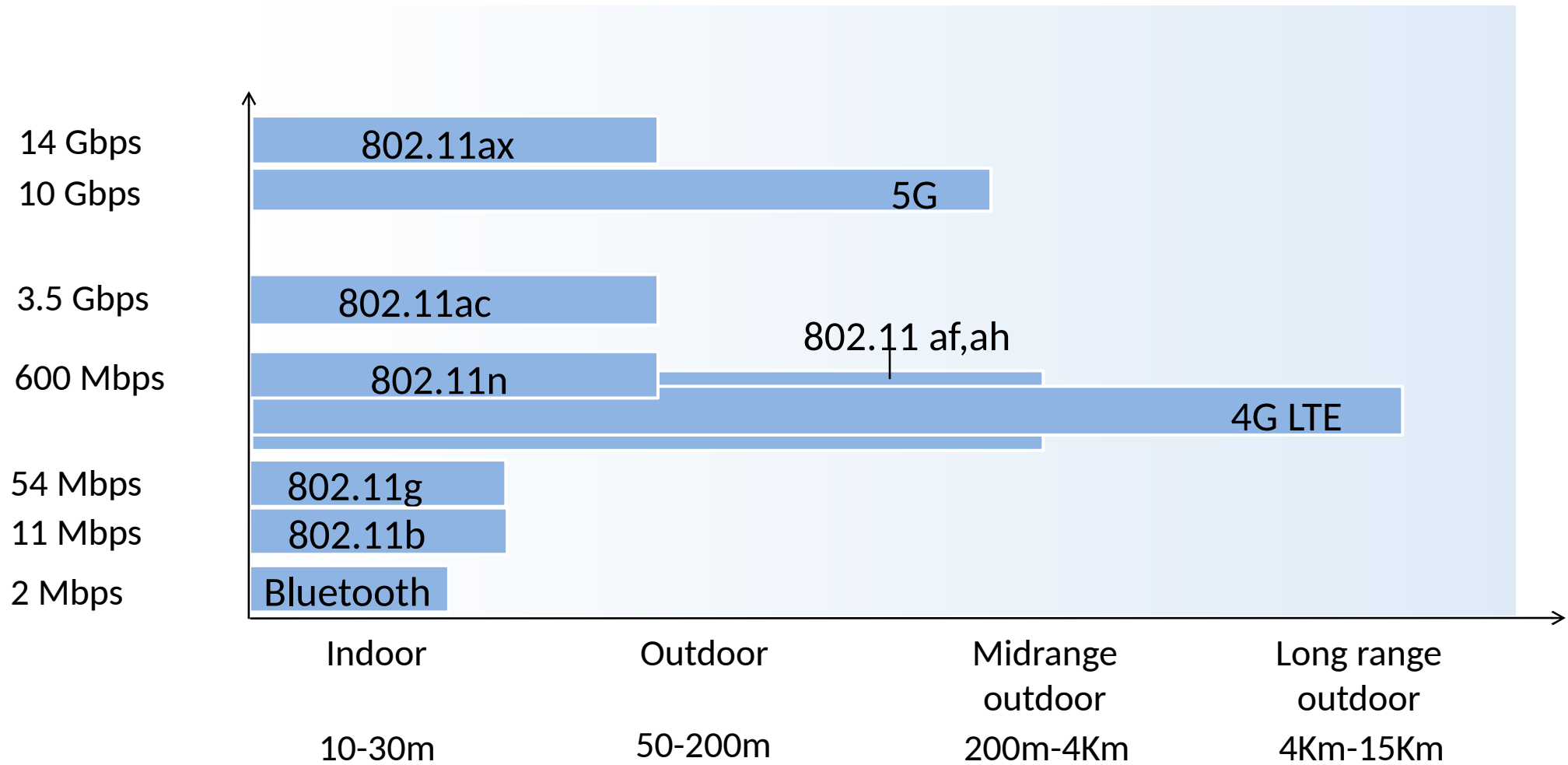


wireless link

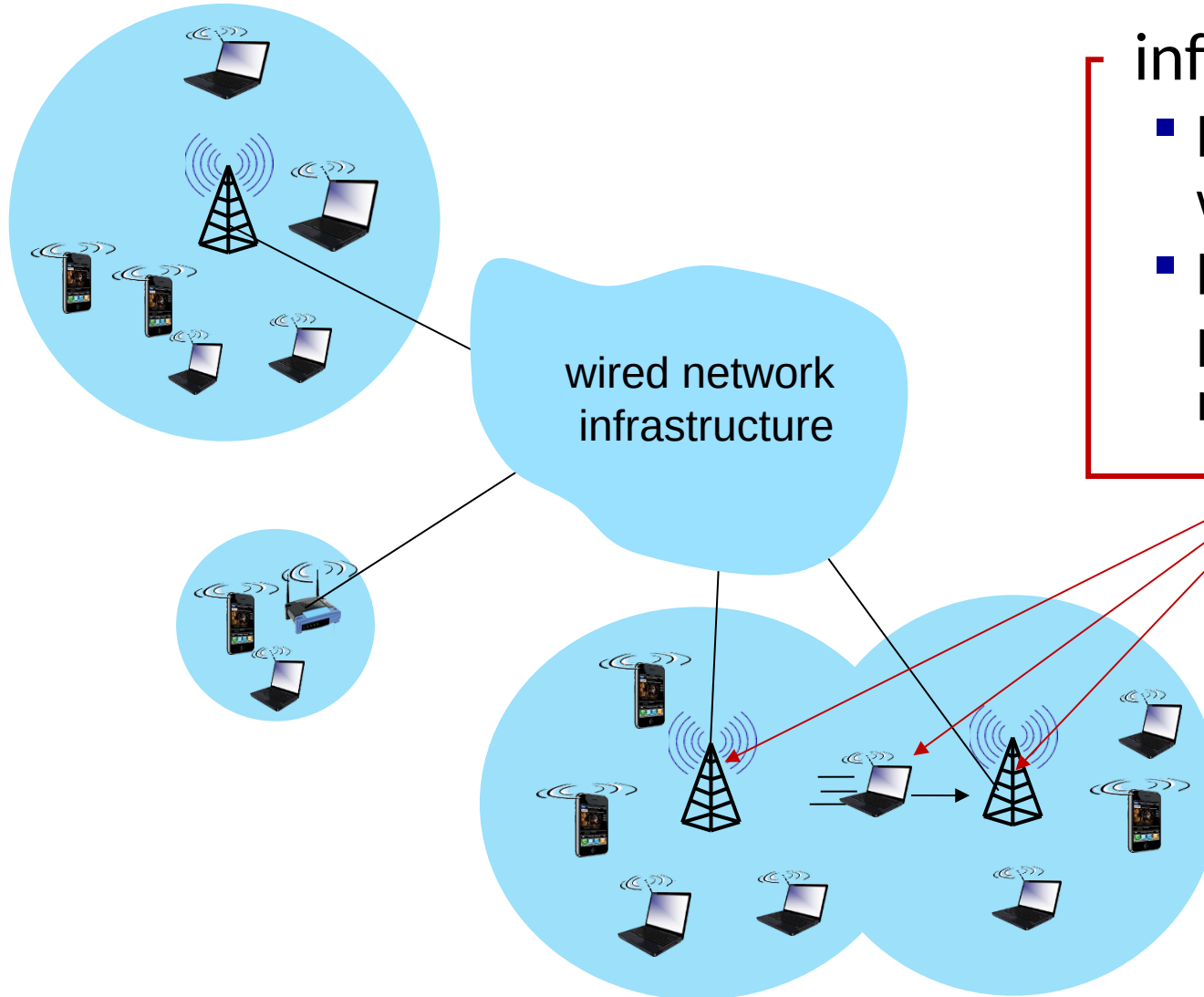


- typically used to connect mobile(s) to base station, also used as backbone link
- multiple access protocol coordinates link access
- various transmission rates and distances, frequency bands

Characteristics of selected wireless links



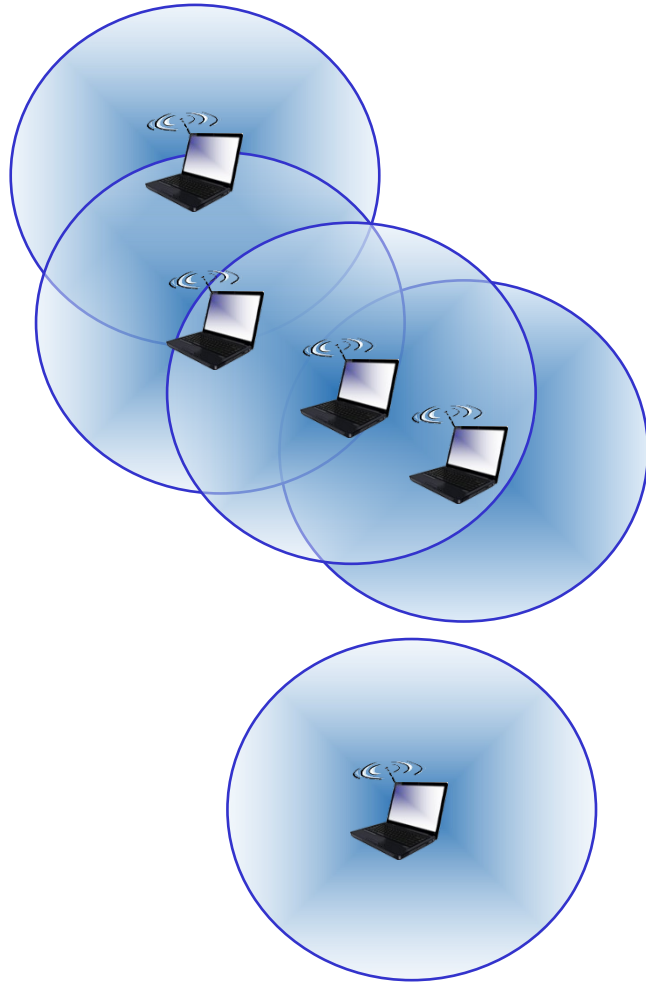
Elements of a wireless network



infrastructure mode

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

Elements of a wireless network



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, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: <i>mesh net</i>
<i>no infrastructure</i>	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 MANET, VANET

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- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G

Mobility

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Wireless link characteristics (1)

important differences from wired link

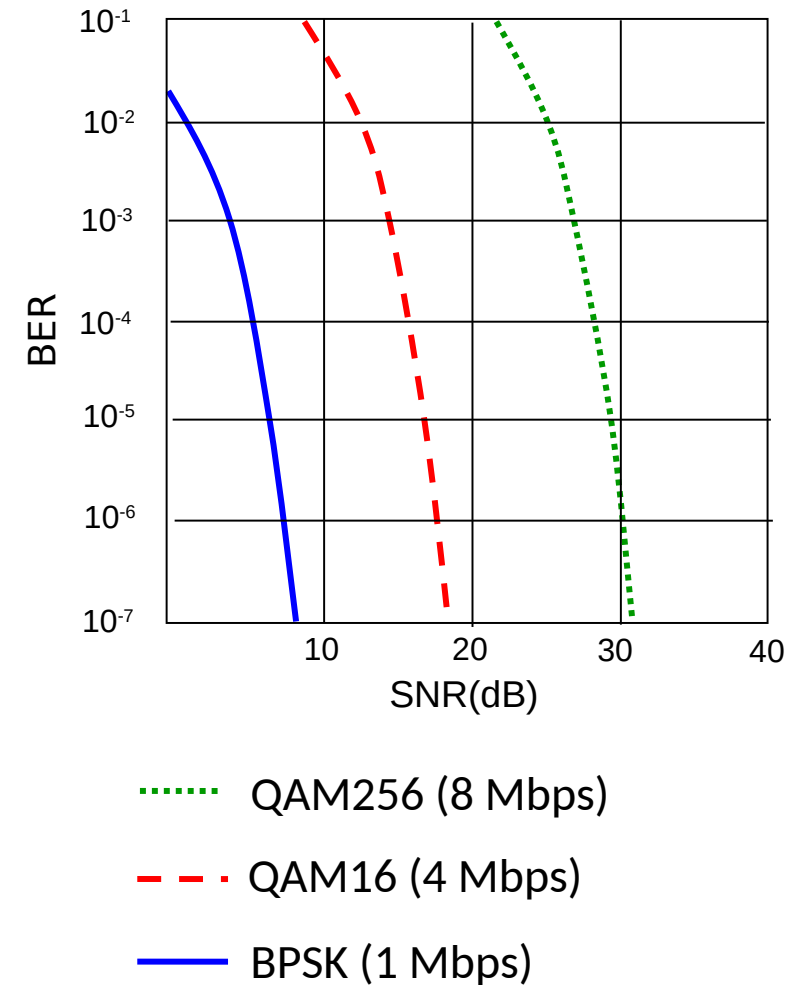
- **decreased signal strength:** radio signal attenuates as it propagates through matter (path loss)
- **interference from other sources:** wireless network frequencies (e.g., 2.4 GHz) shared by many devices (e.g., WiFi, cellular, motors): interference
- **multipath propagation:** radio signal reflects off objects ground, arriving at destination at slightly different times

.... make communication across (even a point to point) wireless link much more “difficult”



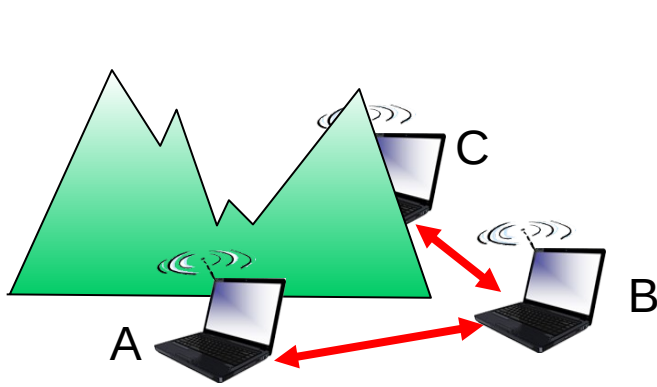
Wireless link characteristics (2)

- 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)



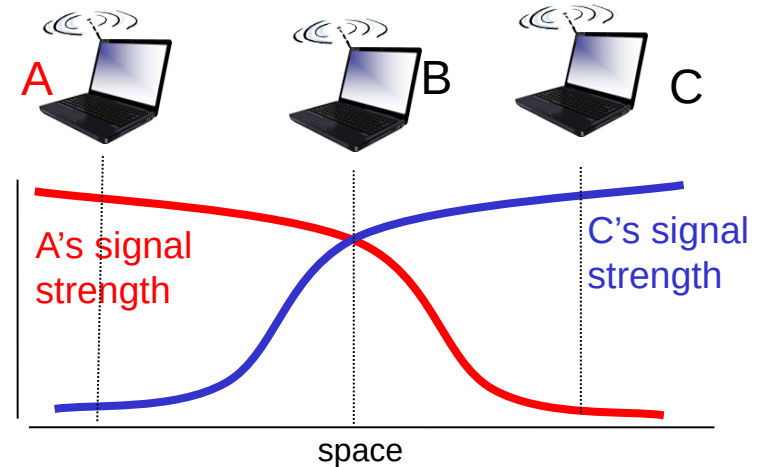
Wireless link characteristics (3)

Multiple wireless senders, 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



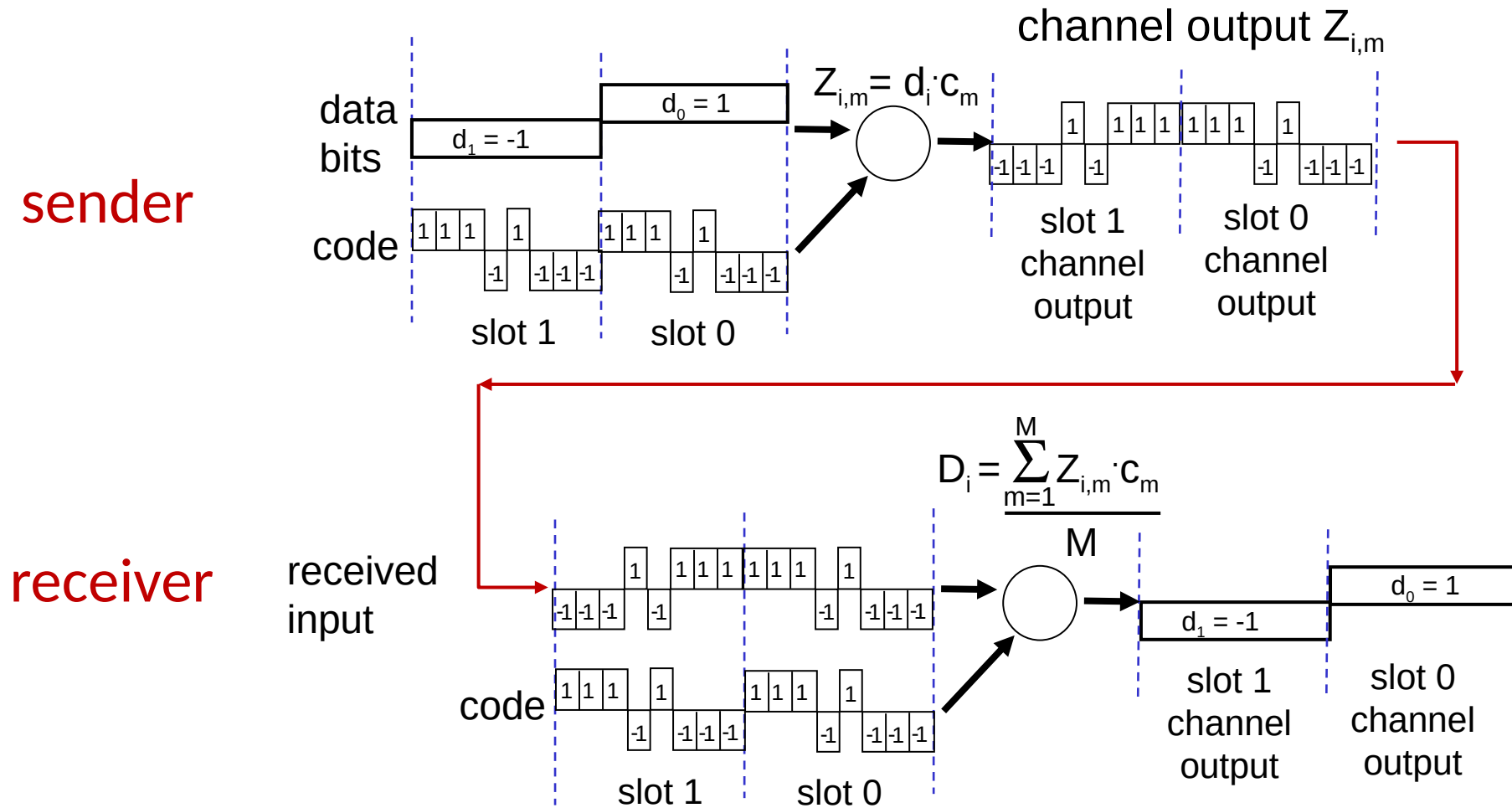
Signal attenuation:

- 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”)
- **encoding:** inner product: (original data) \times (chipping sequence)
- **decoding:** summed inner-product: (encoded data) \times (chipping sequence)

CDMA encode/decode

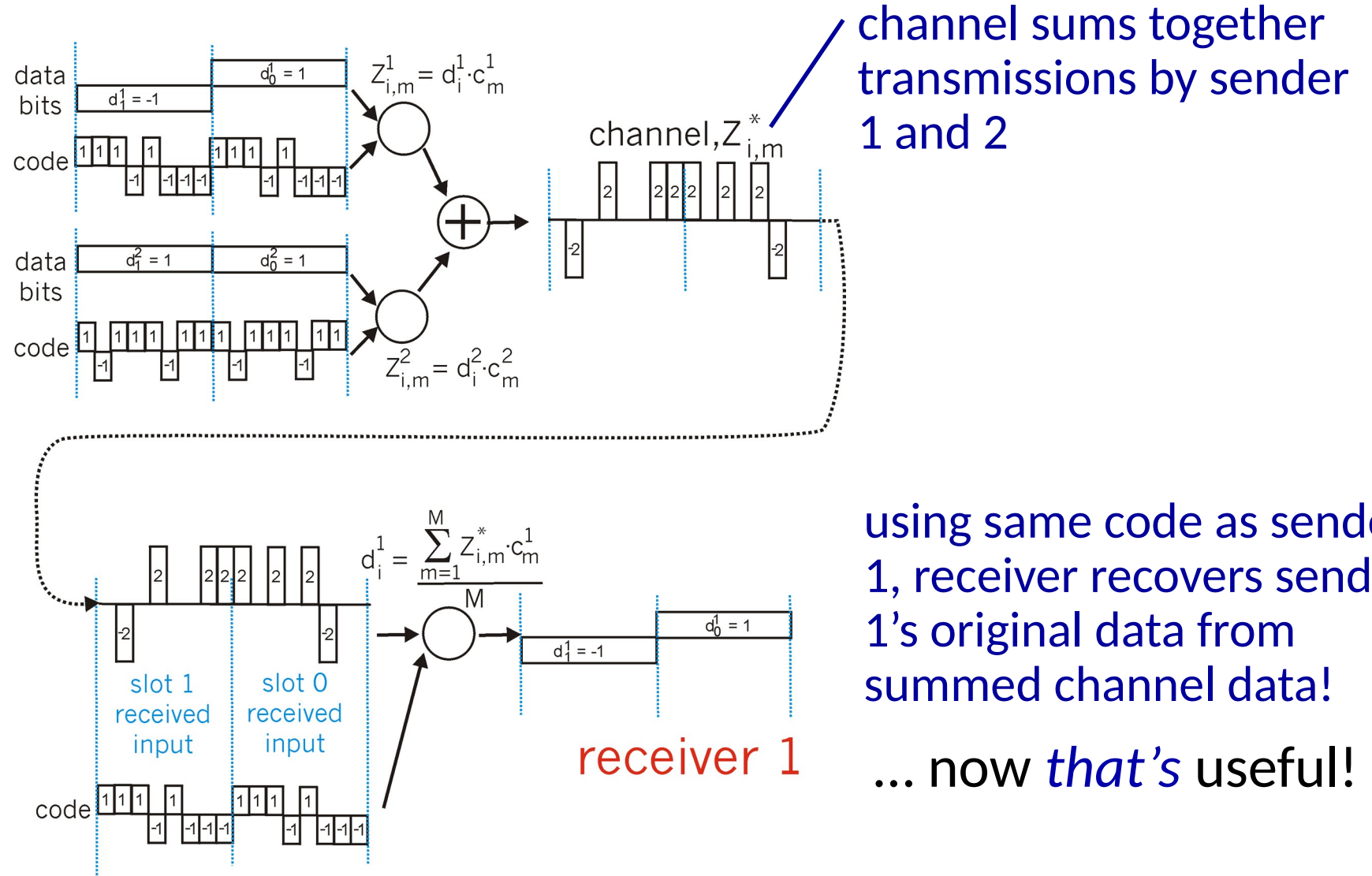


... but this isn't really useful yet!

CDMA: two-sender interference

Sender 1

Sender 2



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- Mobility management: practice
 - 4G/5G networks
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- Mobility: impact on higher-layer protocols

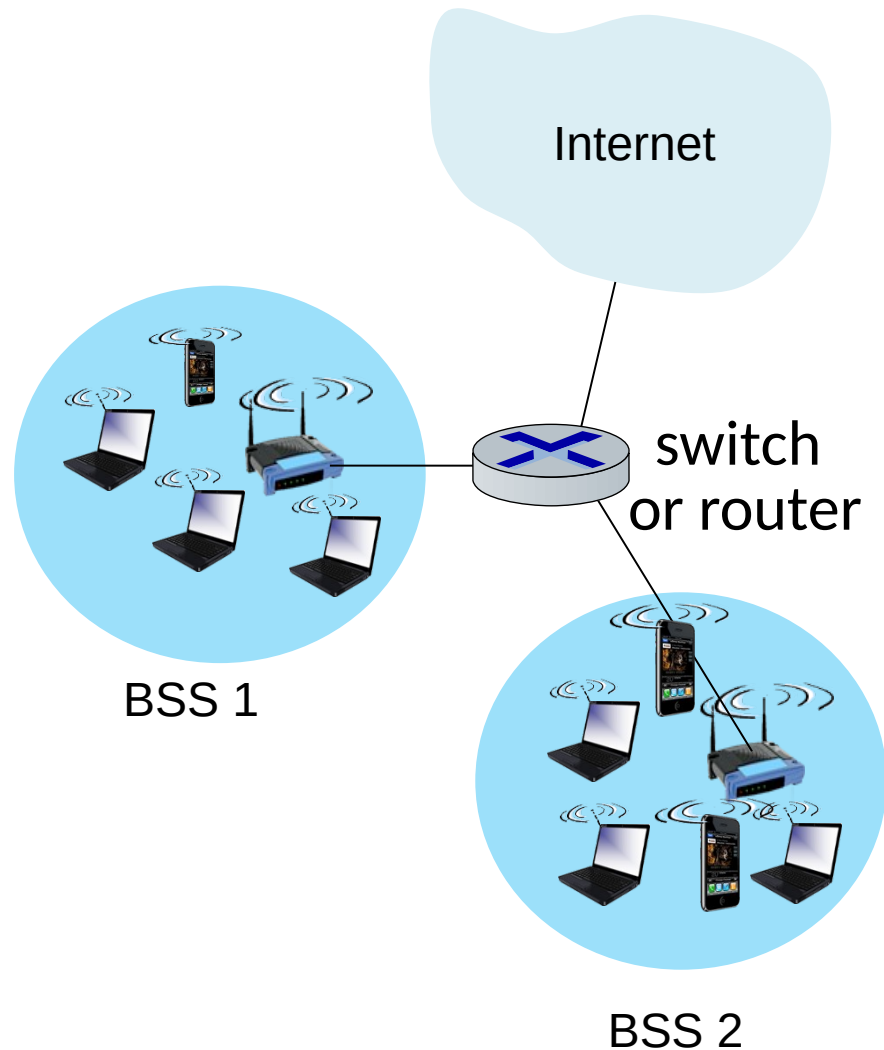


IEEE 802.11 Wireless LAN

IEEE 802.11 standard	Year	Max data rate	Range	Frequency
802.11b	1999	11 Mbps	30 m	2.4 Ghz
802.11g	2003	54 Mbps	30m	2.4 Ghz
802.11n (WiFi 4)	2009	600	70m	2.4, 5 Ghz
802.11ac (WiFi 5)	2013	3.47Gpbs	70m	5 Ghz
802.11ax (WiFi 6)	2020 (exp.)	14 Gbps	70m	2.4, 5 Ghz
802.11af	2014	35 – 560 Mbps	1 Km	unused TV bands (54-790 MHz)
802.11ah	2017	347Mbps	1 Km	900 Mhz

- all use CSMA/CA for multiple access, and have base-station and ad-hoc network versions

802.11 LAN architecture



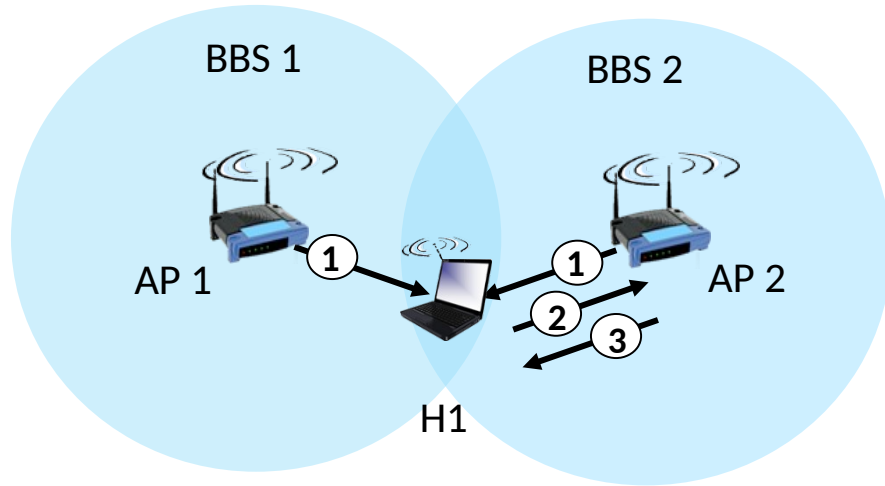
- wireless host communicates with base station
 - base station = access point (AP)
- Basic Service Set (BSS) (aka “cell”) in infrastructure mode contains:
 - wireless hosts
 - access point (AP): base station
 - ad hoc mode: hosts only

802.11: Channels, association

- spectrum divided into channels at different frequencies
 - AP admin chooses frequency for AP
 - interference possible: channel can be same as that chosen by neighboring AP!
- arriving 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
 - then may perform authentication [Chapter 8]
 - then typically run DHCP to get IP address in AP's subnet

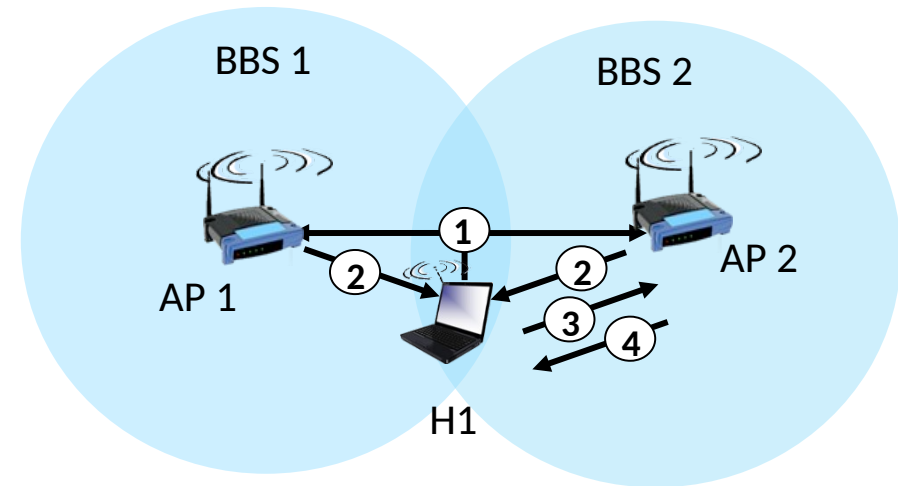


802.11: passive/active scanning



passive scanning:

- 1) beacon frames sent from APs
- 2) association Request frame sent: H1 to selected AP
- 3) association Response frame sent from selected AP to H1

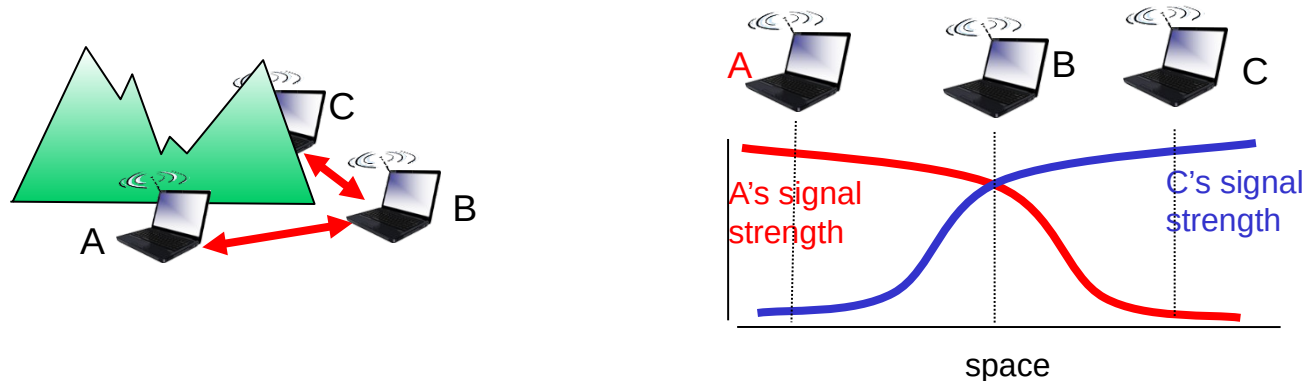


active scanning:

- 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: CSMA - sense before transmitting
 - don't collide with detected ongoing transmission by another node
- 802.11: *no* collision detection!
 - difficult to sense collisions: high transmitting signal, weak received signal due to fading
 - can't sense all collisions in any case: hidden terminal, fading
 - goal: *avoid collisions*: CSMA/CollisionAvoidance



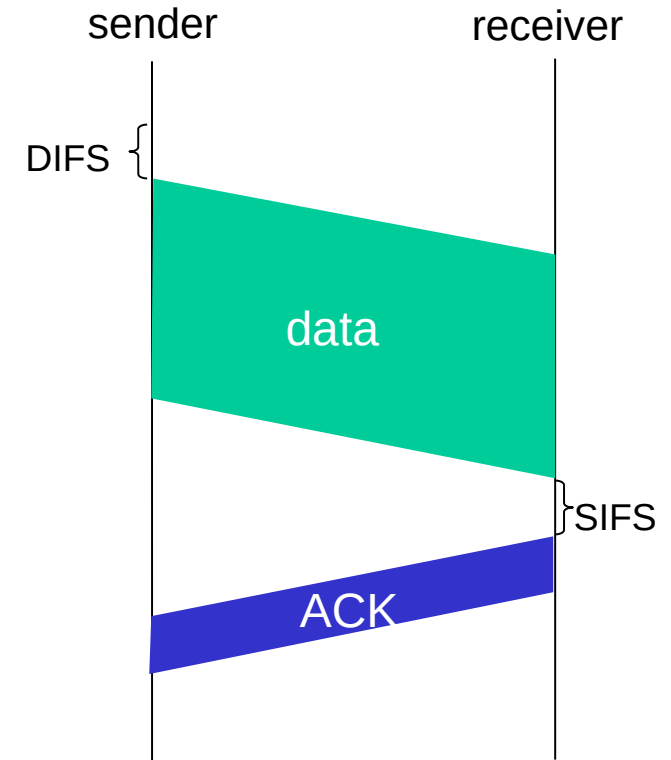
IEEE 802.11 MAC Protocol: CSMA/CA

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)

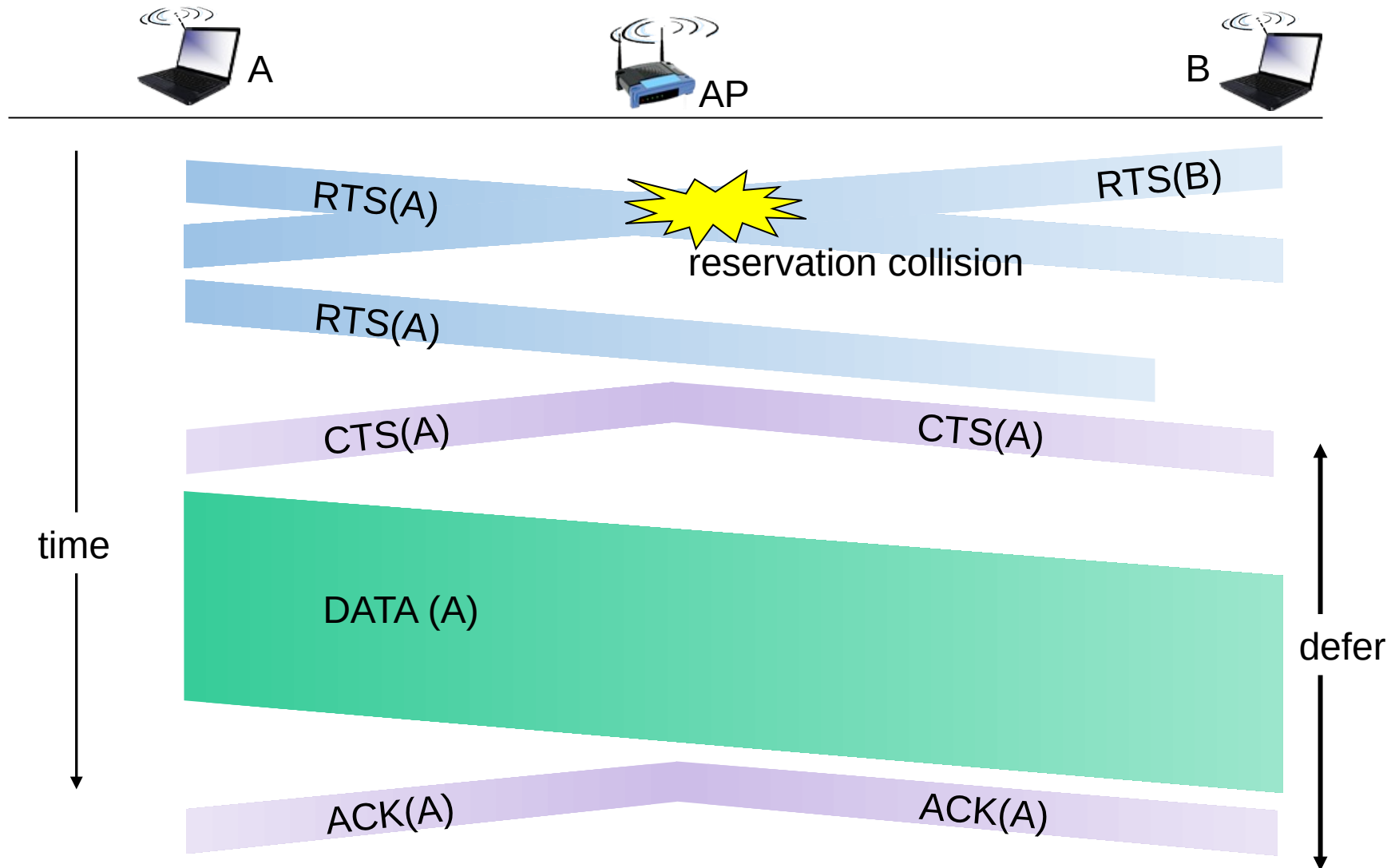


Avoiding collisions (more)

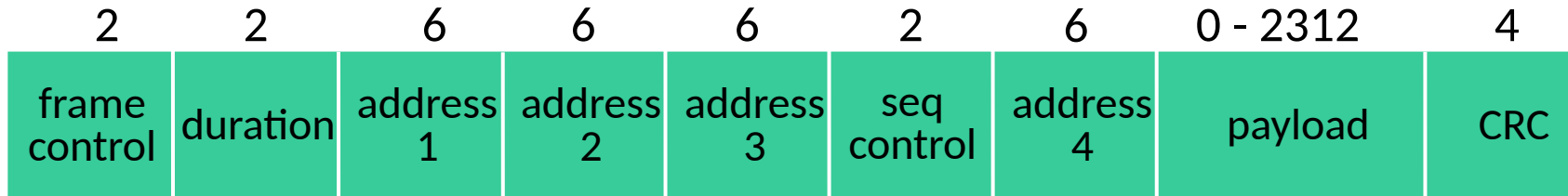
idea: sender “reserves” channel use for data frames using small reservation packets

- sender first transmits *small* request-to-send (RTS) packet 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

Collision Avoidance: RTS-CTS exchange



802.11 frame: addressing



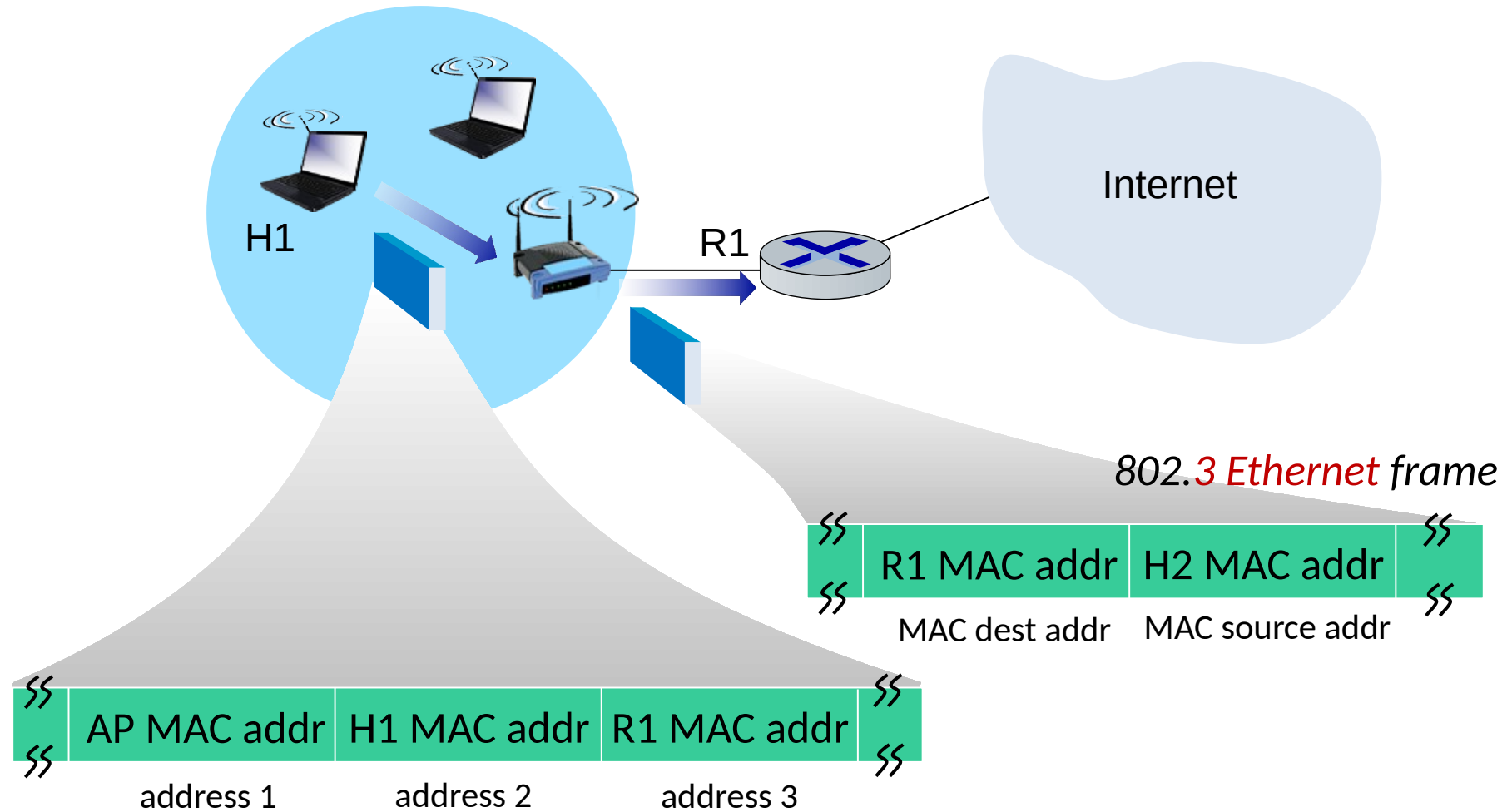
Address 1: MAC address of wireless host or AP to receive this frame

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

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

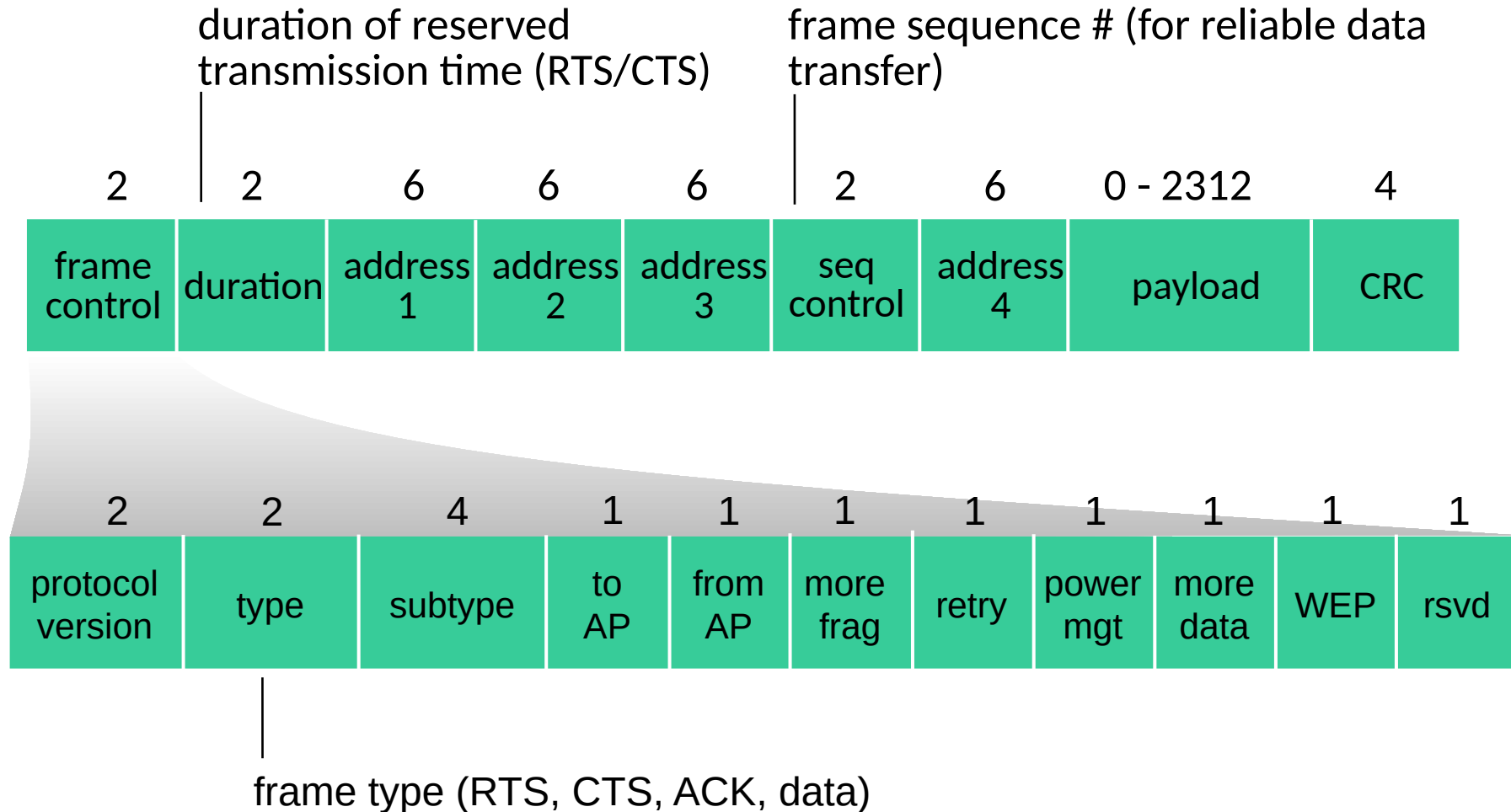
Address 4: used only in ad hoc mode

802.11 frame: addressing



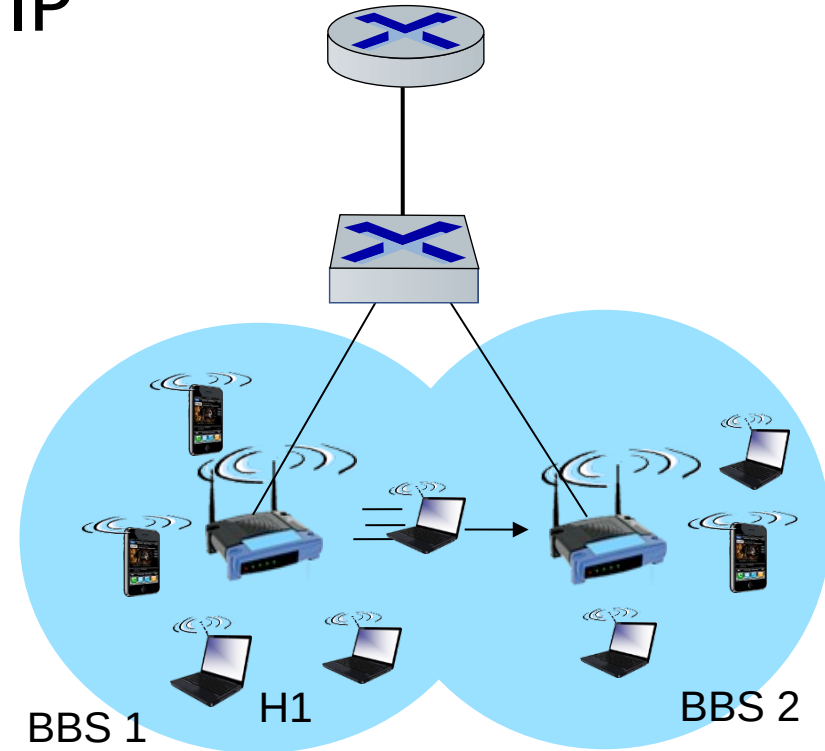
802.11 WiFi frame

802.11 frame: addressing



802.11: mobility within same subnet

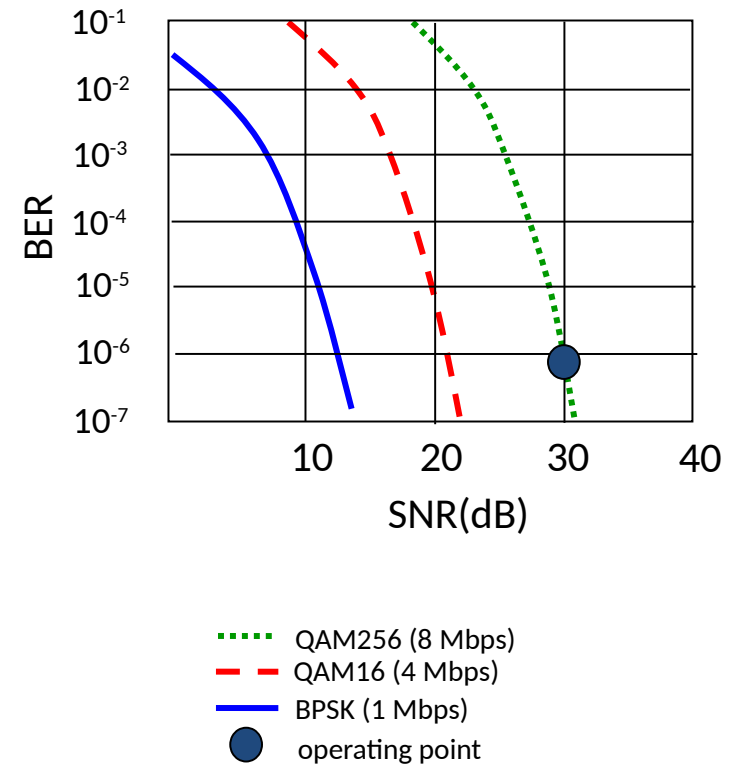
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
 - self-learning (Ch. 6): switch will see frame from H1 and “remember” which switch port can be used to reach H1



802.11: advanced capabilities

Rate adaptation

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



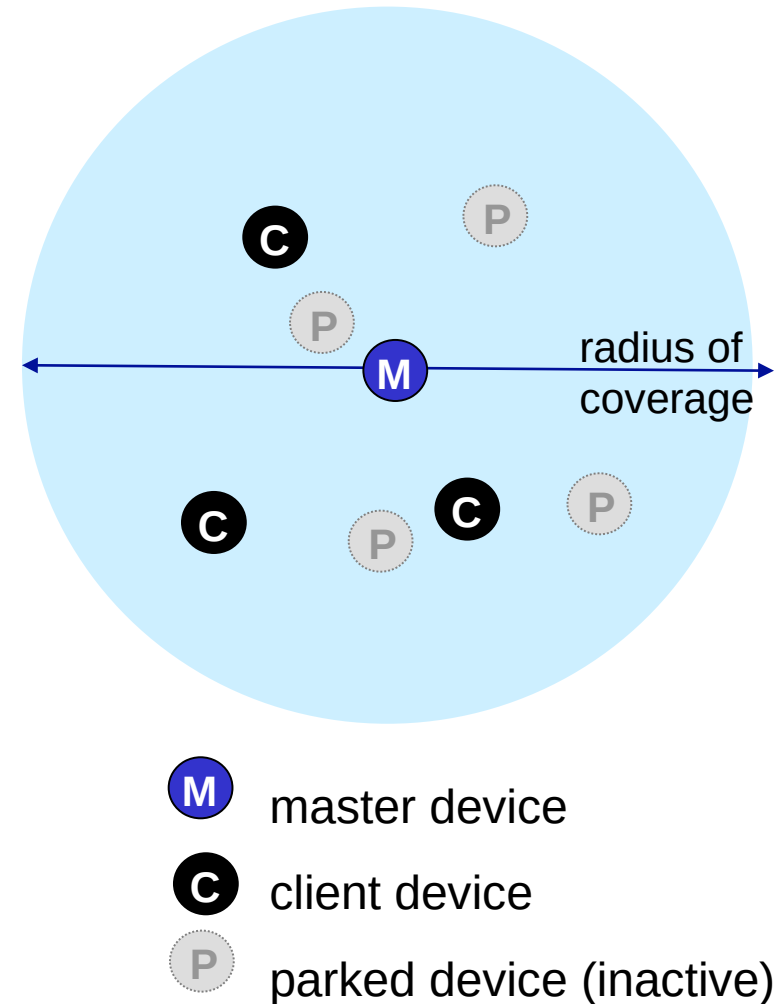
802.11: advanced capabilities

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

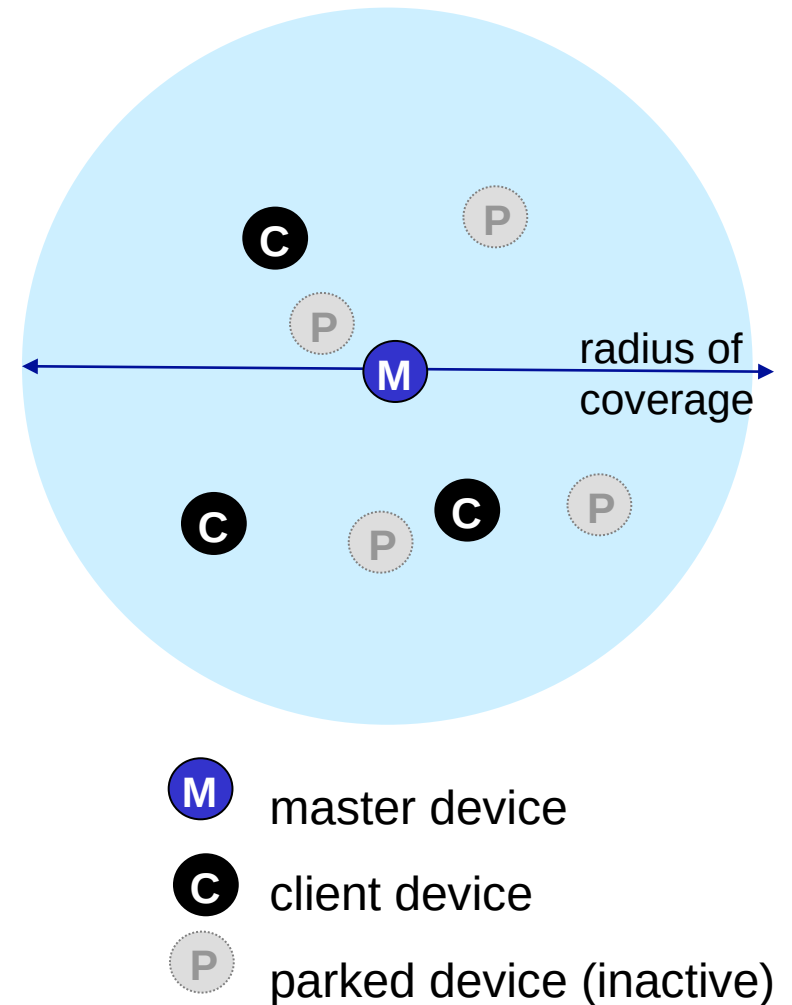
Personal area networks: Bluetooth

- less than 10 m diameter
- replacement for cables (mouse, keyboard, headphones)
- ad hoc: no infrastructure
- 2.4-2.5 GHz ISM radio band, up to 3 Mbps
- master controller / clients devices:
 - master polls clients, grants requests for client transmissions



Personal area networks: Bluetooth

- TDM, 625 μ sec sec. slot
- FDM: sender uses 79 frequency channels in known, pseudo-random order slot-to-slot (spread spectrum)
 - other devices/equipment not in piconet only interfere in some slots
- **parked mode:** clients can “go to sleep” (park) and later wakeup (to preserve battery)
- **bootstrapping:** nodes self-assemble (plug and play) into piconet



Chapter 7 outline

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Wireless

- Wireless links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G

Mobility

- Mobility management: principles
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4G/5G cellular networks

- *the* solution for wide-area mobile Internet
- widespread deployment/use:
 - more mobile-broadband-connected devices than fixed-broadband-connected devices (5-1 in 2019)!
 - 4G availability: 97% of time in Korea (90% in US)
- transmission rates up to 100's Mbps
- technical standards: 3rd Generation Partnership Project (3GPP)
 - www.3gpp.org
 - 4G: Long-Term Evolution (LTE) standard

4G/5G cellular networks

similarities to wired Internet

- edge/core distinction, but both below to same carrier
- global cellular network: a network of networks
- widespread use of protocols we've studied: HTTP, DNS, TCP, UDP, IP, NAT, separation of data/control planes, SDN, Ethernet, tunneling
- interconnected to wired Internet

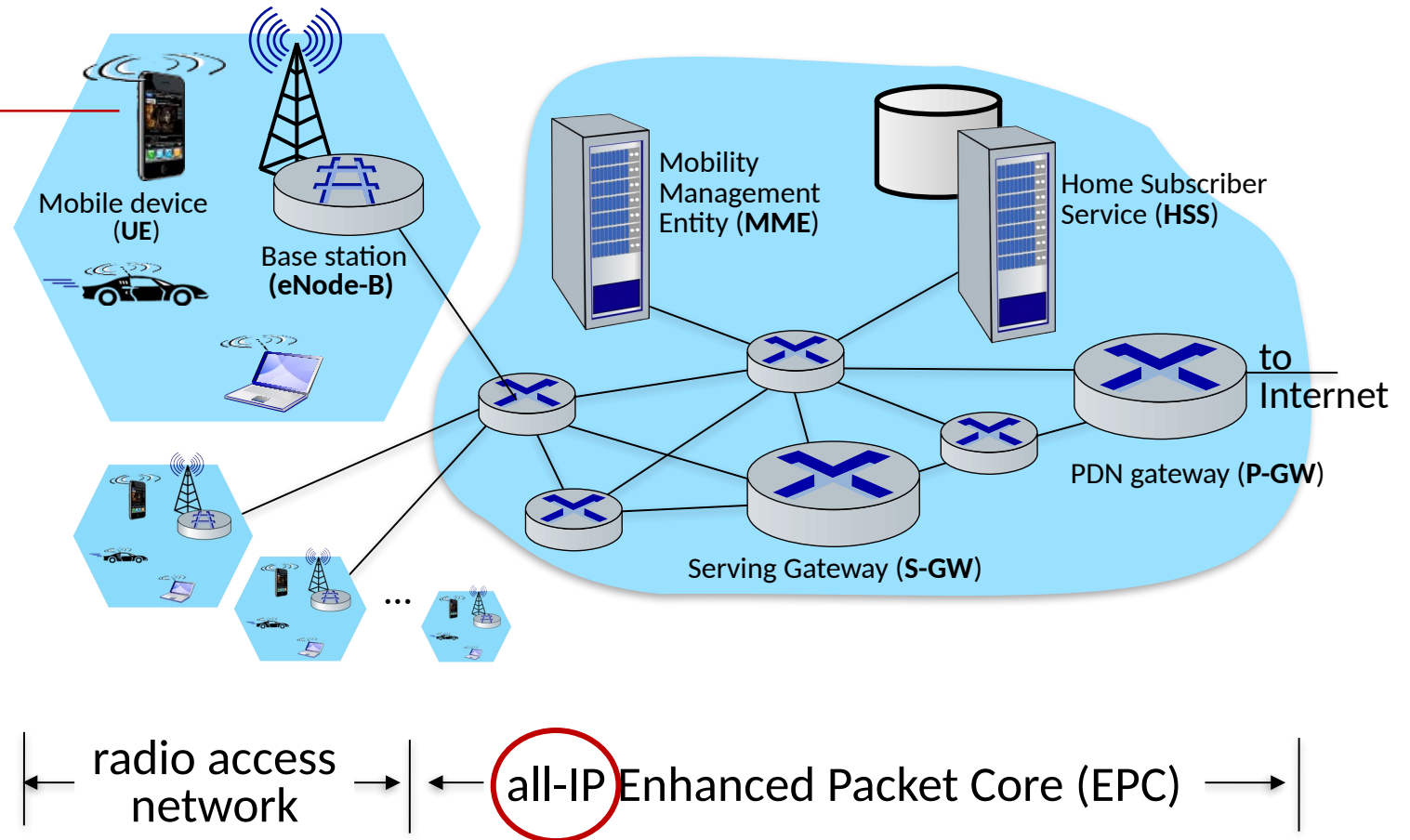
differences from wired Internet

- different wireless link layer
- mobility as a 1st class service
- user “identity” (via SIM card)
- business model: users subscribe to a cellular provider
 - strong notion of “home network” versus roaming on visited nets
 - global access, with authentication infrastructure, and inter-carrier settlements

Elements of 4G LTE architecture

Mobile device:

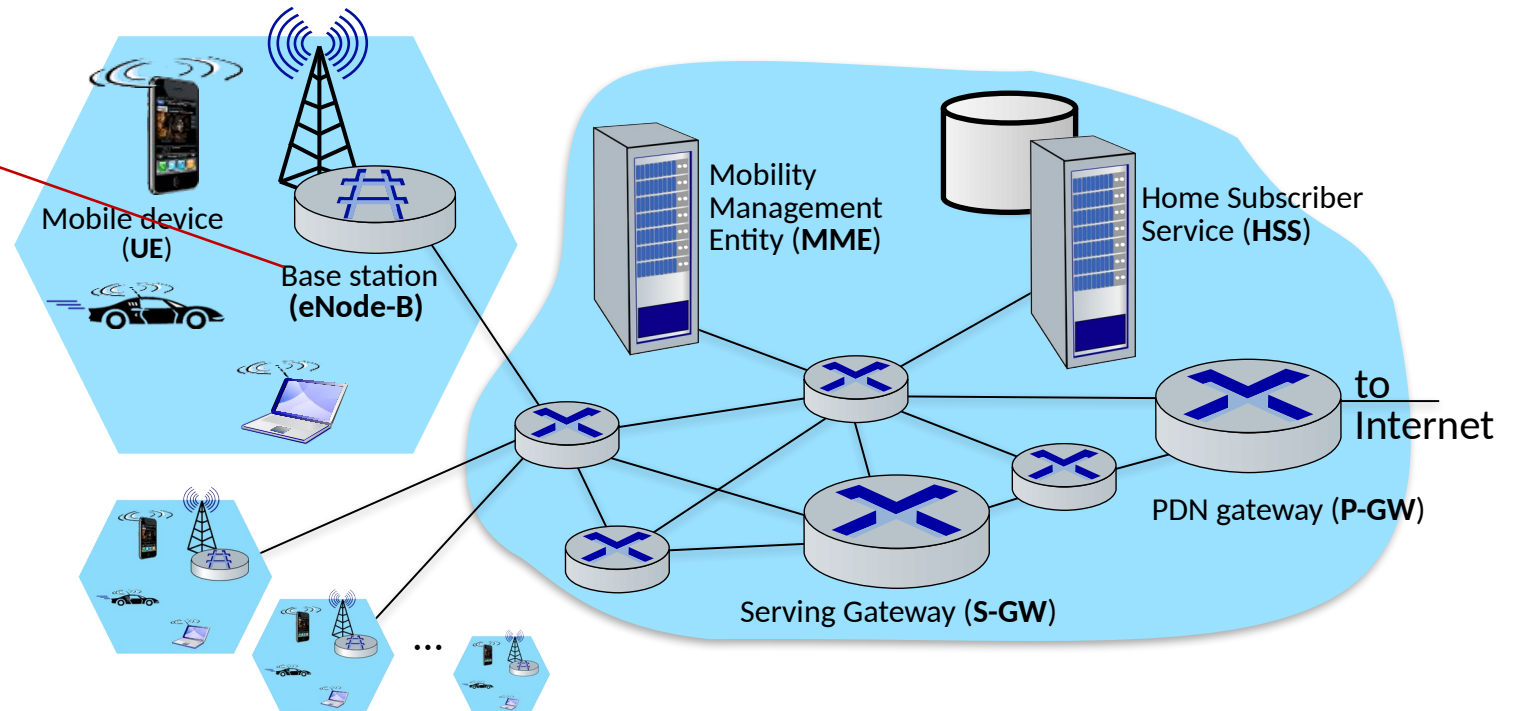
- smartphone, tablet, laptop, IoT, ... with 4G LTE radio
- 64-bit International Mobile Subscriber Identity (IMSI), stored on SIM (Subscriber Identity Module) card
- LTE jargon: User Equipment (UE)



Elements of 4G LTE architecture

Base station:

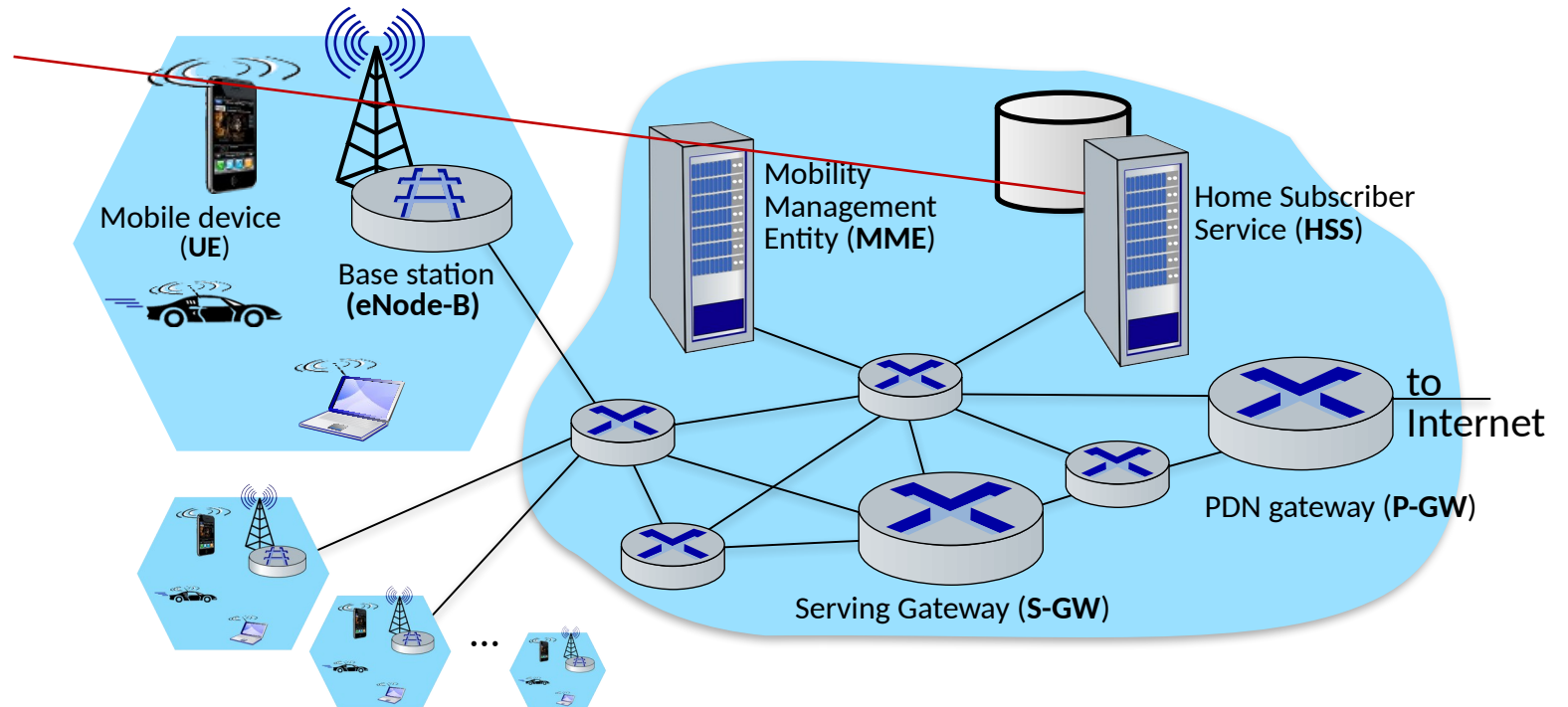
- at “edge” of carrier’s network
- manages wireless radio resources, mobile devices in its coverage area (“cell”)
- coordinates device authentication with other elements
- similar to WiFi AP but:
 - active role in user mobility
 - coordinates with nearby base stations to optimize radio use
- LTE jargon: eNode-B



Elements of 4G LTE architecture

Home Subscriber Service

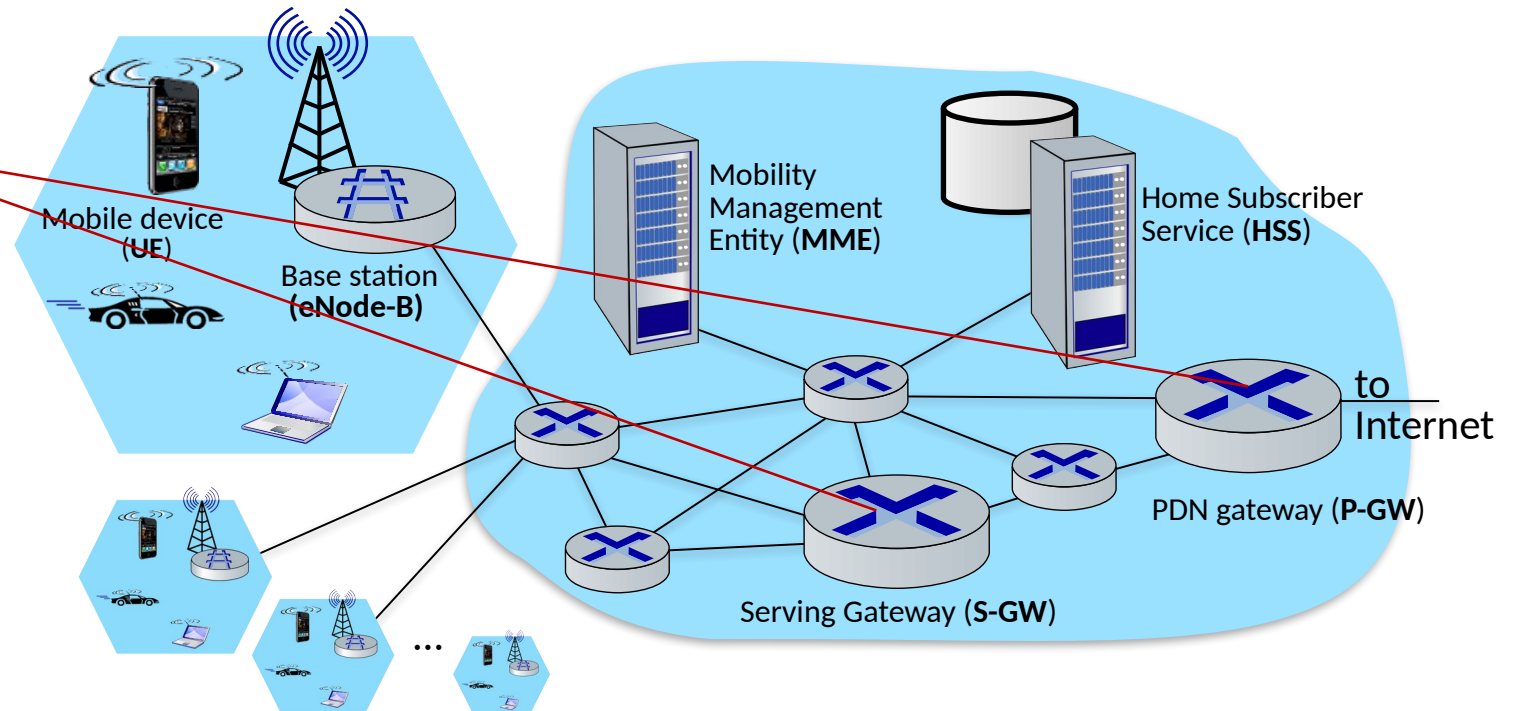
- stores info about mobile devices for which the HSS's network is their “home network”
- works with MME in device authentication



Elements of 4G LTE architecture

Serving Gateway (S-GW), PDN Gateway (P-GW)

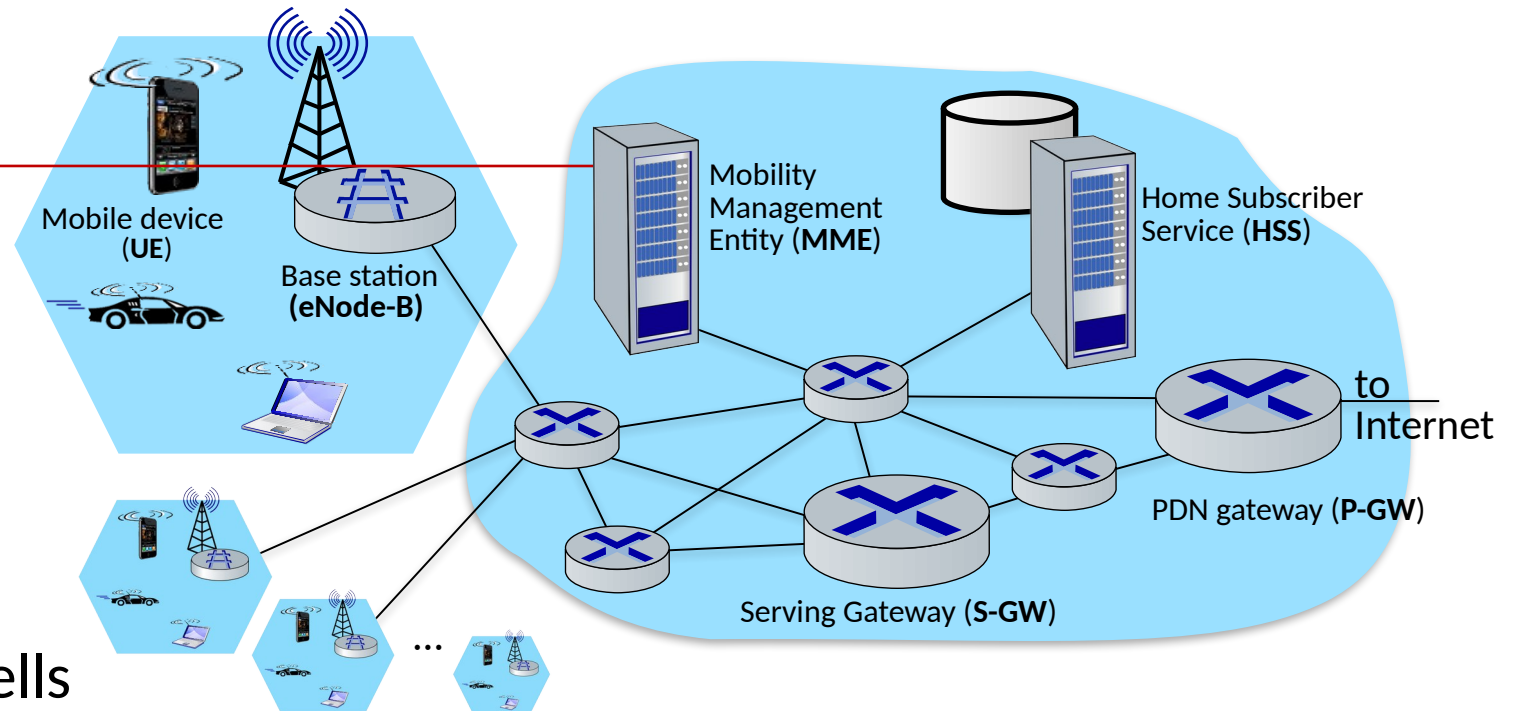
- lie on data path from mobile to/from Internet
- P-GW
 - gateway to mobile cellular network
 - Looks like any other internet gateway router
 - provides NAT services
- other routers:
 - extensive use of tunneling



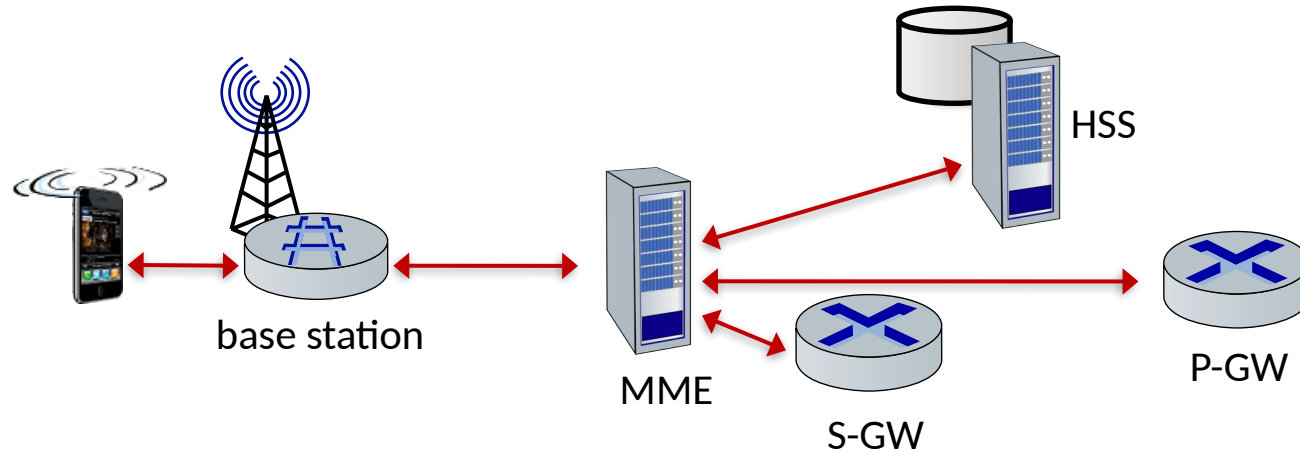
Elements of 4G LTE architecture

Mobility Management Entity

- device authentication (device-to-network, network-to-device) coordinated with mobile home network HSS
- mobile device management:
 - device handover between cells
 - tracking/paging device location
- path (tunneling) setup from mobile device to P-GW

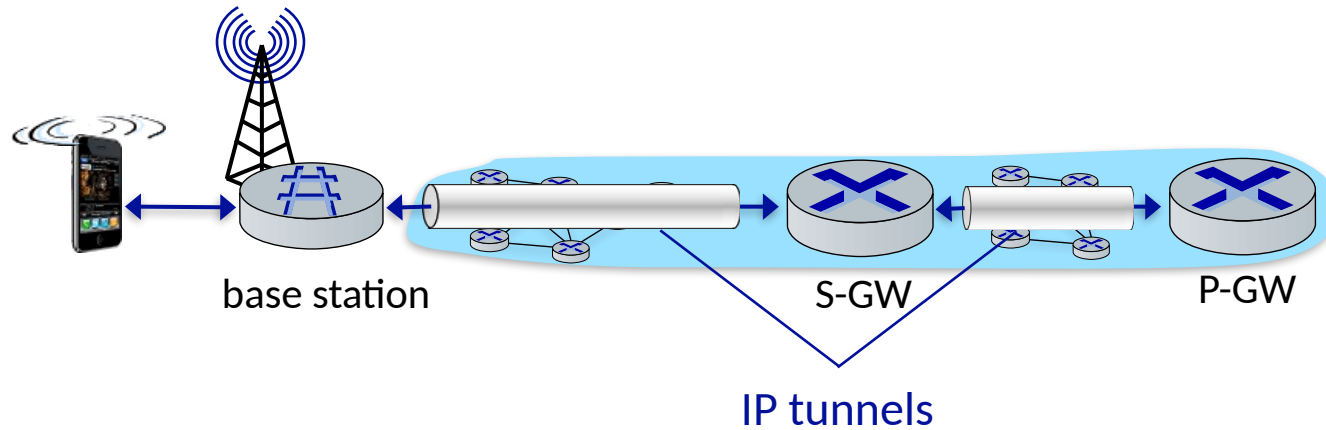


LTE: data plane control plane separation



control plane

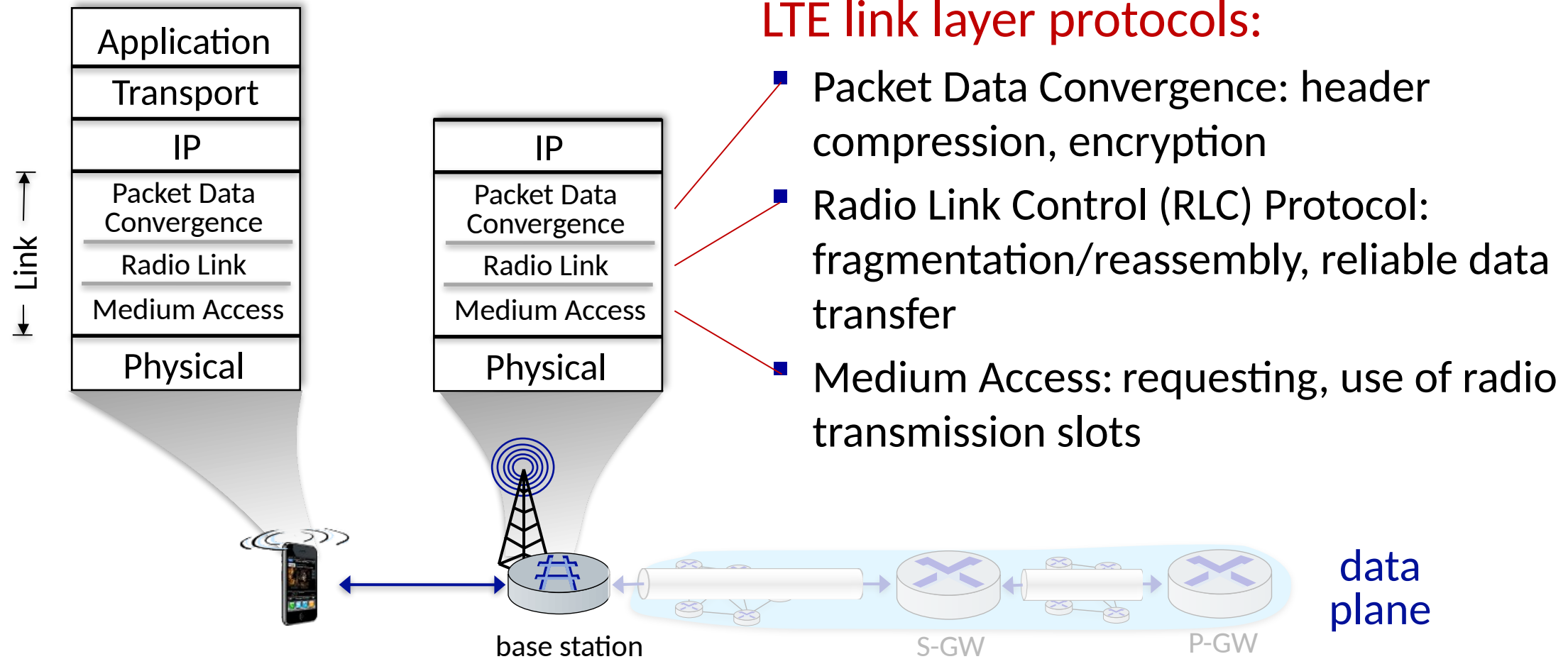
- new protocols for mobility management , security, authentication (later)



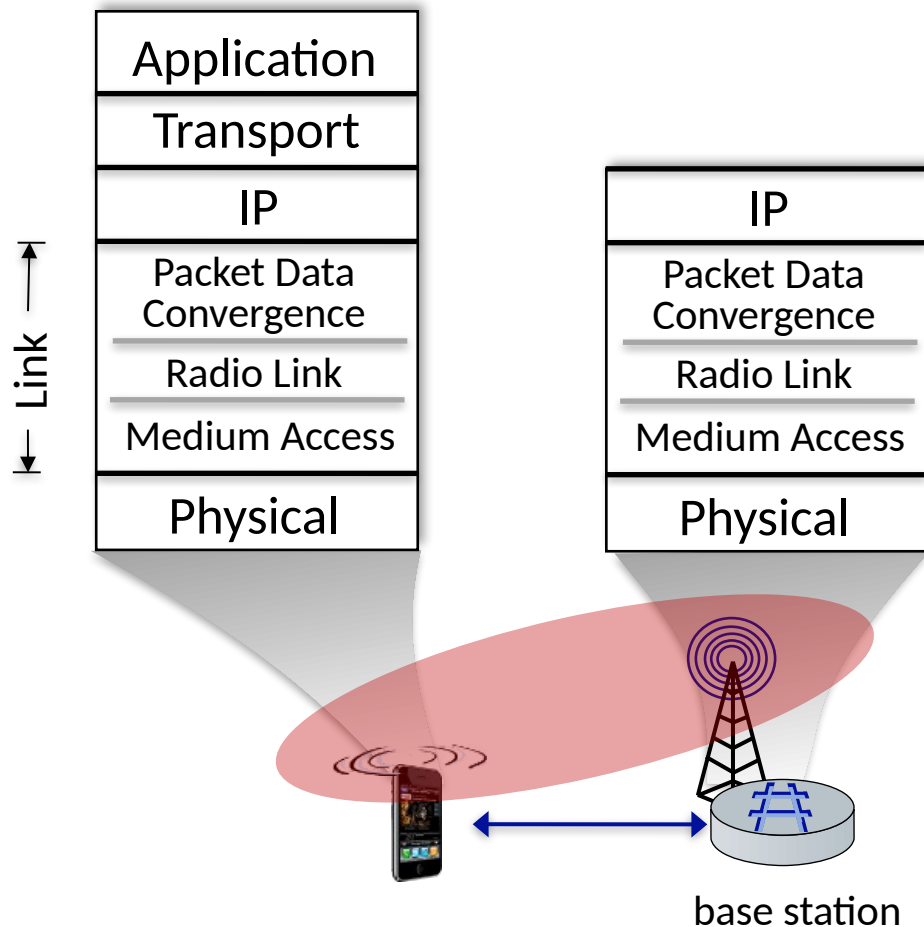
data plane

- new protocols at link, physical layers
- extensive use of tunneling to facilitate mobility

LTE data plane protocol stack: first hop



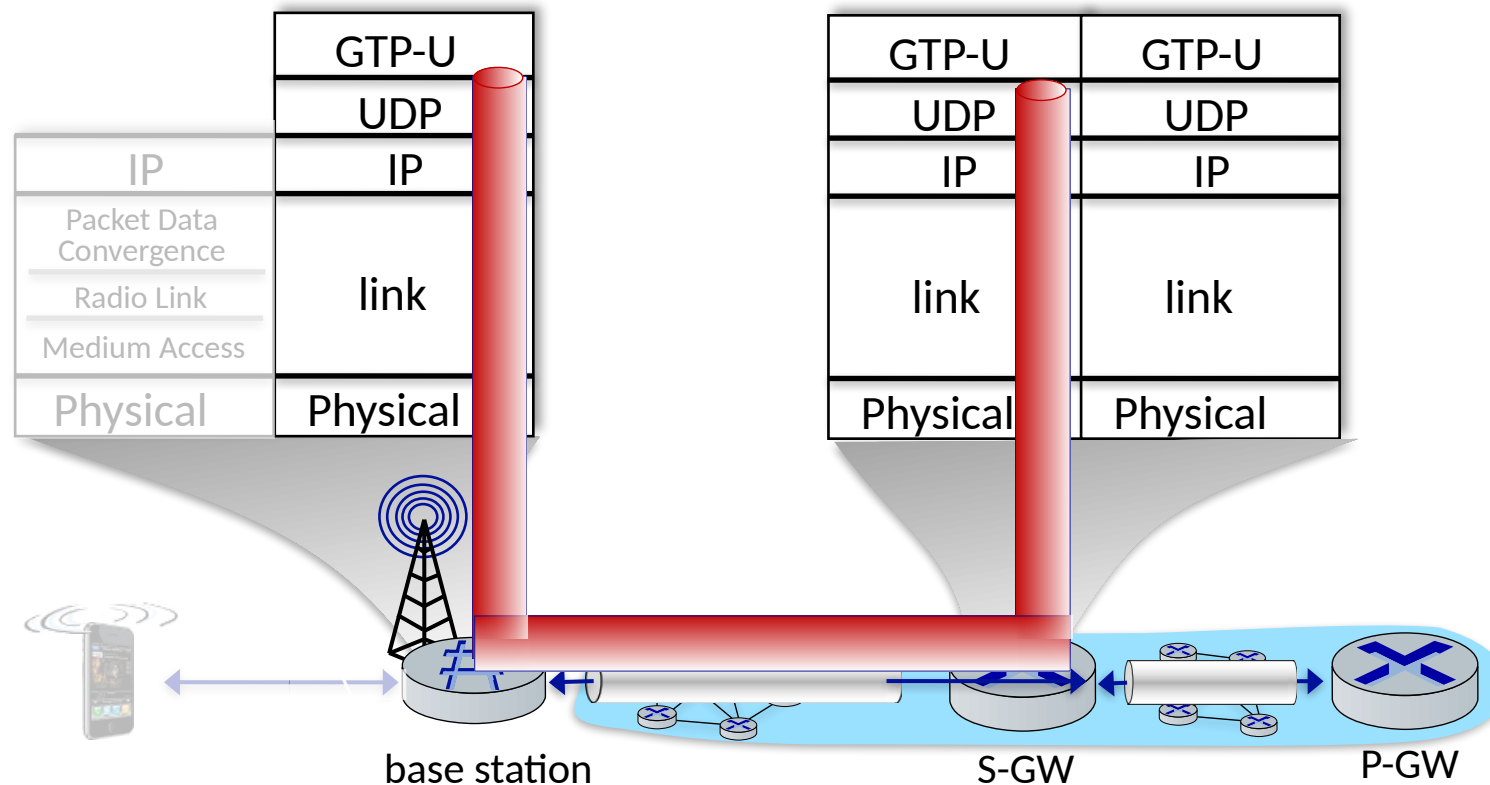
LTE data plane protocol stack: first hop



LTE radio access network:

- **downstream channel:** FDM, TDM within frequency channel (OFDM - orthogonal frequency division multiplexing)
 - “orthogonal”: minimal interference between channels
 - **upstream:** FDM, TDM similar to OFDM
- each active mobile device allocated two or more 0.5 ms time slots over 12 frequencies
 - scheduling algorithm not standardized – up to operator
 - 100's Mbps per device possible

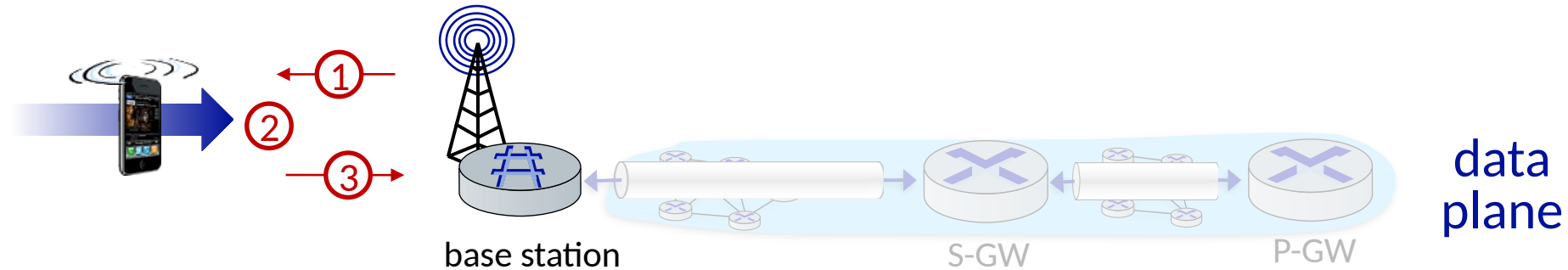
LTE data plane protocol stack: packet core



tunneling:

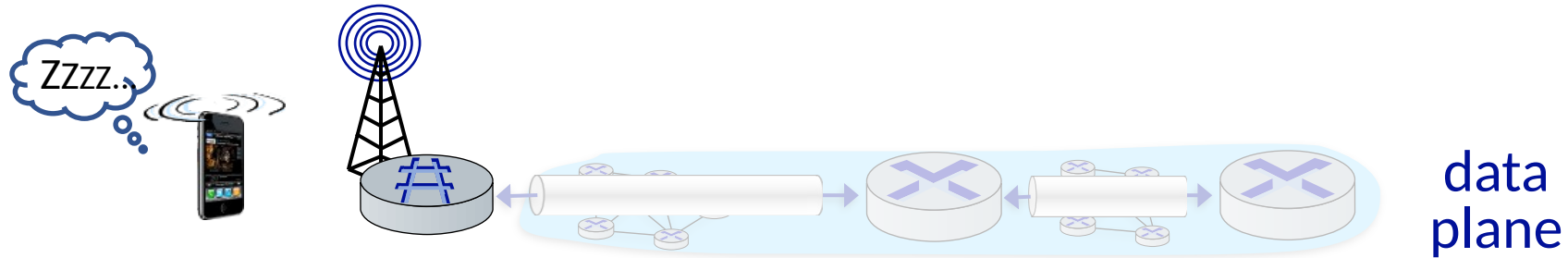
- mobile datagram encapsulated using GPRS Tunneling Protocol (GTP), sent inside UDP datagram to S-GW
- S-GW re-tunnels datagrams to P-GW
- supporting mobility: only tunneling endpoints change when mobile user moves

LTE data plane: associating with a BS



- ① BS broadcasts primary synch signal every 5 ms on all frequencies
 - BSs from multiple carriers may be broadcasting synch signals
- ② mobile finds a primary synch signal, then locates 2nd synch signal on this freq.
 - mobile then finds info broadcast by BS: channel bandwidth, configurations; BS's cellular carrier info
 - mobile may get info from multiple base stations, multiple cellular networks
- ③ mobile selects which BS to associate with (e.g., preference for home carrier)
- ④ more steps still needed to authenticate, establish state, set up data plane

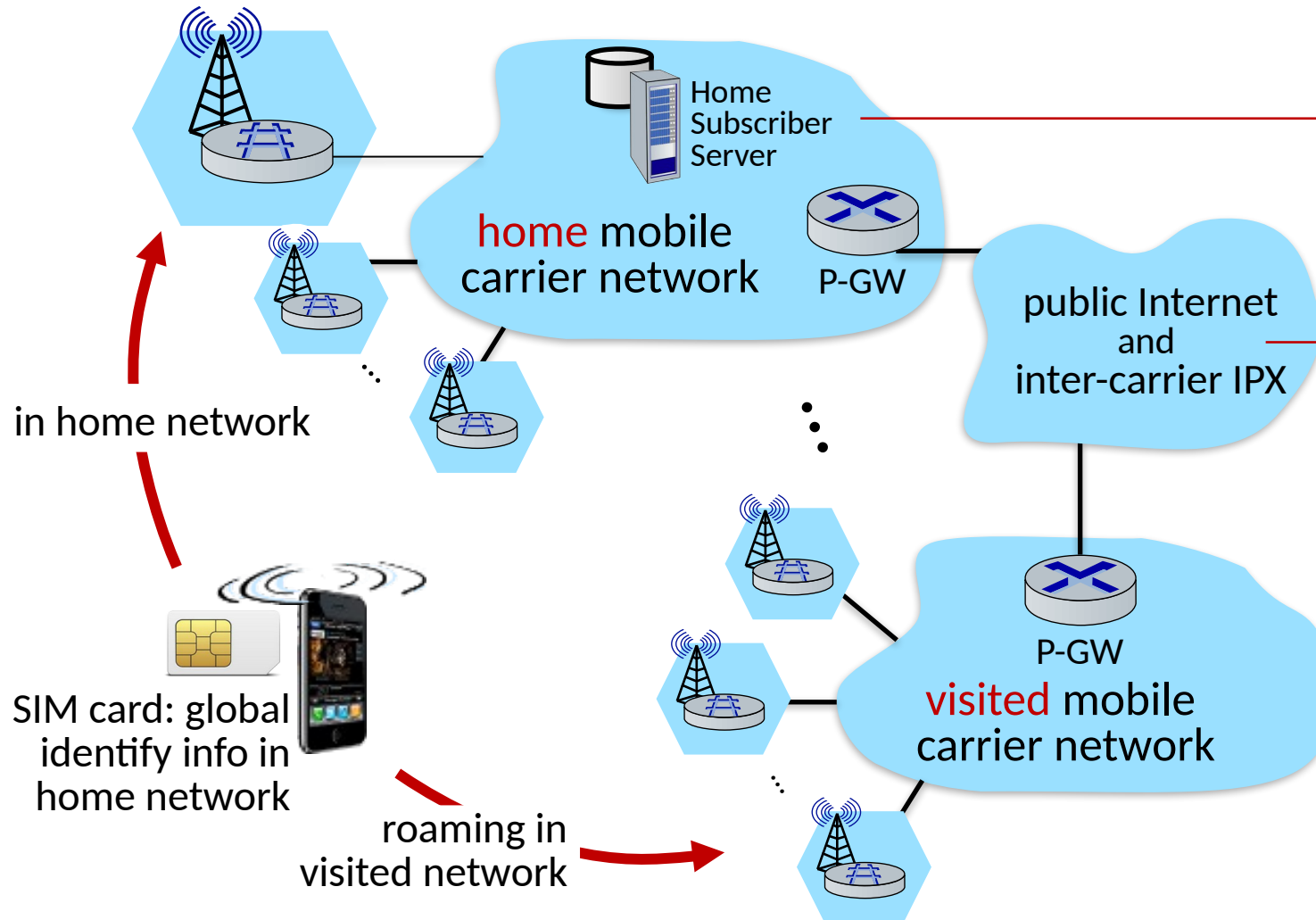
LTE mobiles: sleep modes



as in WiFi, Bluetooth: LTE mobile may put radio to “sleep” to conserve battery:

- **light sleep:** after 100's msec of inactivity
 - wake up periodically (100's msec) to check for downstream transmissions
- **deep sleep:** after 5-10 secs of inactivity
 - mobile may change cells while deep sleeping – need to re-establish association

Global cellular network: a network of IP networks



home network HSS:

- identify & services info, while in home network and roaming

all IP:

- carriers interconnect with each other, and public internet at exchange points
- legacy 2G, 3G: not all IP, handled otherwise

On to 5G!

- **goal:** 10x increase in peak bitrate, 10x decrease in latency, 100x increase in traffic capacity over 4G
- **5G NR (new radio):**
 - two frequency bands: FR1 (450 MHz–6 GHz) and FR2 (24 GHz–52 GHz): millimeter wave frequencies
 - not backwards-compatible with 4G
 - MIMO: multiple directional antennae
- **millimeter wave frequencies:** much higher data rates, but over shorter distances
 - pico-cells: cells diameters: 10-100 m
 - massive, dense deployment of new base stations required