

Miscellaneous

- Project presentation today and tomorrow
- Final Exam
 - 16:30-18:30, June 8, Wednesday
 - Range: Chapter 1 – Chapter 7
- Q & A Session
 - 9:30-11:30AM, June 6, Monday
 - CoE South Building 516

Quick review

- Link Layer
 - Multiple access protocols
 - ARP protocol
 - Ethernet
 - Switches

Chapter 6

The Link Layer and LANs

Instructor: Zhuozhao Li

Lab: Qing Wang

Department of Computer Science and Engineering

Link layer, LANs: roadmap

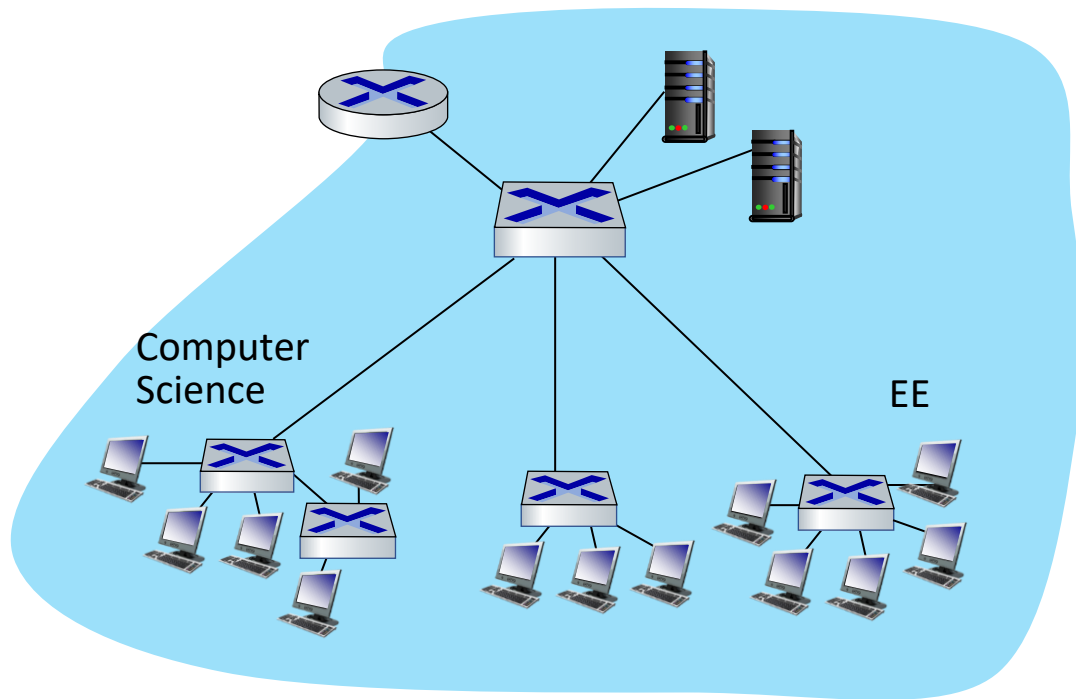
- introduction
- error detection, correction
- multiple access protocols
- **LANs**
 - addressing, ARP
 - Ethernet
 - switches
 - **VLANs**
- data center networking



- a day in the life of a web request

Virtual LANs (VLANs): motivation

Q: what happens as LAN sizes scale, users change point of attachment?

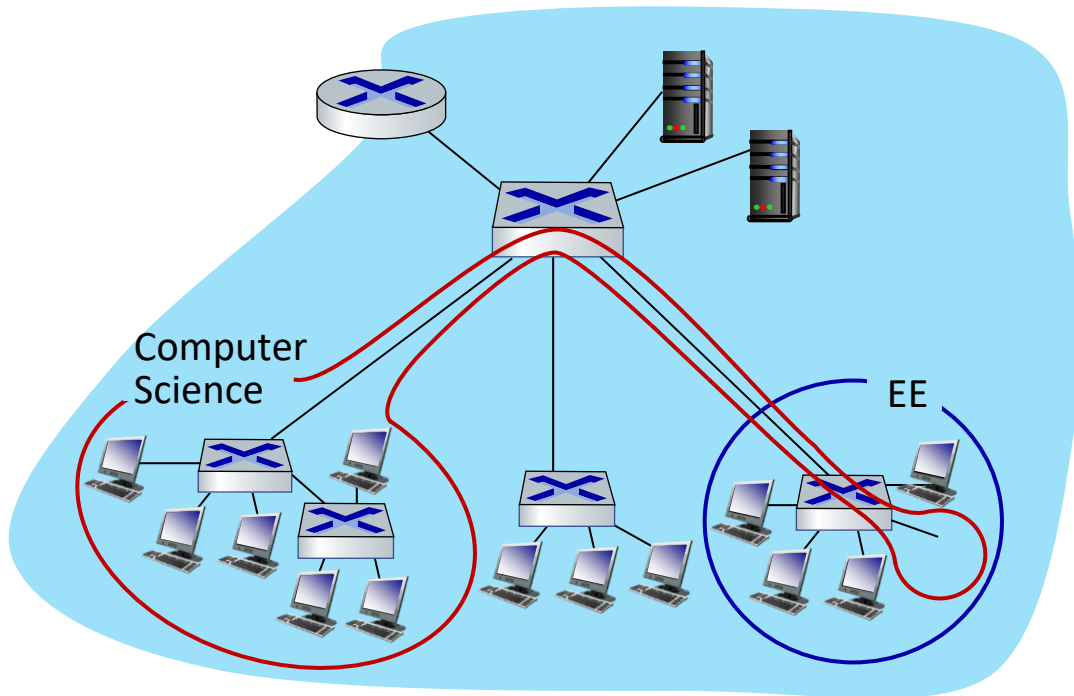


single broadcast domain:

- *scaling*: all layer-2 broadcast traffic (ARP, DHCP, unknown MAC) must cross entire LAN
- efficiency, security, privacy issues

Virtual LANs (VLANs): motivation

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single broadcast domain:

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- efficiency, security, privacy, efficiency issues

administrative issues:

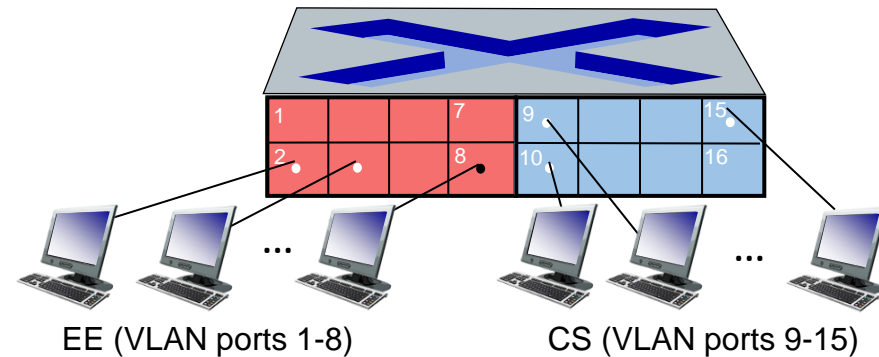
- CS user moves office to EE - *physically* attached to EE switch, but wants to remain *logically* attached to CS switch

Port-based VLANs

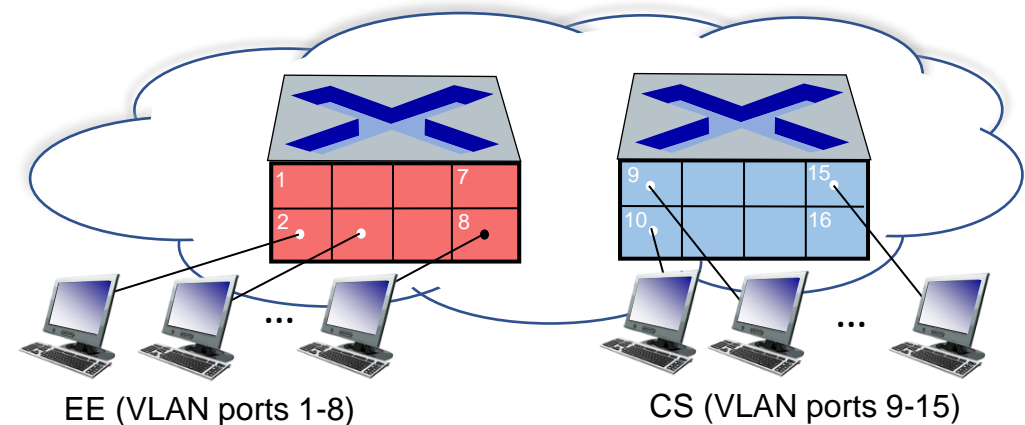
Virtual Local Area Network (VLAN)

switch(es) supporting VLAN capabilities can be configured to define multiple *virtual* LANS over single physical LAN infrastructure.

port-based VLAN: switch ports grouped (by switch management software) so that *single* physical switch

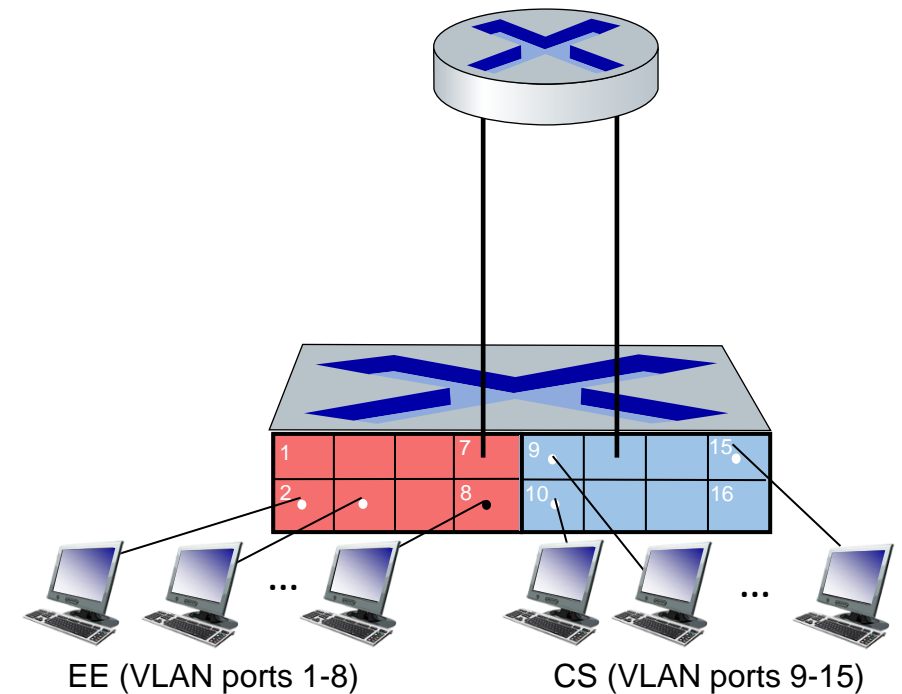


... operates as **multiple** virtual switches

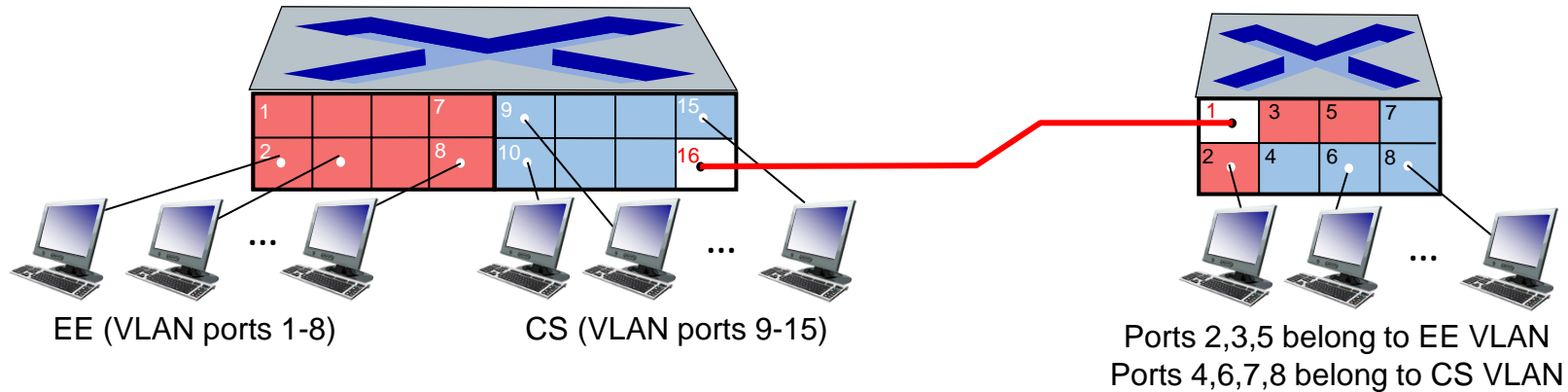


Port-based VLANs

- **traffic isolation:** frames to/from ports 1-8 can *only* reach ports 1-8
 - can also define VLAN based on MAC addresses of endpoints, rather than switch port
- **dynamic membership:** ports can be dynamically assigned among VLANs
- **forwarding between VLANs:** done via routing (just as with separate switches)
 - in practice vendors sell combined switches plus routers



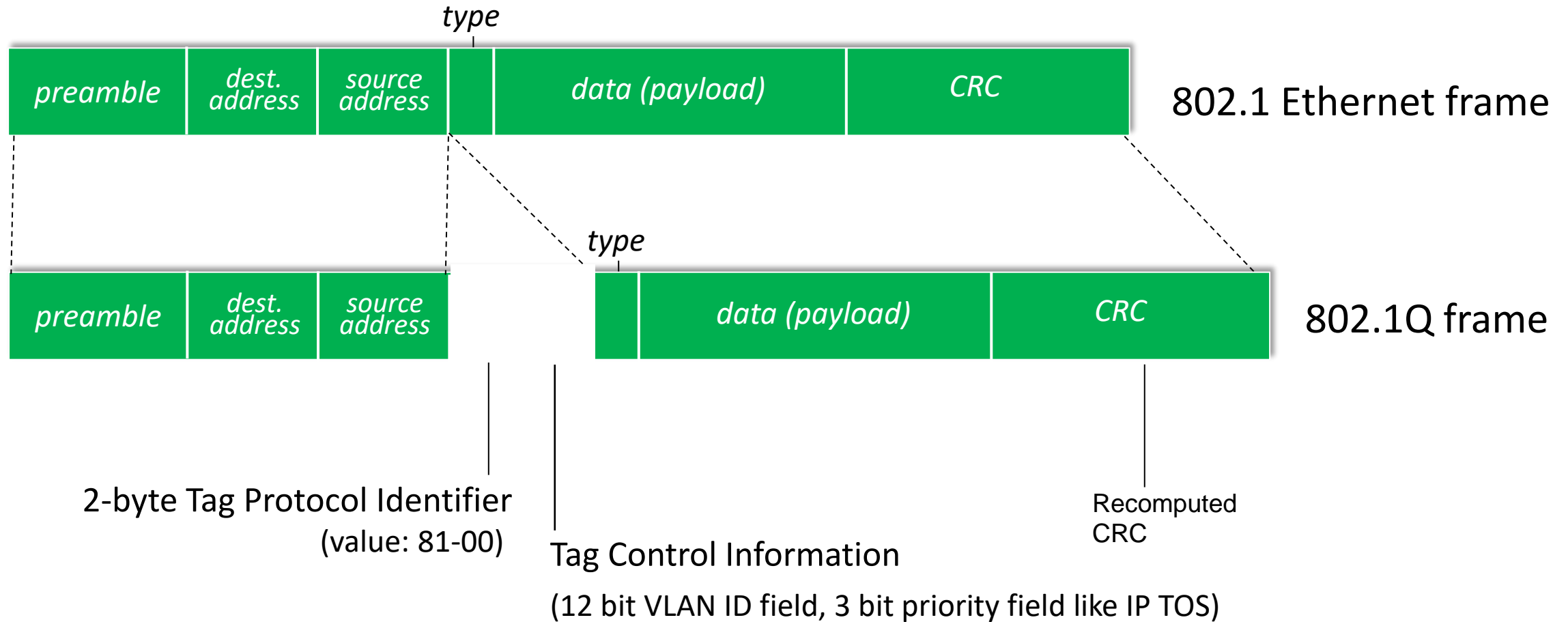
VLANs spanning multiple switches



trunk port: carries frames between VLANs defined over multiple physical switches

- frames forwarded within VLAN between switches can't be vanilla 802.1 frames (must carry VLAN ID info)
- 802.1q protocol adds/removed additional header fields for frames forwarded between trunk ports

802.1Q VLAN frame format



Link layer, LANs: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
 - VLANs
- link virtualization: MPLS
- data center networking



- a day in the life of a web request

Datacenter networks

10's to 100's of thousands of hosts, often closely coupled, in close proximity:

- e-business (e.g. Amazon)
- content-servers (e.g., YouTube, Akamai, Apple, Microsoft)
- search engines, data mining (e.g., Google)

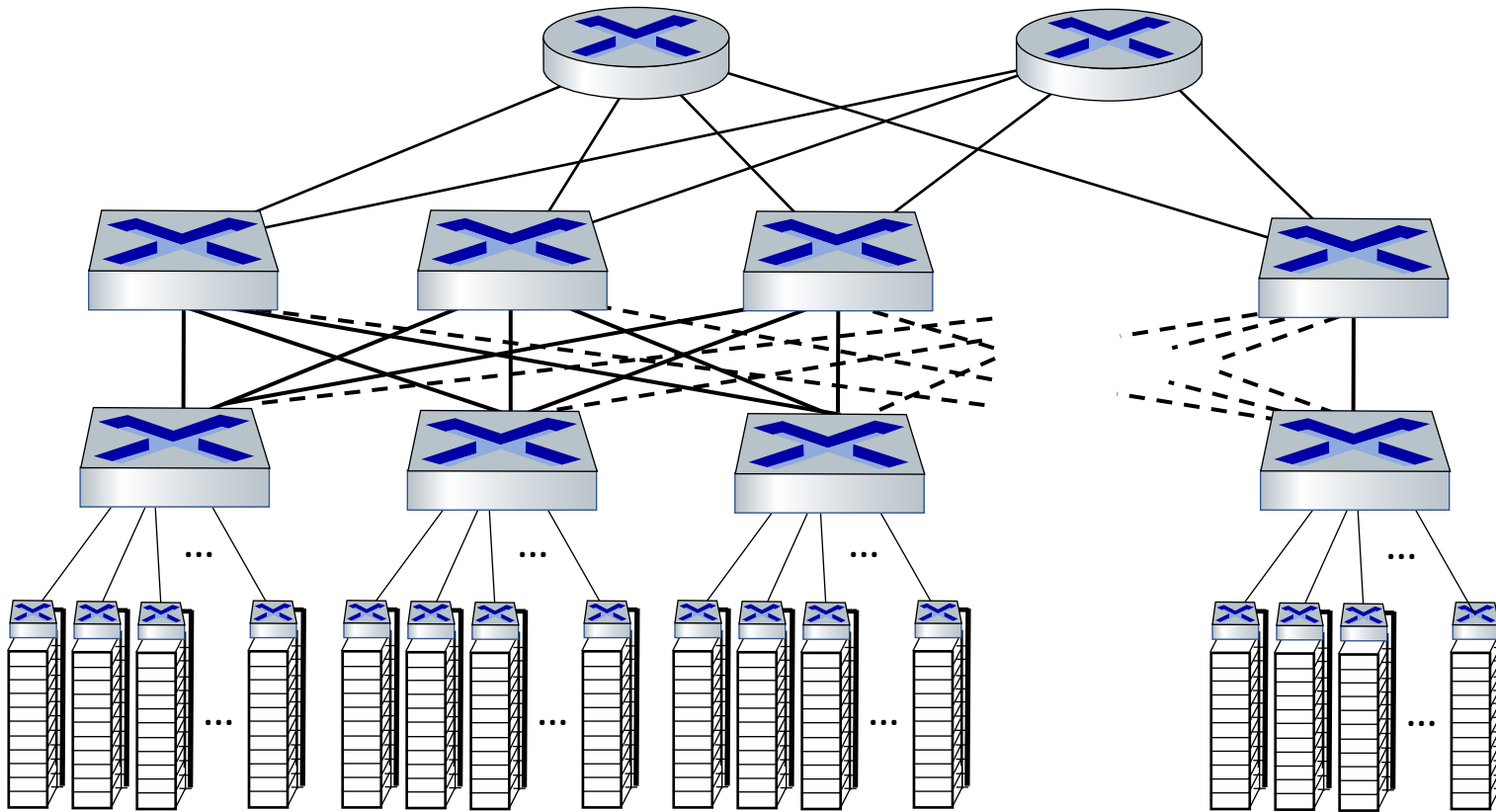
challenges:

- multiple applications, each serving massive numbers of clients
- reliability
- managing/balancing load, avoiding processing, networking, data bottlenecks



Inside a 40-ft Microsoft container, Chicago data center

Datacenter networks: network elements (fat-tree)



Border routers

- connections outside datacenter

Tier-1 switches

- connecting to ~16 T-2s below

Tier-2 switches

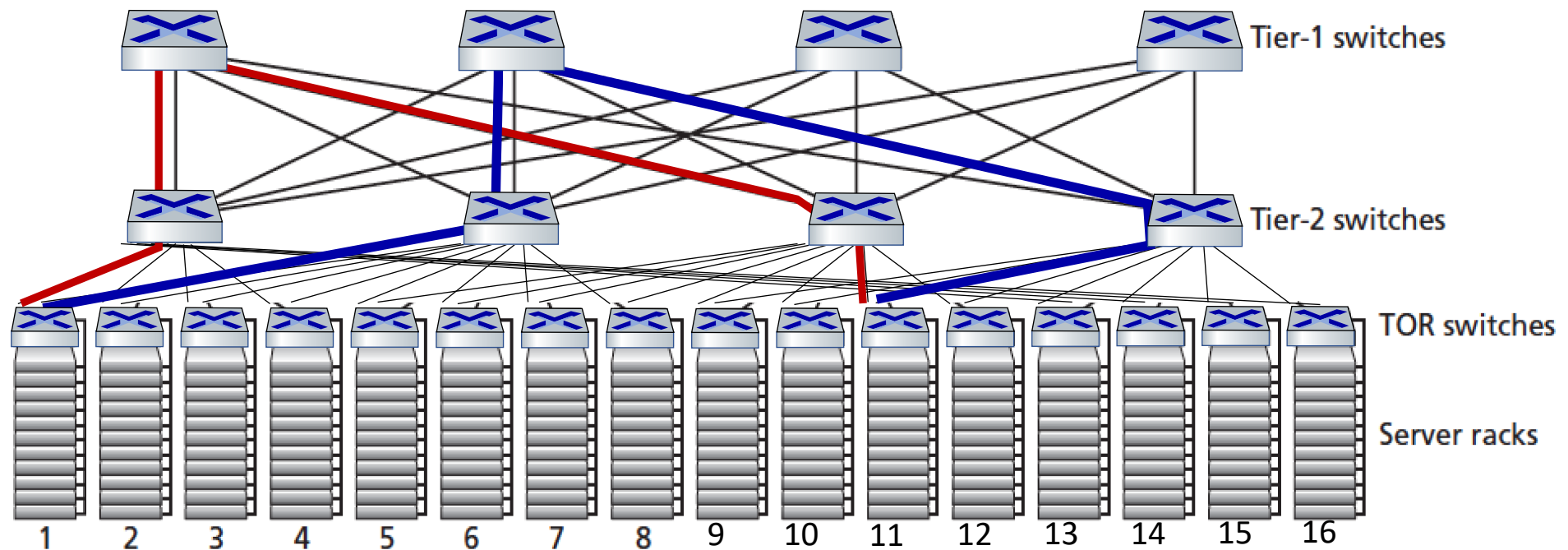
- connecting to ~16 TORs below

Top of Rack (TOR) switch

- one per rack
- 40-100Gbps Ethernet to blades

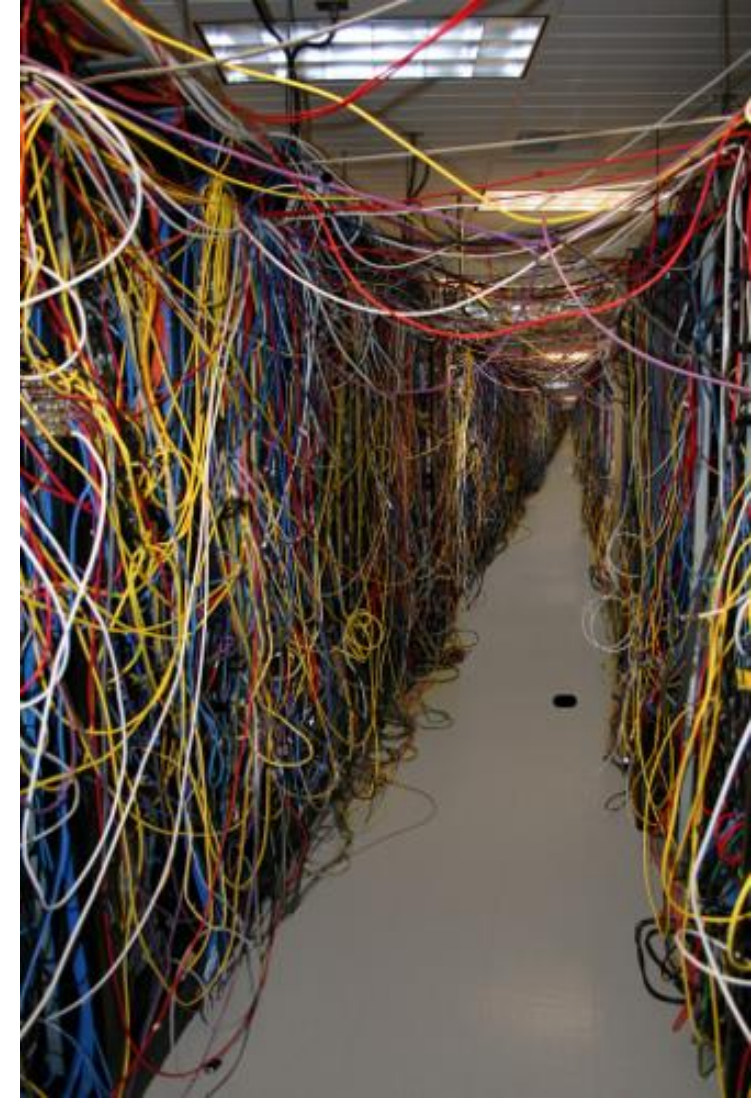
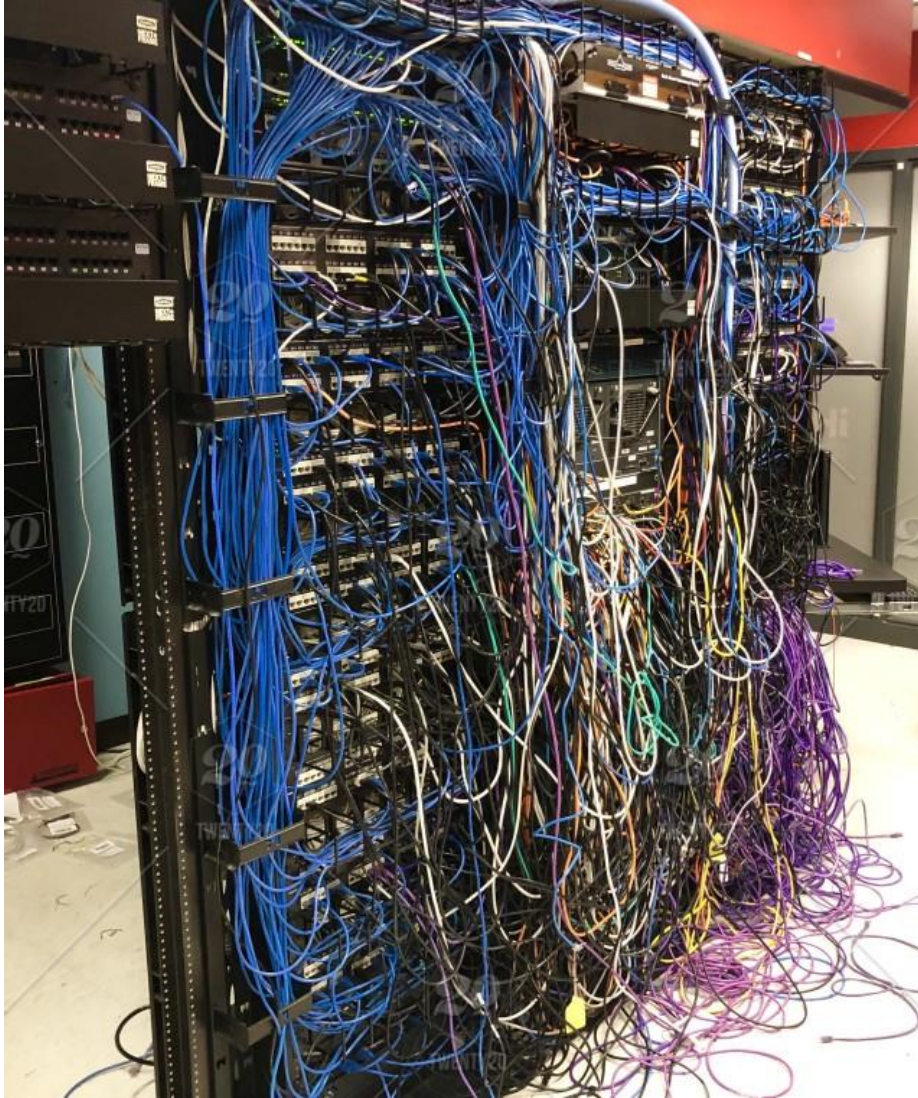
Datacenter networks: multipath (fat-tree)

- rich interconnection among switches, racks:
 - increased throughput between racks (multiple routing paths possible)
 - increased reliability via redundancy

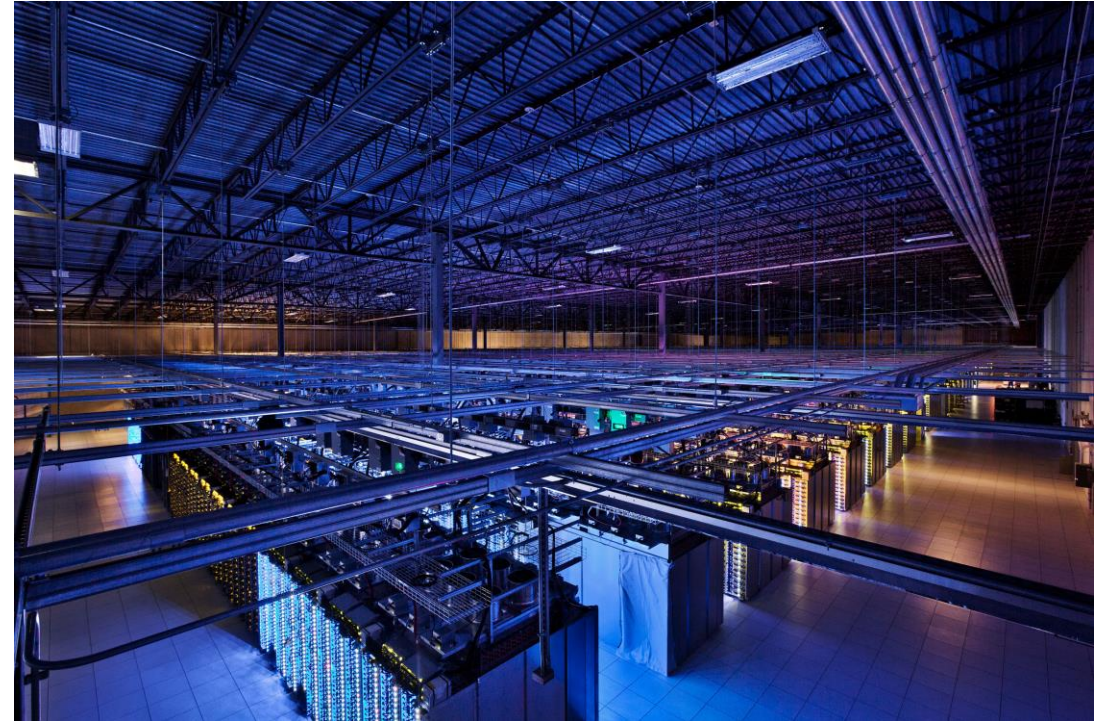
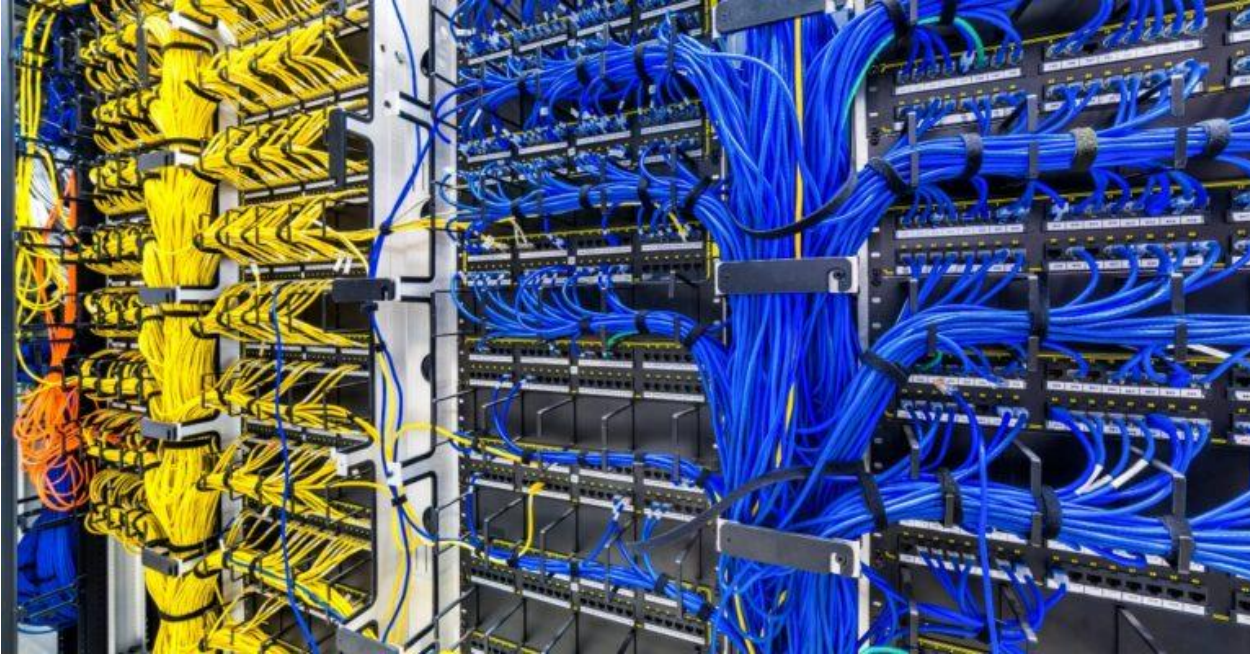


two **disjoint** paths highlighted between racks 1 and 11

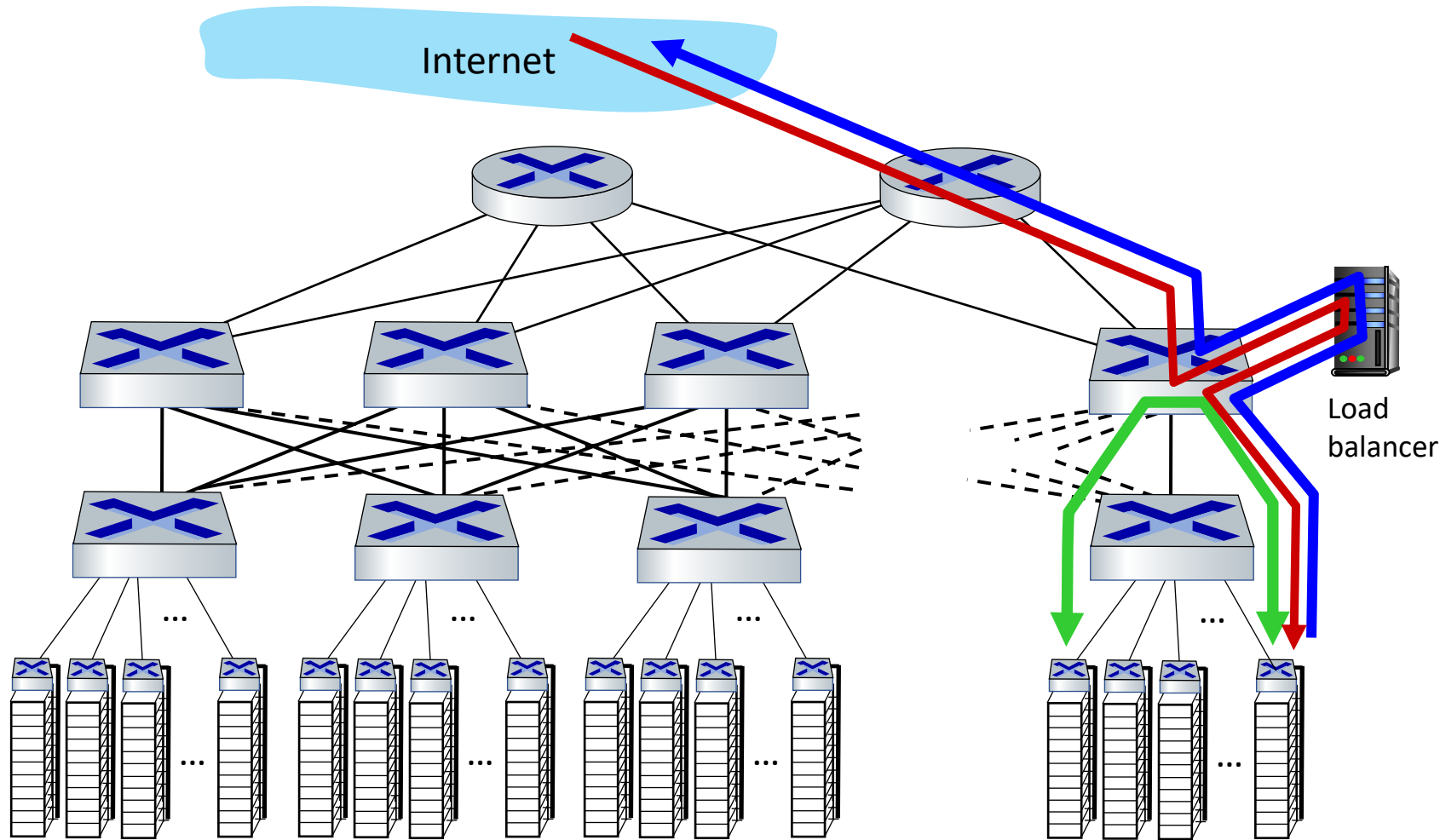
Datacenter networks: multipath (fat-tree)



Datacenter networks: multipath (fat-tree)



Datacenter networks: application-layer routing



load balancer:
application-layer
routing

- receives external client requests
- directs workload within data center
- returns results to external client (hiding data center internals from client)

Datacenter networks: protocol innovations

- link layer:

- RoCE: remote DMA (RDMA) over Converged Ethernet

- transport layer:

- ECN (explicit congestion notification) used in transport-layer congestion control (DCTCP, DCQCN)
- experimentation with hop-by-hop (backpressure) congestion control

- routing, management:

- SDN widely used within/among organizations' datacenters
- place related services, data as close as possible (e.g., in same rack or nearby rack) to minimize tier-2, tier-1 communication

Link layer, LANs: roadmap

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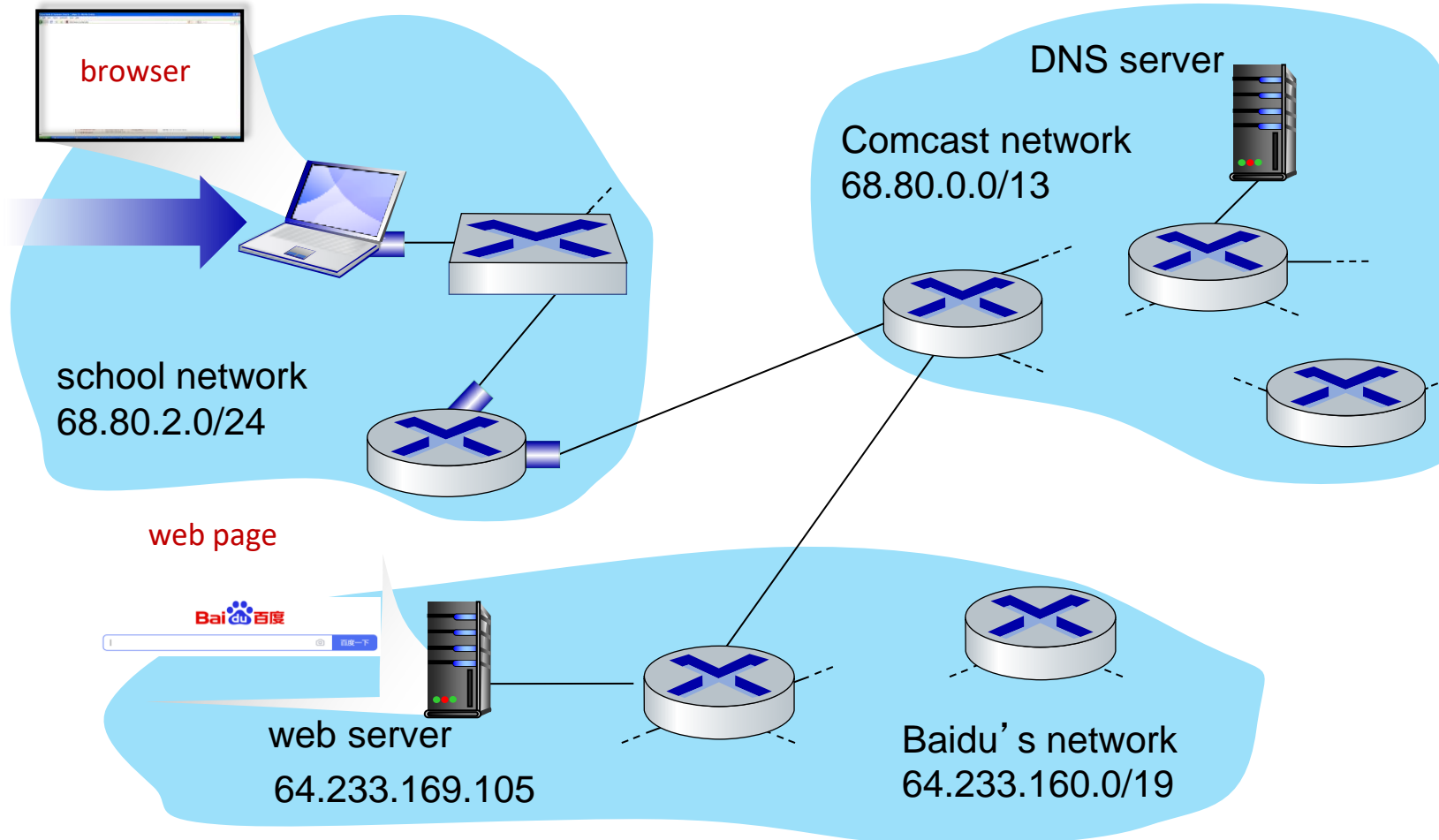


- a day in the life of a web request

Synthesis: a day in the life of a web request

- our journey down the protocol stack is now complete!
 - application, transport, network, link
- putting-it-all-together: synthesis!
 - *goal*: identify, review, understand protocols (at all layers) involved in seemingly simple scenario: requesting www page
 - *scenario*: student attaches laptop to campus network, requests/receives `www.baidu.com`

A day in the life: scenario

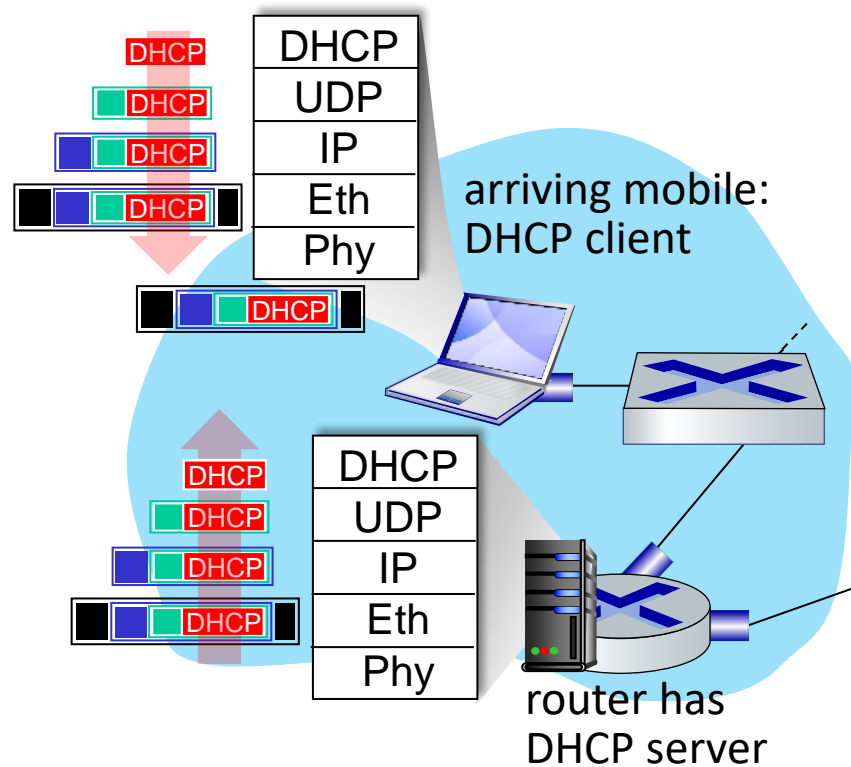


scenario:

- arriving mobile client attaches to network ...
- requests web page:
www.baidu.com

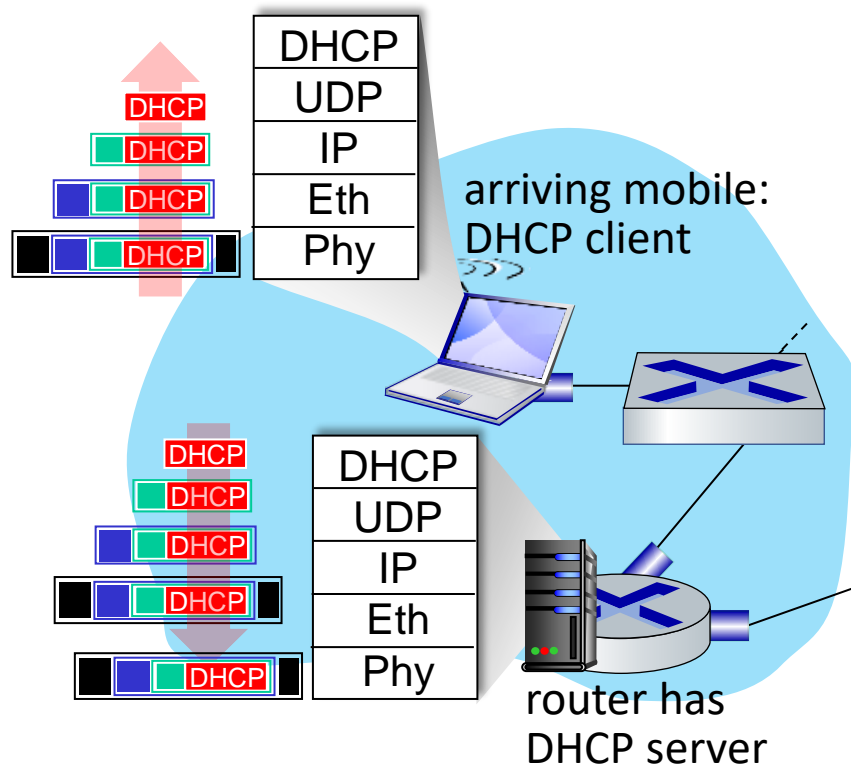
Sounds simple! 

A day in the life: connecting to the Internet



- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use **DHCP**
- DHCP request **encapsulated** in **UDP**, encapsulated in **IP**, encapsulated in **802.3** Ethernet
- Ethernet frame **broadcast** (dest: FFFFFFFFFFFFFFFF) on LAN, received at router running **DHCP** server
- Ethernet **demuxed** to IP demuxed, UDP demuxed to DHCP

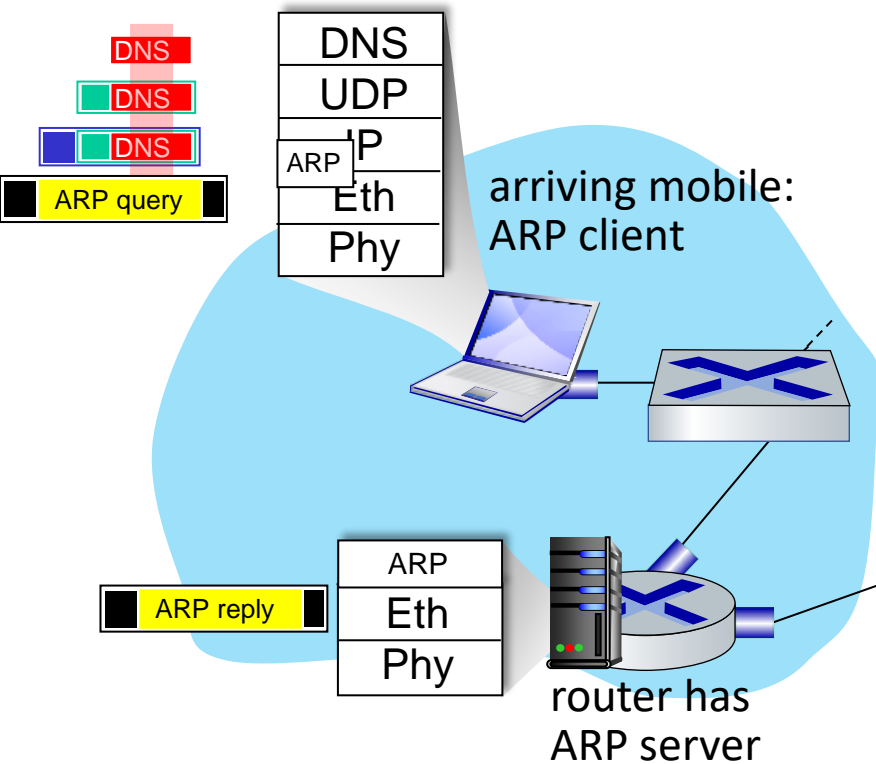
A day in the life: connecting to the Internet



- DHCP server formulates **DHCP ACK** containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation at DHCP server, frame forwarded (**switch learning**) through LAN, demultiplexing at client
- DHCP client receives DHCP ACK reply

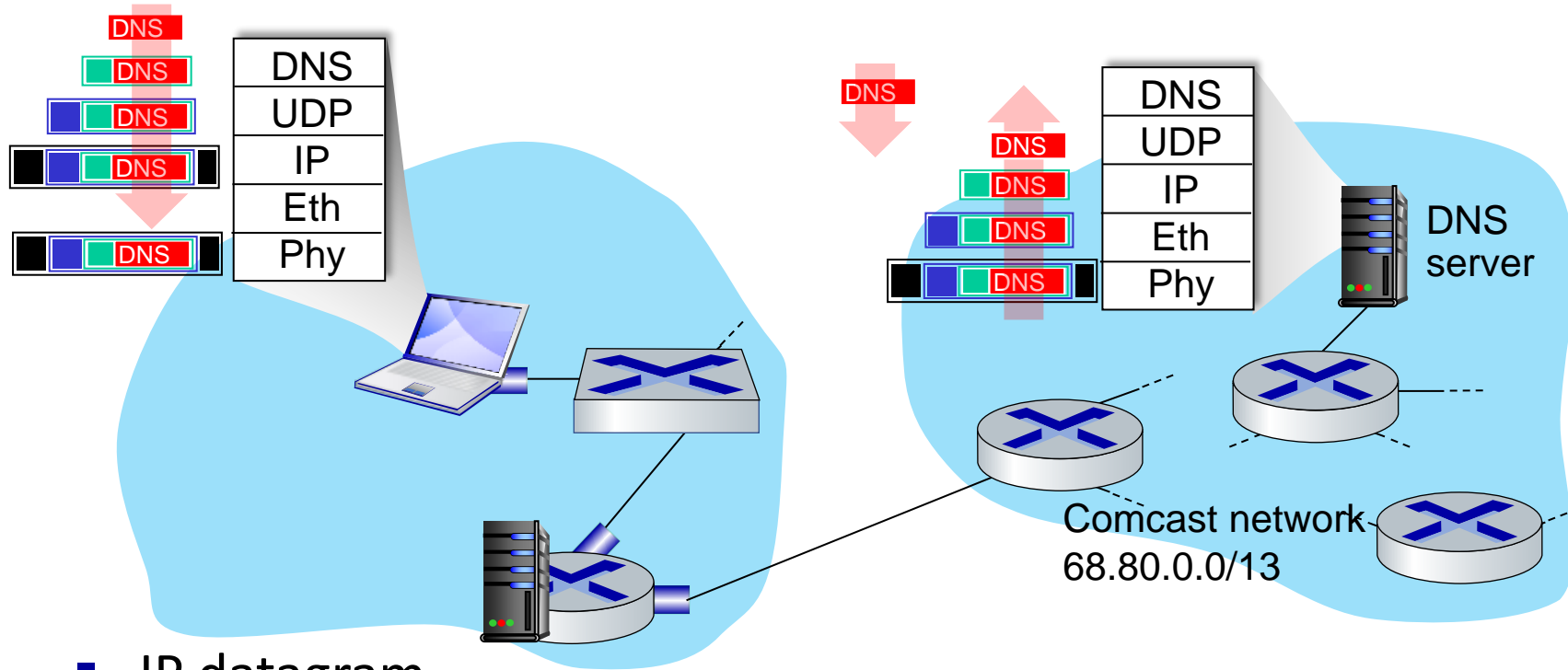
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

A day in the life... ARP (before DNS, before HTTP)



- before sending **HTTP** request, need IP address of `www.baidu.com`: **DNS**
- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: **ARP**
- **ARP query** broadcast, received by router, which replies with **ARP reply** giving MAC address of router interface
- client now knows MAC address of first hop router, so can now send frame containing DNS query

A day in the life... using DNS

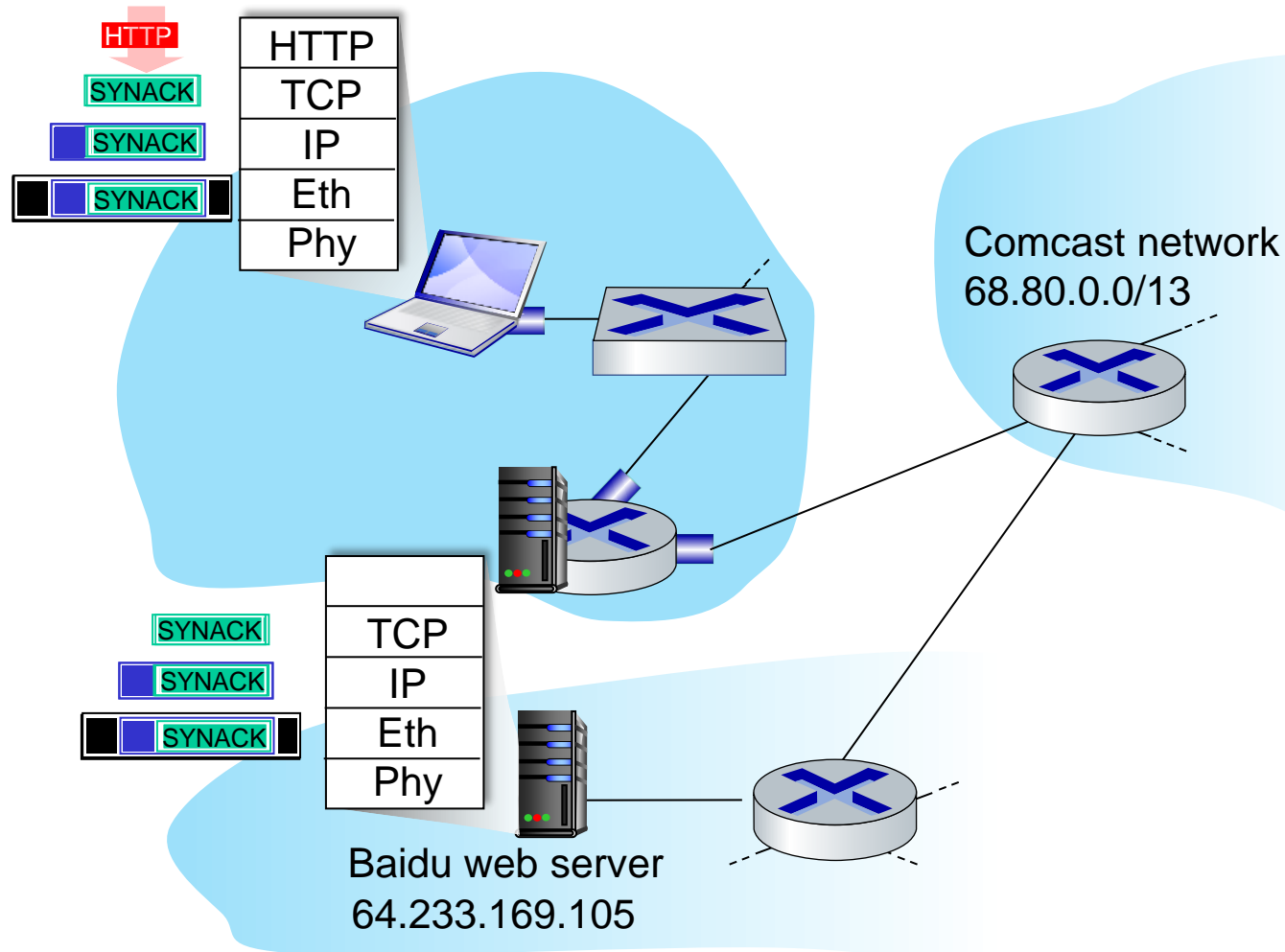


- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router

- IP datagram forwarded from campus network into Comcast network, routed (tables created by **RIP**, **OSPF**, **IS-IS** and/or **BGP** routing protocols) to DNS server

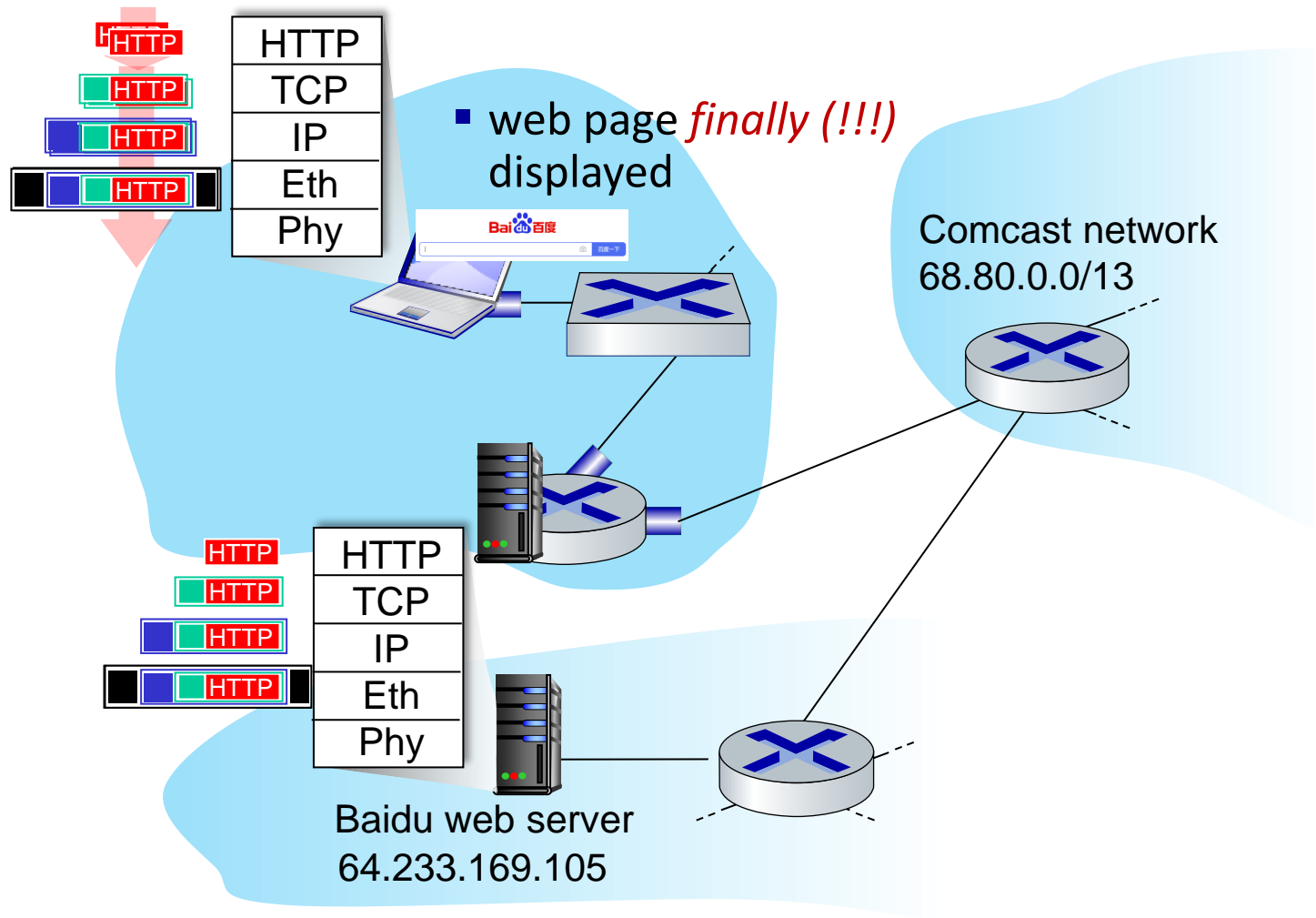
- demuxed to DNS
- DNS replies to client with IP address of www.baidu.com

A day in the life...TCP connection carrying HTTP



- to send HTTP request, client first opens **TCP socket** to web server
- TCP **SYN segment** (step 1 in TCP 3-way handshake) inter-domain routed to web server
- web server responds with **TCP SYNACK** (step 2 in TCP 3-way handshake)
- TCP **connection established!**

A day in the life... HTTP request/reply



- **HTTP request** sent into TCP socket
- IP datagram containing HTTP request routed to `www.baidu.com`
- web server responds with **HTTP reply** (containing web page)
- IP datagram containing HTTP reply routed back to client

Chapter 6: Summary

- principles behind data link layer services:
 - error detection, correction
 - sharing a broadcast channel: multiple access
 - link layer addressing
- instantiation, implementation of various link layer technologies
 - Ethernet
 - switched LANS, VLANs
 - virtualized networks as a link layer: MPLS
- synthesis: a day in the life of a web request

Chapter 7

Wireless and Mobile Networks

Instructor: Zhuozhao Li

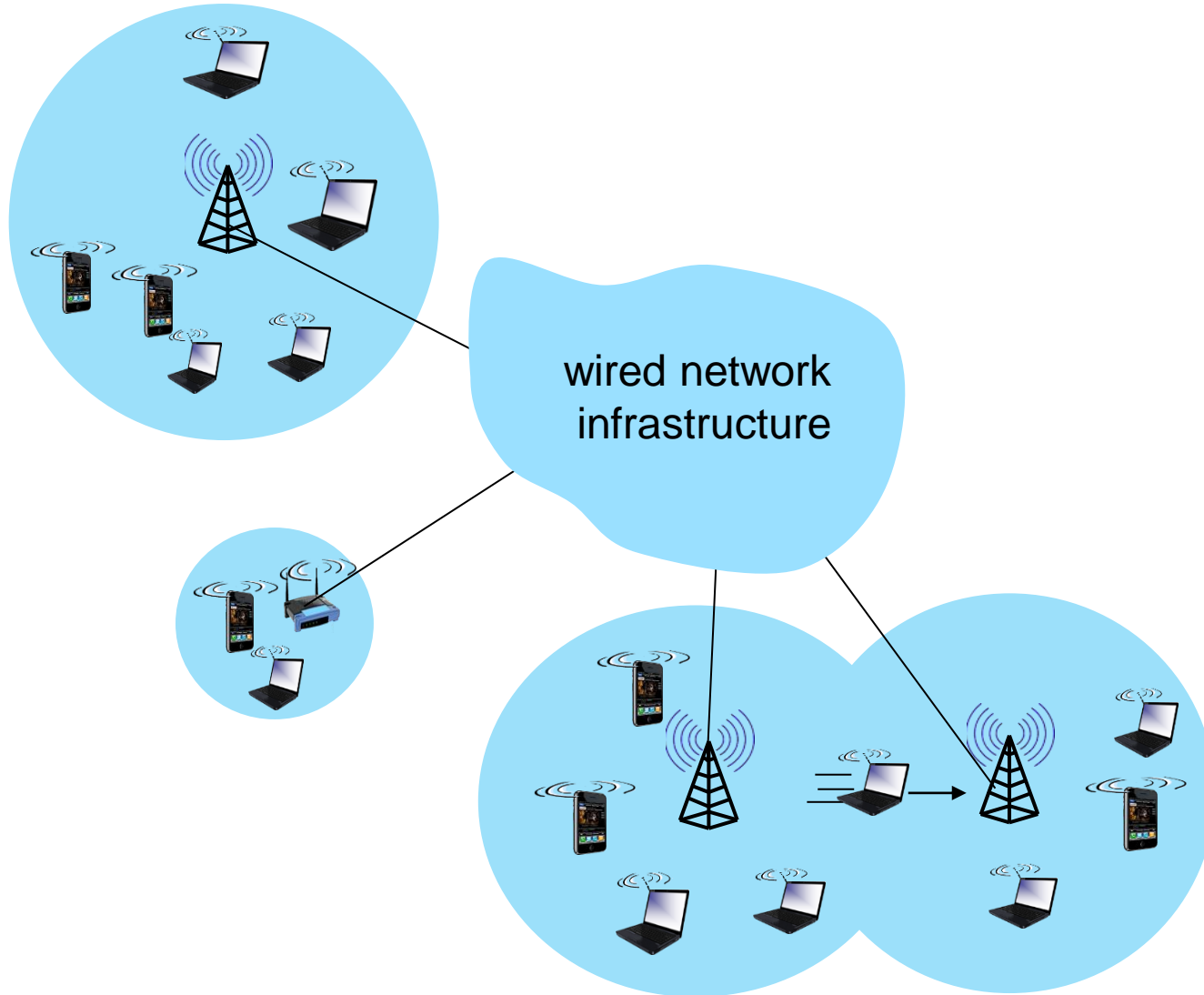
Lab: Qing Wang

Department of Computer Science and Engineering

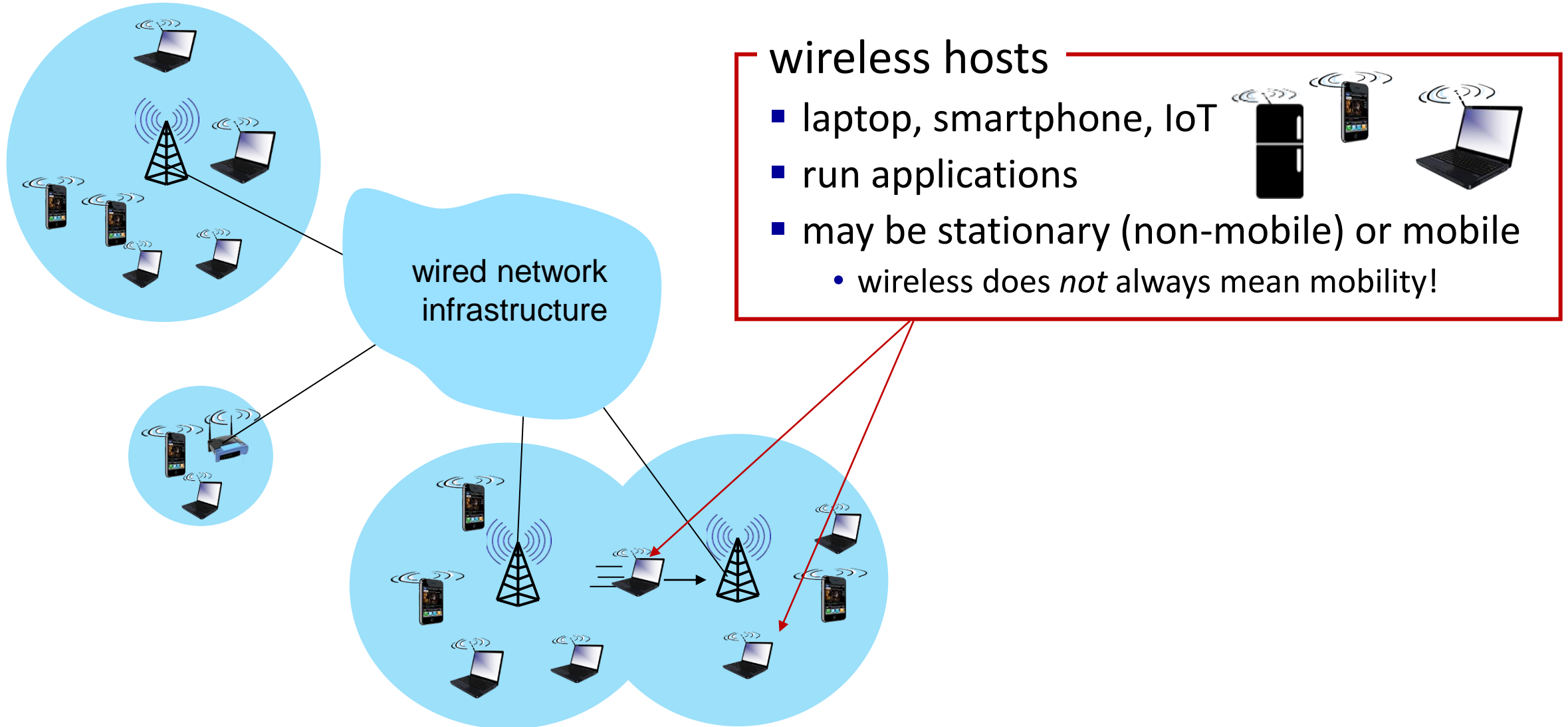
Wireless and Mobile Networks: context

- 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

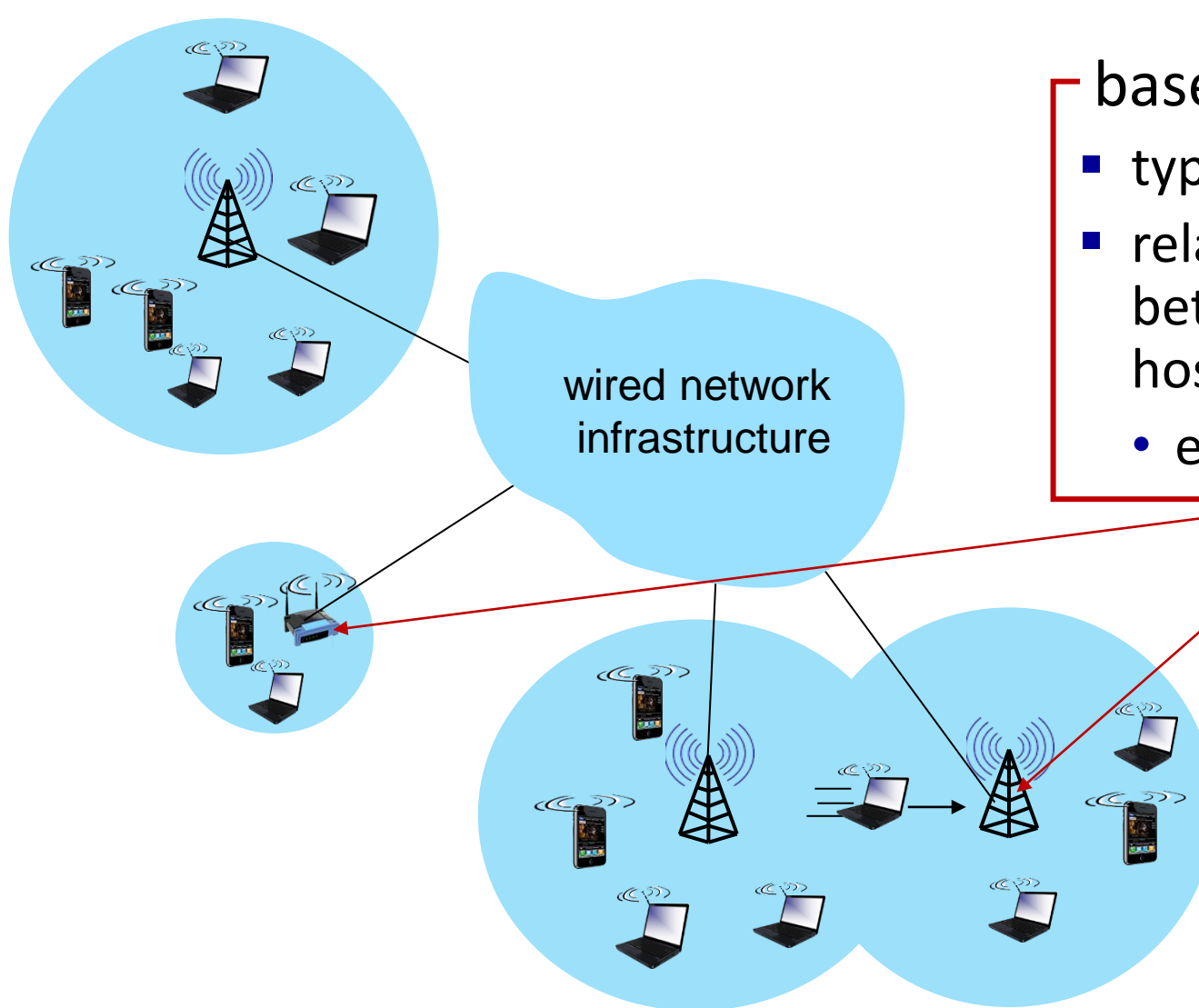
Elements of a wireless network



Elements of a wireless network



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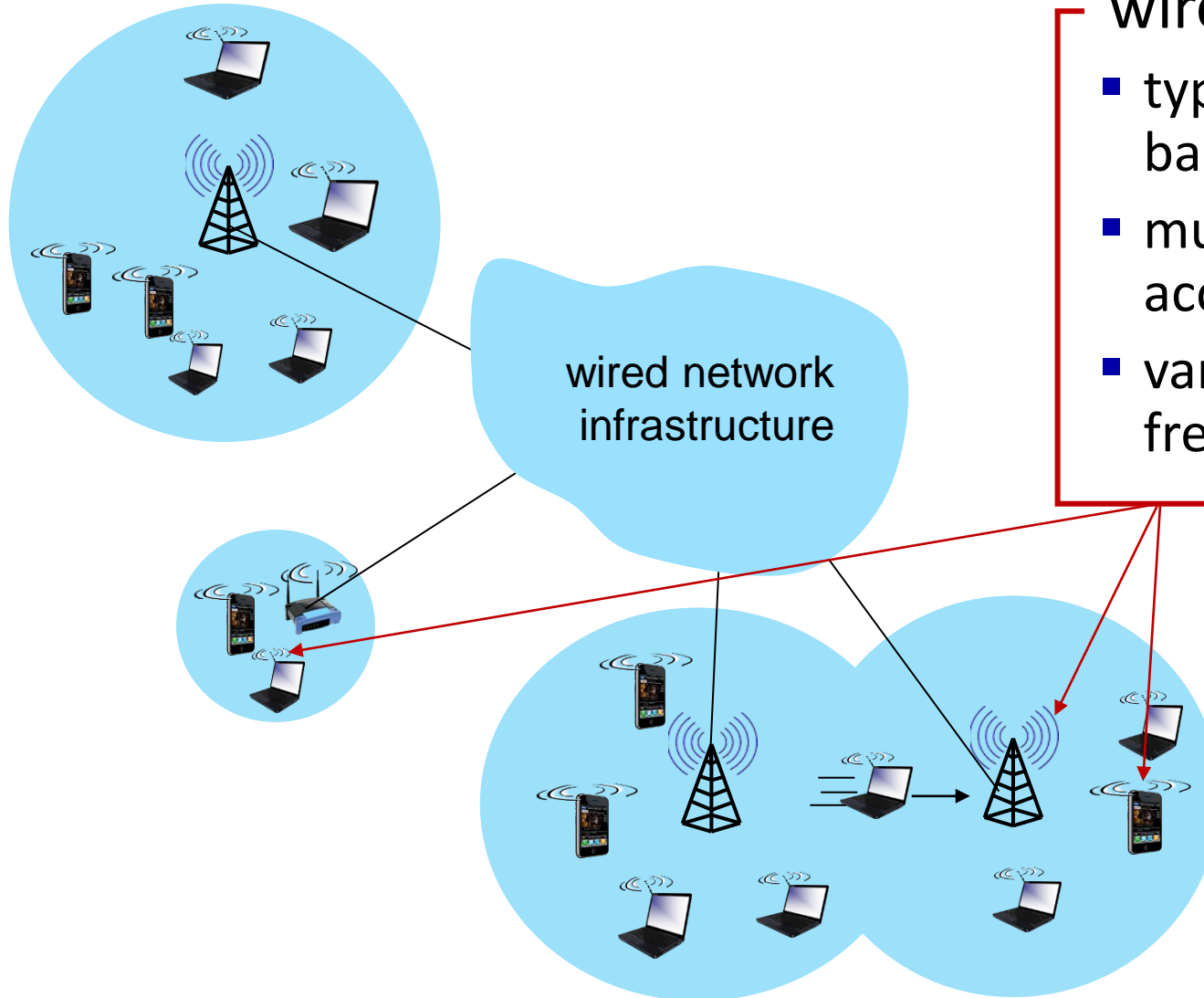


base station



- 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

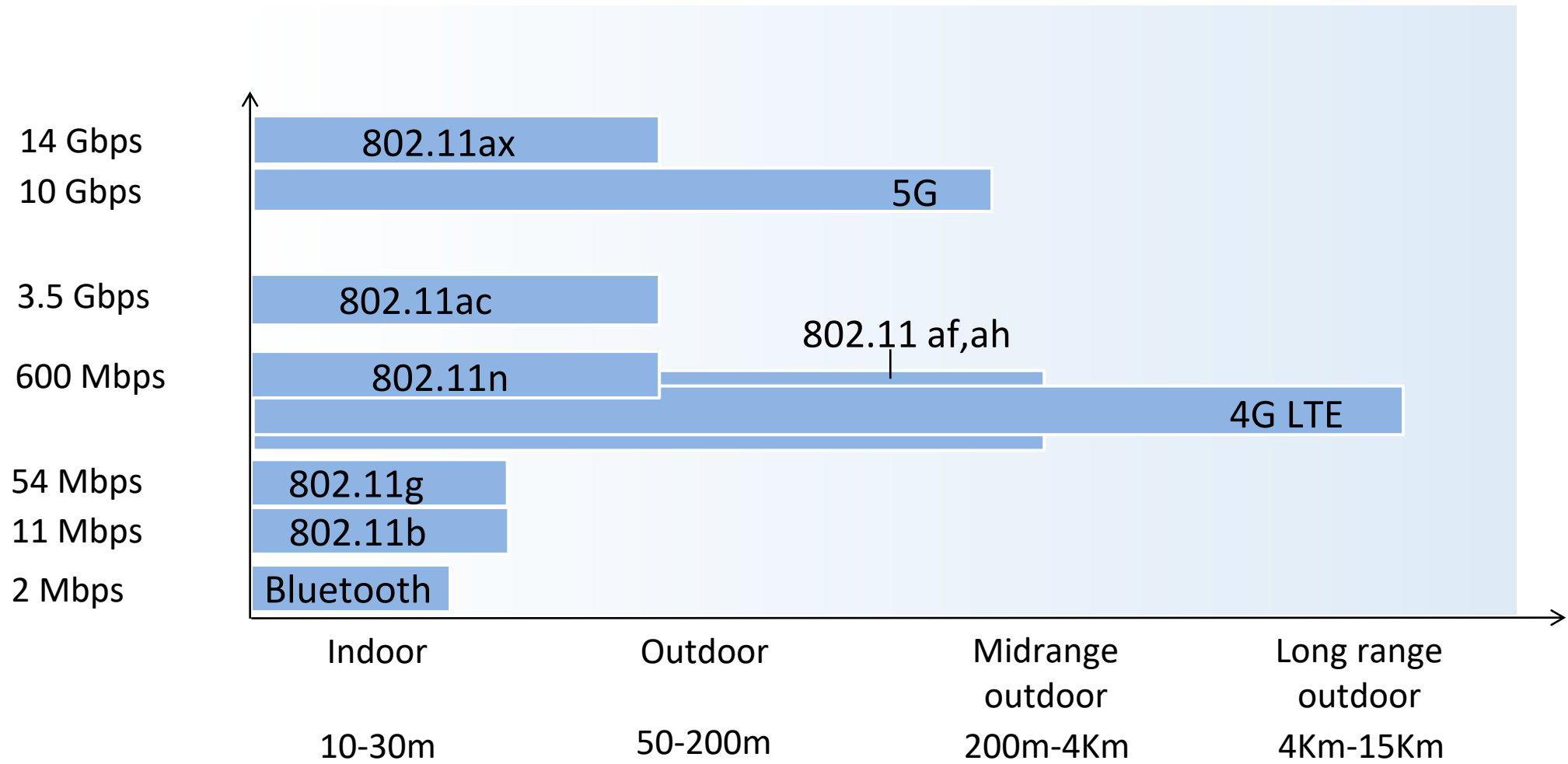


wireless link

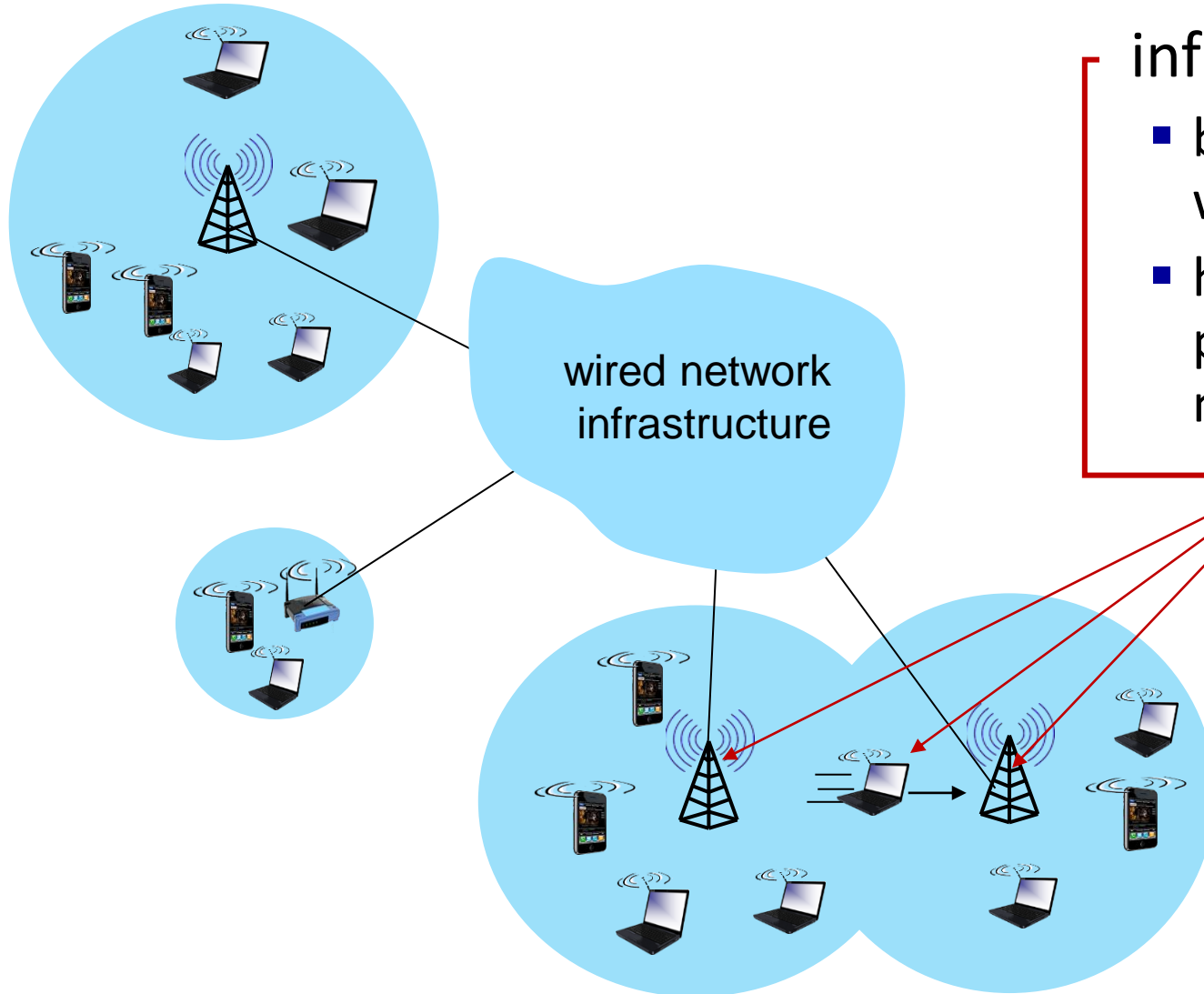


- typically used to connect mobile(s) to base station, also used as backbone link
- multiple access protocol coordinates link access
- various transmission rates and distances, frequency bands

Characteristics of selected wireless links



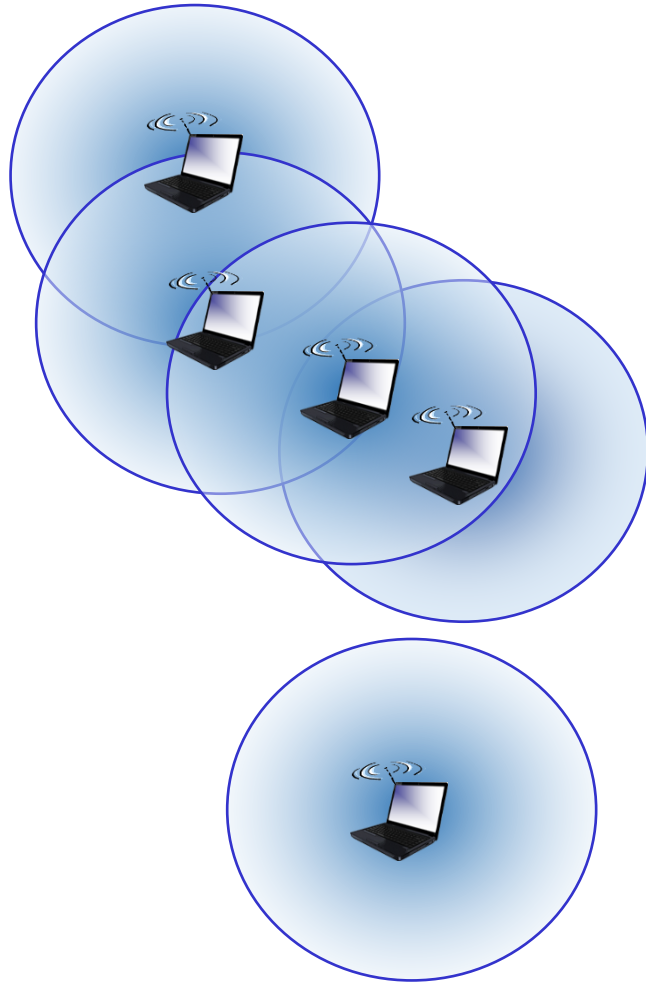
Elements of a wireless network



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

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

Wireless link characteristics (1)

important differences from wired link

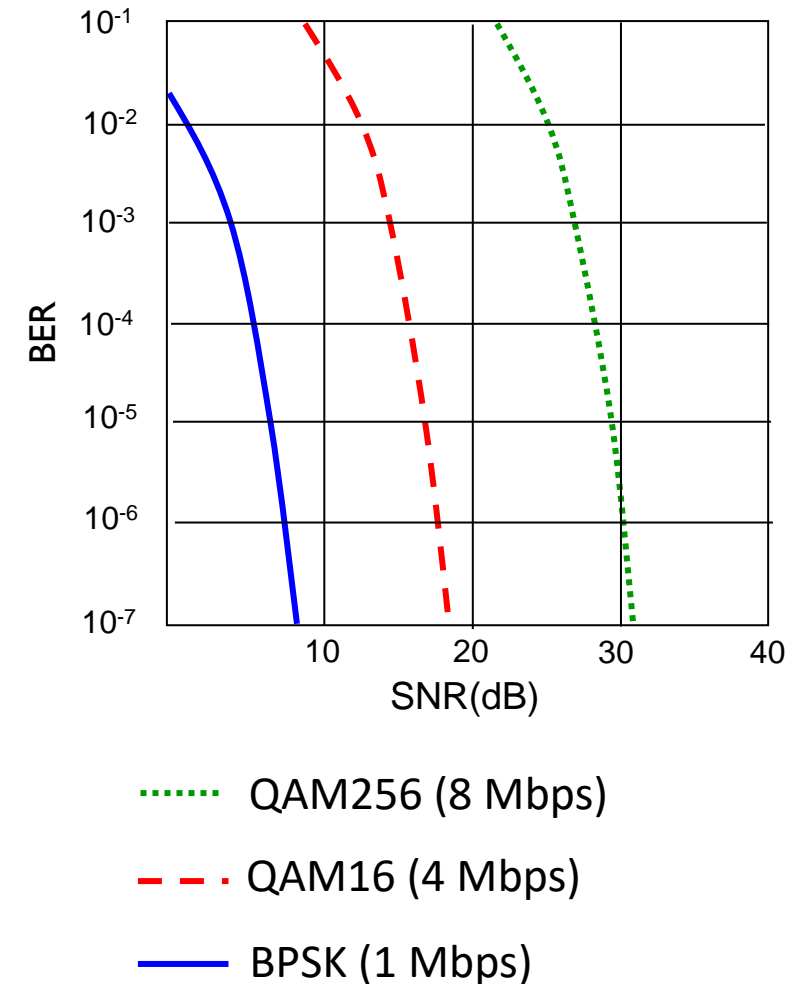
- **decreased signal strength:** radio signal attenuates as it propagates through matter (path loss)
- **interference from other sources:** wireless network frequencies (e.g., 2.4 GHz) shared by many devices (e.g., WiFi, cellular, motors): interference
- **multipath propagation:** radio signal reflects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

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



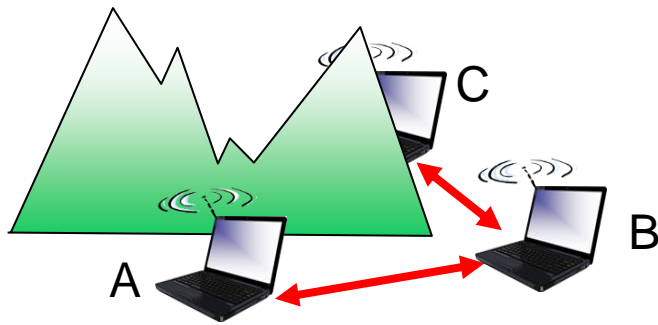
Wireless link characteristics (2)

- 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)



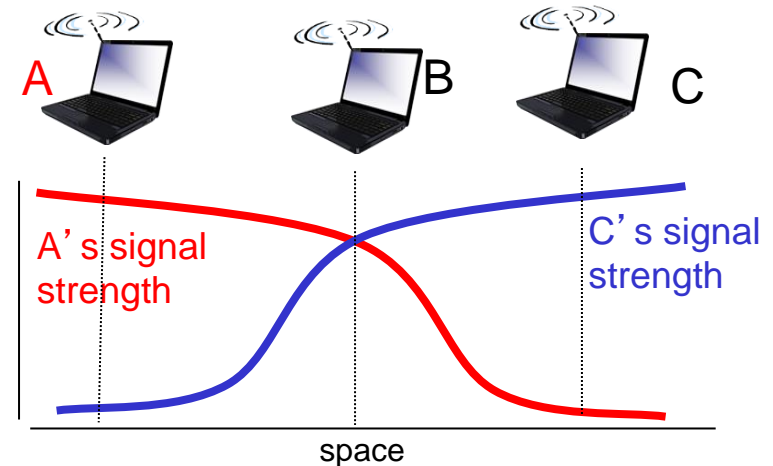
Wireless link characteristics (3)

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



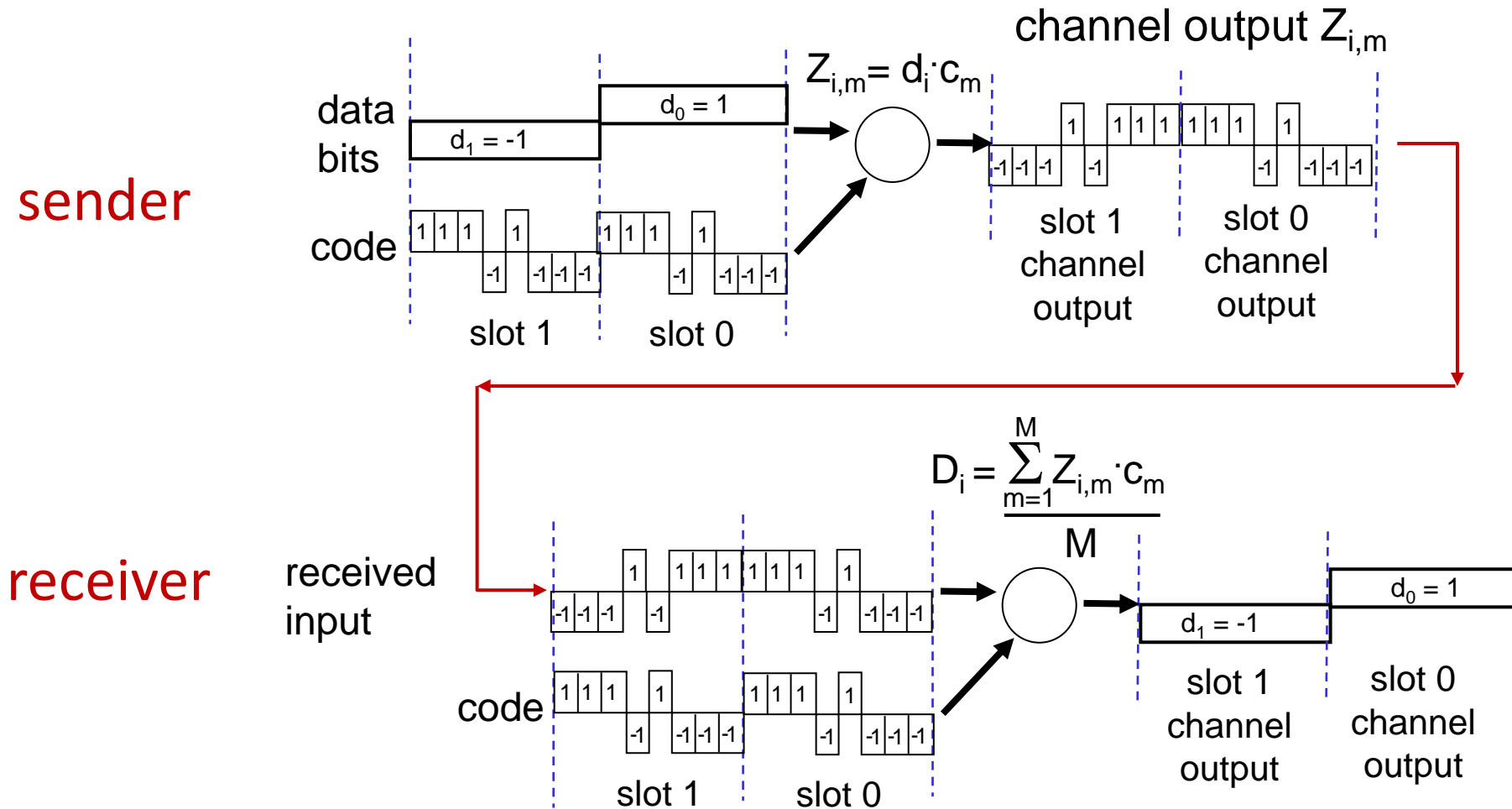
Signal attenuation:

- 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

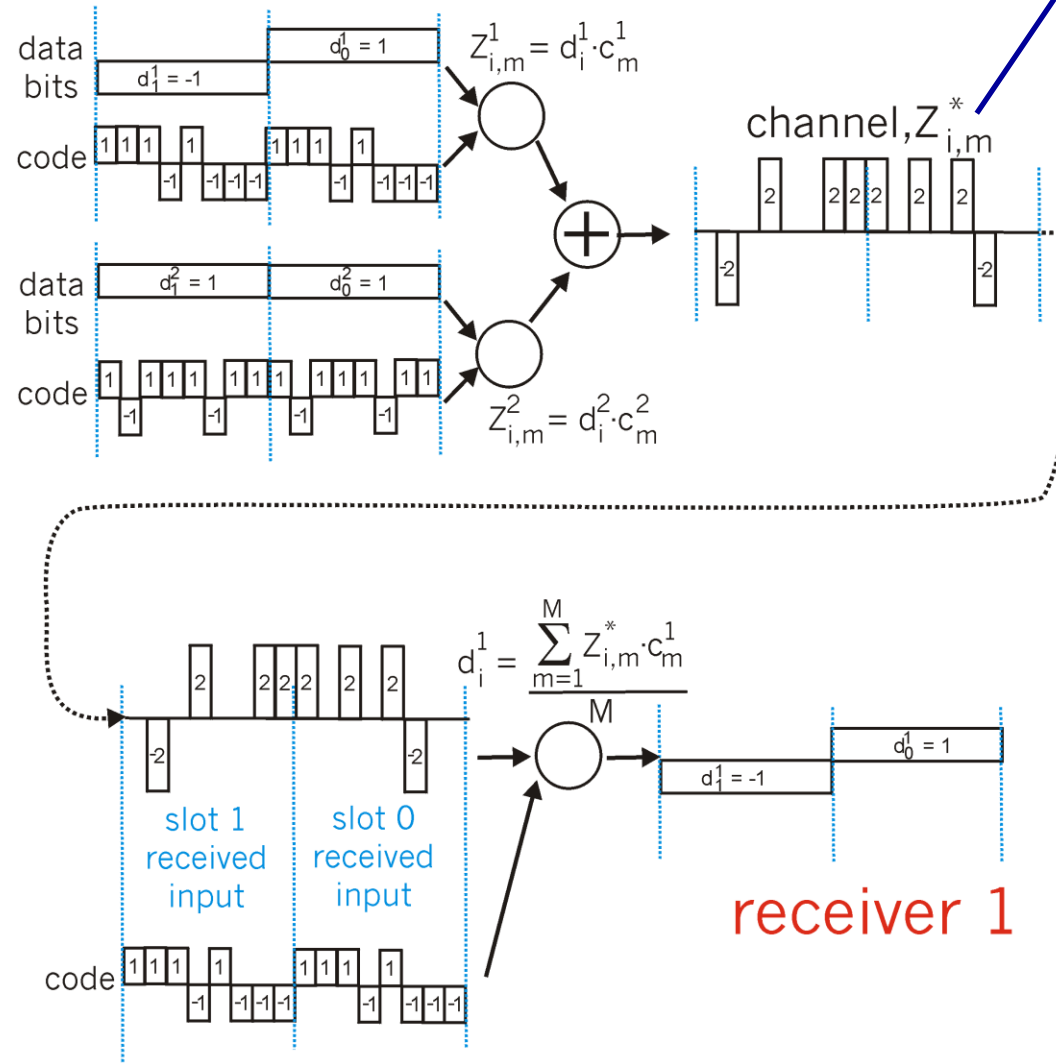


... but this isn't really useful yet!

CDMA: two-sender interference

Sender 1

Sender 2



channel sums together transmissions by sender 1 and 2

using same code as sender 1, receiver recovers sender 1's original data from summed channel data!

... now *that's* useful!

Chapter 7 outline

- Introduction

Wireless

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



Mobility

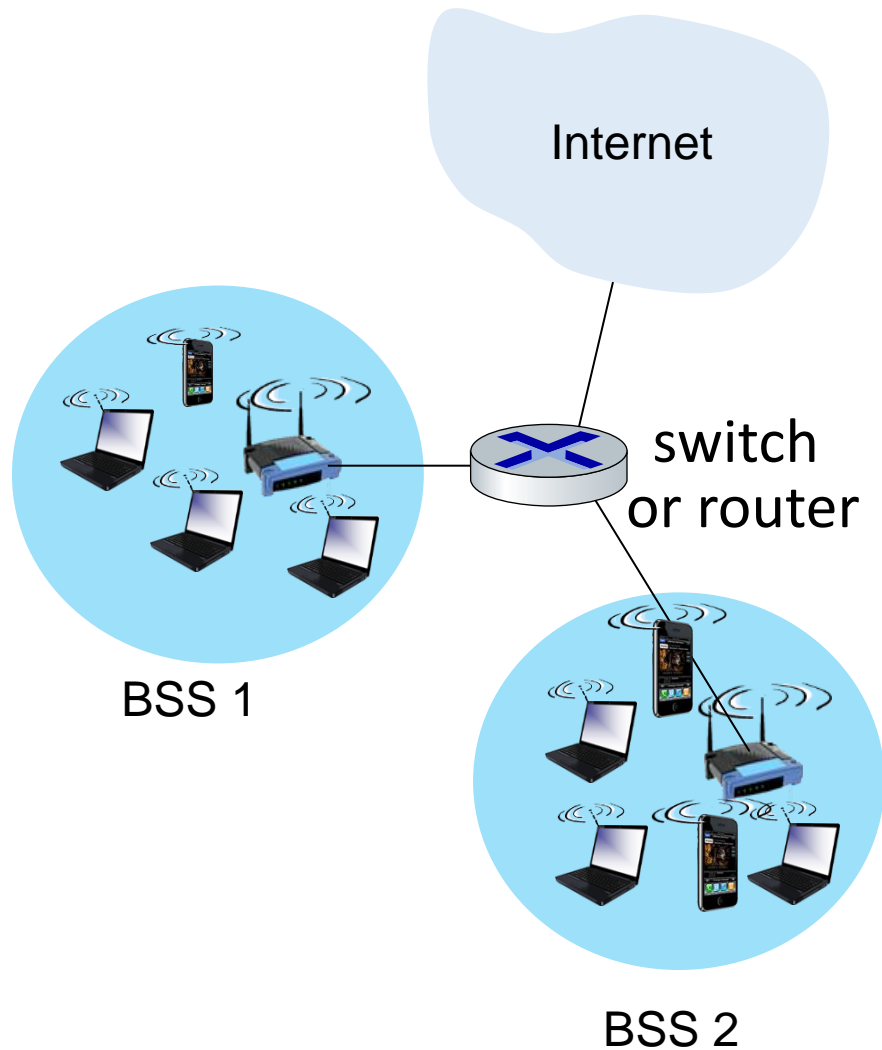
- Mobility management: principles
- Mobility management: practice
 - 4G/5G networks
 - Mobile IP
- Mobility: impact on higher-layer protocols

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

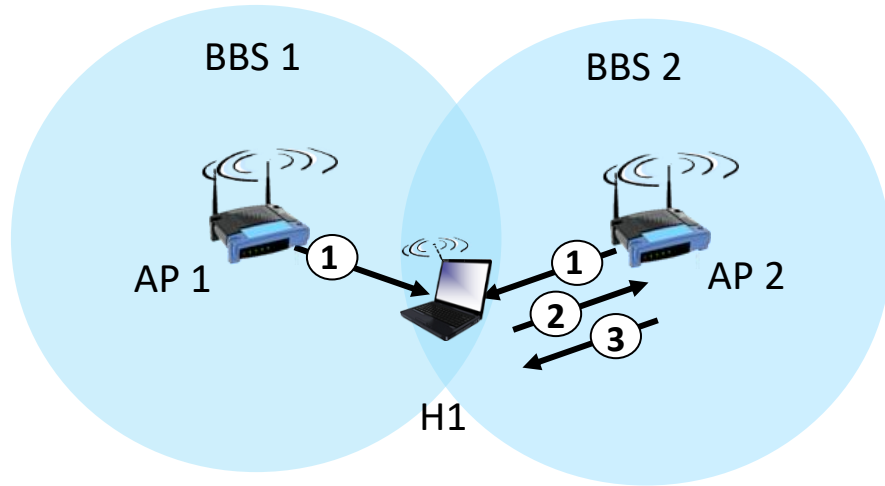
- spectrum divided into channels at different frequencies
 - AP admin chooses frequency for AP
 - interference possible: channel can be same as that chosen by neighboring AP!
- arriving host: must **associate** with an AP
 - scans channels, listening for *beacon frames* containing AP's name (SSID) and 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



SSID:

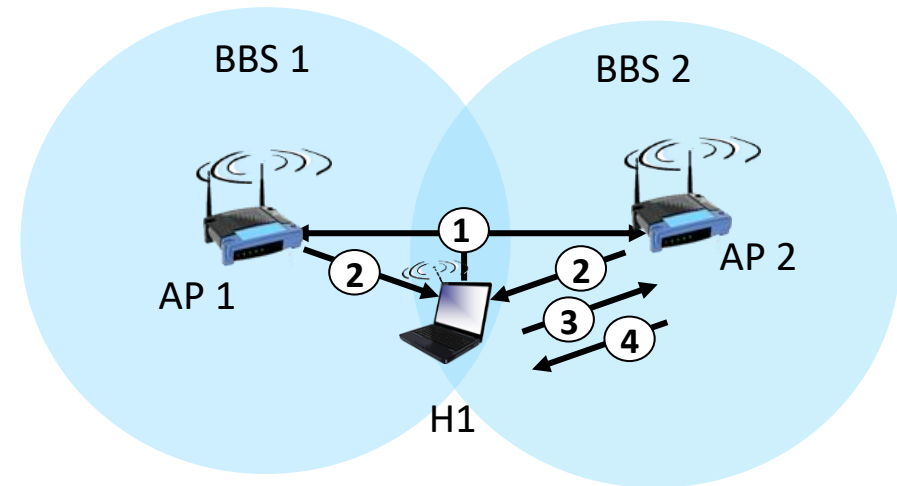
SUSTech-wifi-5G

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

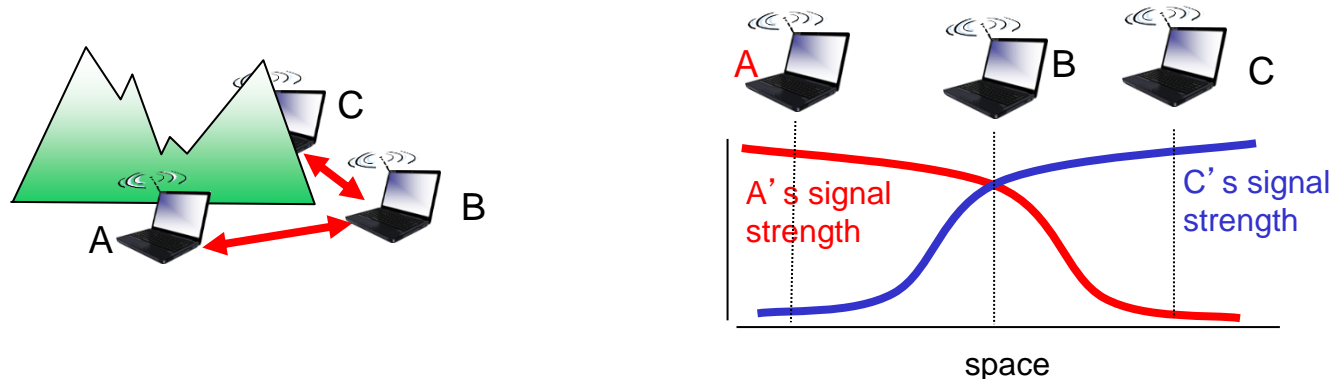


active scanning:

- (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



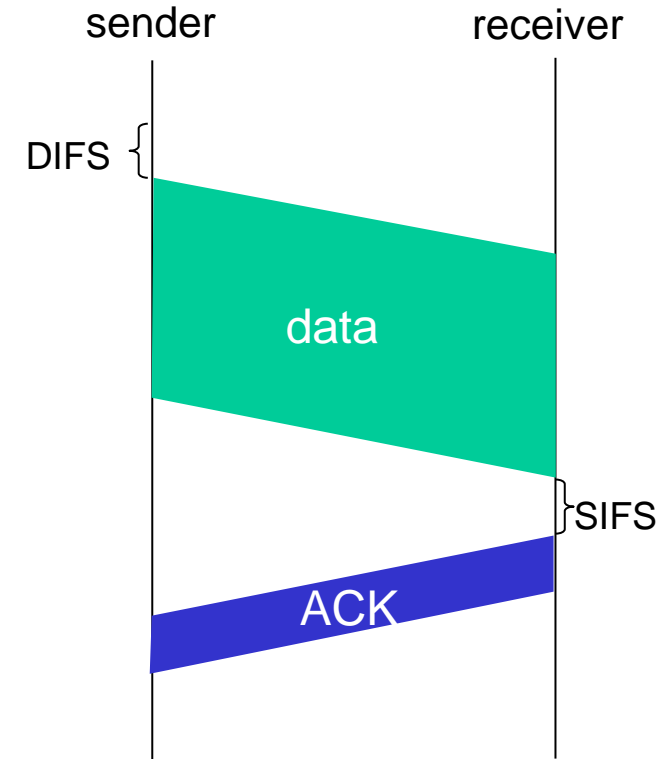
IEEE 802.11 MAC Protocol: CSMA/CA

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)

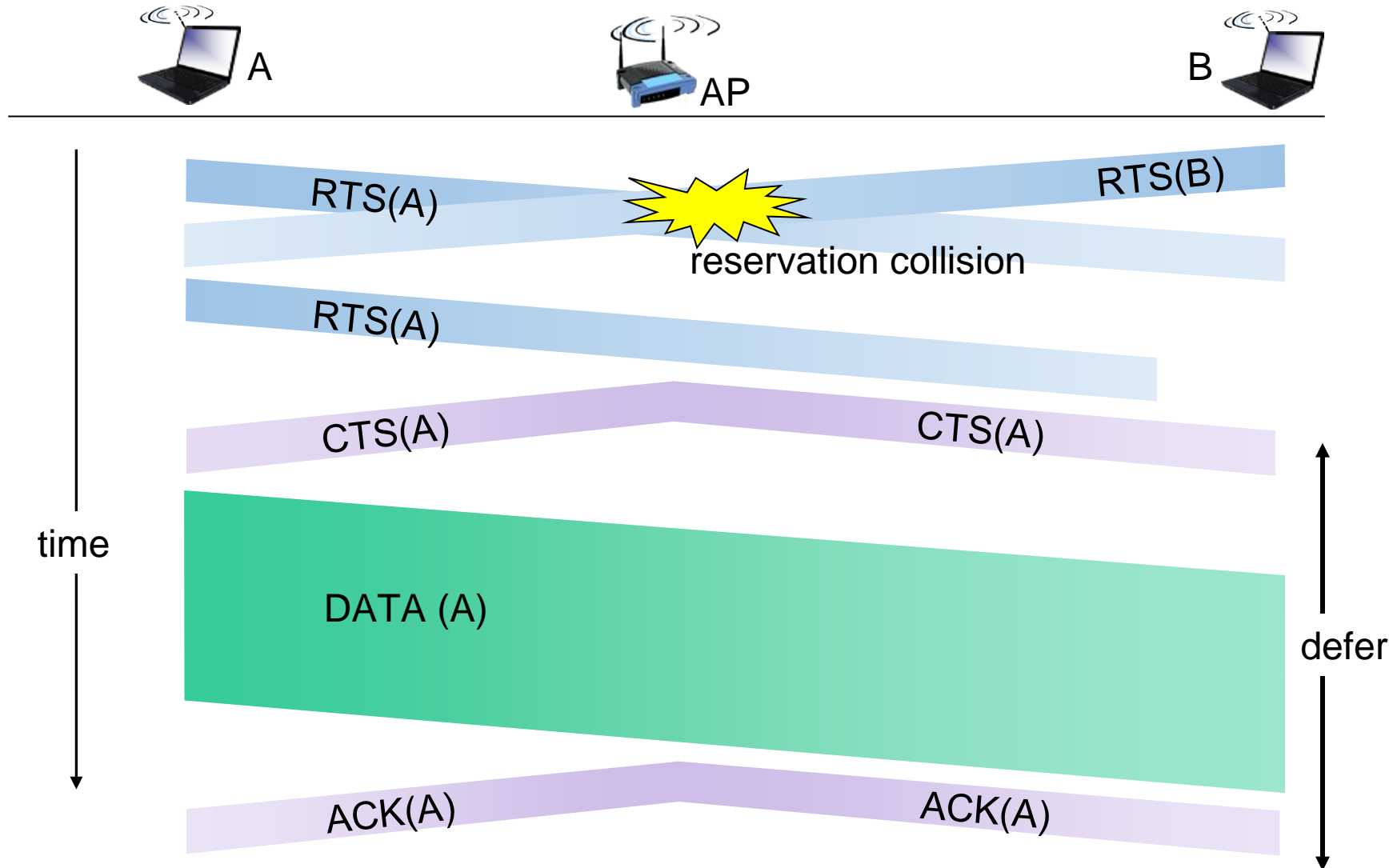


Avoiding collisions (more)

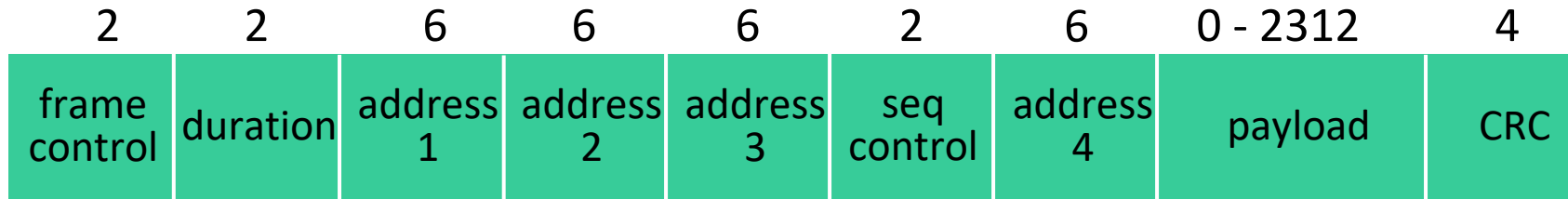
idea: sender “reserves” channel use for data frames using small reservation packets

- 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



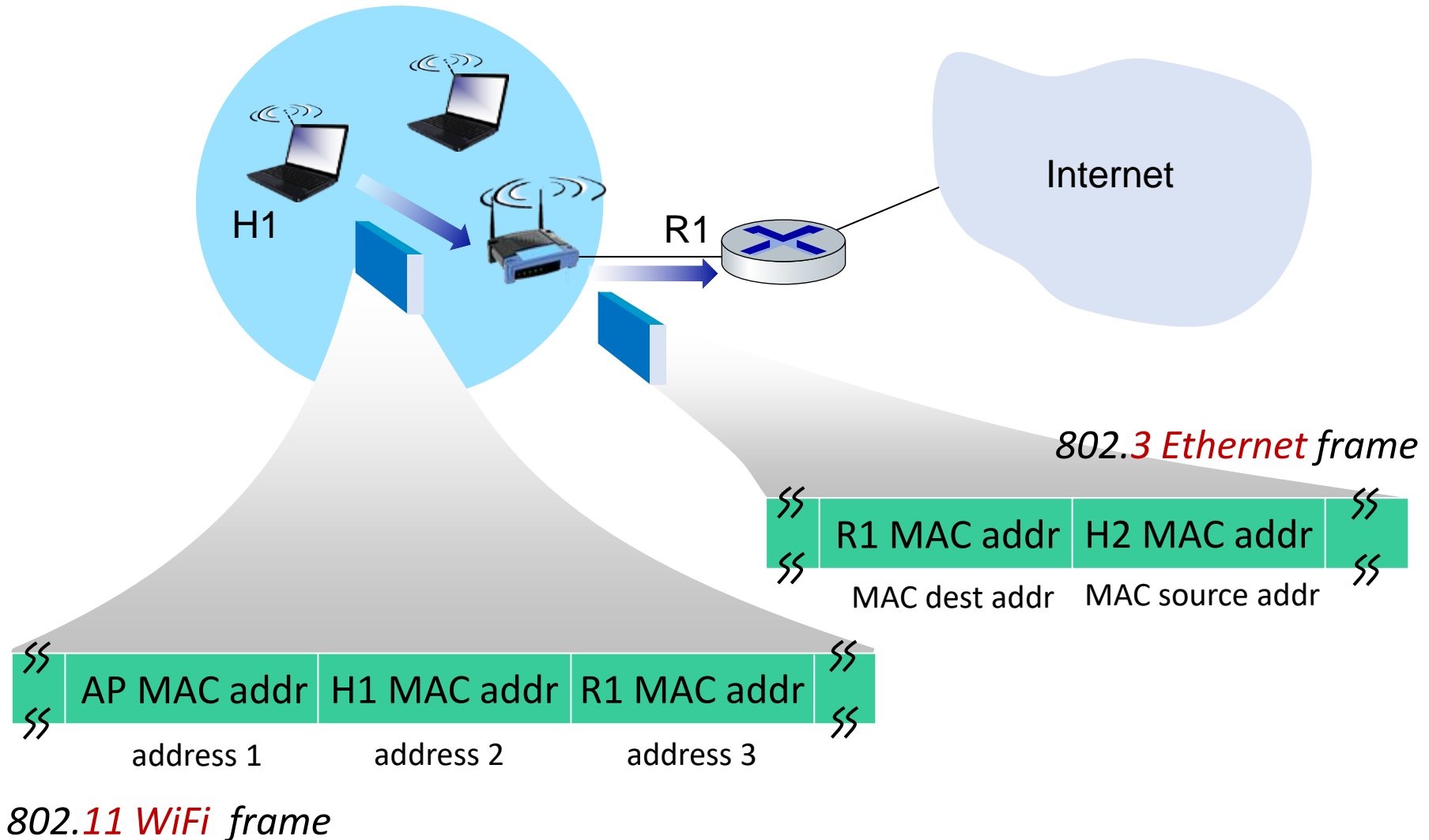
Address 1: MAC address of wireless host or AP to receive this frame

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

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

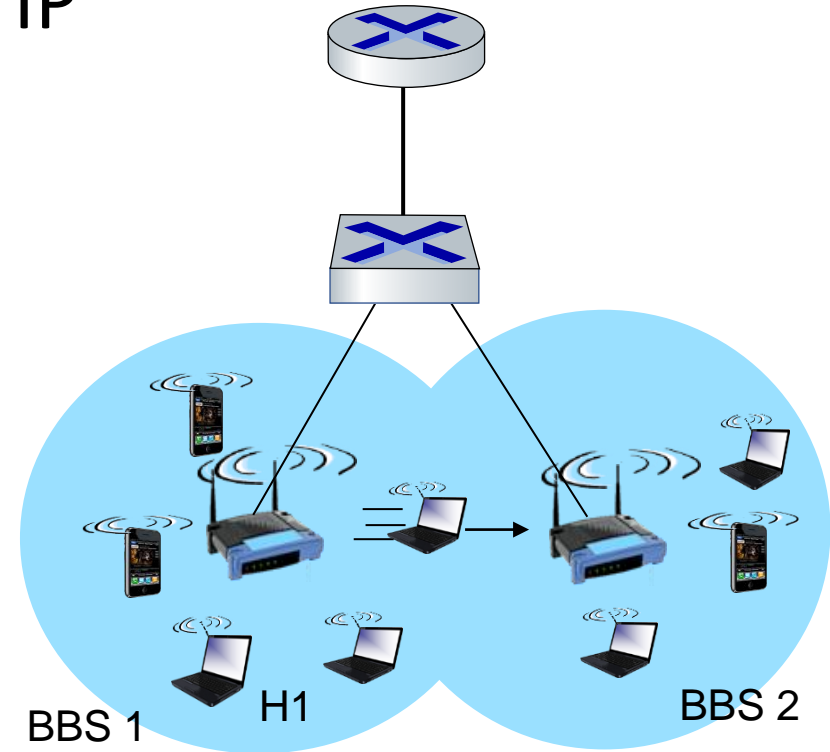
Address 4: used only in ad hoc mode

802.11 frame: addressing



802.11: mobility within same subnet

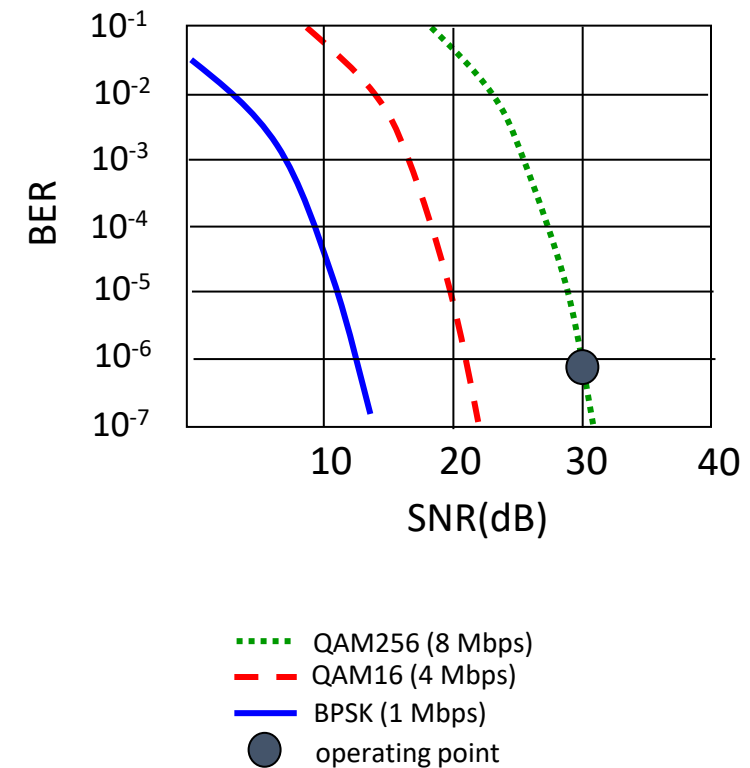
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
 - self-learning (Ch. 6): switch will see frame from H1 and “remember” which switch port can be used to reach H1



802.11: advanced capabilities

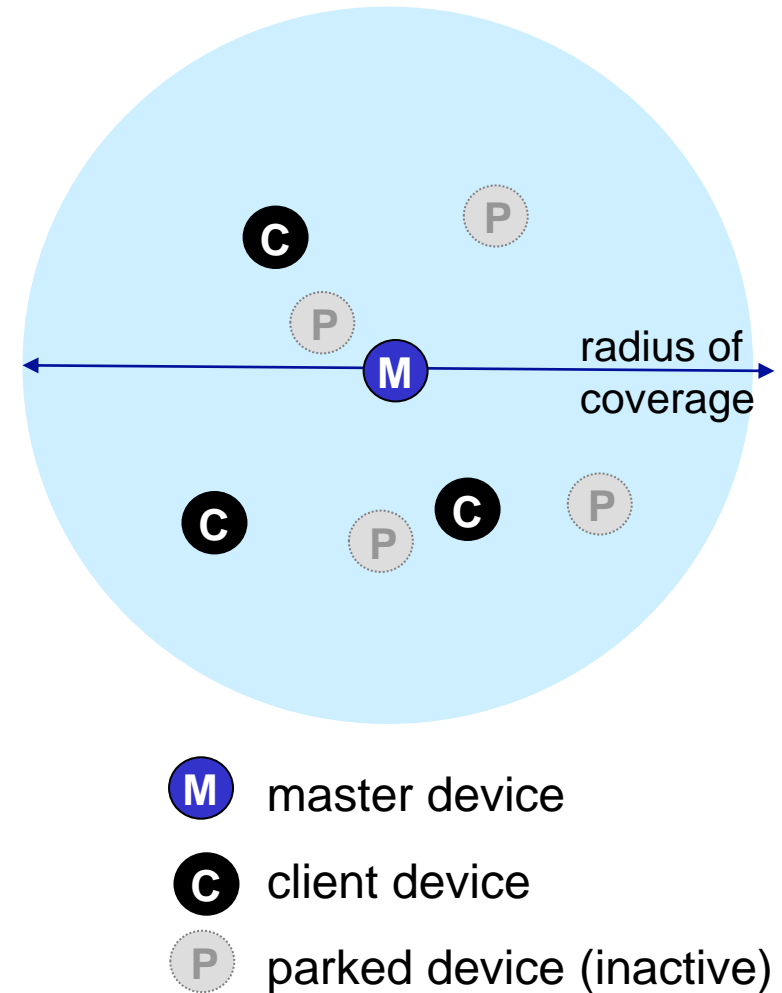
Rate adaptation

- 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



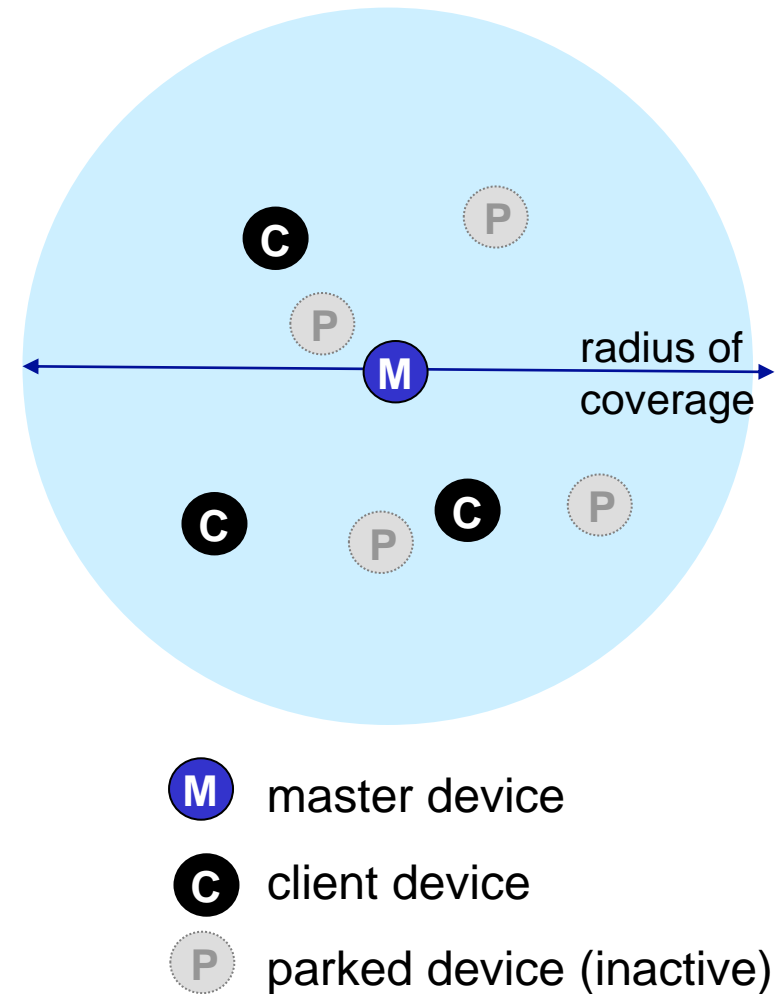
Personal area networks: Bluetooth

- 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)



Chapter 7 outline

- Introduction

Wireless

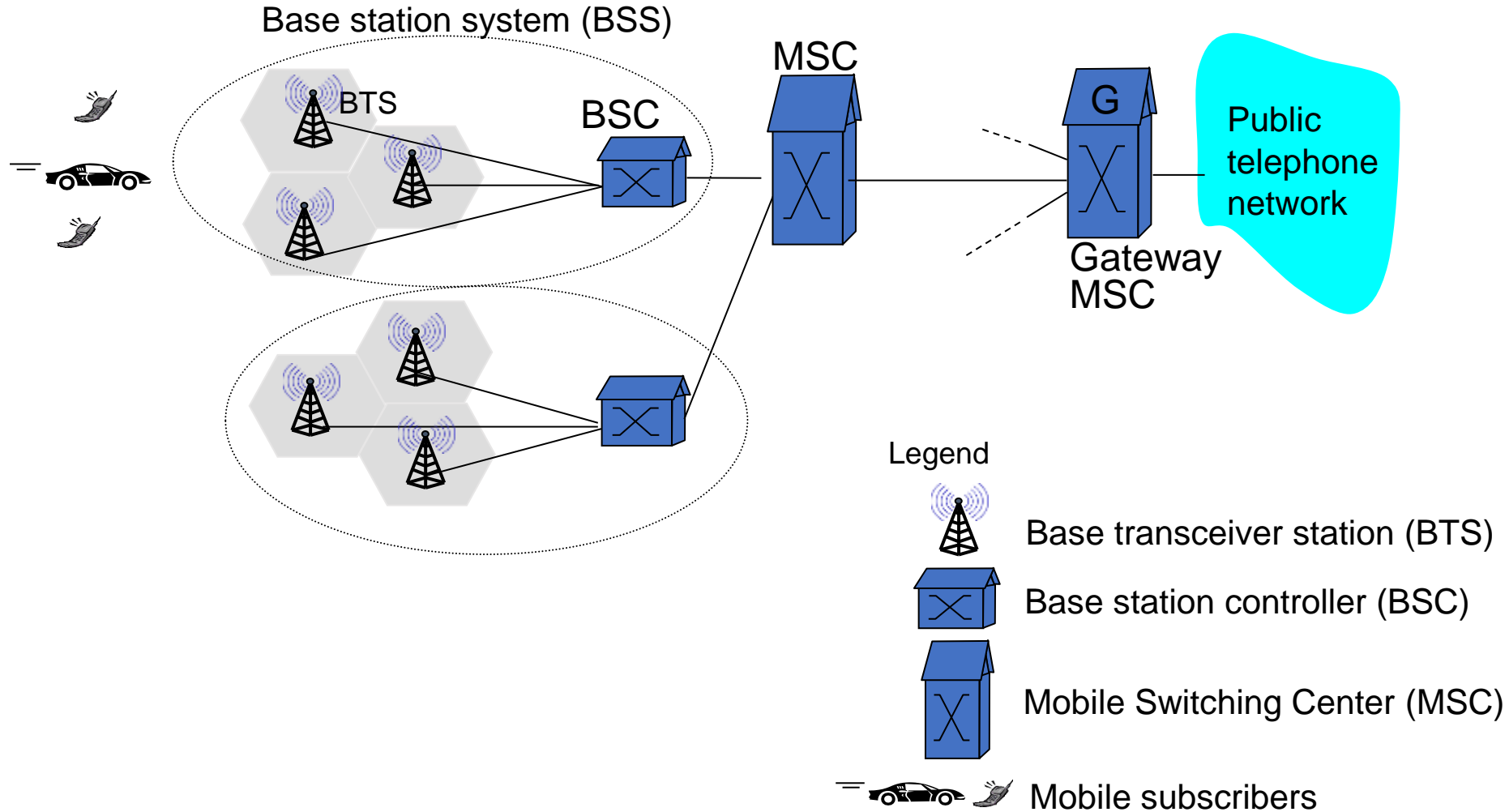
- Wireless links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G



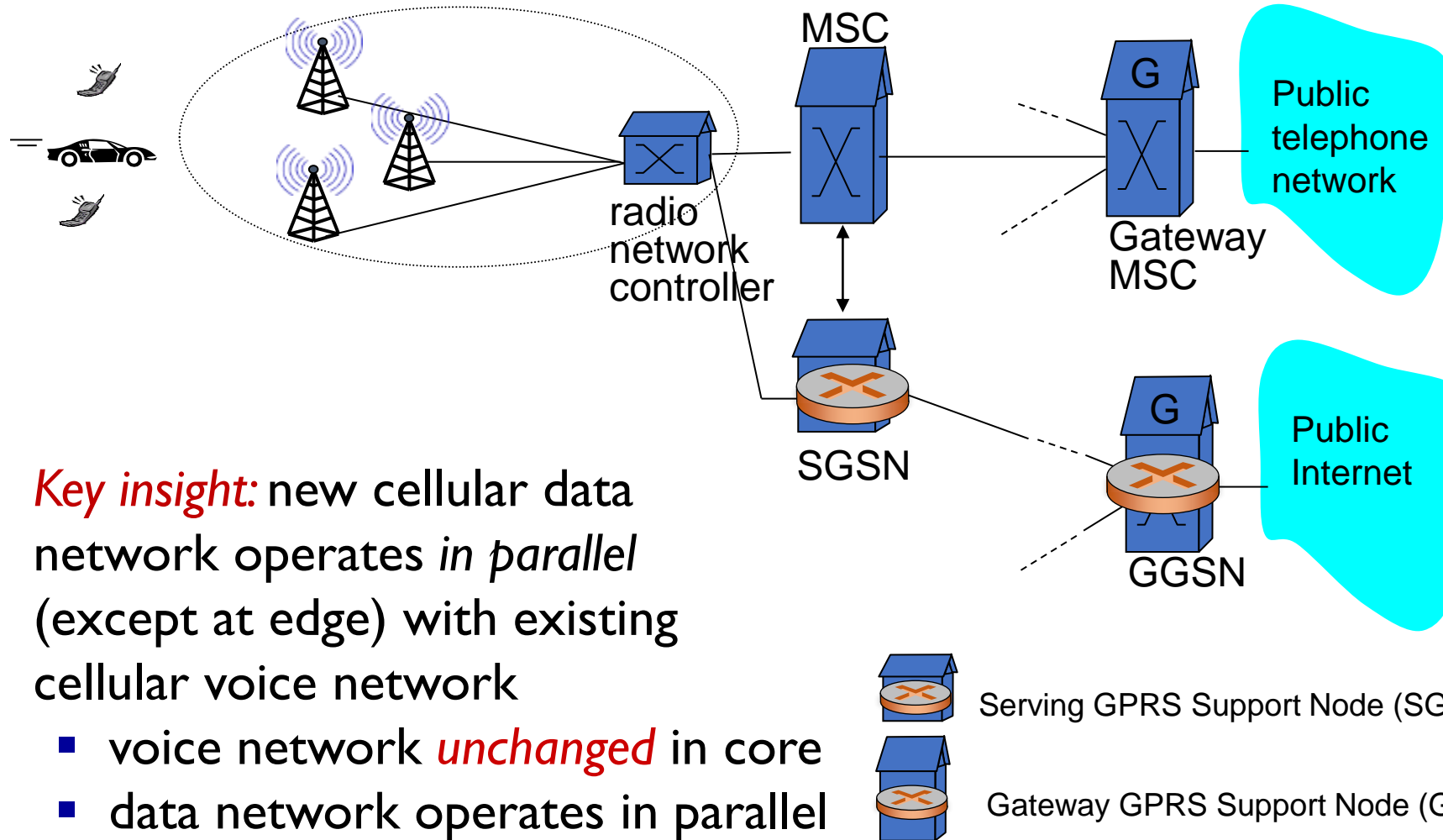
Mobility

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

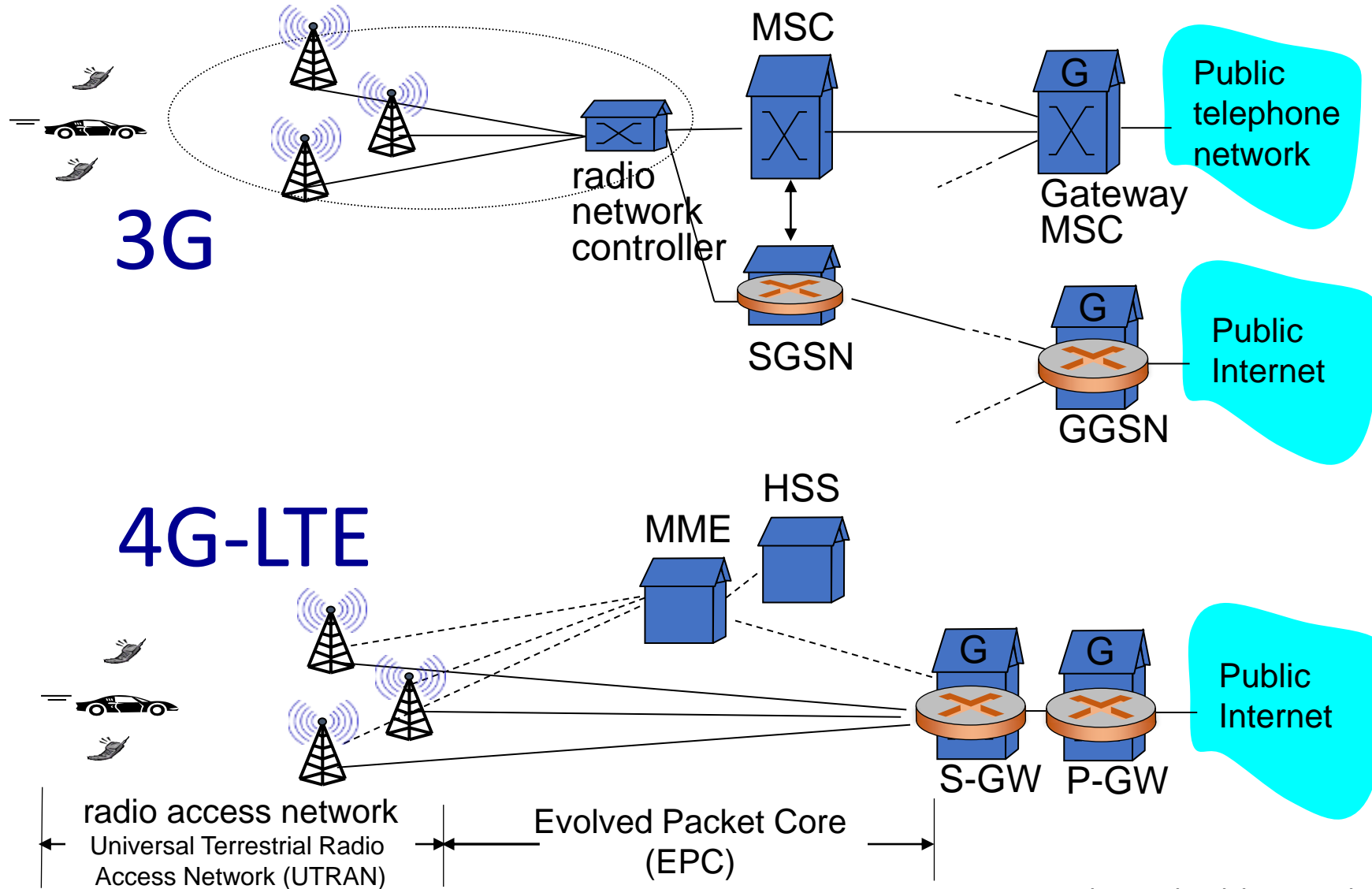
2G (voice) network architecture



3G (voice+data) network architecture

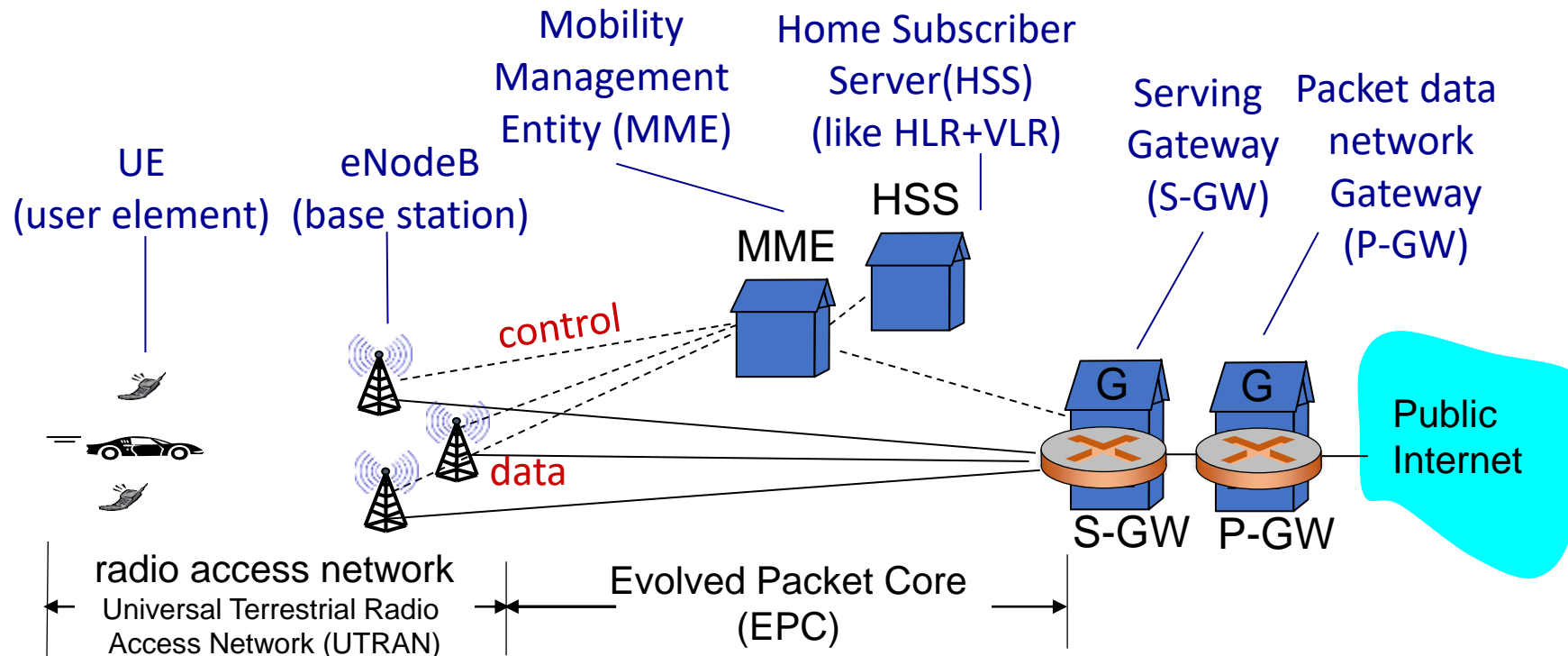


3G versus 4G LTE network architecture



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



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

On to 5G!

频率范围	波段	波长范围
≤ 3 赫兹 ($\leq 3\text{Hz}$)		$\geq 100,000$ 千米
3-30 赫兹 (3Hz-30Hz)	极长波	100,000千米 – 10,000千米
30-300 赫兹 (30Hz-300Hz)	超长波	10,000千米 – 1,000千米
300-3000 赫兹 (300Hz-3KHz)	特长波	1,000千米 – 100千米
3-30 千赫 (3KHz-30KHz)	甚长波	100千米 – 10千米
30-300 千赫 (30KHz-300KHz)	长波	10千米 – 1千米
300-3000 千赫 (300KHz-3MHz)	中波	1千米 – 100米
3-30 兆赫 (3MHz-30MHz)	短波	100米 – 10米
30-300 兆赫 (30MHz-300MHz)	米波	10米 – 1米
300-3000 兆赫 (300MHz-3GHz)	分米波	1米 – 100毫米
3-30 吉赫 (3GHz-30GHz)	厘米波	100毫米 – 10毫米
30-300 吉赫 (30GHz-300GHz)	毫米波	10毫米 – 1毫米

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Mobility

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What is mobility?

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

no mobility

high mobility



device moves
between
networks, but
powers down
while moving

device moves
within same AP in
one provider
network

device moves
among APs in
one provider
network

device moves
among multiple
provider networks,
while maintaining
ongoing
connections

We're interested in these!

Mobility approaches

- **let network (routers) handle it:**
 - routers advertise well-known name, address (e.g., permanent 32-bit IP address), or number (e.g., cell #) of visiting mobile node via usual routing table exchange
 - Internet routing could do this already *with no* changes! Routing tables indicate where each mobile located via longest prefix match!

Mobility approaches

- let network (routers) handle it:
 - routers advertise well-known address (e.g., permanent 32-bit IP address), or number of visiting mobile node via usual routing table exchange
 - Internet routing could do it *very easily with no changes!* Routing tables indicate where each mobile located via longest prefix match!
- **let end-systems handle it: functionality at the “edge”**
 - *indirect routing*: communication from correspondent to mobile goes through home network, then forwarded to remote mobile
 - *direct routing*: correspondent gets foreign address of mobile, send directly to mobile

not
scalable
to billions of
mobiles

Contacting a mobile friend:

Consider friend frequently changing locations, how do you find him/her?

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

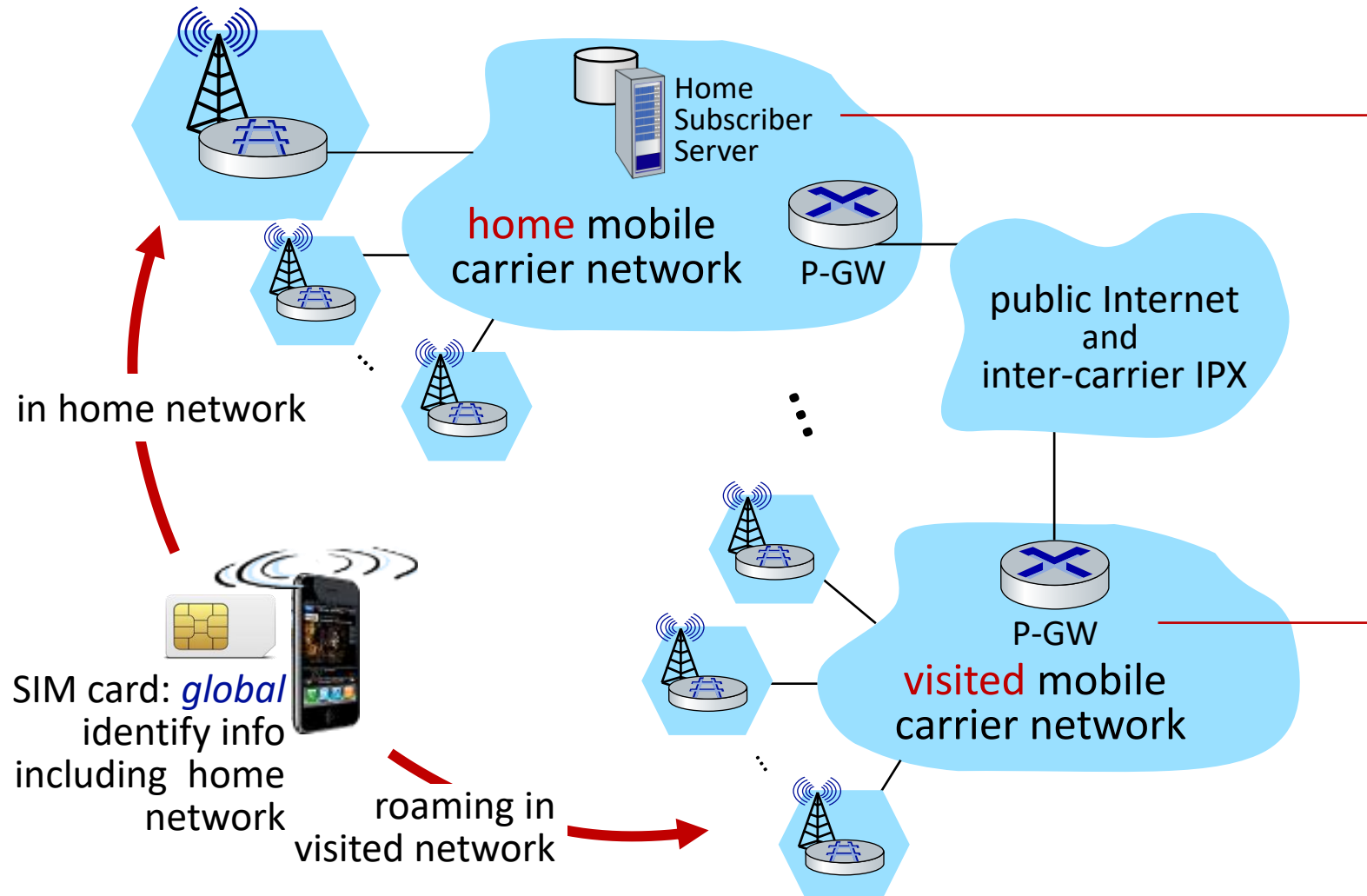
- call his/her parents?
- Facebook!

The importance of having a “home”:

- a definitive source of information about you
- a place where people can find out where you are



Home network, visited network: 4G/5G



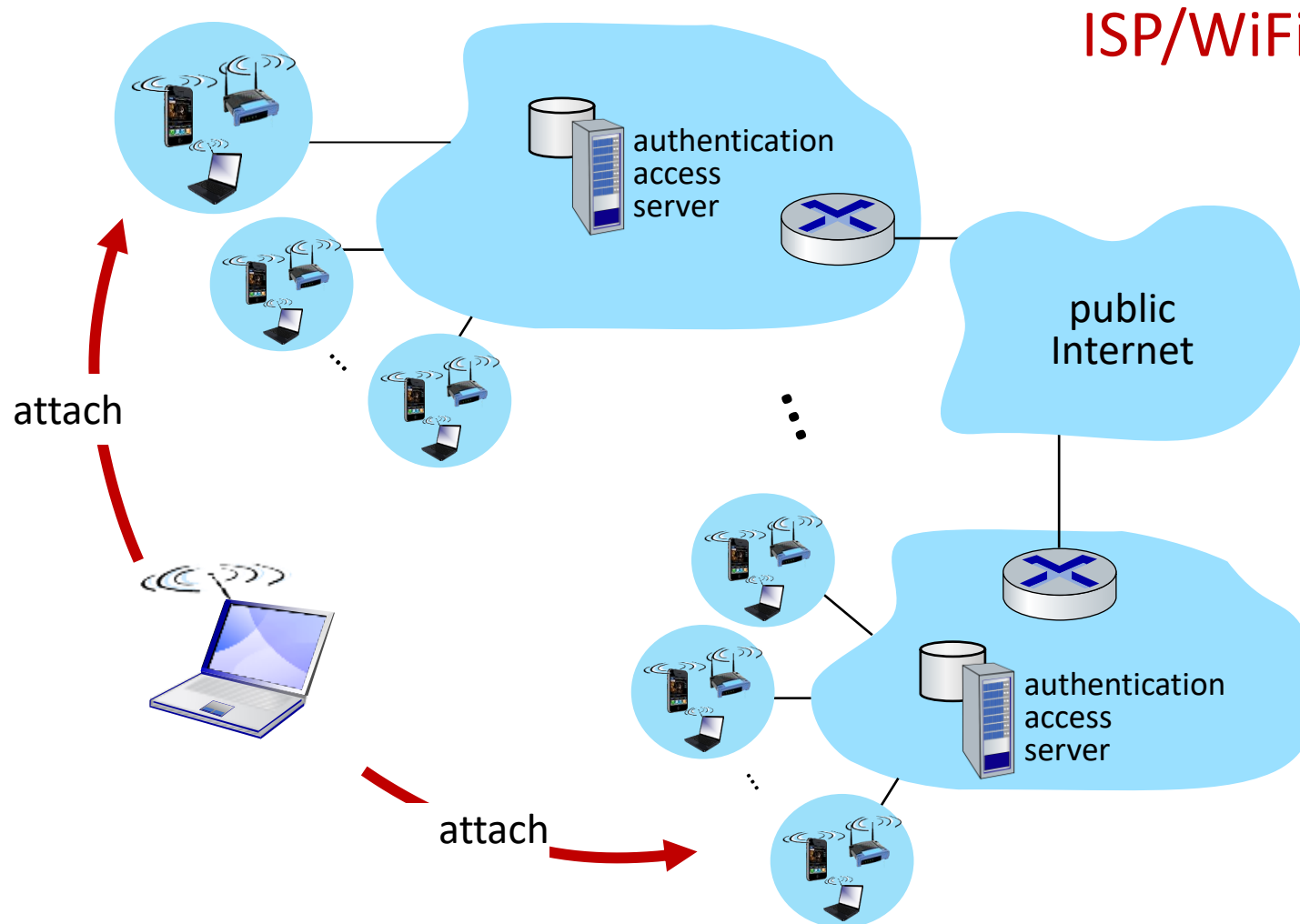
home network:

- (paid) service plan with cellular provider, e.g., Verizon, Orange
- home network HSS stores identify & services info

visited network:

- any network other than your home network
- service agreement with other networks: to provide access to visiting mobile

Home network, visited network: ISP/WiFi



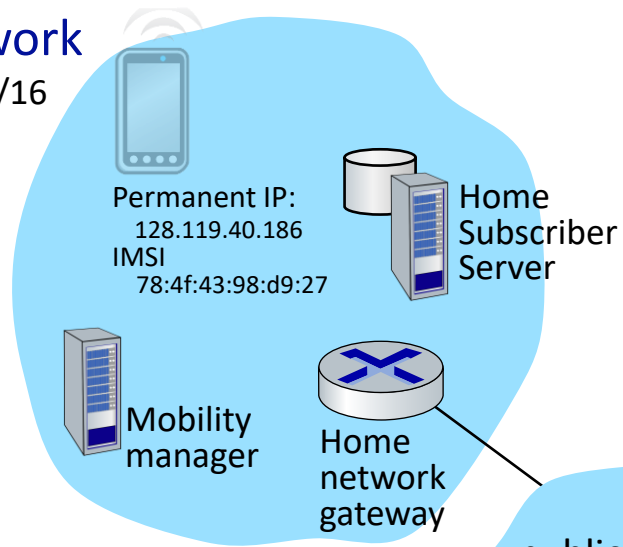
ISP/WiFi: no notion of global “home”

- credentials from ISP (e.g., username, password) stored on device or with user
- ISPs may have national, international presence
- different networks: different credentials
 - some exceptions (e.g., eduroam)
 - architectures exist (mobile IP) for 4G-like mobility, but not used

Home network, visited network: generic

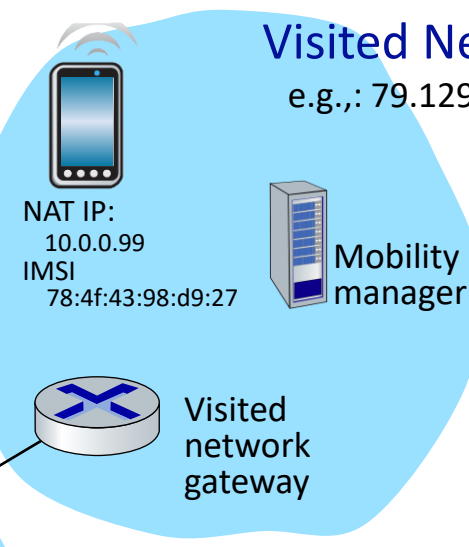
Home Network

e.g.,: 128.119/16



Visited Network

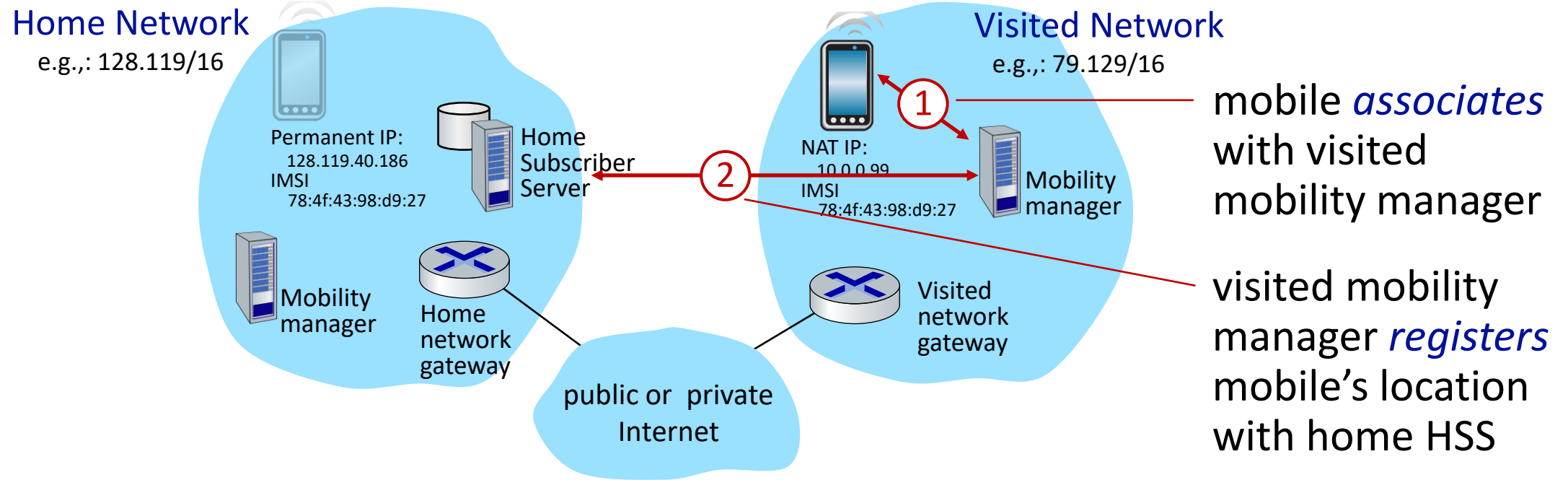
e.g.,: 79.129/16



public or private
Internet

Correspondent

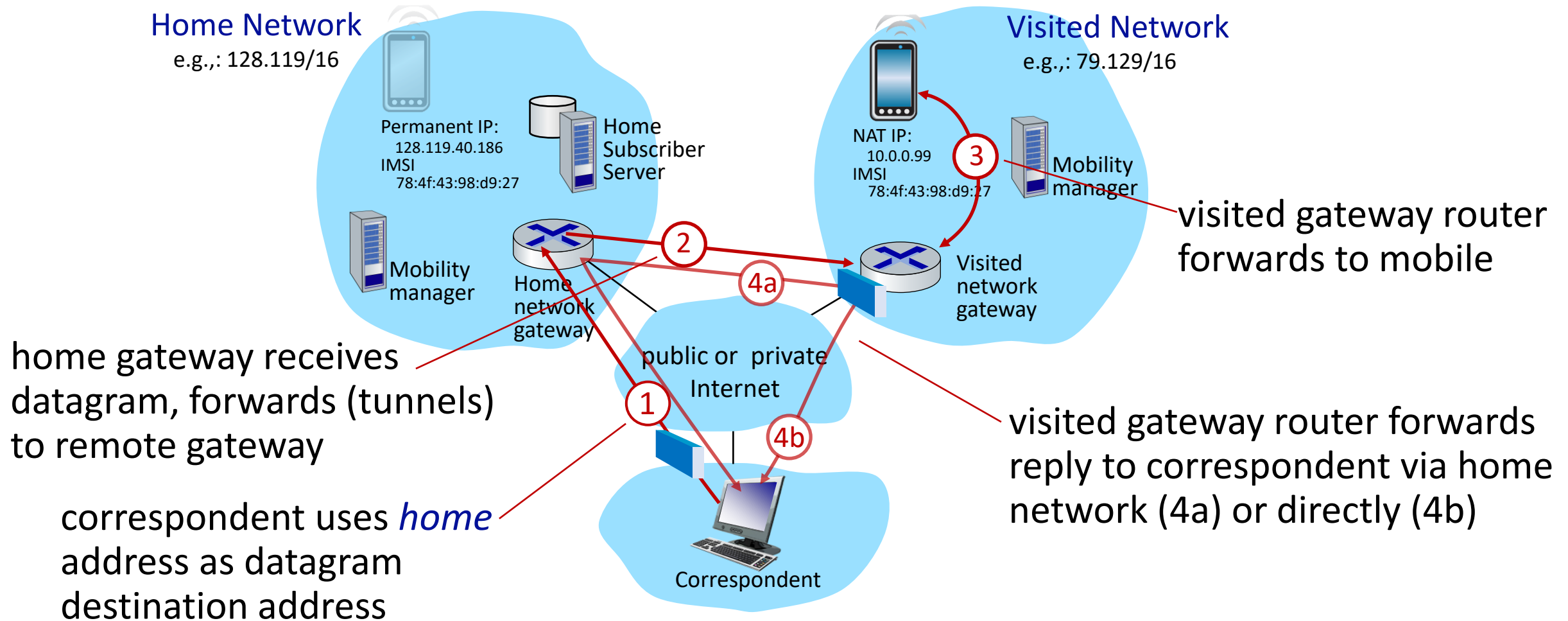
Registration: home needs to know where you are!



end result:

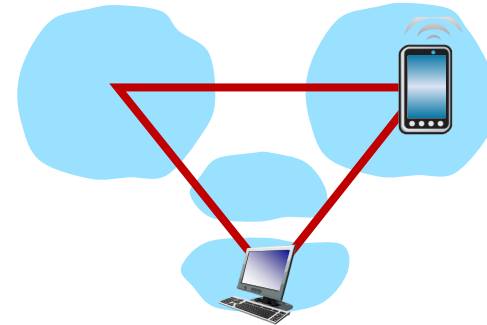
- visited mobility manager knows about mobile
- home HSS knows location of mobile

Mobility with indirect routing

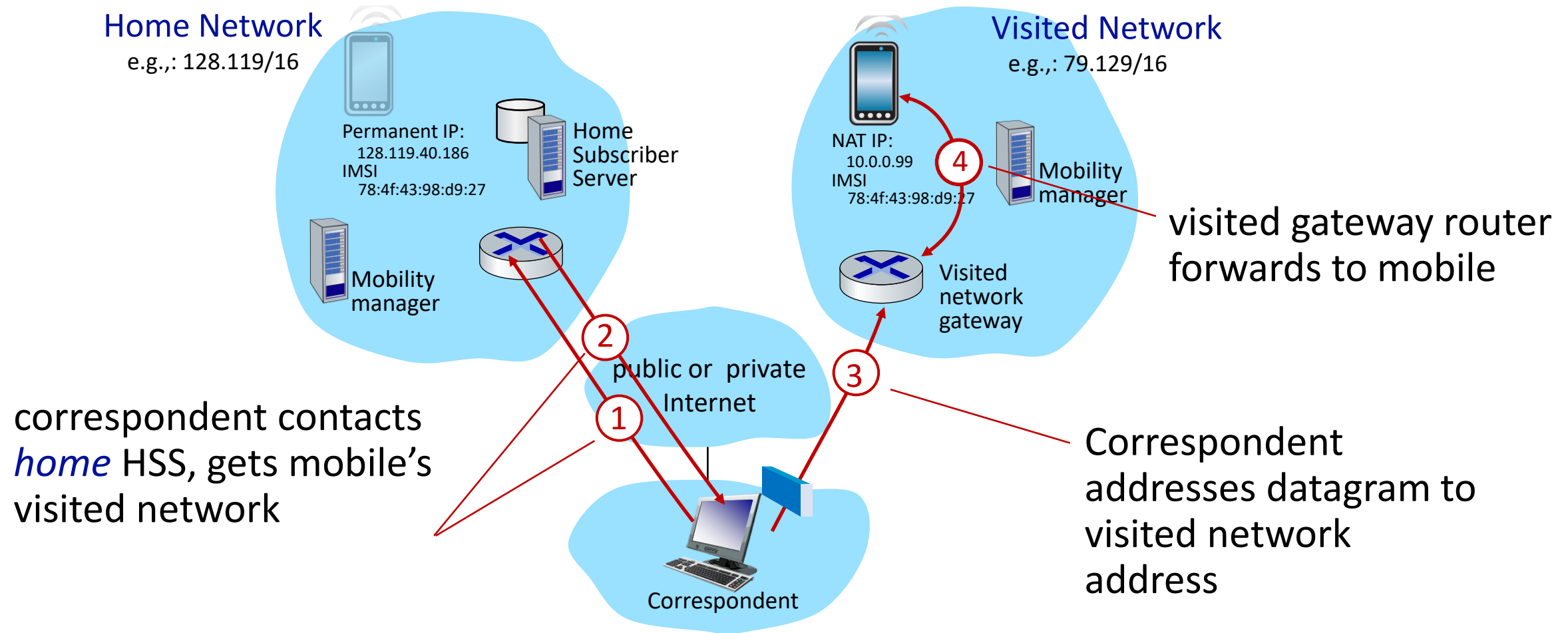


Mobility with indirect routing: comments

- triangle routing:
 - inefficient when correspondent and mobile are in same network
- mobile moves among visited networks: transparent to correspondent!
 - registers in new visited network
 - new visited network registers with home HSS
 - datagrams continue to be forwarded from home network to mobile in new network
 - *on-going (e.g., TCP) connections between correspondent and mobile can be maintained!*



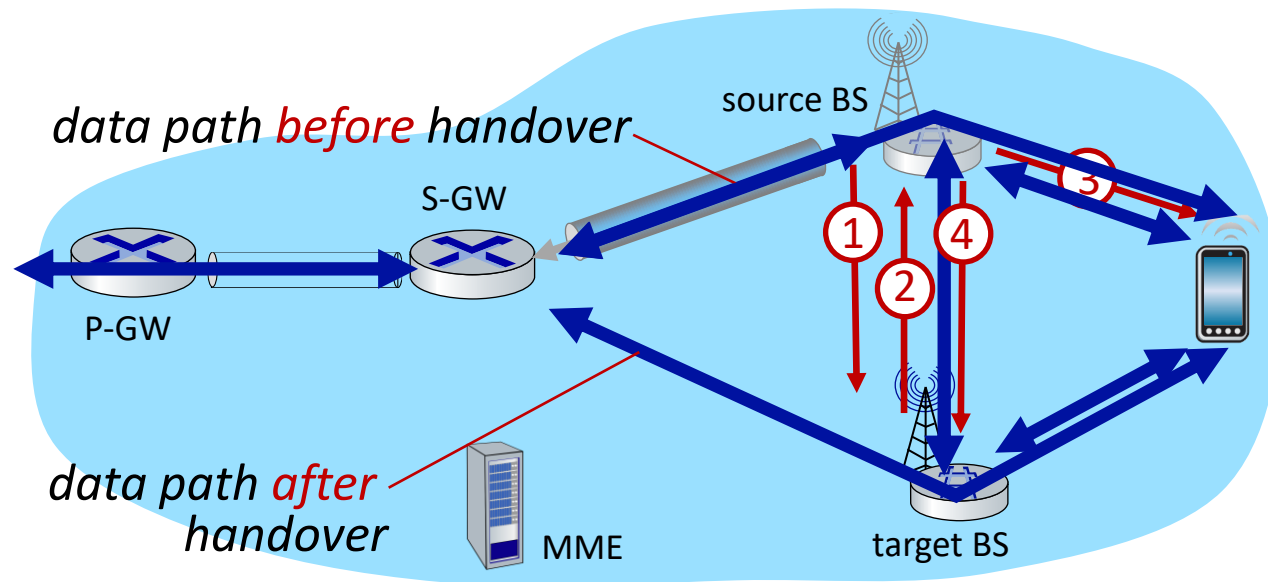
Mobility with direct routing



Mobility with direct routing: comments

- overcomes triangle routing inefficiencies
- *non-transparent to correspondent*: correspondent must get care-of-address from home agent
- what if mobile changes visited network?
 - can be handled, but with additional complexity

Handover between BSs in same cellular network



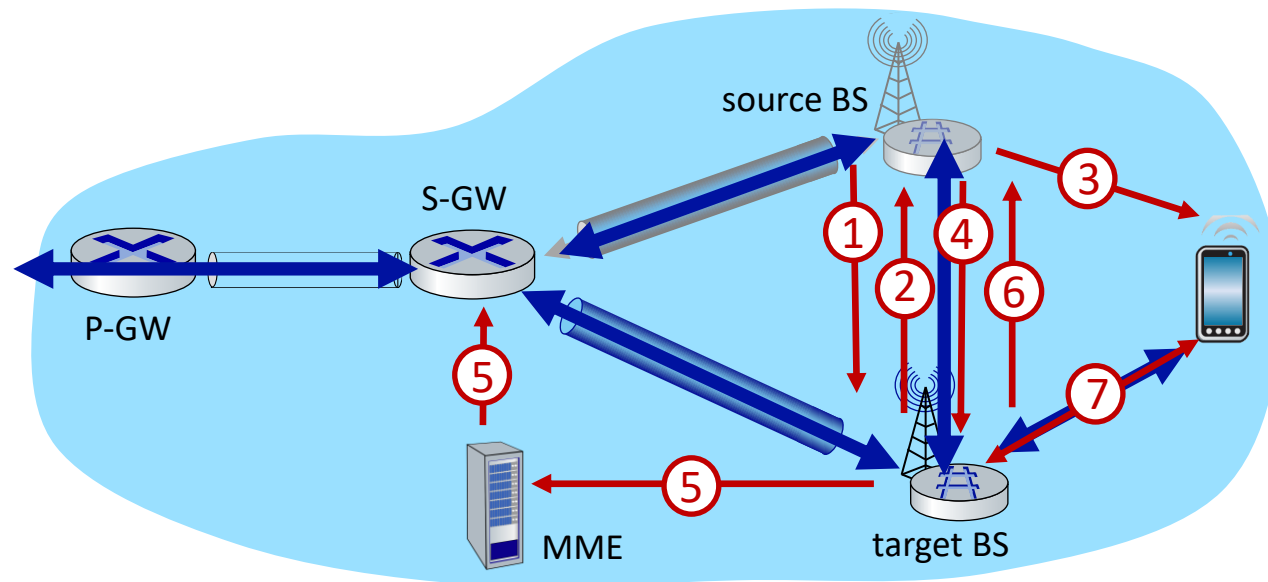
① current (source) BS selects target BS, sends *Handover Request* message to target BS

② target BS pre-allocates radio time slots, responds with HR ACK with info for mobile

③ source BS informs mobile of new BS
■ mobile can now send via new BS - handover *looks* complete to mobile

④ source BS stops sending datagrams to mobile, instead forwards to new BS (who forwards to mobile over radio channel)

Handover between BSs in same cellular network



- ⑤ target BS informs MME that it is new BS for mobile
- MME instructs S-GW to change tunnel endpoint to be (new) target BS

- ⑥ target BS ACKs back to source BS: handover complete, source BS can release resources

- ⑦ mobile's datagrams now flow through new tunnel from target BS to S-GW

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Final exam

- 16:30-18:30, June 8, Wednesday,
 - Range: Chapter 1 – Chapter 7
- Q & A Session
 - 9:30-11:30AM, June 6, Monday
 - CoE 516

Thank you!

Please finish the evaluation online