

# Chapter 7 Wireless and Mobile Networks

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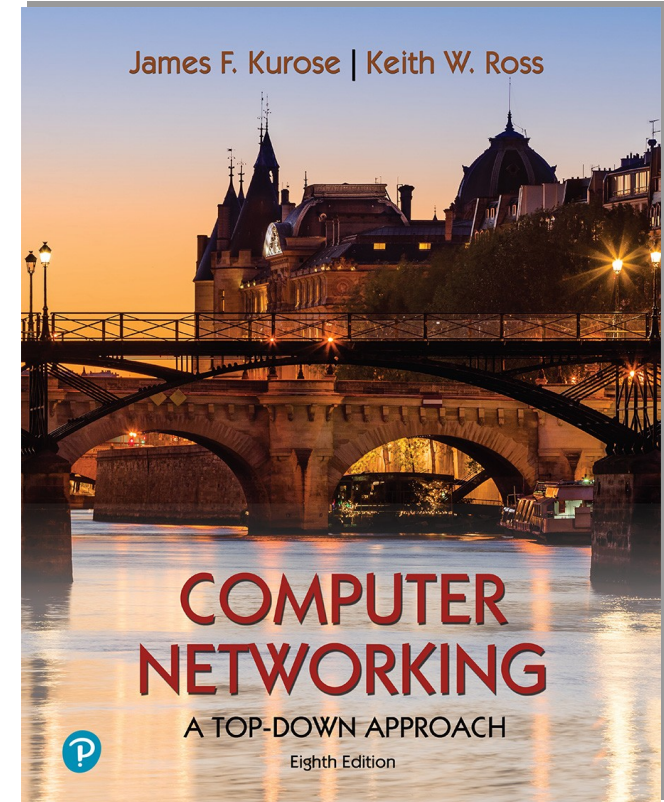
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## Computer Networking: A Top-Down Approach

8<sup>th</sup> edition

Jim Kurose, Keith Ross  
Pearson, 2020

# 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

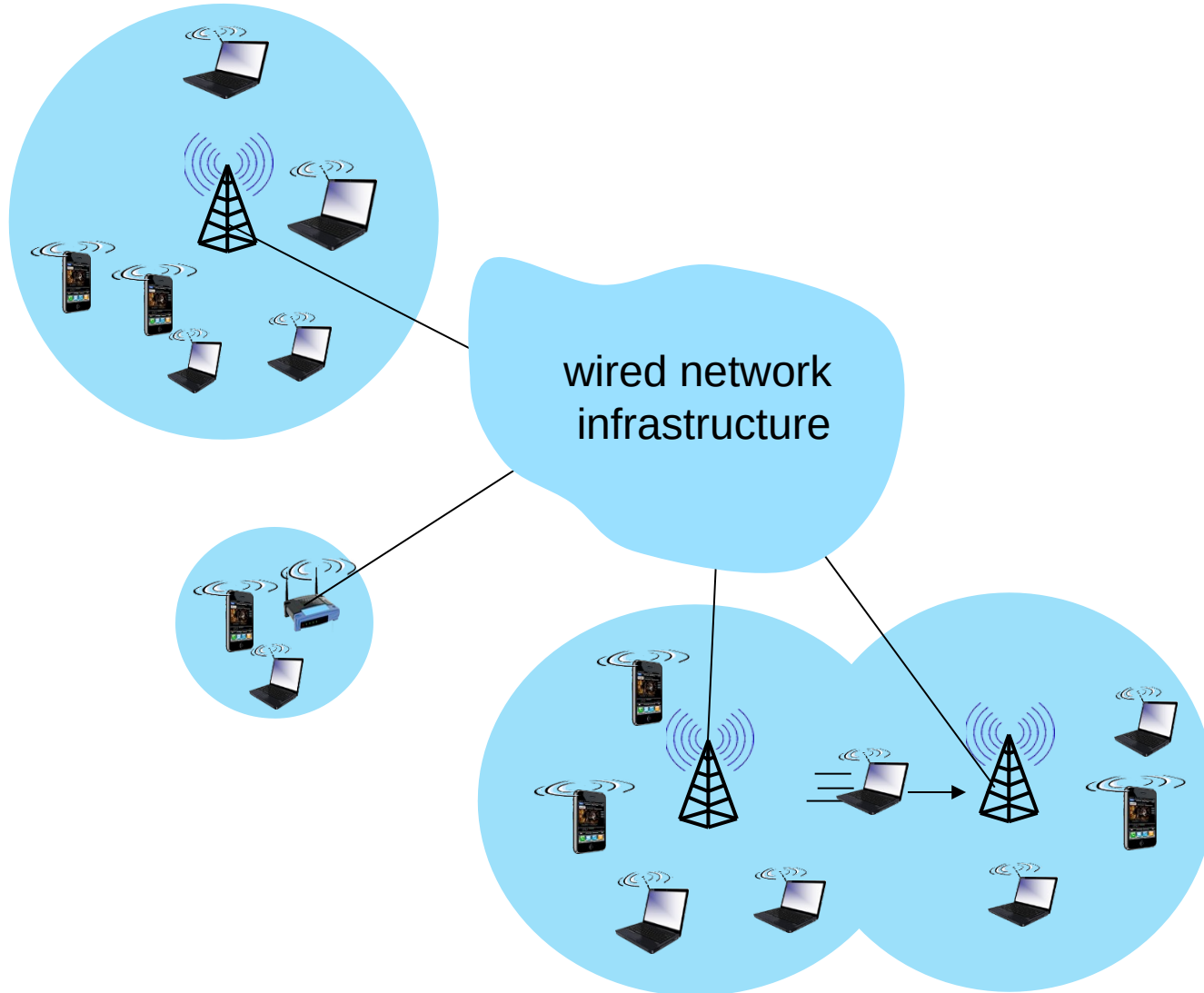
- Wireless Links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G

## Mobility

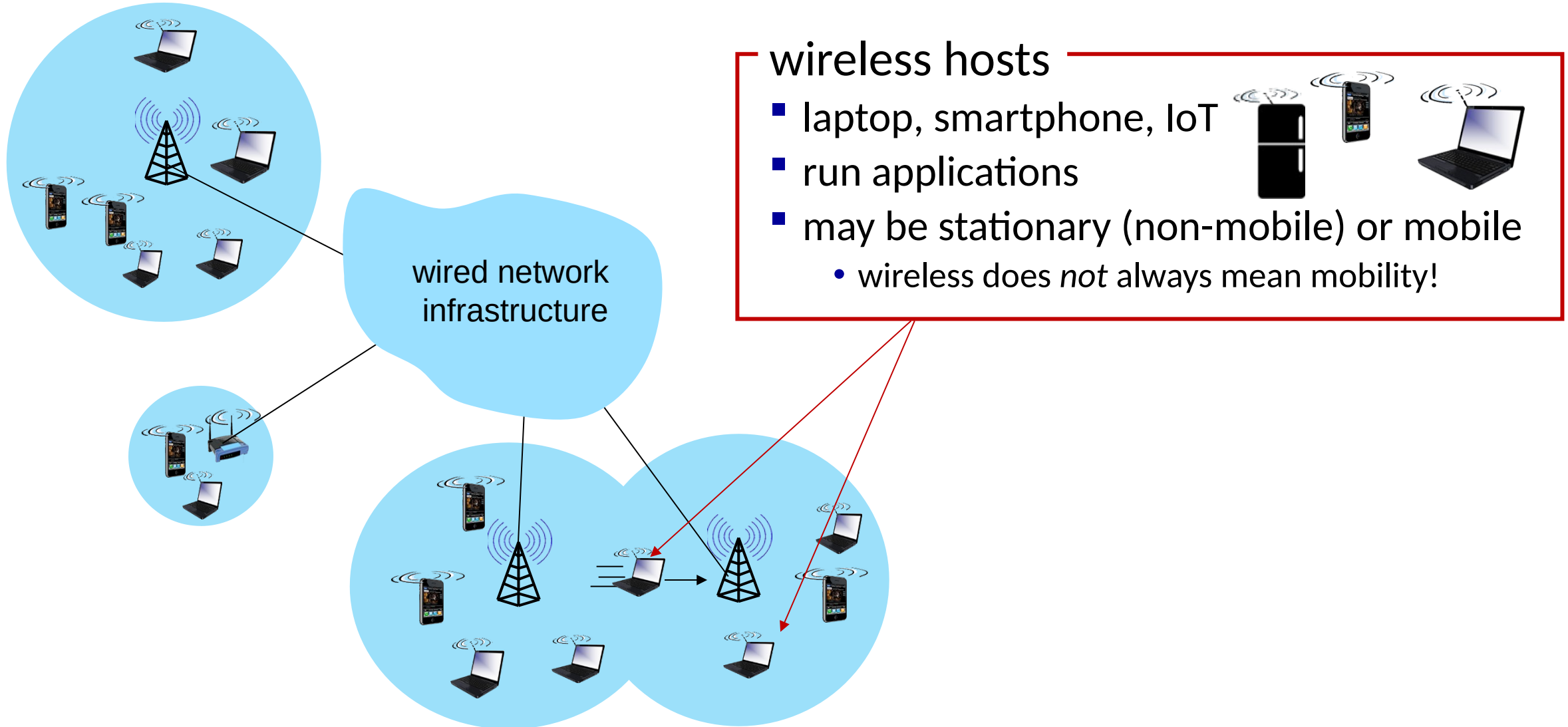
- Mobility management: principles
- Mobility management: practice
  - 4G/5G networks
  - Mobile IP
- Mobility: impact on higher-layer protocols



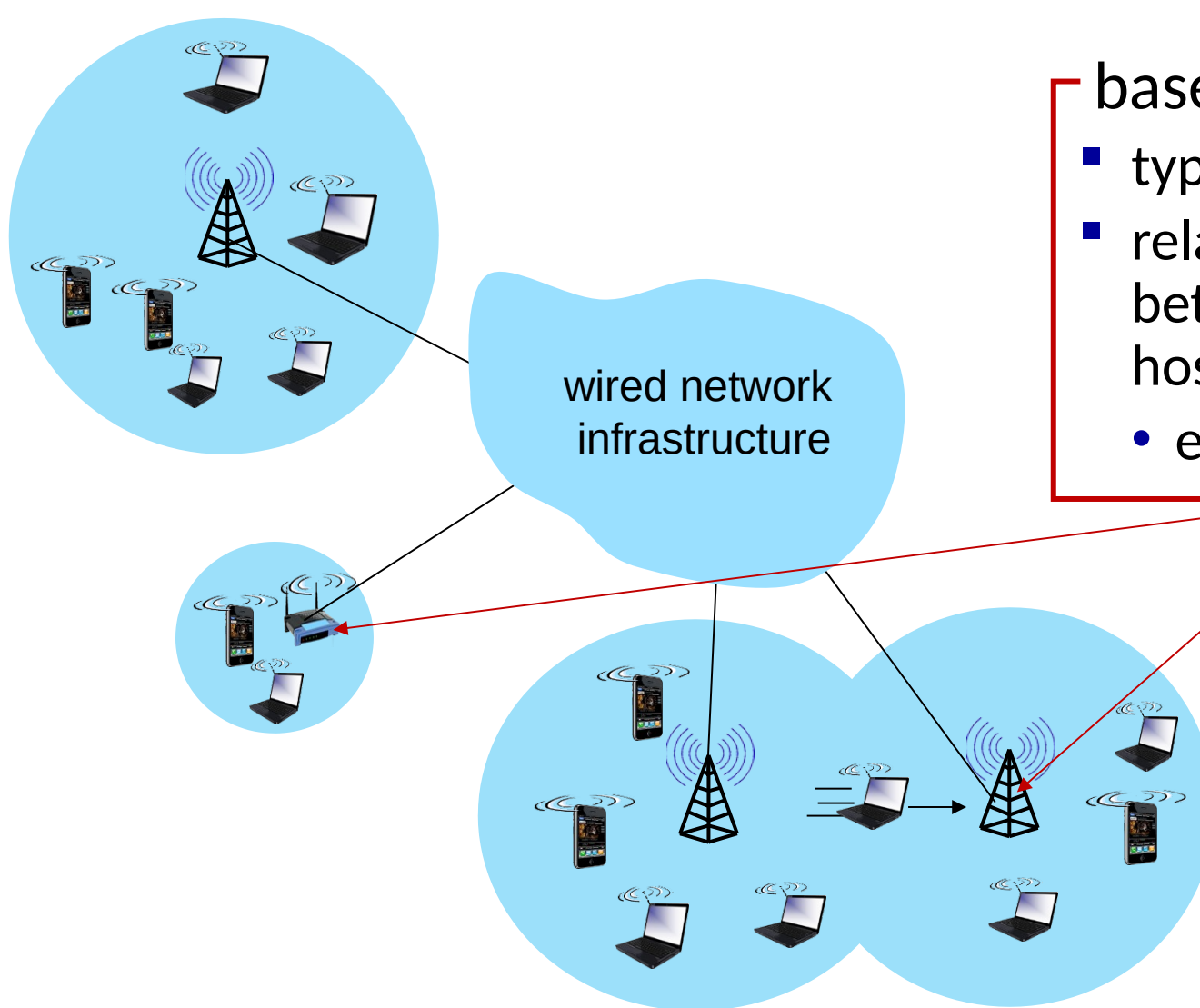
# Elements of a wireless network



# Elements of a wireless network



# Elements of a wireless network

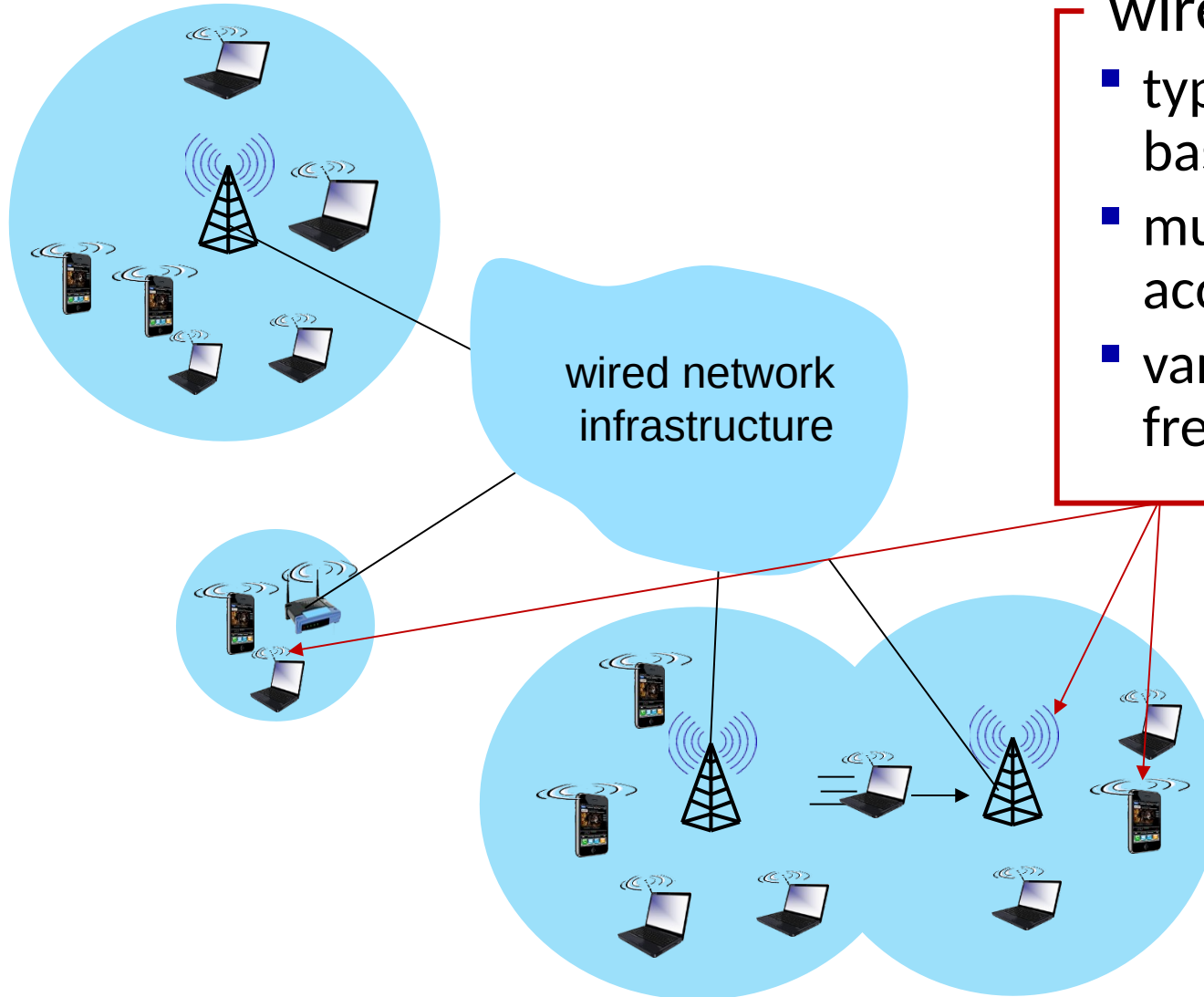


base station



- 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

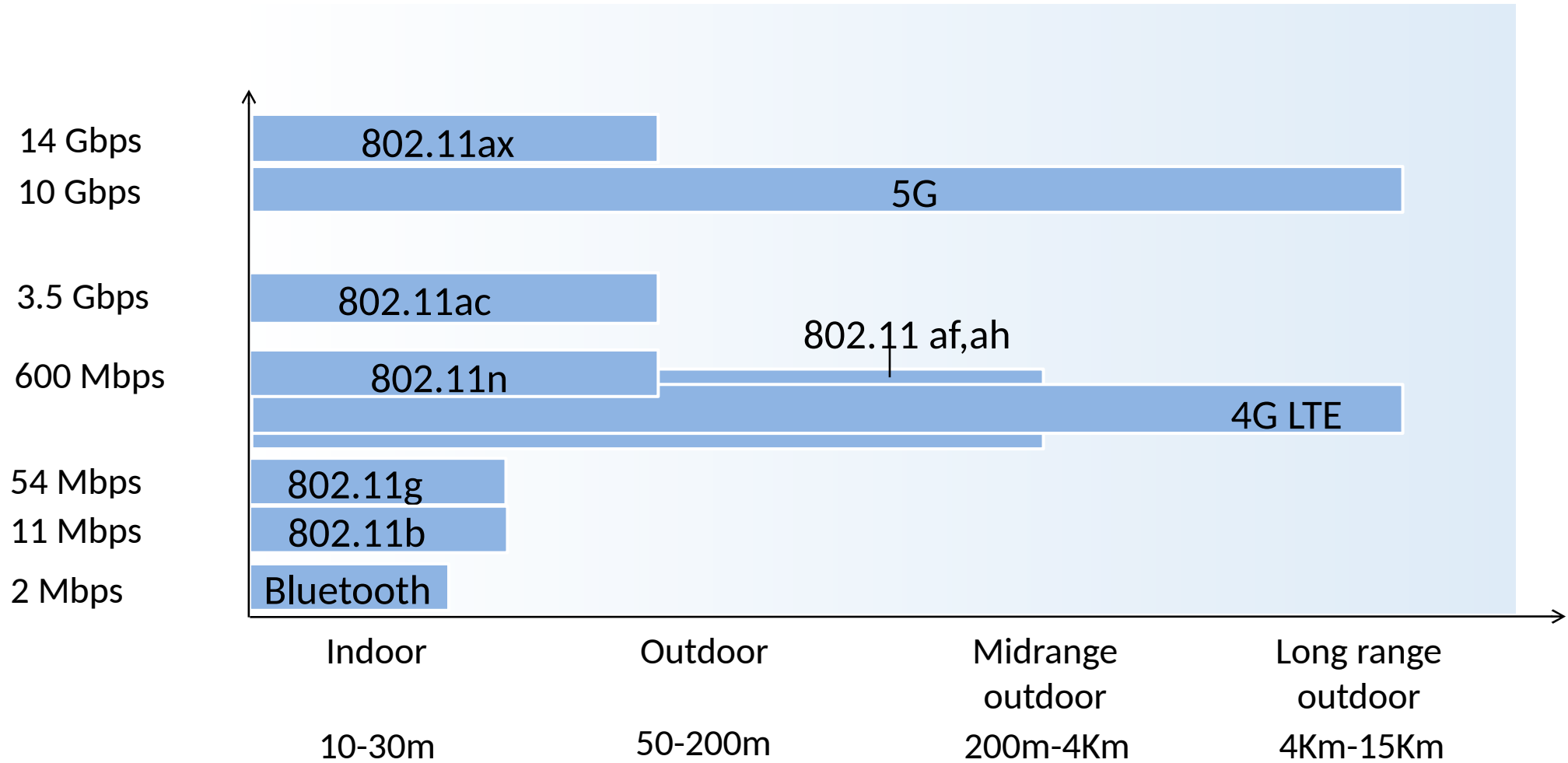


wireless link



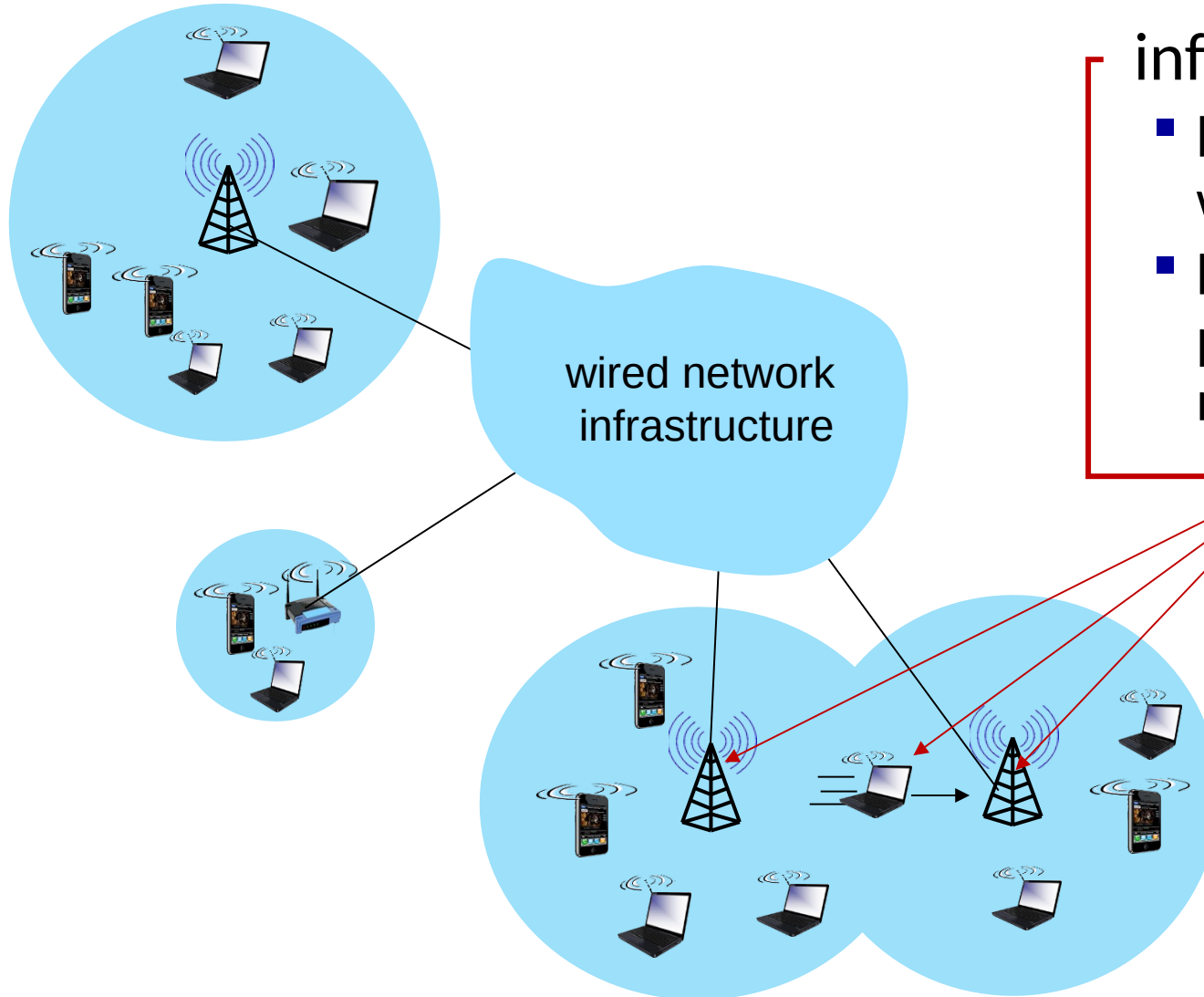
- typically used to connect mobile(s) to base station, also used as backbone link
- multiple access protocol coordinates link access
- various transmission rates and distances, frequency bands

# Characteristics of selected wireless links





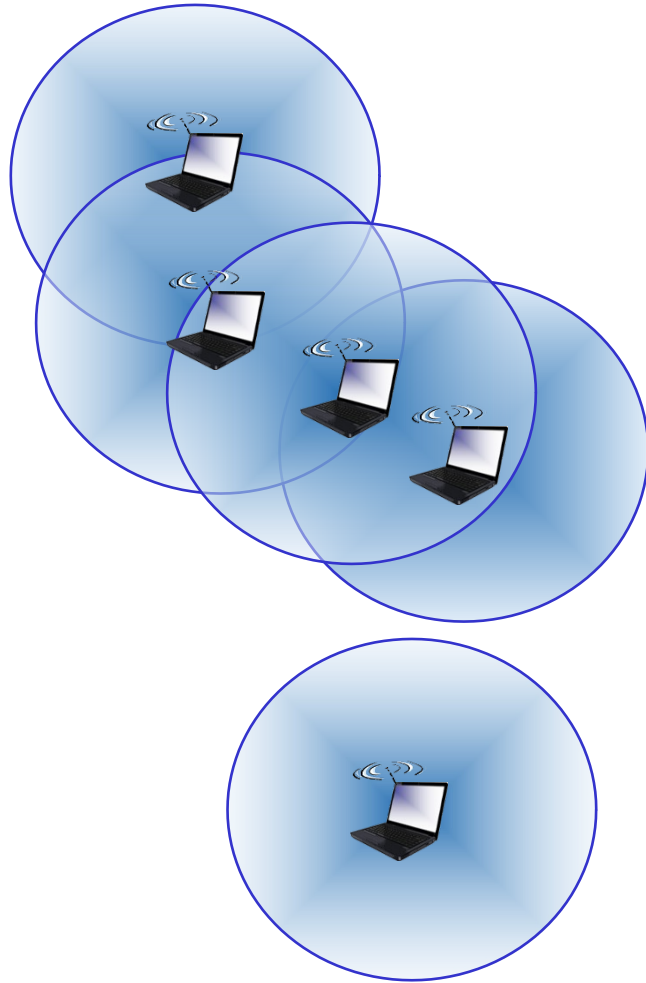
# Elements of a wireless network



## 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

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



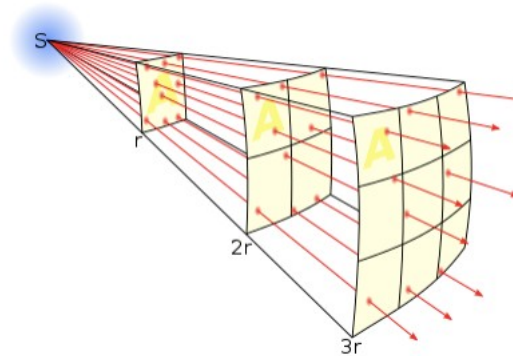
# Wireless link characteristics: fading (attenuation)

**Wireless** radio signal attenuates (loses power) as it propagates (free space “path loss”)

Free space path loss  $\sim (fd)^2$

$f$ : frequency

$d$ : distance



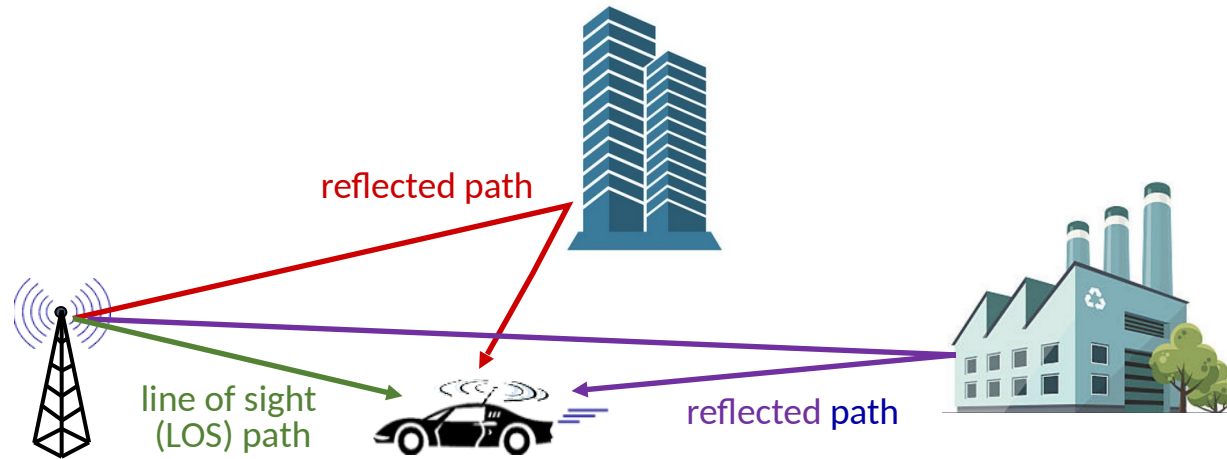
higher frequency or  
longer distance



larger free space  
path loss

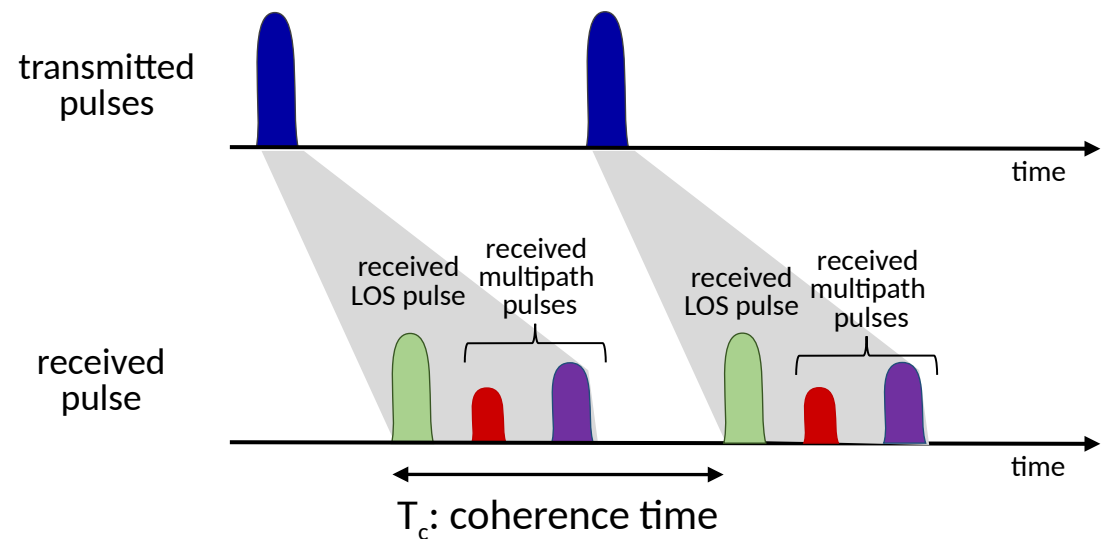
# Wireless link characteristics: multipath

**multipath propagation:** radio signal reflects off objects ground, built environment, arriving at destination at slightly different times



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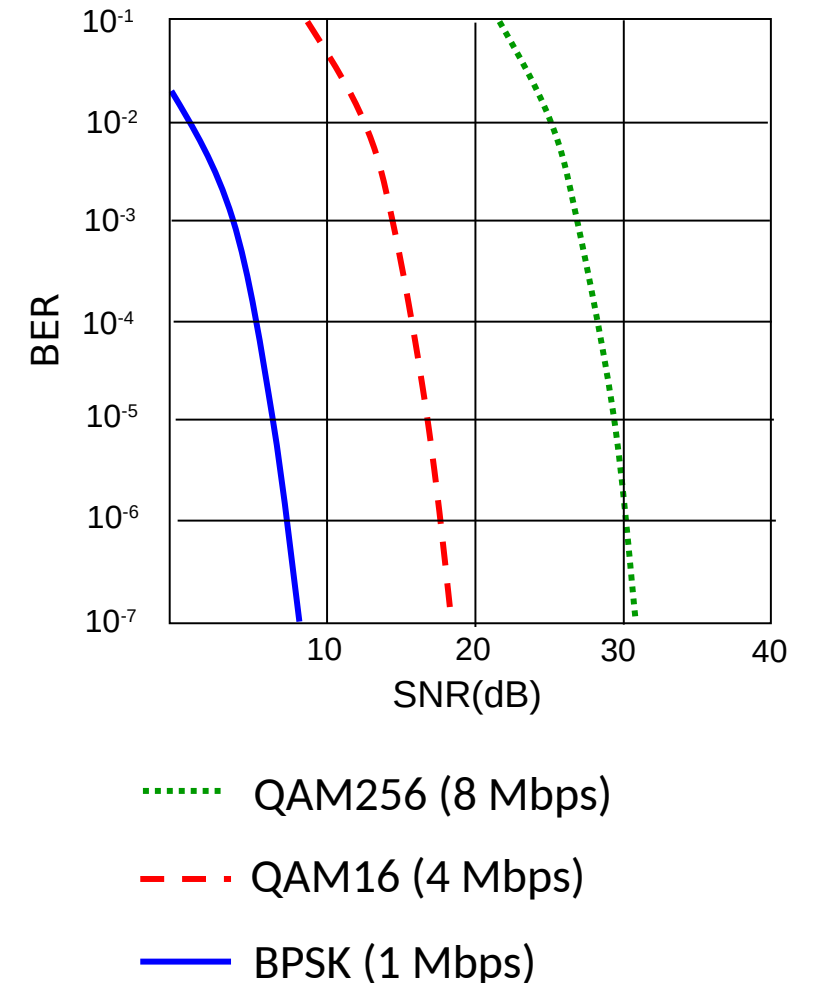


## Coherence time:

- amount of time bit is present in channel to be received
- influences maximum possible transmission rate, since coherence times can not overlap
- inversely proportional to
  - frequency
  - receiver velocity

# Wireless link characteristics: noise

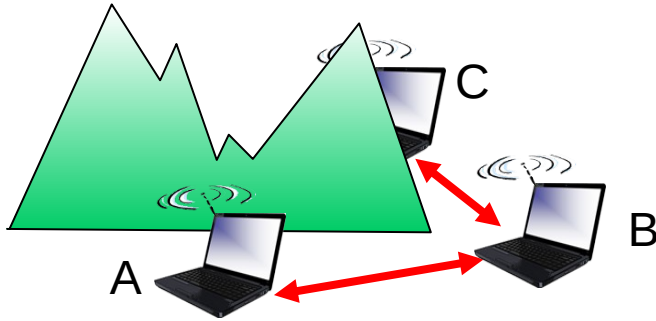
- interference from other sources on wireless network frequencies: motors, appliances
- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a “good thing”)
- SNR versus BER tradeoff
  - *given physical layer*: increase power -> increase SNR->decrease BER
  - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)





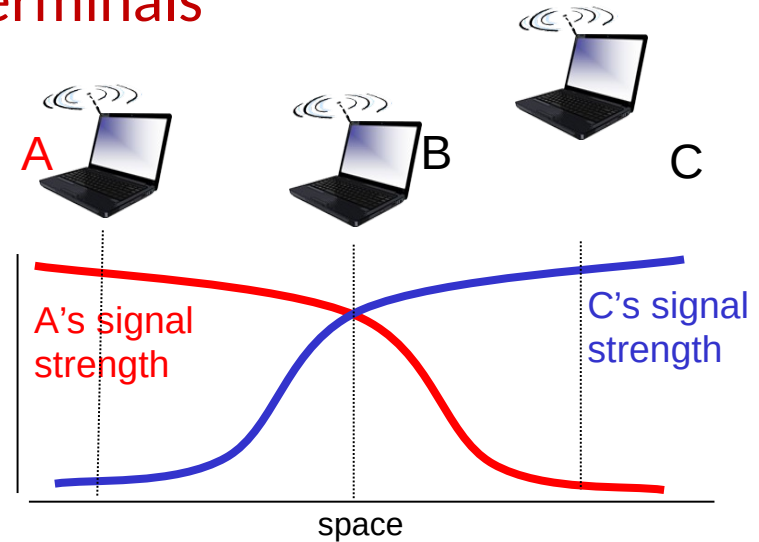
# Wireless link characteristics: hidden terminals

## 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

## Attenuation also causes “hidden terminals”



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

# Chapter 7 outline

- Introduction

## Wireless

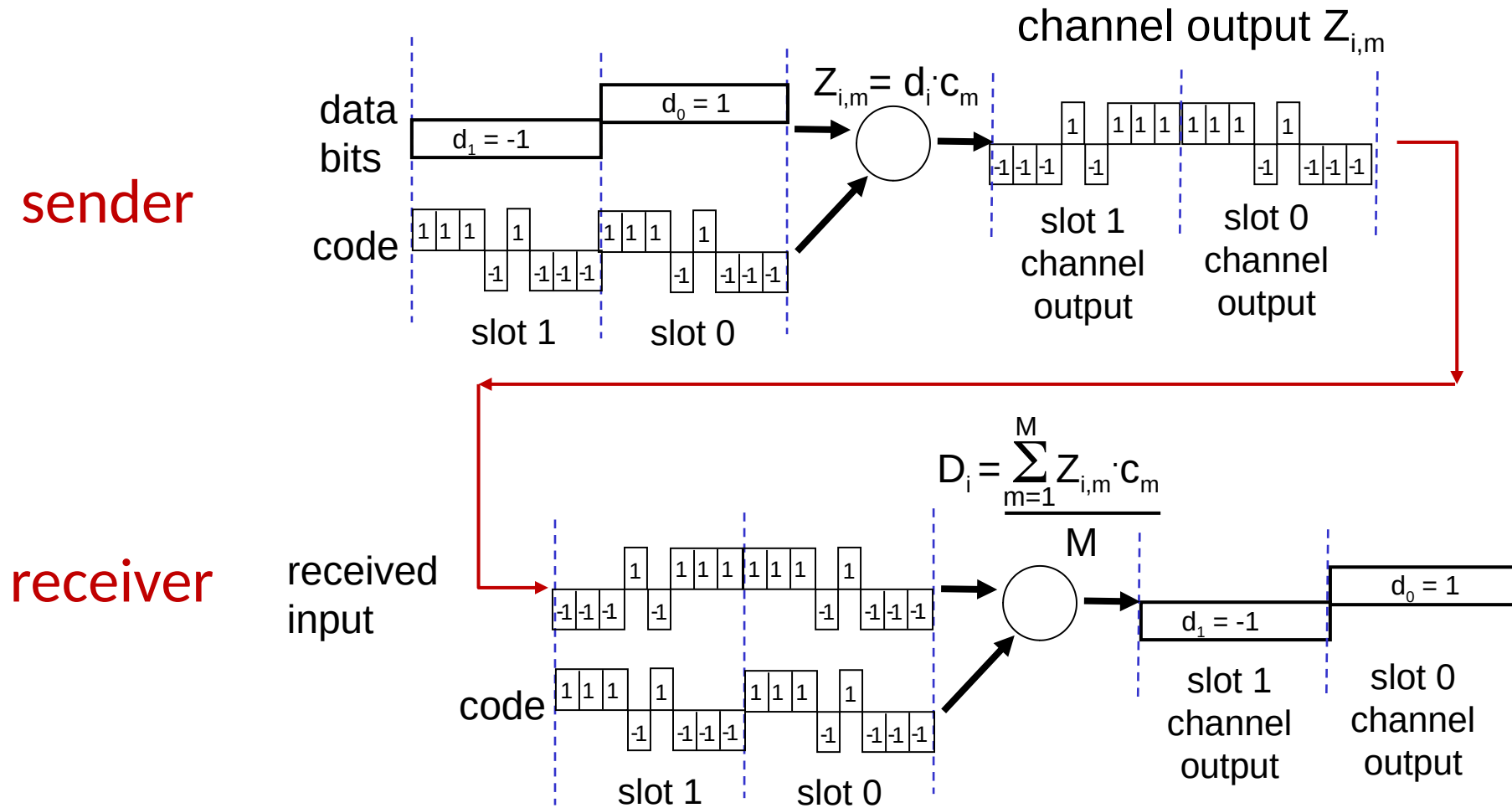
- Wireless links and network characteristics
- CDMA: code division multiple access
- WiFi: 802.11 wireless LANs
- Bluetooth



# 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

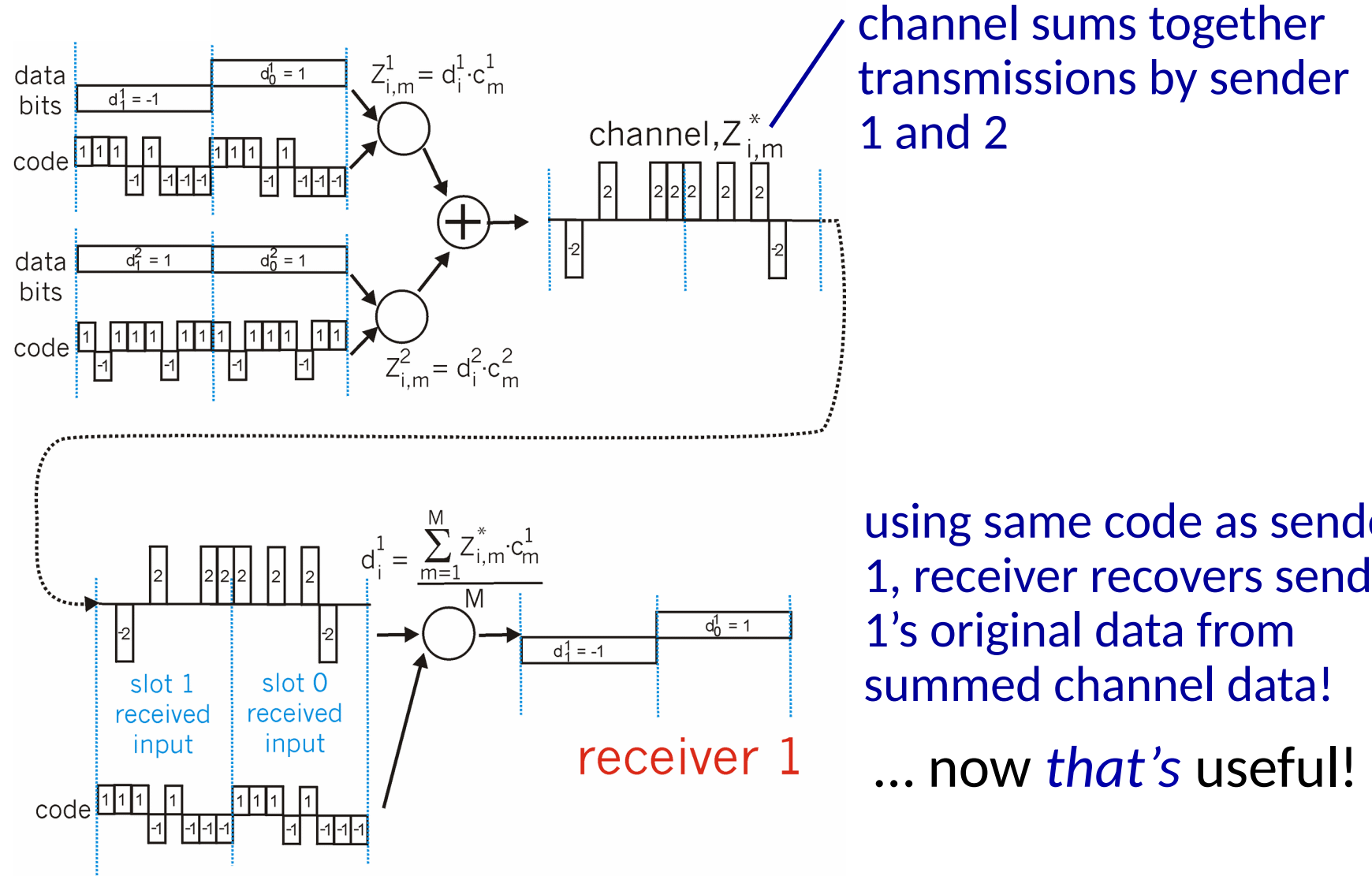


... but this isn't really useful yet!

# CDMA: two-sender interference

Sender  
1

Sender  
2



# 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

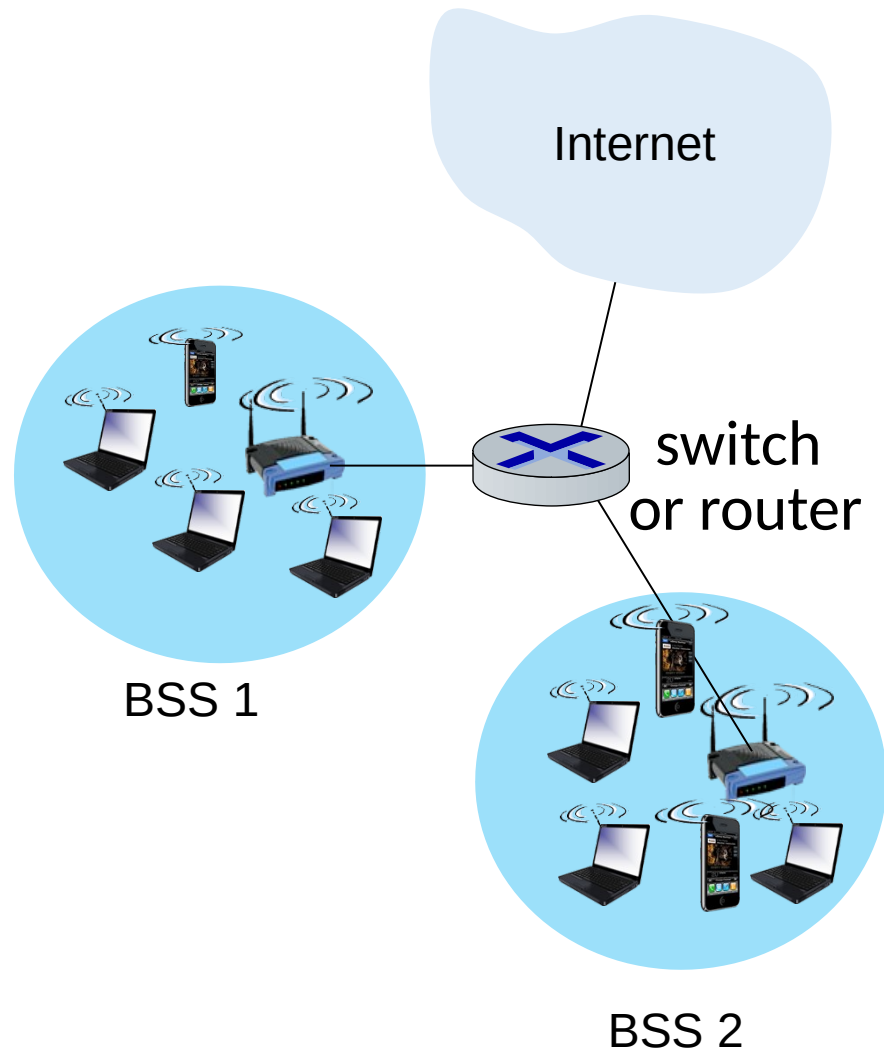


# IEEE 802.11 Wireless LAN

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



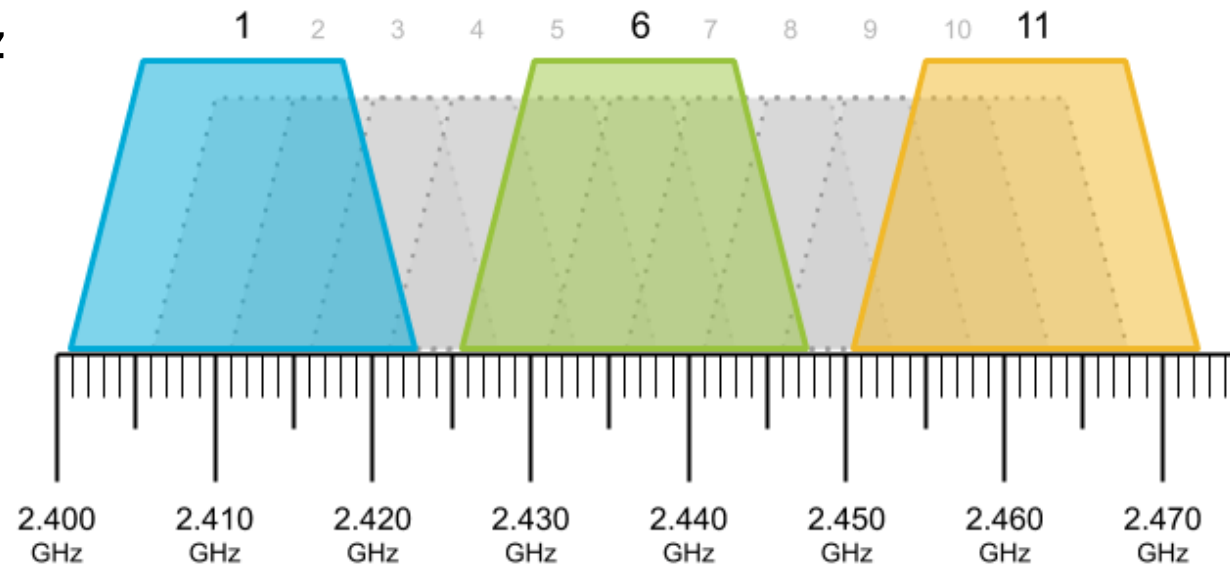
- wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka “cell”) in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only



# 802.11: Channels

- 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!

Example: 2.4 GHz

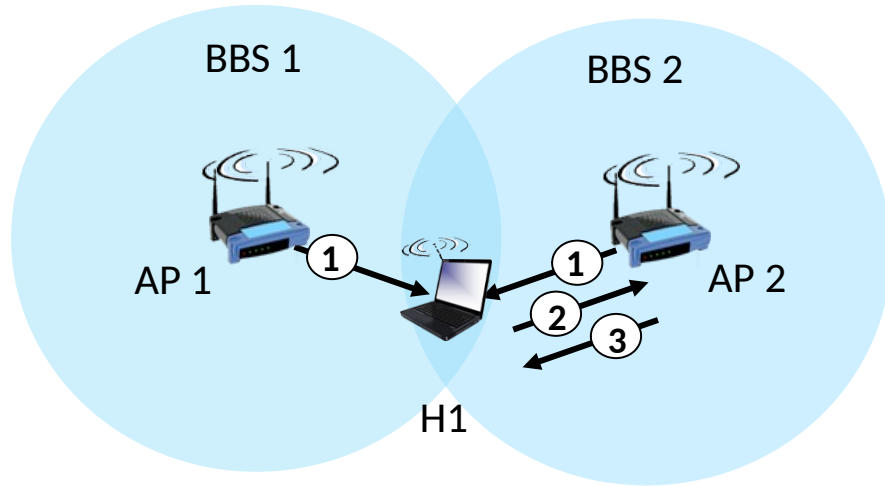


# 802.11: Association

- 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

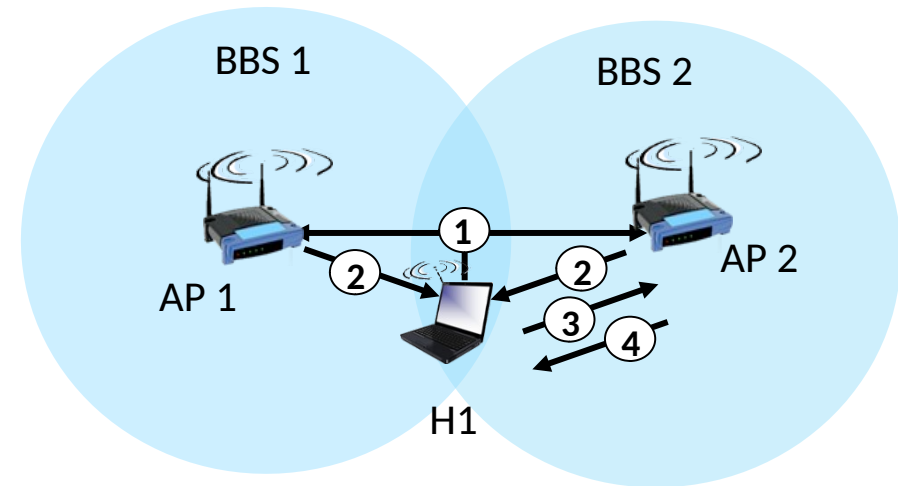


# 802.11: passive/active scanning



## 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

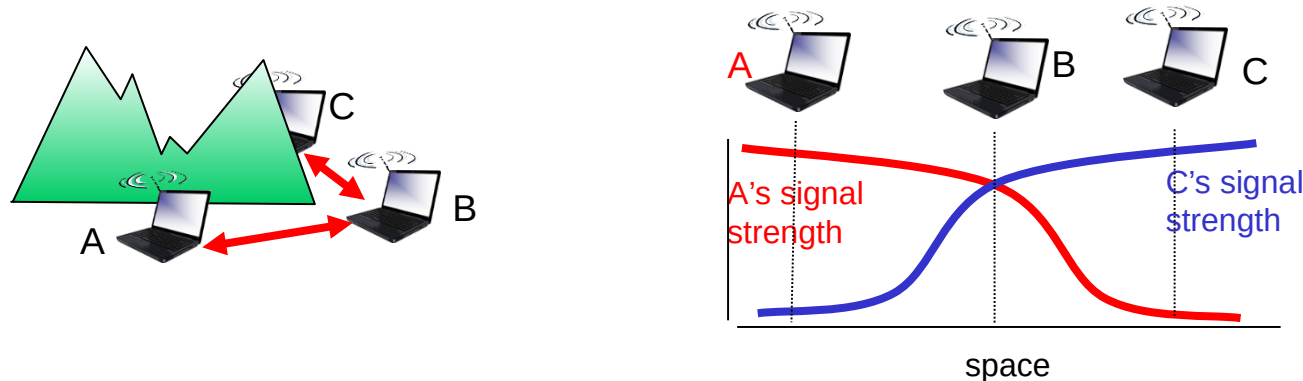


## active scanning:

- (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



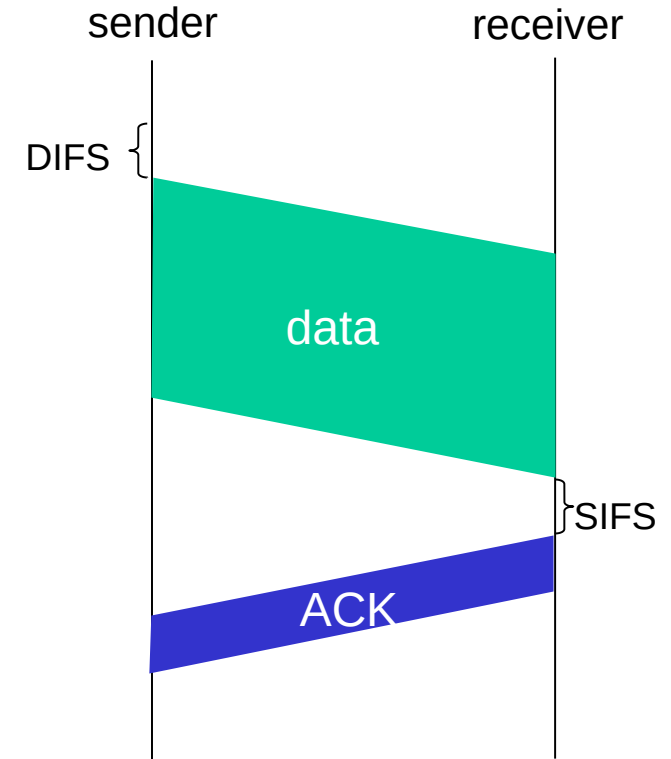
# IEEE 802.11 MAC Protocol: CSMA/CA

## 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)

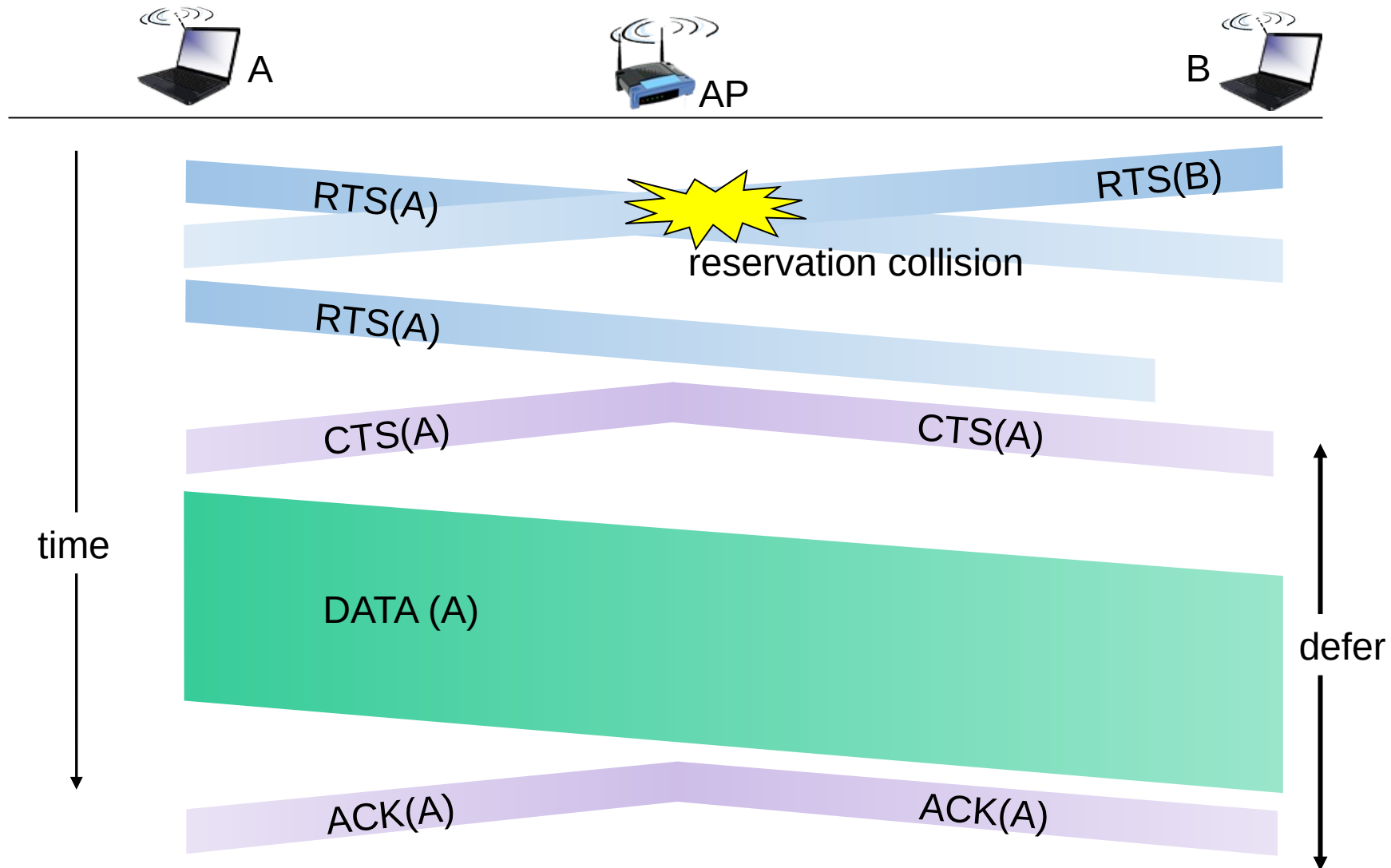


# Avoiding collisions (more)

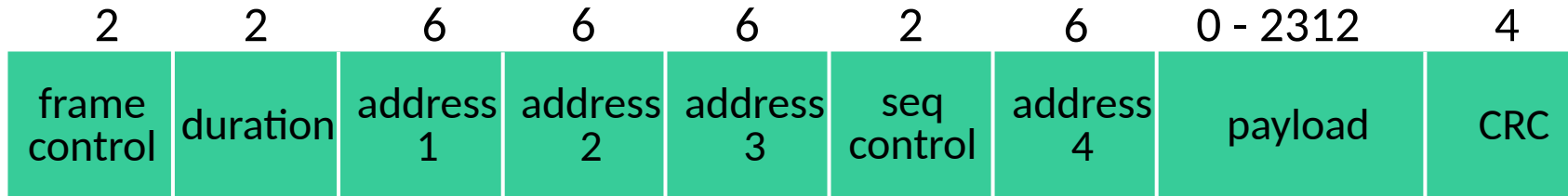
**idea:** sender “reserves” channel use for data frames using small reservation packets

- 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

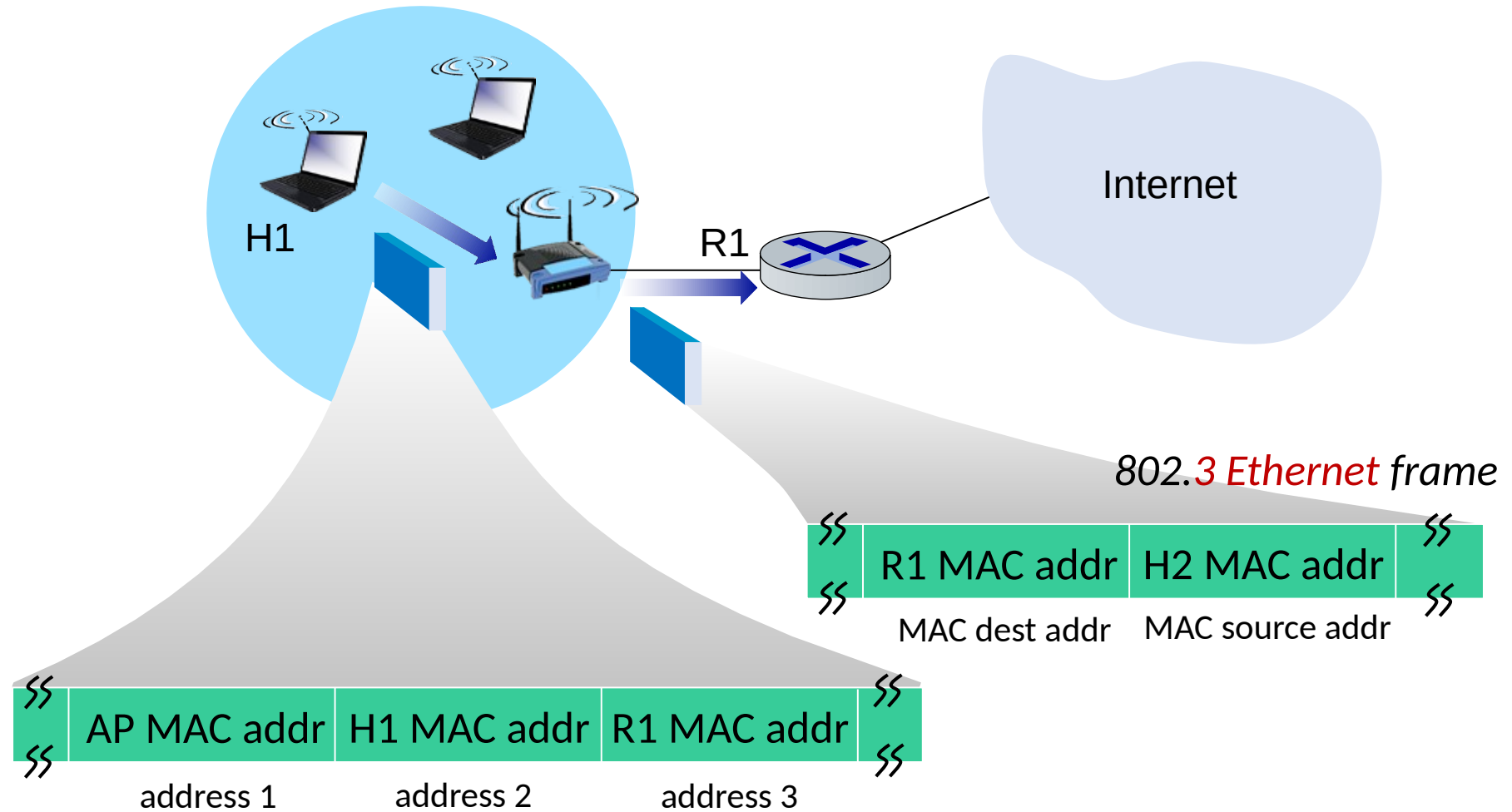
**Address 2:** MAC address of wireless host or AP transmitting this frame

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

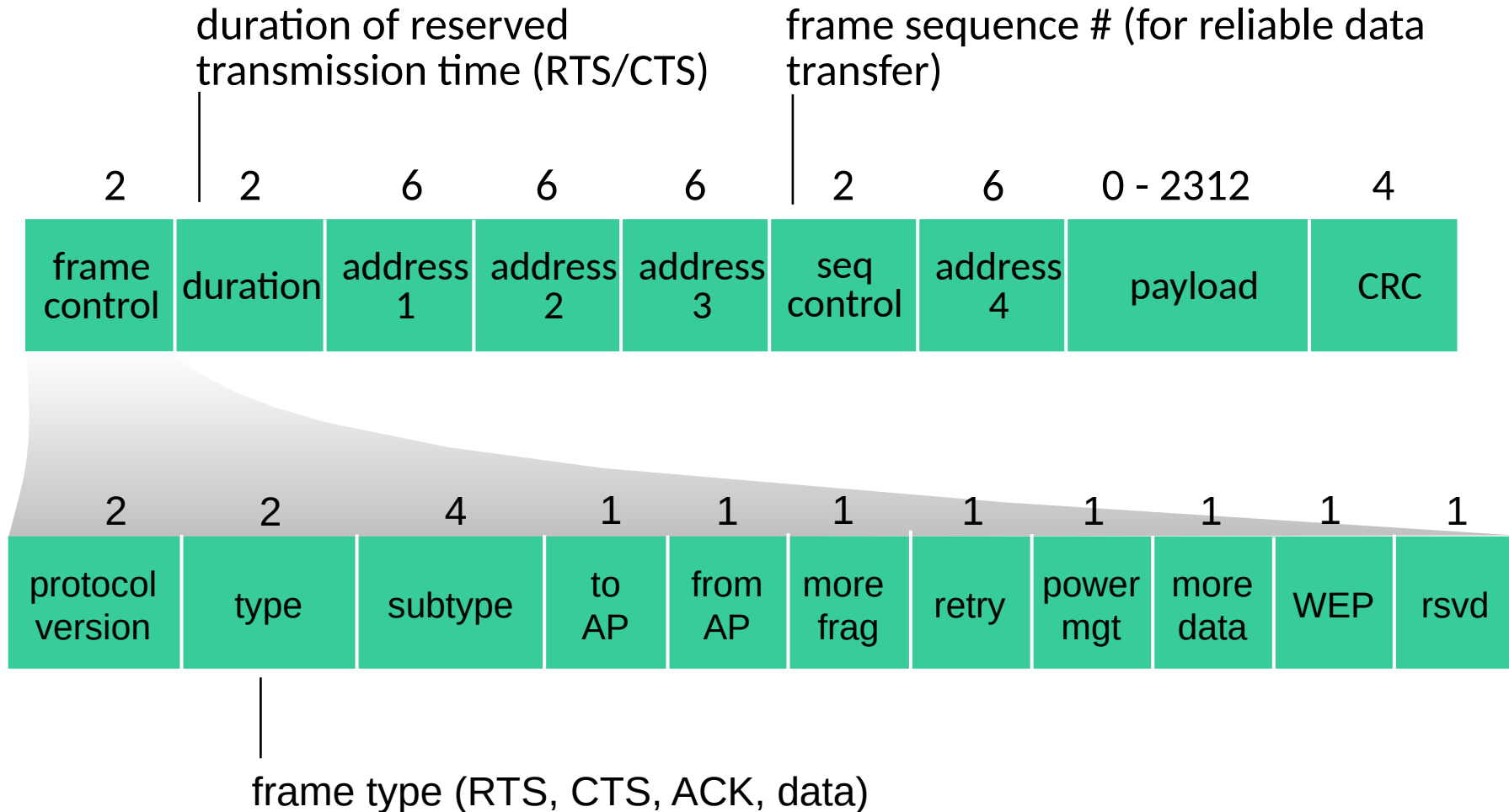
**Address 4:** used only in ad hoc mode



# 802.11 frame: addressing

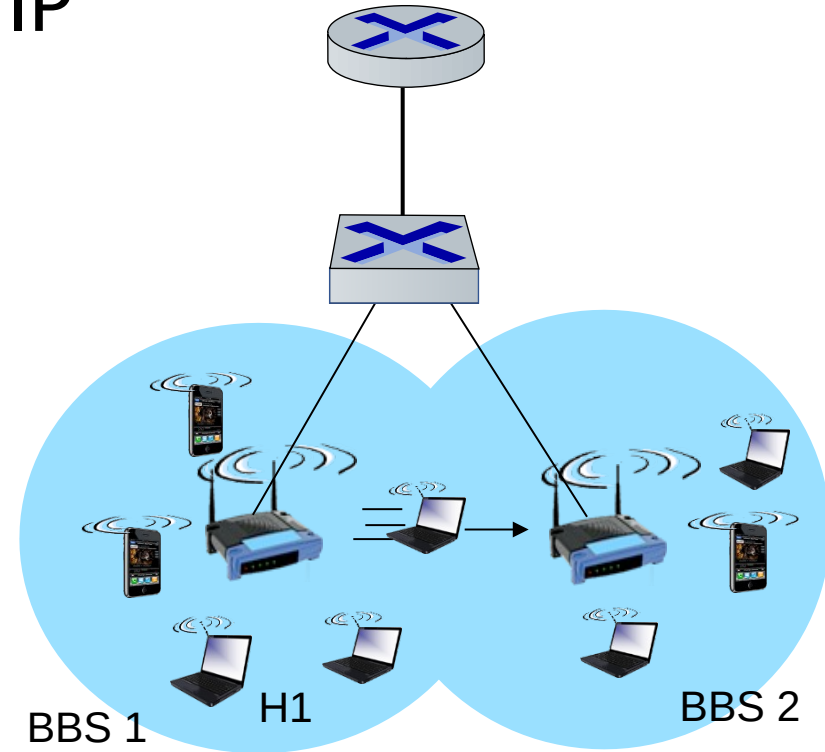


# 802.11 frame: addressing



# 802.11: mobility within same subnet

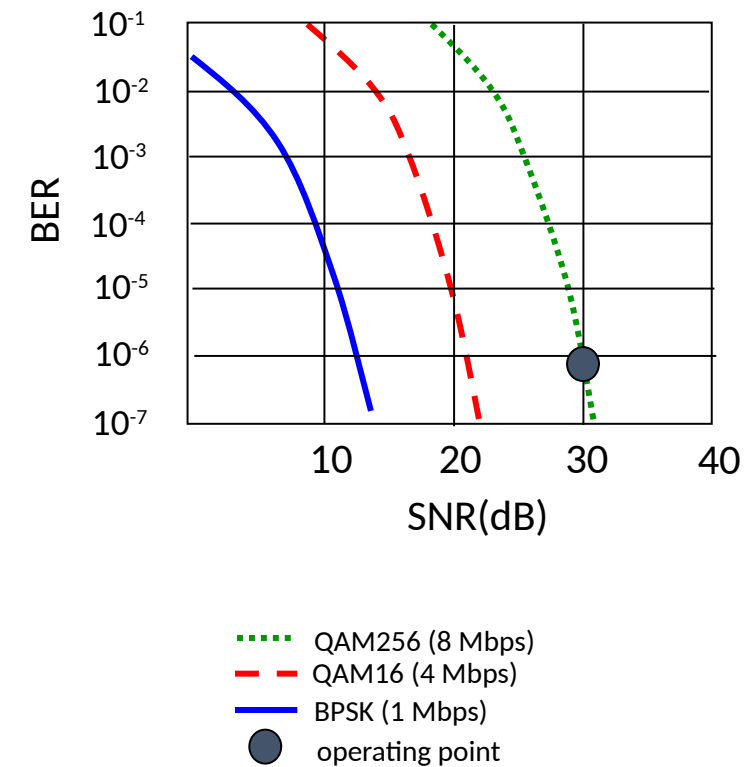
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - self-learning (Ch. 6): switch will see frame from H1 and “remember” which switch port can be used to reach H1



# 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

# Chapter 7 outline

- Introduction

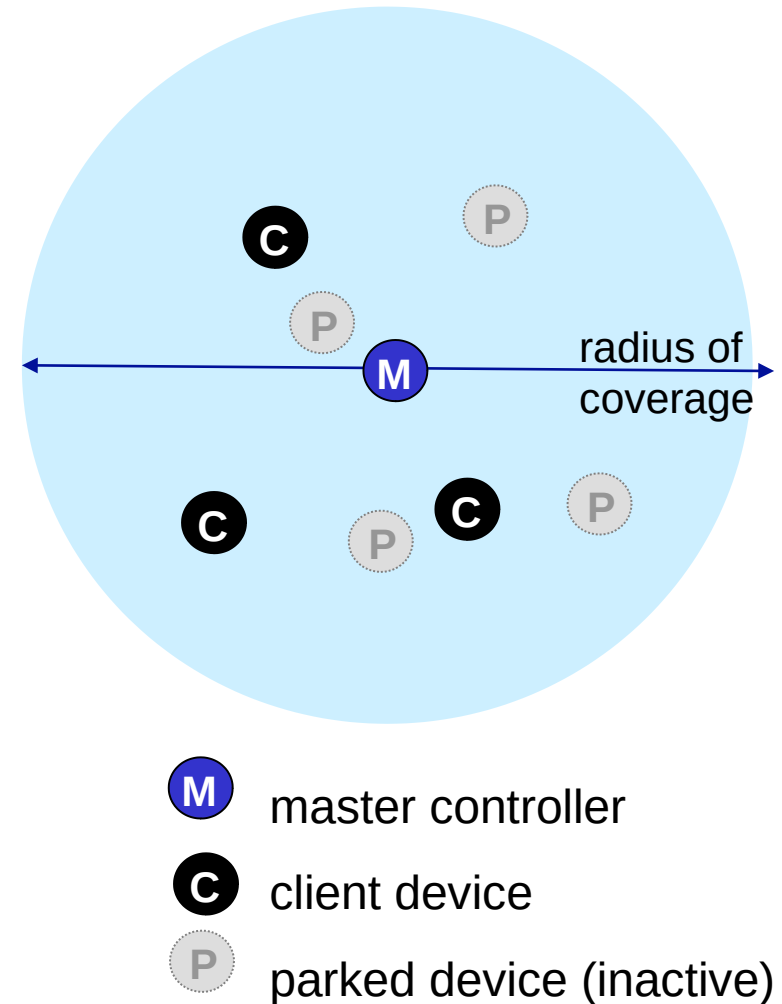
## Wireless

- Wireless links and network characteristics
- CDMA: code division multiple access
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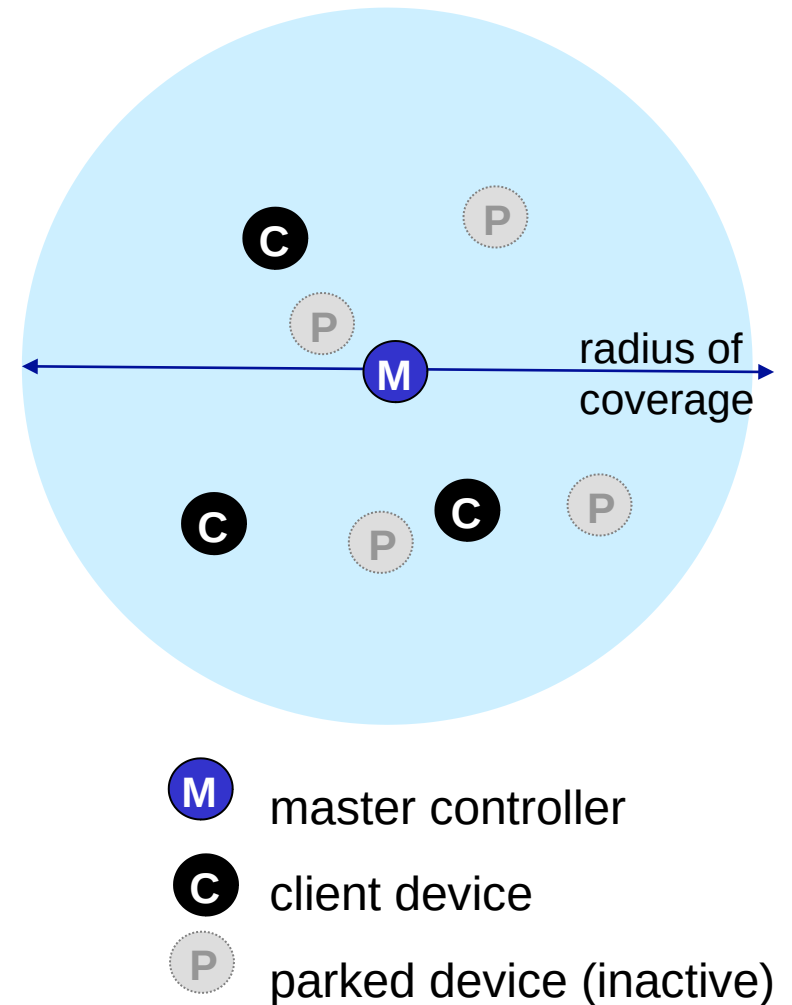
# Personal area networks: Bluetooth

- 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 / client devices:
  - master polls clients, grants requests for client transmissions



# Personal area networks: Bluetooth

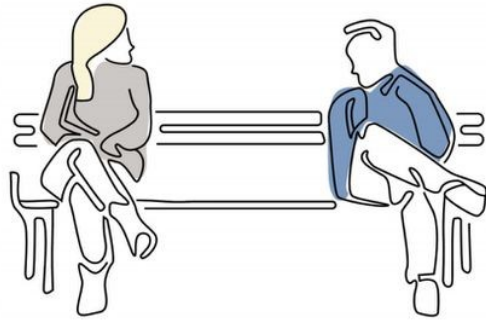
- TDM, 625  $\mu$ sec sec. slot
- FDM: sender uses 79 frequency channels in known, pseudo-random order slot-to-slot (spread spectrum)
  - other devices/equipment not in piconet only interfere in some slots
- **parked mode:** clients can “go to sleep” (park) and later wakeup (to preserve battery)
- **bootstrapping:**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





# Pandemic + Bluetooth

Alice and Bob meet each other for the first time and have a 10-minute conversation.

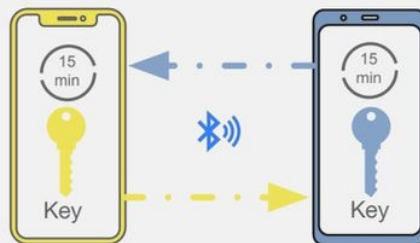


Bob is positively diagnosed for COVID-19 and enters the test result in an app from a public health authority.



A few days later...

Their phones exchange anonymous identifier beacons (which change frequently).



With Bob's consent, his phone uploads the last 14 days of keys for his broadcast beacons to the cloud.



Apps can only get more information via user consent



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## Mobility

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



# 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](http://www.3gpp.org)
  - 4G: Long-Term Evolution (LTE) standard

# 4G/5G cellular networks

## *similarities to wired Internet*

- edge/core distinction, but both belong 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

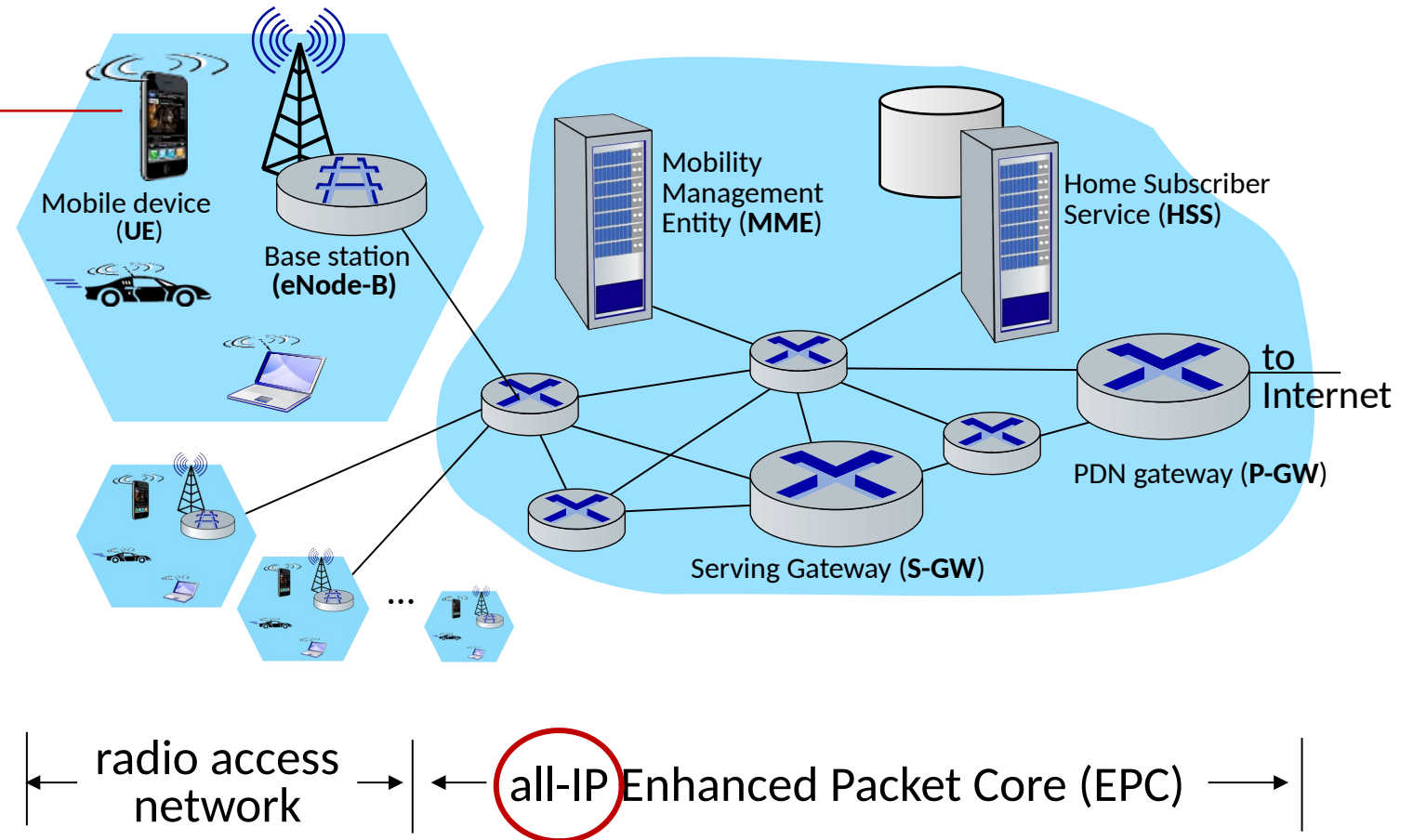
## *differences from wired Internet*

- different wireless link layer
- mobility as a 1<sup>st</sup> 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:

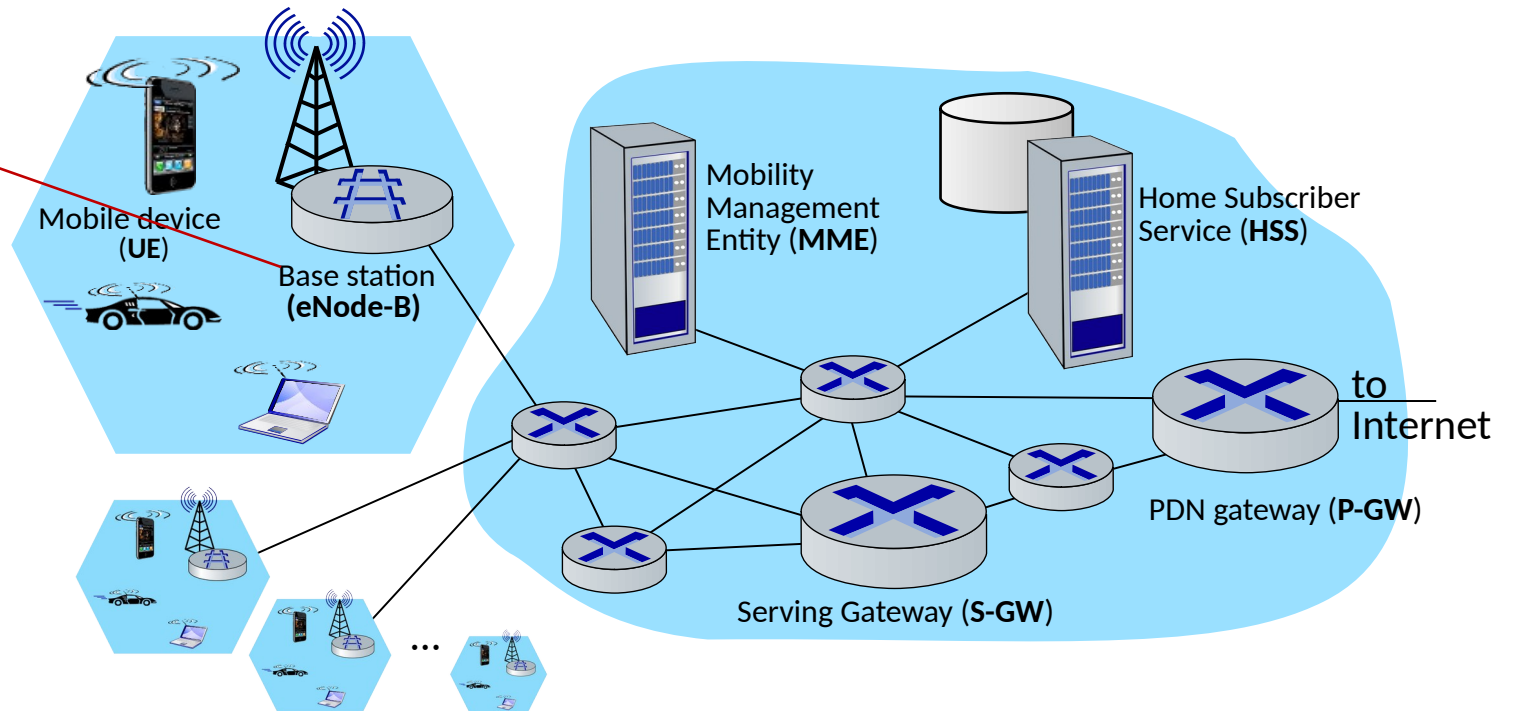
- smartphone, tablet, laptop, IoT, ... with 4G LTE radio
- 64-bit International Mobile Subscriber Identity (IMSI), stored on SIM (Subscriber Identity Module) card
- LTE jargon: User Equipment (UE)



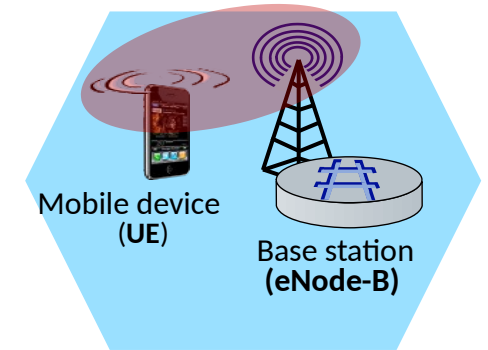
# Elements of 4G LTE architecture

## 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



# Radio Access Network: 4G radio



- connects device (UE) to a base station (eNode-B)
  - multiple devices connected to each base station
- many different possible frequencies bands, multiple channels in each band
  - popular bands: 600, 700, 850, 1500, 1700, 1900, 2100, 2600, 3500 MHz
  - separate upstream and downstream channels
- sharing 4G radio channel among users:
  - **OFDM**: Orthogonal Frequency Division Multiplexing
  - combination of FDM, TDM
- 100's Mbps possible per user/device



# Spectrum

## UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM

### RADIO SERVICES COLOR LEGEND


### ACTIVITY CODE

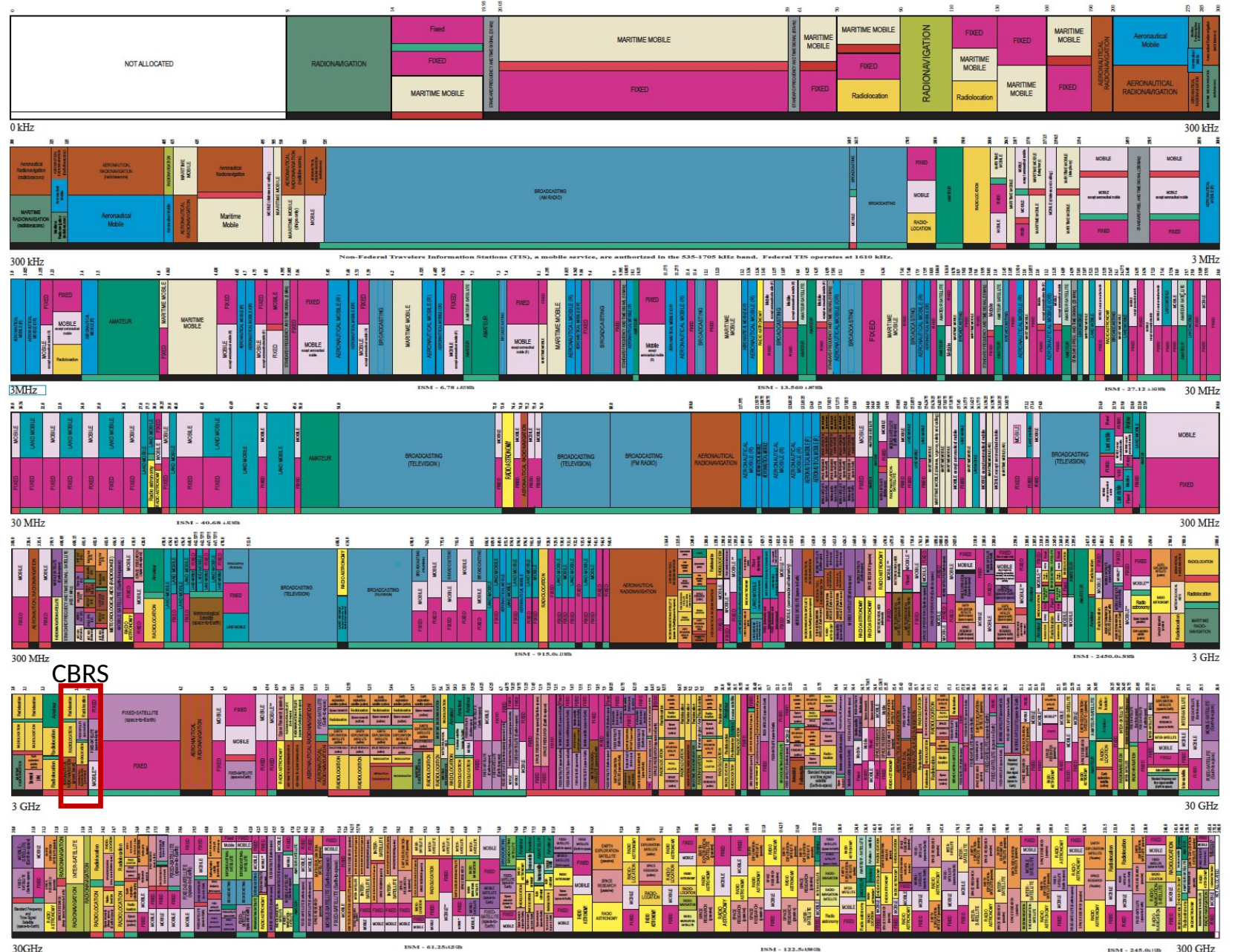
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### NON-FEDERAL EXCLUSIVE

### ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic representation of the portion of the Table of Frequency Allocations used by the FCC and NTIA. It is not a legal document and does not represent the actual frequency allocations. It is intended for informational purposes only.



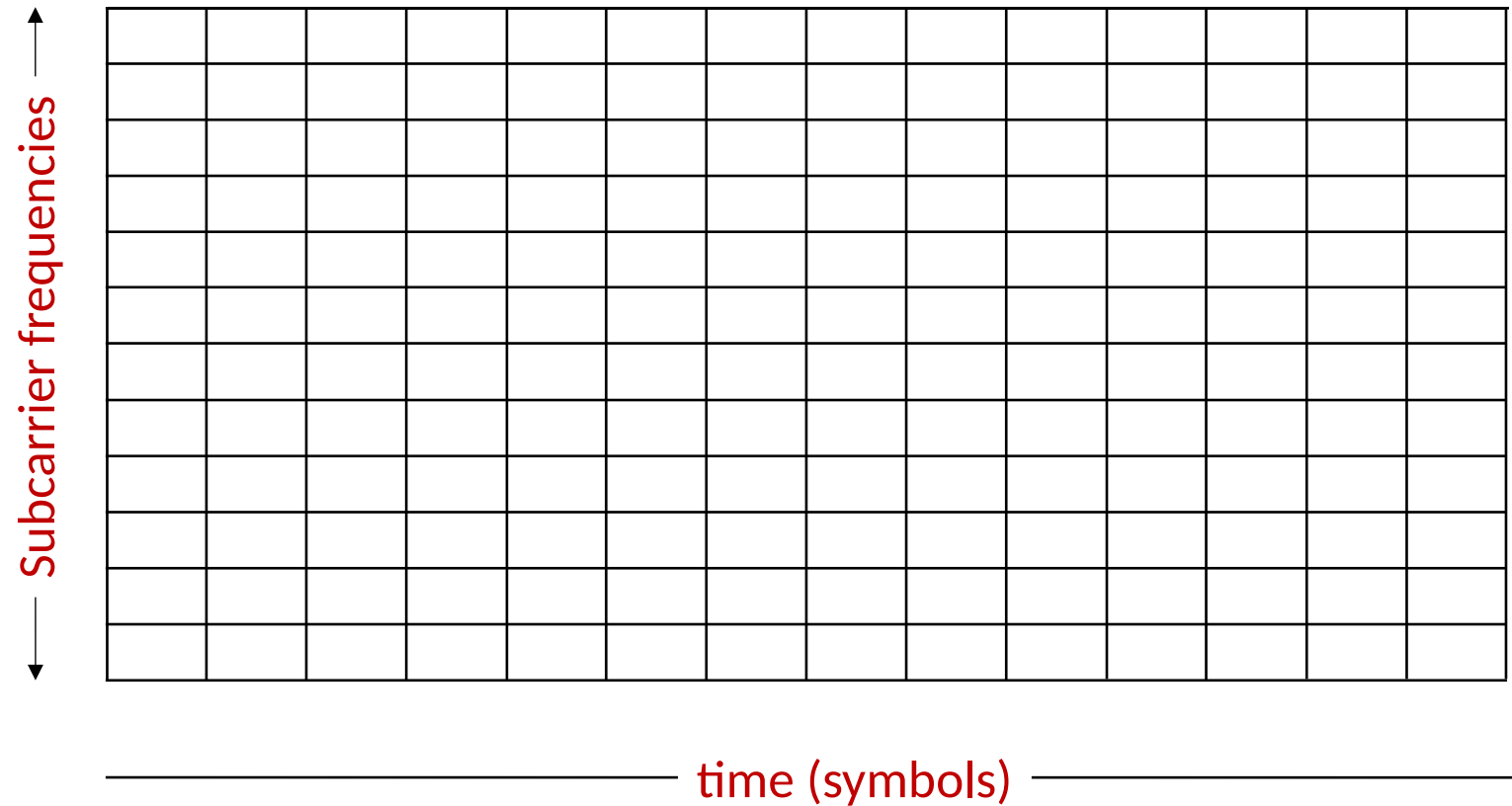
\* EXCEPT AERONAUTICAL MOBILE (S)

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PLEASE NOTE: THIS CHART IS A GRAPHIC REPRESENTATION OF THE PORTION OF THE TABLE OF FREQUENCY ALLOCATIONS USED BY THE FCC AND NTIA. IT IS NOT A LEGAL DOCUMENT AND DOES NOT REPRESENT THE ACTUAL FREQUENCY ALLOCATIONS. IT IS INTENDED FOR INFORMATIONAL PURPOSES ONLY.



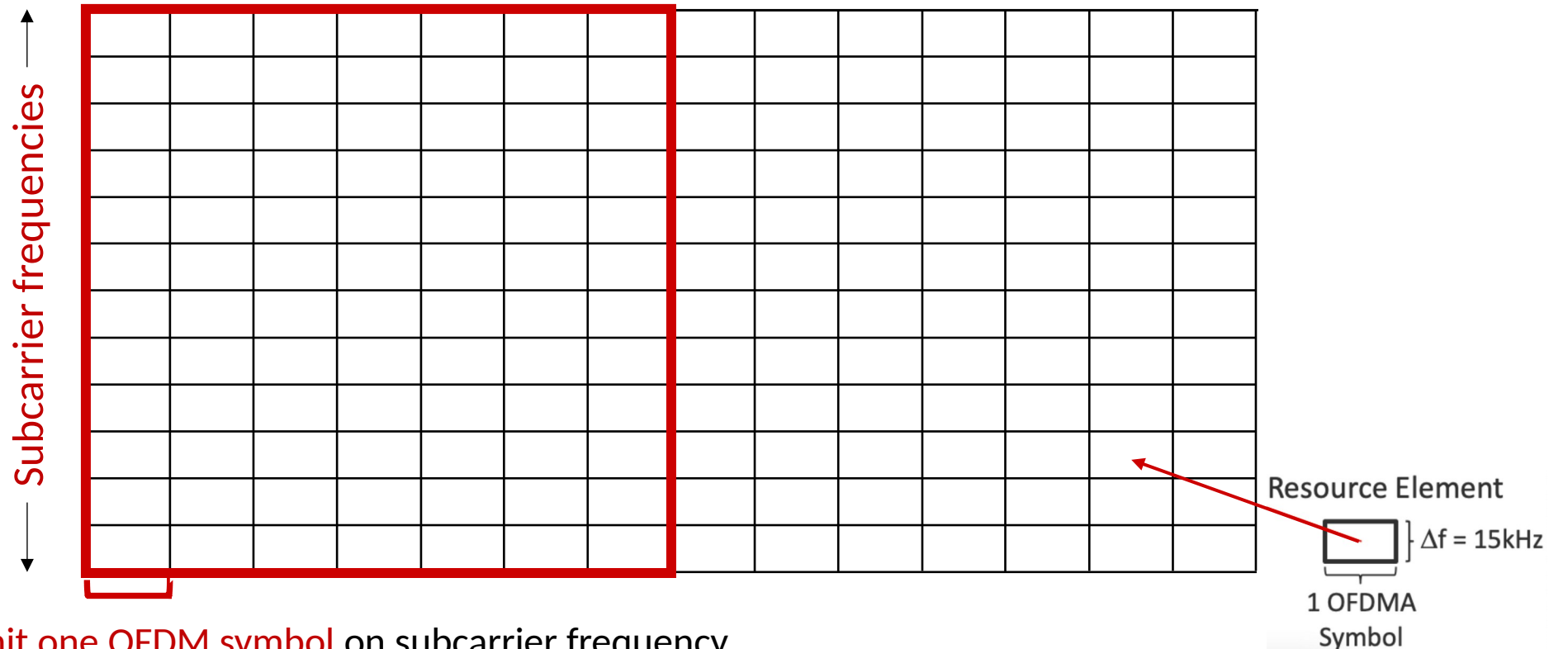
# OFDMA: time division (LTE)



# OFDMA: time division (LTE)

Physical Resource Block (PRB): blocks of  $7 \times 12 = 84$  resource elements








- unit of transmission scheduling

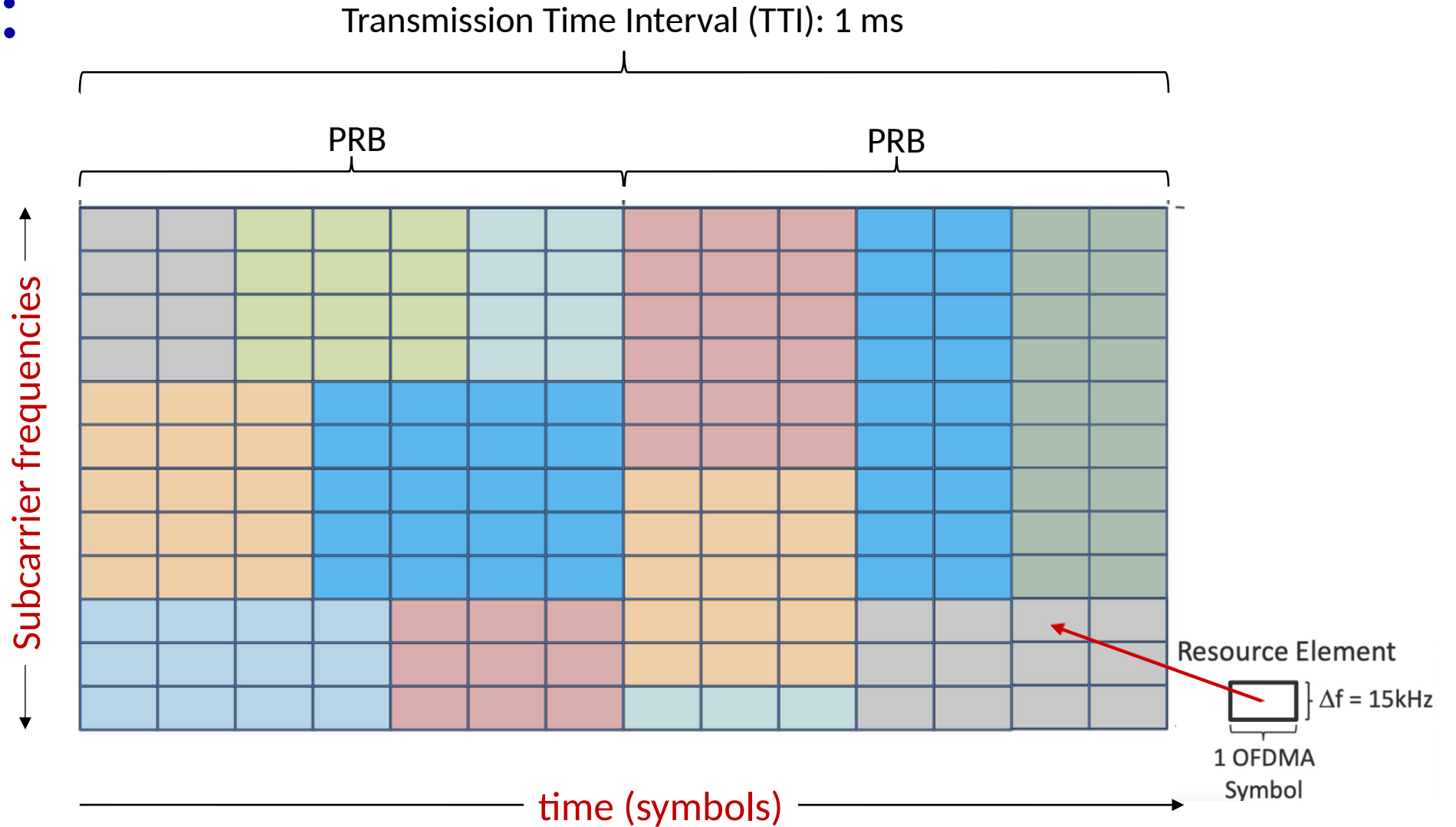


# OFDMA:

## Transmission scheduling example:

- Send to 7 UEs in 7 blocks of REs in one PRB

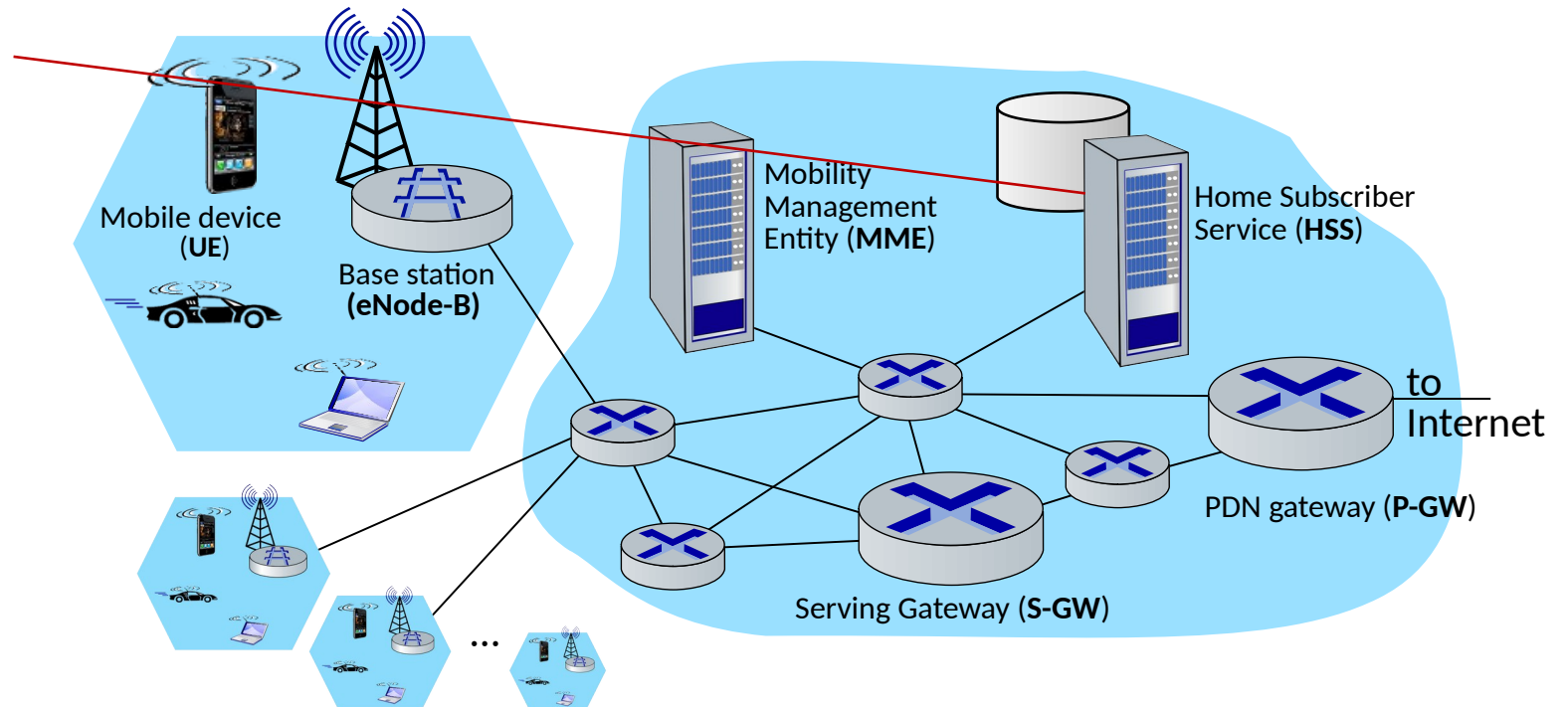
UE <sub>1</sub>	
UE <sub>2</sub>	
UE <sub>3</sub>	
UE <sub>4</sub>	
UE <sub>5</sub>	
UE <sub>6</sub>	
UE <sub>7</sub>	



# Elements of 4G LTE architecture

## Home Subscriber Service

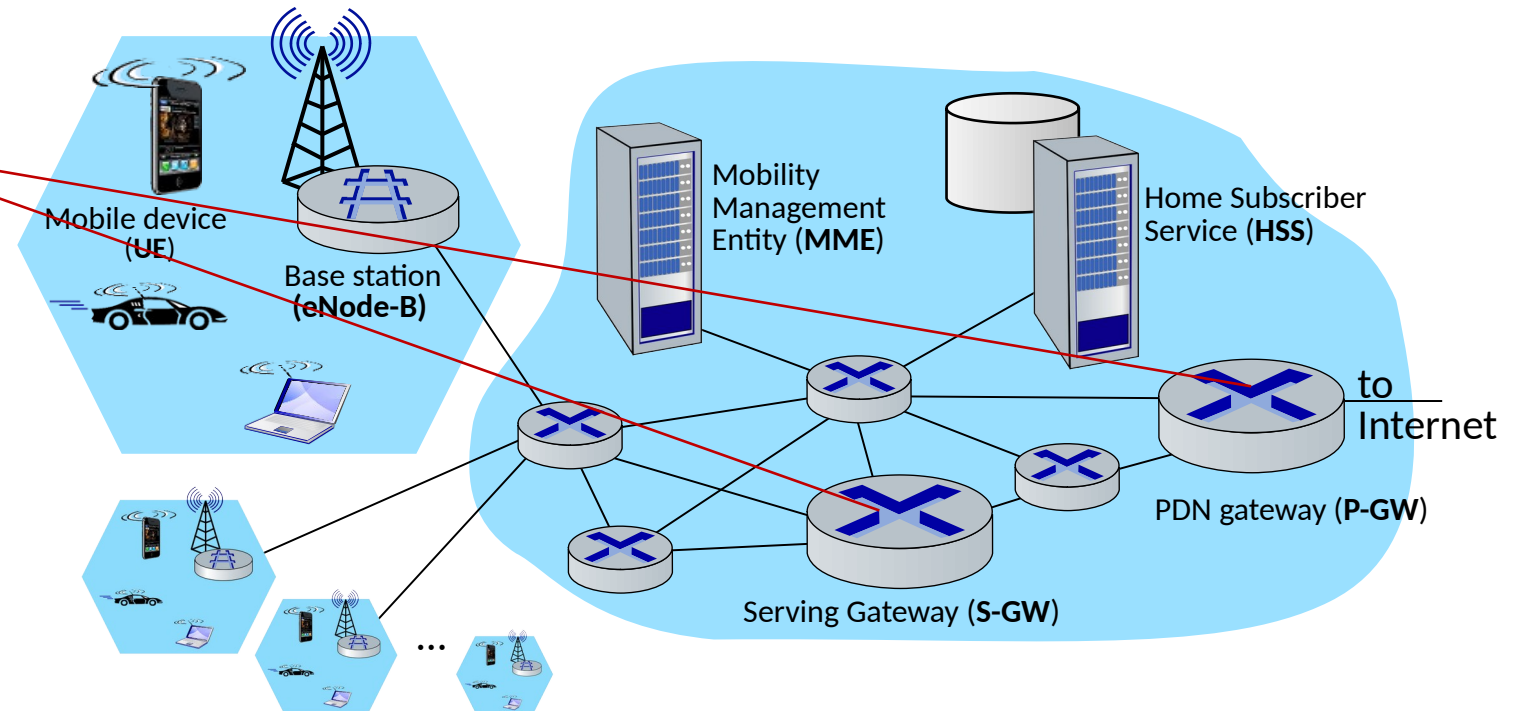
- stores info about mobile devices for which the HSS's network is their “home network”
- works with MME in device authentication



# Elements of 4G LTE architecture

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

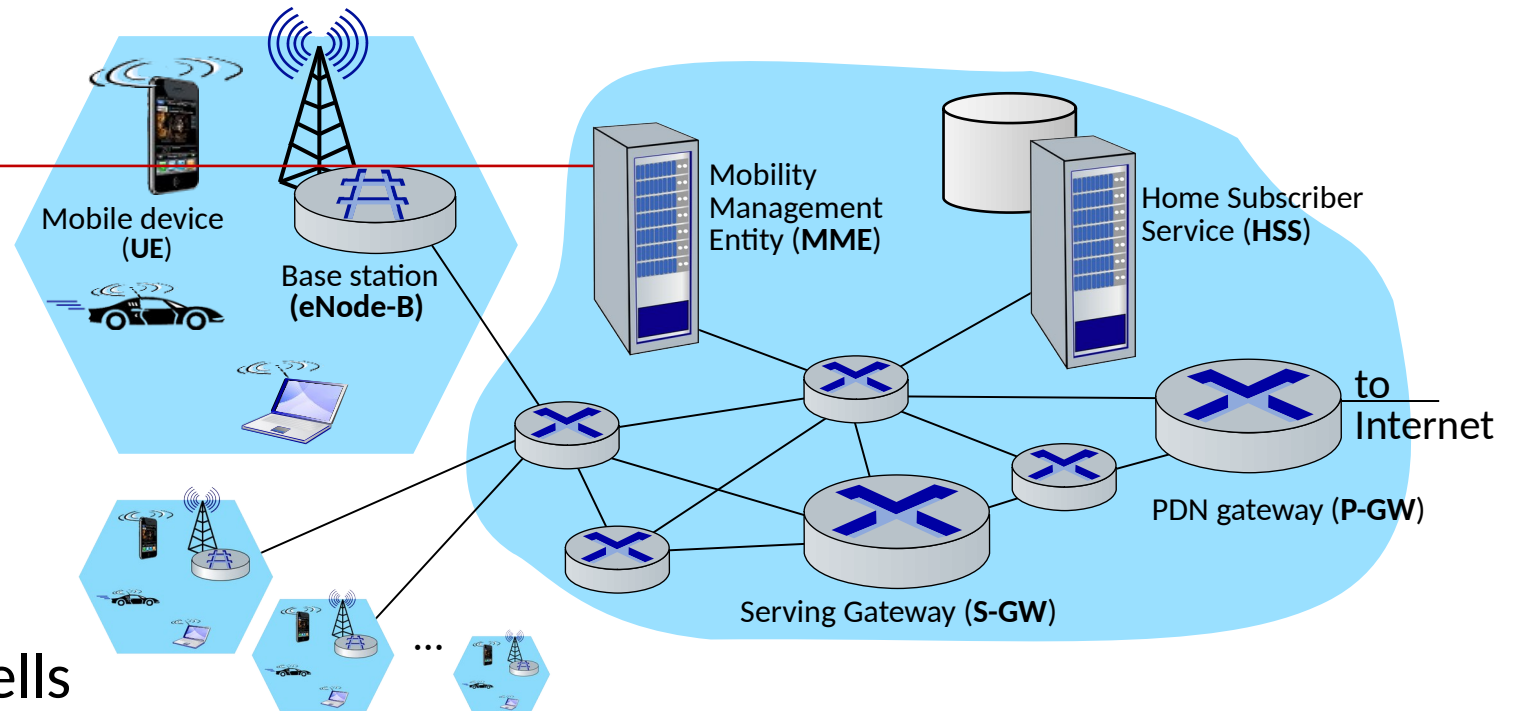
- lie on data path from mobile to/from Internet
- P-GW
  - gateway to mobile cellular network
  - Looks like any other internet gateway router
  - provides NAT services
- other routers:
  - extensive use of tunneling



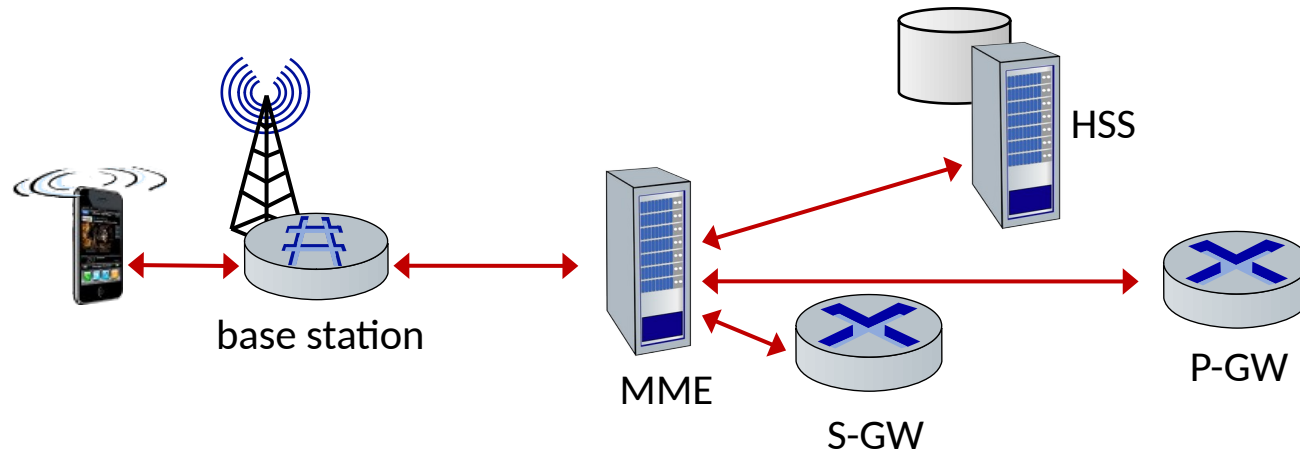
# Elements of 4G LTE architecture

## 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

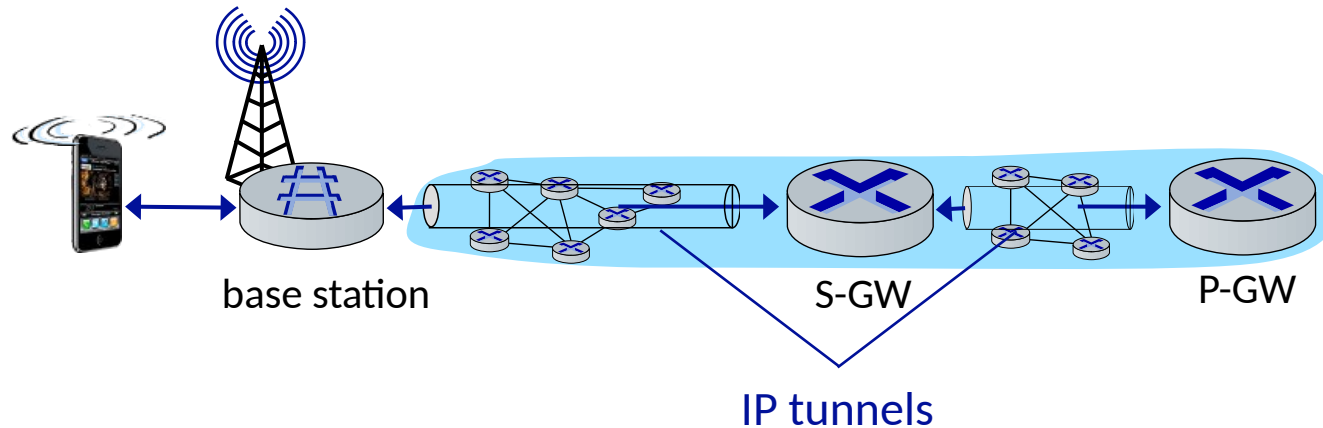


# LTE: data plane control plane separation



## control plane

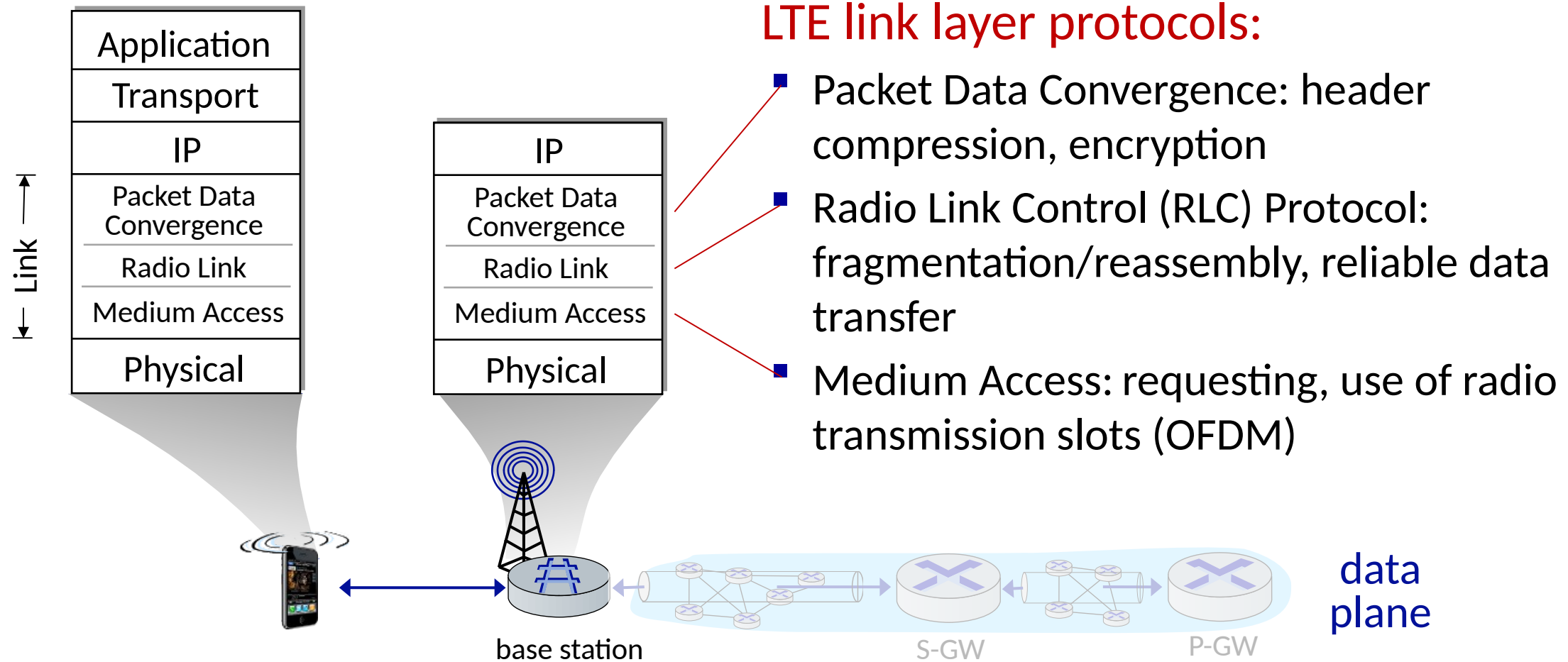
- new protocols for mobility management, security, authentication (later)



## data plane

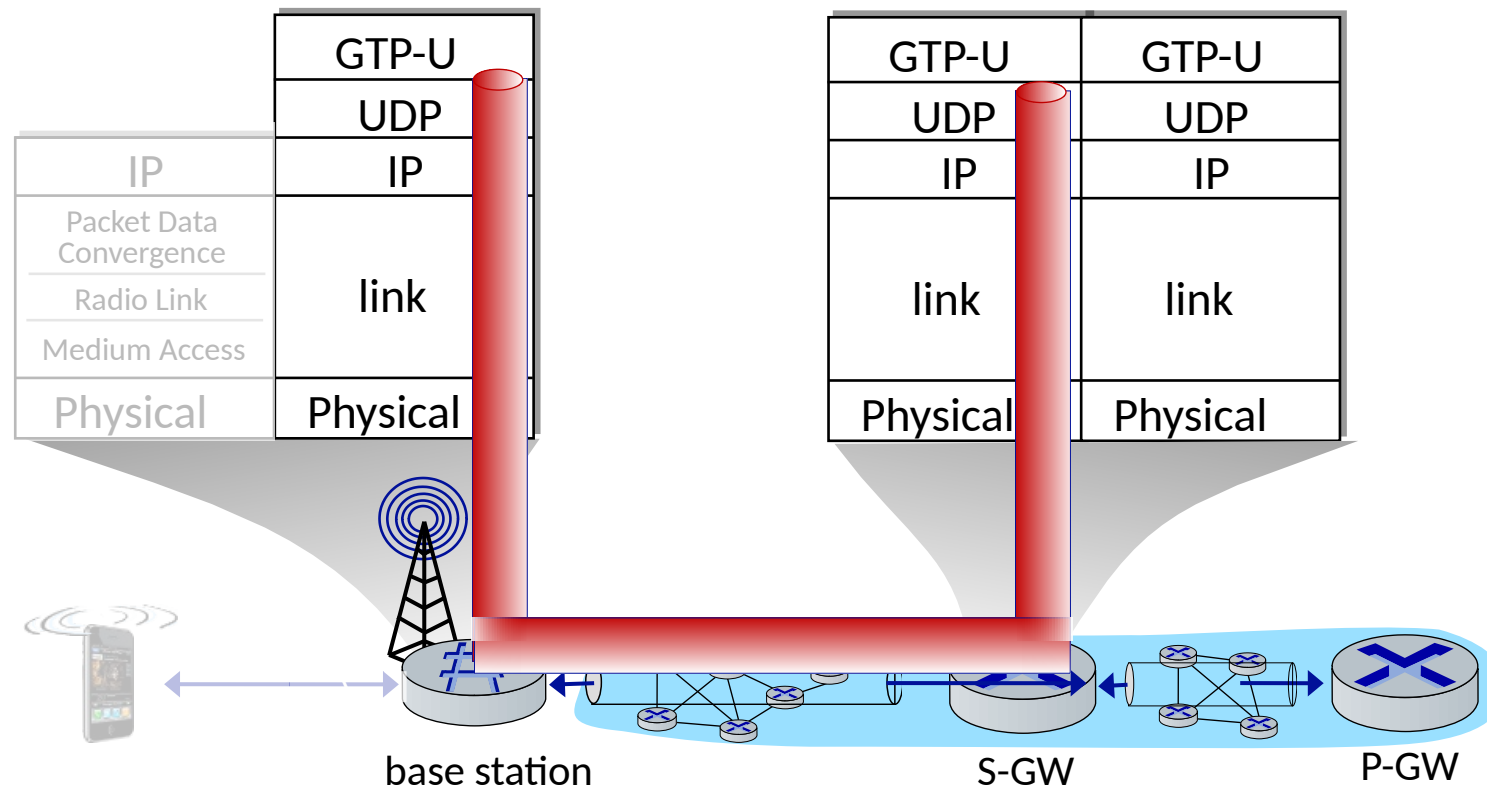
- new protocols at link, physical layers
- extensive use of tunneling to facilitate mobility

# LTE data plane protocol stack: first hop





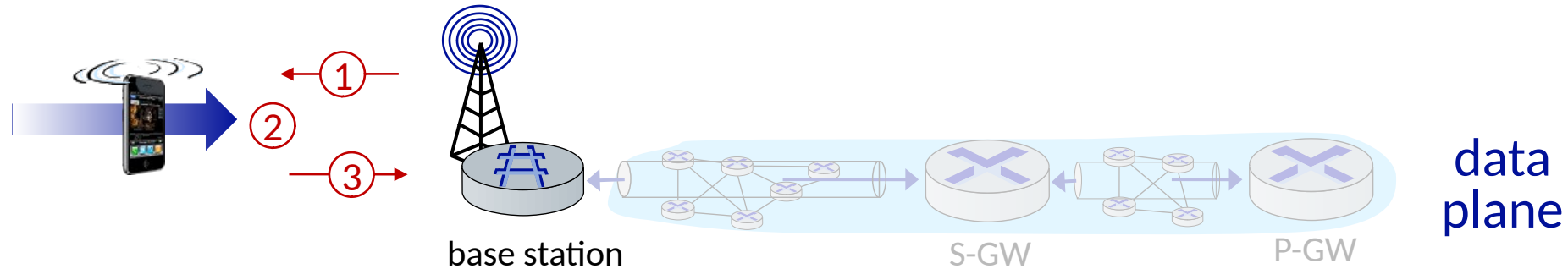
# LTE data plane protocol stack: packet core



## tunneling:

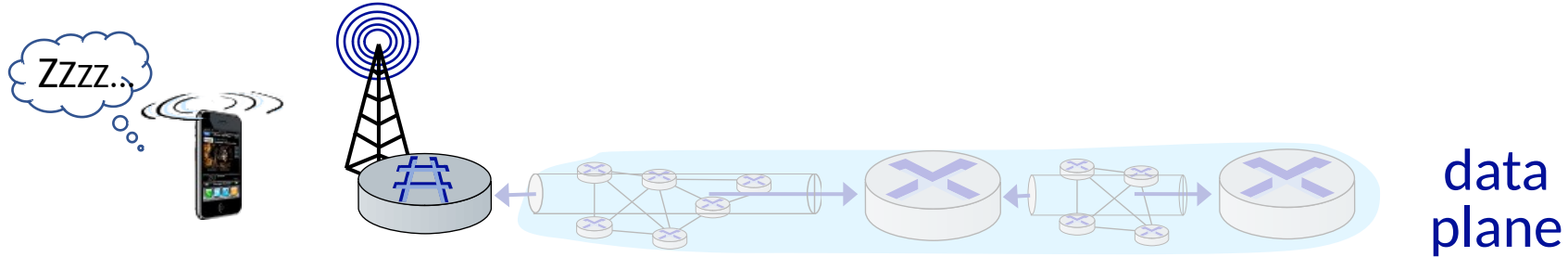
- mobile datagram encapsulated using GPRS Tunneling Protocol (GTP), sent inside UDP datagram to S-GW
- S-GW re-tunnels datagrams to P-GW
- supporting mobility: only tunneling endpoints change when mobile user moves

# 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 2<sup>nd</sup> 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

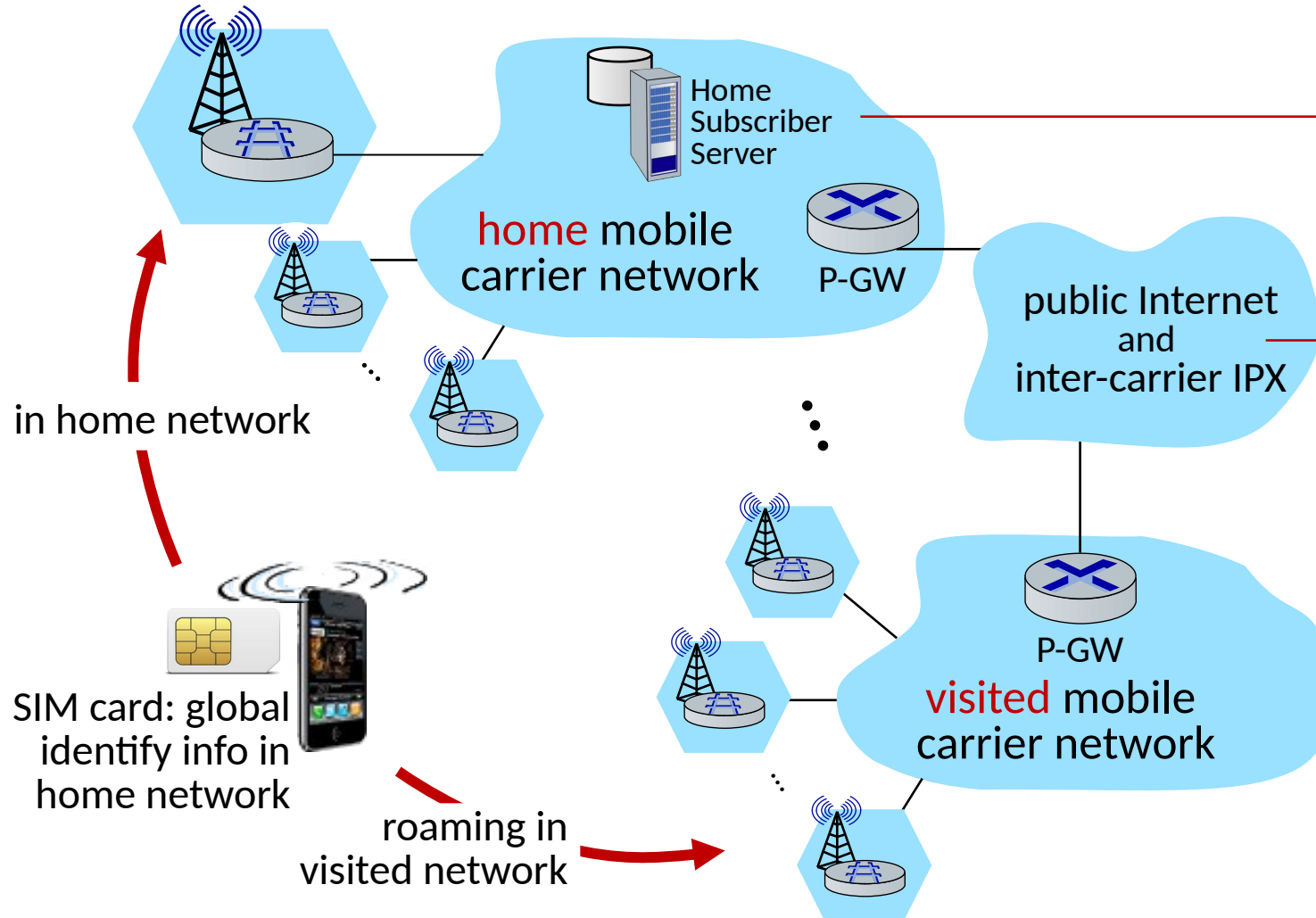
# LTE mobiles: sleep modes



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



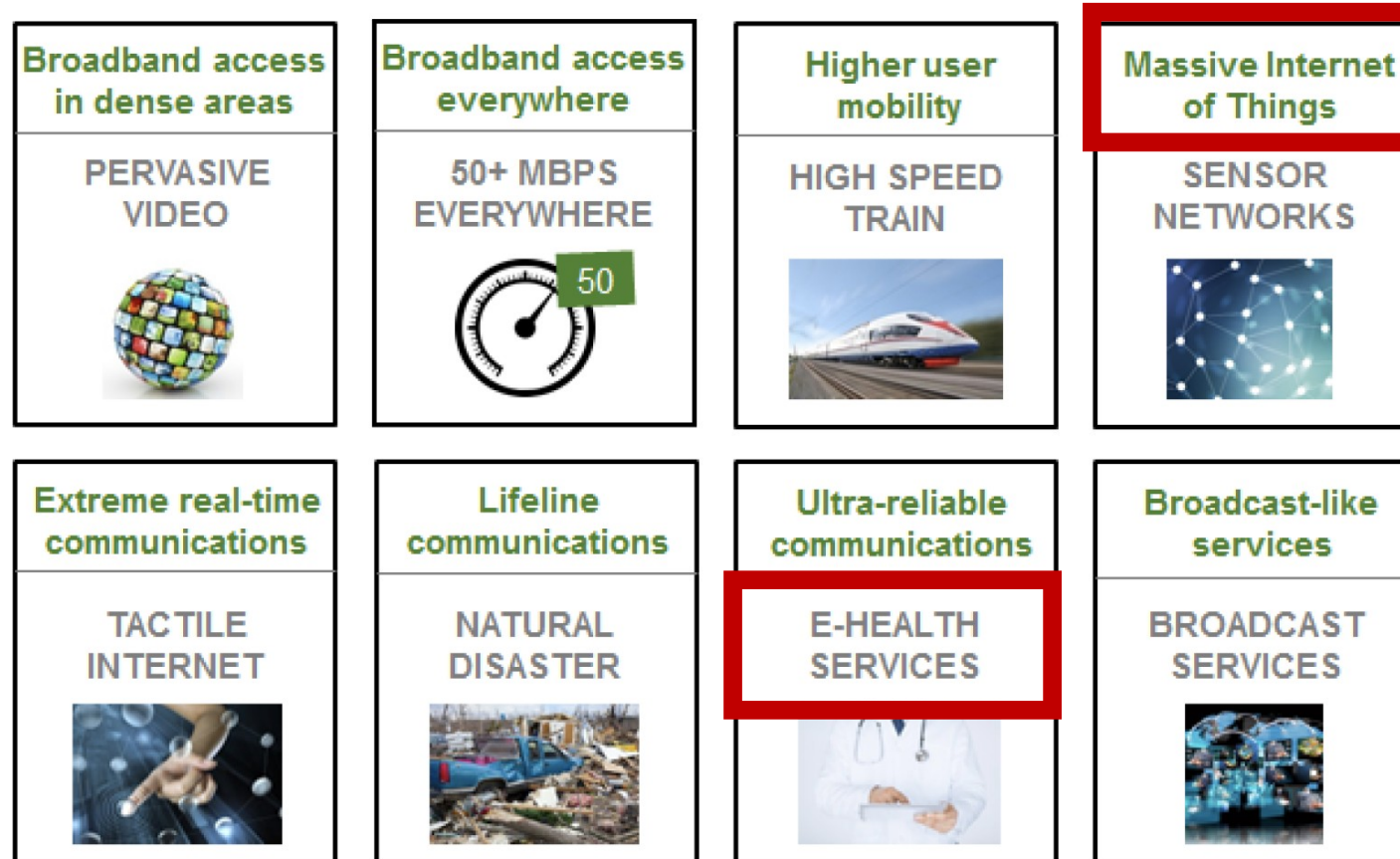
## home network HSS:

- 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: motivation



From Next Generation Mobile Networks (NGMS) alliance: 2020 white paper

Hype/wishes need to be separated from reality or likely nearer-term reality

# On to 5G: motivation

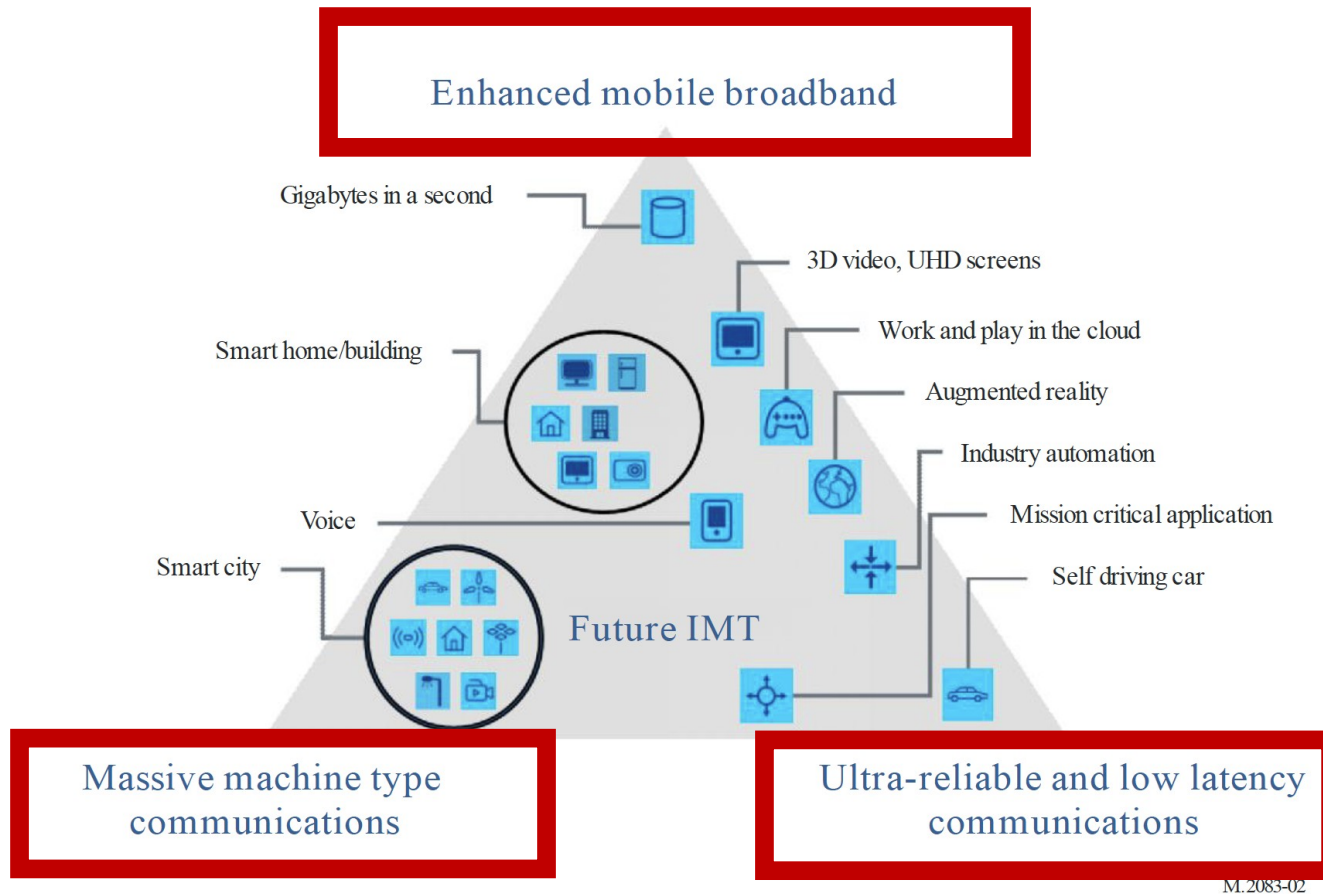
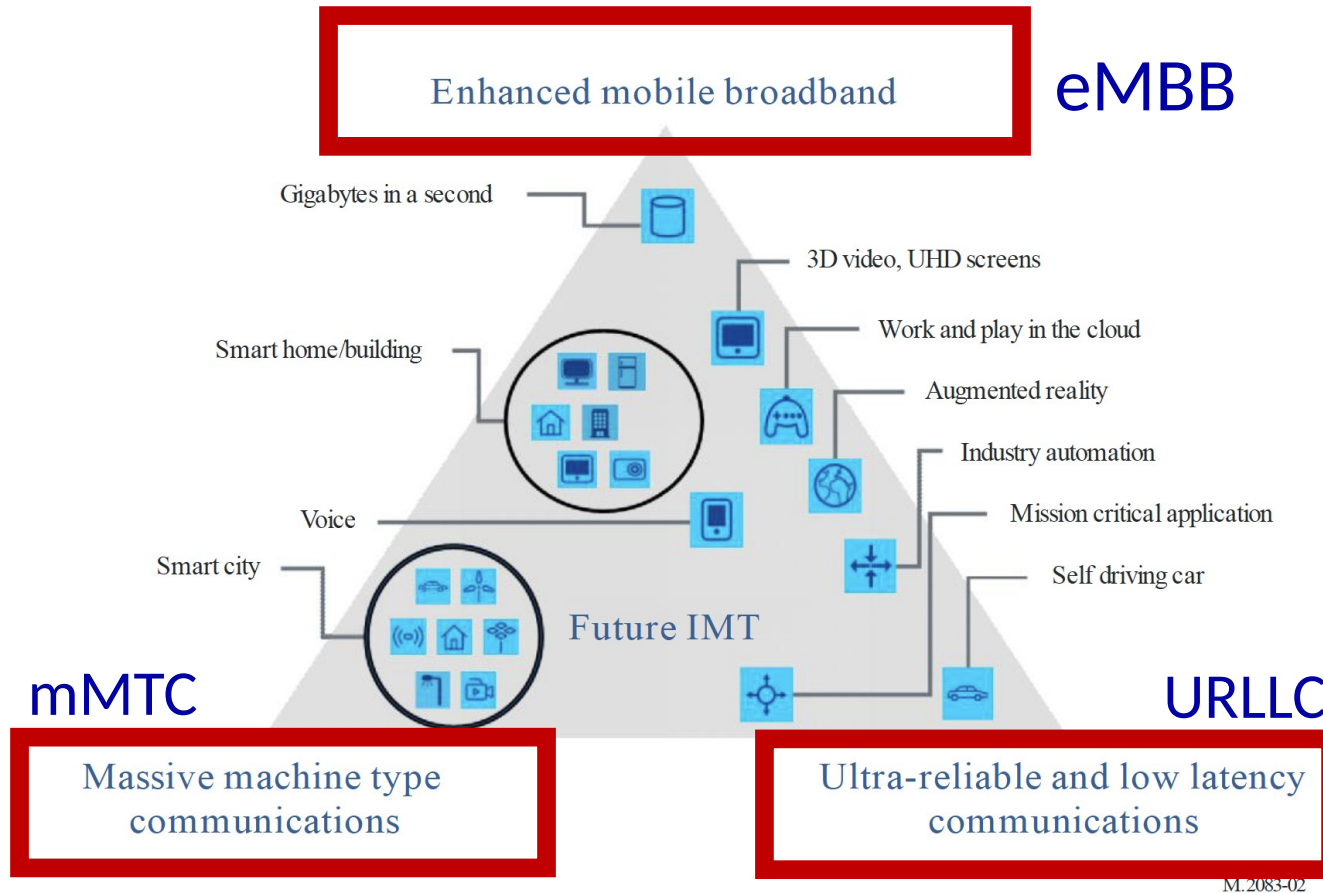


Figure: from Recommendation ITU-R M.2083-0 (2015)

“initial standards and launches have mostly focused on **enhanced Mobile Broadband**, 5G is expected to increasingly enable new business models and countless new use cases, in particular those of **massive Machine Type Communications** and **Ultra-reliable and Low Latency Communications**.”

# On to 5G: motivation



## Industry verticals:

- Manufacturing
- Constructions
- Transport
- Health
- Smart communities
- Education
- Tourism
- Agriculture
- Finance

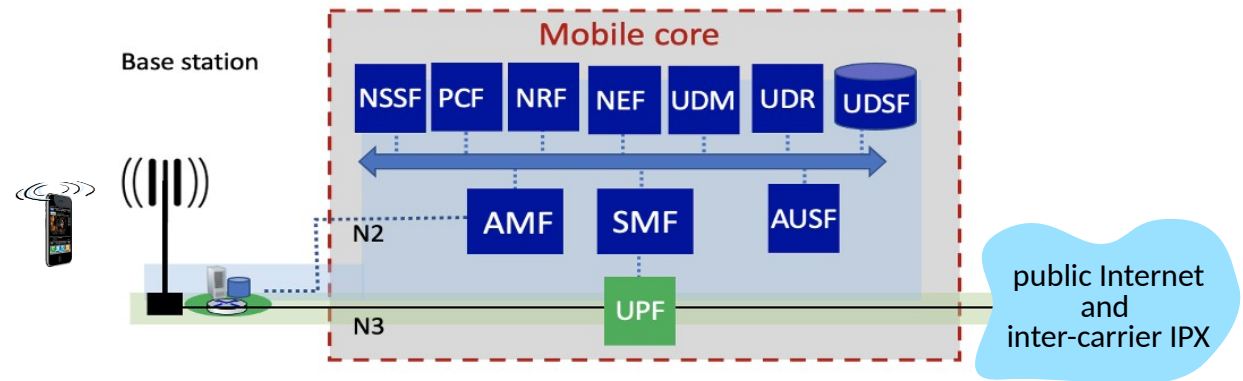
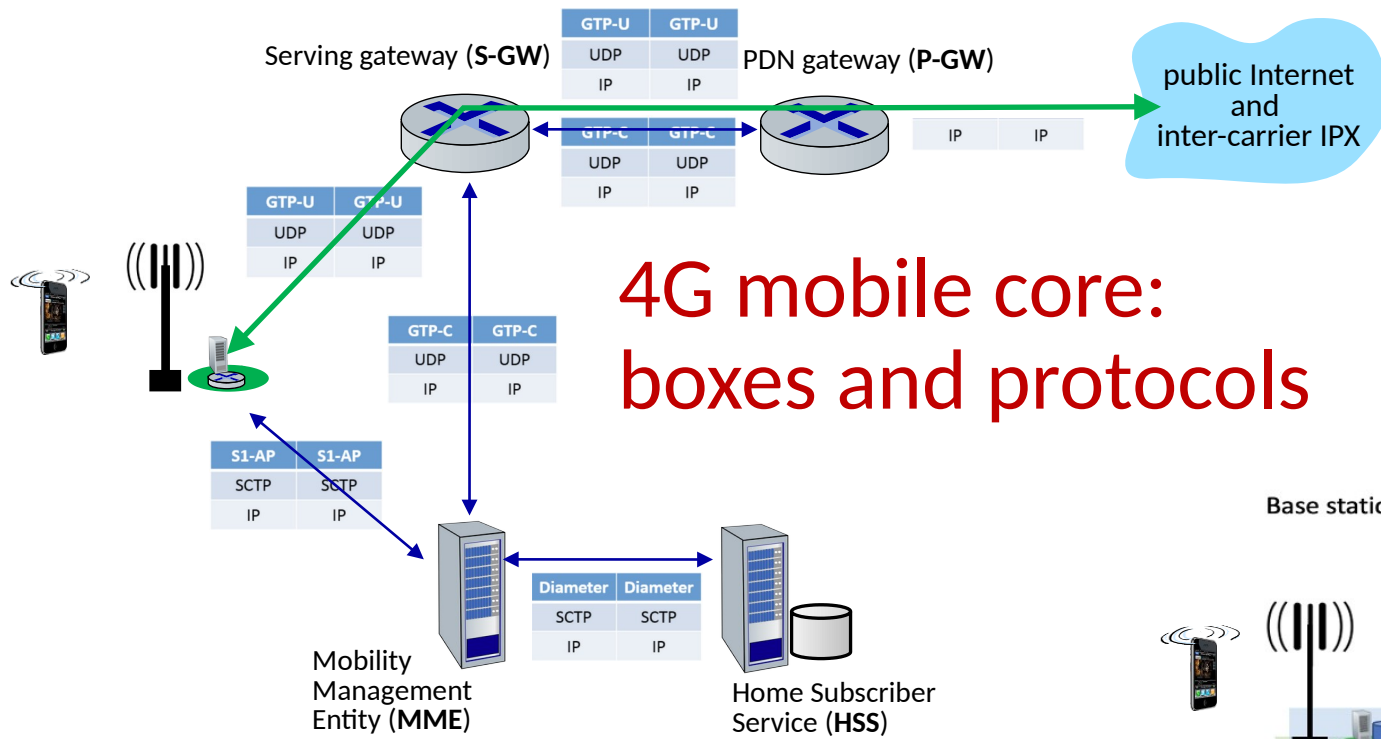
K. Schwab, "The Fourth Industrial Revolution," World Economic Forum.

# On to 5G: Radio

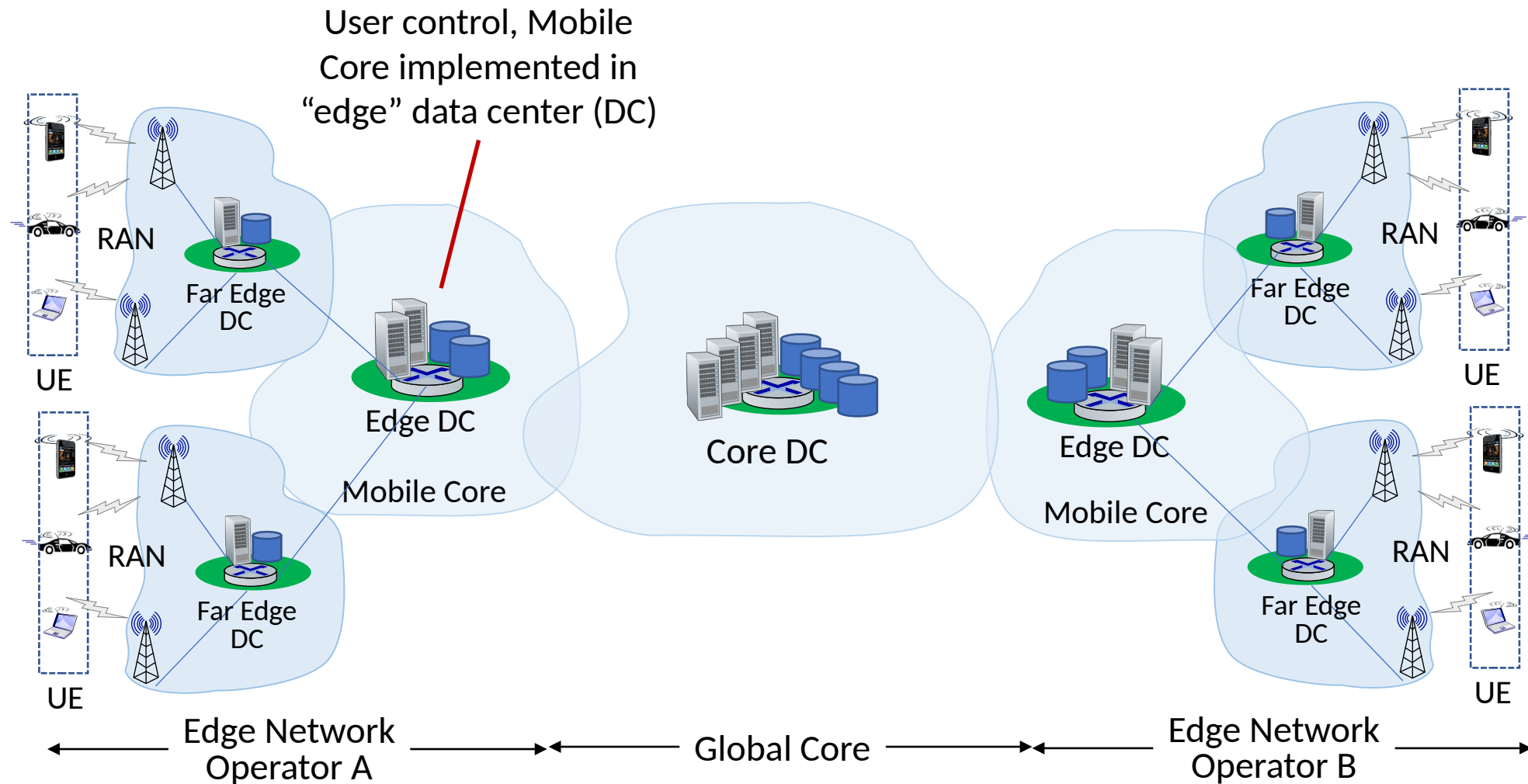
- **goal:** 10x increase in peak bitrate, 10x decrease in latency, 100x increase in traffic capacity over 4G
- **5G NR (new radio):**
  - two frequency bands: FR1 (450 MHz–6 GHz) and FR2 (24 GHz–52 GHz): millimeter wave frequencies
  - not backwards-compatible with 4G
  - MIMO: multiple directional antennae
- **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



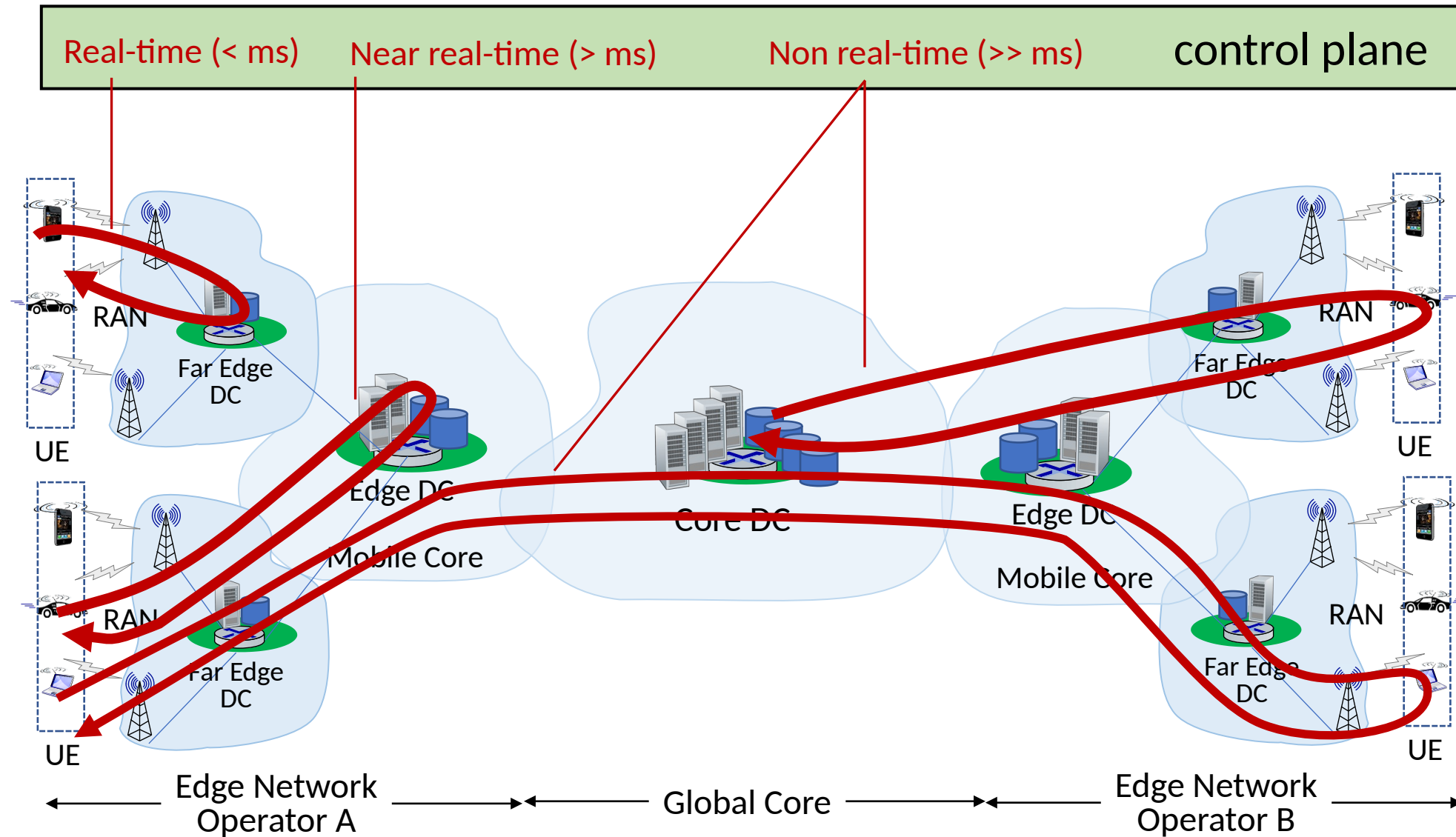
# On to 5G: SDN-like architecture



## Functional elements: **communication, computation, data**

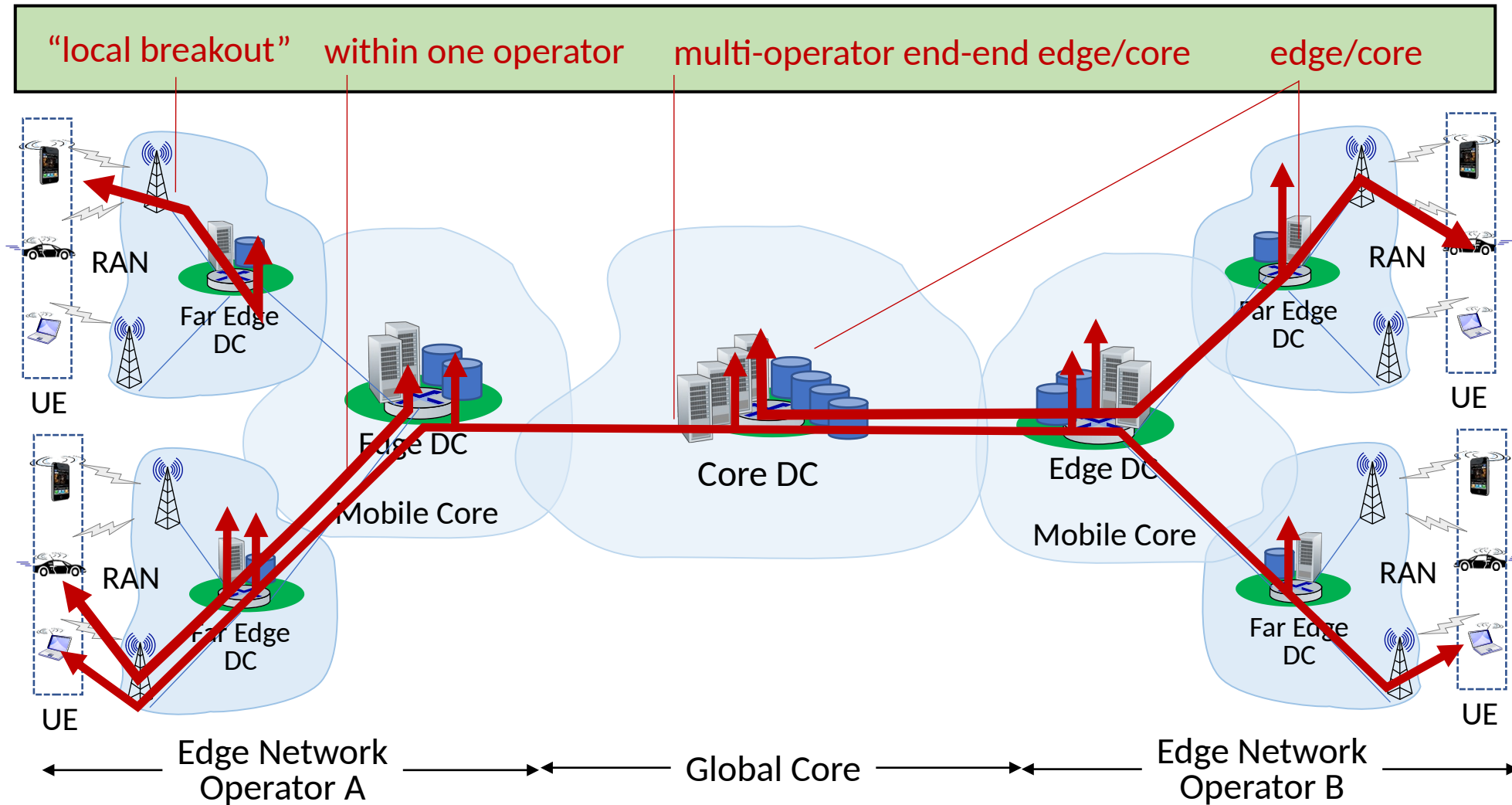


# Control plane: resource control



# User plane: resources, as used by users (application)

## *User plane*



# On beyond 5G?

- “6G” not obviously next: “NextG” and “Beyond 5G” heard more often than “6G”
- 5G on an evolutionary path (like the Internet)
  - **agility**: cloud technologies (SDN) mean new features can be introduced rapidly, deployed continuously
  - **customization**: change can be introduced bottom-up (e.g., by enterprises and edge cloud partners with Private 5G)
    - No need to wait for standardization
    - No need to reach agreement (among all incumbent stakeholders)

# Chapter 7 outline

- Introduction

## Wireless

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

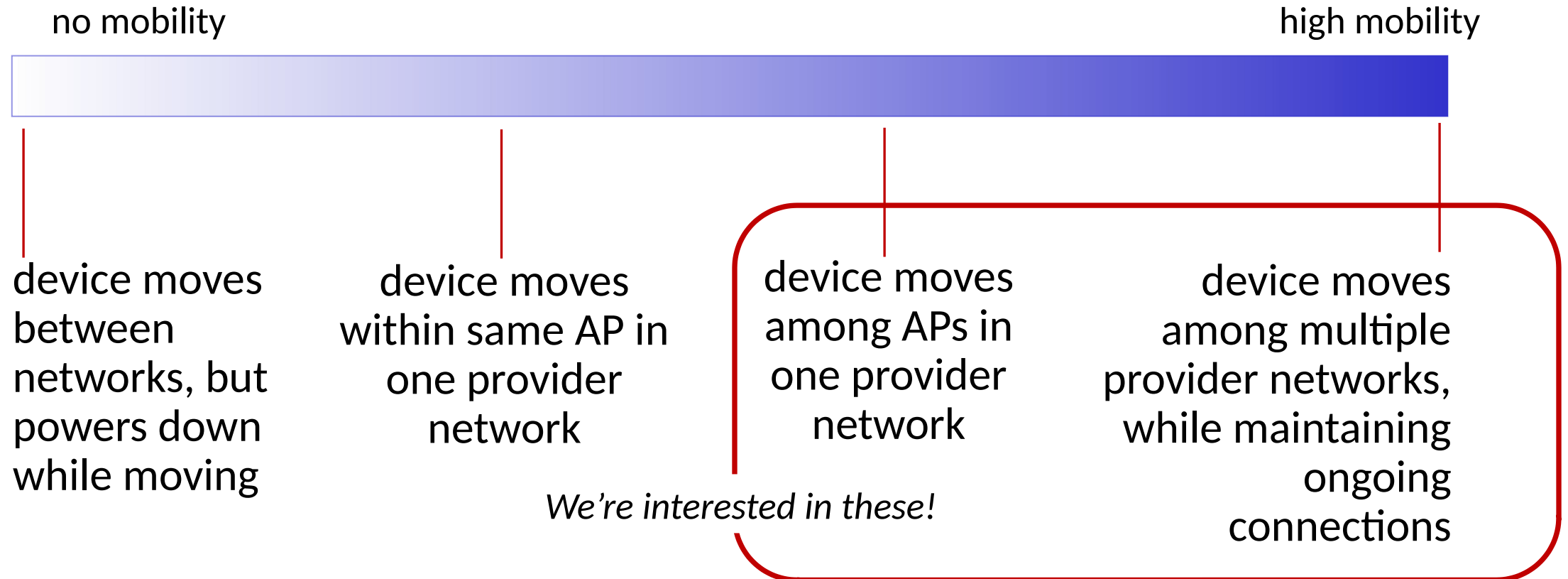
## Mobility

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



# What is mobility?

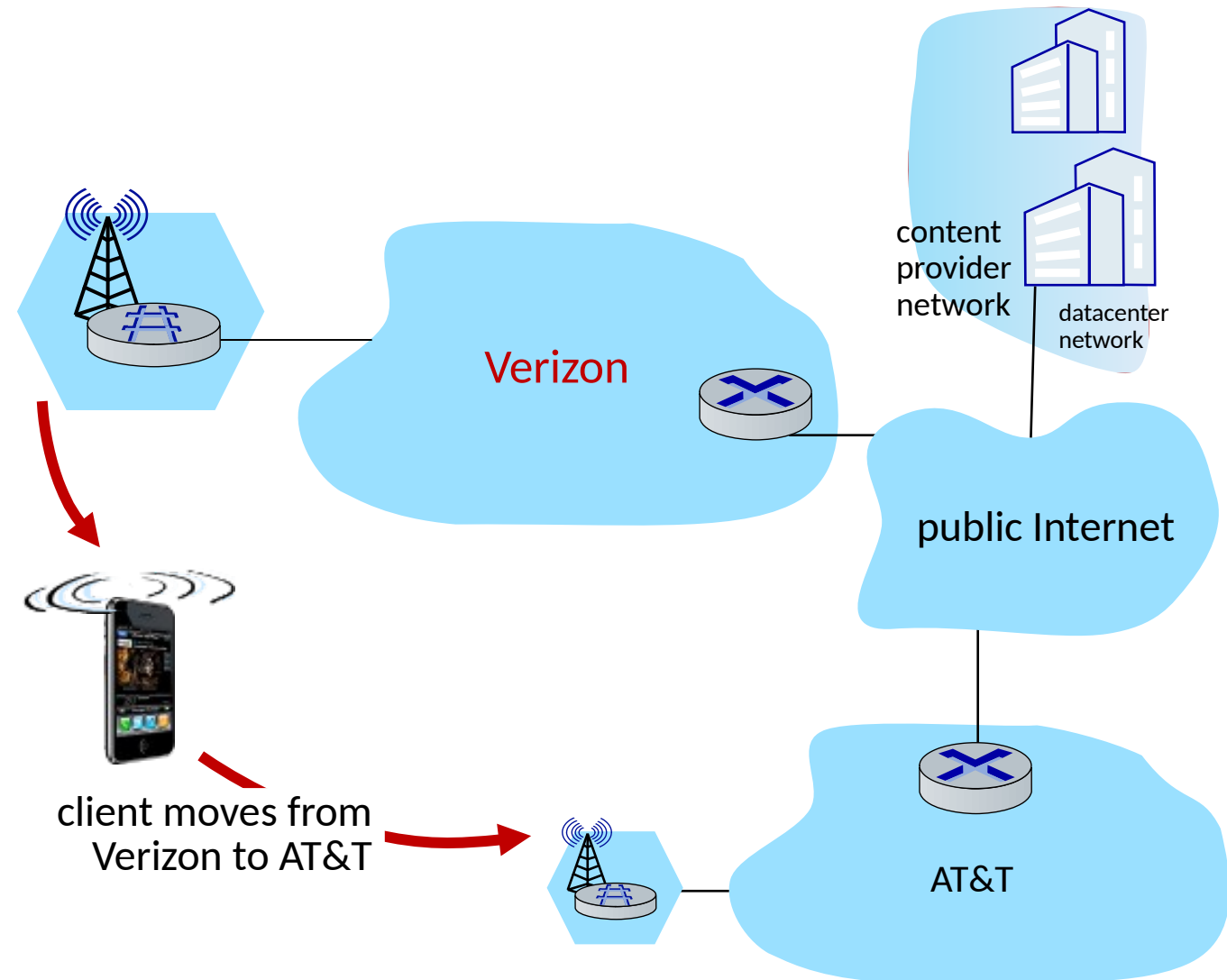
- spectrum of mobility, from the **network** perspective:



# Mobility challenge:

If a device moves from one network another:

- How will the “network” know to forward packets to the *new* network?





# 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 this *ready 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?

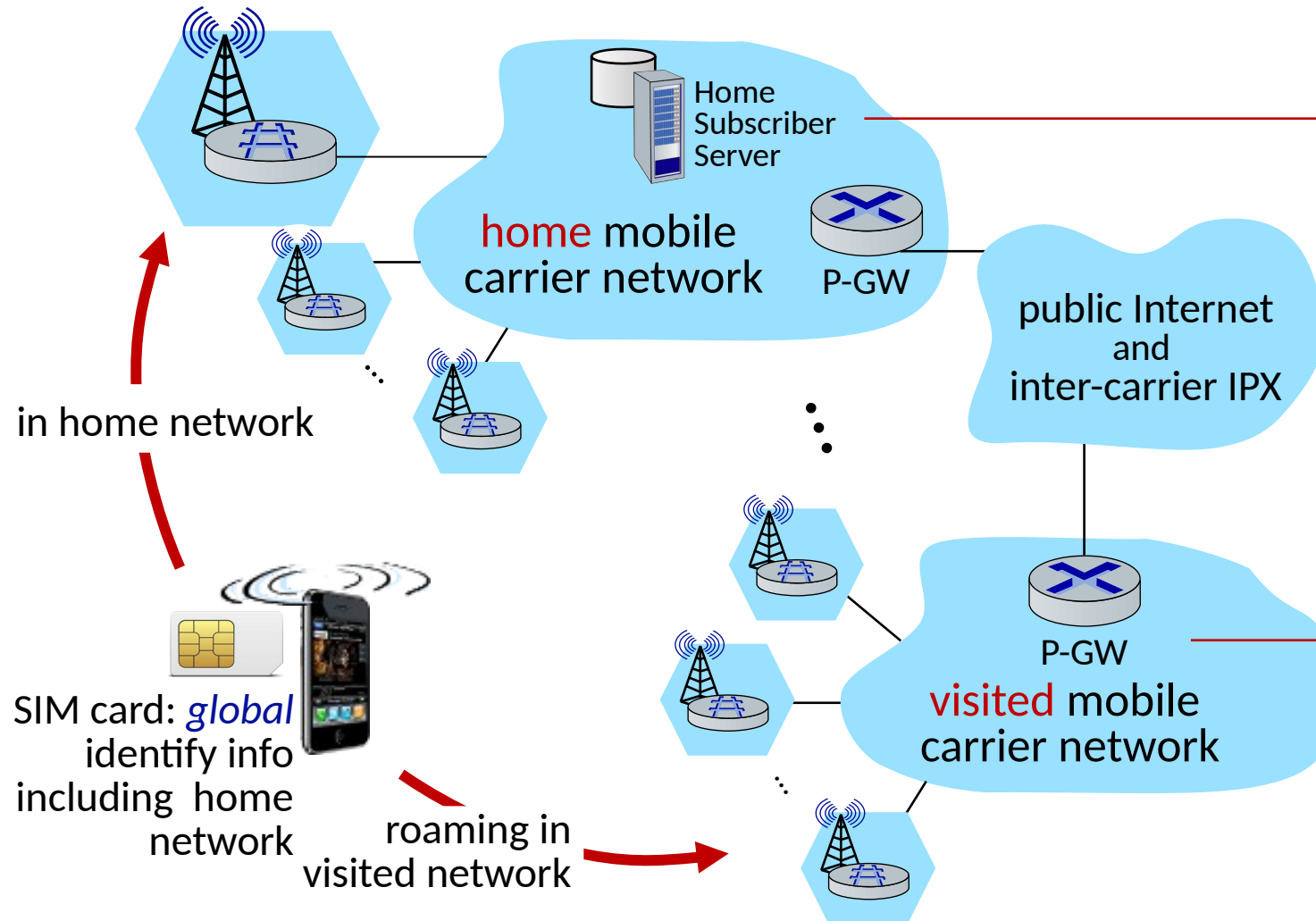
- call his/her parents?
- Facebook!

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



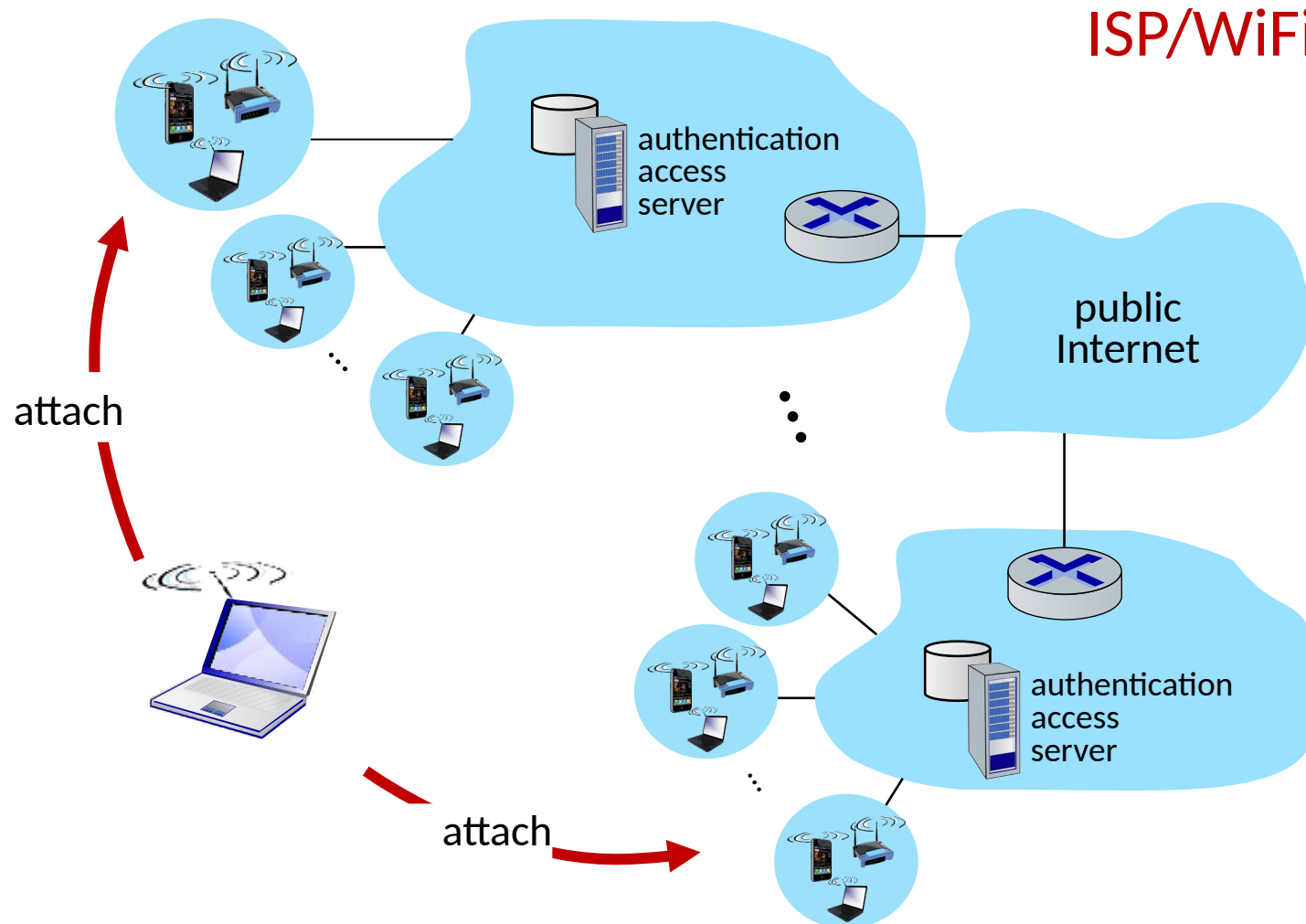
## home network:

- (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

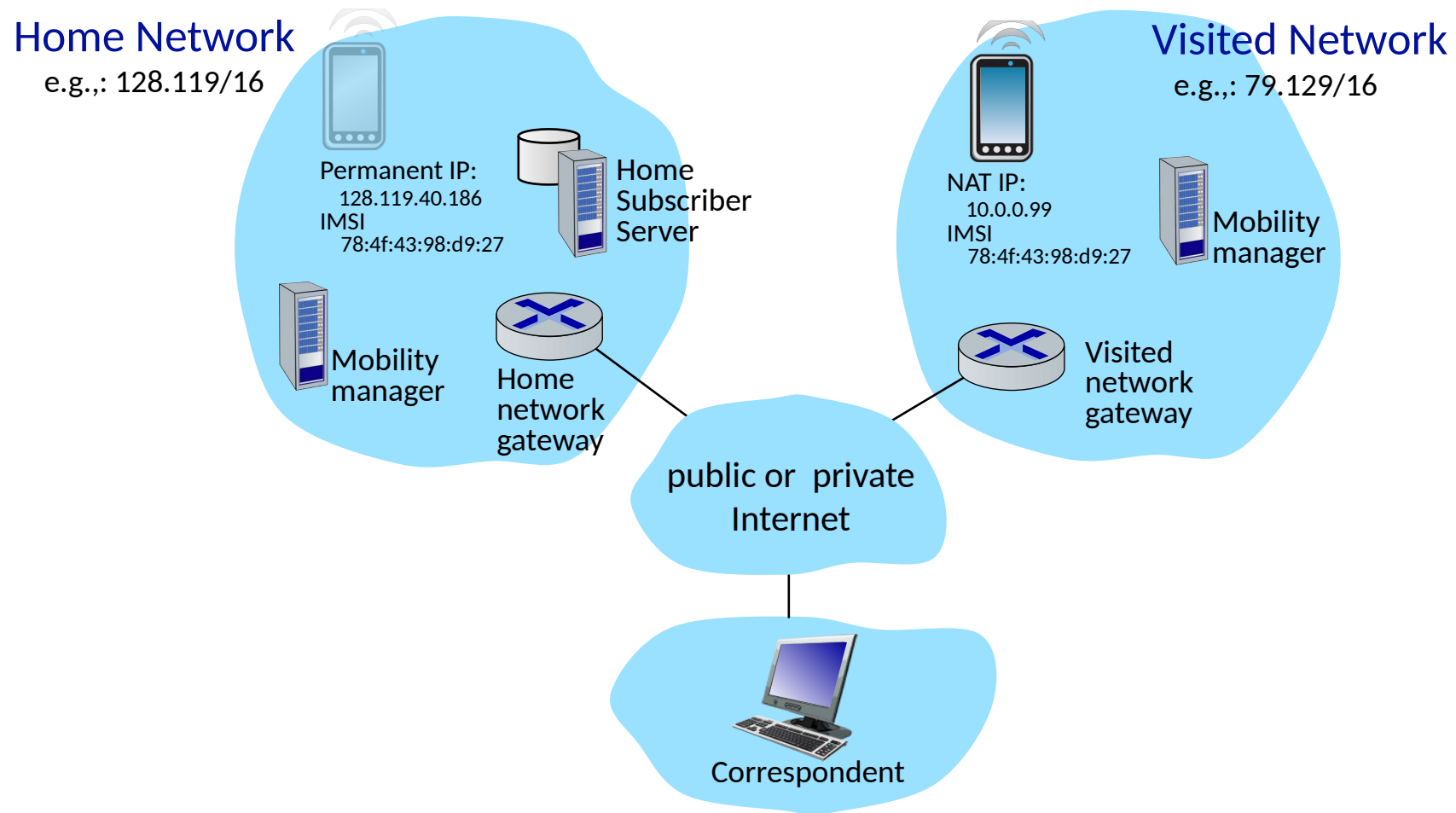
# Home network, visited network: ISP/WiFi



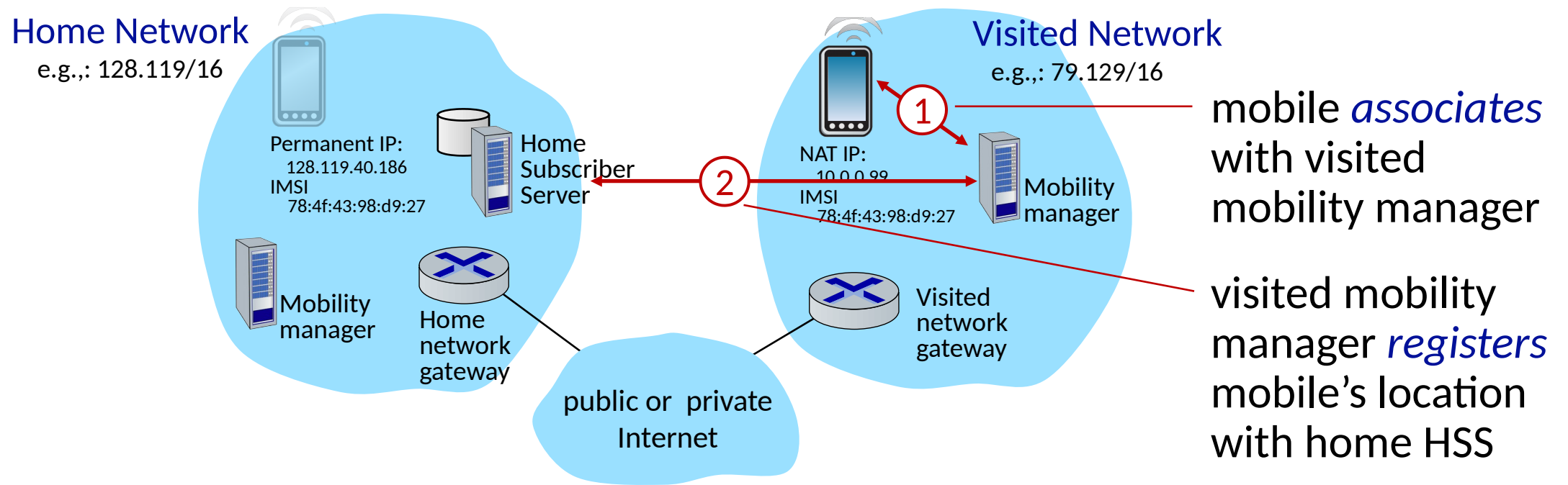
ISP/WiFi: no notion of global “home”

- 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



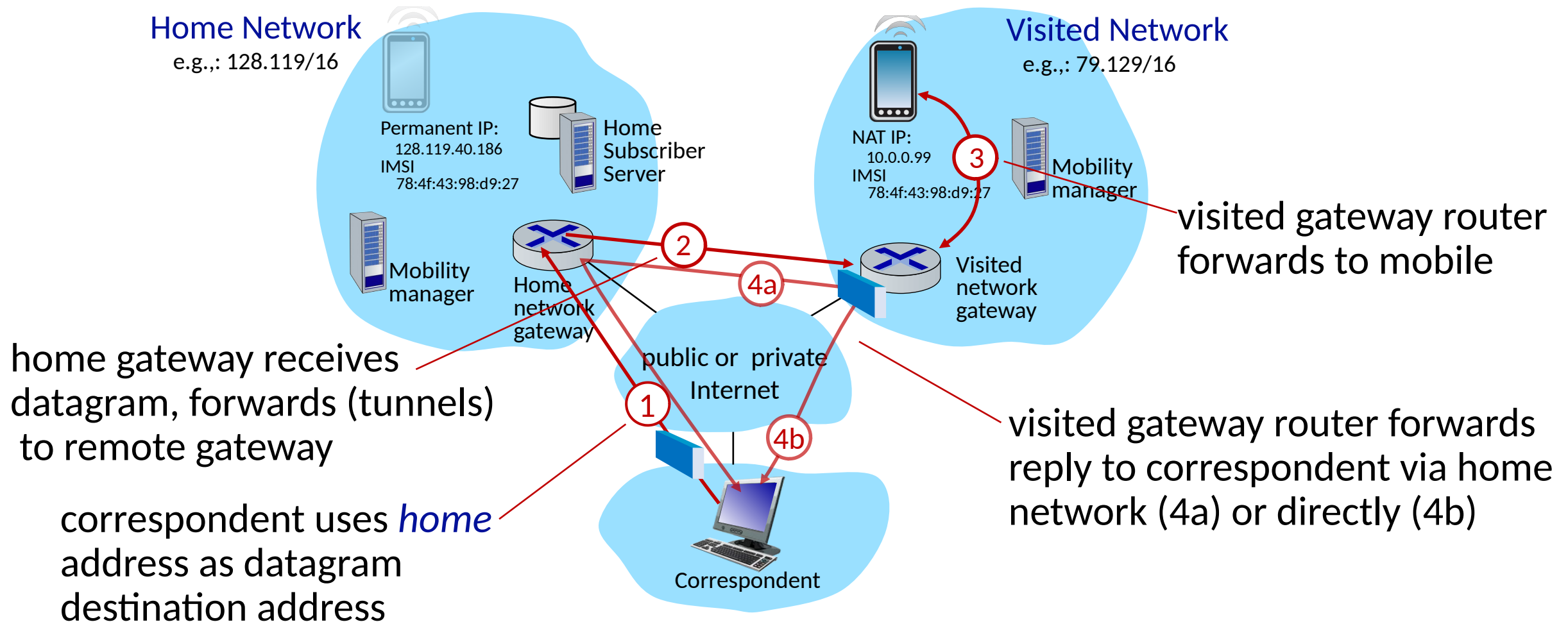
# Registration: home needs to know where you are!



end result:

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

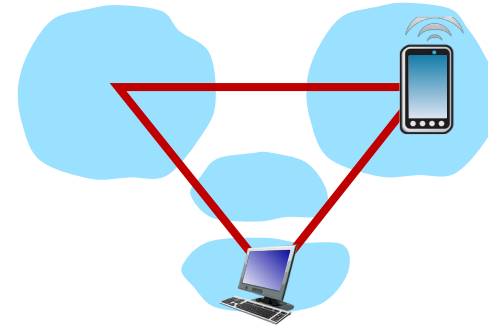
# Mobility with indirect routing



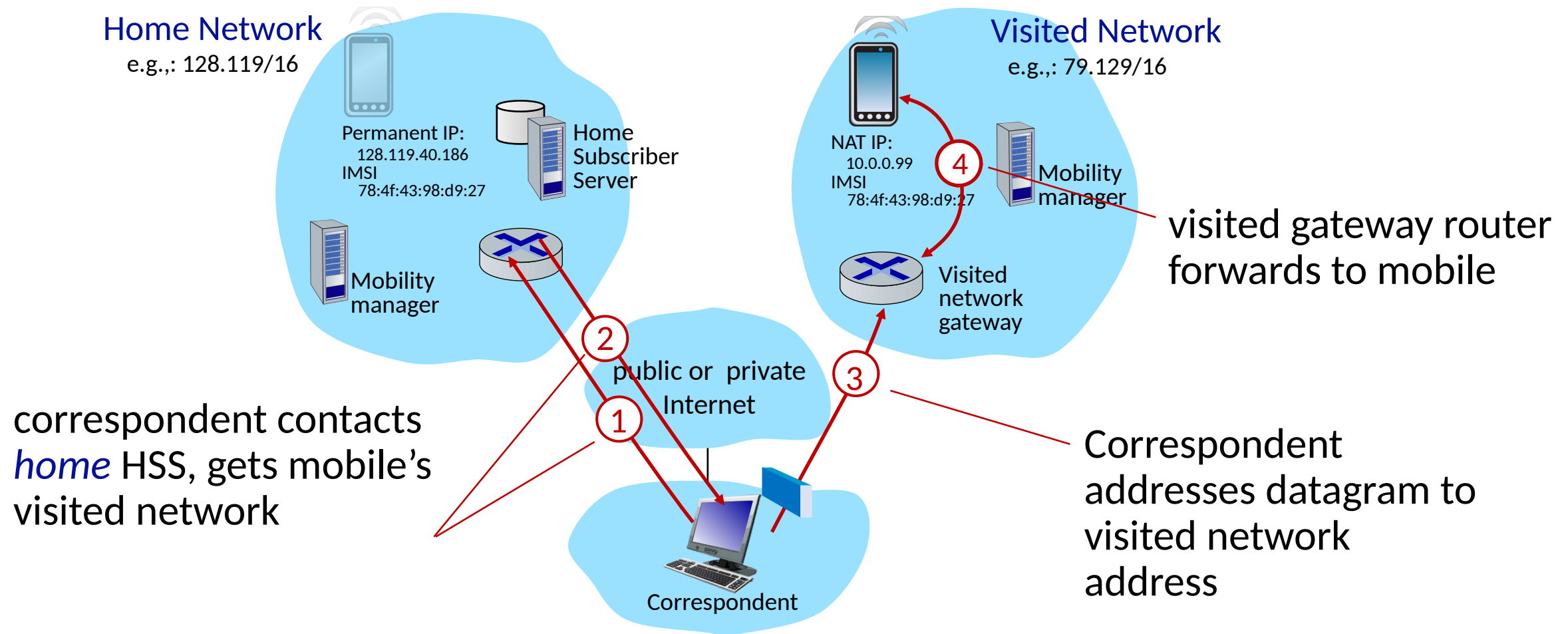


# Mobility with indirect routing: comments

- 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

# Chapter 7 outline

- Introduction

## Wireless

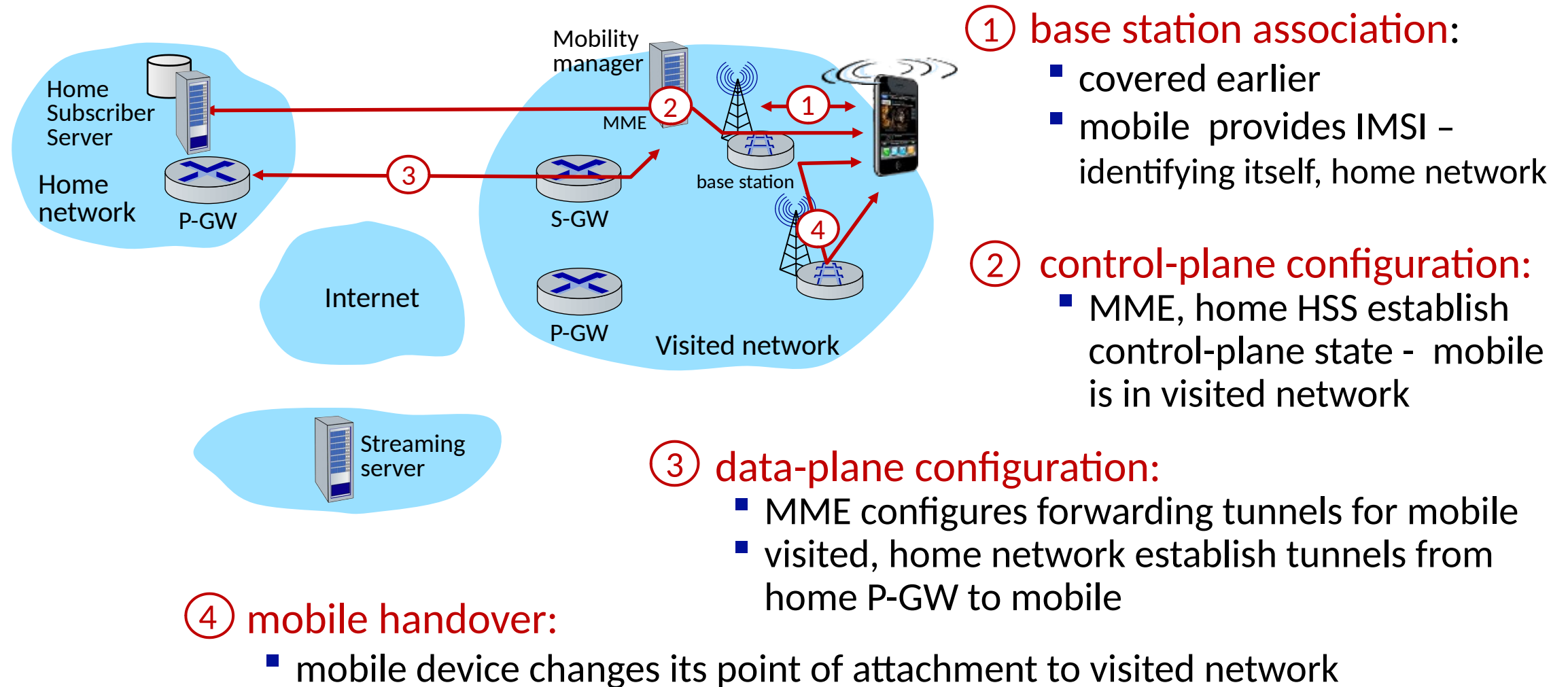
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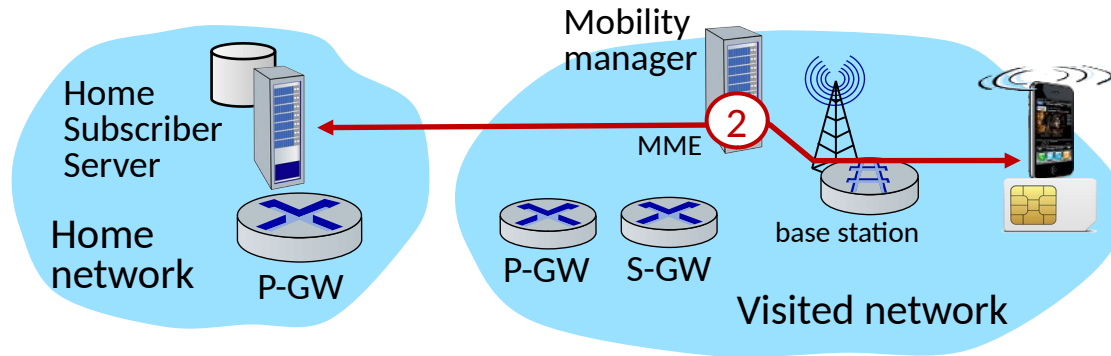
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# Mobility in 4G networks: major mobility tasks



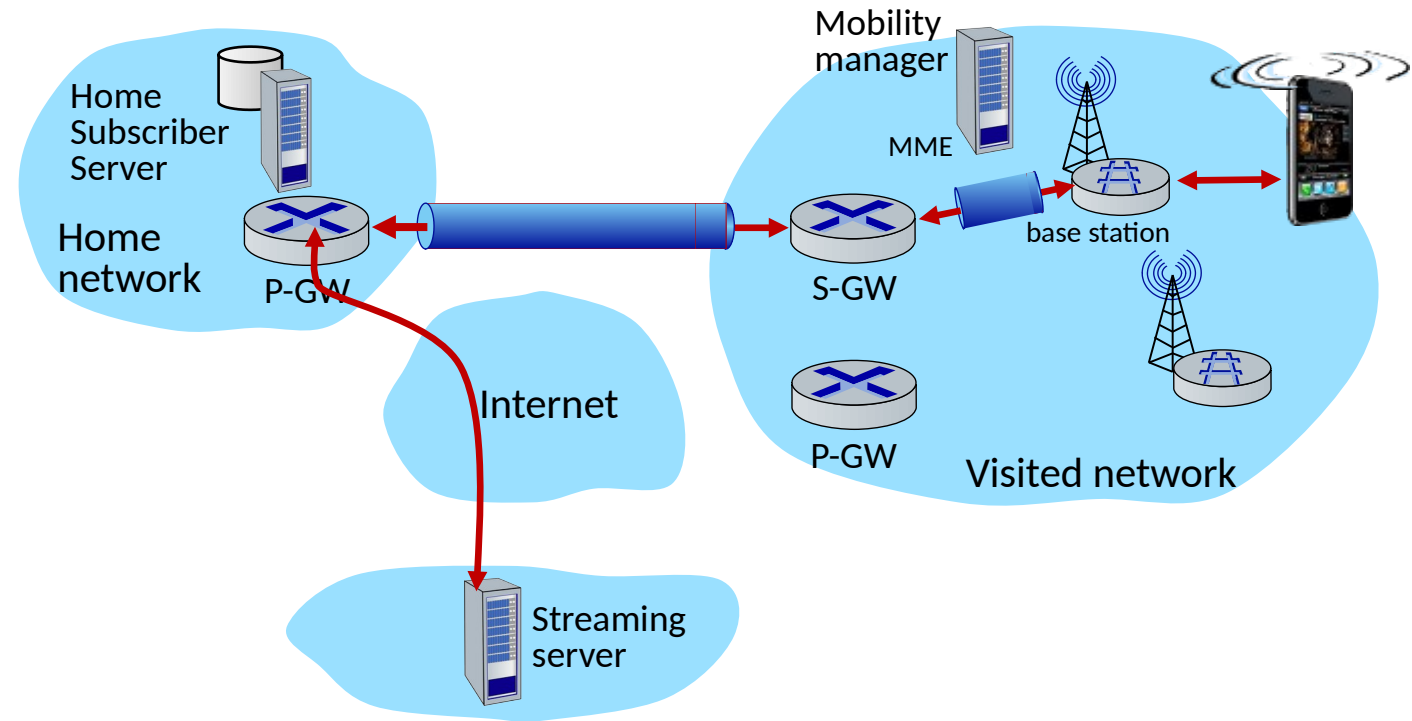
# Configuring LTE control-plane elements



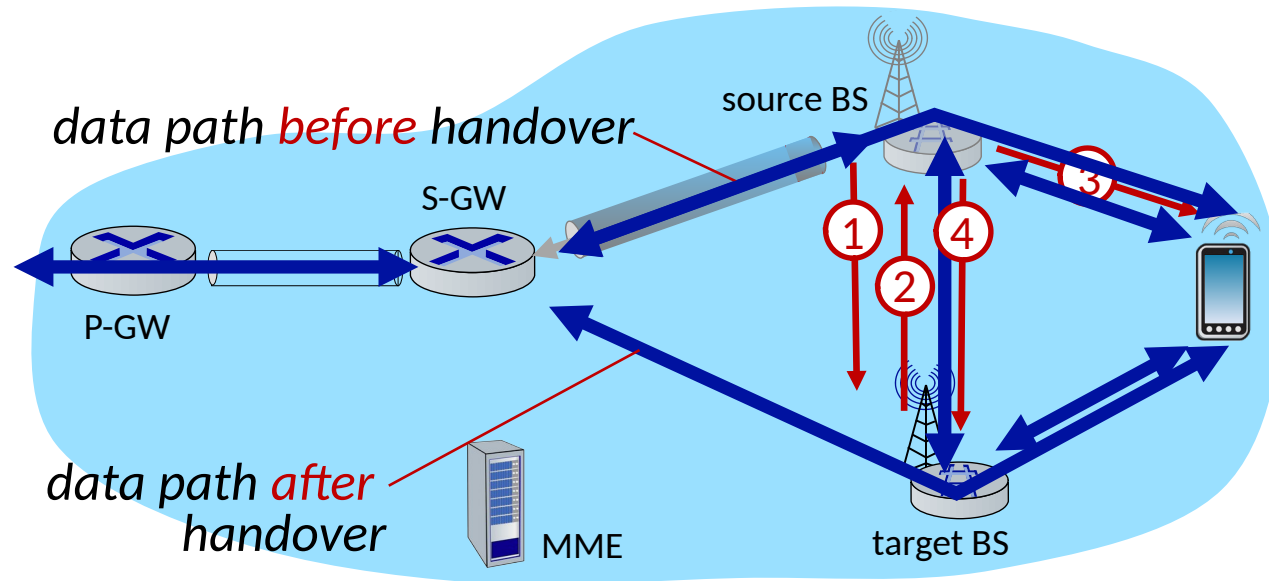
- Mobile communicates with local MME via BS control-plane channel
- MME uses mobile's IMSI info to contact mobile's home HSS
  - retrieve authentication, encryption, network service information
  - home HSS knows mobile now resident in visited network
- BS, mobile select parameters for BS-mobile data-plane radio channel

# Configuring data-plane tunnels for mobile

- **S-GW to BS tunnel:** when mobile changes base stations, simply change endpoint IP address of tunnel
- **S-GW to home P-GW tunnel:** implementation of indirect routing
- **tunneling via GTP** (GPRS tunneling protocol): mobile's datagram to streaming server encapsulated using GTP inside UDP, inside datagram



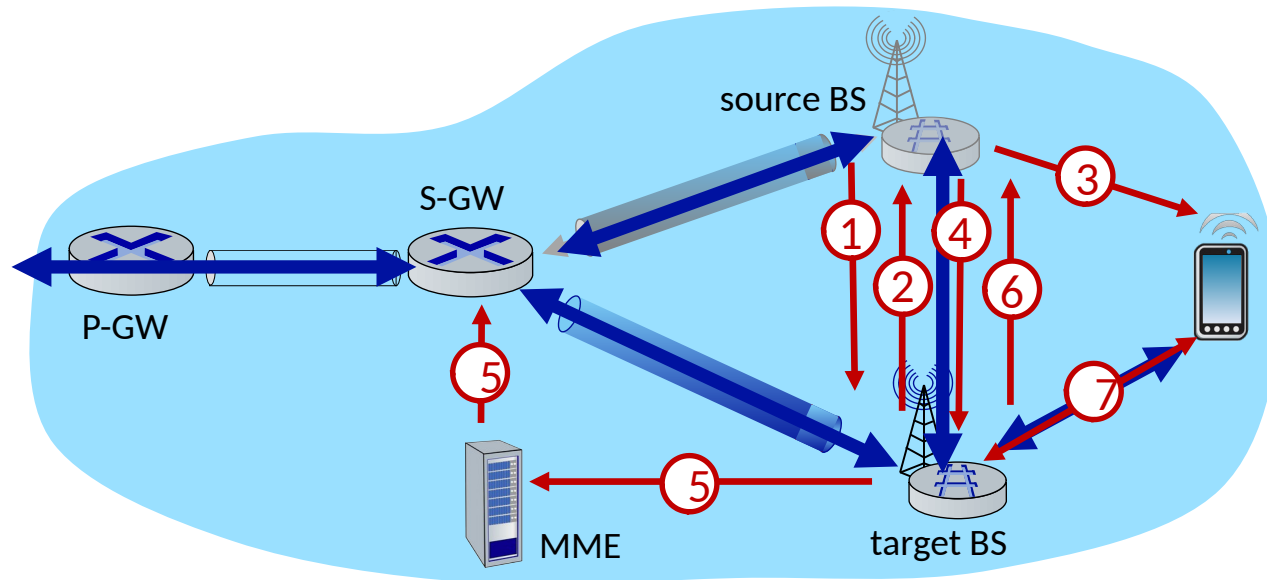
# Handover between BSs in same cellular network



- 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

# Mobile IP

- mobile IP architecture standardized ~20 years ago [RFC 5944]
  - long before ubiquitous smartphones, 4G support for Internet protocols
  - did not see wide deployment/use
  - perhaps WiFi for Internet, and 2G/3G phones for voice were “good enough” at the time
- mobile IP architecture:
  - indirect routing to node (via home network) using tunnels
  - mobile IP home agent: combined roles of 4G HSS and home P-GW
  - mobile IP foreign agent: combined roles of 4G MME and S-GW
  - protocols for agent discovery in visited network, registration of visited location in home network via ICMP extensions

# 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 handover loss
  - TCP interprets loss as congestion, will decrease congestion window unnecessarily
  - delay impairments for real-time traffic
  - bandwidth a scarce resource for wireless links

# Chapter 7 summary

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