



# Computer Networks

## CS3953

### Wireless and Mobile Networks

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The slides are adapted from those provided by Prof. J.F Kurose and K.W. Ross.

# 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

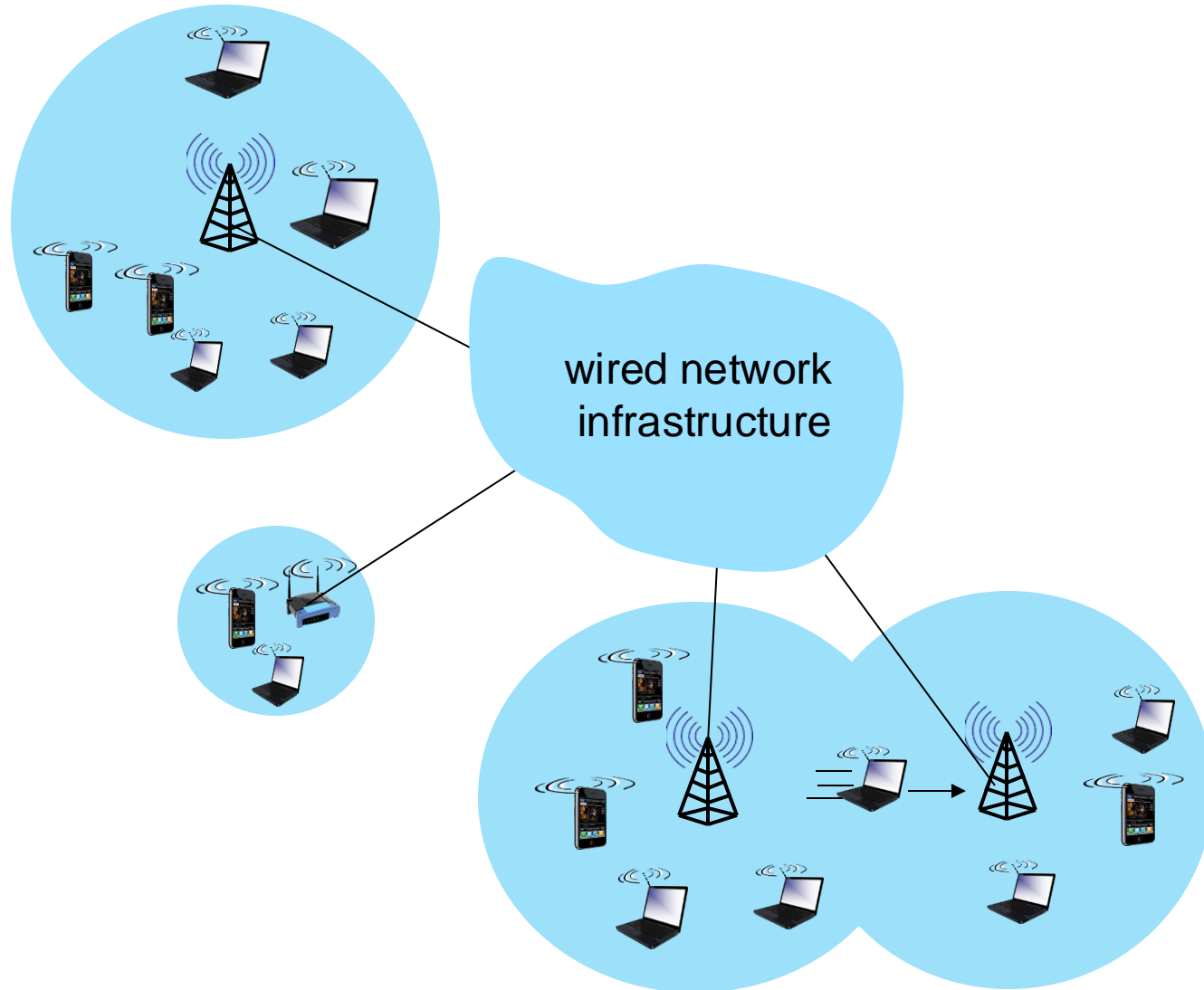
- Wireless Links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G

## Mobility

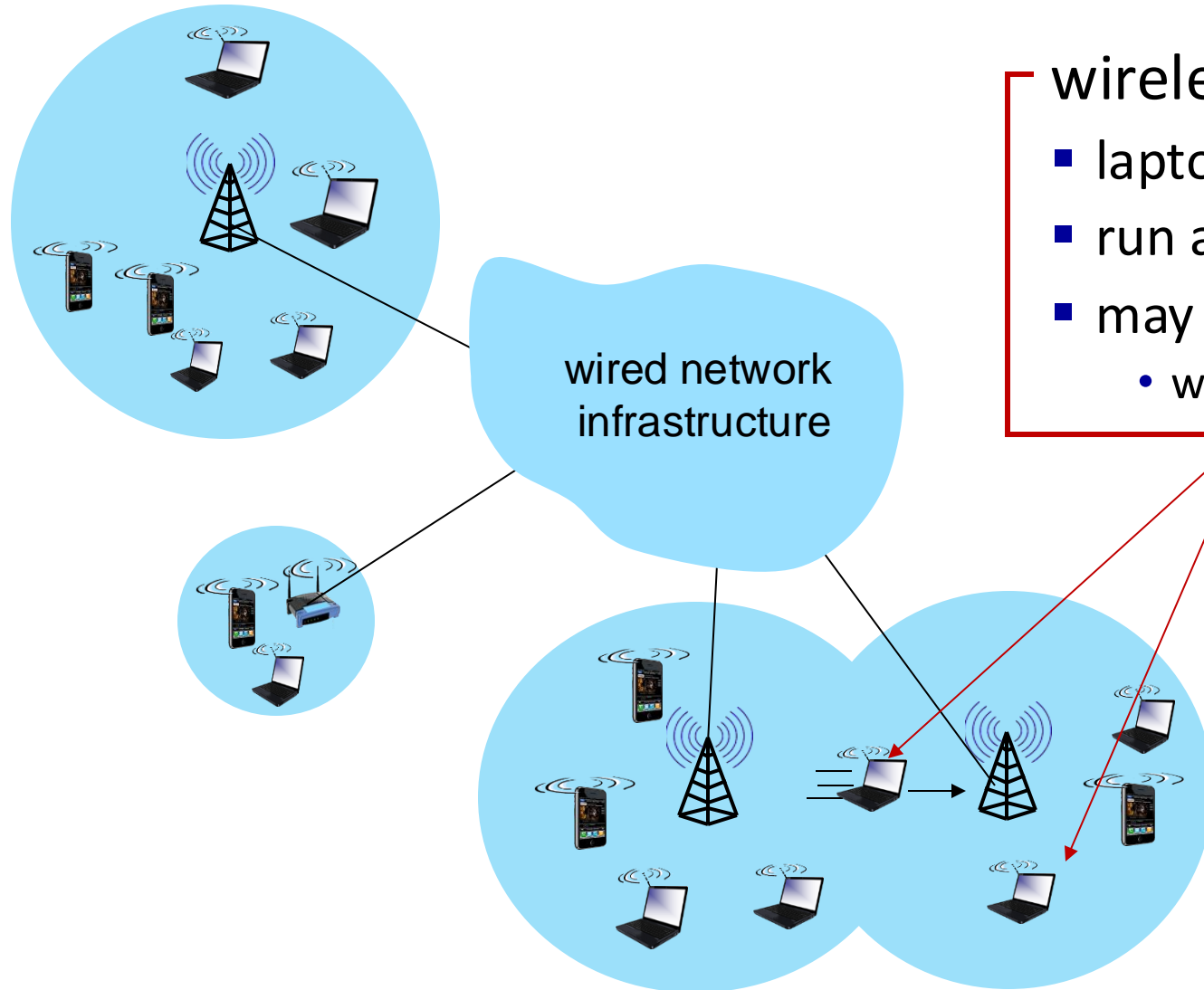
- Mobility management: principles
- Mobility management: practice
  - 4G/5G networks
  - Mobile IP
- Mobility: impact on higher-layer protocols



# Elements of a wireless network



# Elements of a wireless network

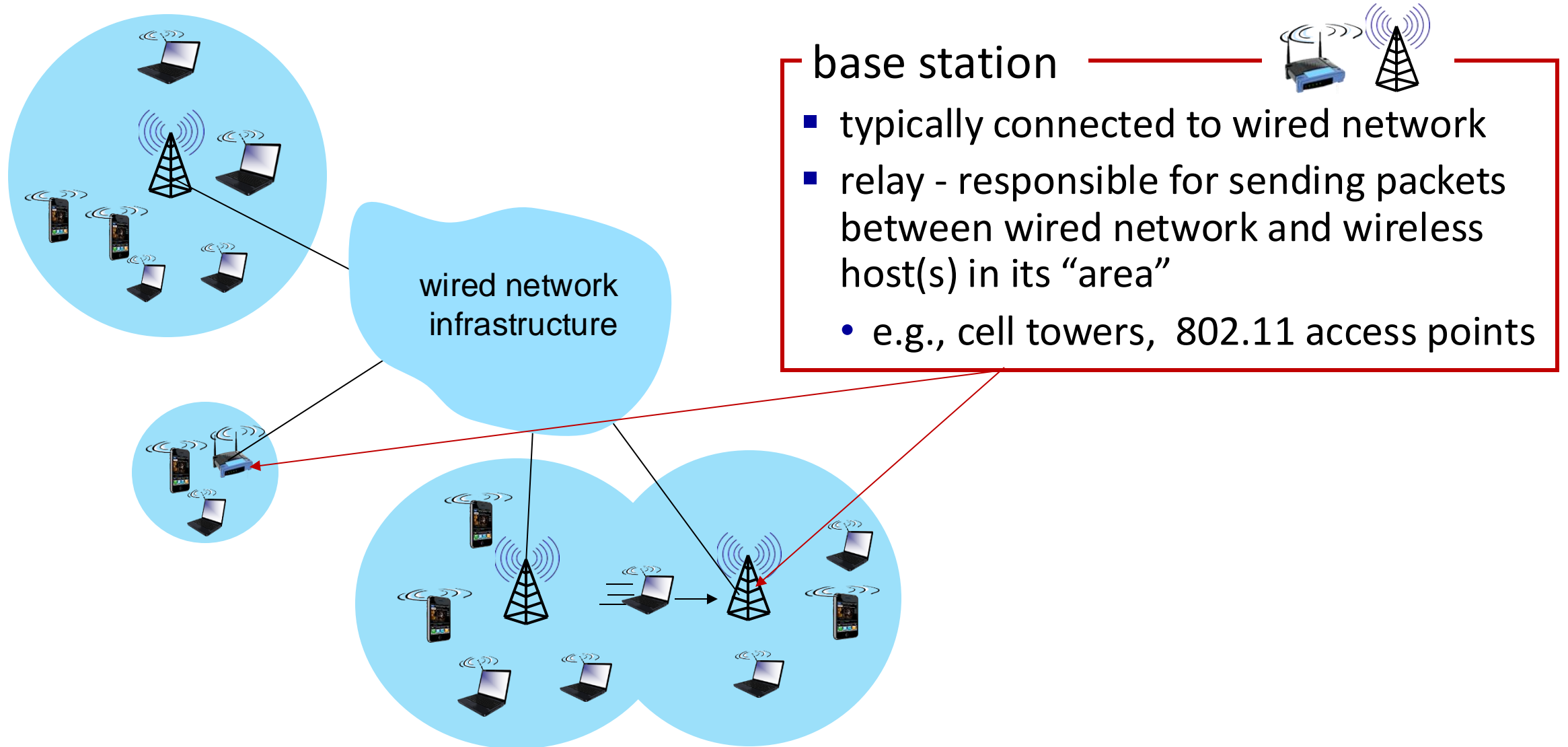


## wireless hosts

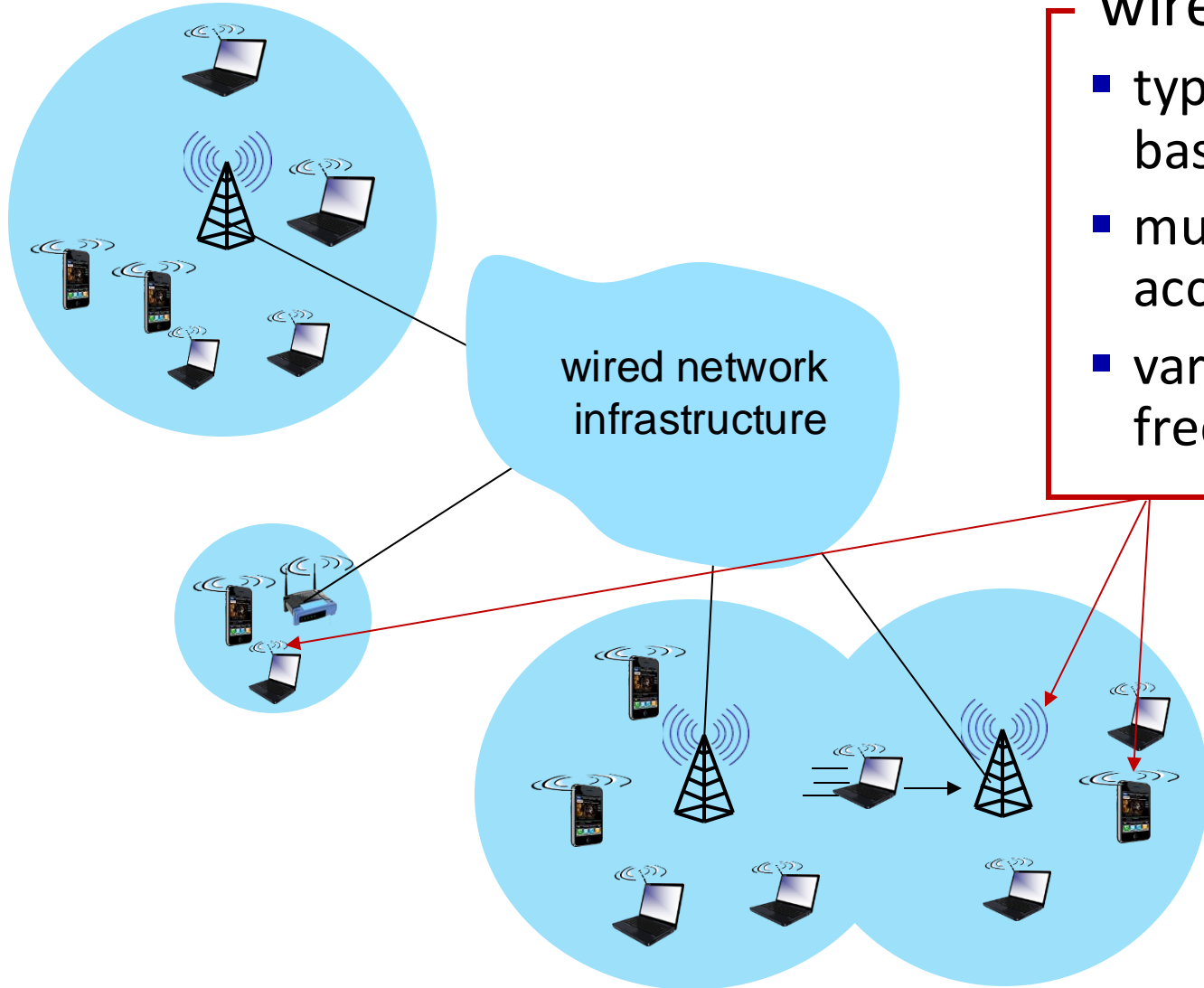
- laptop, smartphone, IoT
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility!



# Elements of a wireless network



# Elements of a wireless network

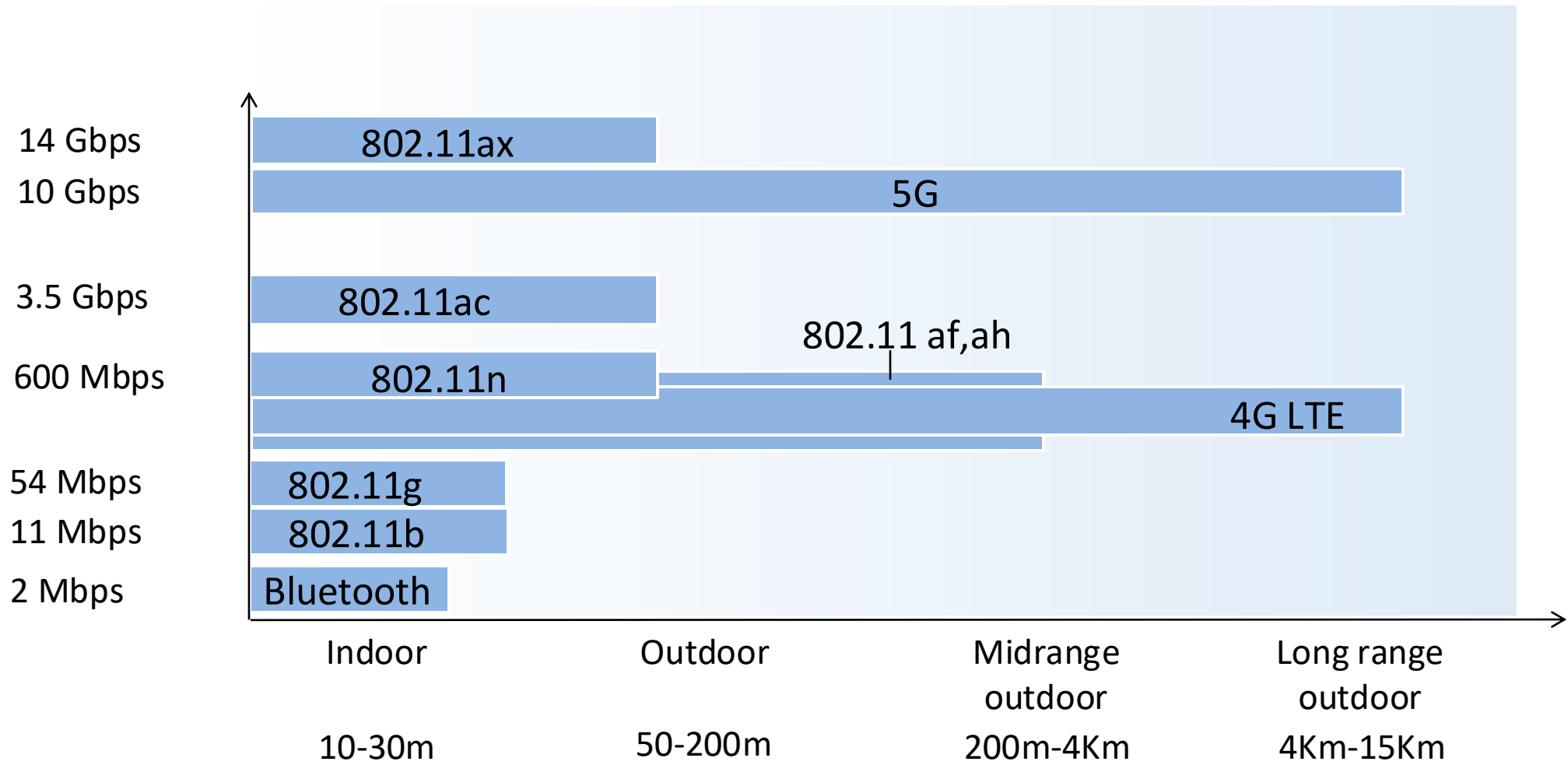


wireless link



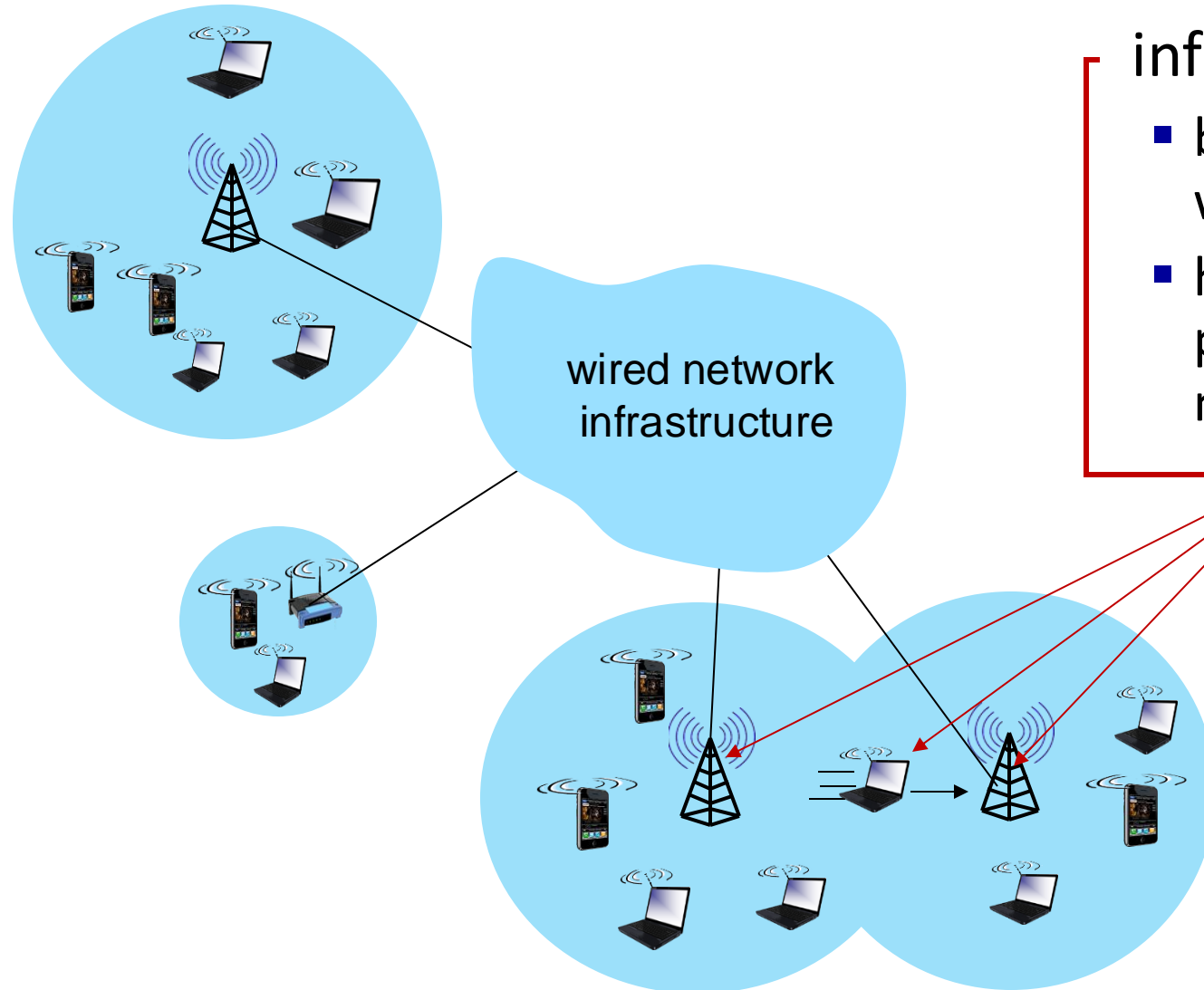
- typically used to connect mobile(s) to base station, also used as backbone link
- multiple access protocol coordinates link access
- various transmission rates and distances, frequency bands

# Characteristics of selected wireless links





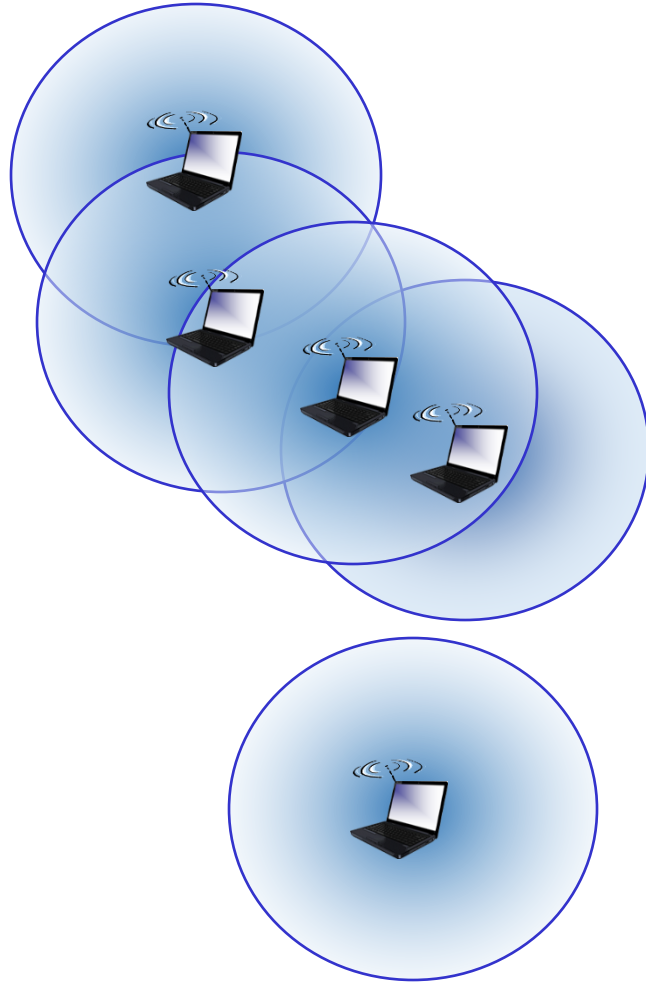
# Elements of a wireless network



## 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

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## Mobility

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



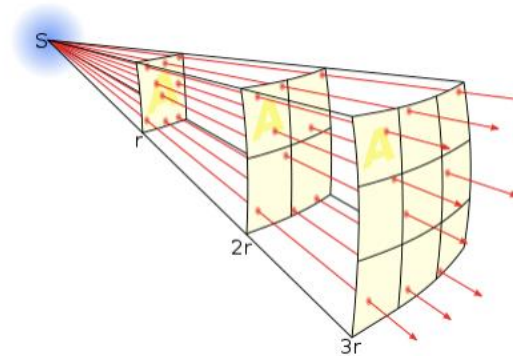
# Wireless link characteristics: fading (attenuation)

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

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

$f$ : frequency

$d$ : distance



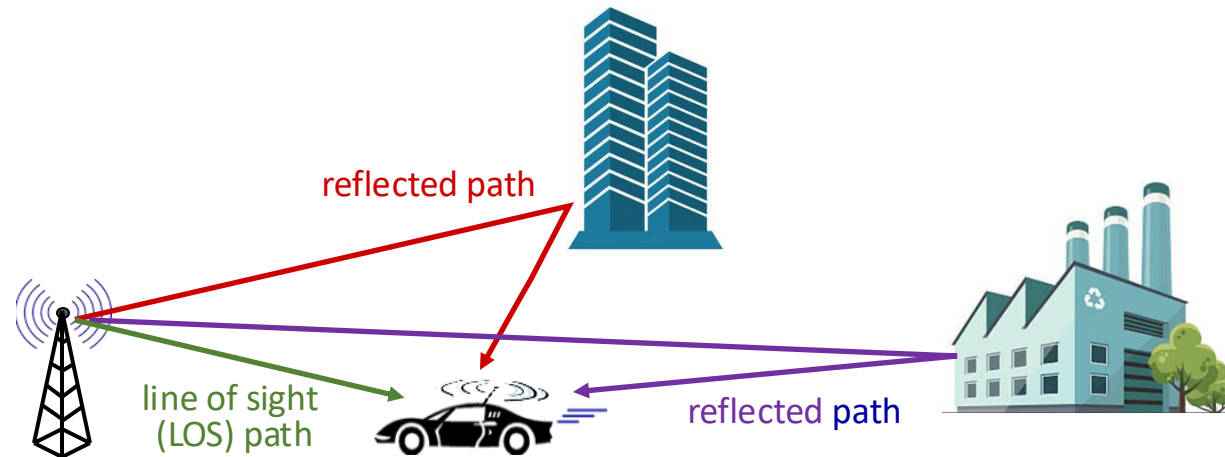
higher frequency or  
longer distance



larger free space  
path loss

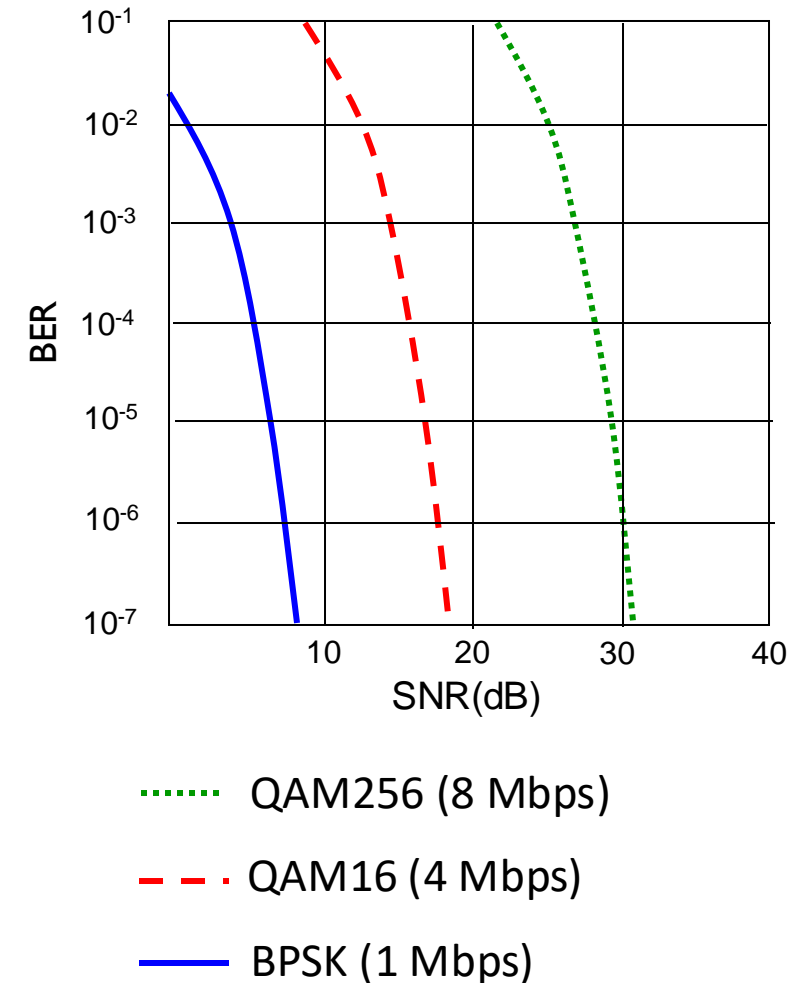
# Wireless link characteristics: multipath

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



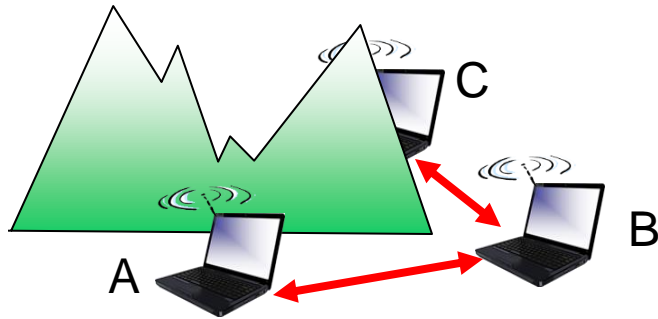
# Wireless link characteristics: noise

- **interference from other sources on wireless network frequencies**
- **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)



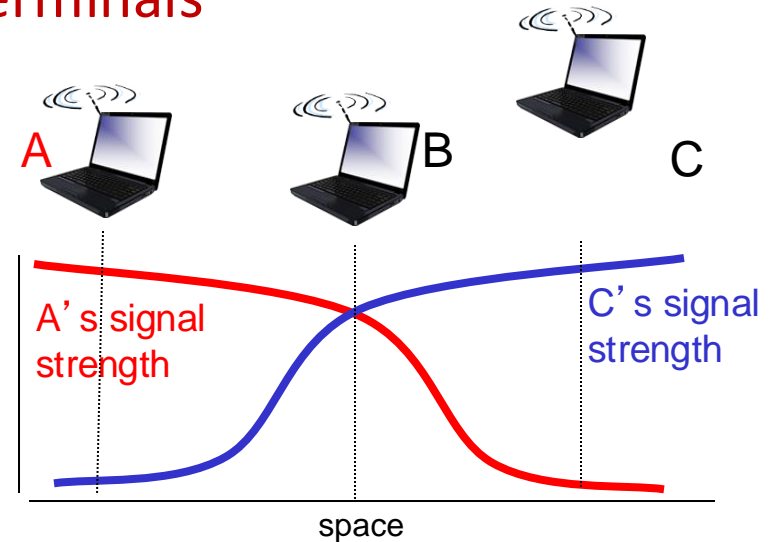
# Wireless link characteristics: hidden terminals

## 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

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- **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

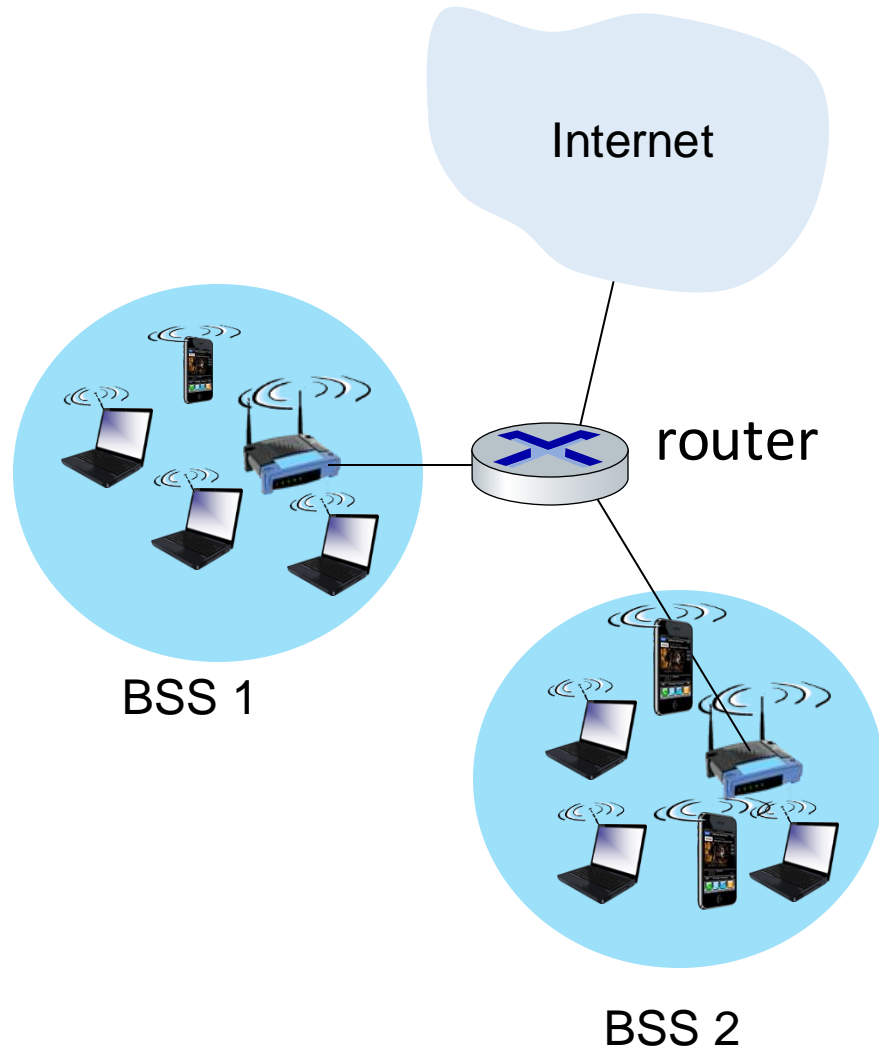


# IEEE 802.11 Wireless LAN

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

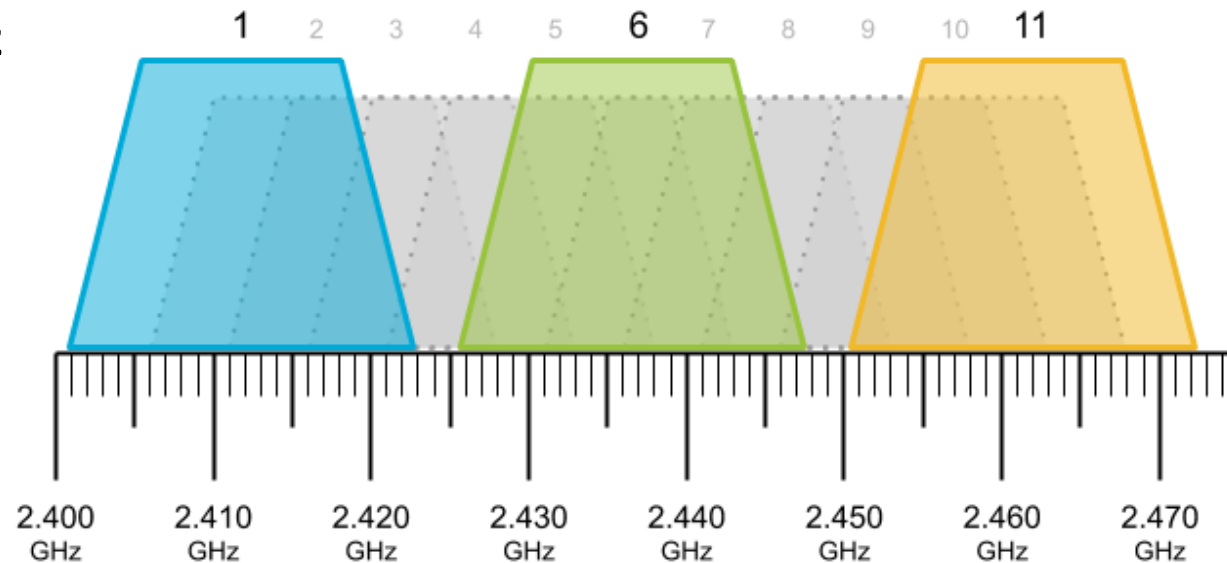


- wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka “cell”) in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only

# 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

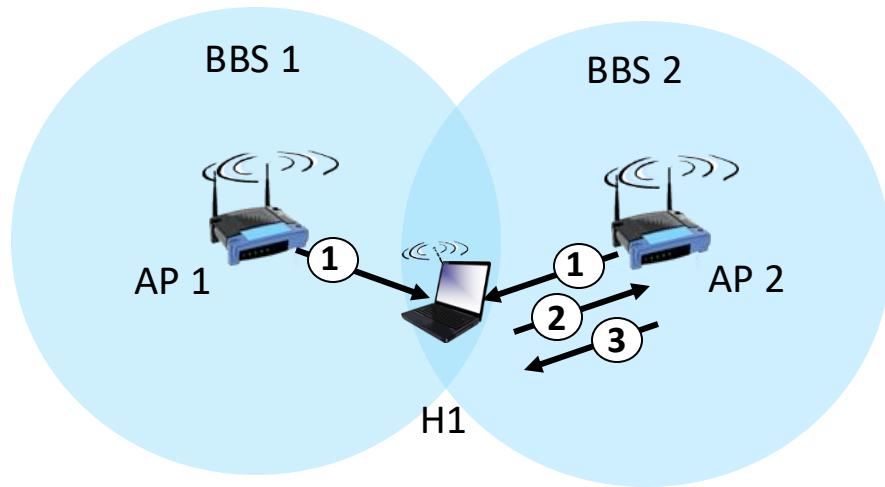


# 802.11: Association

- 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

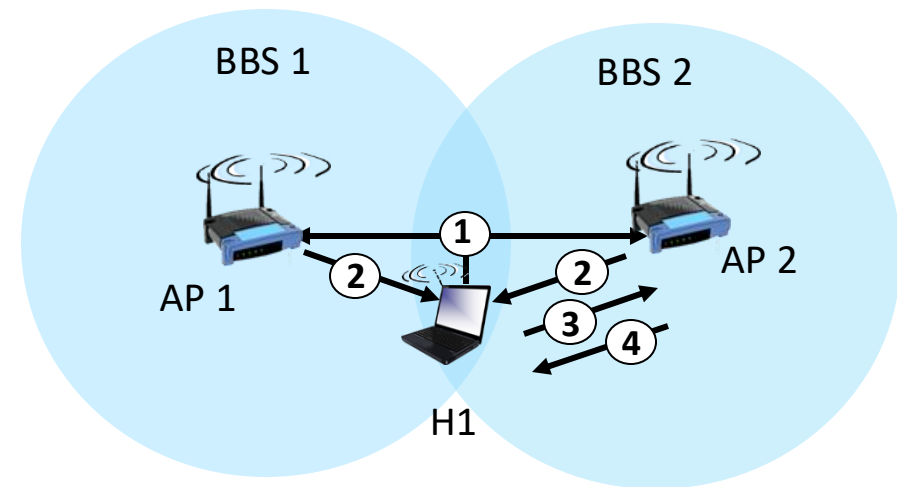


# 802.11: passive/active scanning



## 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

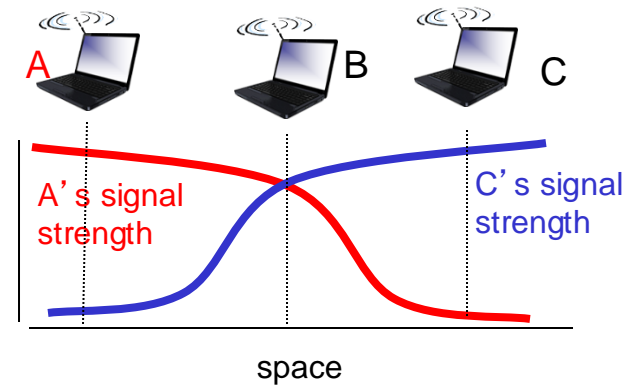
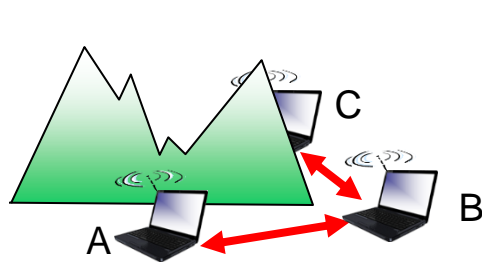


## active scanning:

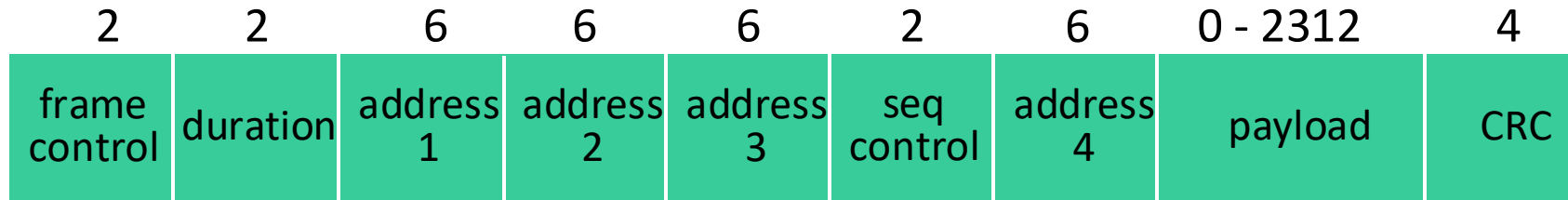
- (1) Probe Request frame broadcast from H1
- (2) Probe Response frames sent from APs
- (3) Association Request frame sent: H1 to selected AP
- (4) Association Response frame sent from selected AP to H1

# IEEE 802.11: multiple access

- avoid collisions: 2<sup>+</sup> 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



# 802.11 frame: addressing



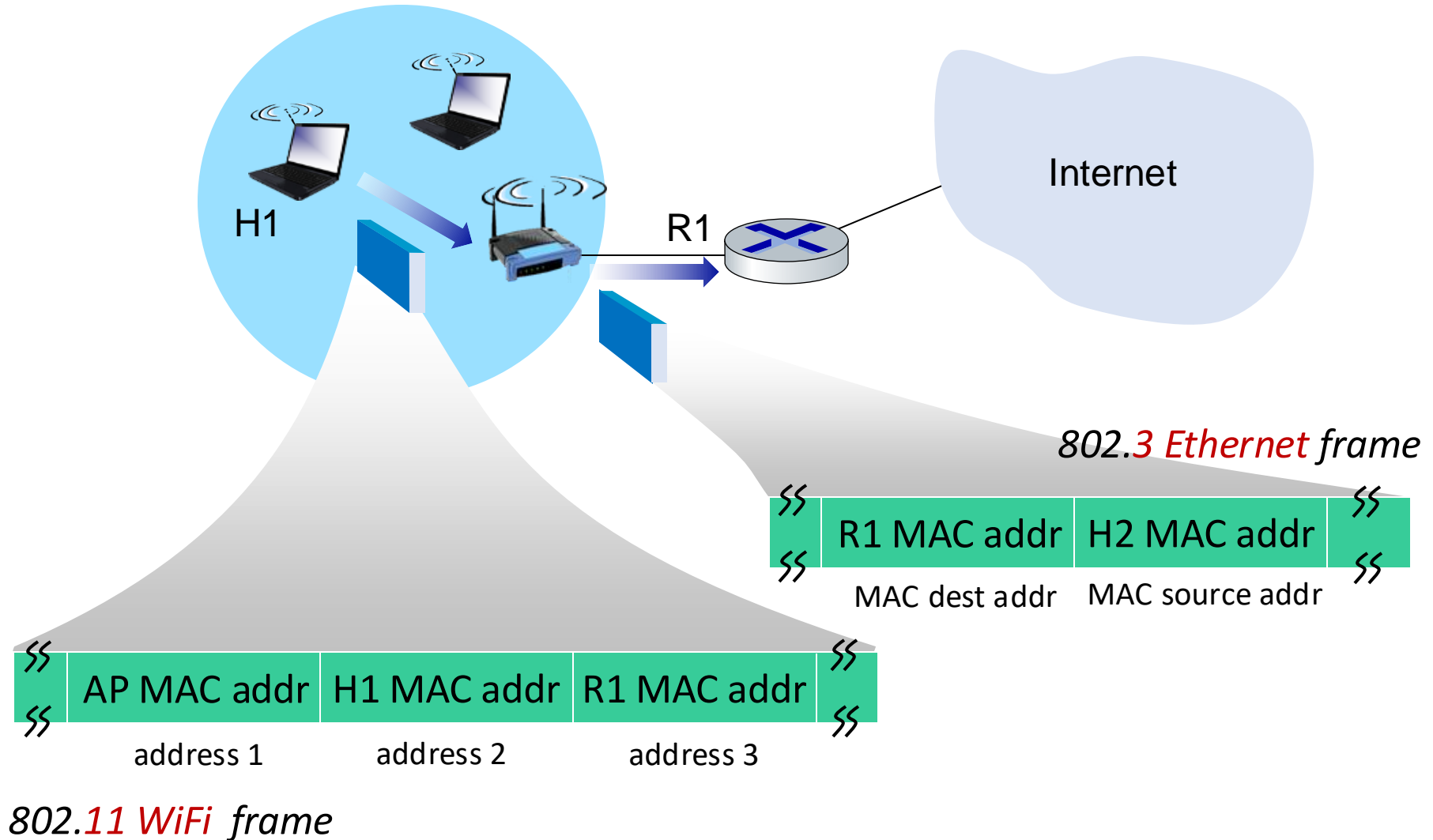
**Address 1:** MAC address of wireless host or AP to receive this frame

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

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

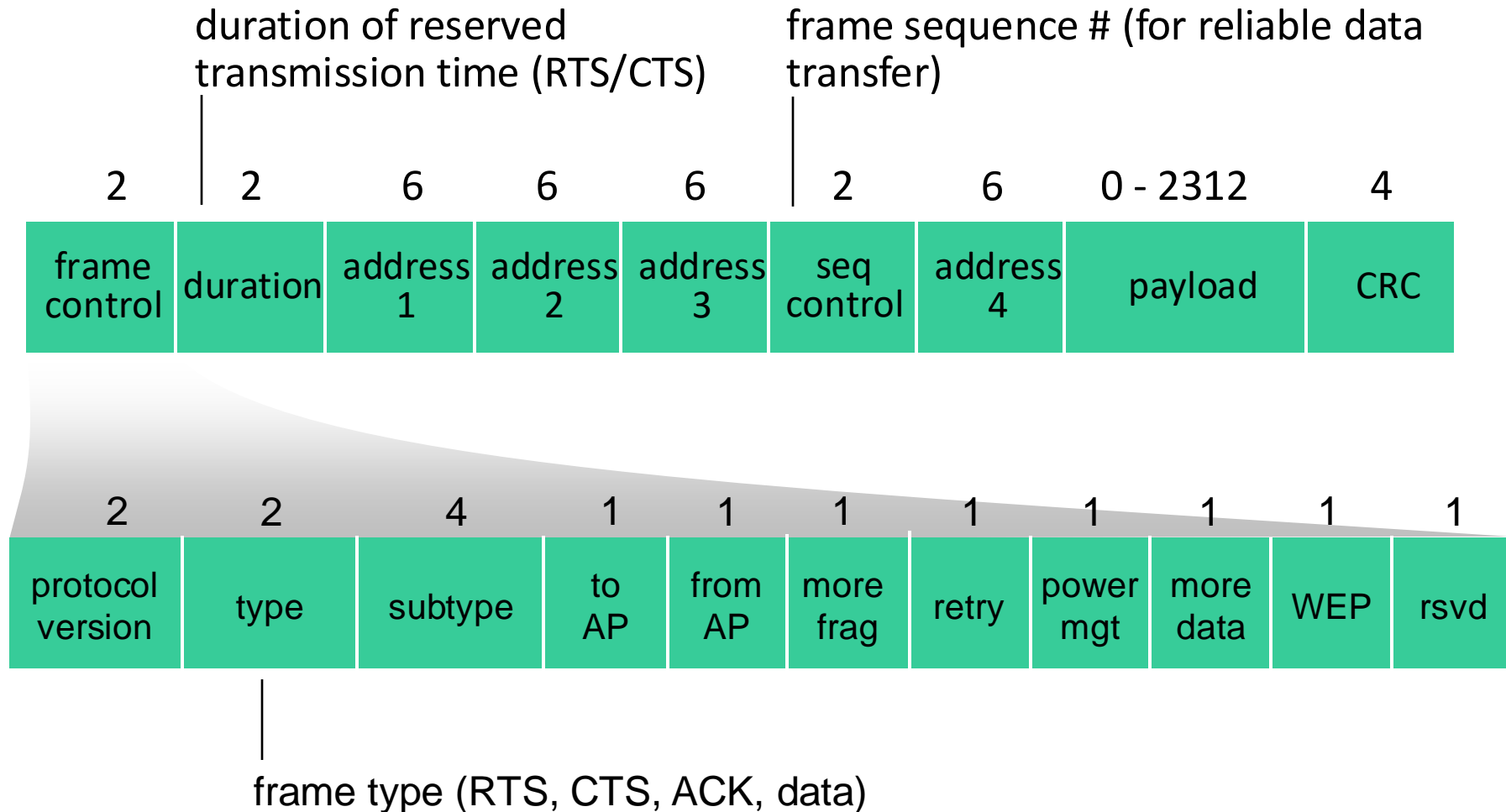
**Address 4:** used only in ad hoc mode

# 802.11 frame: addressing



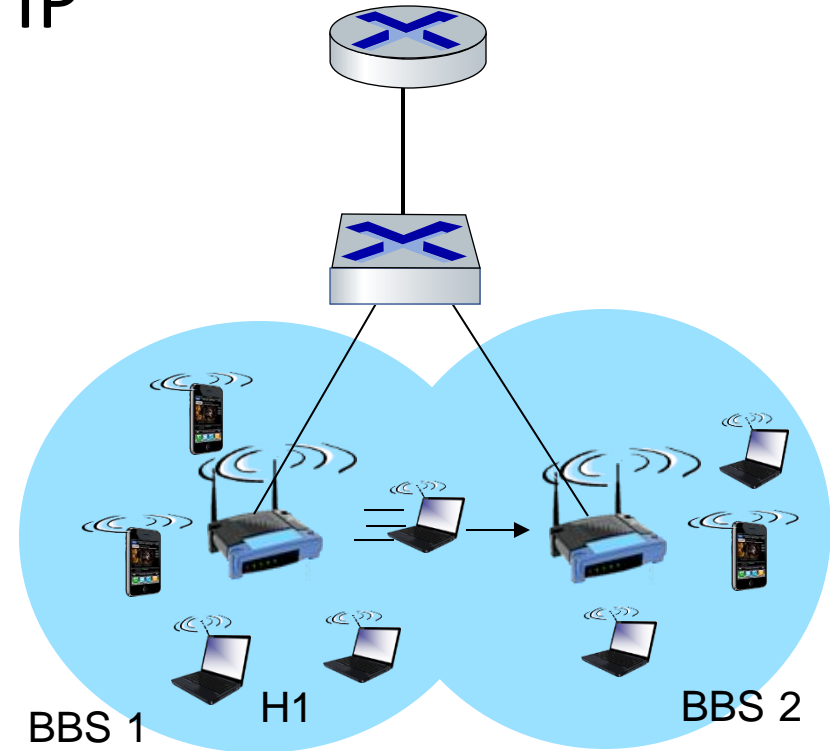


# 802.11 frame: addressing



# 802.11: mobility within same subnet

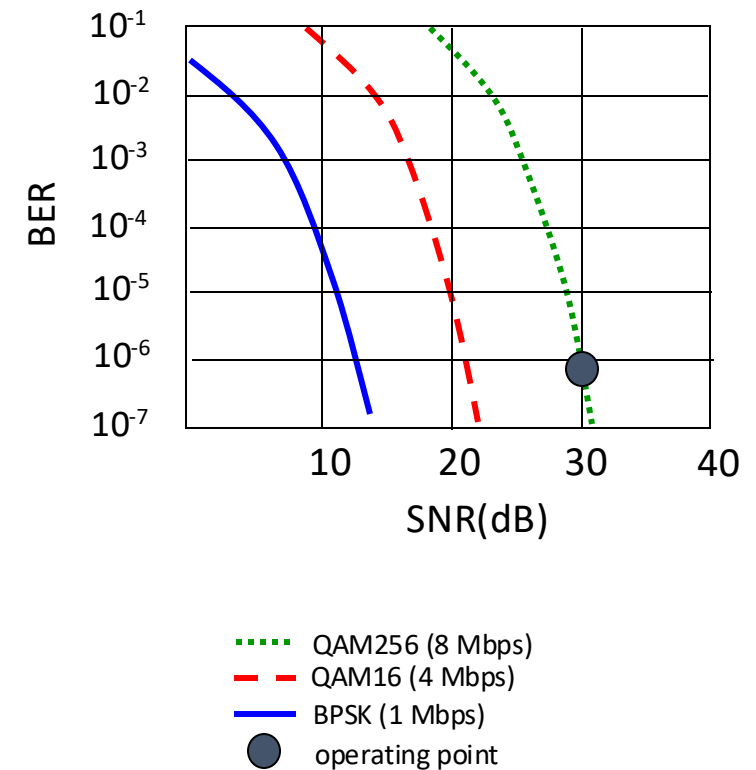
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - self-learning (Ch. 6): switch will see frame from H1 and “remember” which switch port can be used to reach H1



# 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

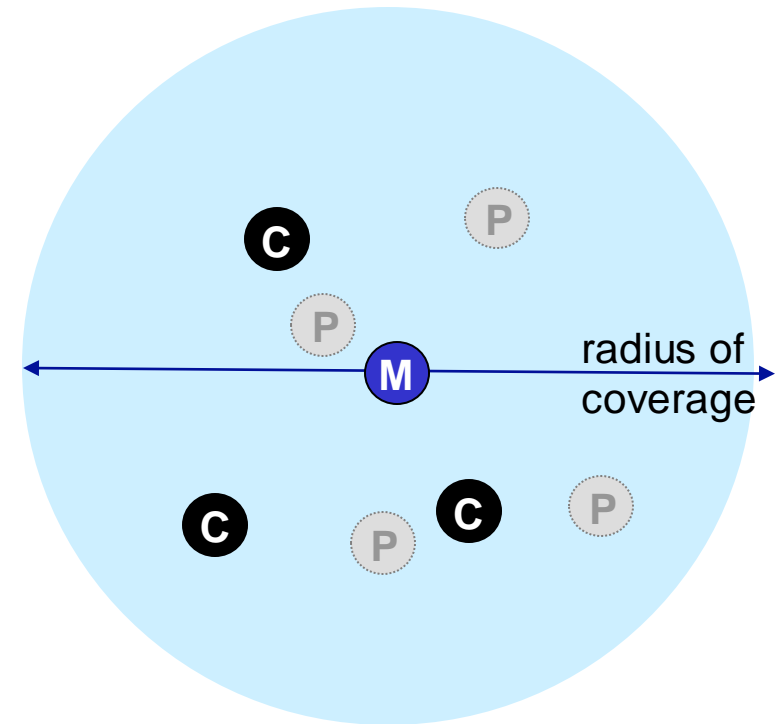
## Wireless

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



# Personal area networks: Bluetooth

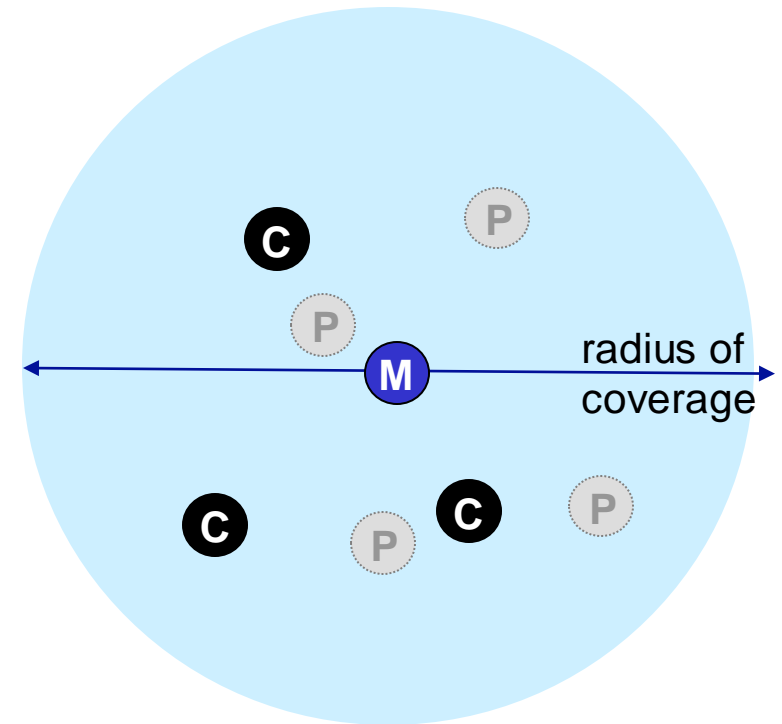
- less than 10 m diameter
- replacement for cables (mouse, keyboard, headphones)
- ad hoc: no infrastructure
- 2.4-2.5 GHz ISM radio band, up to 3 Mbps
- master controller / client devices:
  - master polls clients, grants requests for client transmissions



- M** master controller
- C** client device
- P** parked device (inactive)

# 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)
- **parked mode:** clients can “go to sleep” (park) and later wakeup (to preserve battery)



- M** master controller
- C** client device
- P** parked device (inactive)

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## Mobility

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  - 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: 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

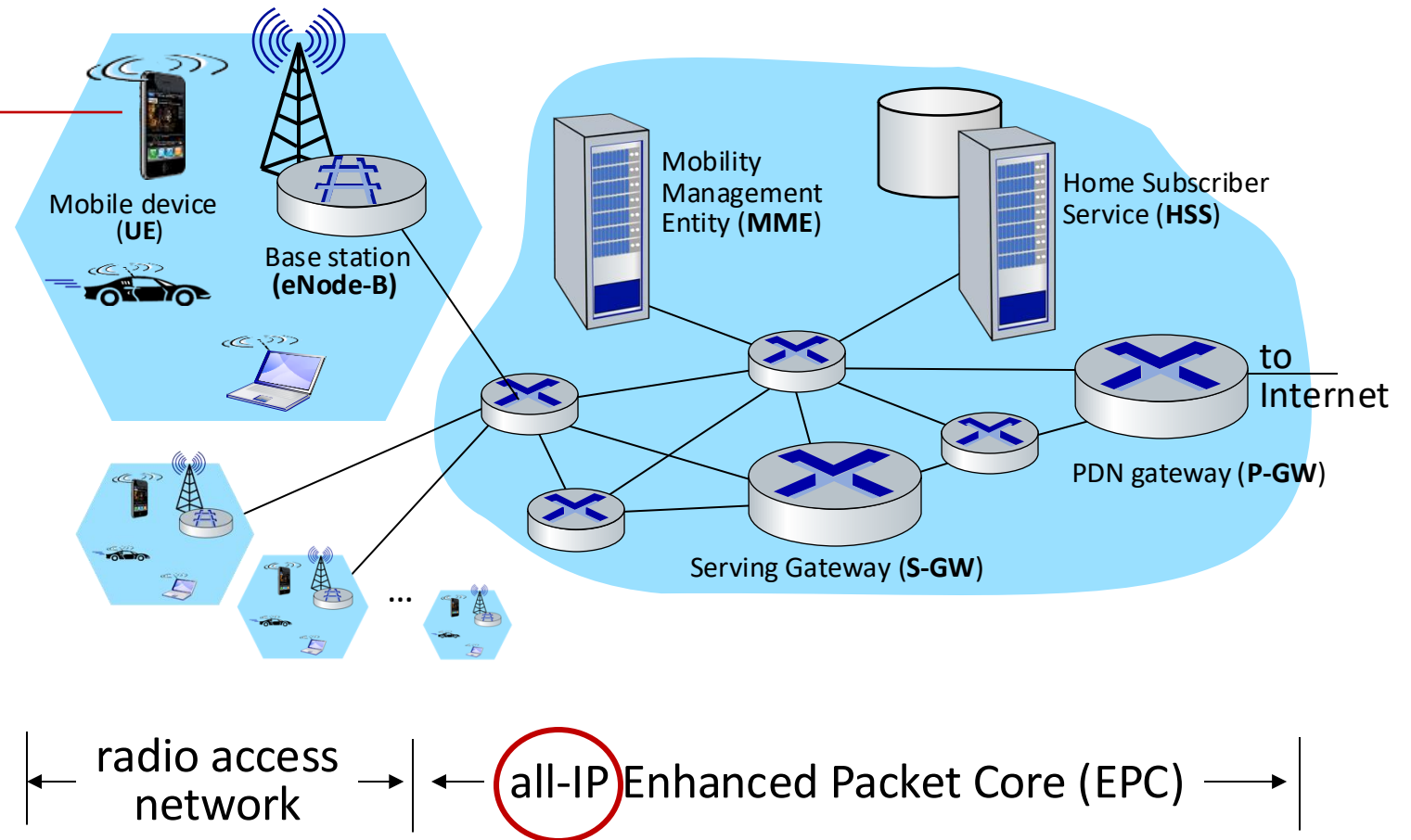
## *differences from wired Internet*

- 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:

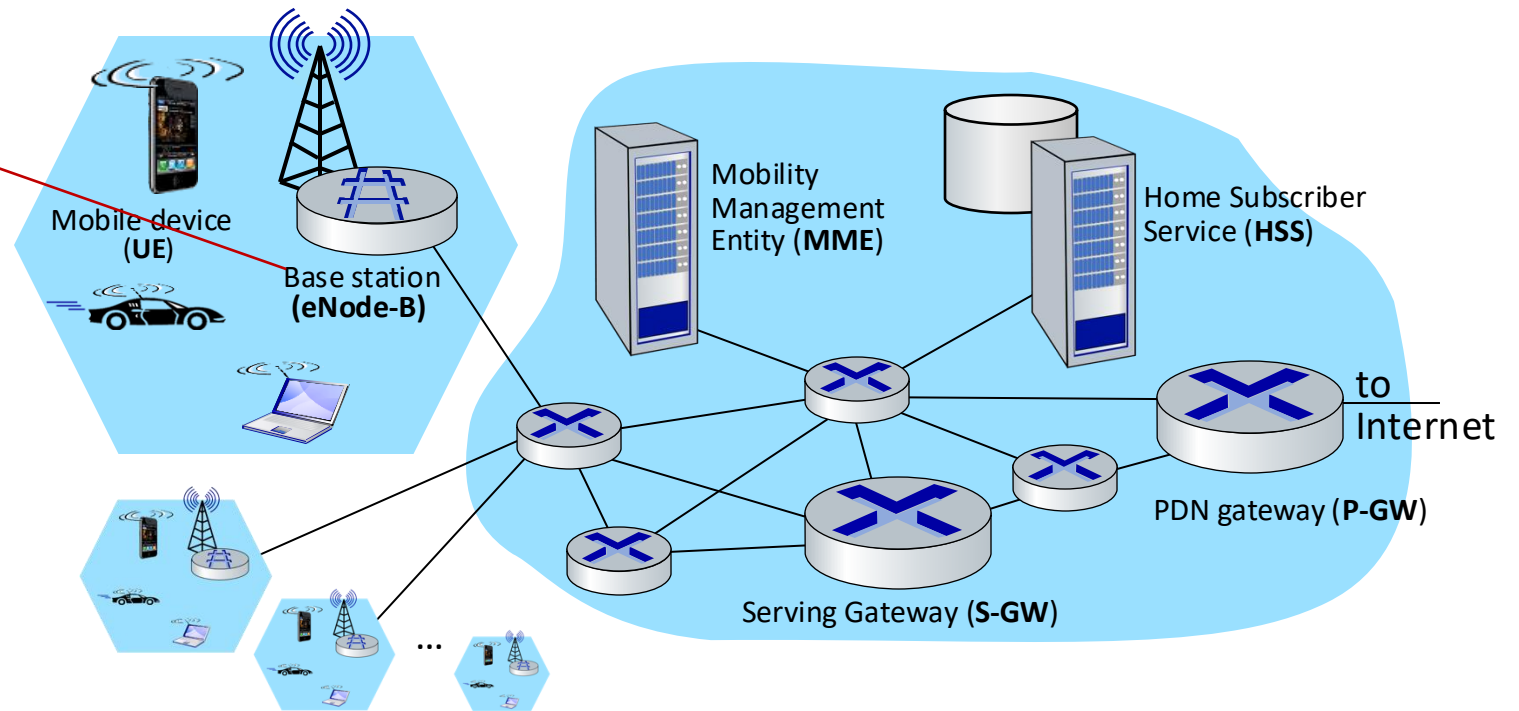
- smartphone, tablet, laptop, IoT, ... with 4G LTE radio
- 64-bit International Mobile Subscriber Identity (IMSI), stored on SIM (Subscriber Identity Module) card
- LTE jargon: User Equipment (UE)



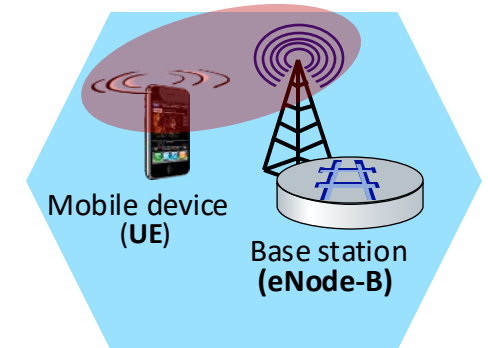
# Elements of 4G LTE architecture

## 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

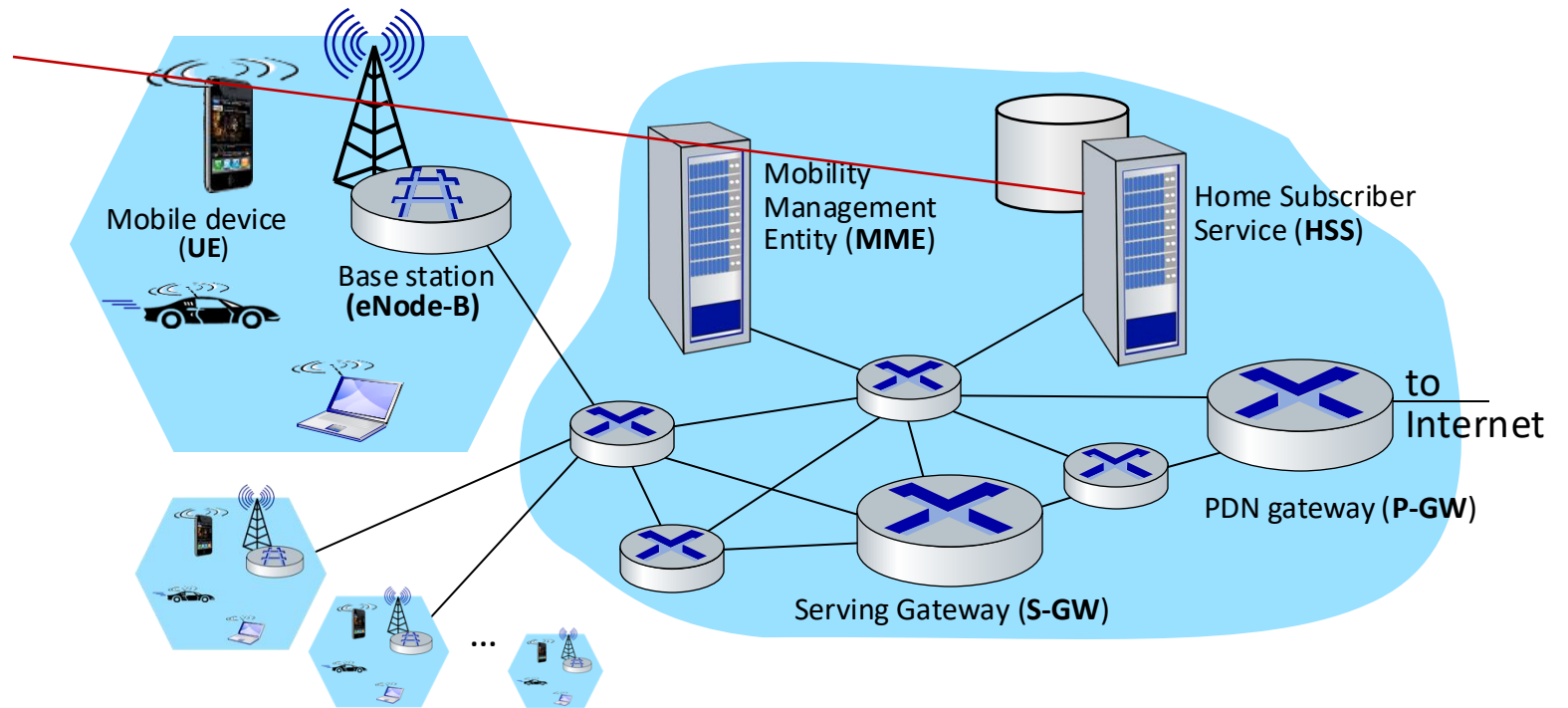


- connects device (UE) to a base station (eNode-B)
  - multiple devices connected to each base station
- many different possible frequencies bands, multiple channels in each band
  - popular bands: 600, 700, 850, 1500, 1700, 1900, 2100, 2600, 3500 MHz
  - separate upstream and downstream channels
- sharing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

# Elements of 4G LTE architecture

## Home Subscriber Service

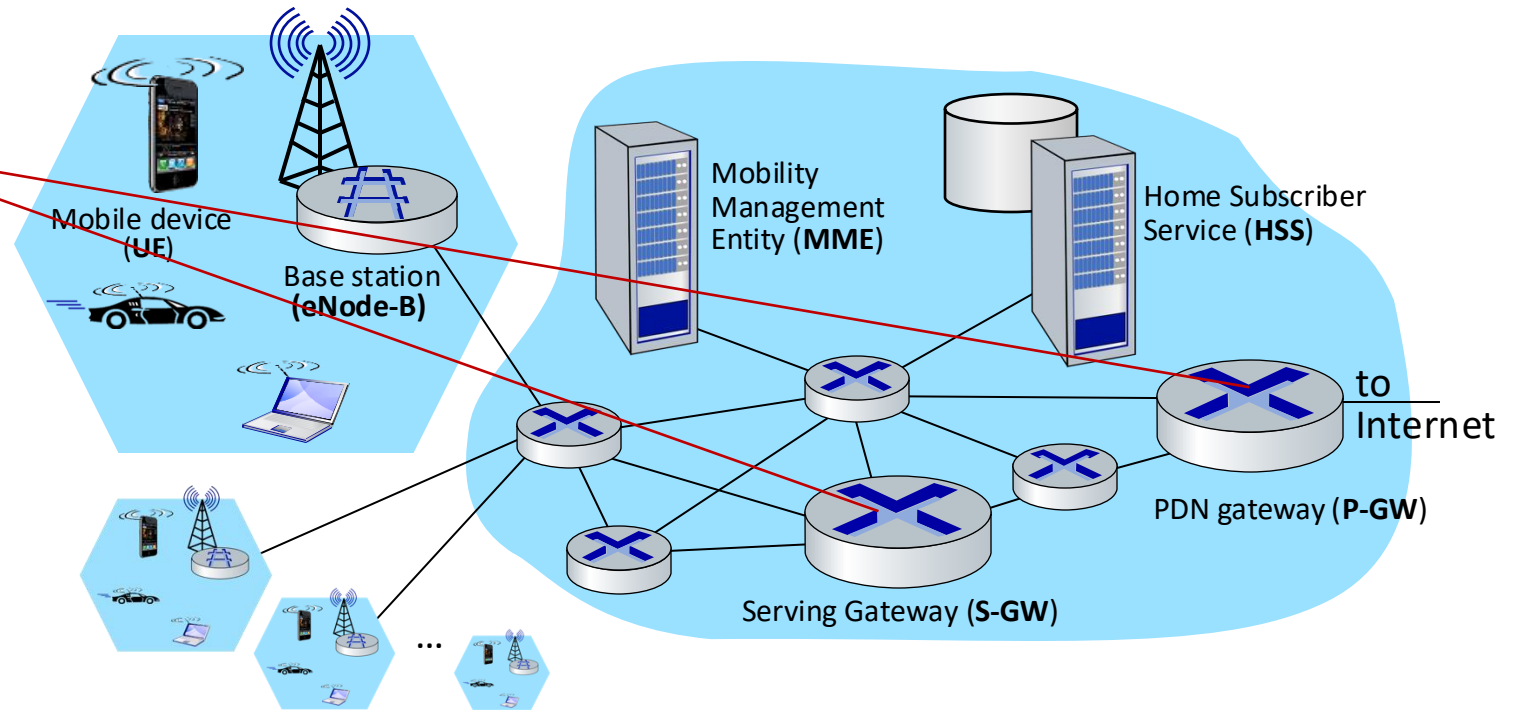
- stores info about mobile devices for which the HSS's network is their "home network"
- works with MME in device authentication



# Elements of 4G LTE architecture

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

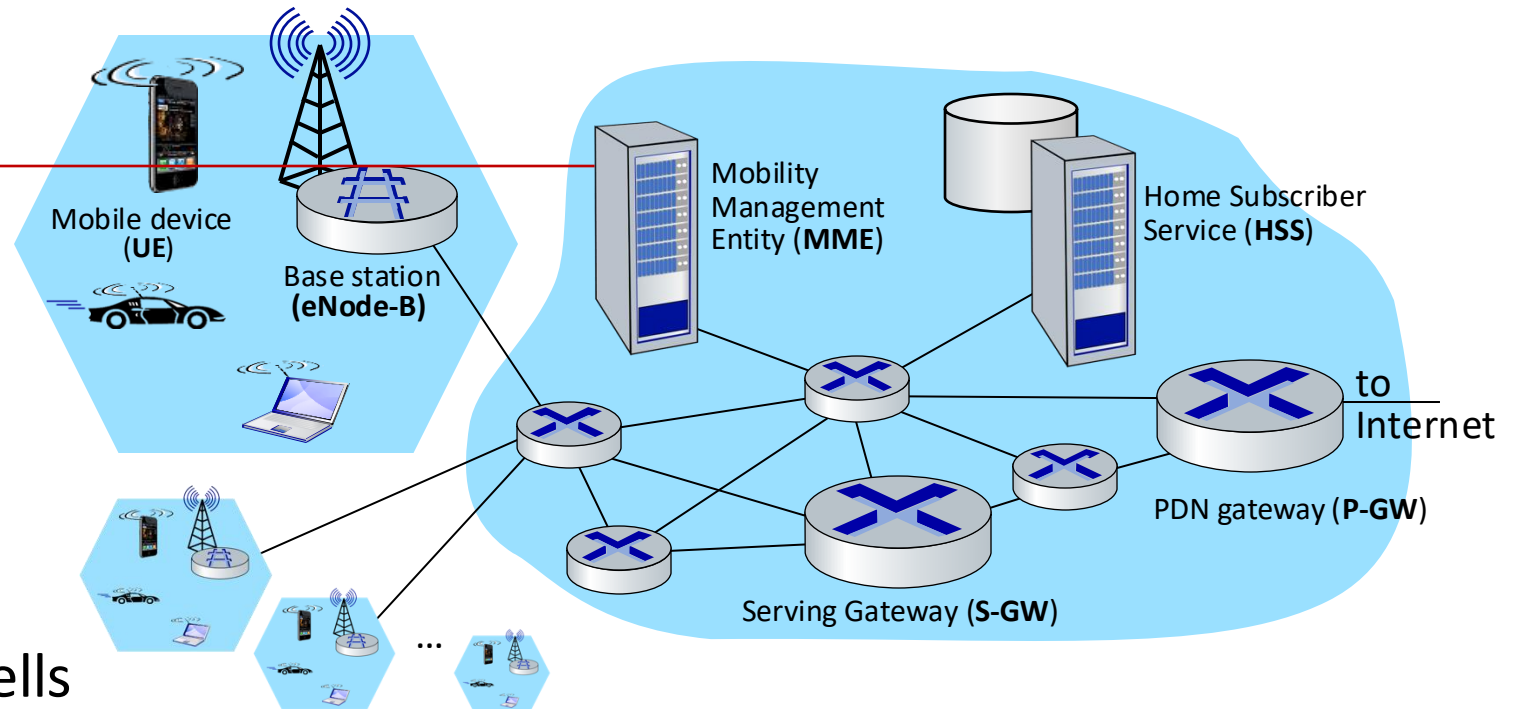
- lie on data path from mobile to/from Internet
- P-GW
  - gateway to mobile cellular network
  - Looks like any other internet gateway router
  - provides NAT services



# Elements of 4G LTE architecture

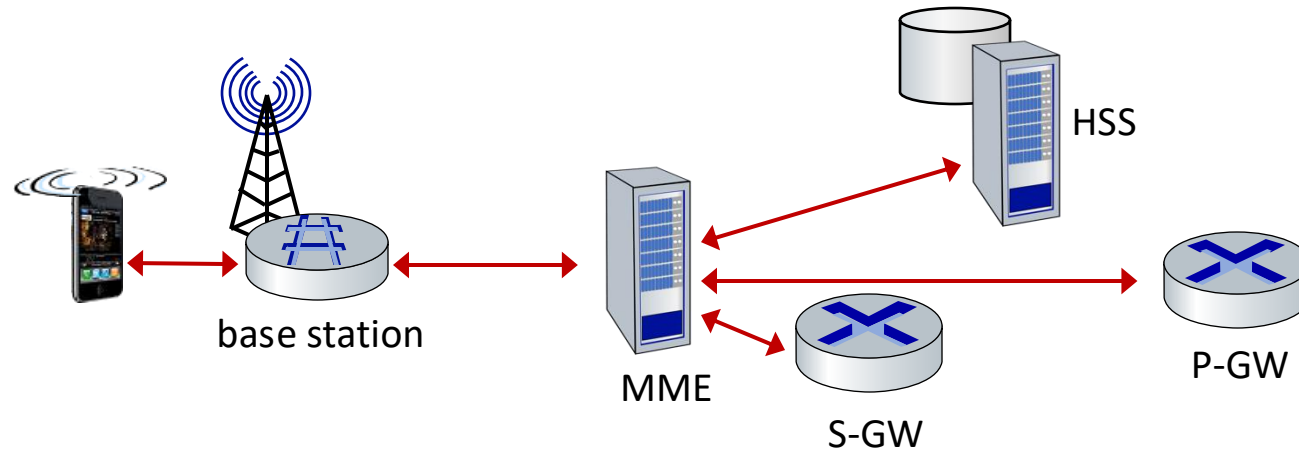
## Mobility Management Entity

- 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



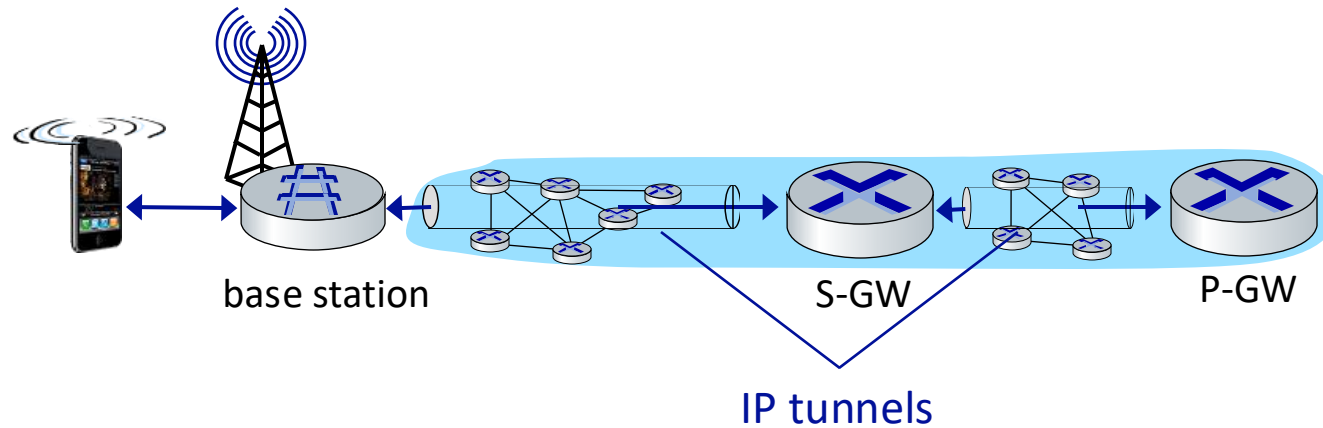


# LTE: data plane control plane separation



## control plane

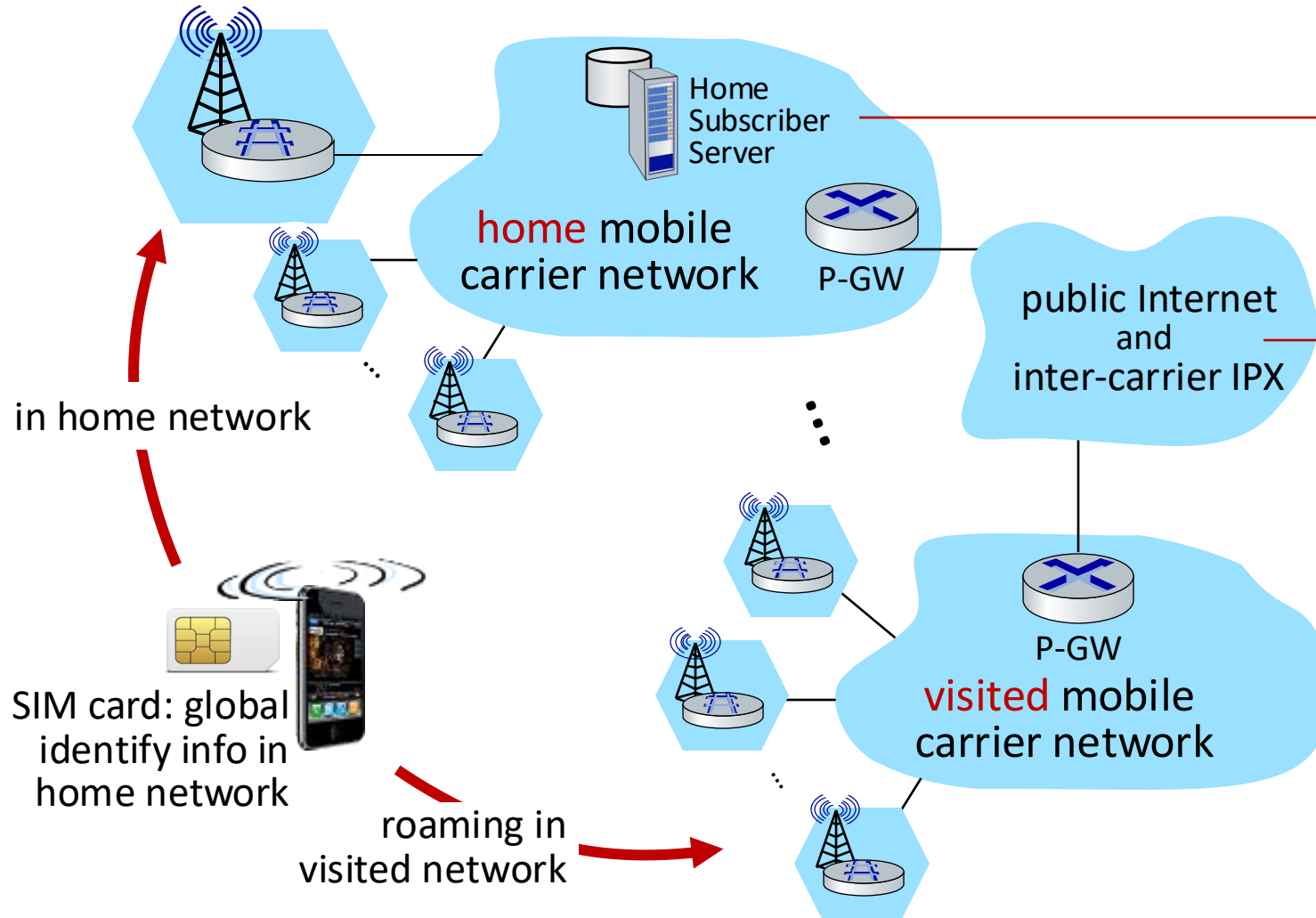
- new protocols for mobility management, security, authentication (later)



## data plane

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

# Global cellular network: a network of IP networks



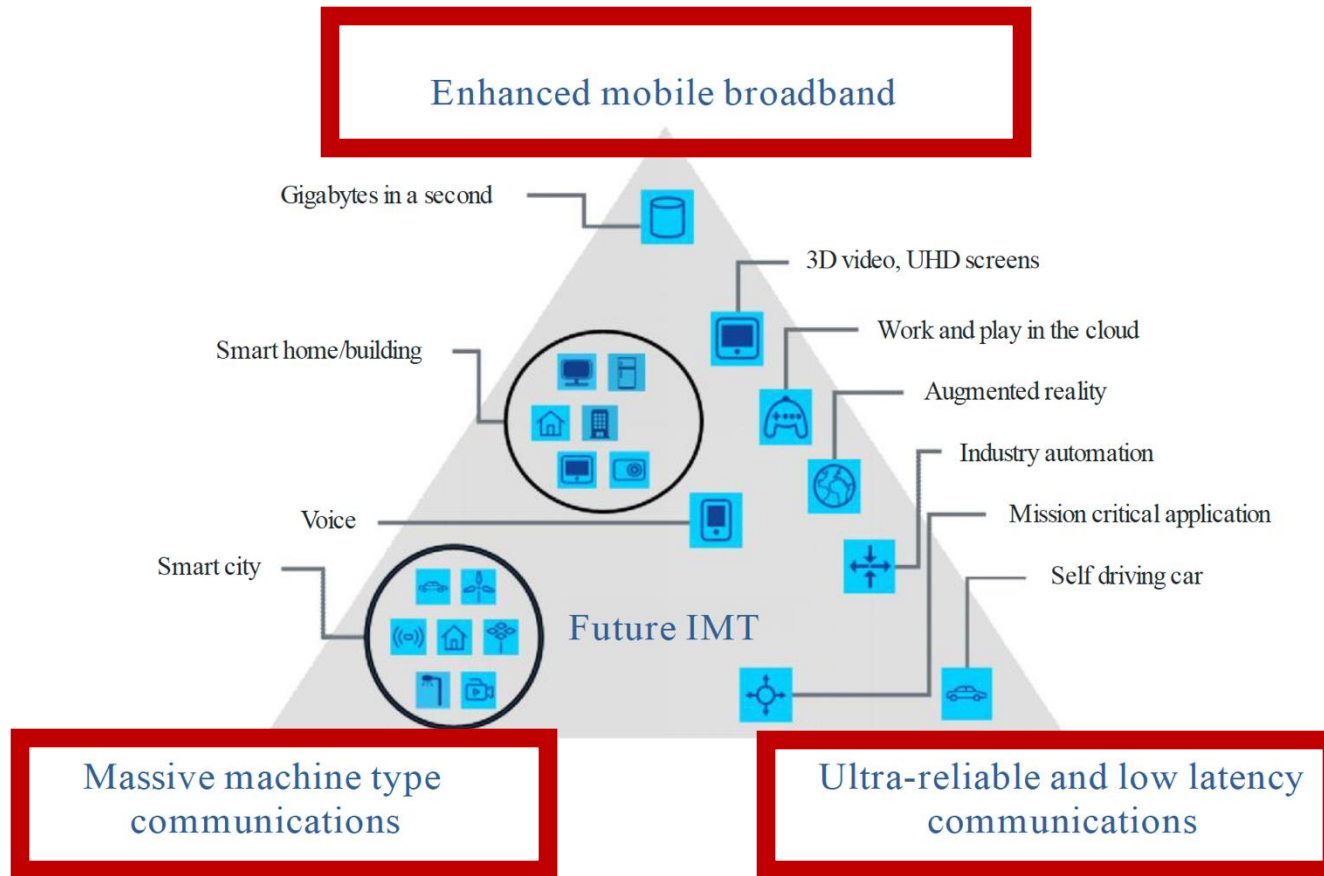
## home network HSS:

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

## all IP:

- carriers interconnect with each other, and public internet at exchange points

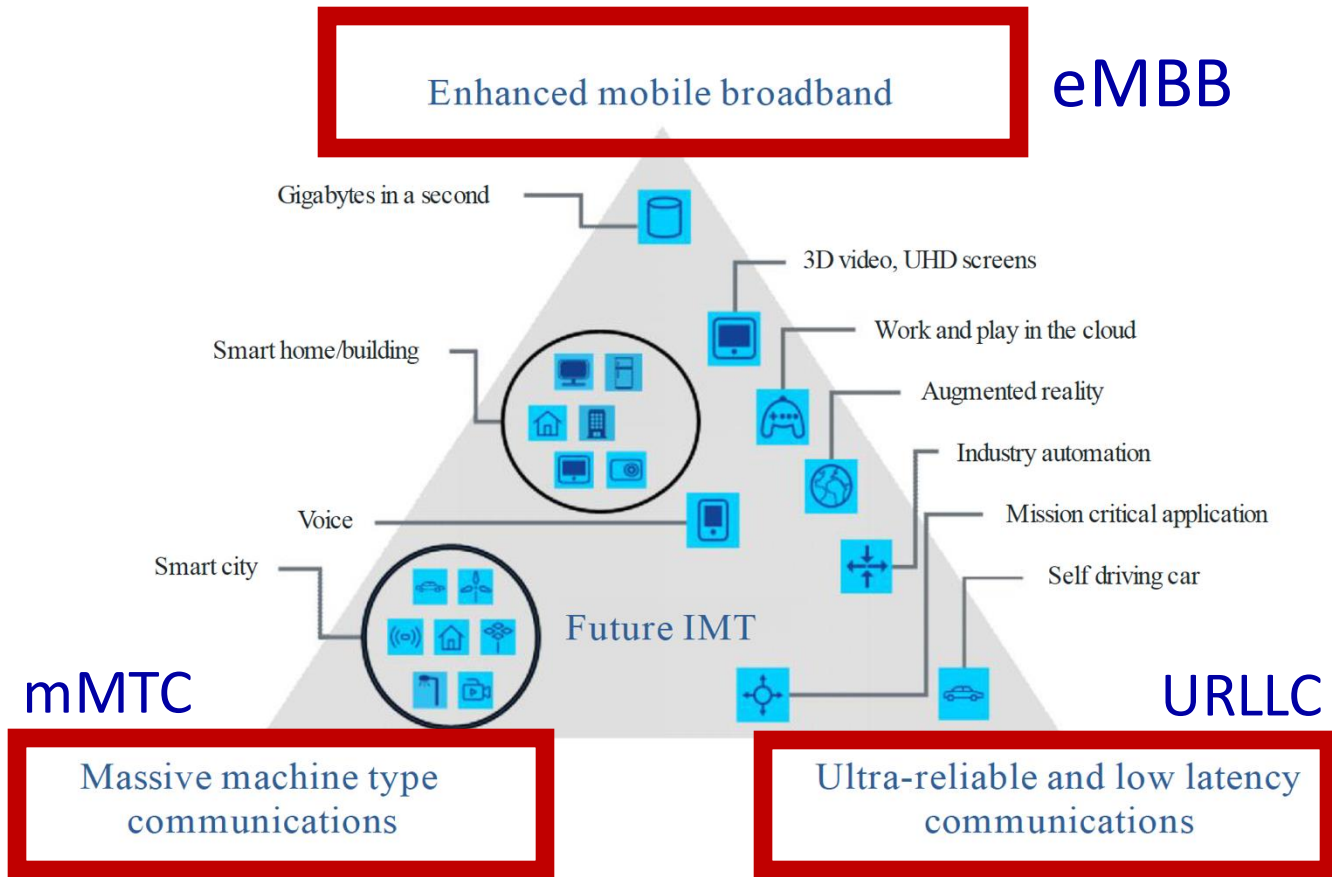
# On to 5G: motivation



“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**.”

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

# 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 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)

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