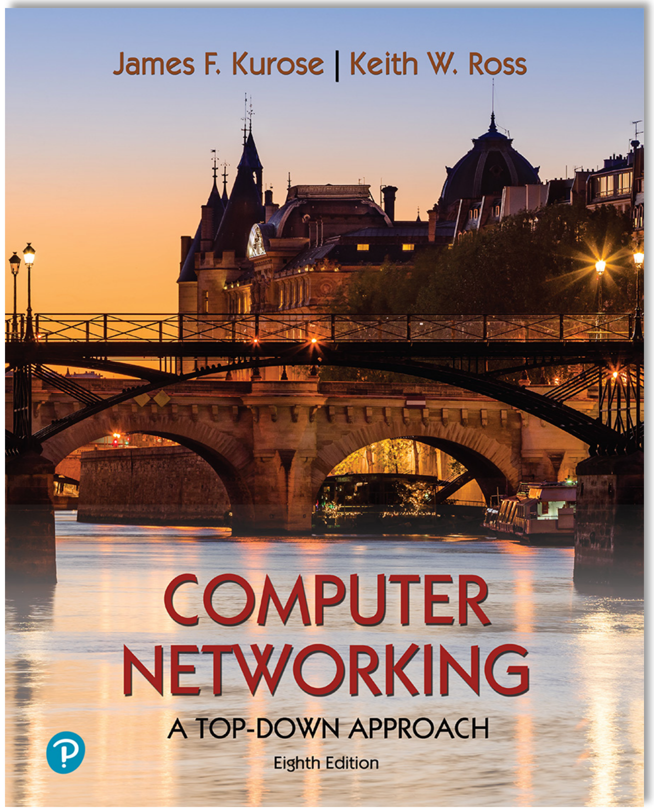
Chapter 7
Wireless and Mobile Networks



Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Acknowledgement: Based on the textbook's website:
https://gaia.cs.umass.edu/kurose_ross/index.php

IMPORTANT

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 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

IMPORTANT

Chapter 7 outline

- Introduction

Wireless

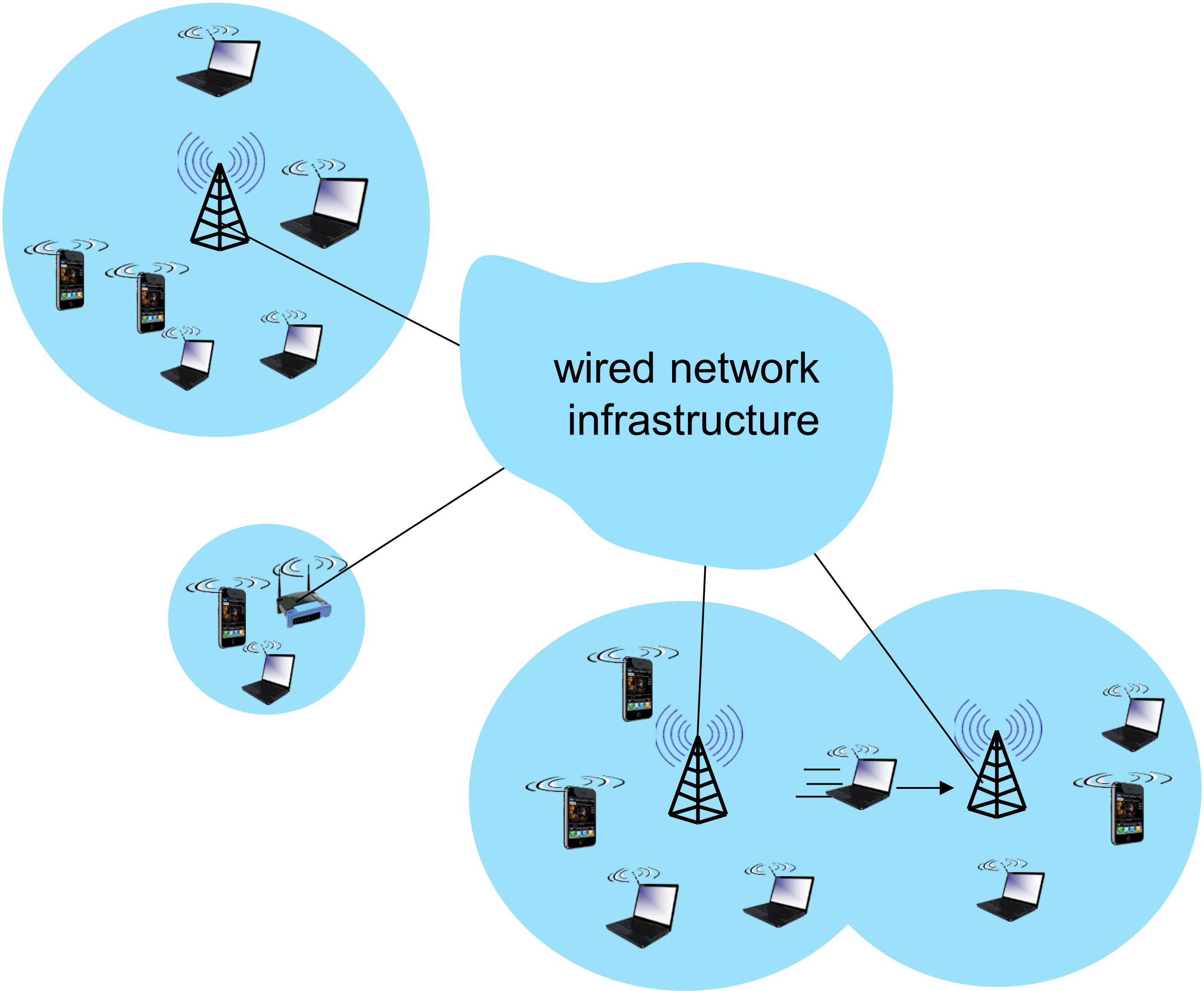
- Wireless Links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G

Mobility

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

IMPORTANT

Elements of a wireless network



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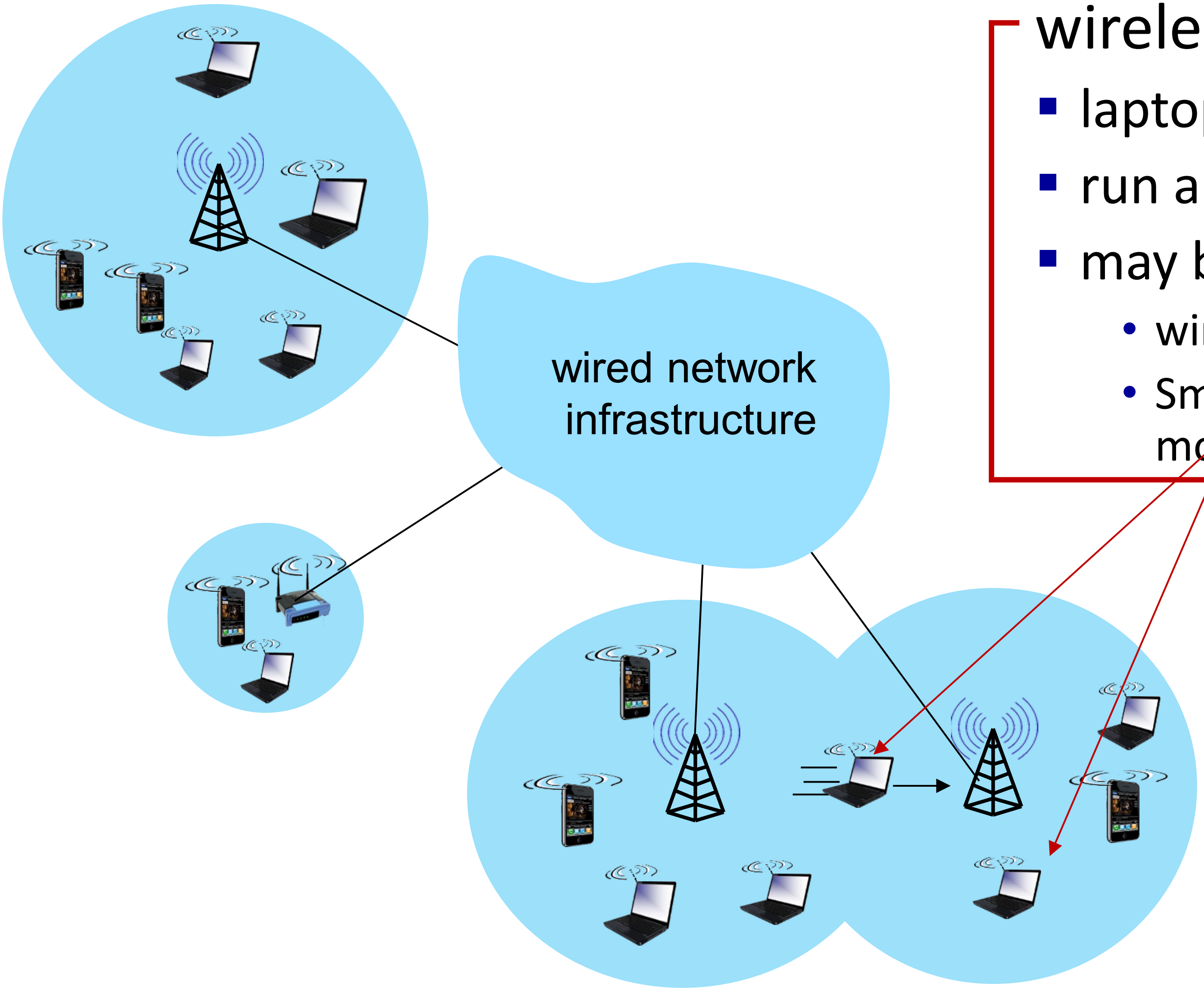
Elements of a wireless network



wireless hosts

- laptop, smartphone, IoT
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility!
  - Smart sensors in a building are wireless but not mobile

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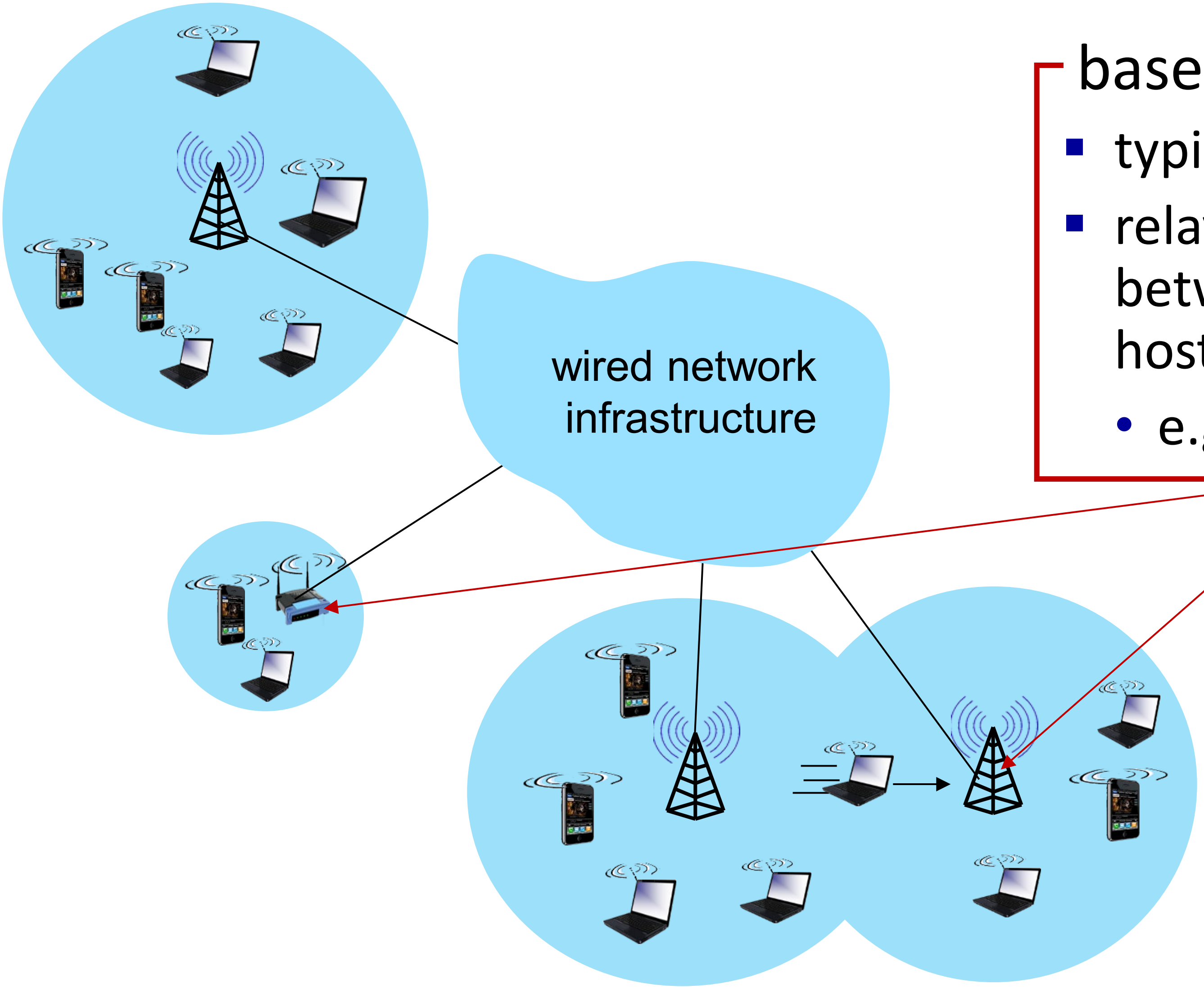
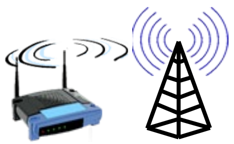
Elements of a wireless network



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

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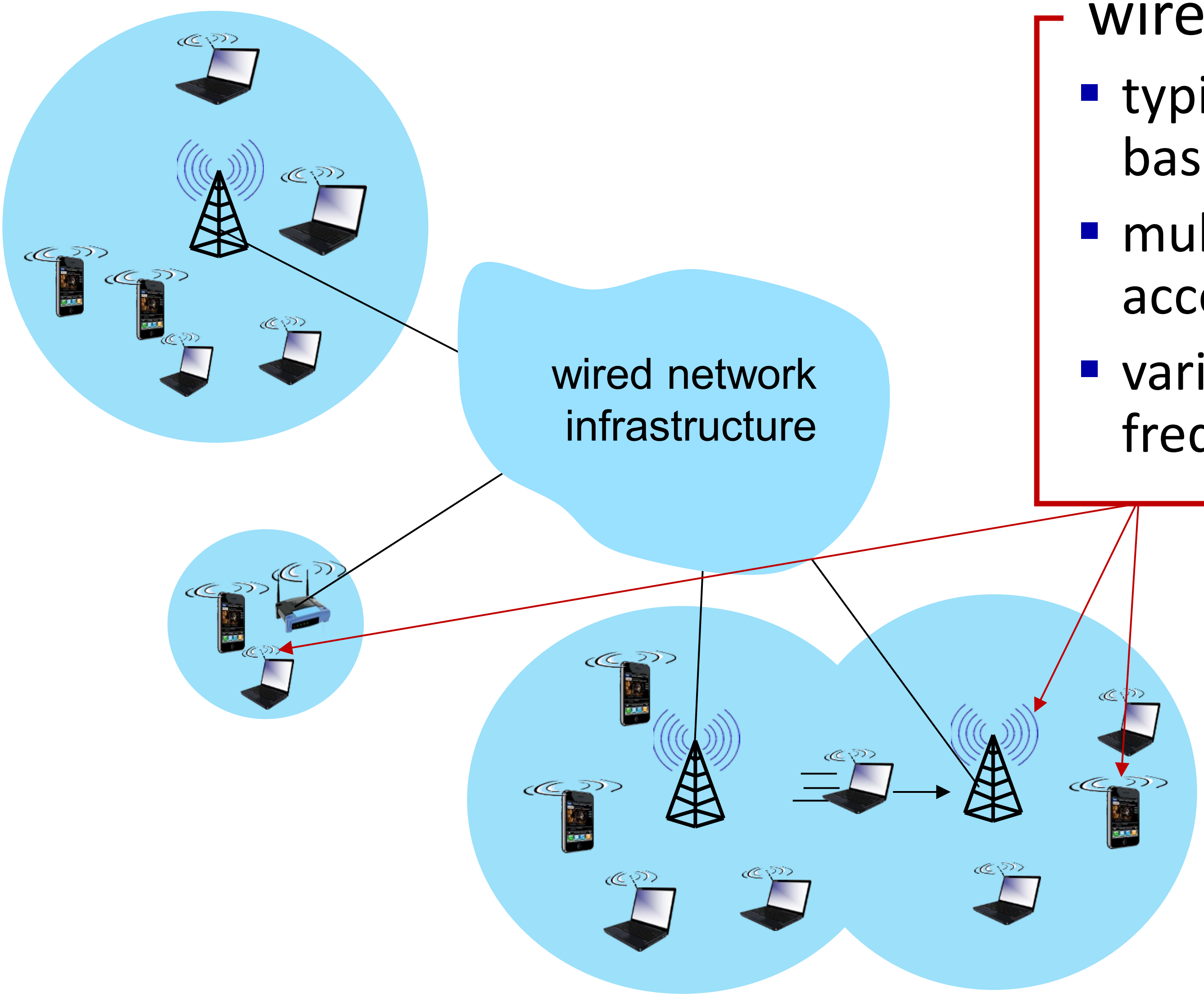
Elements of a wireless network



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

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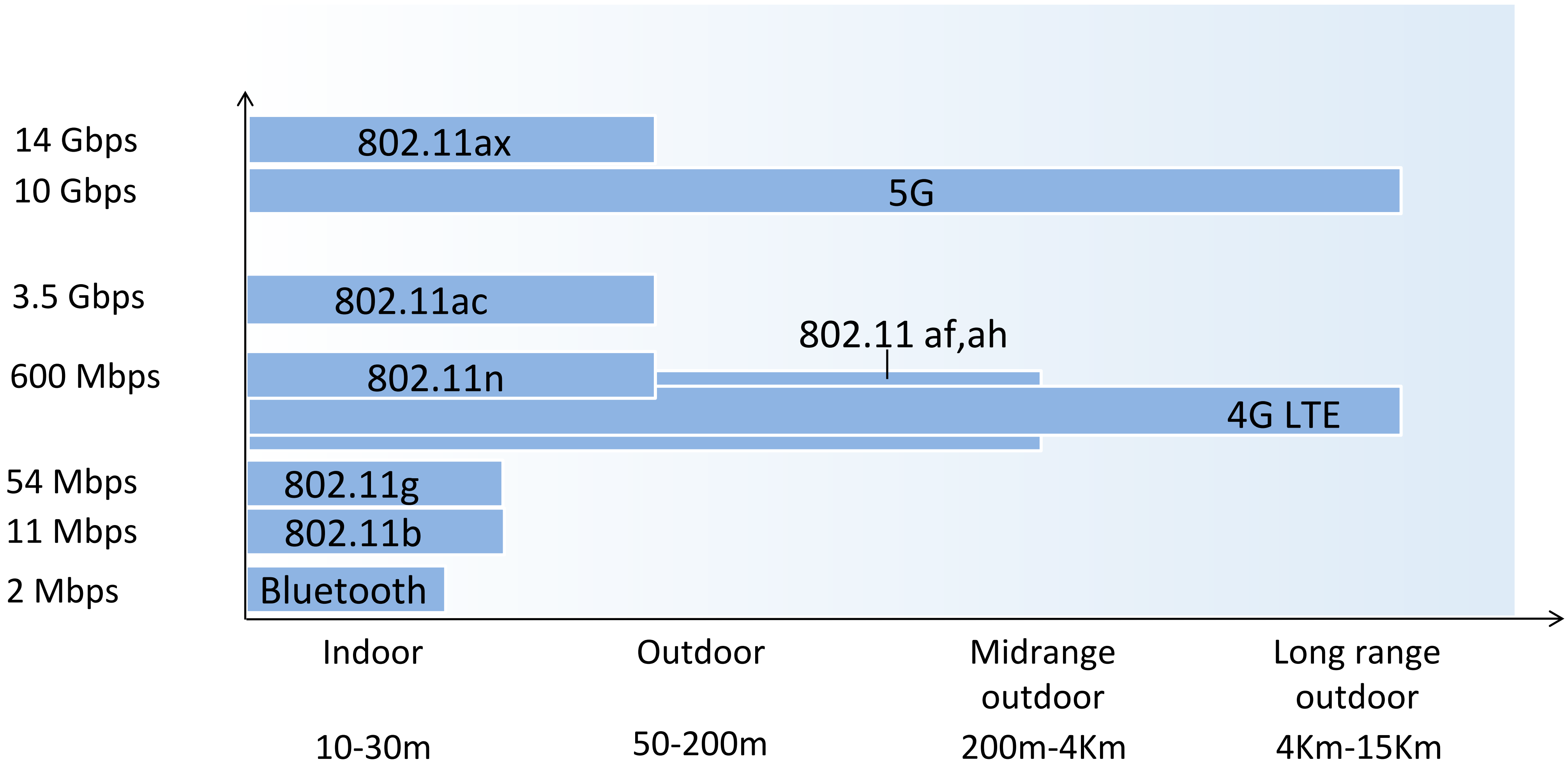
Characteristics of selected wireless links



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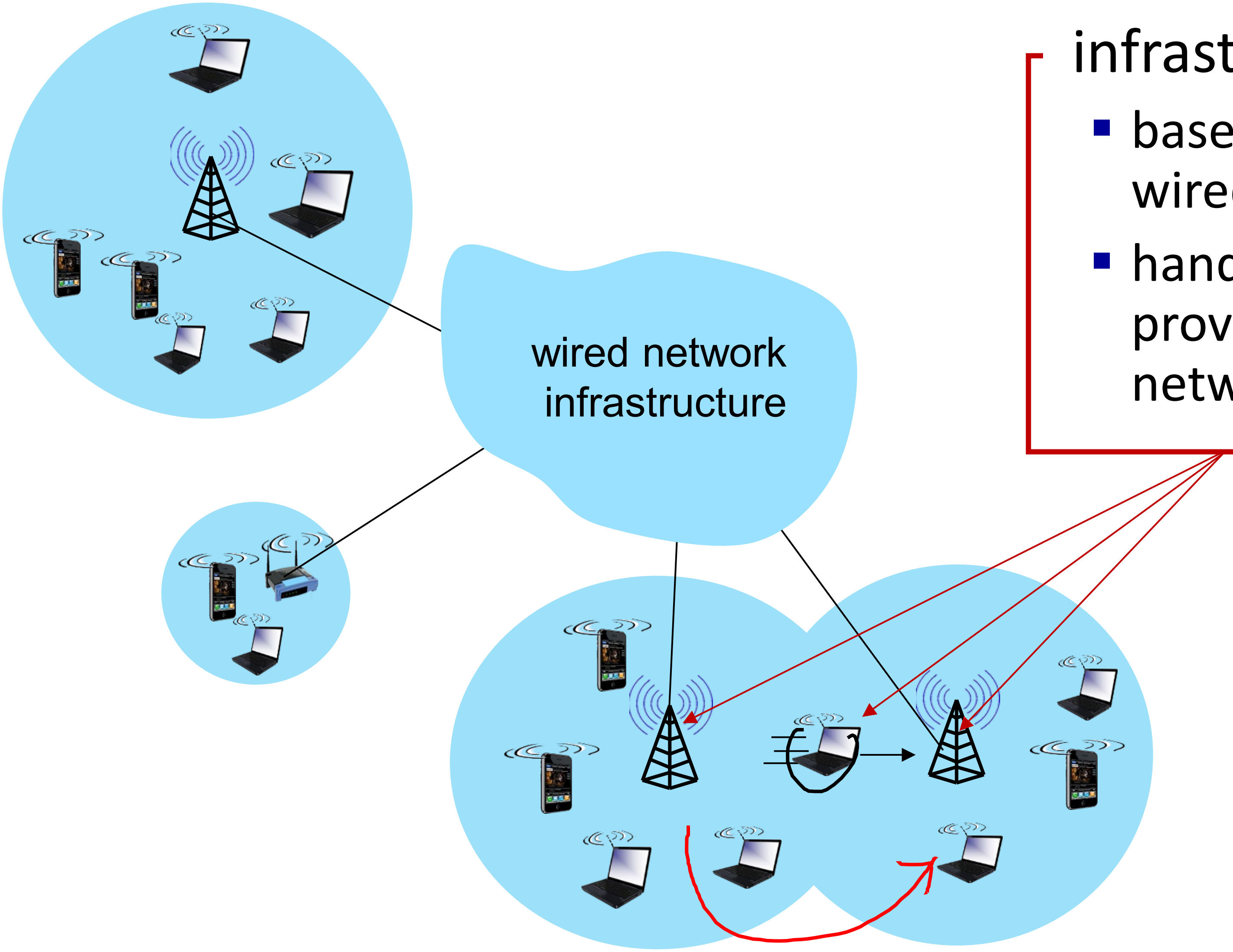
Elements of a wireless network



infrastructure mode

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

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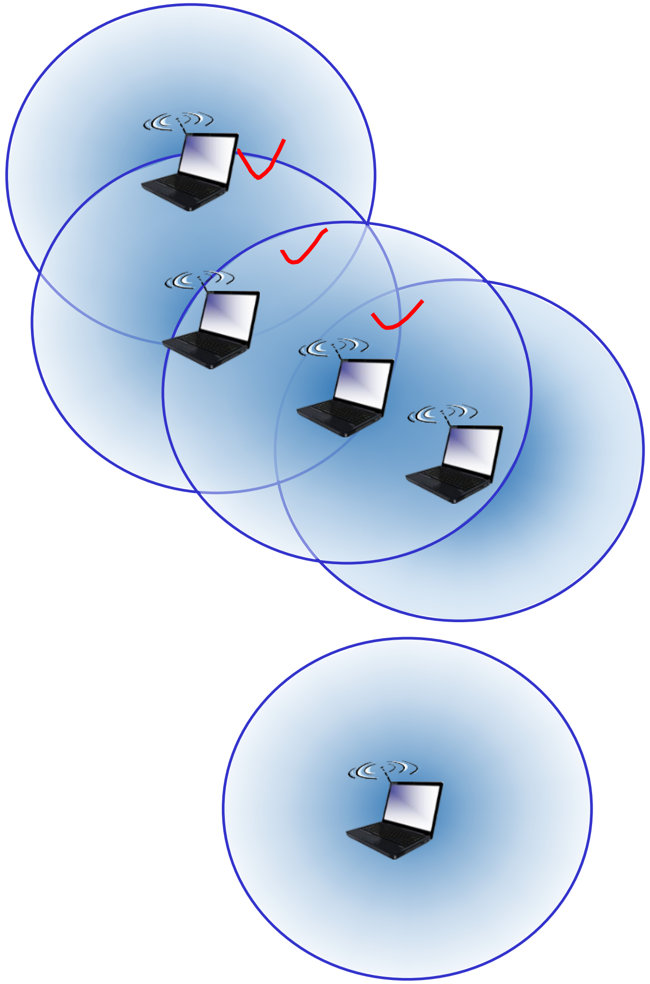
Elements of a wireless network



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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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: *mesh net*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

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- Cellular networks: 4G and 5G

Mobility

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

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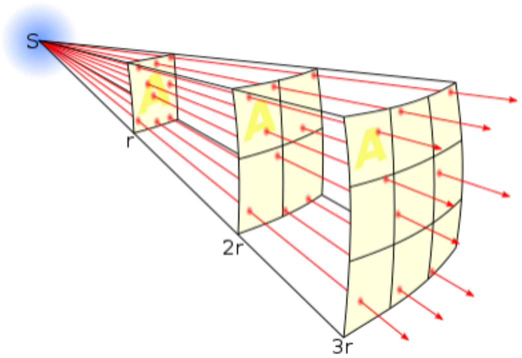
Wireless link characteristics: fading (attenuation)

Wireless radio signal attenuates (loses power) as it propagates (free space "path loss")

Free space path loss ~ $(fd)^2$

f: frequency
d: distance



higher frequency or longer distance → larger free space path loss

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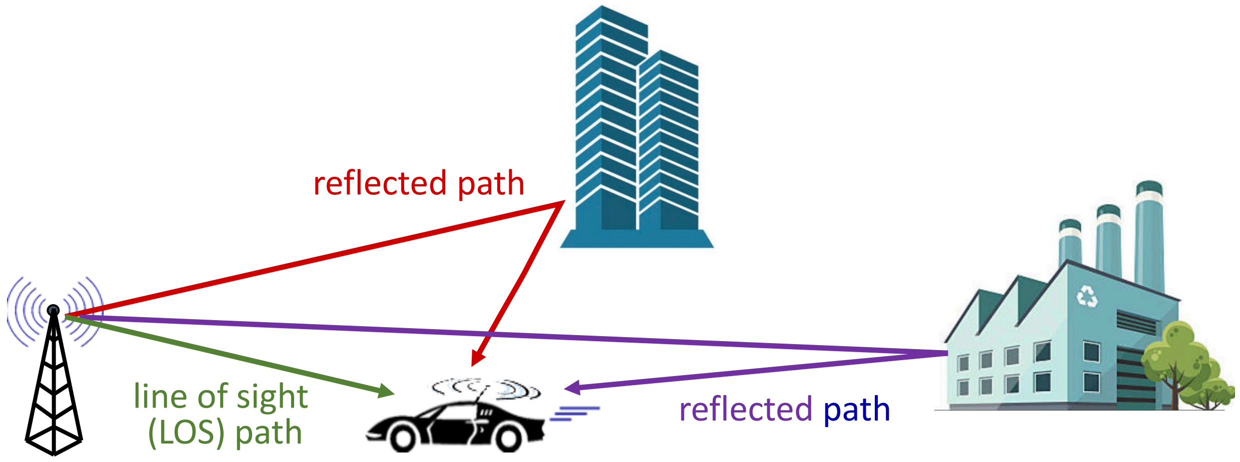
Wireless link characteristics: multipath

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



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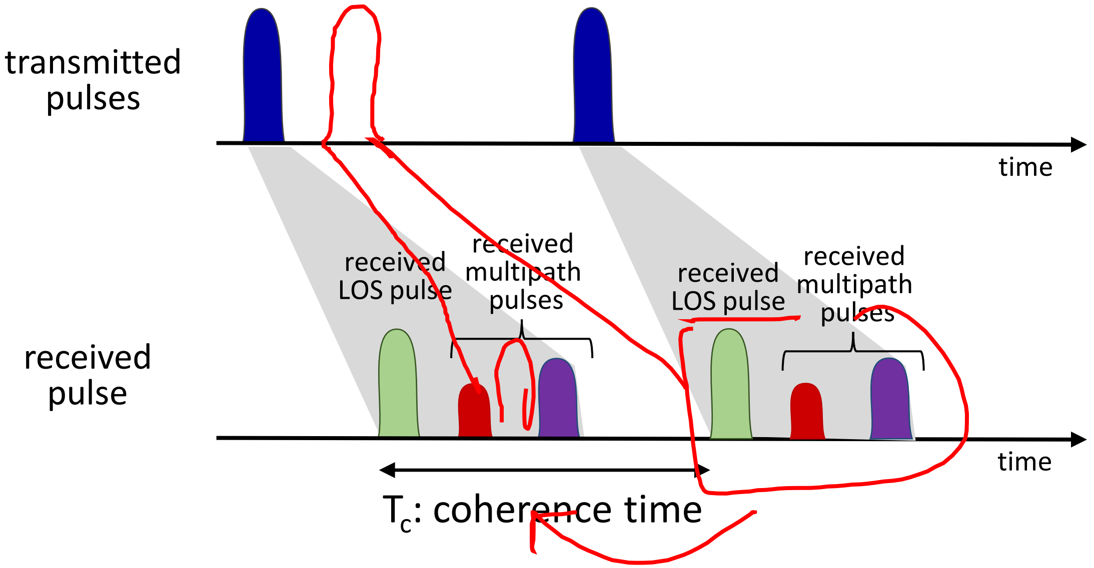
Wireless link characteristics: multipath

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



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

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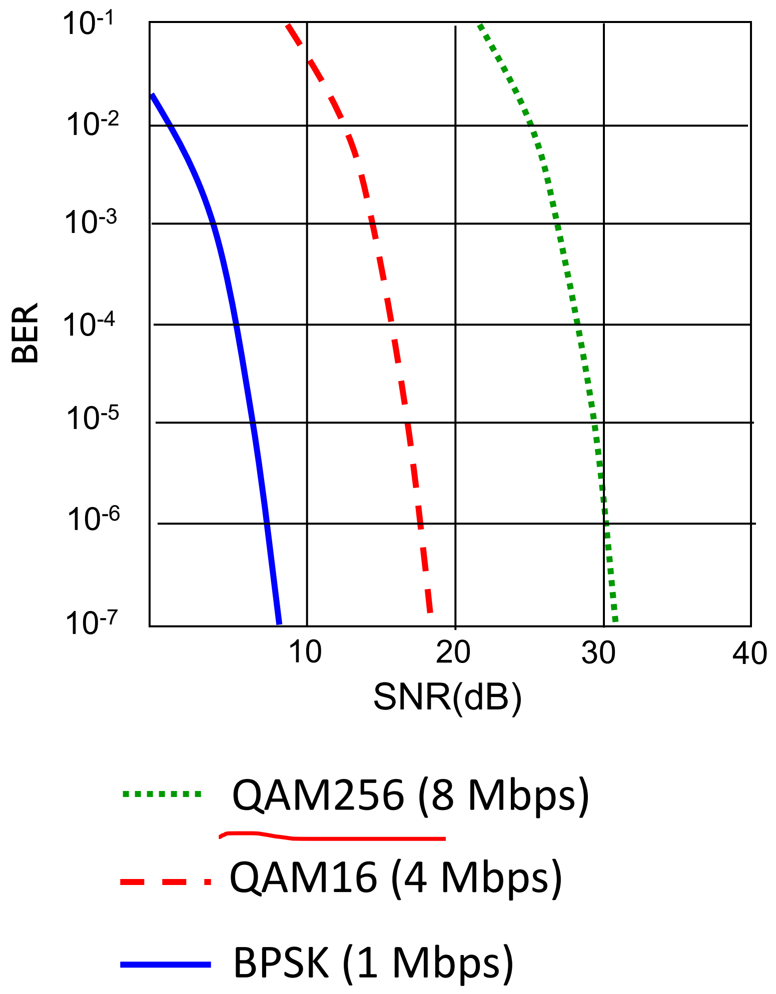
Wireless link characteristics: noise

- 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 Bit Error Rate (BER) tradeoff
  - *given physical layer:* increase power -> increase SNR->decrease BER
  - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



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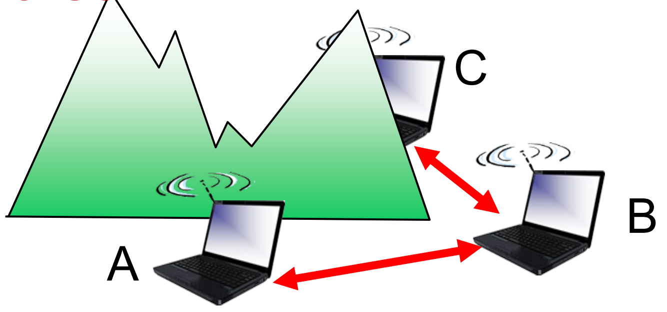
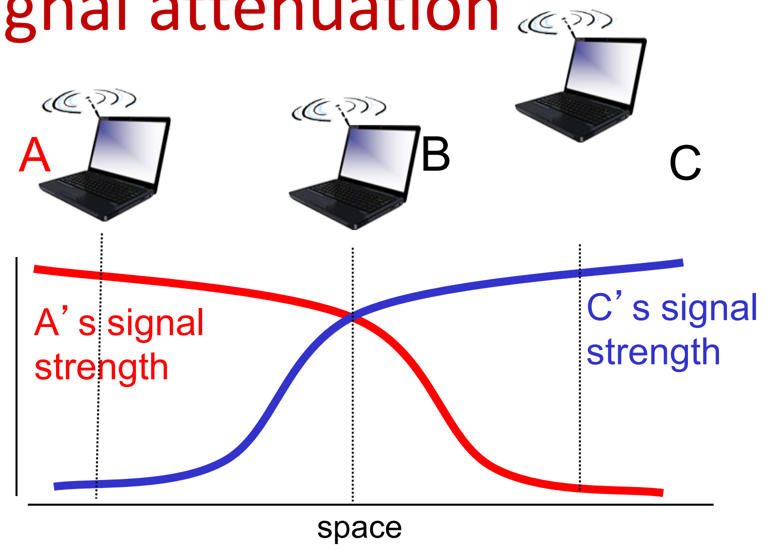
Wireless link characteristics: hidden terminals

Hidden terminal problem due to obstacles



- 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

Hidden terminal problem due to signal attenuation



- 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

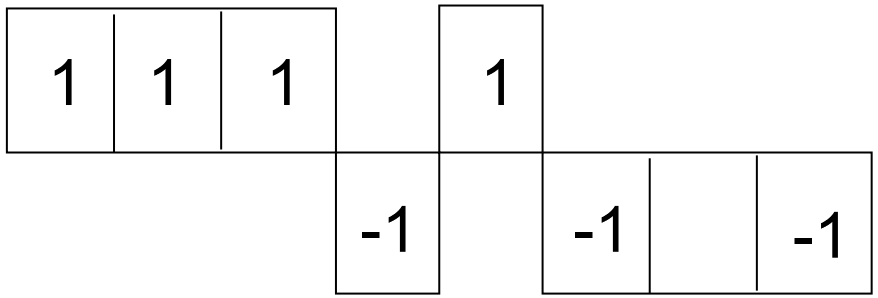
IMPORTANT

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")
  - analogy: people speaking different languages in the same roo do not interfere with each other
- encoding: scalar-vector product: (original data) $*$ (chipping sequence)
  - $d * (x_1, x_2, \ldots, x_n) = (d*x_1, d*x_2, \ldots, d*x_n)$, where d = 1 or -1.
- decoding: vector-vector inner-product: (encoded data) · (chipping sequence)
  - Defined as sum of elementwise product:
  - $(x_1, x_2, \ldots, x_n) \cdot (y_1, y_2, \ldots, y_n) = (x_1*y_1+x_2*y_2+\ldots+x_n*y_n)$

IMPORTANT

Direct-Sequence Spread Spectrum CDMA



- Chipping sequence (Code): (1,1,1,-1,1,-1,-1,-1)
- The 8-bit sequence 1*(1,1,1,-1,1,-1,-1,-1) encodes data bit 1 (corresponding to application bit 1).
- The 8-bit sequence (-1)*(1,1,1,-1,1,-1,-1,-1) = (-1,-1,-1,1,-1,1,1,1) encodes data bit -1 (corresponding to application bit 0).
- Spreading factor = Code length/data bit = 8
  - 10-100 commercial (Min 10 by FCC), 10,000 for military
- Two codes are orthogonal to each other, if their inner product equals 0.

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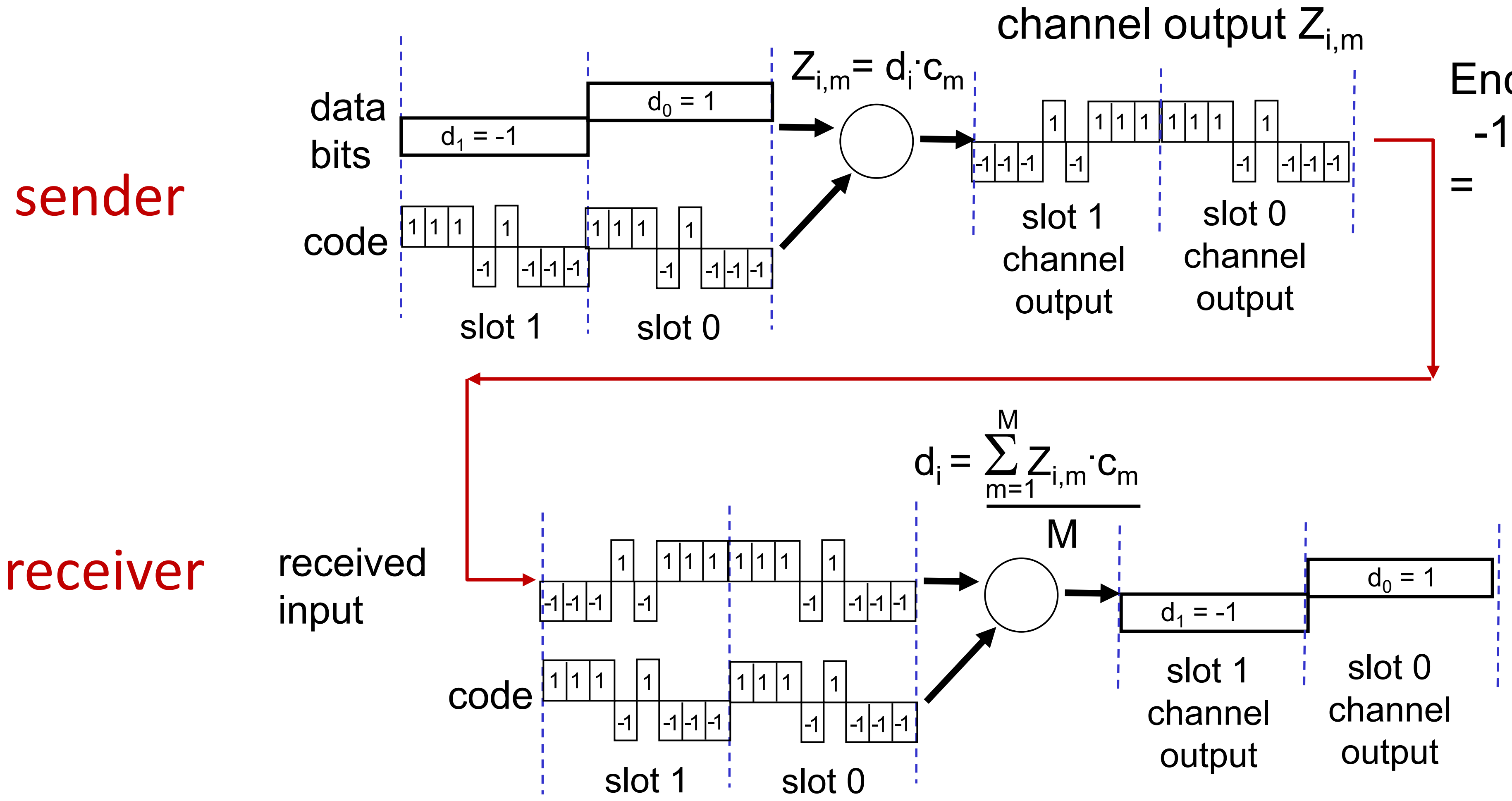
CDMA encode/decode



Encoded data in slot 1:
-1*(1,1,1,-1,1,-1,-1,-1)
= (-1,-1,-1,1,-1,1,1,1)

Decoded data in slot 1:
= (1/8)*(-1,-1,-1,1,-1,1,1,1) · (1,1,1,-1,1,-1,-1,-1)
= -1

IMPORTANT

CDMA encode/decode

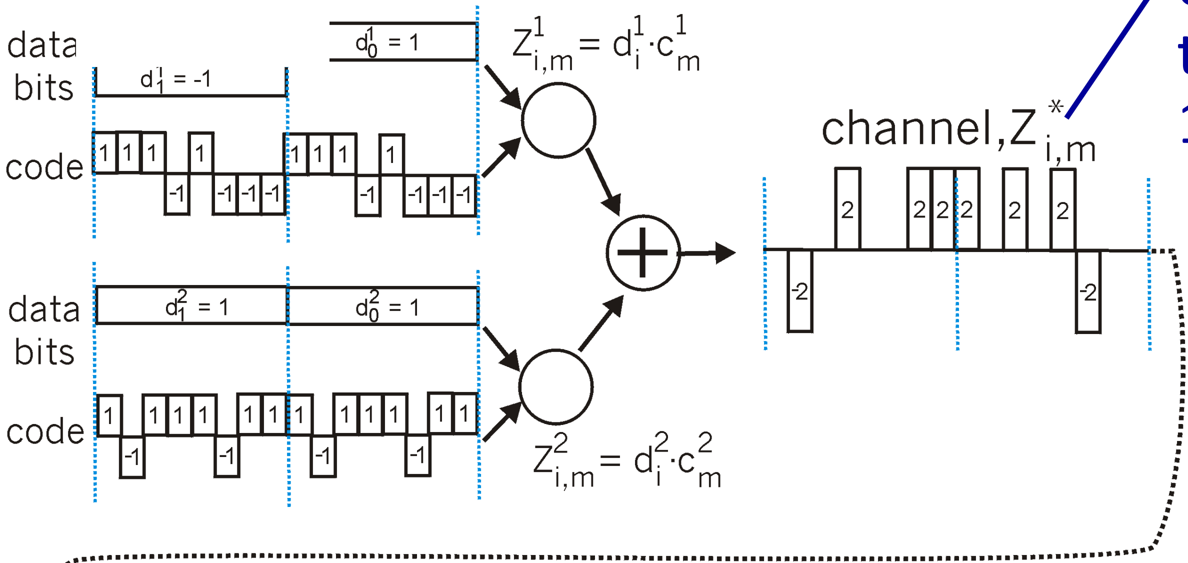
- Sender 1 Code $c_m, m = 1 \ldots M$: (1,1,1,-1,1,-1,-1,-1)
- Encoded data in slot 1: $Z_{1,m} = d_1 * c_m$
  - -1*(1,1,1,-1,1,-1,-1,-1)
  - = (-1,-1,-1,1,-1,1,1,1)
- Decoded data in slot 1 is normalized (divided by code length M) inner product of the encoded $Z_{i,m}$ with Sender 1 Code: $d_1 = \frac{1}{M}\sum_{m=1}^{M} Z_{1,m} \cdot c_m$
  - = (1/8)*(-1,-1,-1,1,-1,1,1,1) · (1,1,1,-1,1,-1,-1,-1)
  - = (1/8)*((-1)*1+(-1)*1+(-1)*1+1*(-1) +(-1)*1+1*(-1)+1*(-1)+1*(-1))
  - = (1/8)*(-8)
  - = -1

CDMA: two-sender interference

senders

Sender 1

Sender 2



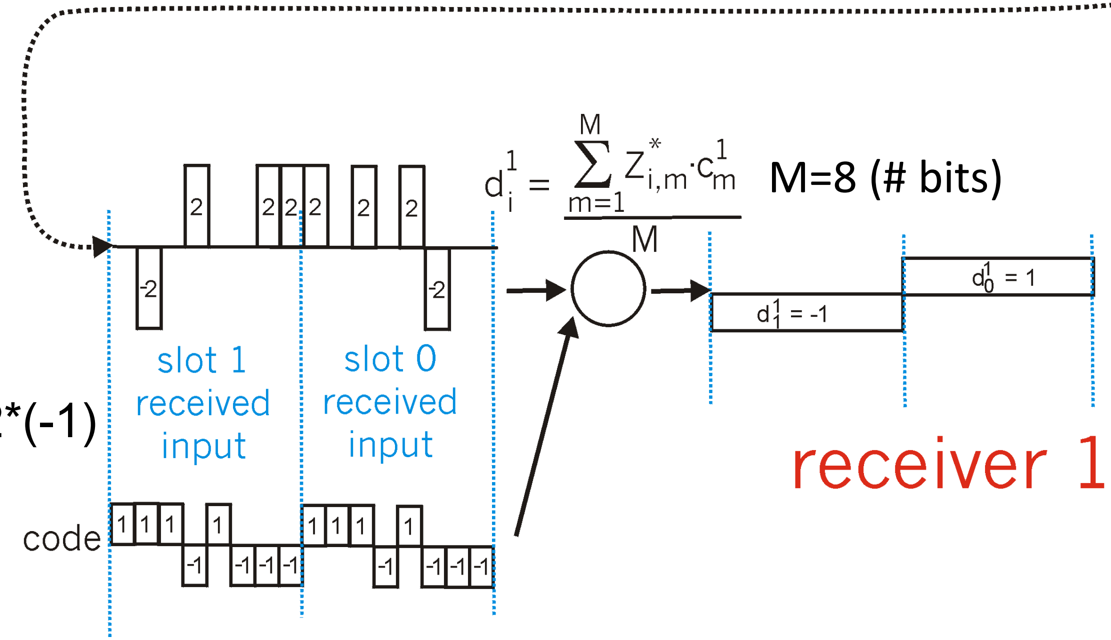
channel sums together transmissions by sender 1 and 2

Encoded data in slot 1:

-1*(1,1,1,-1,1,-1,-1,-1)

+ 1*(1,-1,1,1,1,-1,1,1)

= (0,-2,0,2,0,0,2,2)



receiver 1

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

(provided the codes for different senders are orthogonal)

Decoded data in slot 1 for Sender 1:

d_1^1=(1/8)*(0*1+(-2)*1+0*1+2*(-1)+0*1+0*(-1)+2*(-1)+2*(-1))

=(1/8)*(-8)=-1

IMPORTANT

CDMA: two-sender interference

- Orthogonal codes:
  - Sender 1 Code: $c_m^1, m = 1 \dots 8$: (1,1,1,-1,1,-1,-1,-1)
  - Sender 2 Code: $c_m^2, m = 1 \dots 8$: (1,-1,1,1,1,-1,1,1)
  - Orthogonal since their inner product is 0:
  - (1,1,1,-1,1,-1,-1,-1) · (1,-1,1,1,1,-1,1,1)
  - =1*1+1*(-1)+1*1+(-1)*1 +1*1+(-1)*(-1)+(-1)*1+(-1)*1
  - =0
- Encoded data in slot 1 is sum of encoded -1 for Sender 1 and encoded 1 for Sender 2:
  - $Z_{1,m}^* = d_1^1 * c_m^1, Z_{2,m}^* = d_1^2 * c_m^2$
  - -1*(1,1,1,-1,1,-1,-1,-1) + 1*(1,-1,1,1,1,-1,1,1)
  - = (0,-2,0,2,0,0,2,2)
- Decoded data for Sender 1 in slot 1 is $d_1^1 = \frac{1}{M}\sum_{m=1}^{M} Z_{1,m}^* \cdot c_m^1$:
  - d_1^1 = (1/8)*(0,-2,0,2,0,0,2,2) · (1,1,1,-1,1,-1,-1,-1)
  - =(1/8)*(0*1+(-2)*1+0*1+2*(-1) +0*1+0*(-1)+2*(-1)+2*(-1))
  - =(1/8)*(-8)
  - =-1
- Decoded data for Sender 2 in slot 1 is $d_1^2 = \frac{1}{M}\sum_{m=1}^{M} Z_{1,m}^* \cdot c_m^2$:
  - d_1^2 = (1/8)*(0,-2,0,2,0,0,2,2) · (1,-1,1,1,1,-1,1,1)
  - =(1/8)*(0*1+(-2)*(-1)+0*1+2*1+0*1+0*(-1)+2*1+2*1)
  - =(1/8)*8
  - =1

IMPORTANT

CDMA: two-sender interference: Sender 1

- Decoded data for Sender 1 in slot 1 is $d_1^1 = \frac{1}{M}\sum_{m=1}^{M} Z_{1,m}^* \cdot c_m^1$
- =(1/8)*((-1)*(1,1,1,-1,1,-1,-1,-1) + 1*(1,-1,1,1,1,-1,1,1)) · (1,1,1,-1,1,-1,-1,-1))
- =(1/8)*((-1)*(1,1,1,-1,1,-1,-1,-1) · (1,1,1,-1,1,-1,-1,-1) + (1/8)*1*(1,-1,1,1,1,-1,1,1) · (1,1,1,-1,1,-1,-1,-1))

(First term: Sender 1 Code's inner product with itself is sum of M 1's, M=8 is its dimension. Second term: Sender 1 Code's inner product with Sender 2 Code equals 0, since the codes for different senders are orthogonal)

- = (1/8)*(-1*(1+1+1+1+1+1+1+1) + 1*(1*1+1*(-1)+1*1+(-1)*1 +1*1+(-1)*(-1)+(-1)*1+(-1)*1))
- = (1/8)*(-1*8 + 1*0)
- = -1

IMPORTANT

CDMA: two-sender interference: Sender 2

- Decoded data for Sender 2 in slot 1 is $d_1^1 = \frac{1}{M}\sum_{m=1}^{M} Z_{2,m}^{*} \cdot c_m^2$
- =(1/8)*((-1)*(1,1,1,-1,1,-1,-1,-1) + 1*(1,-1,1,1,1,-1,1,1)) ·(1,-1,1,1,1,-1,1,1)
- =(1/8)*((-1)*(1,1,1,-1,1,-1,-1,-1) · (1,-1,1,1,1,-1,1,1) + (1/8)*1*(1,-1,1,1,1,-1,1,1) · (1,-1,1,1,1,-1,1,1))

(First term: Sender 1 Code's inner product with Sender 2 Code equals 0, since the codes for different senders are orthogonal. Second term: Sender 2 Code's inner product with itself is sum of M 1's, M=8 is its dimension.)

- = (1/8)*(-1*0 + 1*(1*1+(-1)*(-1)+1*1+1*1+1*1+(-1)*(-1) +1*1+1*1))
- = (1/8)*(-1*0 + 1*8)
- = 1

IMPORTANT

Quiz 1

- Q1: Consider the codes for two senders: Sender 1 Code: (1,-1,-1,-1,1,-1,-1,-1), Sender 2 Code: (1,-1,1,-1,1,-1,1,-1). Are they orthogonal?
- A: Inner product (1,-1,-1,-1,1,-1,-1,-1) · (1,-1,1,-1,1,-1,1,-1) = 4, so not orthogonal
- Q2: Consider the codes for two senders: Sender 1 Code: (1,-1,1,-1,1,-1,-1,-1), Sender 2 Code: (1,1,1,1,1,1,1,-1). Are they orthogonal?
- A: inner product (1,-1,1,-1,1,-1,-1,-1)· (1,1,1,1,1,1,1,-1) = 0, so they are orthogonal
- Q3: With the codes in Q2, suppose Sender 1 sends data bit 1 and Sender 2 sends data bit -1 simultaneously, compute the encoded data.
- A: 1* (1,-1,1,-1,1,-1,-1,-1) + (-1)* (1,1,1,1,1,1,1,-1)=(0,-2,0,-2,0,-2,-2,0)
- Q4: Compute the decoded data bit for Sender 1 and decoded data bit Sender 2.
- A: Decoded bit for Sender 1: (1/8)*(0,-2,0,-2,0,-2,-2,0)·(1,-1,1,-1,1,-1,-1,-1) = 1
- Decoded bit for Sender 2: (1/8)*(0,-2,0,-2,0,-2,-2,0)·(1,1,1,1,1,1,1,-1) = -1

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Quiz 2

- Q: A CDMA receiver receives the following encoded data:
- (-1 +1 -3 +1 -1 -3 +1 +1).
- Assuming the following codes used by four sending stations (they are pairwise orthogonal to each other),
  - A=(-1,-1,-1,+1,+1,-1,+1,+1)
  - B=(-1,-1,+1,-1,+1,+1,+1,-1)
  - C=(-1,+1,-1,+1,+1,+1,-1,-1)
  - D=(-1,+1,-1,-1,-1,-1,+1,-1)
- which stations transmitted, and which bits did each one send?
- A: Compute the normalized inner products with each code:
  - A's data:(1/8)*(-1 +1 -3 +1 -1 -3 +1 +1) · (-1,-1,-1,+1,+1,-1,+1,+1) = 1
  - B's data:(1/8)*(-1 +1 -3 +1 -1 -3 +1 +1) · (-1-1+1-1+1+1+1-1) =-1
  - C's data:(1/8)*(-1 +1 -3 +1 -1 -3 +1 +1) · (-1+1-1+1+1+1-1-1) =0
  - D's data:(1/8)* (-1 +1 -3 +1 -1 -3 +1 +1) · (-1-1-1-1-1-1-1-1) = 1
- Clearly, stations A, B, and D transmitted bits 1, -1, 1 respectively while station C did not transmit.
  - Transmitted bits 1, -1, 1 correspond to application bits 1, 0, 1