COMP 3331/9331: Computer Networks and Applications

Week 11

Data Link Layer + Wireless Networks

Reading Guide: Chapter 6, Sections 6.4

Chapter 7, Sections 7.1 – 7.3

Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

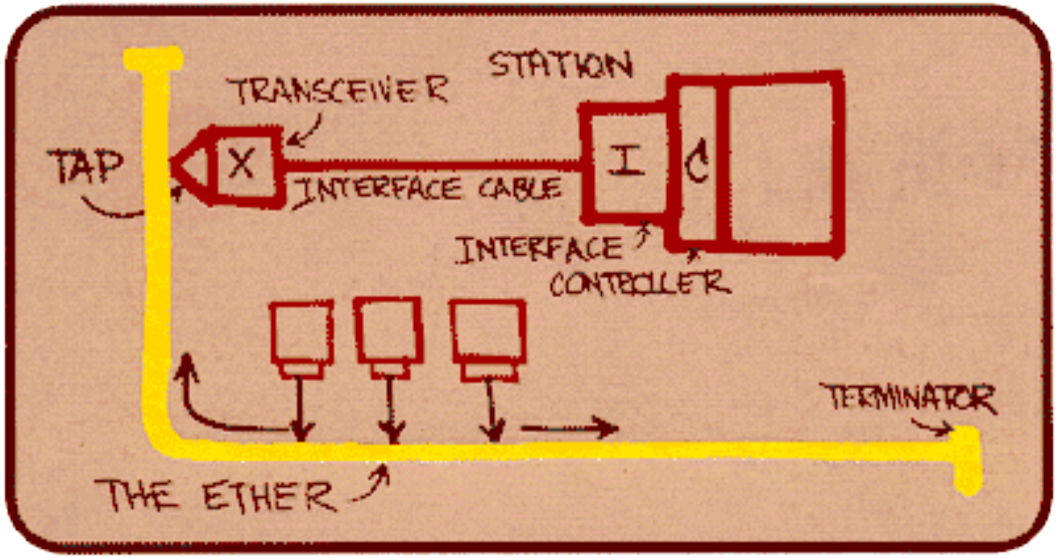
6.4 LANs

- addressing, ARP
- Ethernet
- switches

6.7 a day in the life of a web request

Ethernet

Bob Metcalfe, Xerox PARC, visits Hawaii and gets an idea!



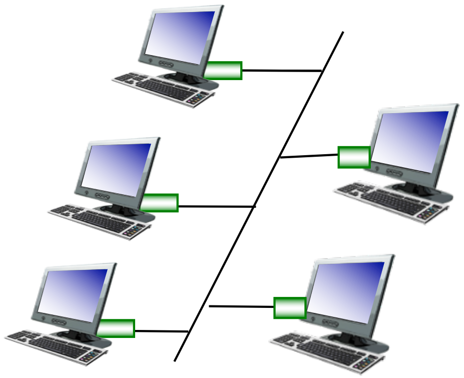
Metcalfe's Ethernet sketch

"dominant" wired LAN technology:

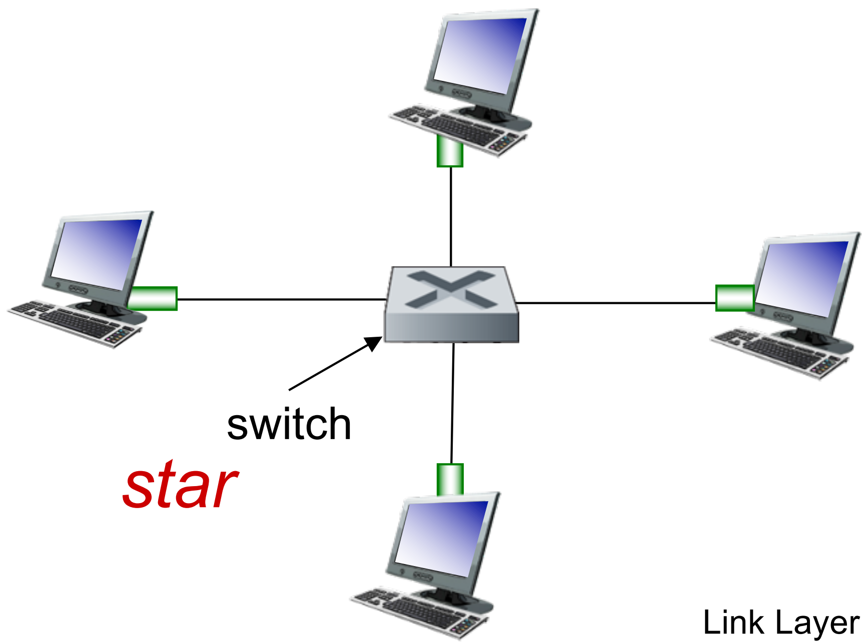
- first widely used LAN technology
- simpler, cheaper than token LANs and ATM
- kept up with speed race: 10 Mbps – 10 Gbps

Ethernet: physical topology

- *bus:* popular through mid 90s
  - all nodes in same collision domain (can collide with each other)
  - CSMA/CD for media access control
- *star:* prevails today
  - active *switch* in center
  - each "spoke" runs a (separate) Ethernet protocol (nodes do not collide with each other)
  - No sharing, no CSMA/CD



bus: coaxial cable



Ethernet frame structure

Sending adapter encapsulates IP datagram (or other network layer protocol packet) in Ethernet frame

Preamble 7 Bytes	SFD 1 Byte	Dest MAC 6 Bytes	Source MAC 6 Bytes	Type/Length 2 Bytes	Payload 46-1500 Bytes	FCS/CRC 4 Bytes	Inter Frame Gap

preamble:

- Start of frame is recognized by
  - Preamble : Seven bytes with pattern 10101010
  - Start of Frame Delimiter (SFD) : 10101011
- used to synchronize receiver, sender clock rates
- Inter Frame Gap is 12 Bytes (96 bits) of idle state
  - 0.96 microsec for 100 Mbit/s Ethernet
  - 0.096 microsec for Gigabit/s Ethernet

Ethernet frame structure (more)

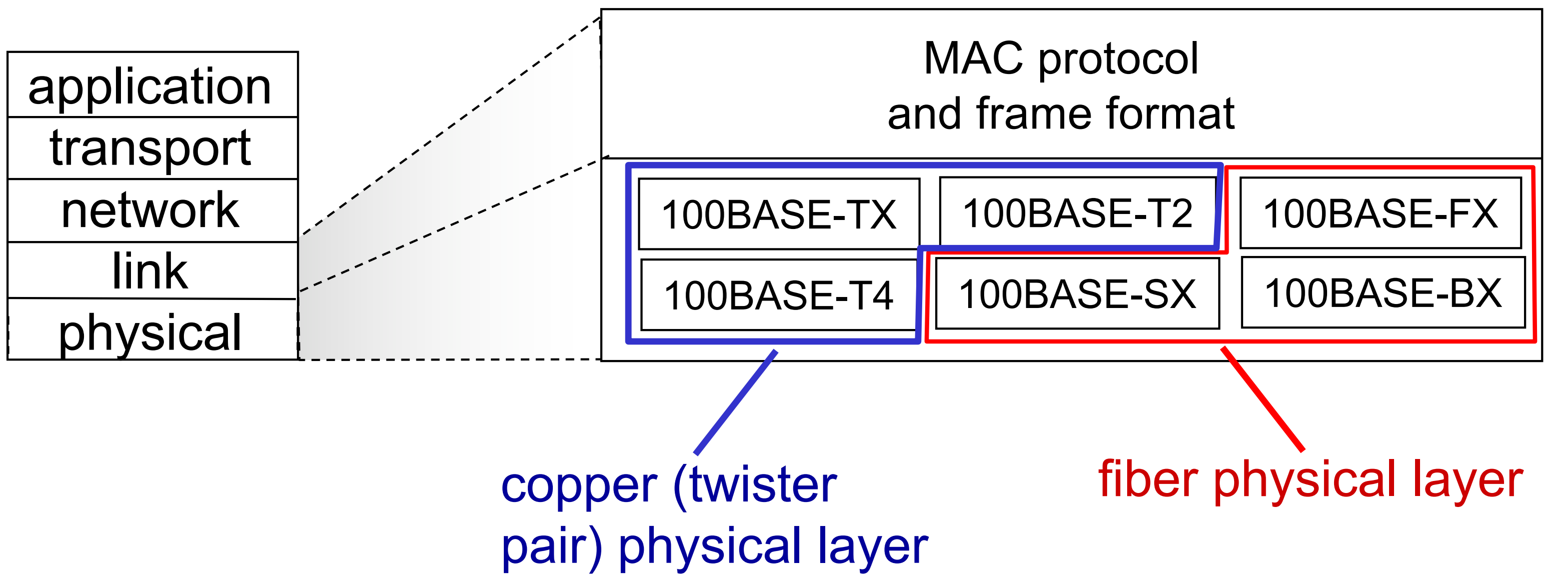
- *addresses:* 6 byte source, destination MAC addresses
  - if adapter receives frame with matching destination address, or with broadcast address (e.g. ARP packet), it passes data in frame to network layer protocol
  - otherwise, adapter discards frame
- *type:* indicates higher layer protocol (mostly IP but others possible, e.g., ARP, Novell IPX, AppleTalk)
- *CRC:* cyclic redundancy check at receiver
  - error detected: frame is dropped

Ethernet: unreliable, connectionless

- *connectionless:* no handshaking between sending and receiving NICs
- *unreliable:* receiving NIC doesnt send acks or nacks to sending NIC
  - data in dropped frames recovered only if initial sender uses higher layer rdt (e.g., TCP), otherwise dropped data lost
- Ethernet's MAC protocol: unslotted *CSMA/CD with binary backoff*

802.3 Ethernet standards: link & physical layers

- *many* different Ethernet standards
  - common MAC protocol and frame format
  - different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10Gbps, 40Gbps, 100Gbps,
  - different physical layer media: fiber, cable



Link layer, LANs: outline

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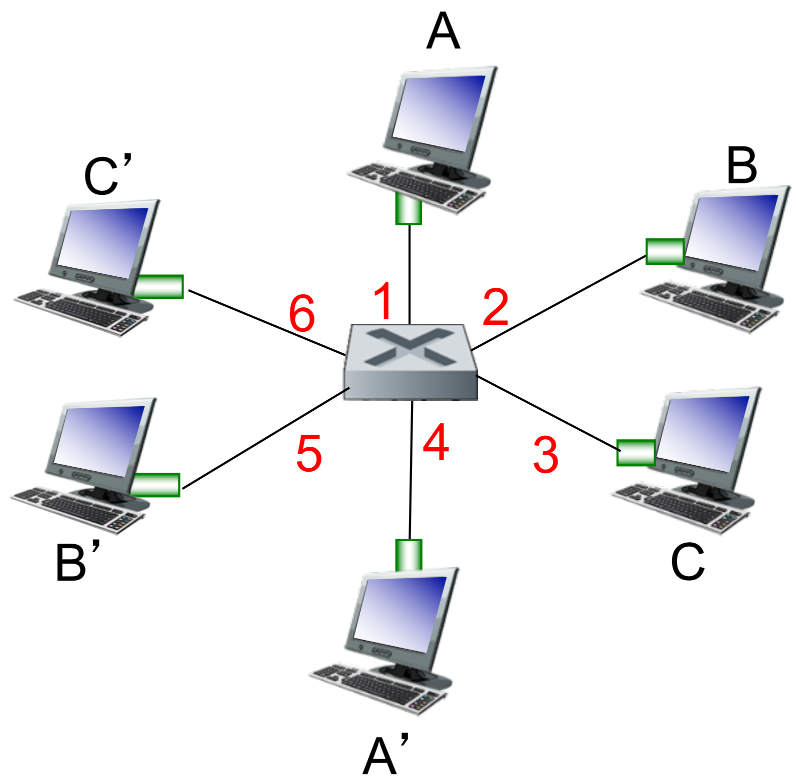
Ethernet switch

- link-layer device: takes an *active* role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, selectively forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment
- *transparent*
  - hosts are unaware of presence of switches
- *plug-and-play, self-learning*
  - switches do not need to be configured

Switch: *multiple* simultaneous transmissions

- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, but no collisions; full duplex
  - each link is its own collision domain
- *switching:* A-to-A' and B-to-B' can transmit simultaneously, without collisions

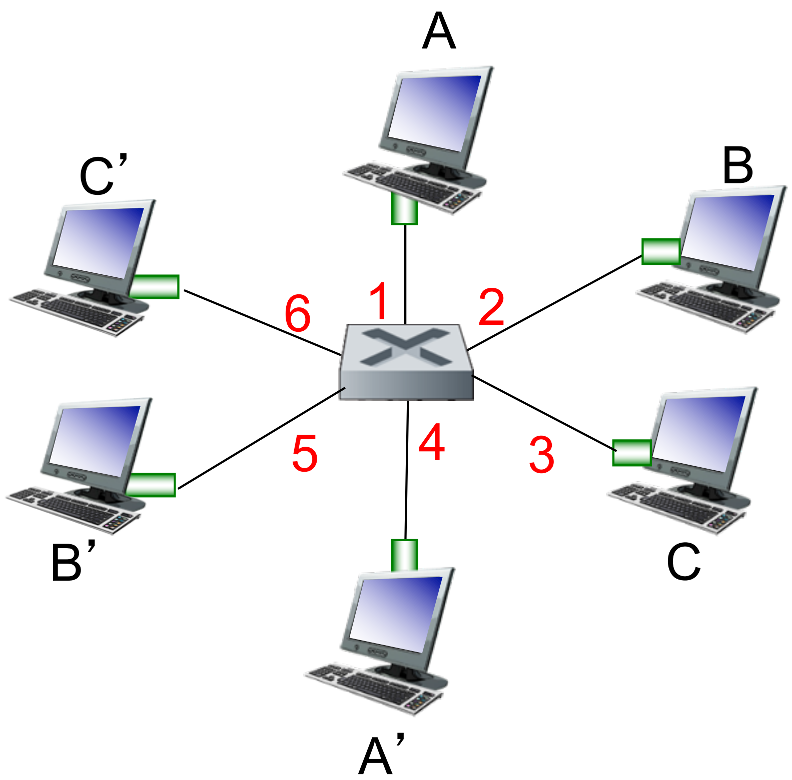


switch with six interfaces (1,2,3,4,5,6)

Switch forwarding table

Q: how does switch know A' reachable via interface 4, B' reachable via interface 5?

- *A: each switch has a switch table, each entry:*
  - *(MAC address of host, interface to reach host, time stamp)*
  - *looks like a routing table!*



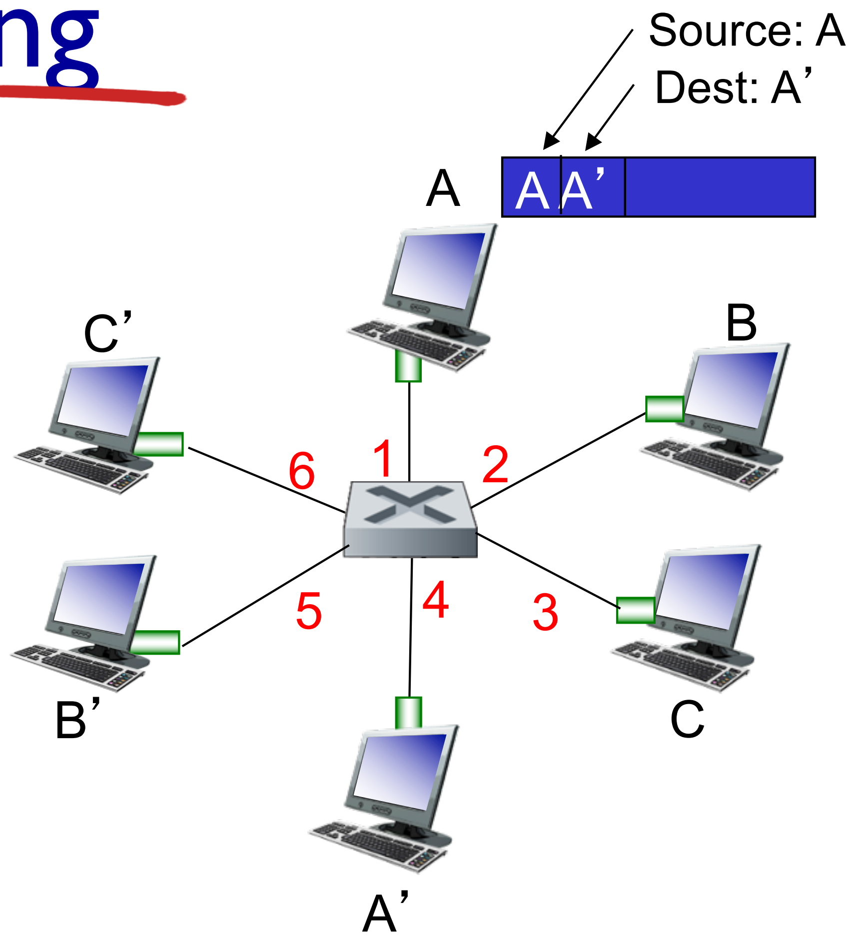
switch with six interfaces (1,2,3,4,5,6)

Q: how are entries created, maintained in switch table?

- *something like a routing protocol?*

Switch: self-learning

- switch *learns* which hosts can be reached through which interfaces
  - when frame received, switch "learns" location of sender: incoming LAN segment
  - records sender/location pair in switch table



MAC addr	interface	TTL
A	*1*	*60*

Switch table (initially empty)

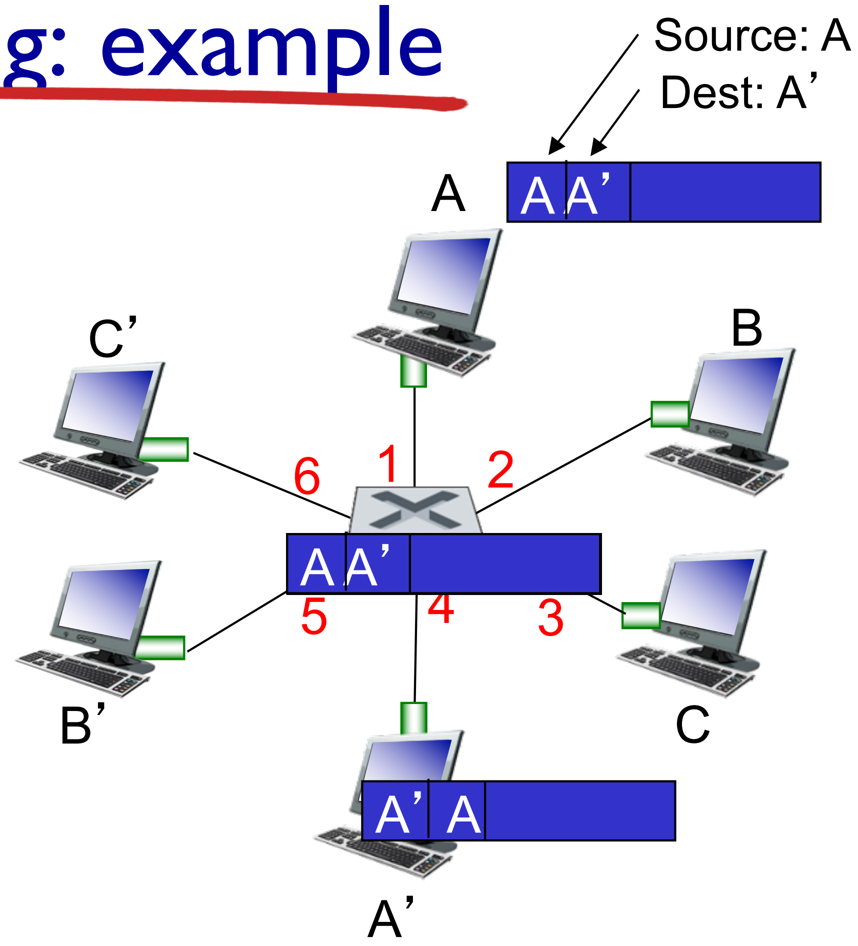
Switch: frame filtering/forwarding

when frame received at switch:

1. record incoming link, MAC address of sending host
2. index switch table using MAC destination address
3. if entry found for destination
   then {
   if destination on segment from which frame arrived
      then drop frame
      else forward frame on interface indicated by entry
   }
   else flood /* forward on all interfaces except arriving
                    interface */

Self-learning, forwarding: example

- frame destination, A', locaton unknown: *flood*
- destination A location known: *selectively send on just one link*

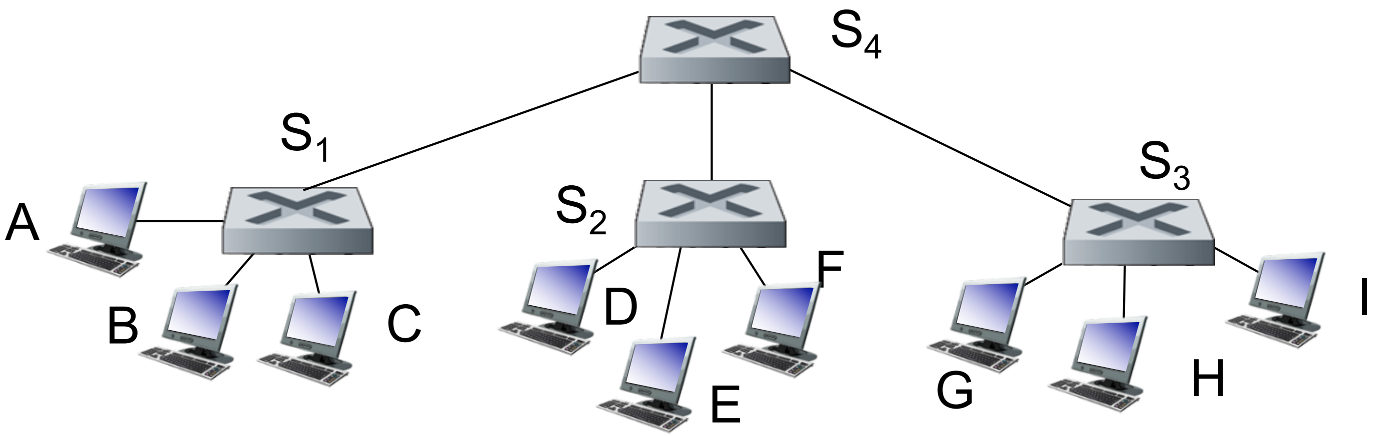


MAC addr	interface	TTL
A	*1*	*60*
A'	*4*	*60*

switch table (initially empty)

Interconnecting switches

- switches can be connected together

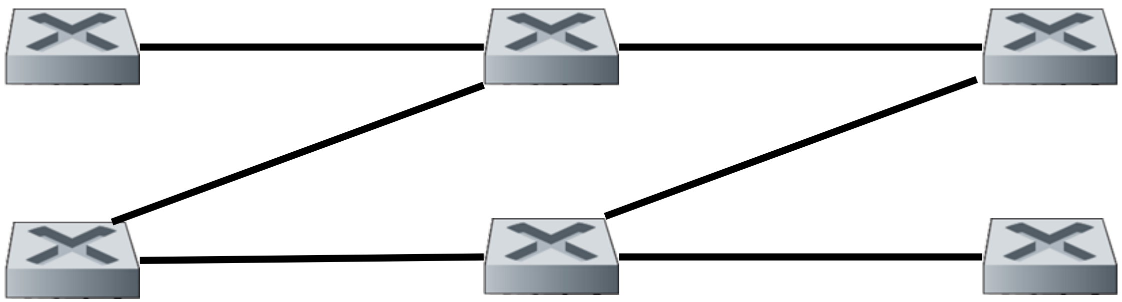


Q: sending from A to G - how does S_1 know to forward frame destined to G via S_4 and S_3?

- *A:* self learning! (works *exactly* the same as in single-switch case!)

Spanning Tree Protocol

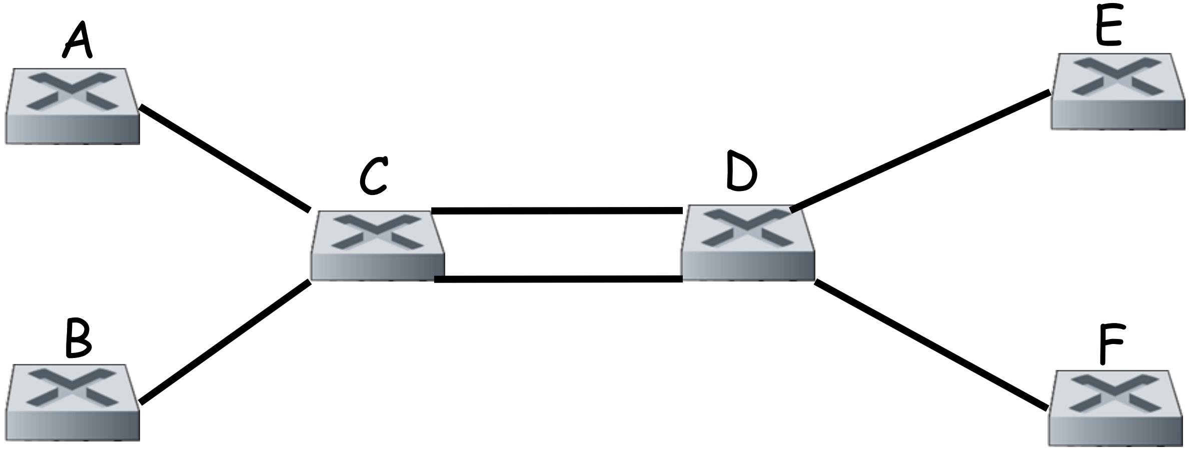
- Can we have loops in the topology ?



- For redundancy
- We want LAN switches to just work with any topology
    - Simple plug-and-play

Spanning Tree Protocol

- A→E



- Switches run the spanning tree protocol to find a loop free topology to reach all the switches
- A subset of the links are used in the form of tree
  - Some links are shutdown
- Multiple ST are possible

Spanning Tree Protocol

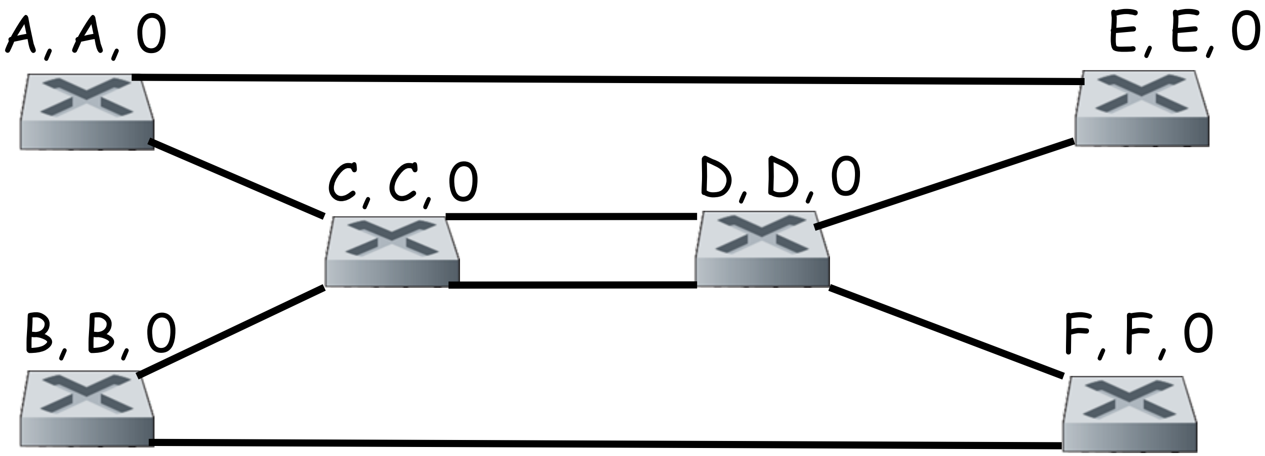
- All switches run the algorithm in parallel
- They start with no information
- Send messages to find out the links to other switches
- Can adapt to link changes/switch failures

Spanning Tree Protocol

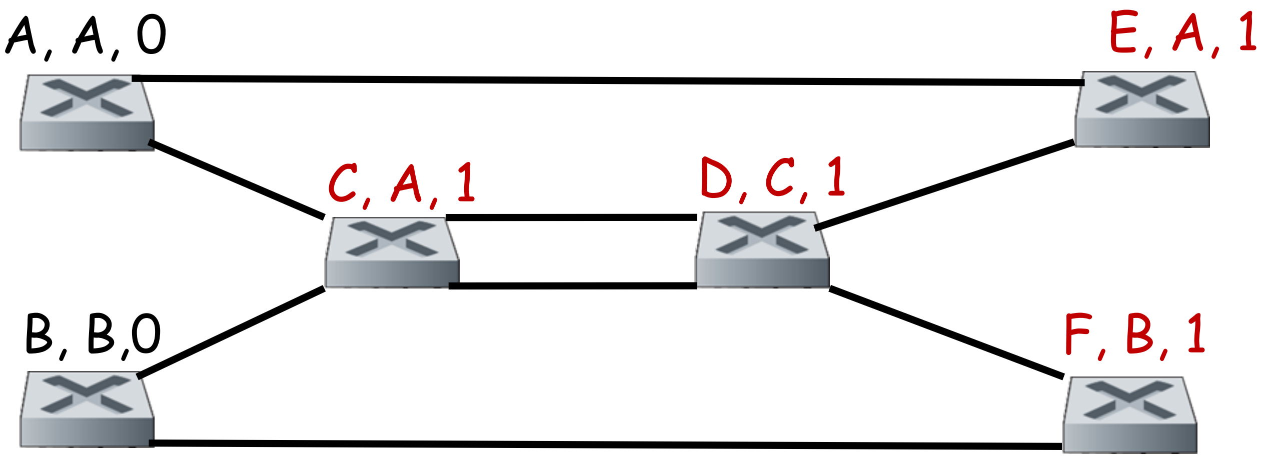
1. Elect a root node of the tree
   (Switch with lowest address)
2. Grow tree as shortest distances from the tree (use lowest address to break distance ties)
3. Turn off ports for forwarding if they are not part of the spanning tree

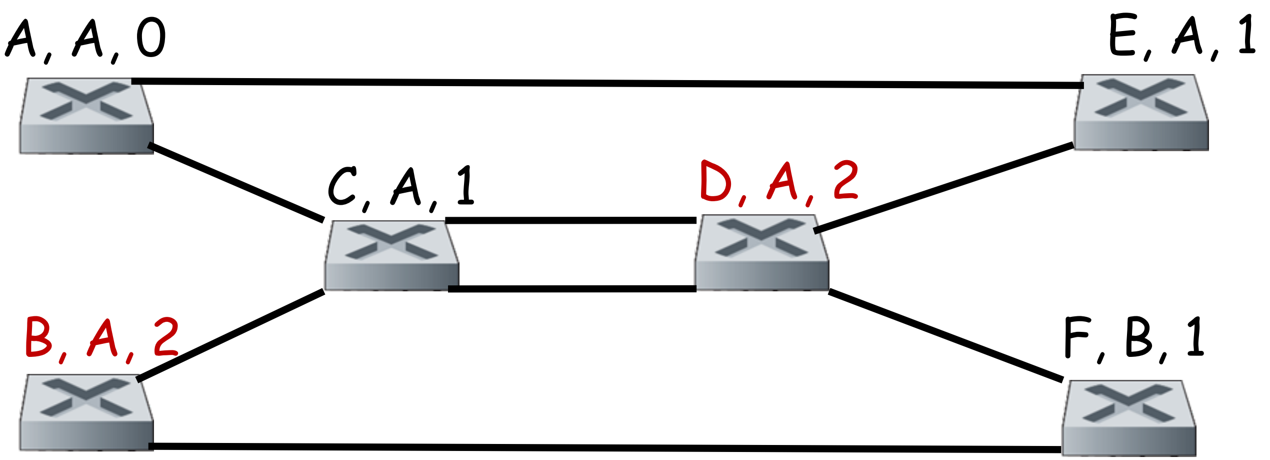
Spanning Tree Protocol

- Each switch initially believes it is the root
- Each switch sends periodic updates to neighbors
  Address, address of root, distance in hops to root
- Switches favors ports with shorter distance to root

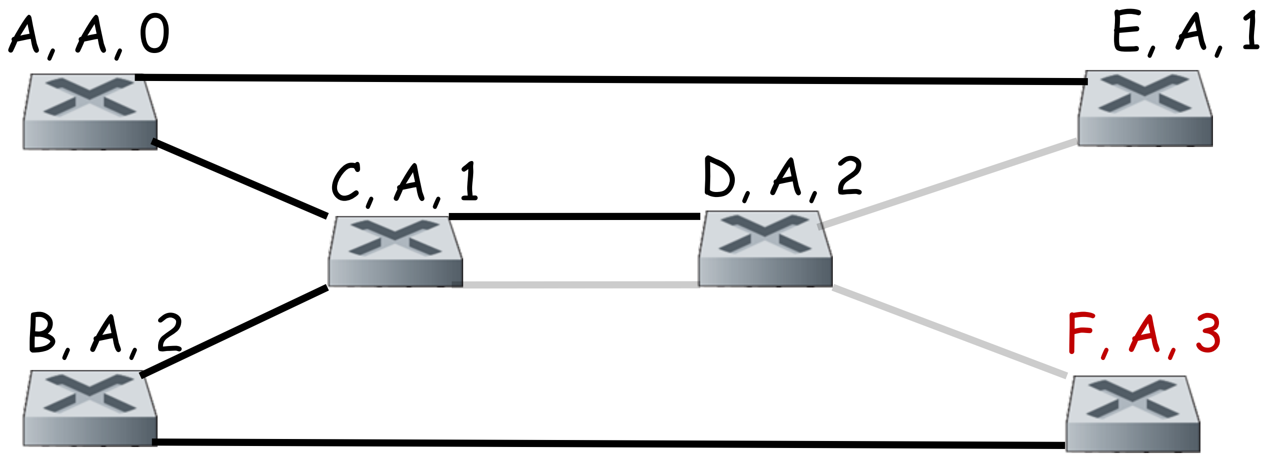


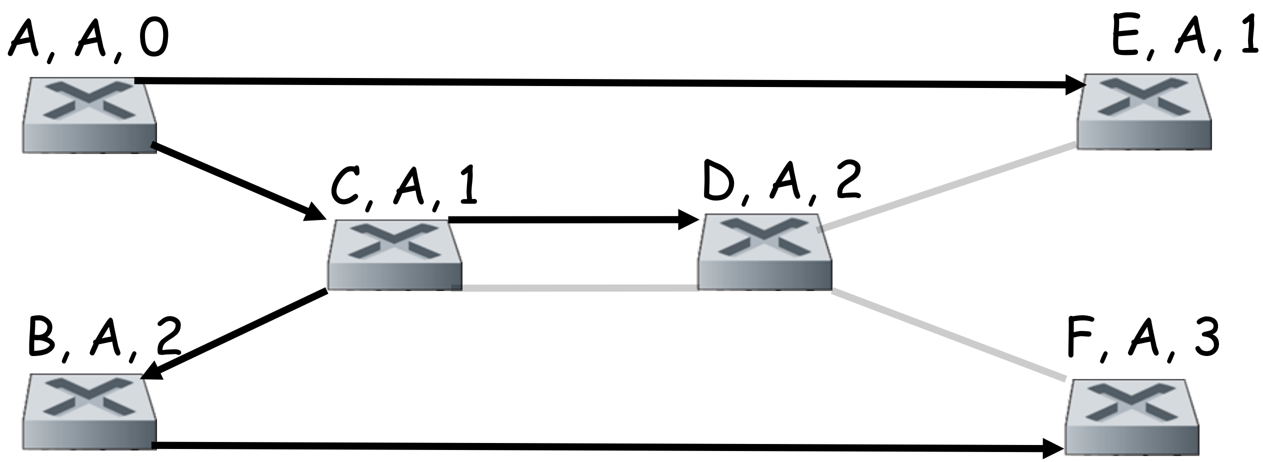
Spanning Tree Protocol



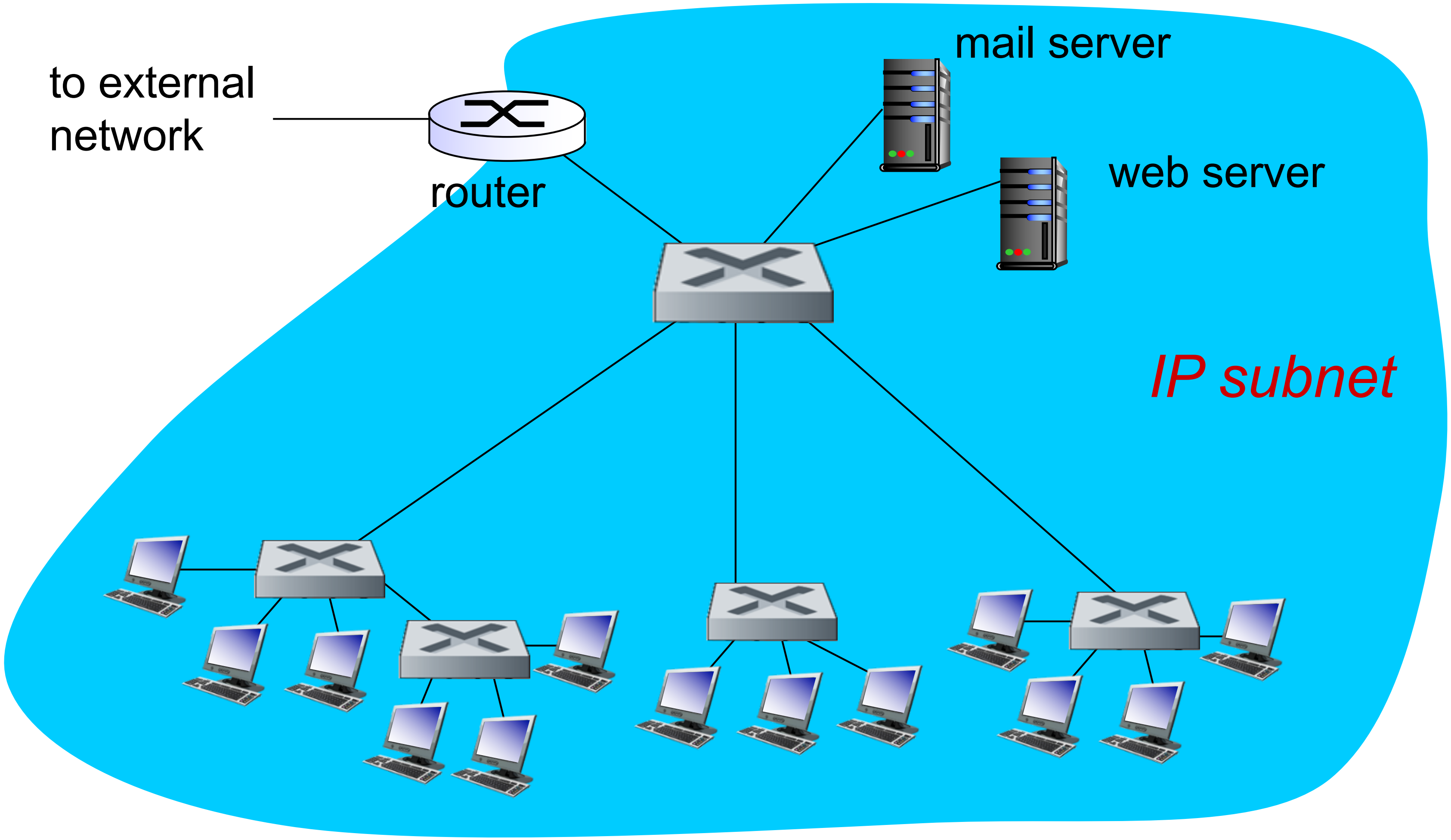


Spanning Tree Protocol





Institutional network



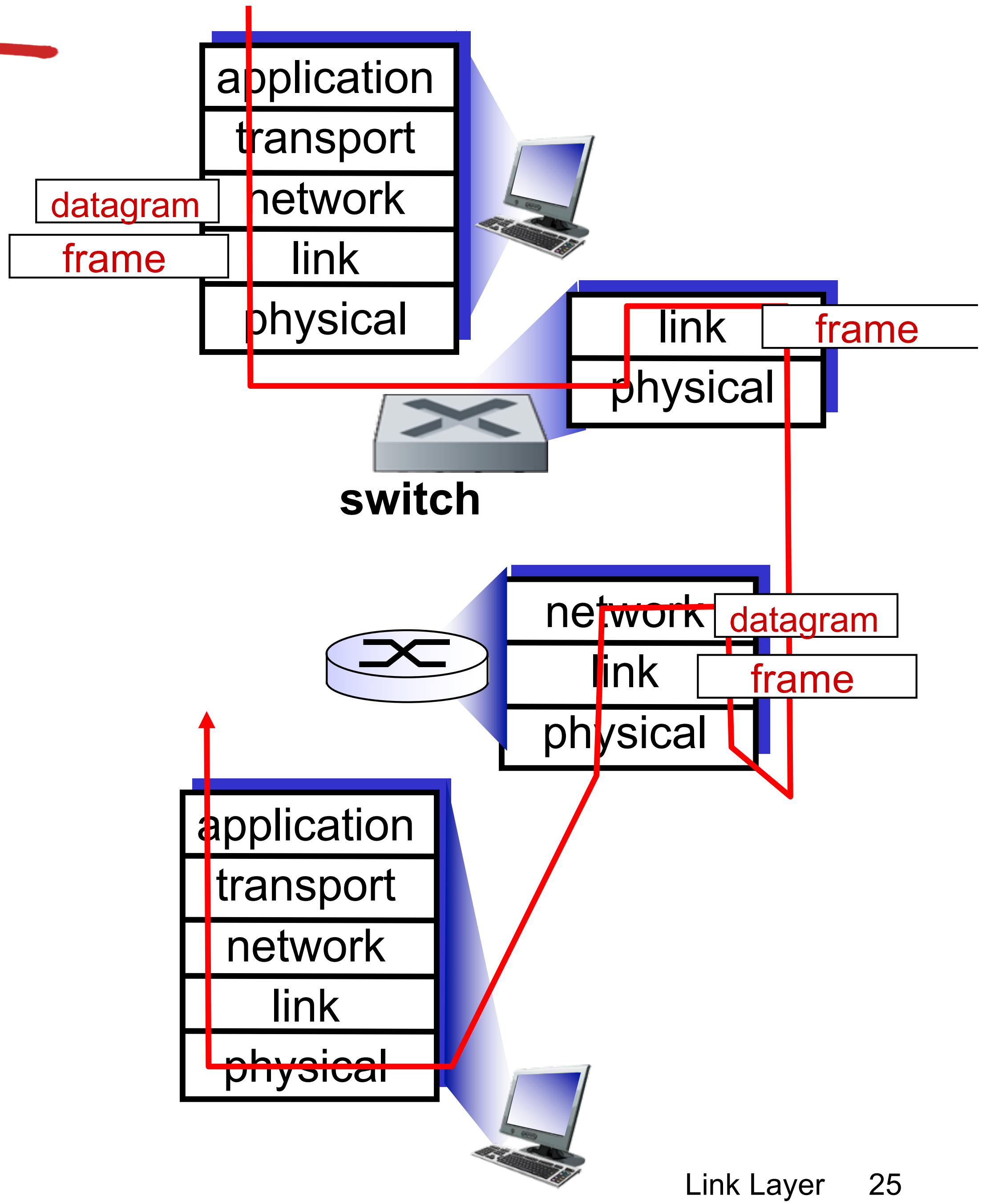
Switches vs. routers

both are store-and-forward:

- *routers:* network-layer devices (examine network-layer headers)
- *switches*: link-layer devices (examine link-layer headers)

both have forwarding tables:

- *routers:* compute tables using routing algorithms, IP addresses
- *switches:* learn forwarding table using flooding, learning, MAC addresses



Security Issues

- In a switched LAN once the switch table entries are established frames are not broadcast
  - Sniffing frames is harder than pure broadcast LANs
  - Note: attacker can still sniff broadcast frames and frames for which there are no entries (as they are broadcast)
- Switch Poisoning: Attacker fills up switch table with bogus entries by sending large # of frames with bogus source MAC addresses
- Since switch table is full, genuine packets frequently need to be broadcast as previous entries have been wiped out

Link Layer: Summary

- principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
- instantiation and implementation of various link layer technologies
  - Ethernet
  - switched LANS

Link Layer: let's take a breath

- journey down protocol stack *complete* (except PHY)
- solid understanding of networking principles, practice
- ….. could stop here …. but *lots* of interesting topics!
  - **wireless**
  - multimedia
  - **security**
  - network management

Wireless Networks

Background:

- # wireless (mobile) phone subscribers now exceeds # wired phone subscribers (5-to-1)!
- # wireless Internet-connected devices equals # wireline Internet-connected devices
  - laptops, Internet-enabled phones promise anytime untethered Internet access
- two important (but different) challenges
  - *wireless:* communication over wireless link
  - *mobility:* handling the mobile user who changes point of attachment to network

We will only focus on wireless challenges

Outline

7.1 Introduction

Wireless

7.2 Wireless links, characteristics

- CDMA

7.3 IEEE 802.11 wireless LANs ("Wi-Fi")

Wireless 101

- **Frequency/Wave-Length –**

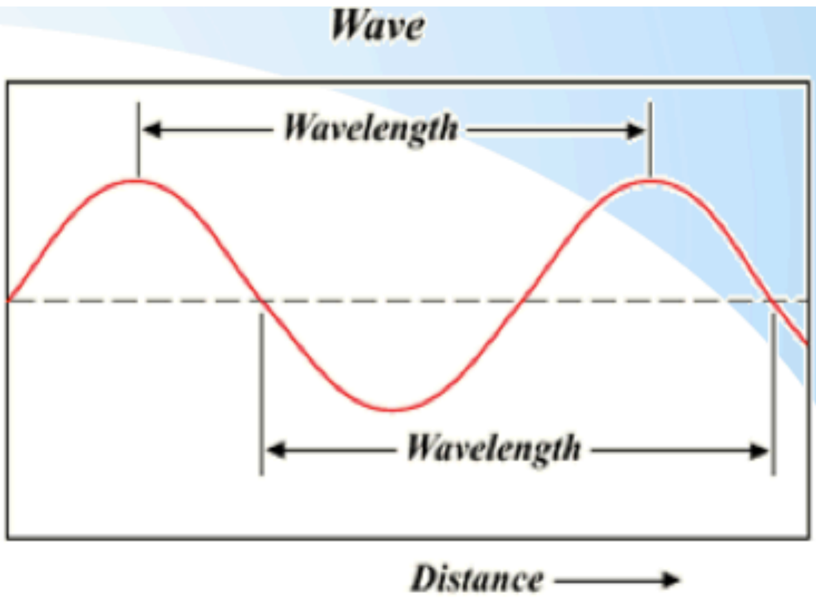
C is the speed of light
f is frequency
λ (lambda) is wavelength

Wavelength

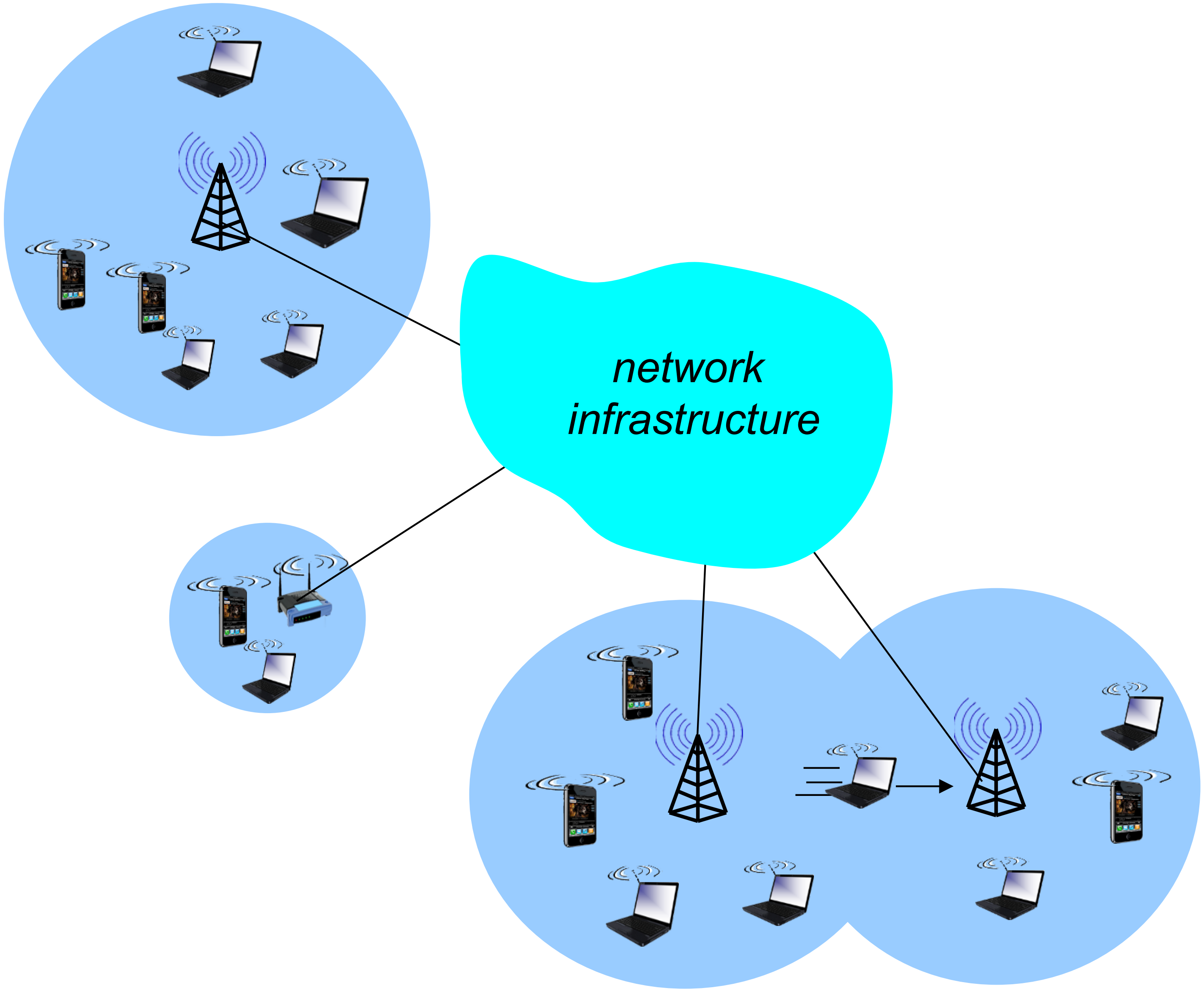
$$\lambda = \frac{C}{f}$$

Frequency

$$f = \frac{C}{\lambda}$$



Elements of a wireless network



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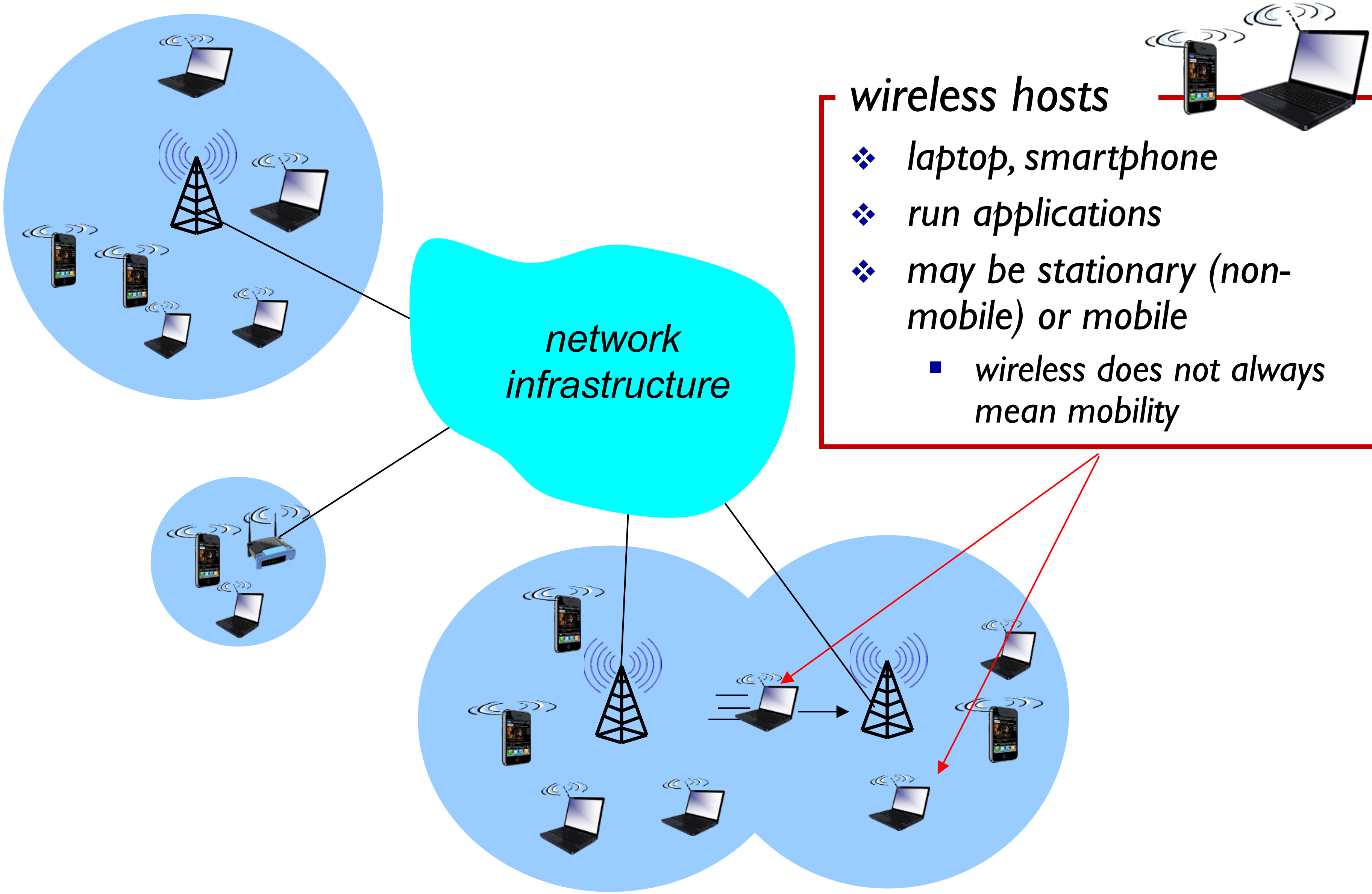
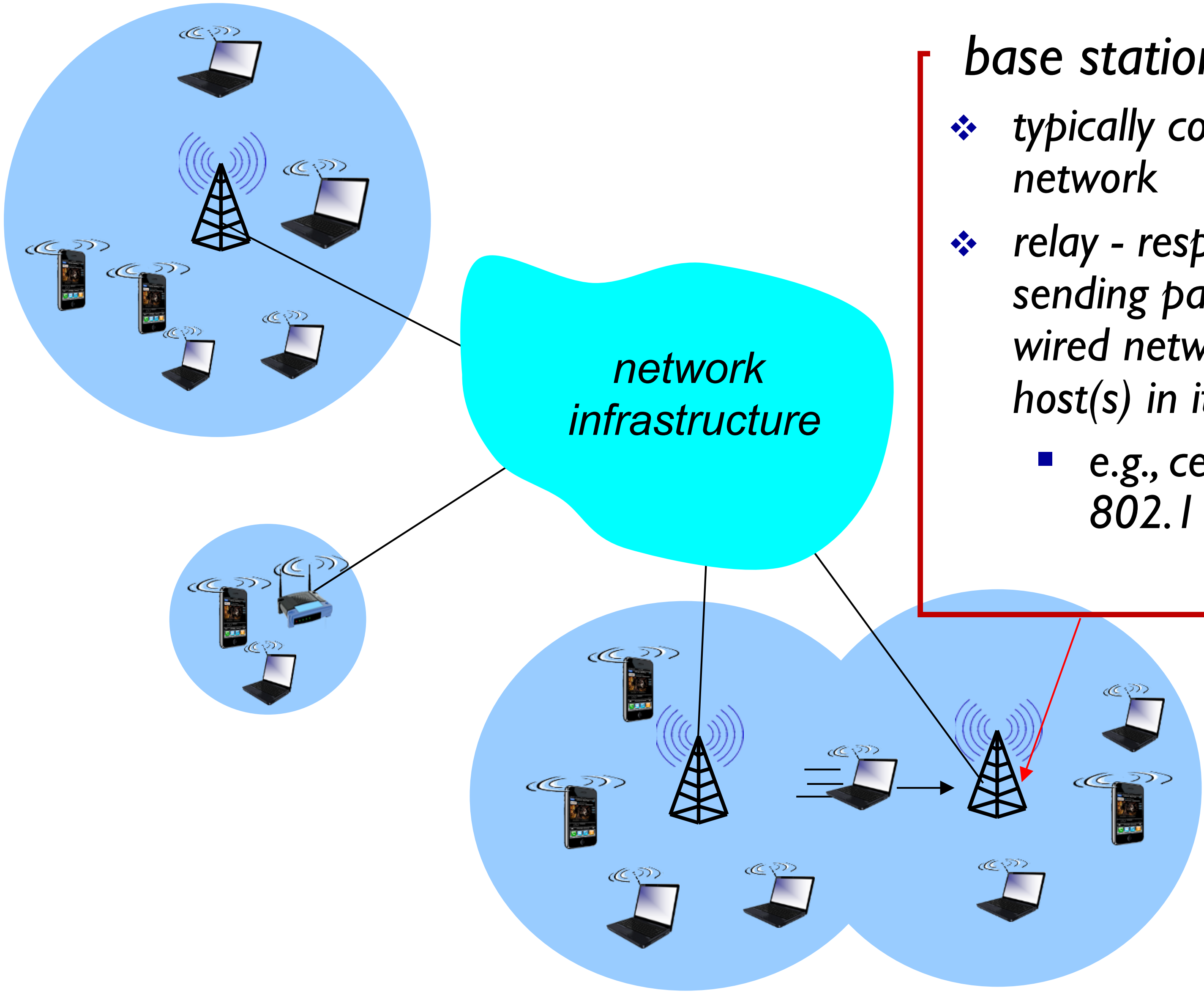


wireless hosts

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

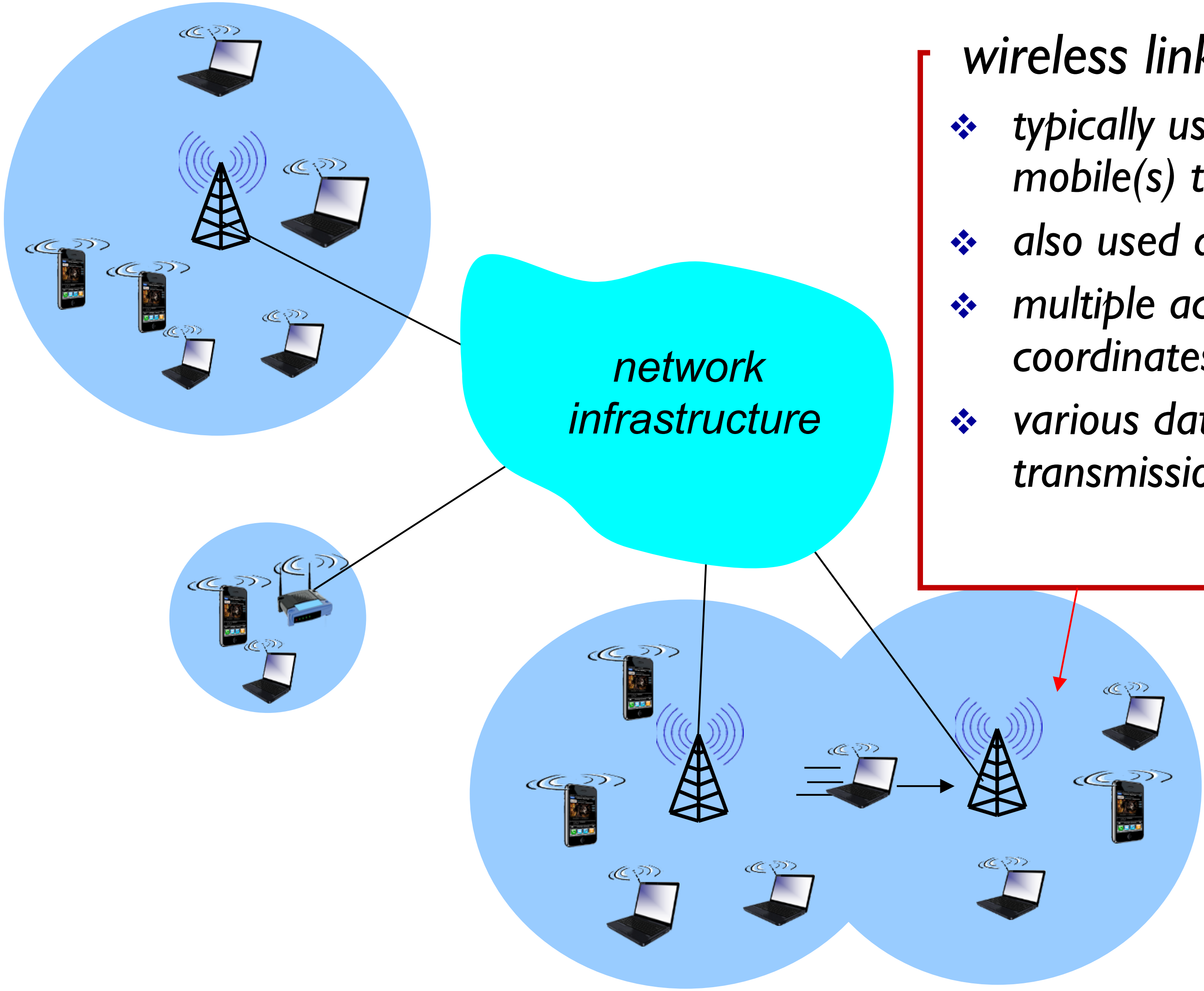
Elements of a wireless network



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*

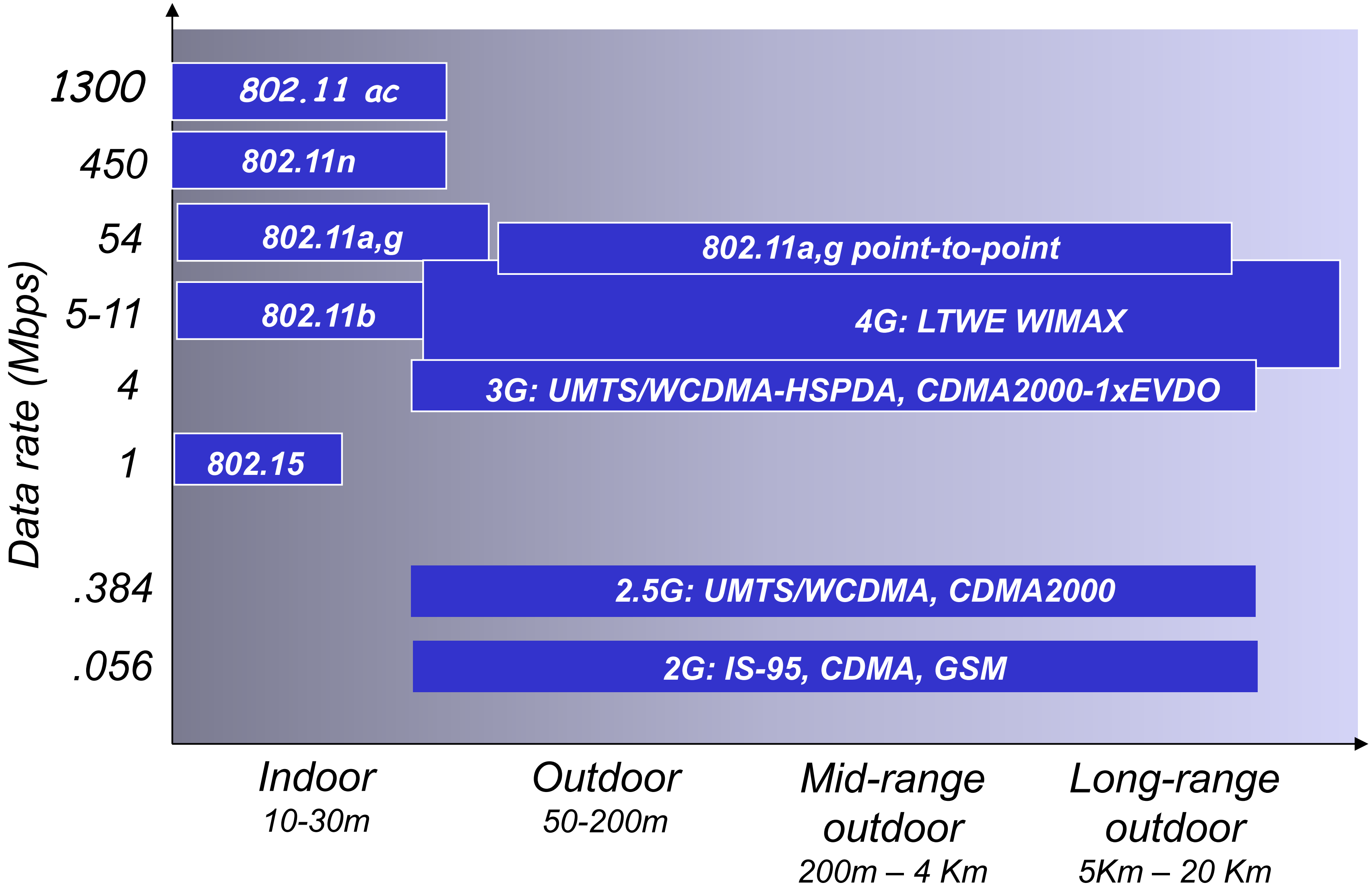
Elements of a wireless network



wireless link

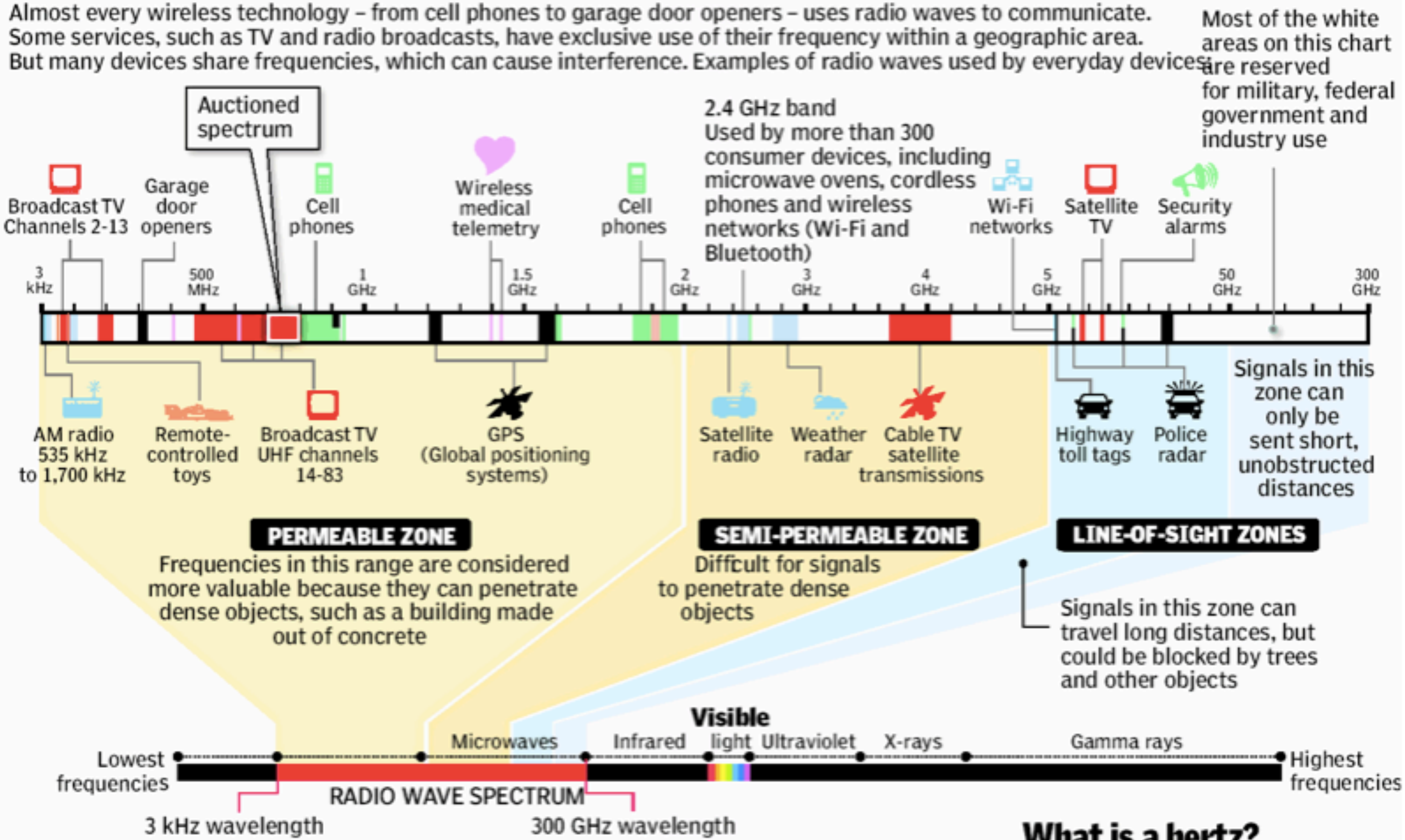
- *typically used to connect mobile(s) to base station*
- *also used as backbone link*
- *multiple access protocol coordinates link access*
- *various data rates, transmission distance*

Characteristics of selected wireless links



Inside the radio wave spectrum

Almost every wireless technology – from cell phones to garage door openers – uses radio waves to communicate. Some services, such as TV and radio broadcasts, have exclusive use of their frequency within a geographic area. But many devices share frequencies, which can cause interference. Examples of radio waves used by everyday devices:



The electromagnetic spectrum

Radio waves occupy part of the electromagnetic spectrum, a range of electric and magnetic waves of different lengths that travel at the speed of light; other parts of the spectrum include visible light and x-rays; the shortest wavelengths have the highest frequency, measured in hertz

What is a hertz?

One hertz is one cycle per second. For radio waves, a cycle is the distance from wave crest to crest

1 kilohertz (kHz) = 1,000 hertz

1 megahertz (MHz) = 1 million hertz

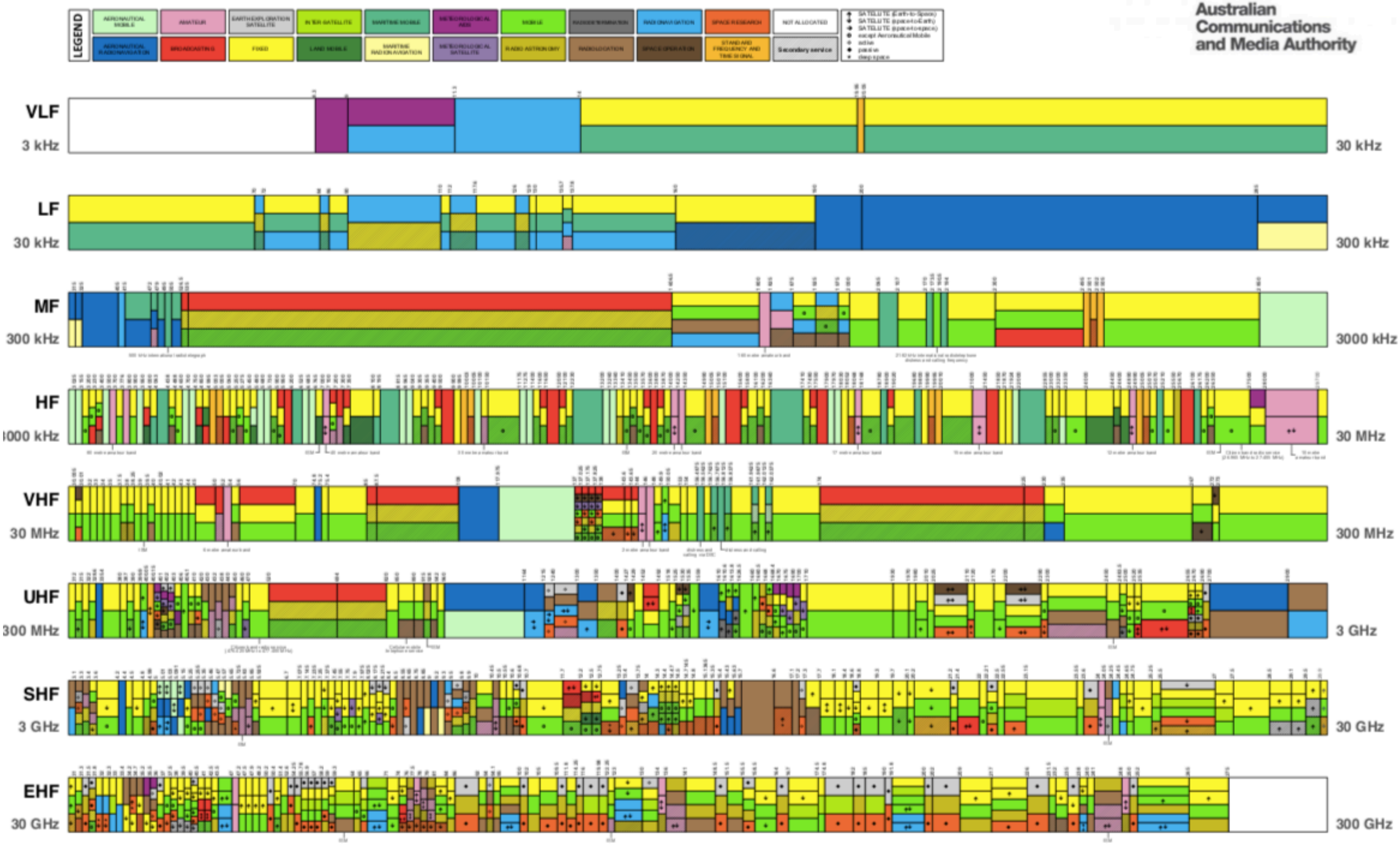
1 gigahertz (GHz) = 1 billion hertz

Source: New America Foundation, MCT, Howstuffworks.com
Graphic: Nathaniel Levine, Sacramento Bee

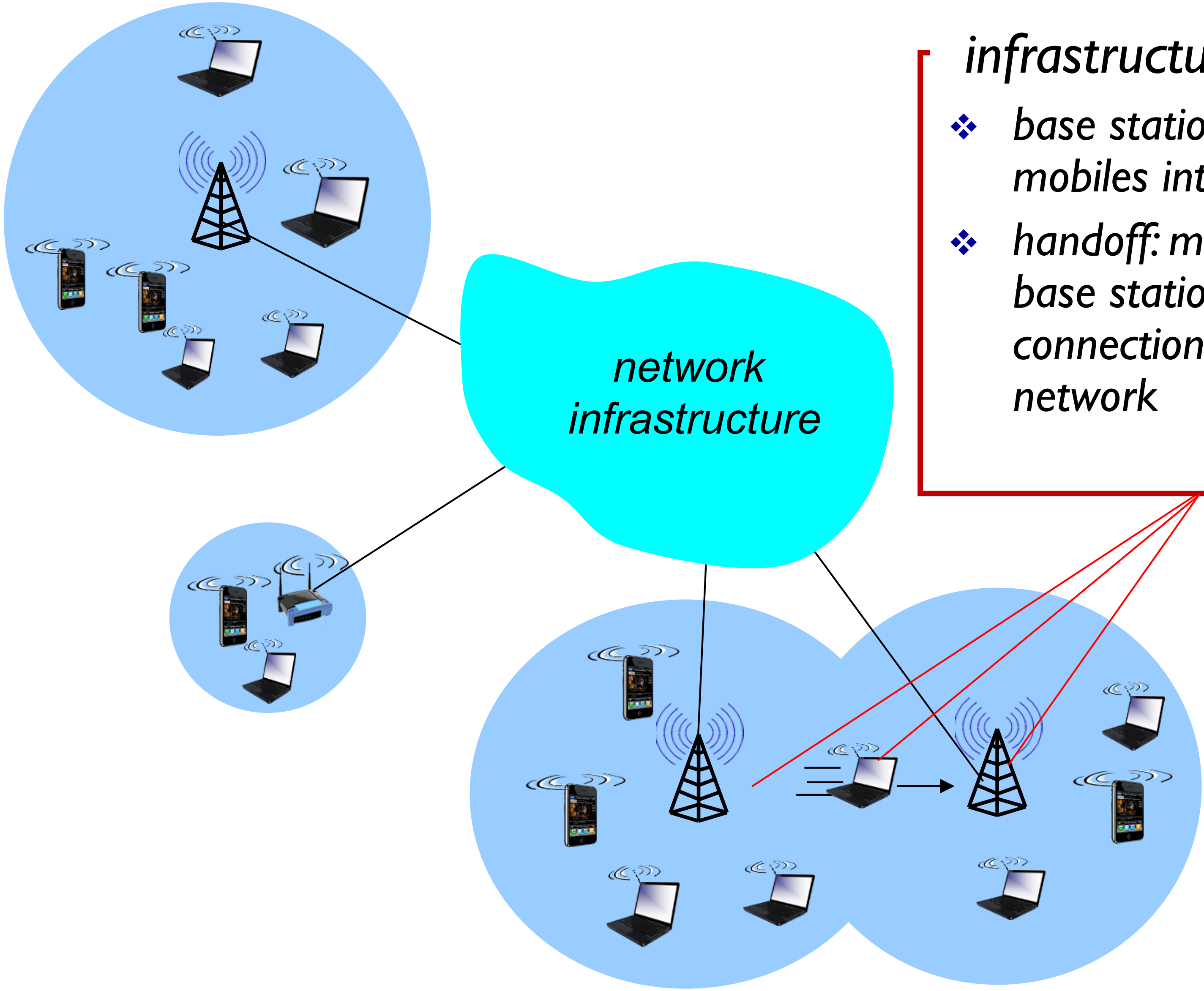
Australian radiofrequency spectrum
allocations chart

Australian Government

acma Australian Communications and Media Authority



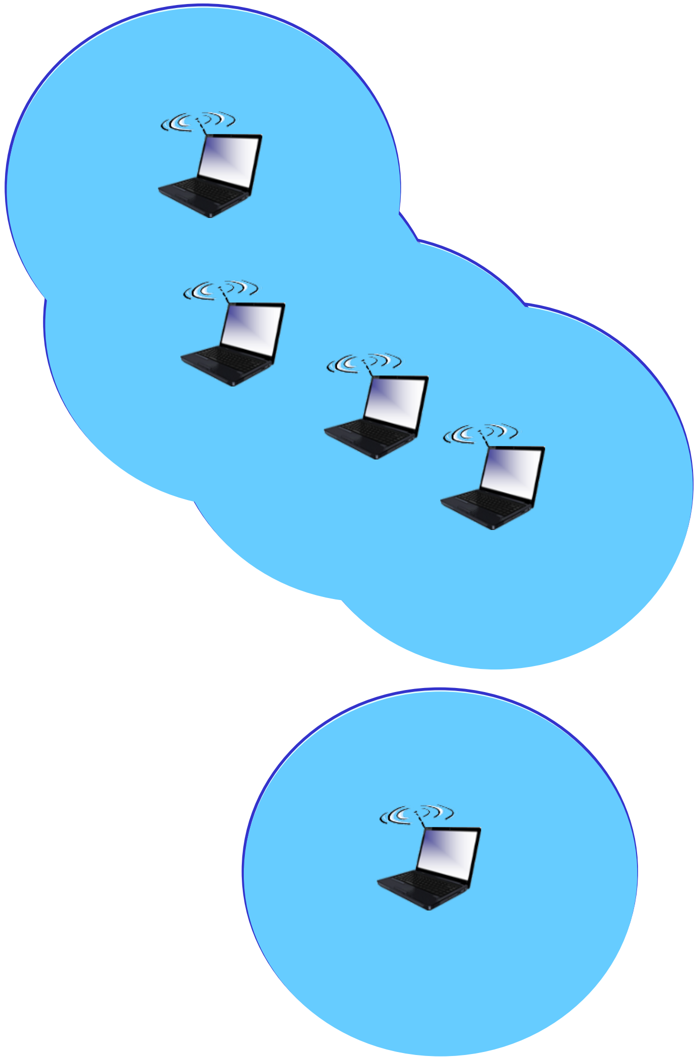
Elements of a wireless network



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, WiMAX, 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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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:* standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- *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"

Path Loss/Path Attenuation

- Free Space Path Loss

  d: distance

  λ: wavelength

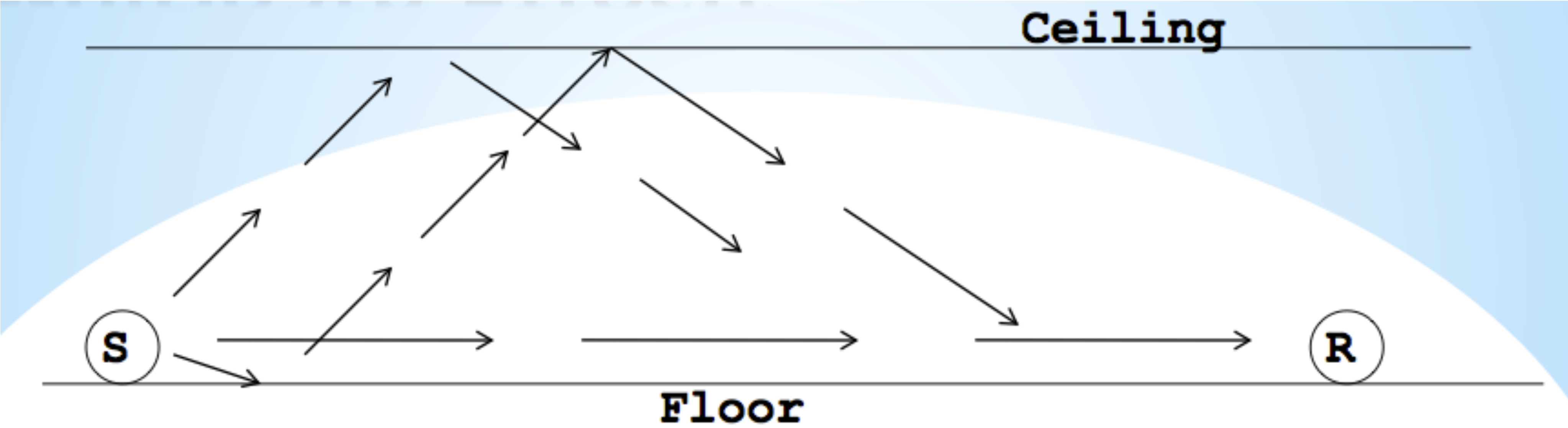
  f: frequency

  c: speed of light

$$\text{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$$

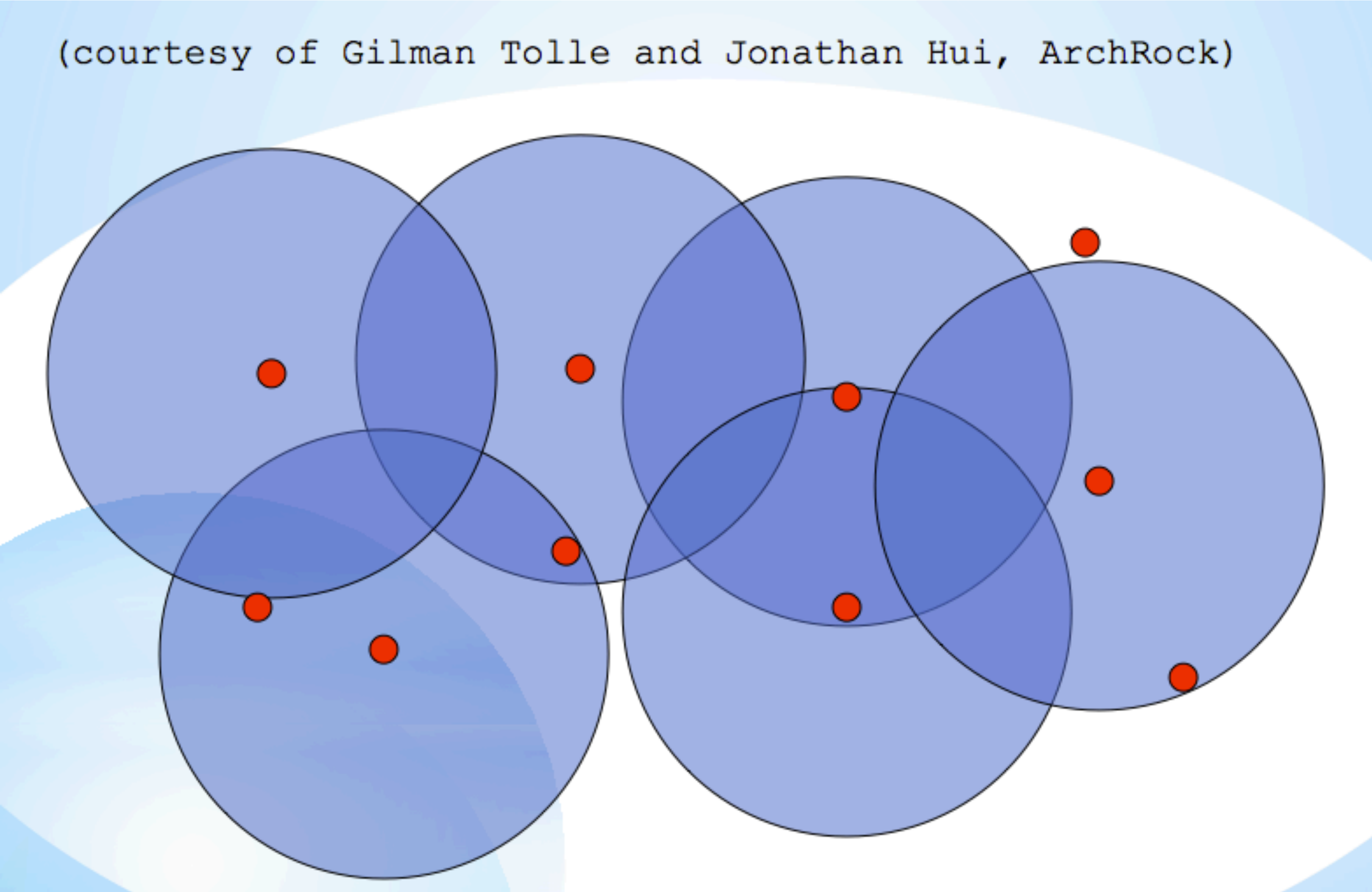
- Reflection, Diffraction, Absorption
- Terrain contours (urban, rural, vegetation)
- Humidity

Multipath Effects

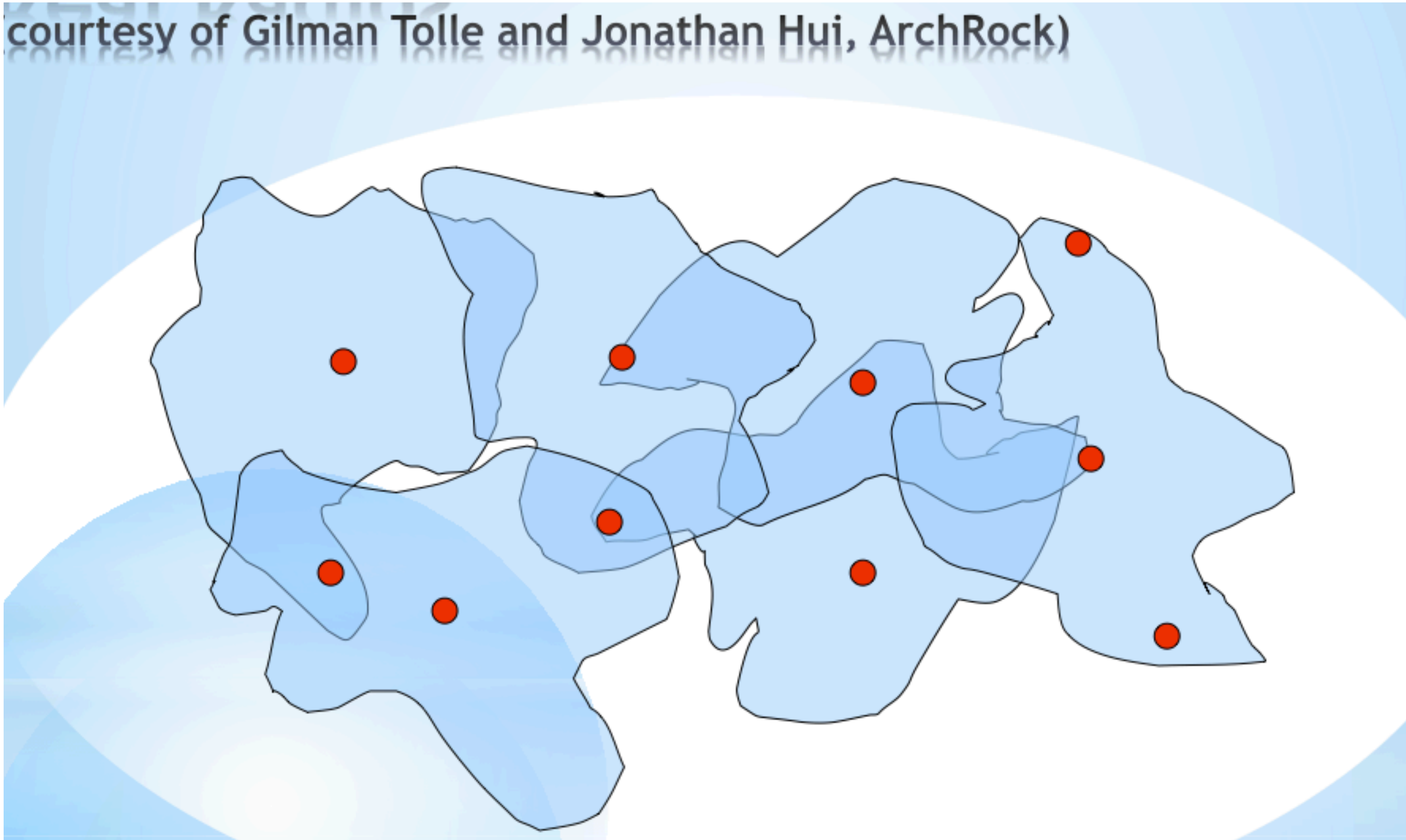


- Signals bounce off surface and interfere (constructive or destructive) with one another
- Self-interference

Ideal Radios

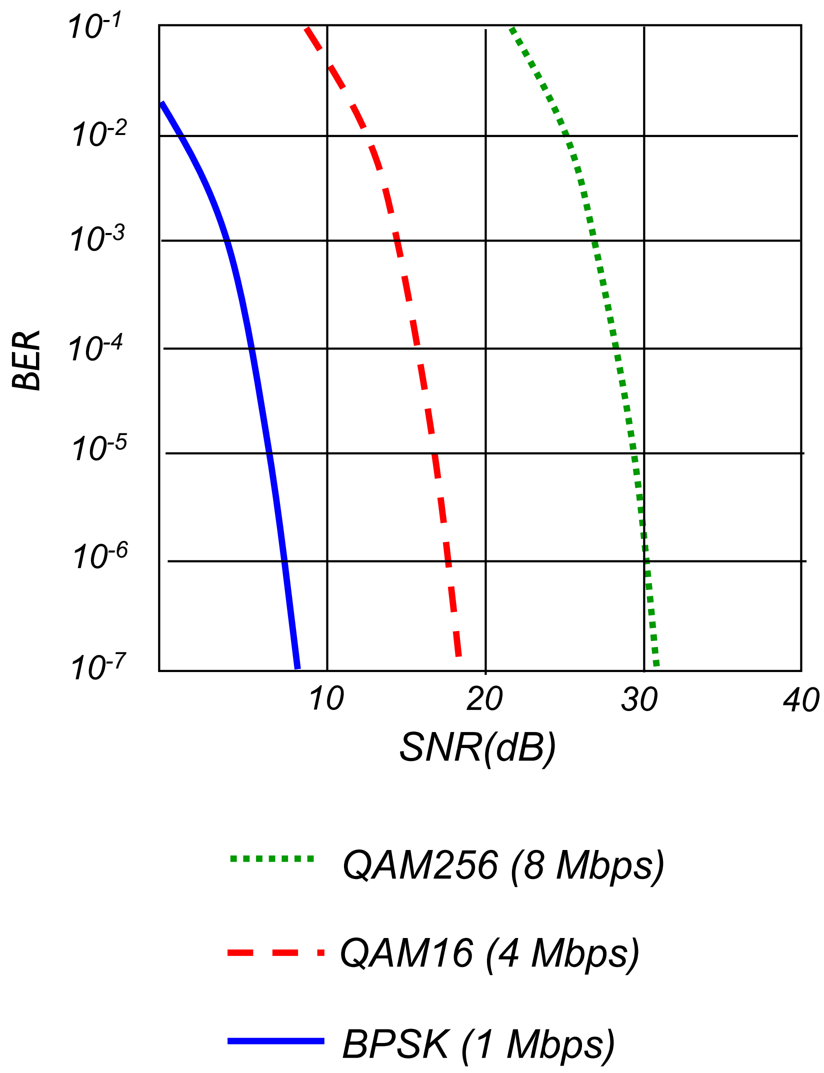


Real Radios



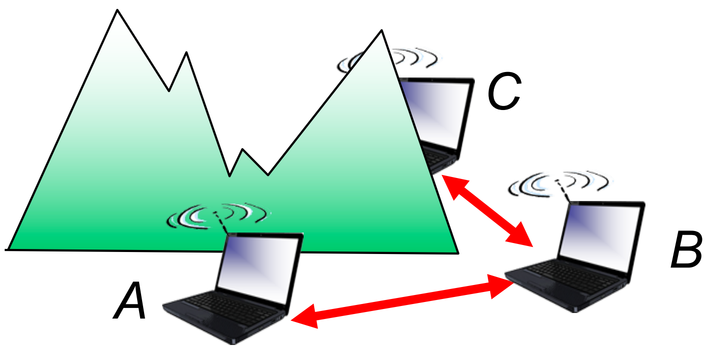
Wireless Link Characteristics (2)

- 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 thruput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



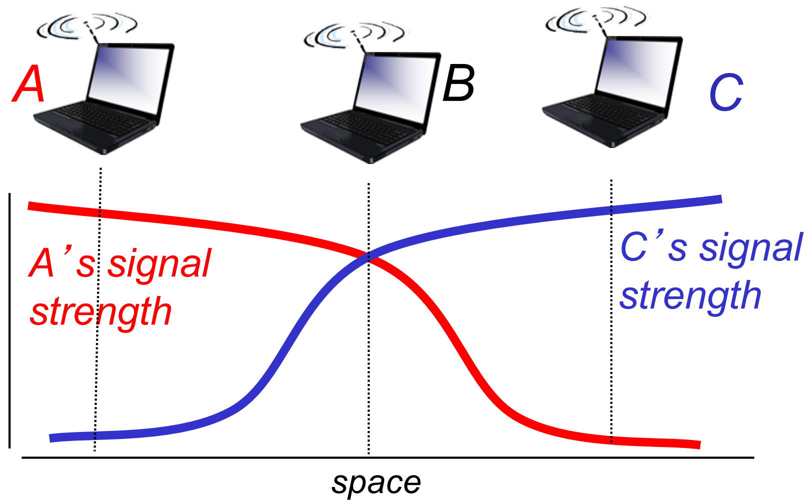
Wireless network characteristics

Multiple wireless senders and 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*
- *Carrier sense will be ineffective*

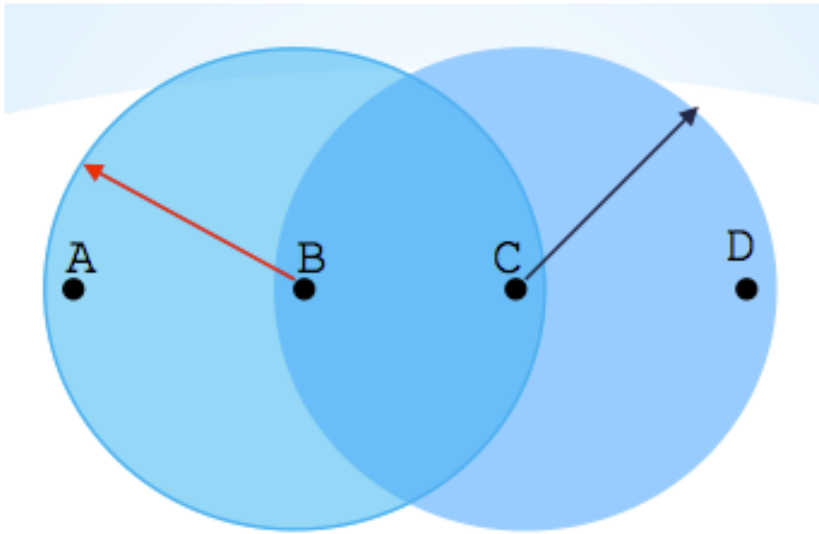


Signal attenuation:

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

Wireless network characteristics

- Exposed Terminals



- Node B sends a packet to A; C hears this and decides not to send a packet to D (despite the fact that this will not cause interference) !!
- Carrier sense would prevent a successful transmission

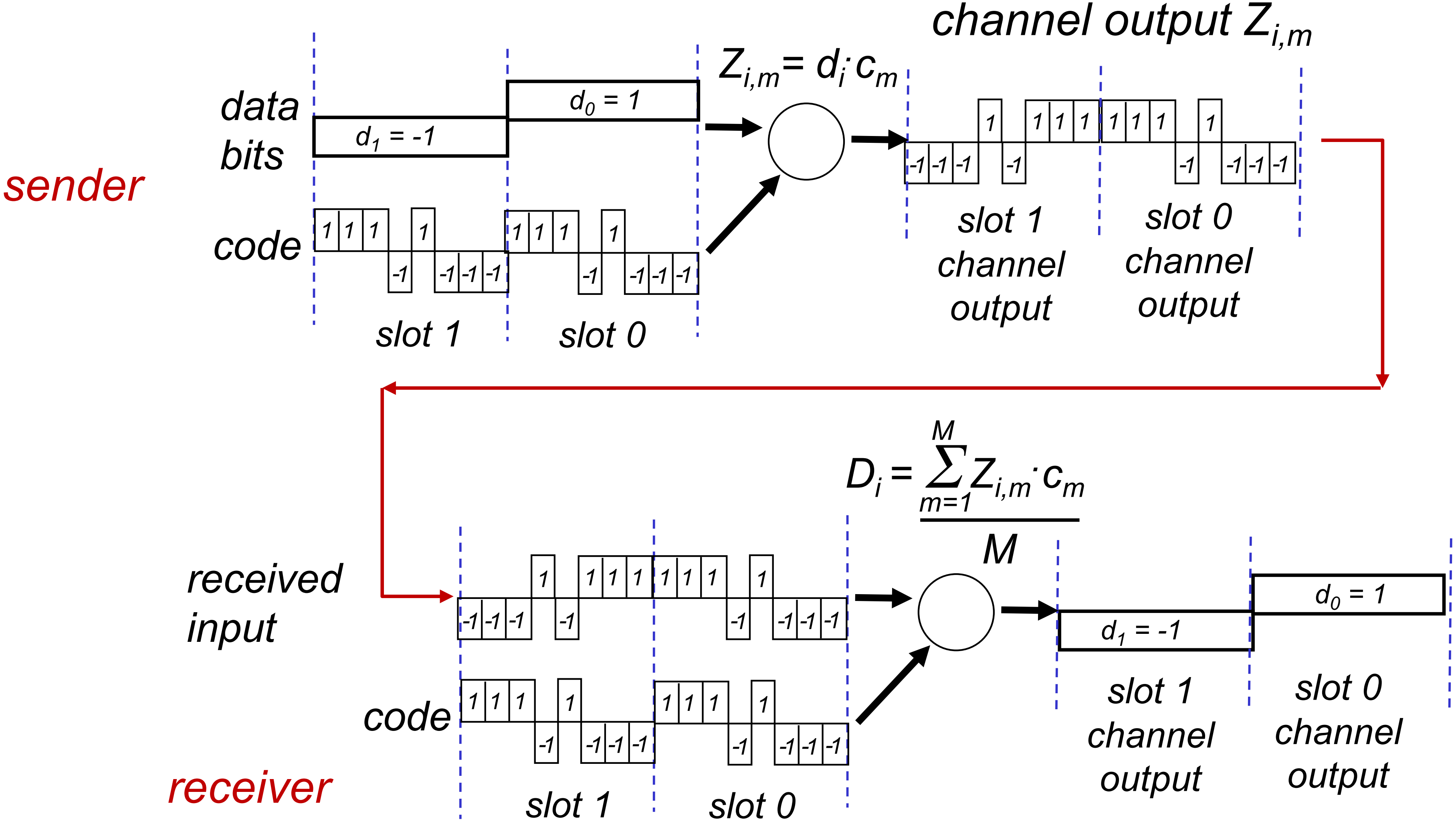
Code Division Multiple Access (CDMA)

- 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")
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence

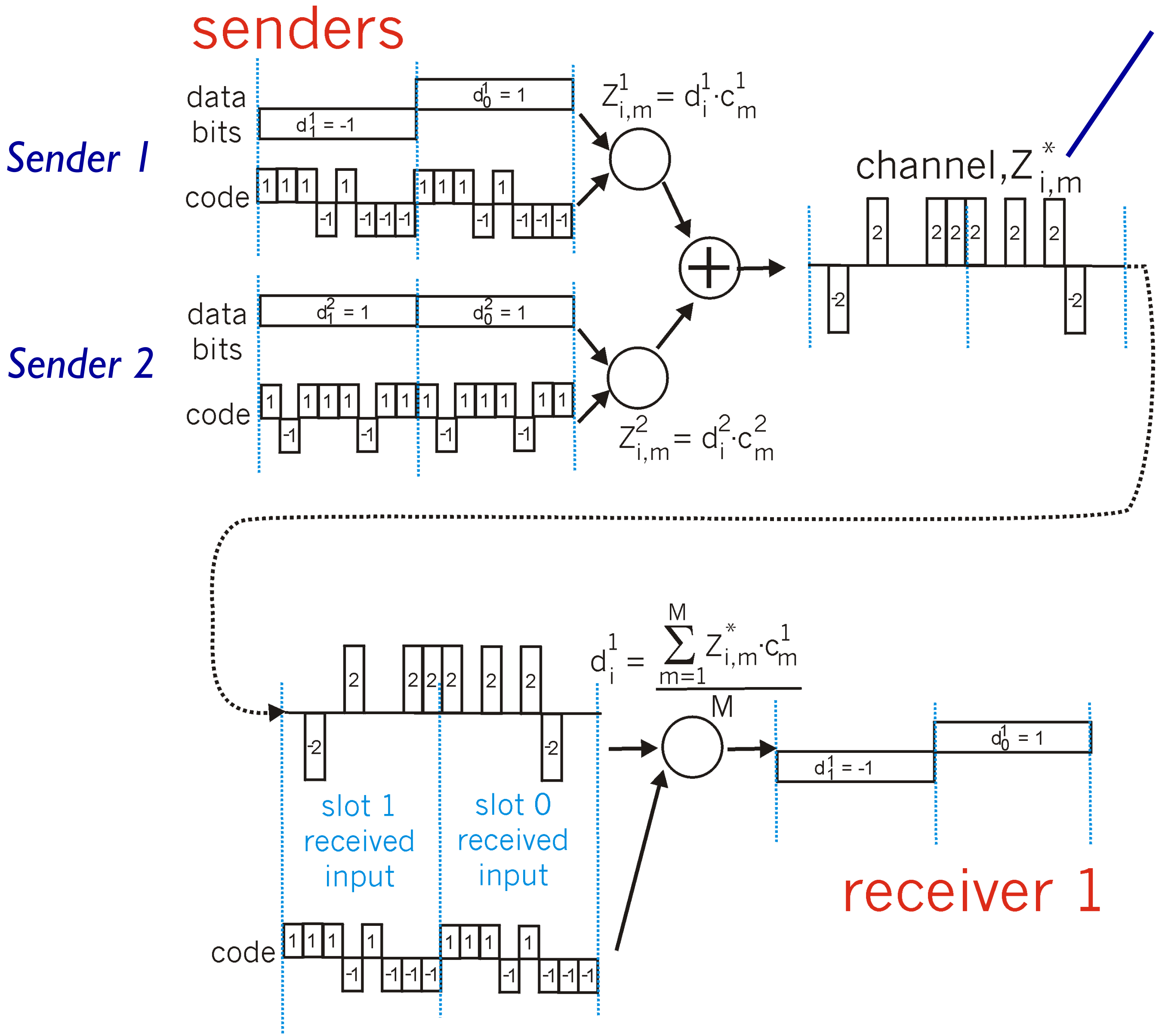
CDMA: Encoding and Decoding

- Assume original data are represented by 1 and -1
- *Encoded signal* = (original data) modulated by (chipping sequence)
  - assume c_m = 1 1 1 -1 1 -1 -1 -1
  - if data is 1, send 1 1 1 -1 1 -1 -1 -1
  - if data is -1 send -1 -1 -1 1 -1 1 1 1
- *Decoding:* inner-product (summation of bit-by-bit product) of encoded signal and chipping sequence
  - if inner-product > threshold, the data is 1; else -1

CDMA encode/decode



CDMA: two-sender interference



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!

CDMA codes

- CDMA codes are orthogonal.
- E.g: (1,1,1,-1,1,-1,-1,-1) and (1,-1,1,1,1,-1,1,1)
- Inner product of the codes should be zero

C_1:	1	1	1	-1	1	-1	-1	-1
C_2:	1	-1	1	1	1	-1	1	1

$C_1 . C_2 = 1 + (-1) + 1 + (-1) + 1 + 1 + (-1) + (-1) = 0$

- If there are multiple CDMA codes all of the codes have to be orthogonal to each other.
  - E.g: 3 codes: C1, C2 and C3. Then C1 x C2 = 0, C2 x C3 = 0 and C1 x C3 = 0

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- CDMA

7.3 IEEE 802.11 wireless LANs ("Wi-Fi")

IEEE 802.11 Wireless LAN

802.11b
- 2.4-5 GHz unlicensed spectrum
- up to 11 Mbps
- direct sequence spread spectrum (DSSS) in physical layer
  - all hosts use same chipping code

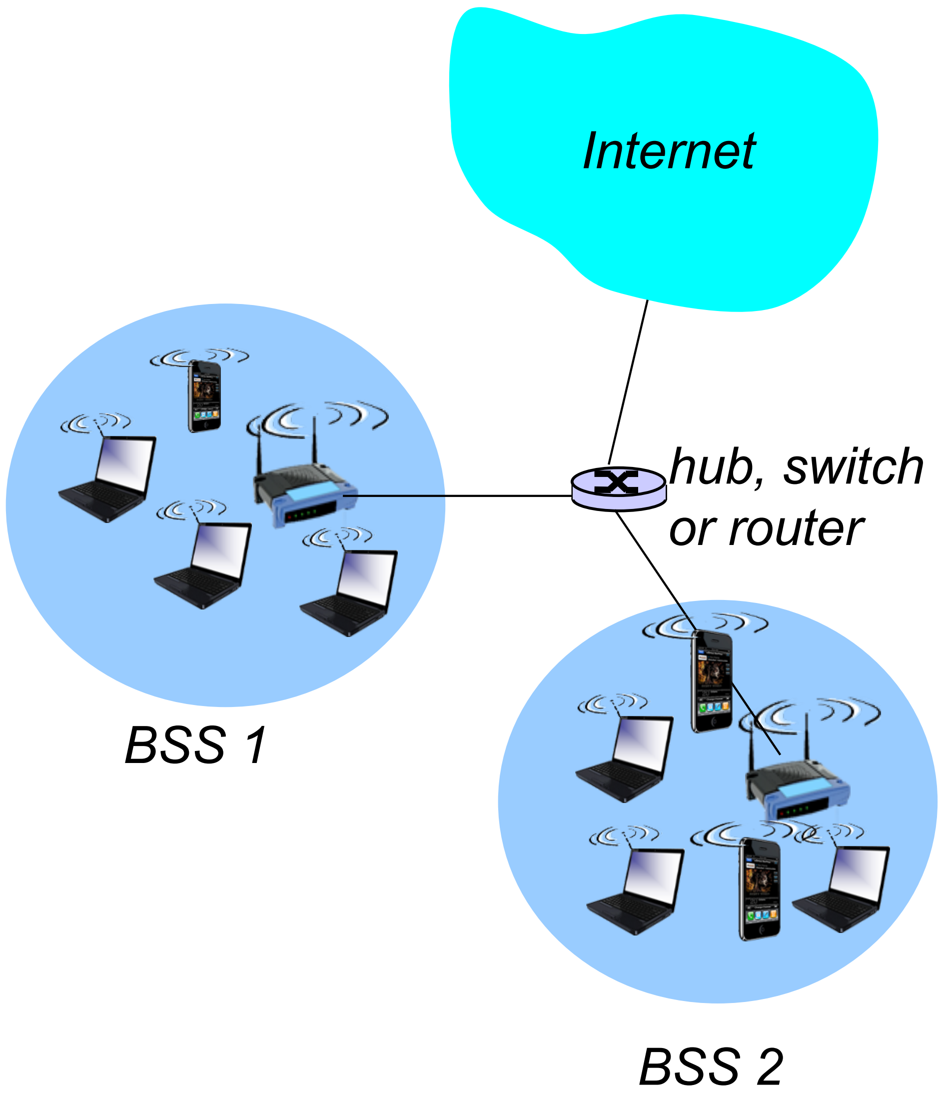
802.11a
- 5-6 GHz range
- up to 54 Mbps

802.11g
- 2.4-5 GHz range
- up to 54 Mbps

802.11n: multiple antennae
- 2.4-5 GHz range
- up to 200 Mbps

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

802.11 LAN architecture

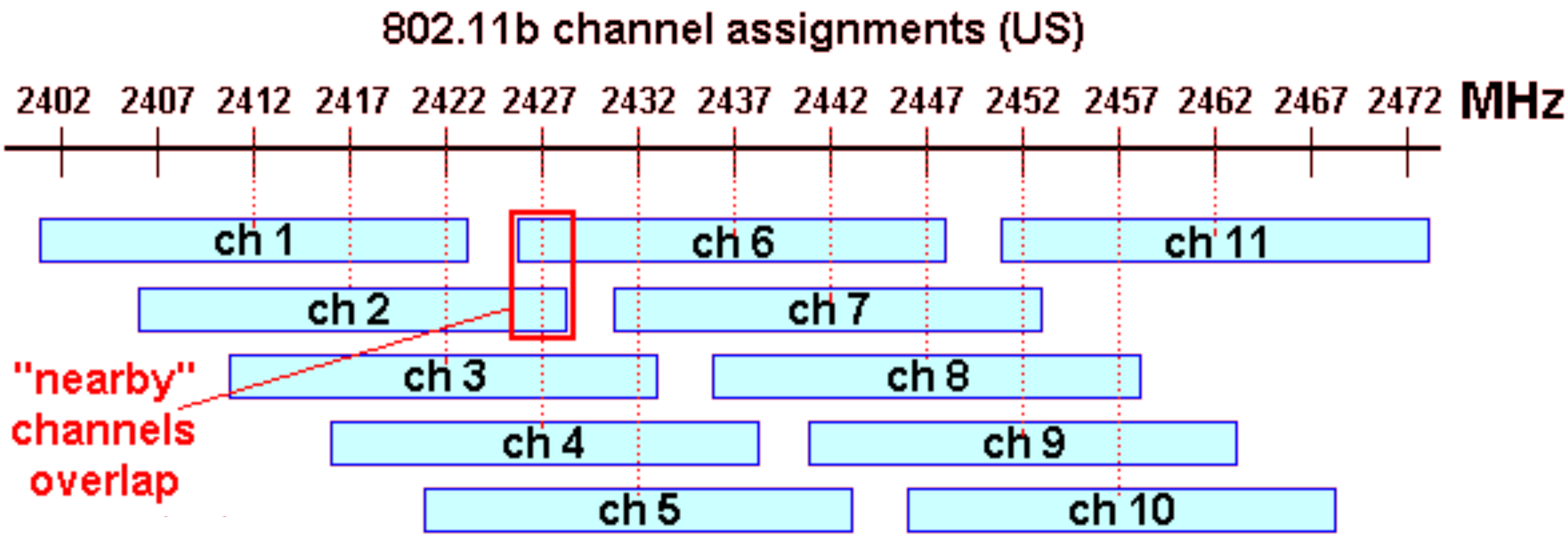


- *wireless host communicates with base station*
  - *base station = access point (AP)*
- *Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:*
  - *wireless hosts*
  - *access point (AP): base station*
  - *ad hoc mode: hosts only*

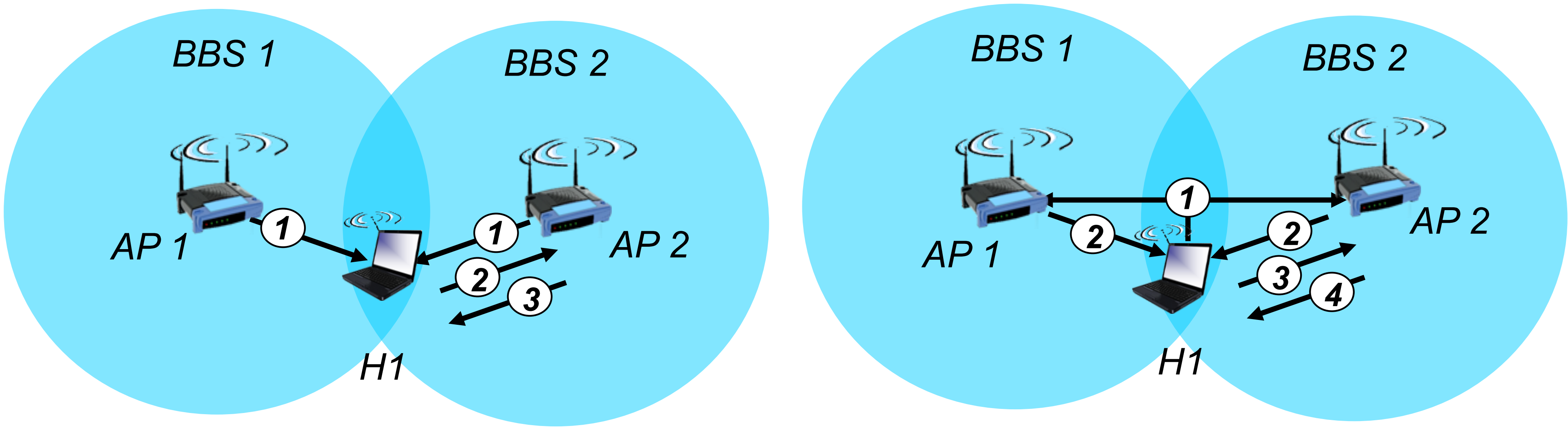
802.11: Channels, association

- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels at different frequencies
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- 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
  - may perform authentication [Chapter 8]
  - will typically run DHCP to get IP address in AP's subnet

802.11b channels



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

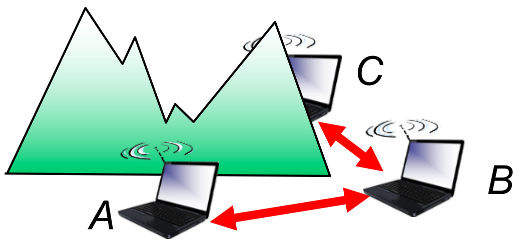
(2) Probe Response frames sent from APs

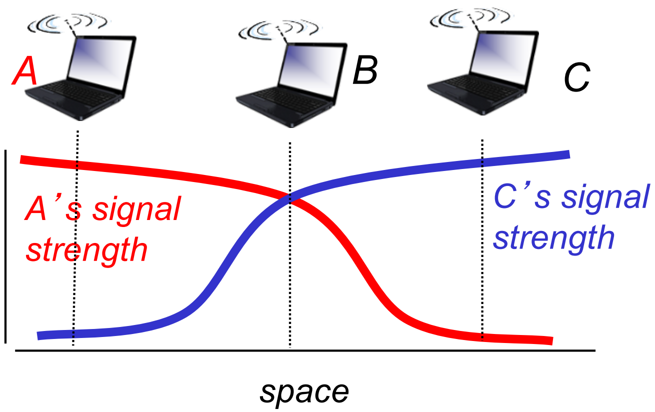
(3) Association Request frame sent: H1 to selected AP

(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 ongoing transmission by other node
- 802.11: *no* collision detection!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/C(ollision)A(voidance)





Multiple access: Key Points

- No concept of a global collision
  - Different receivers hear different signals
  - Different senders reach different receivers
- Collisions are at receiver, not sender
  - Only care if receiver can hear the sender clearly
  - It does not matter if sender can hear someone else
  - As long as that signal does not interfere with receiver
- Goal of protocol
  - Detect if receiver can hear sender
  - Tell senders who might interfere with receiver to shut up

IEEE 802.11 MAC Protocol: CSMA/CA

Distributed Coordination Function (DCF)

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

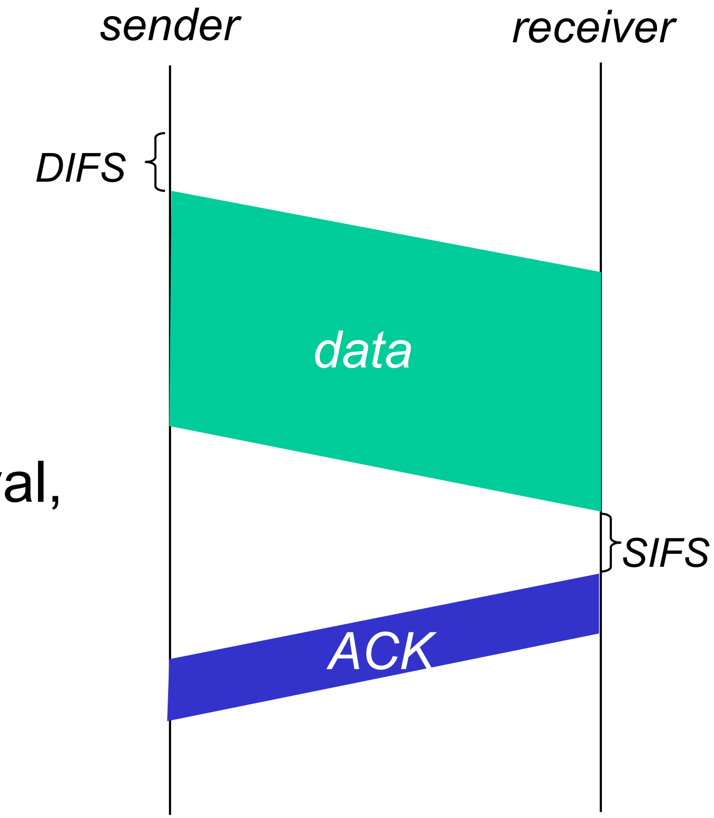
transmit when timer expires

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)



DIFS=DCF Inter Frame space

SIFS= Short Inter Frame Space

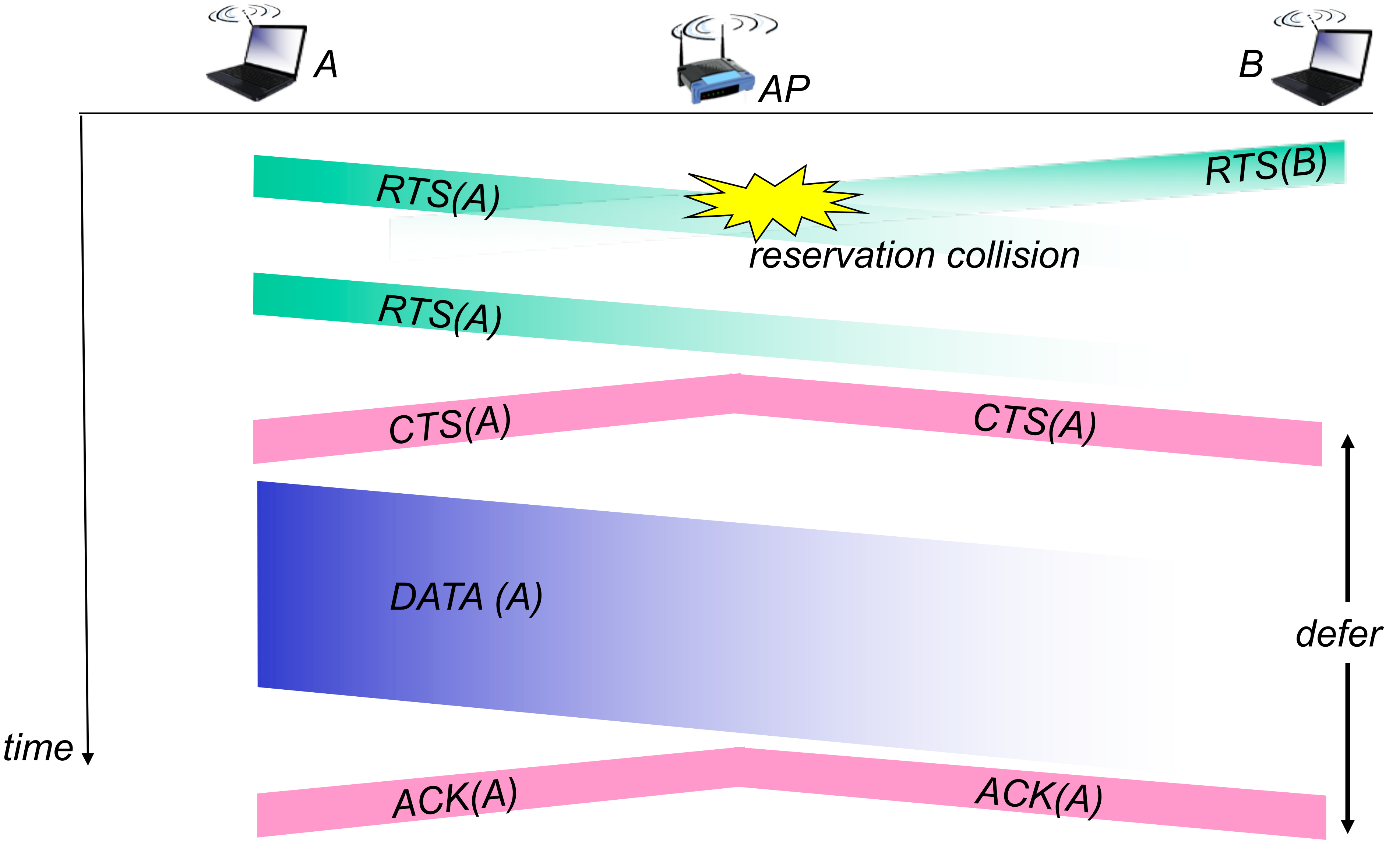
Avoiding collisions (more)

idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

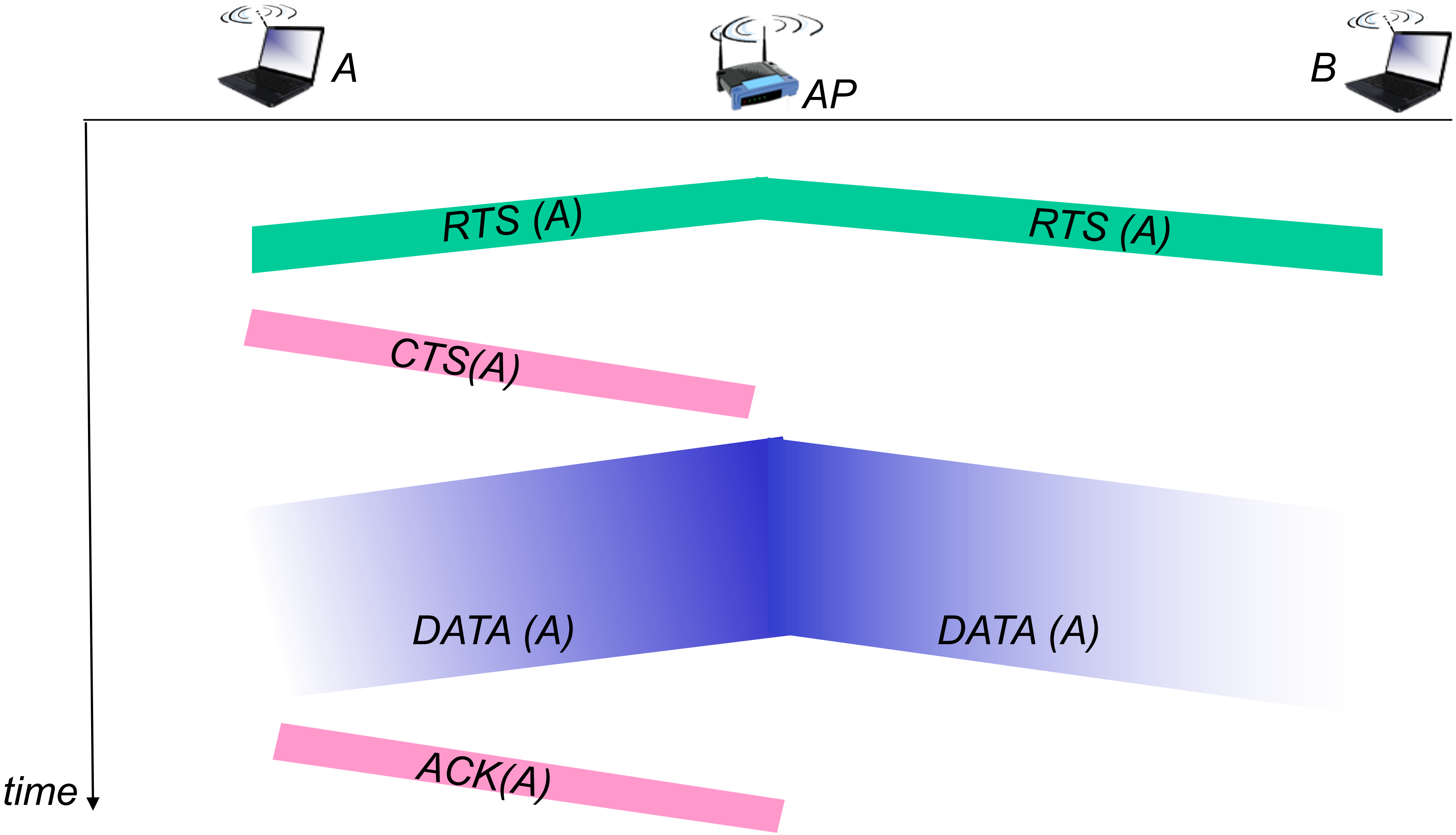
- sender first transmits *small* request-to-send (RTS) packets to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

avoid data frame collisions completely using small reservation packets!

Collision Avoidance: RTS-CTS exchange



Collision Avoidance: RTS-CTS exchange



802.11 frame: addressing

2	2	6	6	6	2	6	0 - 2312	4
frame control	*duration*	*address 1*	*address 2*	*address 3*	*seq control*	*address 4*	*payload*	*CRC*

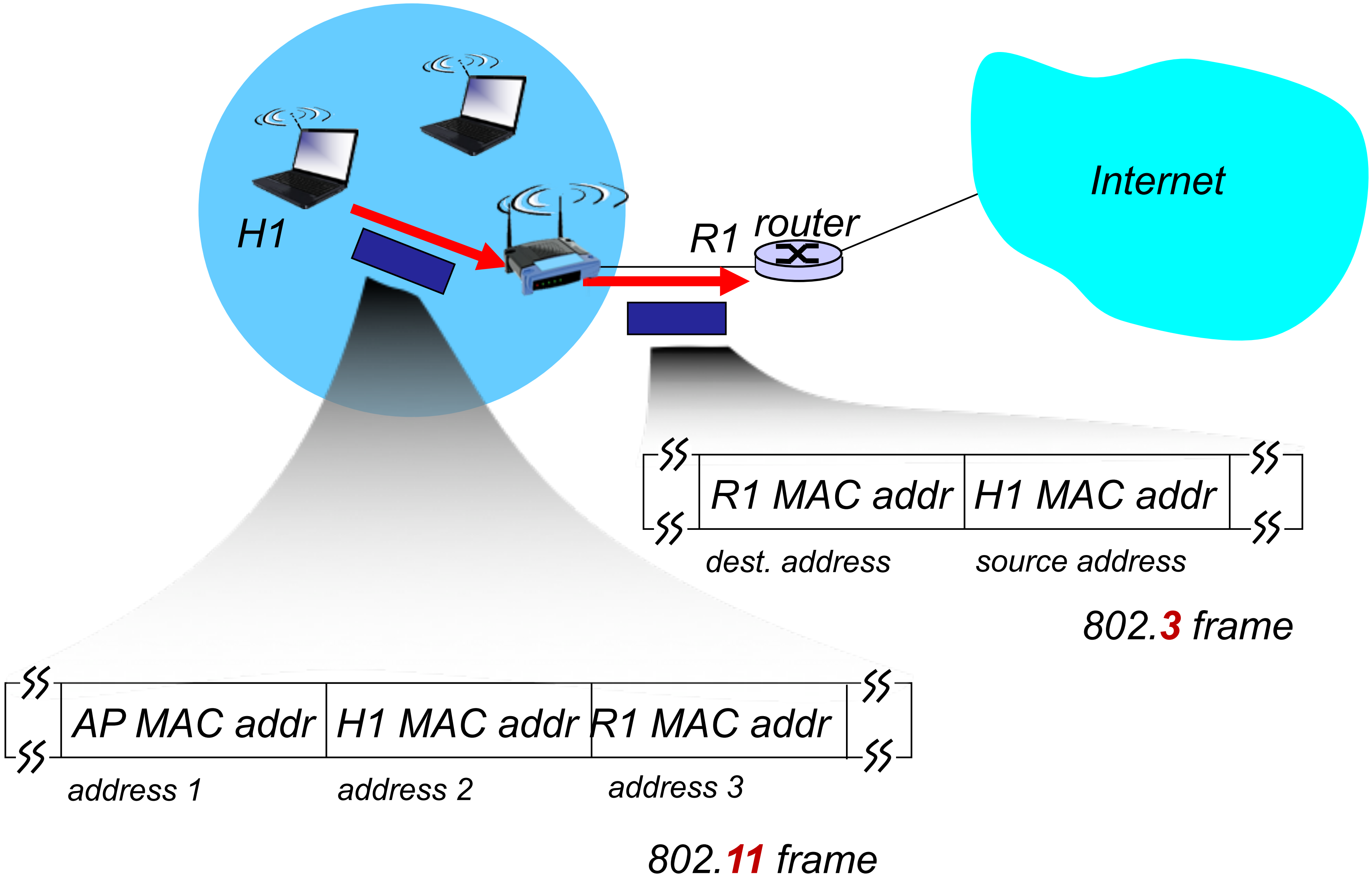
Address 1: MAC address of wireless host or AP to receive this frame

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

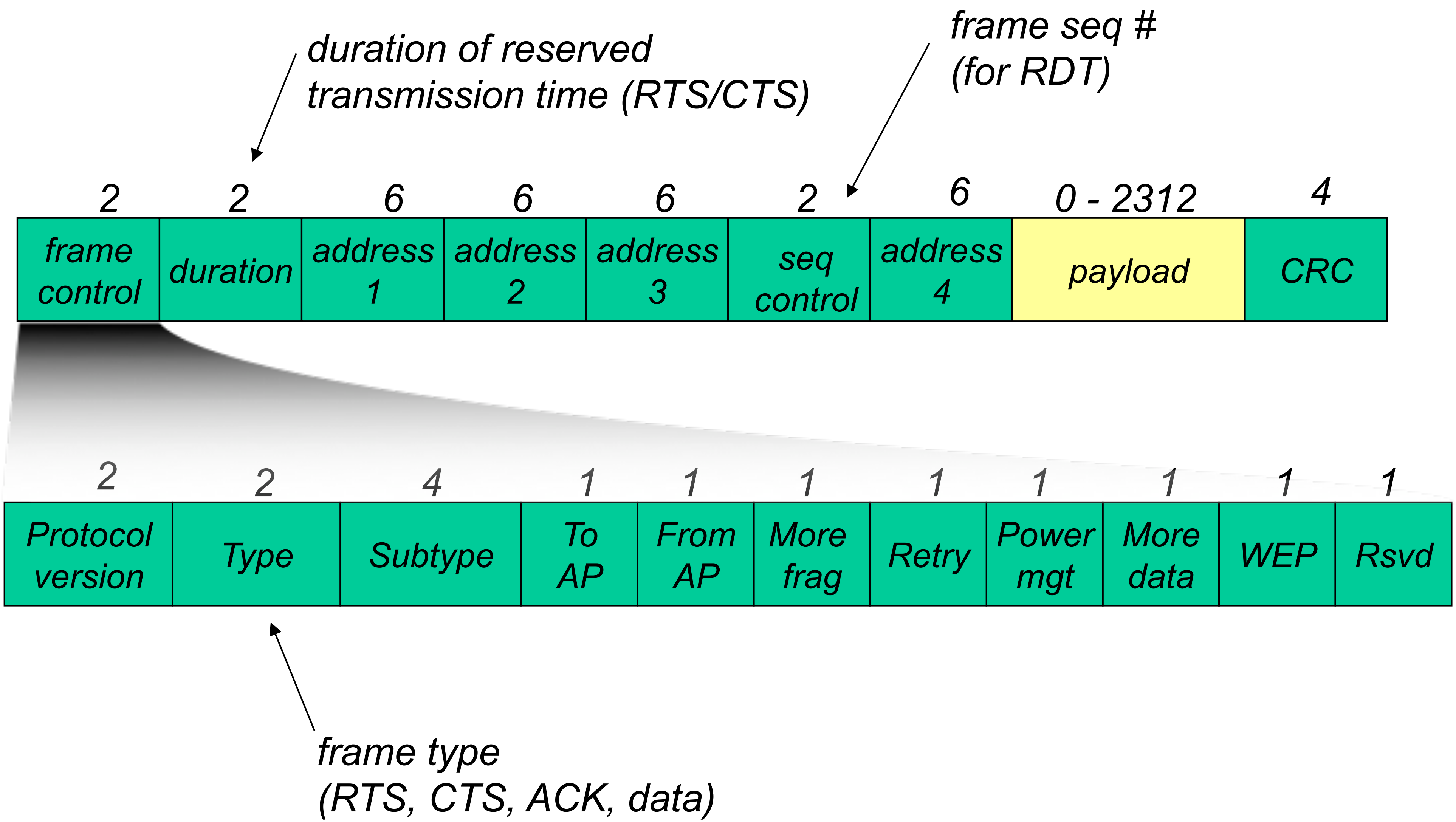
Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

802.11 frame: addressing

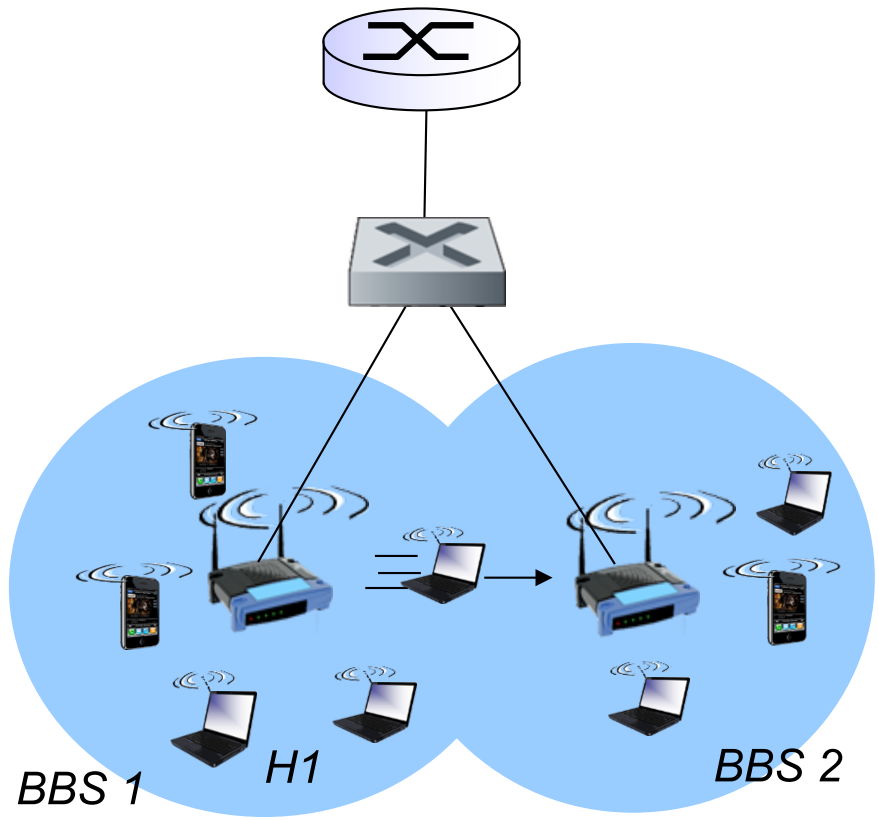


802.11 frame: more



802.11: mobility within same subnet

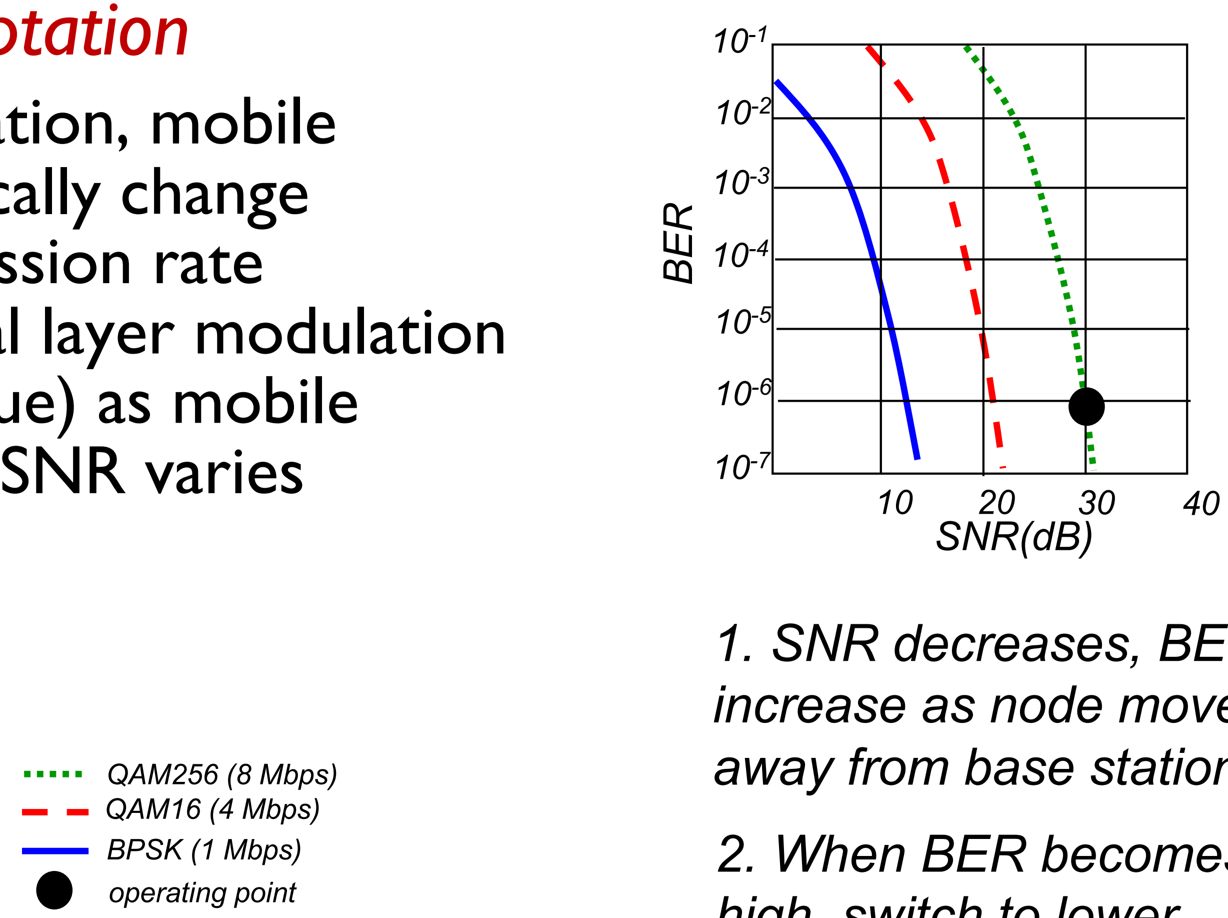
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - self-learning (Ch. 5): switch will see frame from H1 and "remember" which switch port can be used to reach H1



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

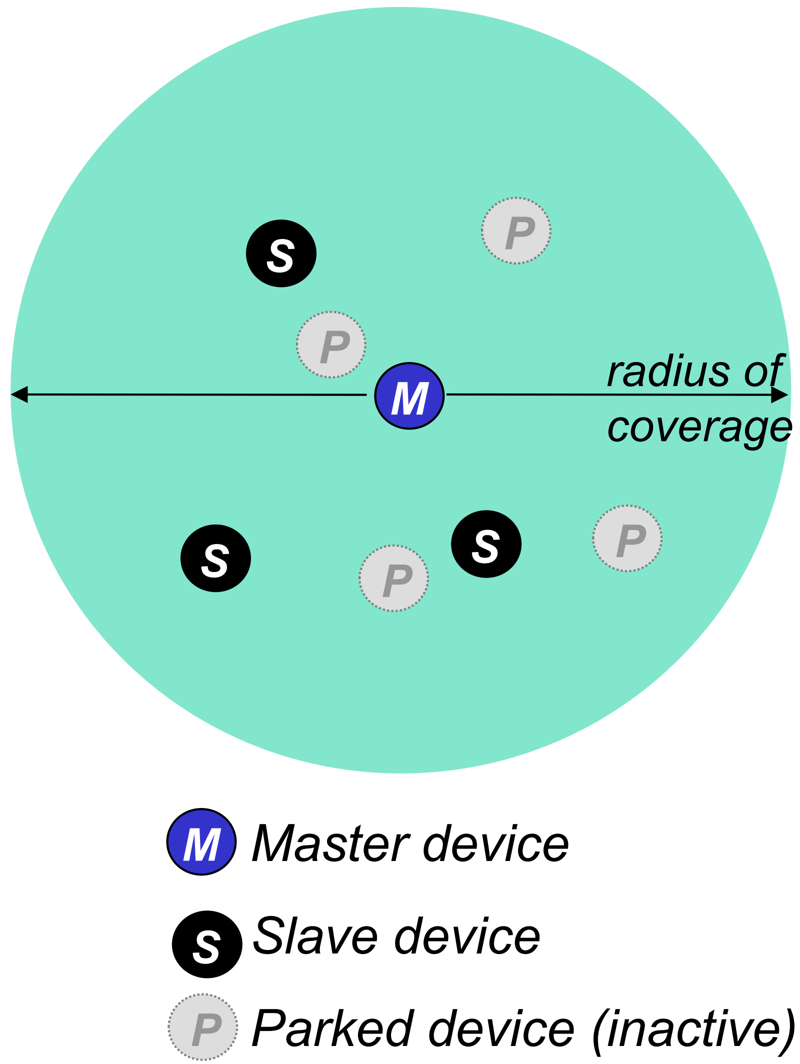
802.11: advanced capabilities

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*

802.15: personal area network

- less than 10 m diameter
- replacement for cables (mouse, keyboard, headphones)
- ad hoc: no infrastructure
- master/slaves:
  - slaves request permission to send (to master)
  - master grants requests
- 802.15: evolved from Bluetooth specification
  - 2.4-2.5 GHz radio band
  - up to 721 kbps



Summary

Wireless

- wireless links:
  - capacity, distance
  - channel impairments
  - CDMA
- IEEE 802.11 (“Wi-Fi”)
  - CSMA/CA reflects wireless channel characteristics