Data Link Layer – Part II

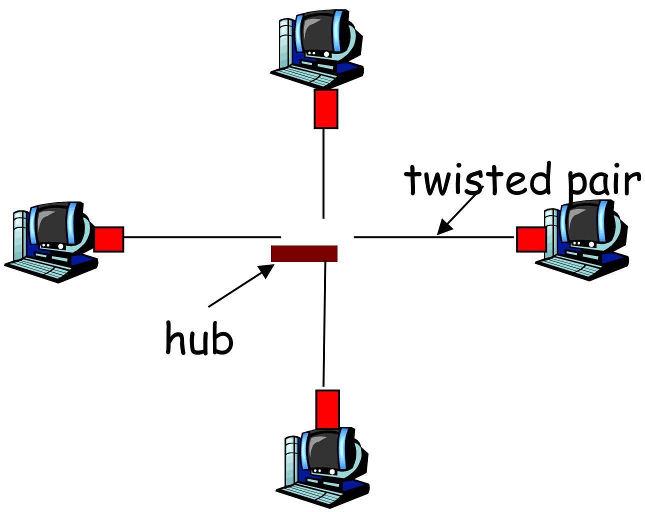
Link Layer

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3 Multiple access protocols
- 5.4 Link-layer Addressing
- 5.5 Ethernet
- 5.6 Link-layer switches
- 5.7 PPP
- 5.8 Wireless links / Wi-Fi
- 5.9 Link Virtualization: ATM, MPLS

Hubs

… physical-layer (“dumb”) repeaters:

- bits coming in one link go out *all* other links at same rate
- all nodes connected to hub can collide with one another
- no frame buffering
- no CSMA/CD at hub: host NICs detect collisions



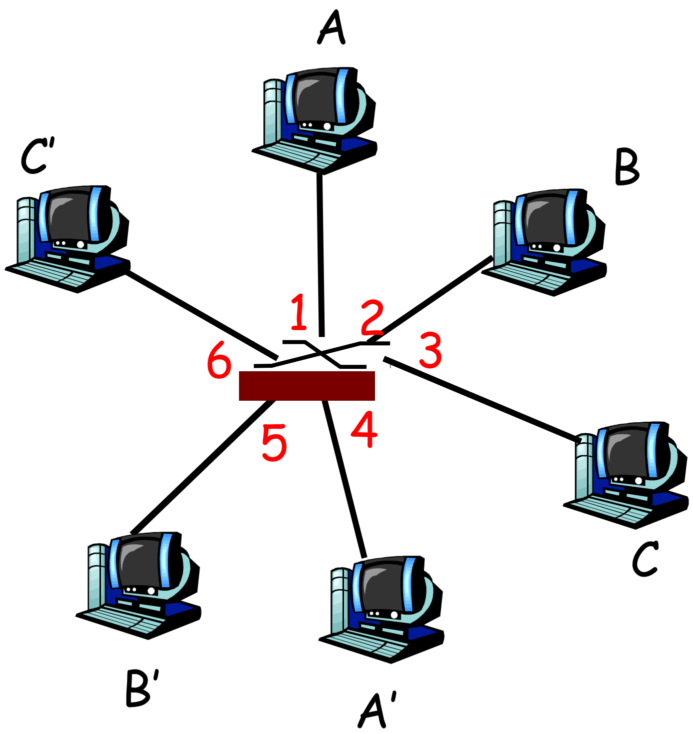
Don‘t really exist anymore

Switch

- link-layer device: smarter than hubs, take *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: allows *multiple* simultaneous transmissions

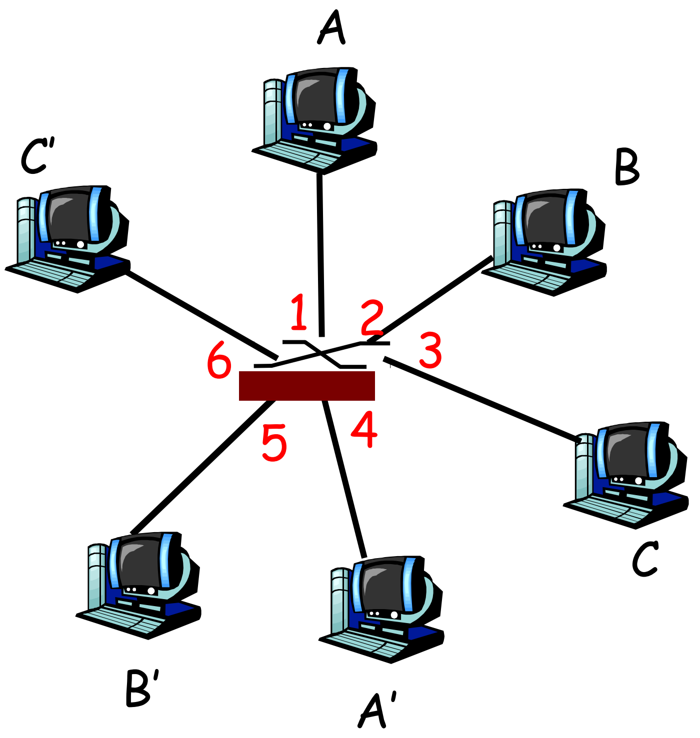
- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, but no collisions; full duplex
  - each link is its own collision domain
- *switching:* A-to-A' and B-to-B' simultaneously, without collisions
  - not possible with dumb hub



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

Switch Table

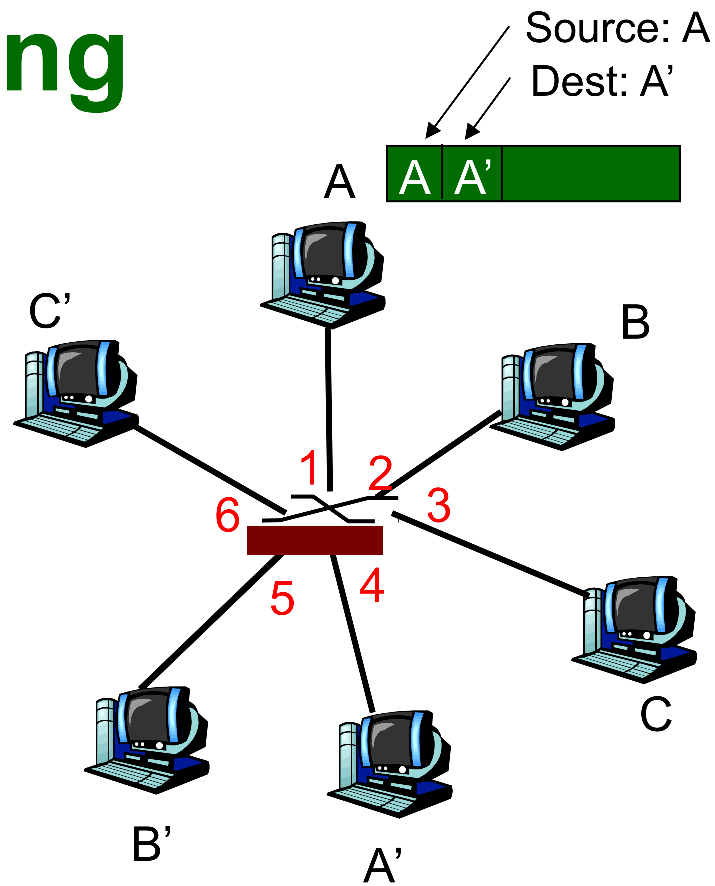
- *Q:* how does switch know that A' reachable via interface 4, B' reachable via interface 5?
- *A:* each switch has a switch table, each entry:
  - (MAC address of host, interface to reach host, time stamp)
- looks like a routing table!
- *Q:* how are entries created, maintained in switch table?
  - something like a routing protocol?



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

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:

1. record link associated with sending host
2. index switch table using MAC dest address
3. **if** entry found for destination

   then {

   if dest on segment from which frame arrived

   then drop the frame

   else forward the frame on interface indicated

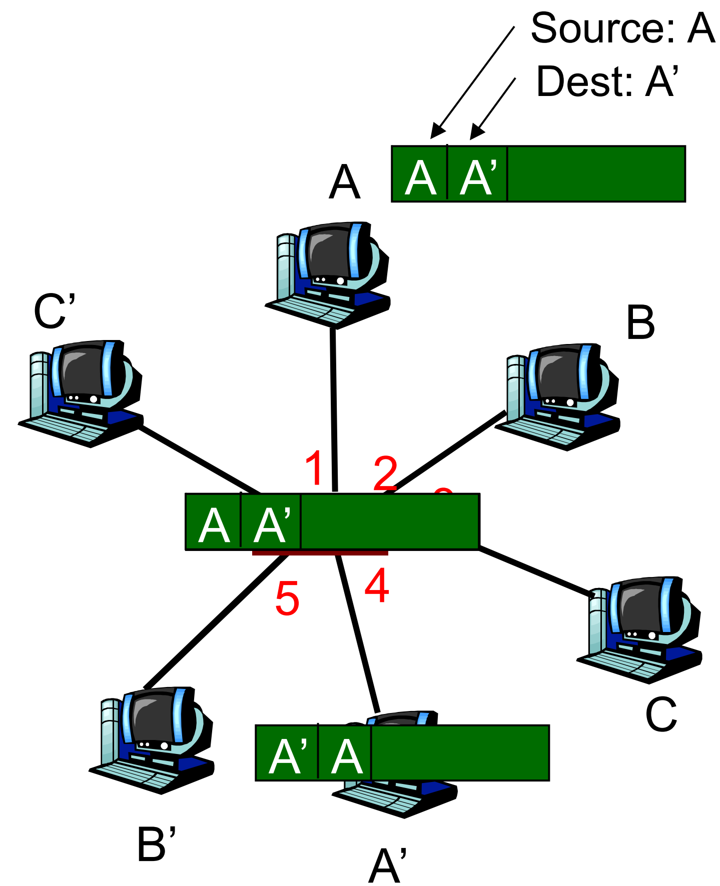
   }

   else flood

forward on all but the interface on which the frame arrived

Self-learning, forwarding: example

- frame destination unknown: *flood*
- destination A location known: *selective send*

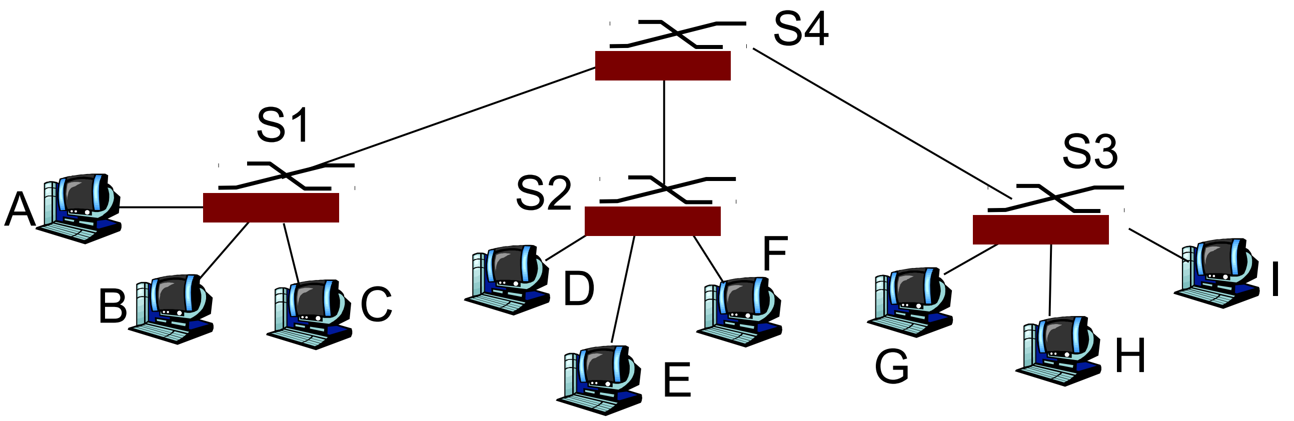


MAC addr	interface	TTL
A	*1*	*60*
A'	*4*	*60*

Switch table (initially empty)

Interconnecting switches

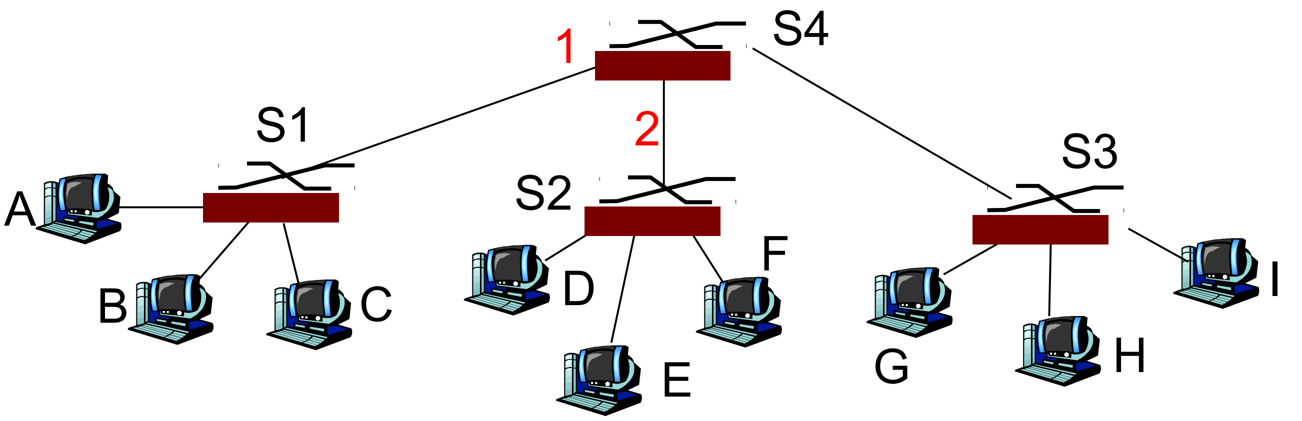
- switches can be connected together



- *Q:* sending from A to G - how does S1 know to forward frame destined to F via S4 and S3?
- *A:* self learning! (works exactly the same as in single-switch case!)

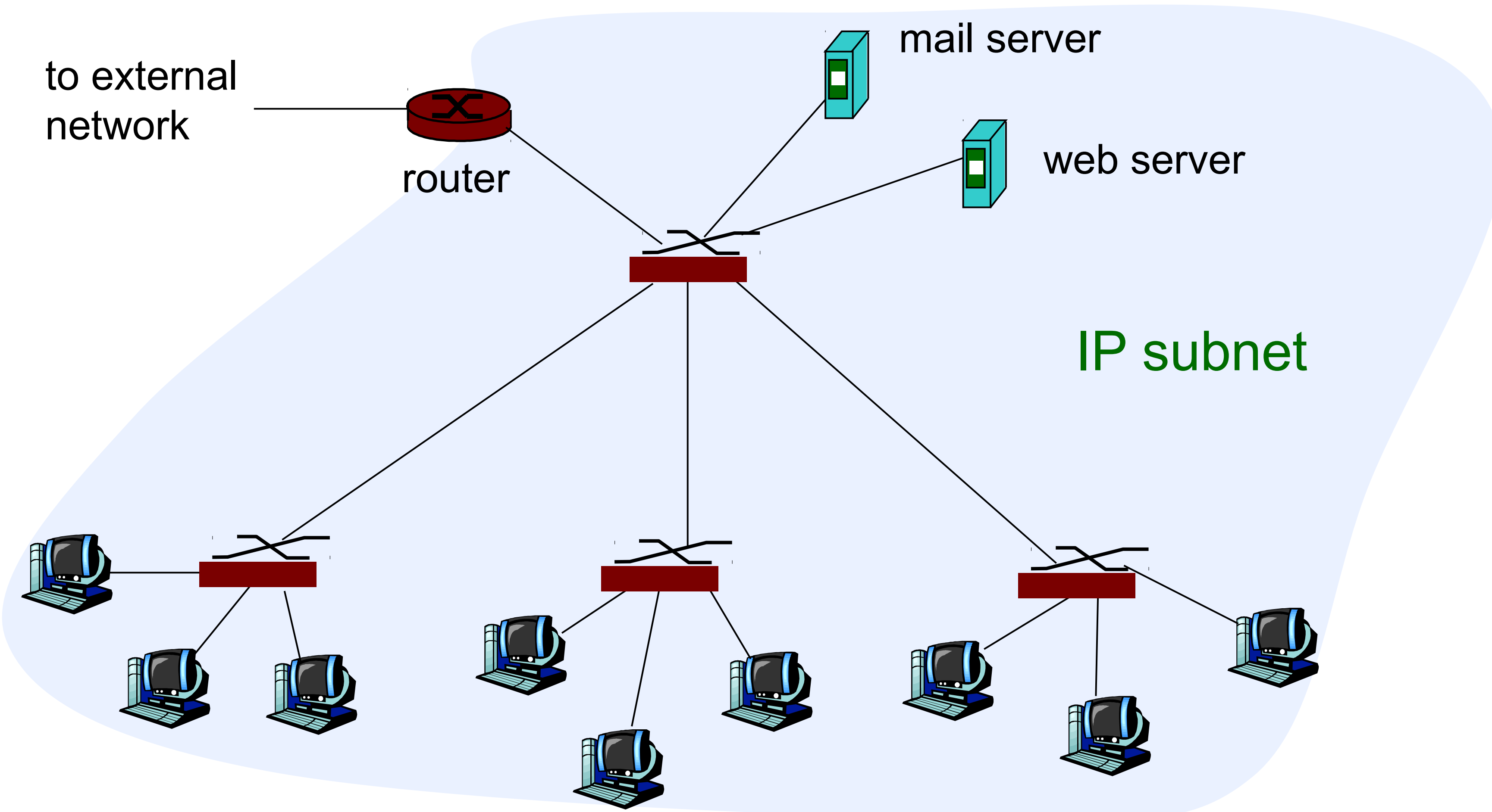
Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



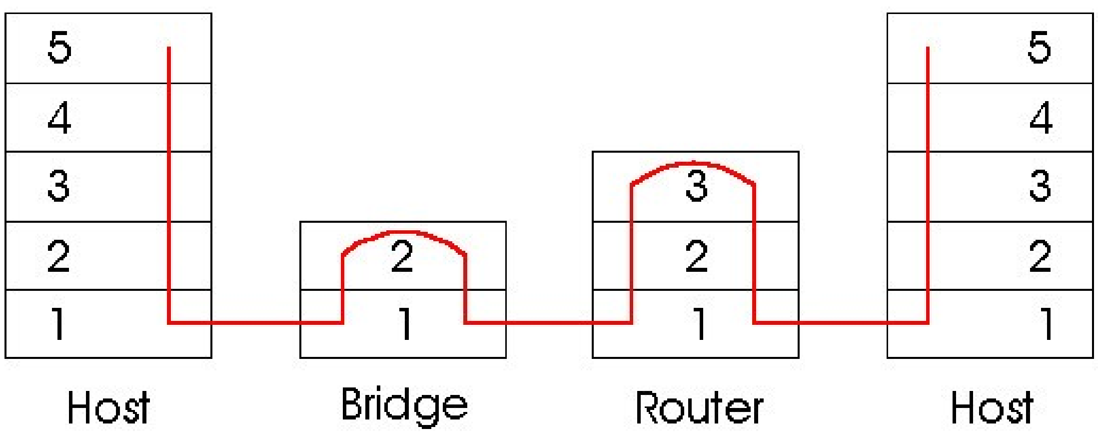
- *Q:* show switch tables and packet forwarding in S1, S2, S3, S4

Institutional network (e.g. GöNet)



Switches vs. Routers

- both store-and-forward devices
  - routers: network layer devices (examine network layer headers)
  - switches are link layer devices
- routers maintain routing tables, implement routing algorithms
- switches maintain switch tables, implement filtering, learning algorithms



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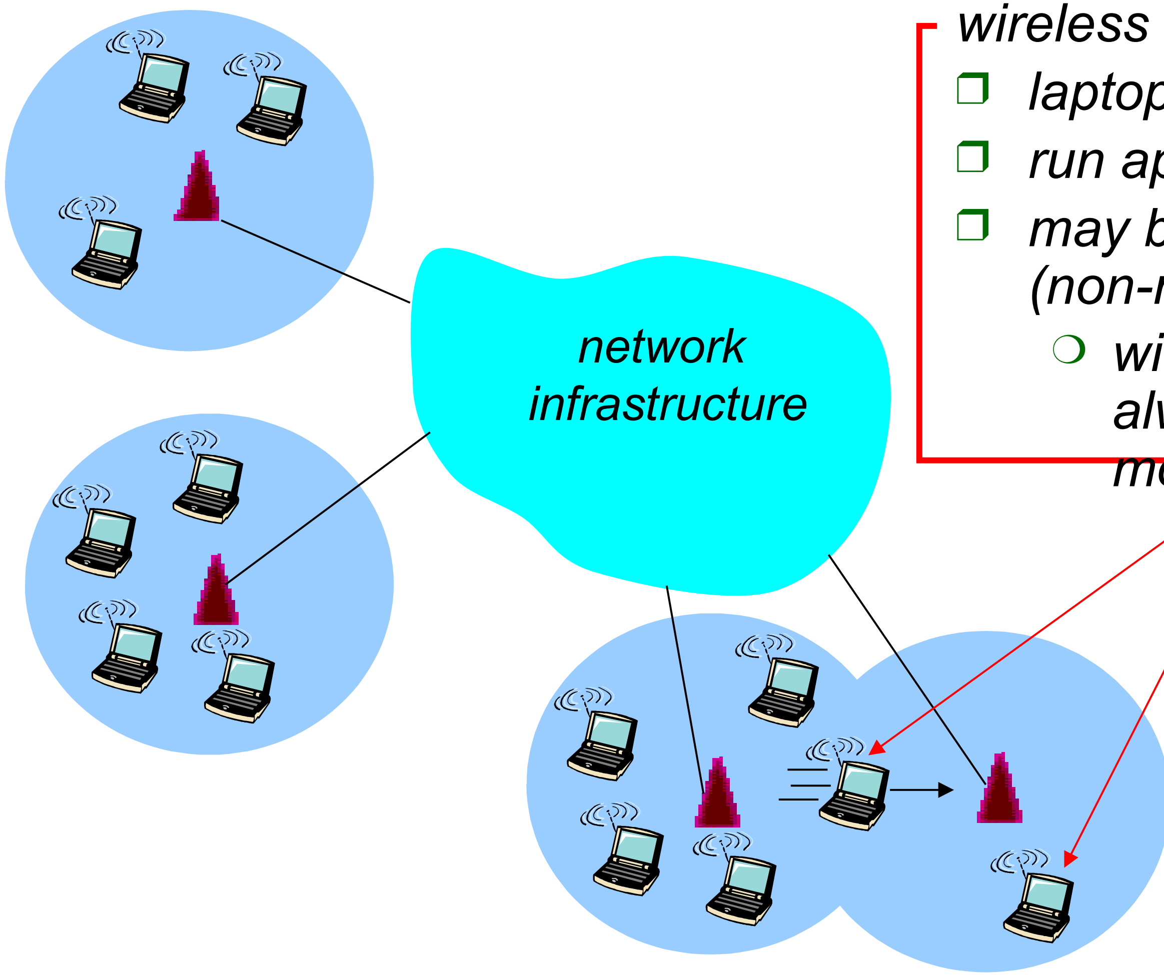
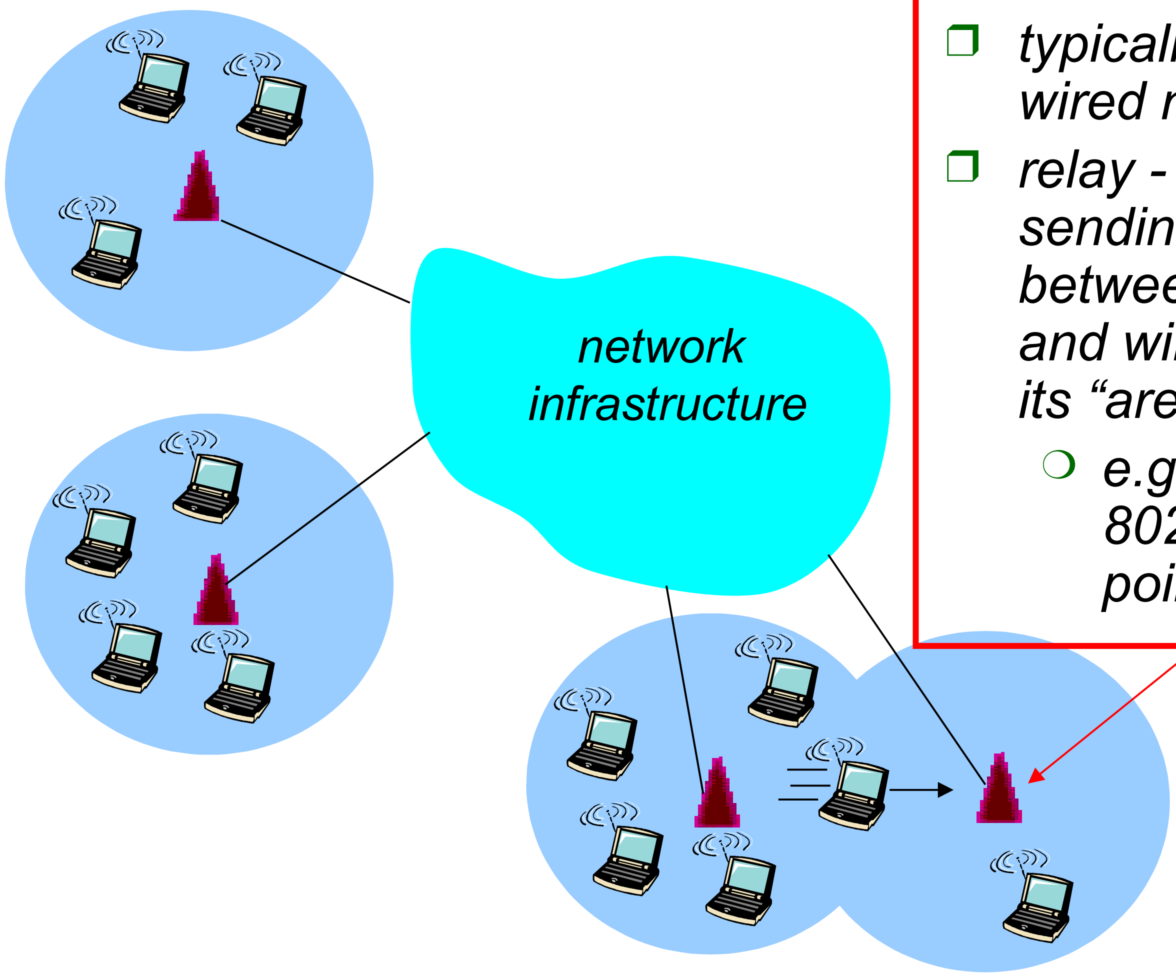
Elements of a wireless network



wireless hosts

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

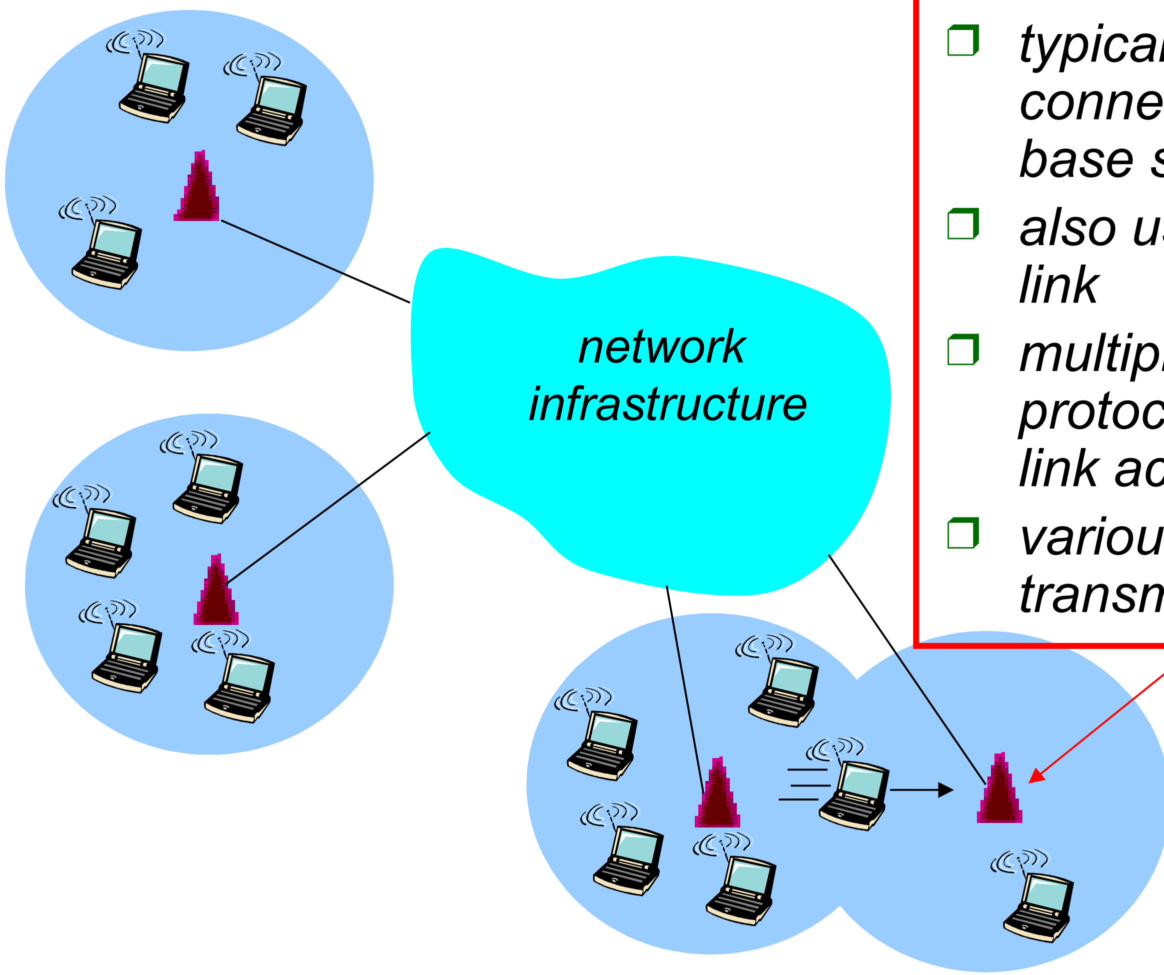
Elements of a wireless network



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*

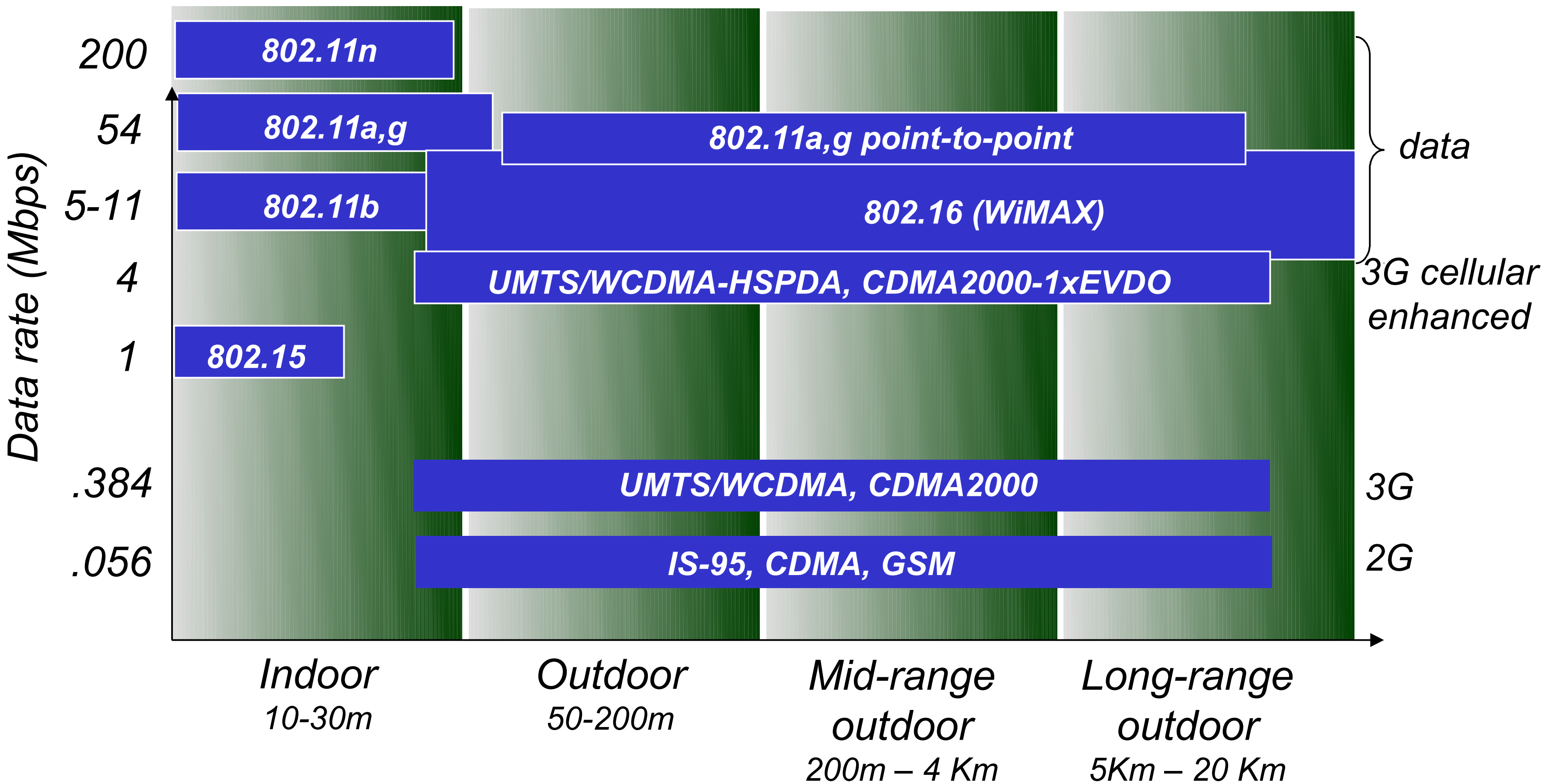
Elements of a wireless network



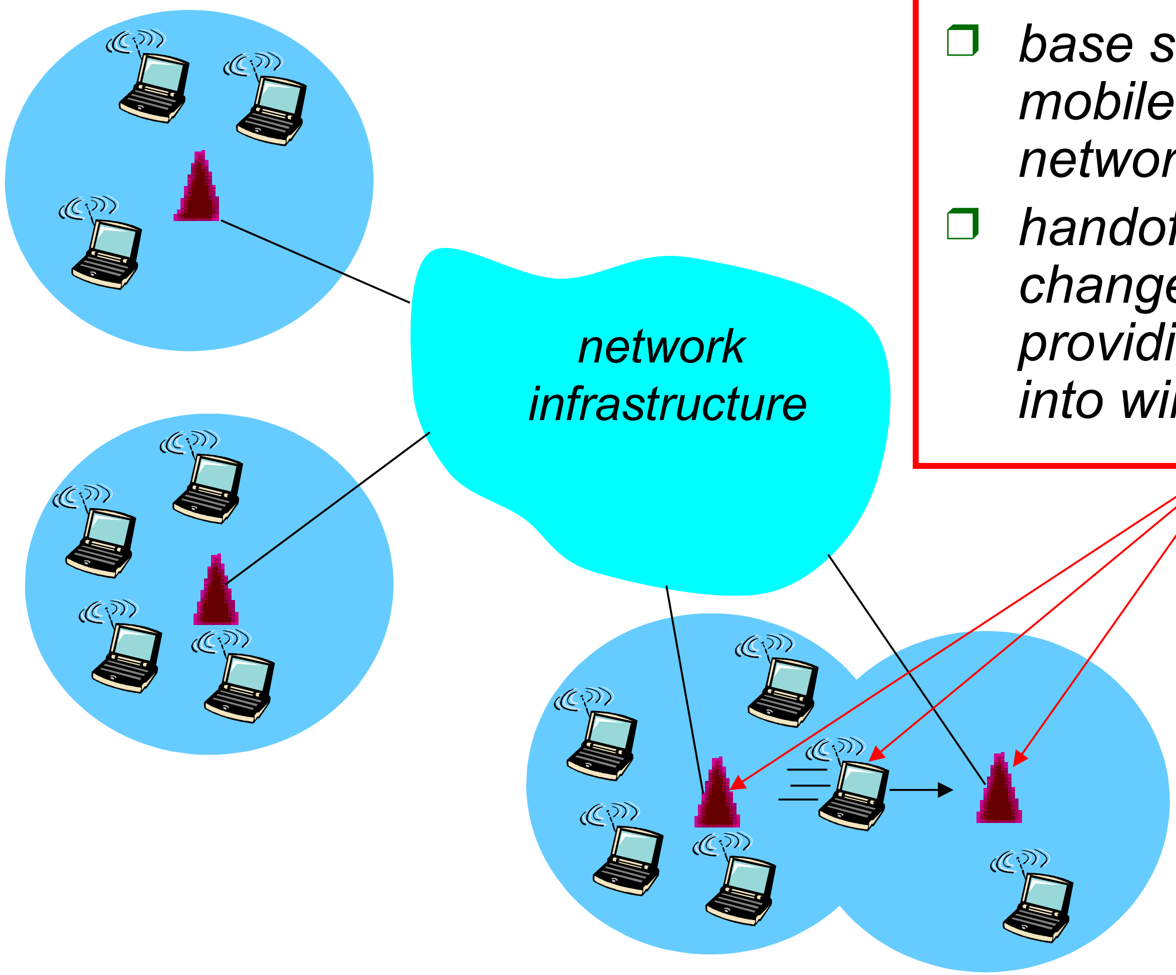
wireless link

- 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 link standards



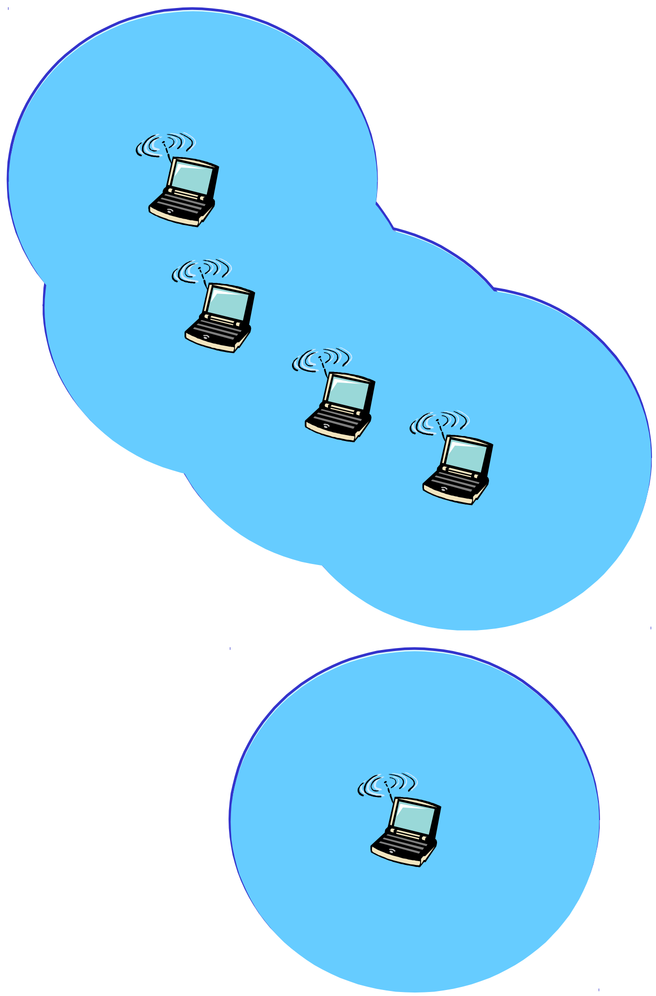
Elements of a wireless network



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

Wireless Link Characteristics

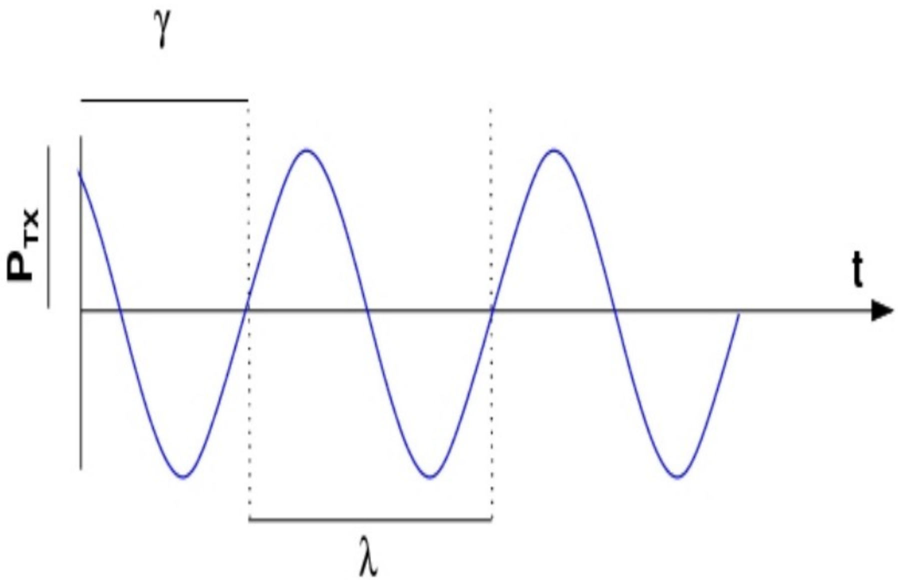
RF transmission

- Electromagnetic signals
- Transmitted in wave-Form
- Omnidirectional transmission
- Speed of light
  - $c = 3 \cdot 10^8 \frac{m}{s}$

Wireless Link Characteristics

RF signal

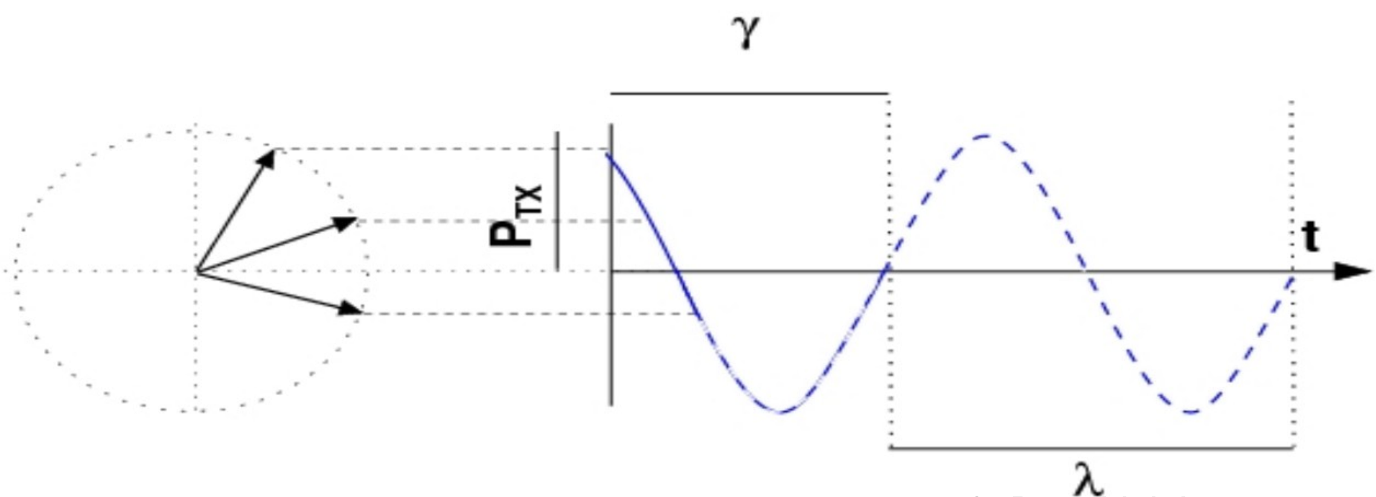
- Transmission power:
  - $P_{TX}[W]$
- Frequency:
  - $f[\frac{1}{sec}]$
- Phase offset:
  - $\gamma[\pi]$
- Wavelength:
  - $\lambda = \frac{c}{f}[m]$



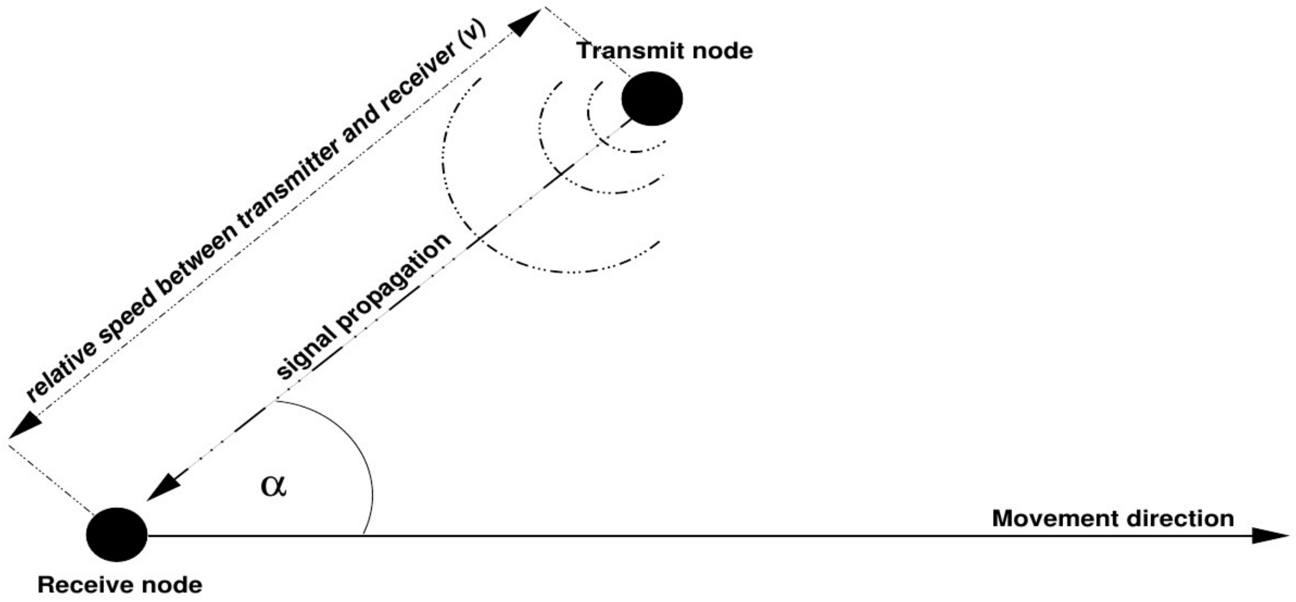
Wireless Link Characteristics

RF signal

- Real part of rotating vector
  - $\zeta = \Re\left(e^{j(ft+\gamma)}\right)$
- Instantaneous signal strength:
  - $\cos(\zeta)$
- Rotation Speed: Frequency f



Wireless Link Characteristics



Doppler Shift

- Frequency of received and transmitted signal may differ
- Dependent on relative speed between transmitter and receiver
- $f_d = \frac{v}{\lambda} \cdot \cos(\alpha)$

Wireless Link Characteristics

Noise

- In every realistic setting, noise can be observed on the wireless channel
- Typical noise power:[1]

$$P_N = -103dBm$$

- Value observed by measurements

[1] 3GPP: 3rd generation partnership project; technical specification group radio access networks; 3g home nodeb study

Wireless Link Characteristics

Noise

- Thermal noise can also be estimated analytically as

$$P_N = \kappa \cdot T \cdot B$$

- $\kappa = 1.3807 \cdot 10^{-23} \frac{J}{K}$: Boltzmann constant
- T: Temperature in Calvin
- B: Bandwidth of the signal.

Wireless Link Characteristics

Example

- GSM system with $200kHz$ bands
- Average temperature: $300K$
- Estimated noise power:

$$
\begin{aligned}
P_N &= \kappa \cdot T \cdot B \\
&= 1.3807 \cdot 10^{-23} \frac{J}{K} \cdot 300K \cdot 200kHz \\
P_N &= -120.82dBm
\end{aligned}
$$

Wireless Link Characteristics

Path-loss

- Signal strength decreases while propagating over a wireless channel
- Order of decay varies in different environments
- Impact higher for higher frequencies
- Can be reduced by antenna gain (e.g. directed)

Location	Mean Path loss exponent	Shadowing variance σ^2 (dB)
Apartment Hallway	2.0	8.0
Parking structure	3.0	7.9
One-sided corridor	1.9	8.0
One-sided patio	3.2	3.7
Concrete Canyon	2.7	10.2
Plant fence	4.9	9.4
Small boulders	3.5	12.8
Sandy flat beach	4.2	4.0
Dense bamboo	5.0	11.6
Dry tall underbrush	3.6	8.4

Wireless Link Characteristics

Path-loss

- For analytic consideration: Path-loss approximated
- Friis free-space equation:

$$P_{TX} \cdot \left(\frac{\lambda}{2\pi d}\right)^2 \cdot G_{TX} \cdot G_{RX}$$

Wireless Link Characteristics

Interference

- A radio system typically requires a specific minimum signal power over interference and noise level:

$$SINR = \frac{P_{\text{signal}}}{P_{\text{noise}} + P_{\text{interference}}}$$

- Concepts to reduce interference:
  - Clustering (cellular networks)
  - Spread spectrum techniques (Code divisioning)

Wireless Link Characteristics

Differences from wired link ….

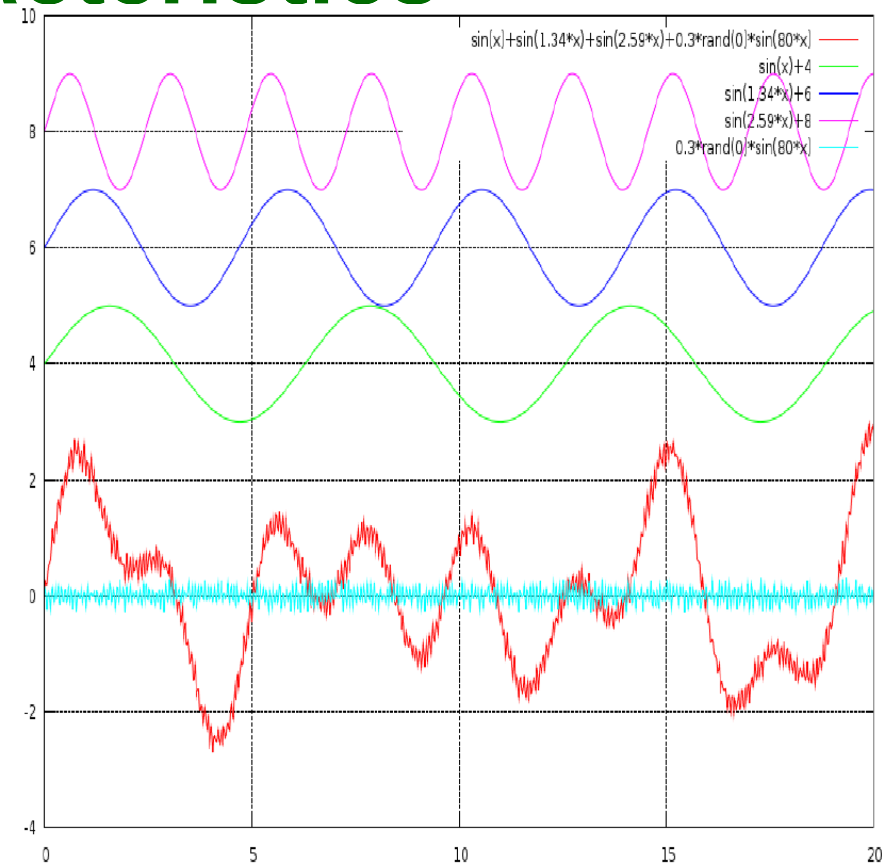
- decreased signal strength: radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- multipath propagation: radio signal reflects off objects ground, arriving ad destination at slightly different times
- SNR (Signal-to-Noise Ratio): larger SNR makes it easier to extract signal from noise (good!)

…. make communication across (even a point to point) wireless link much more "difficult"

Wireless Link Characteristics

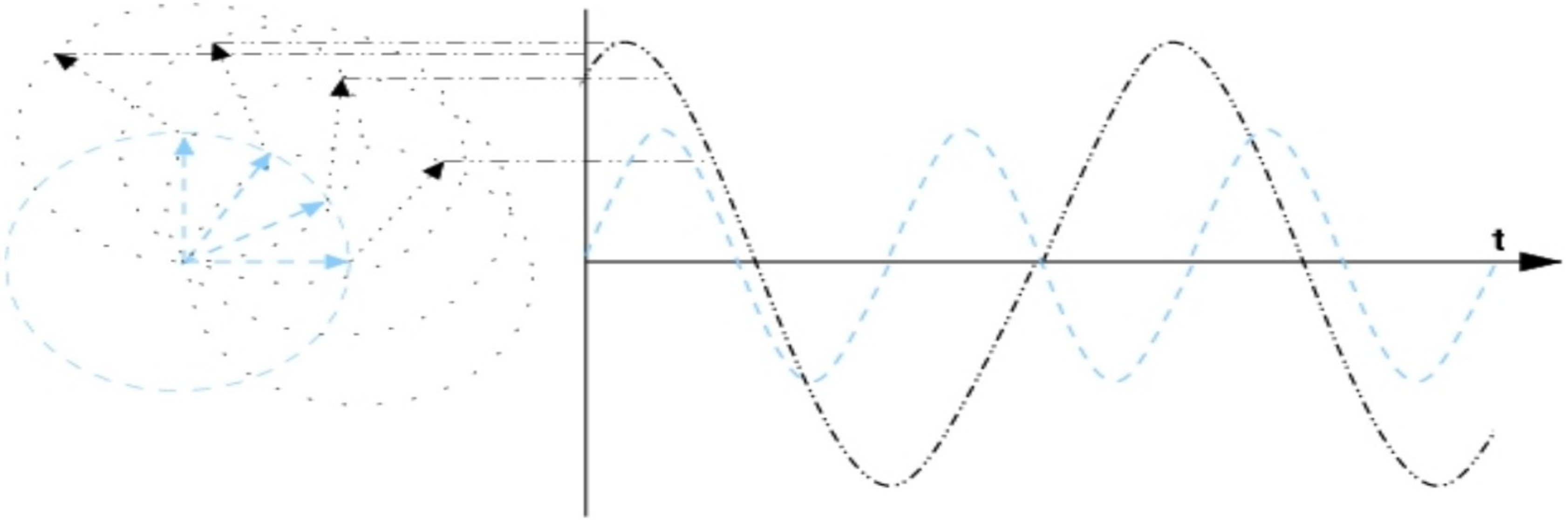
Superimposition of RF signals

- The wireless medium is a broadcast channel
- Multipath transmission
  - Reflection
  - Diffraction
  - Different path lengths
  - Signal components arrive at different times
- Interference



$$\zeta_{\text{sum}} = \sum_{i=1}^{\iota} \Re\left(e^{j(f_i t+\gamma_i)}\right)$$

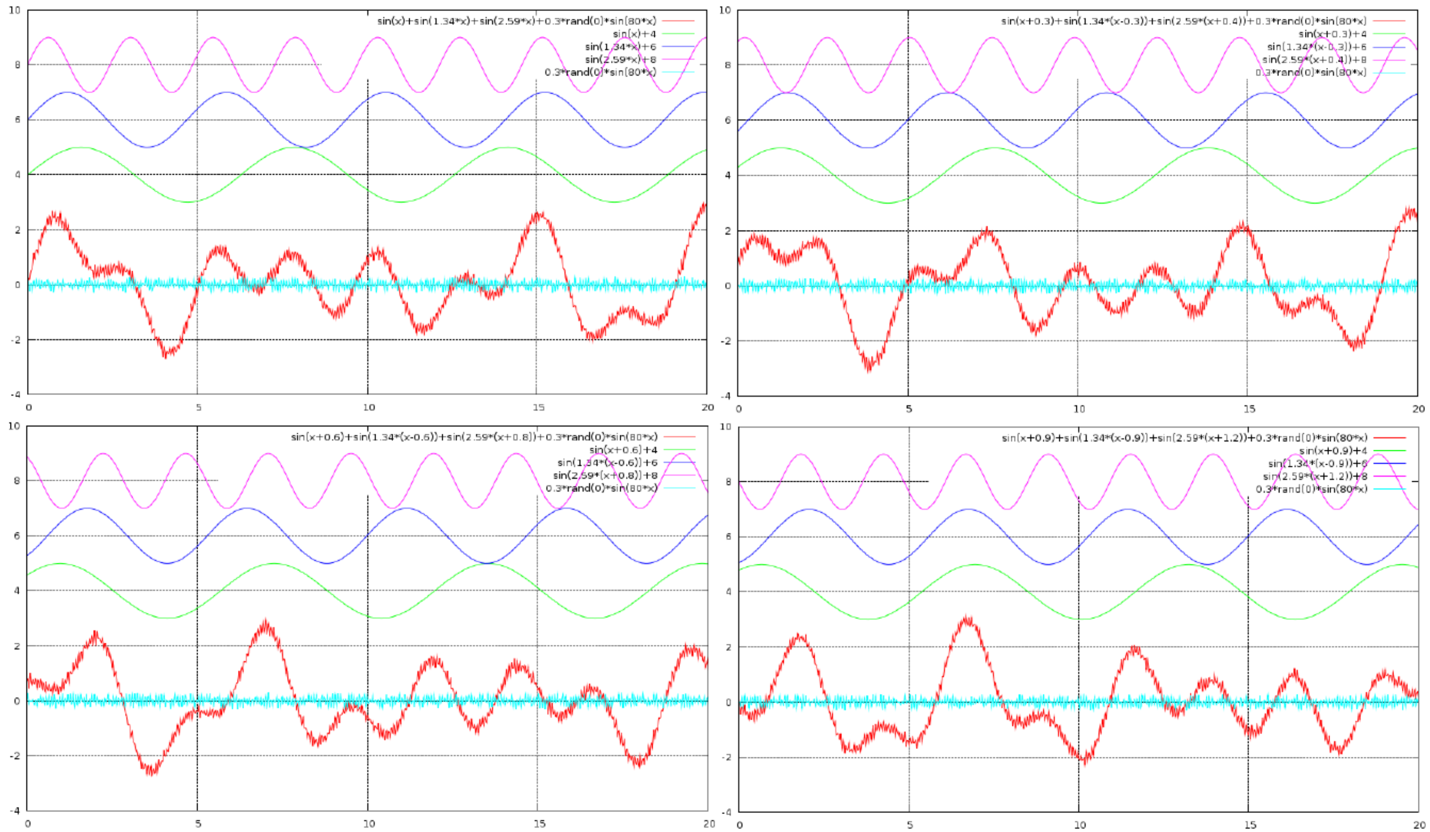
Wireless Link Characteristics



Superimposition of RF signals

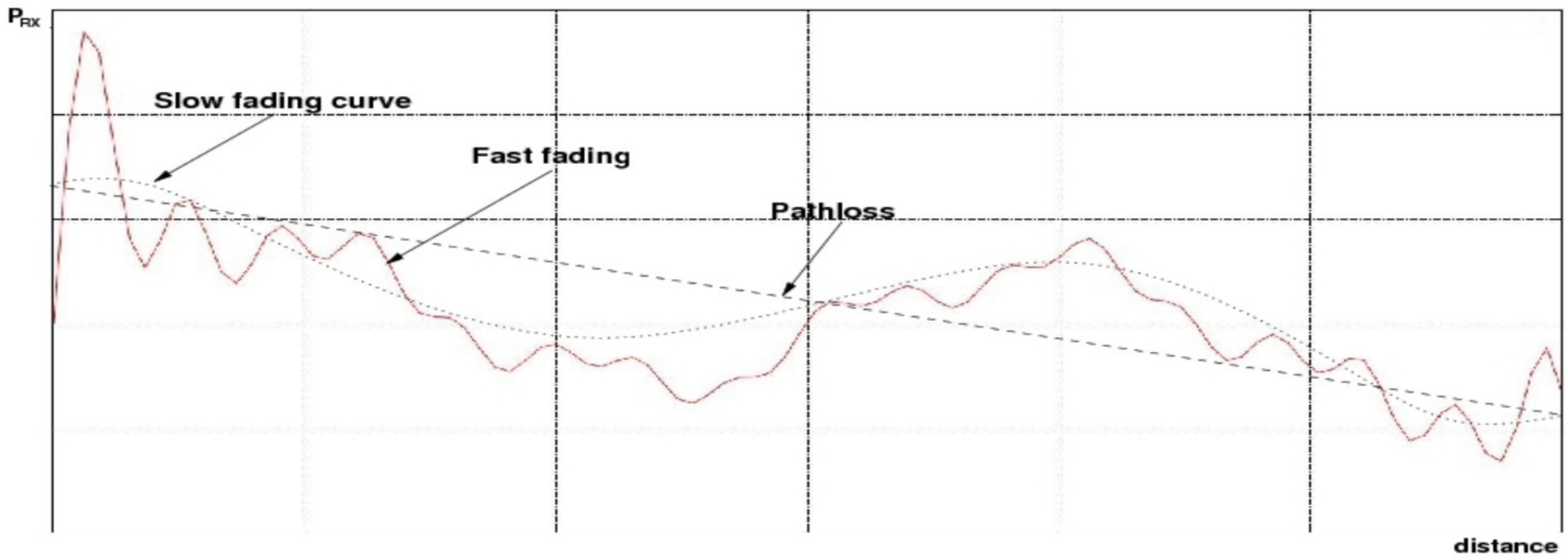
- At a receiver, all incoming signals add up to one superimposed sum signal
- Constructive and destructive interference
- Normally: Heavily distorted sum signal

Wireless Link Characteristics



- Channel conditions are dependent on time and location
- Independent channel conditions typically expected in a distance of $\frac{\lambda}{2}$

Wireless Link Characteristics



Fading

- Signal quality fluctuating with location and time
- Slow fading
- Fast fading

Wireless Link Characteristics

Slow fading

- Result of environmental changes
- Temporary blocking of signal paths
- Changing reflection angles
- Movement in the environment
  - Trees
  - Cars
  - Opening/closing doors
- Amplitude changes can be modelled by log-normal distribution

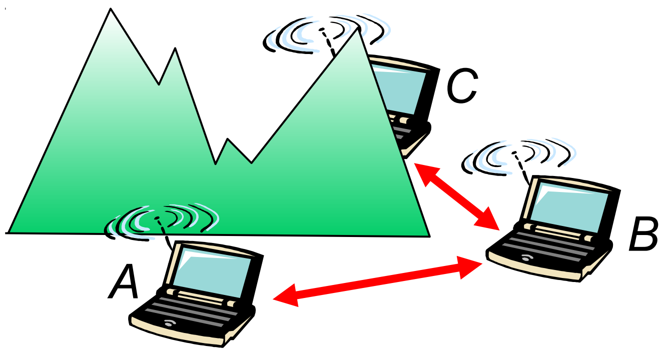
Wireless Link Characteristics

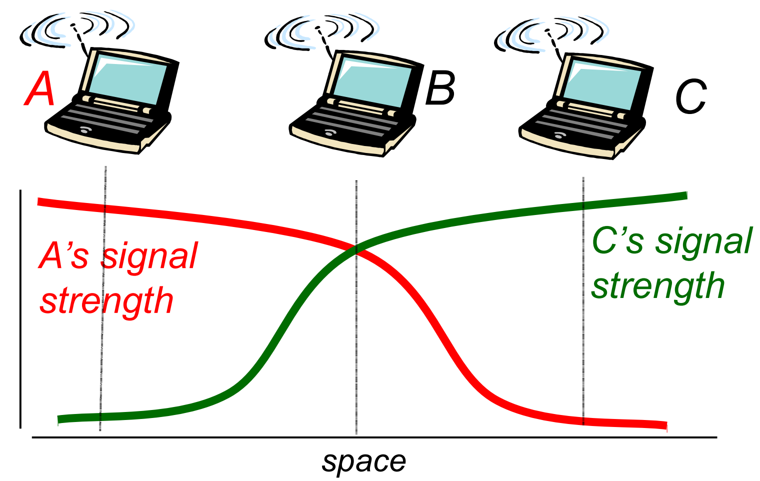
Fast fading

- Signal components of multiple paths
- Cancellation of signal components
- Fading incursions expected in the distance of $\frac{\lambda}{2}$
- Channel quality changes drastically over short distances
- Example: Low radio reception of a car standing in front of a headlight is corrected by small movement
- Stochastic models are utilised to model the probability of fading incursions
  - Rice
  - Rayleigh

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*

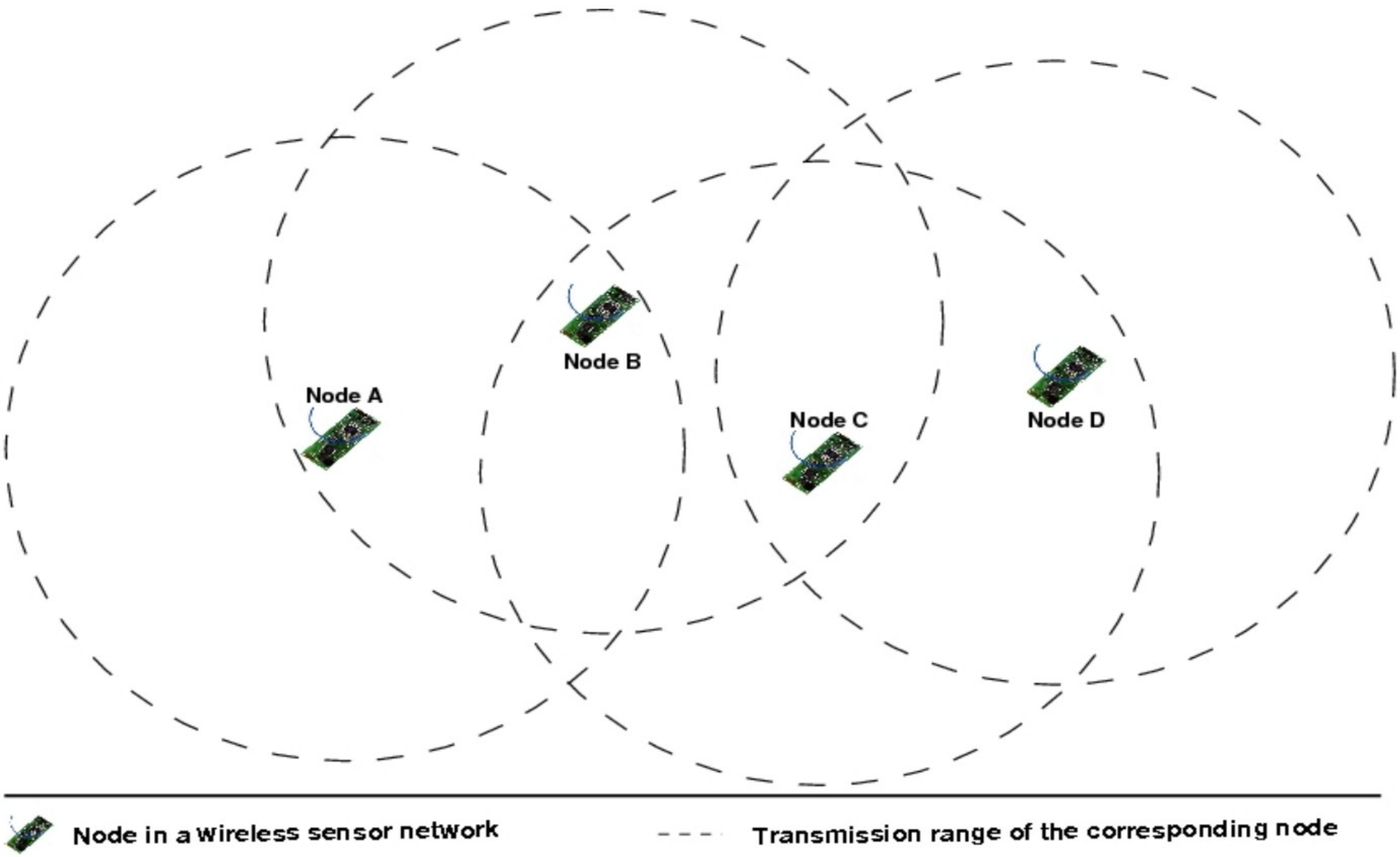
means A, C unaware of their interference at B

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

- The hidden node problem
  - Problem: Collision



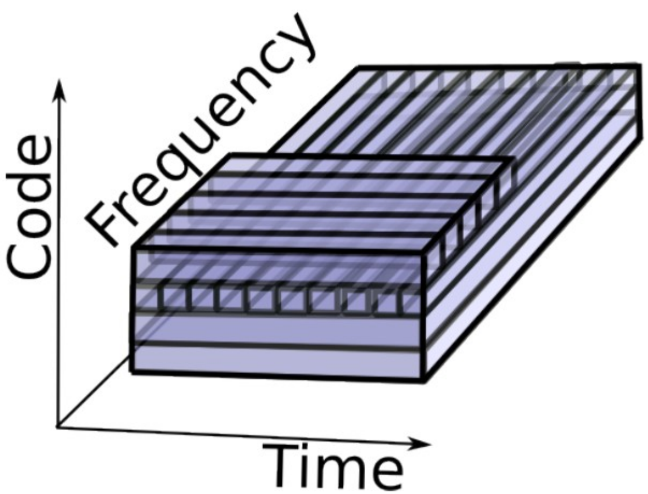
Reminder: Multiple Access protocols

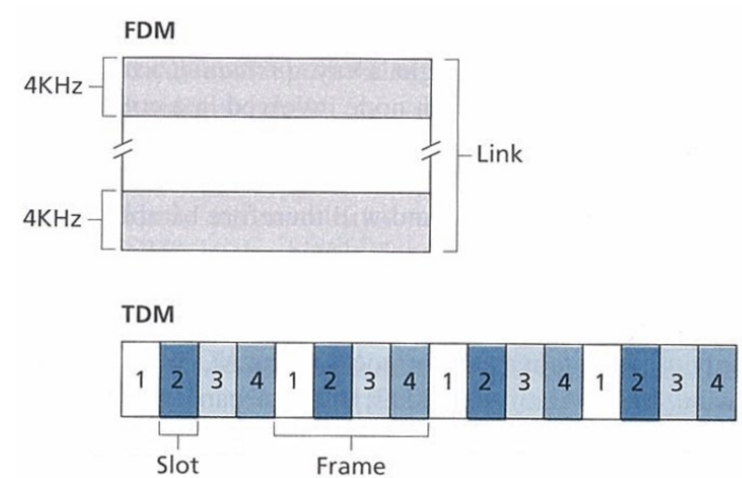
Channel partitioning protocols

TDM
Divide time into time frames and each time frame into N time slots

FDM
Divide frequency into N frequency bands with one frequency band for each channel

CDM
Divide medium into N code spaces with one code word for each channel

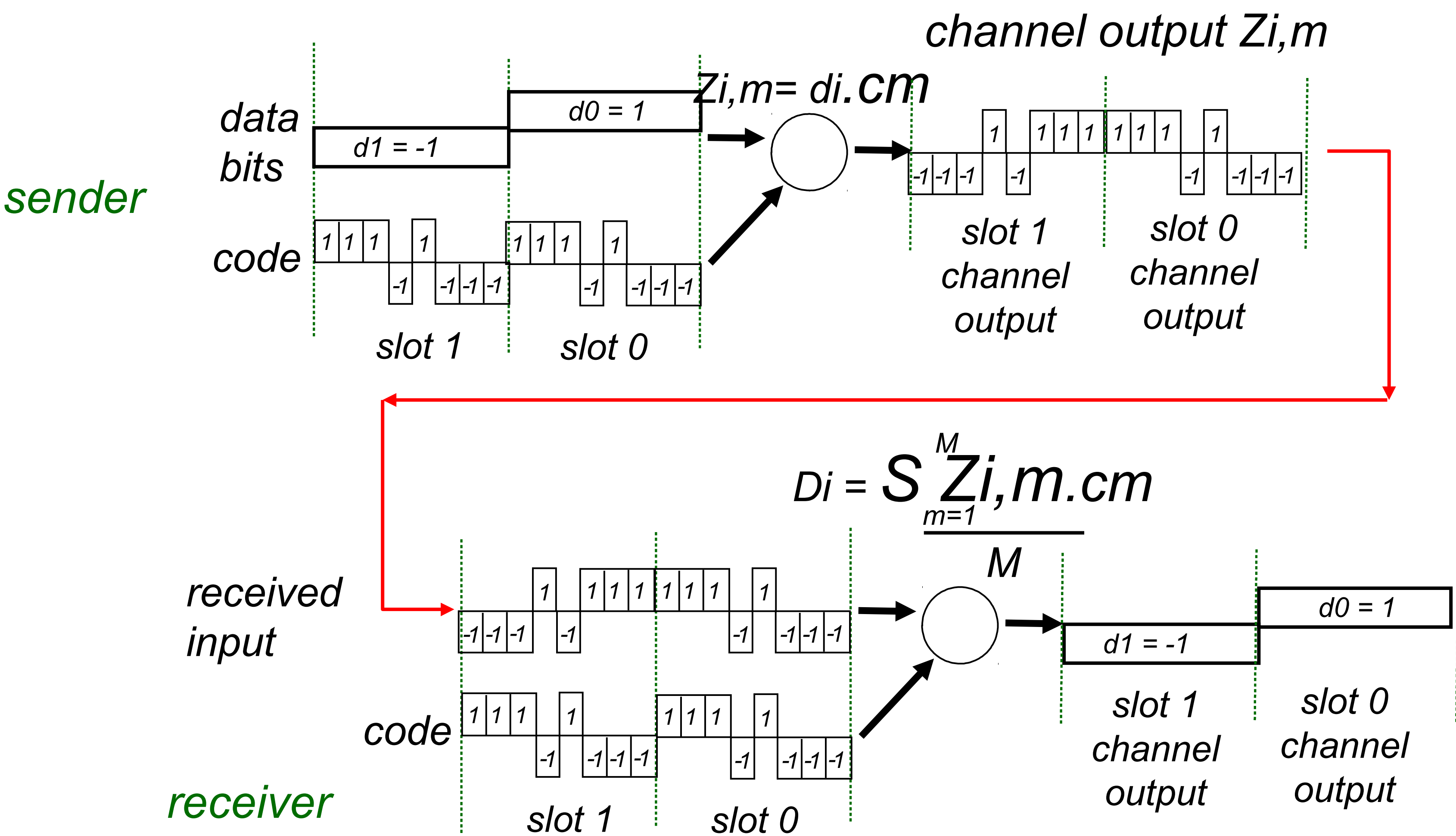




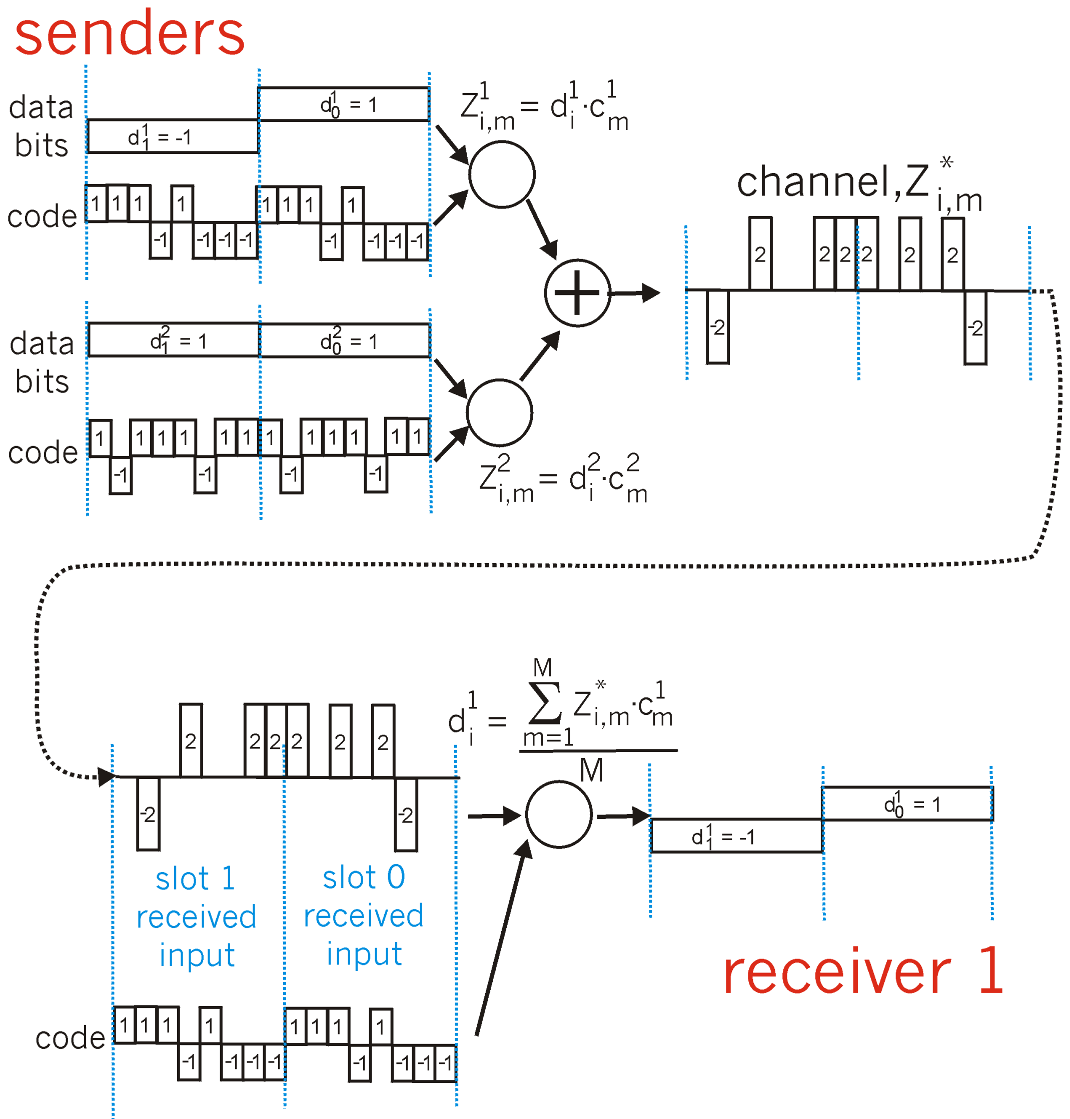
Code Division Multiple Access (CDMA)

- used in several wireless broadcast channels (cellular, satellite, etc) standards
- 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
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence
- allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")

CDMA Encode/Decode



CDMA: two-sender interference



CDMA: two-sender interference

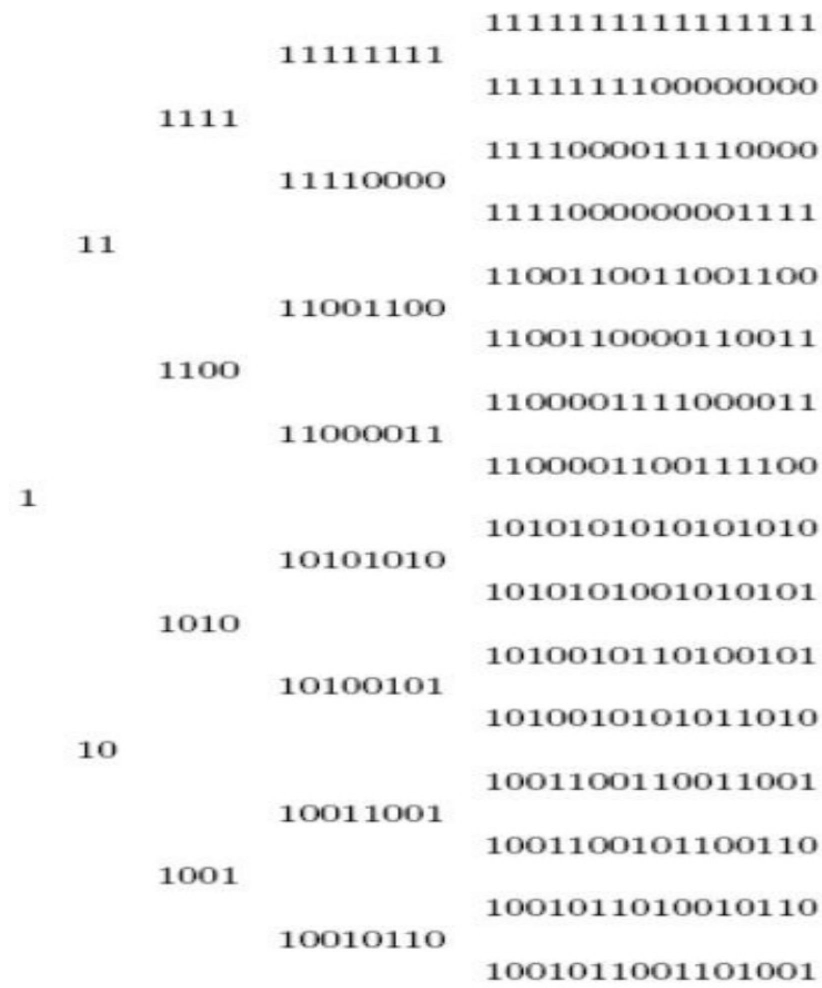
Orthogonal Variable Spreading Factor (OVSF)

- Root spreading code:

$$c_{i,j} \in \{0,1\}^i ; i,j \in \mathbb{N}$$

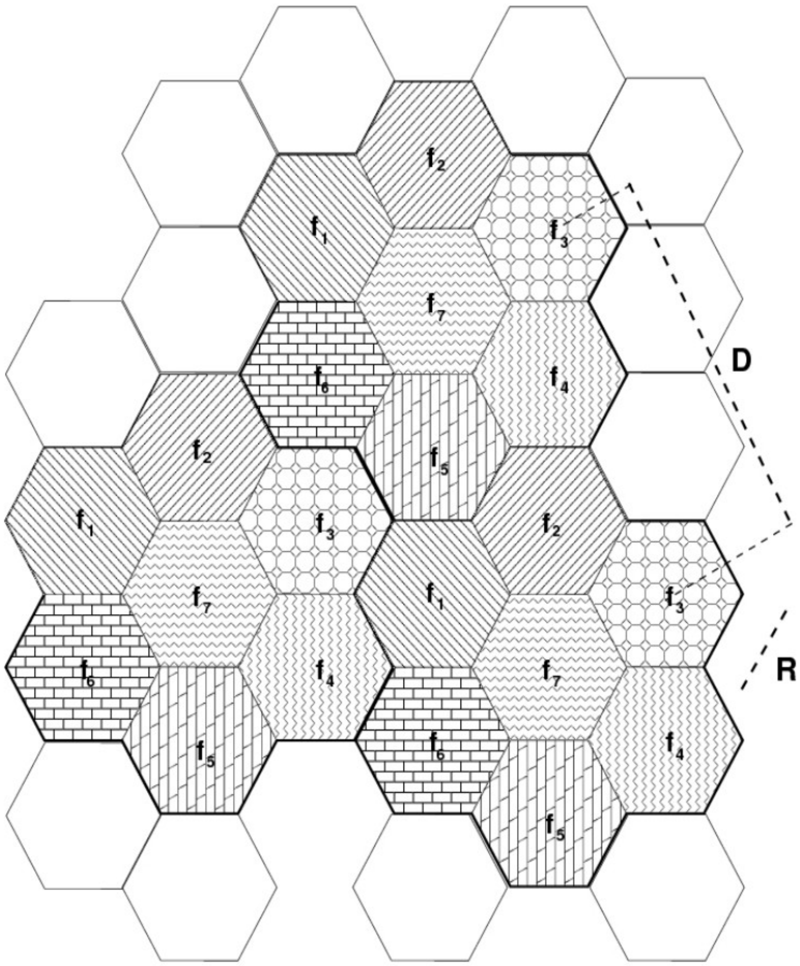
- Create

$$c_{2i,2j-1} = (c_{i,j} c_{i,j})$$
$$c_{2i,2j} = (c_{i,j} \overline{c_{i,j}})$$



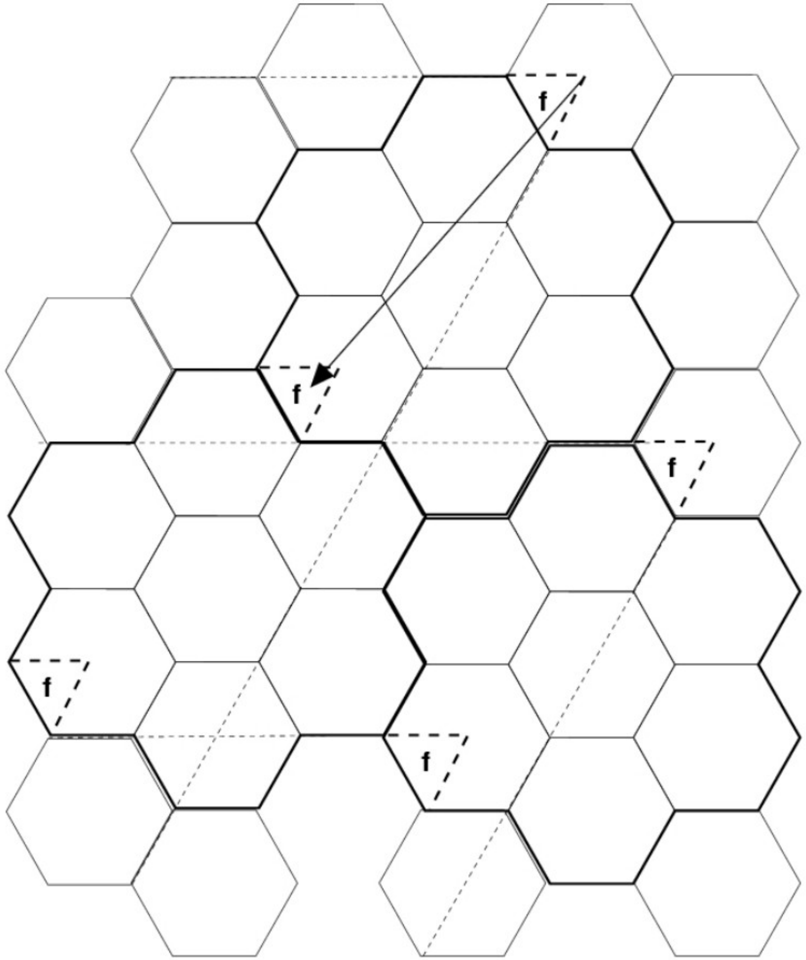
Further techniques for spectrum efficiency

- Clustering
  - Cells with identical frequencies separated
  - Interference in one frequency band reduced



Further techniques for spectrum efficiency

- Clustering
  - Further reduction of interference by sectioning antennas
  - Typically not implemented in WSNs
    - Relative locations of sensors unknown
    - Organisation of cluster structure problematic



Further techniques for spectrum efficiency

- Spatial diversity
  - Clustering
  - Multiple transmit or receive antennas for a single communication link
    - SIMO
    - MISO
    - MIMO
  - Spatially separated antennas
    - Independent communication channels
    - Fading characteristics for these channels different
    - Probability of inferior reception on all channels simultaneously low

Further techniques for spectrum efficiency

Vector-Matrix of a MIMO-System:

$$\overrightarrow{\zeta^{RX}} = \begin{bmatrix} \zeta_1^{RX} \\ \zeta_2^{RX} \\ \vdots \\ \zeta_M^{RX} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1L} \\ h_{21} & \ddots & & h_{2L} \\ \vdots & & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{ML} \end{bmatrix} \begin{bmatrix} \zeta_1^{TX} \\ \zeta_2^{TX} \\ \vdots \\ \zeta_L^{TX} \end{bmatrix} + \begin{bmatrix} \zeta_1^{\text{noise}} \\ \zeta_2^{\text{noise}} \\ \vdots \\ \zeta_M^{\text{noise}} \end{bmatrix}$$

Further techniques for spectrum efficiency

$$\overrightarrow{\zeta^{RX}} = \begin{bmatrix} \zeta_1^{RX} \\ \zeta_2^{RX} \\ \vdots \\ \zeta_M^{RX} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1L} \\ h_{21} & \ddots & & h_{2L} \\ \vdots & & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{ML} \end{bmatrix} \begin{bmatrix} \zeta_1^{TX} \\ \zeta_2^{TX} \\ \vdots \\ \zeta_L^{TX} \end{bmatrix} + \begin{bmatrix} \zeta_1^{\text{noise}} \\ \zeta_2^{\text{noise}} \\ \vdots \\ \zeta_M^{\text{noise}} \end{bmatrix}$$

Vector of received signal components:

$$\overrightarrow{\zeta^{RX}} = (\zeta_1^{RX}, \zeta_2^{RX}, \ldots, \zeta_M^{RX})^T$$

Vector of noise signals:

$$\overrightarrow{\zeta^{\text{noise}}} = (\zeta_1^{\text{noise}}, \zeta_2^{\text{noise}}, \ldots, \zeta_M^{\text{noise}})^T$$

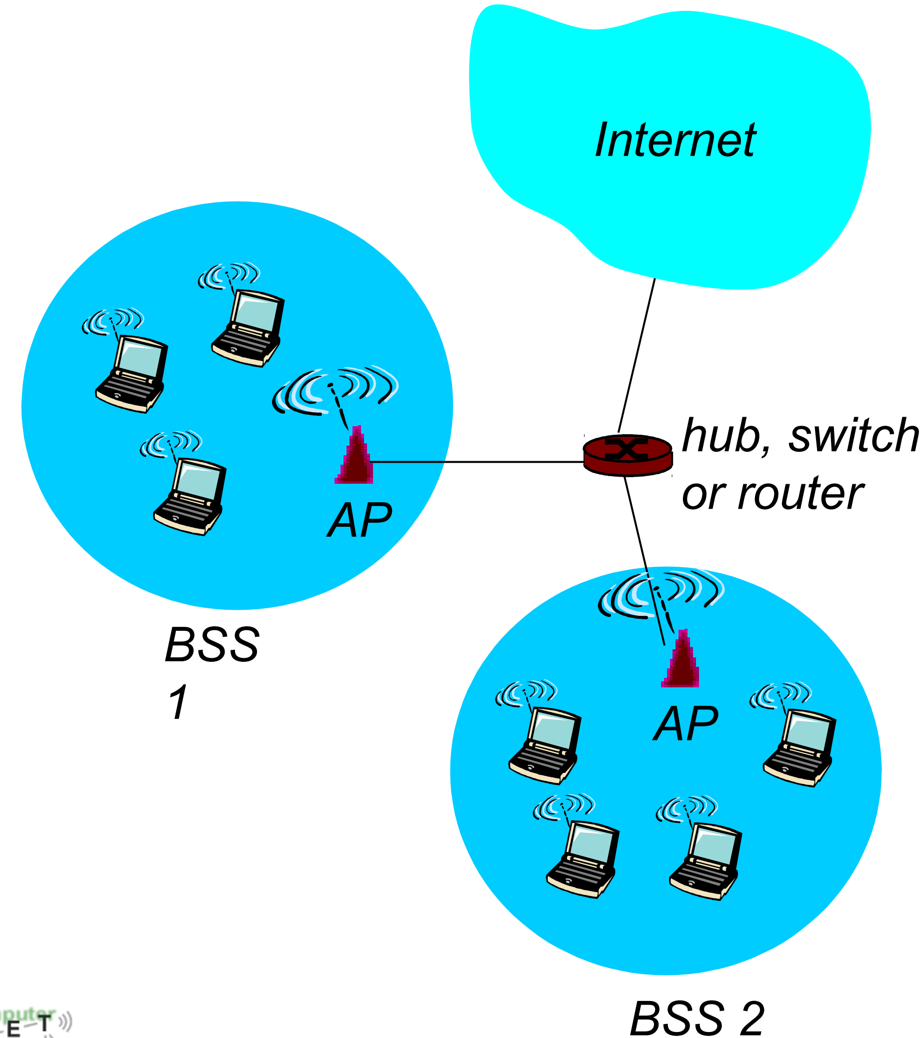
Channel Matrix H describes connection of inputs and outputs.

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

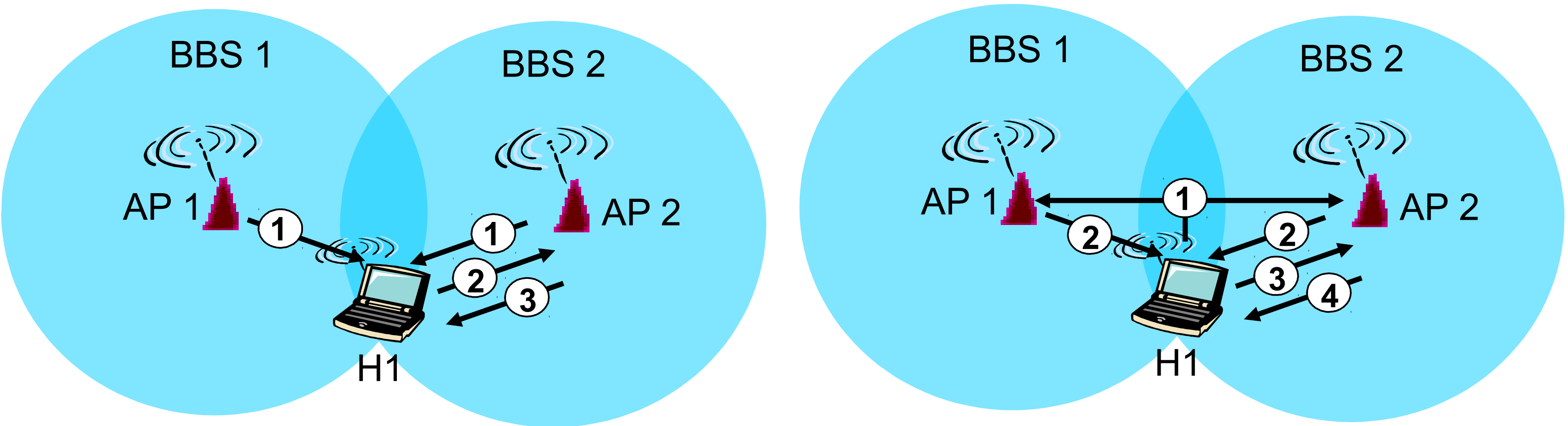


- wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only

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

802.11: passive/active scanning



Passive Scanning:

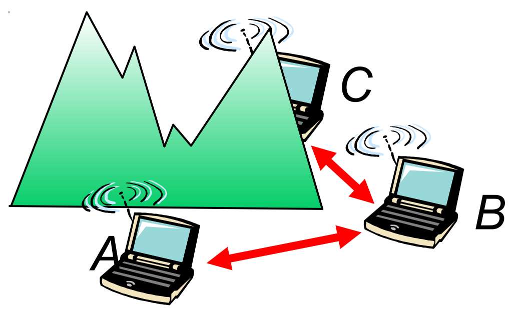
(1) beacon frames sent from APs
(2) association Request frame sent: H1 to selected AP
(3) association Response frame sent: H1 to selected AP

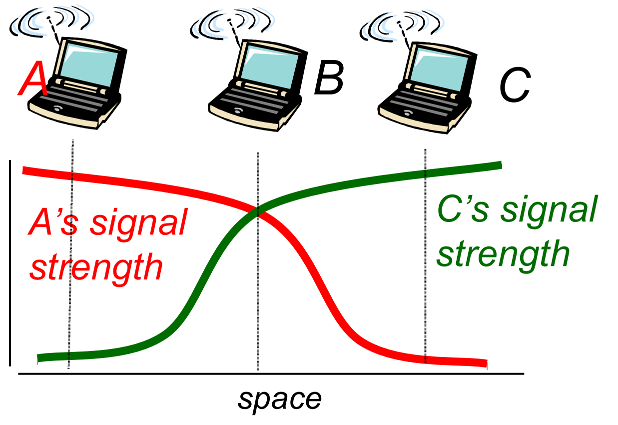
Active Scanning:

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

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)





IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS** then

transmit entire frame (no CD)

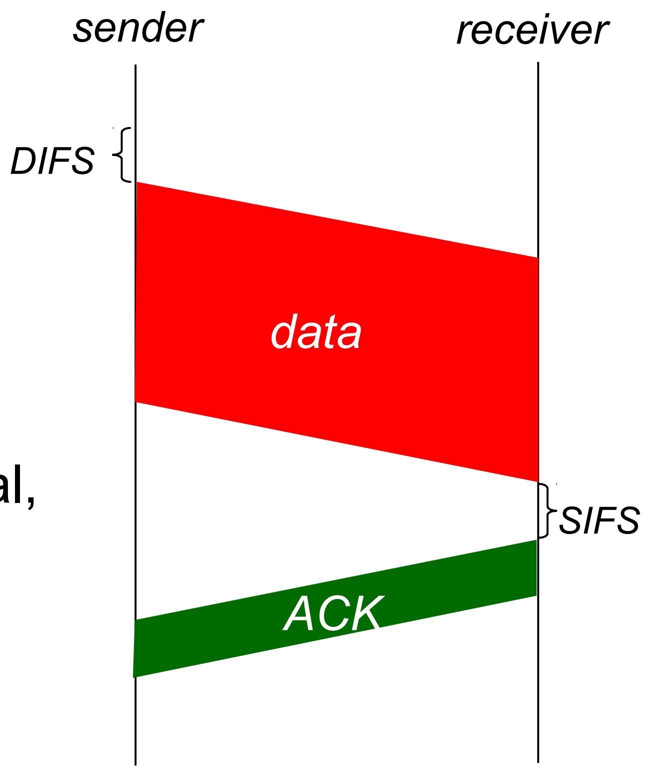
2 if sense channel busy then

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)

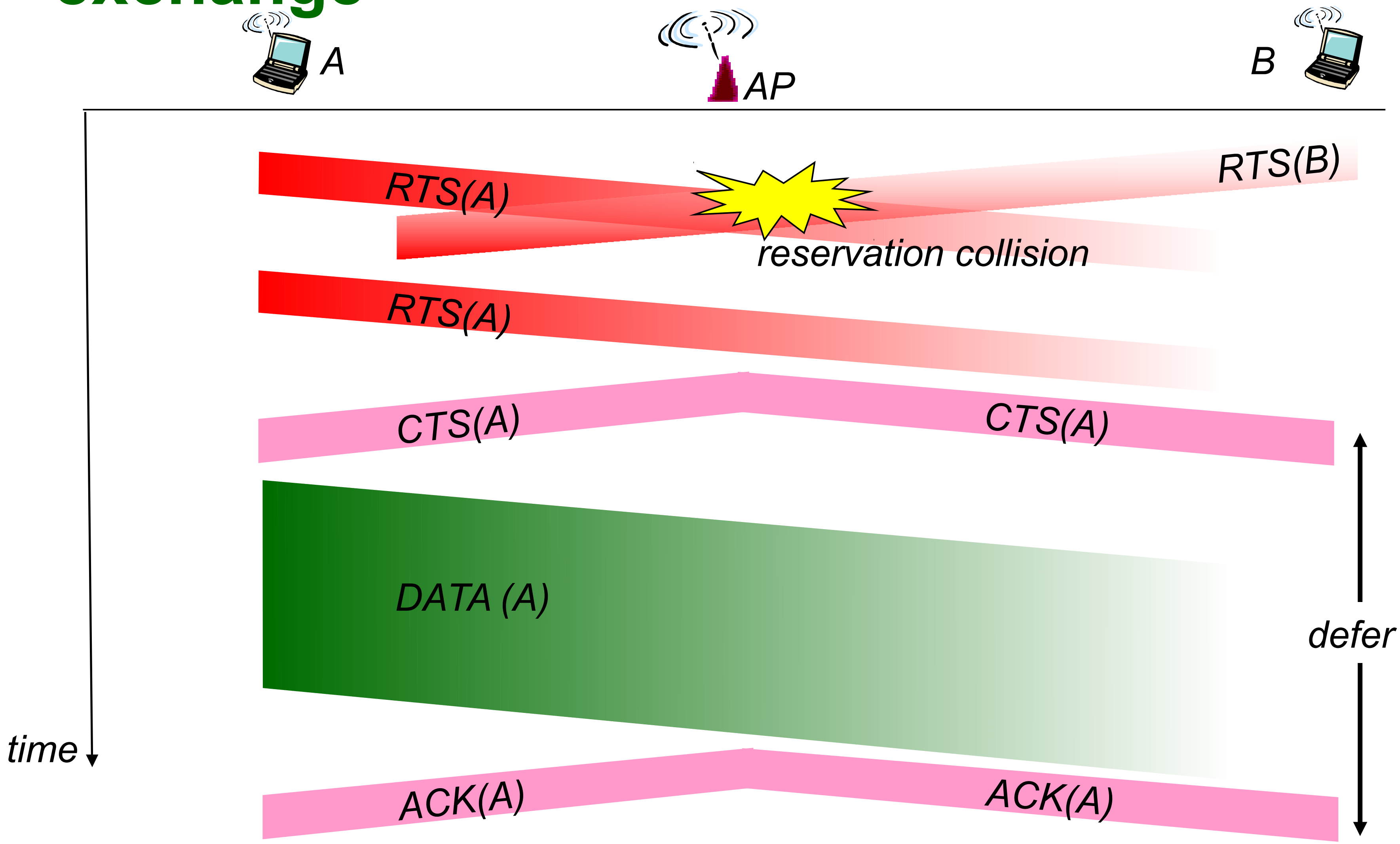
Avoiding collisions (more)

idea: 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



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