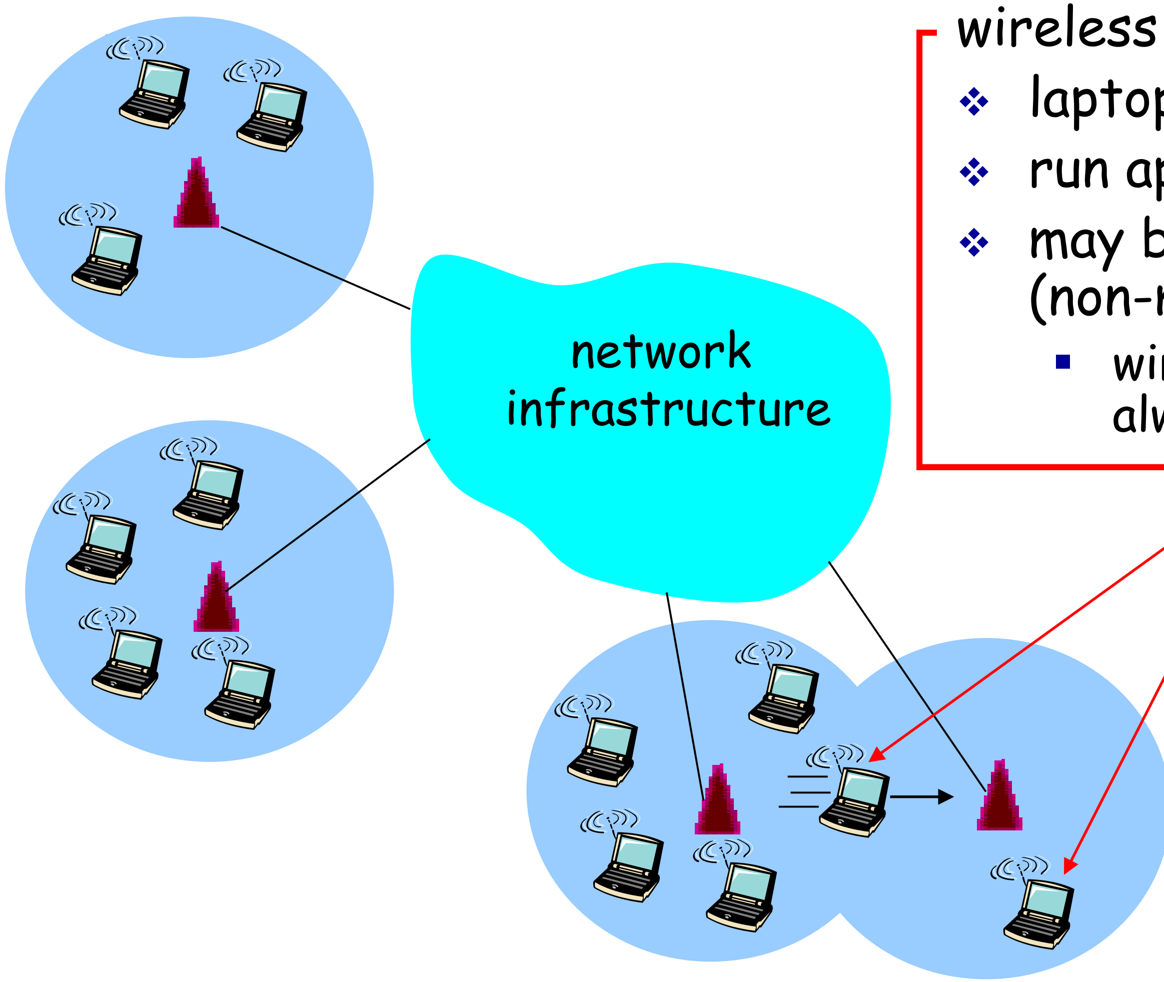
Wireless and Mobile Networks

Background:

- # wireless (mobile) phone subscribers now exceeds # wired phone subscribers!
- # wireless Internet-connected devices soon to exceed # 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

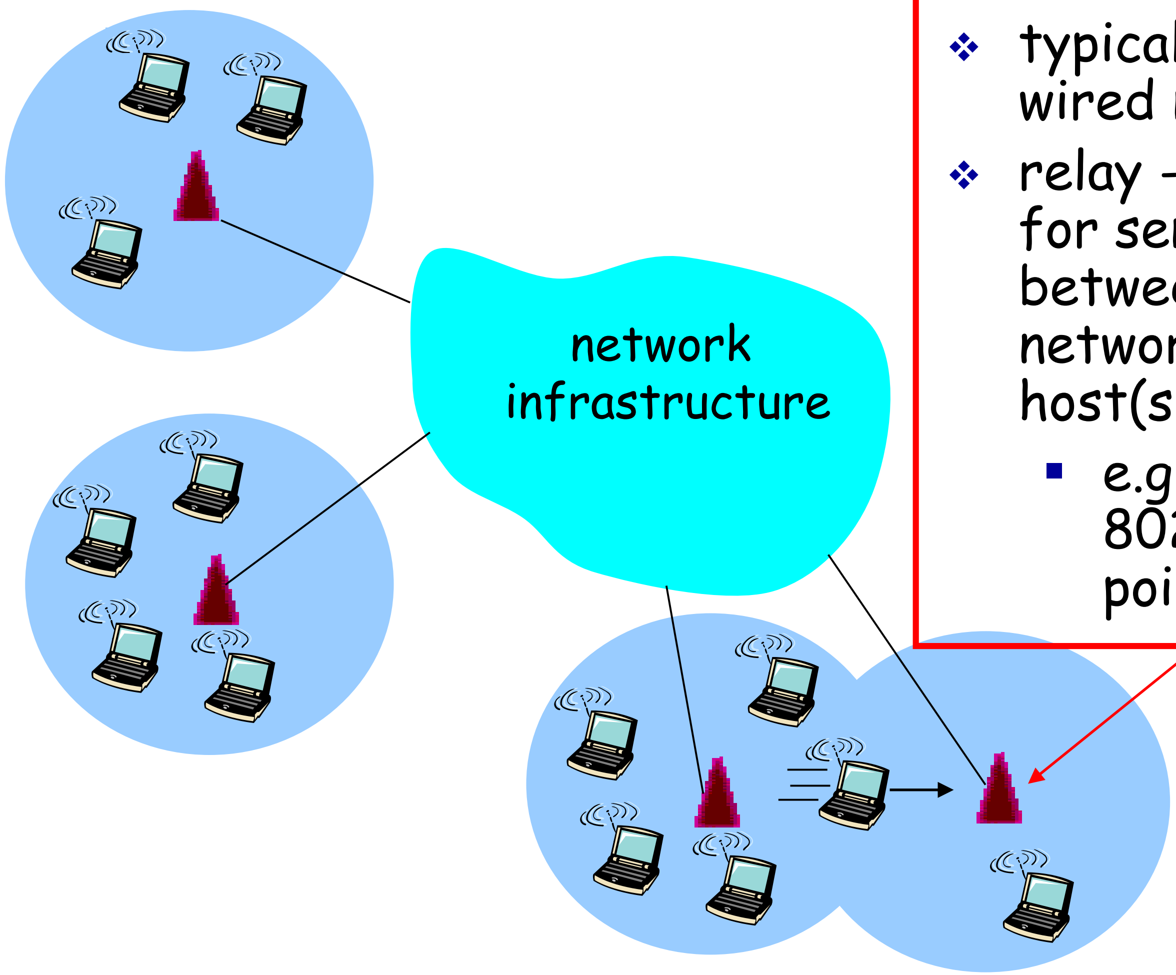
Elements of a wireless network



wireless hosts

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

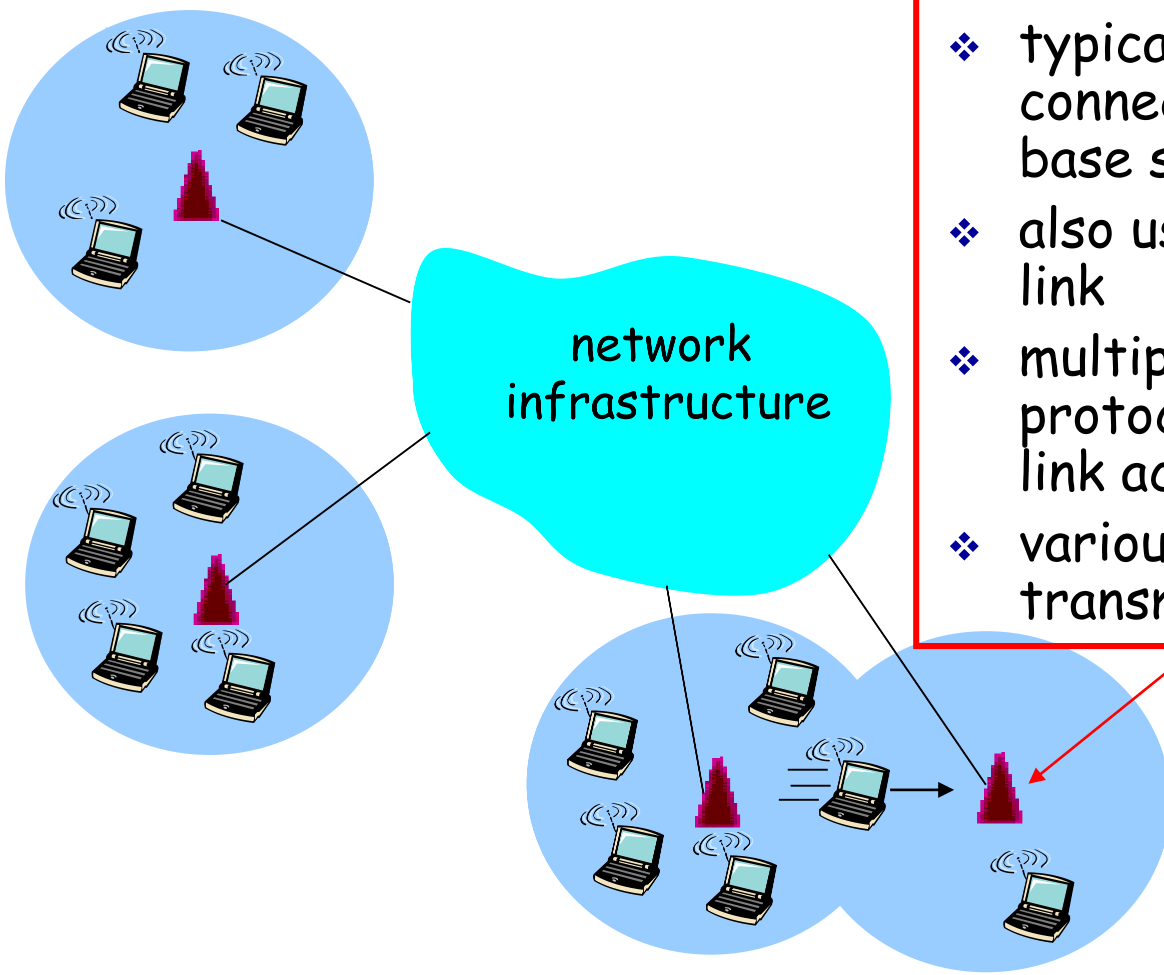
Elements of a wireless network



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

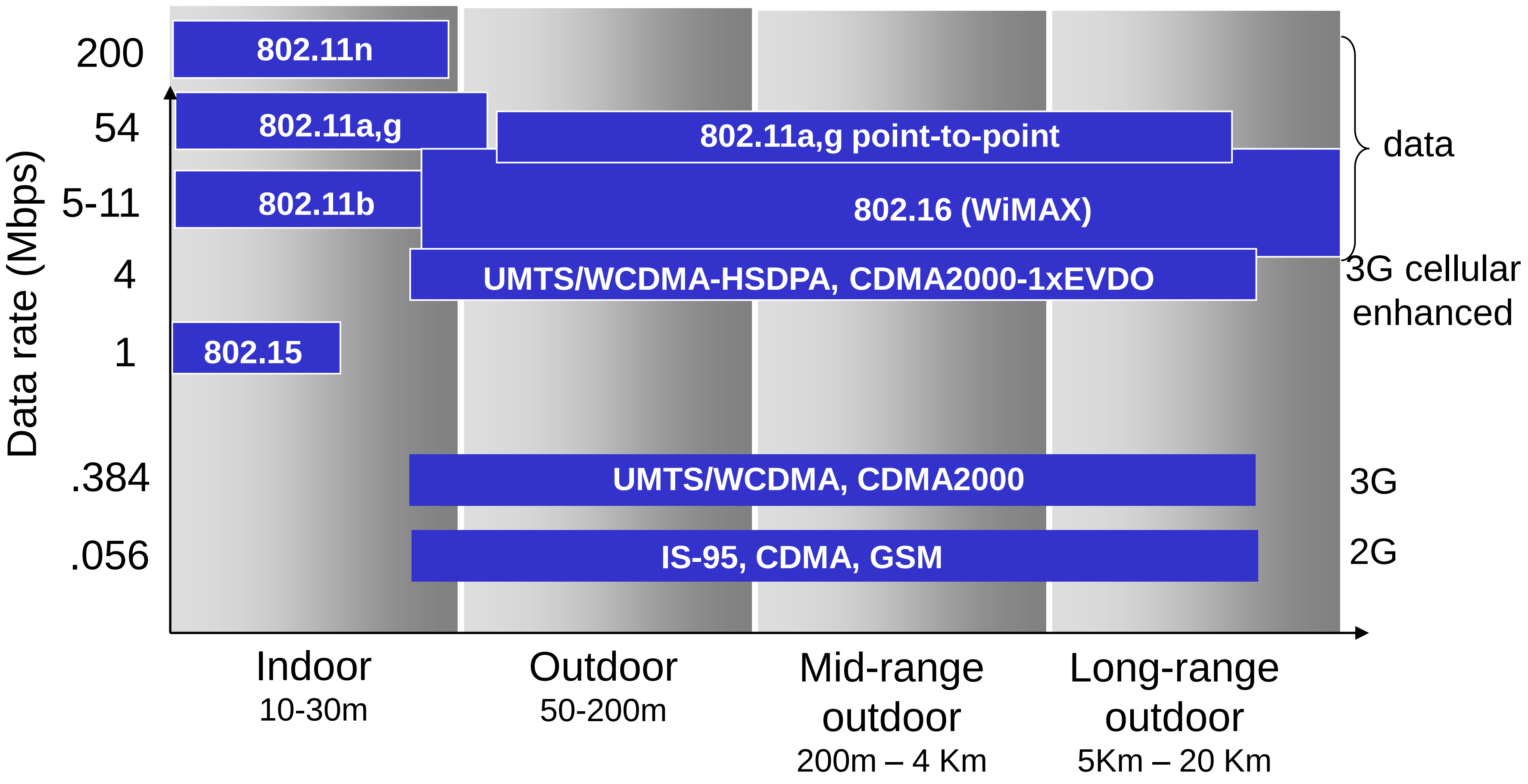
Elements of a wireless network



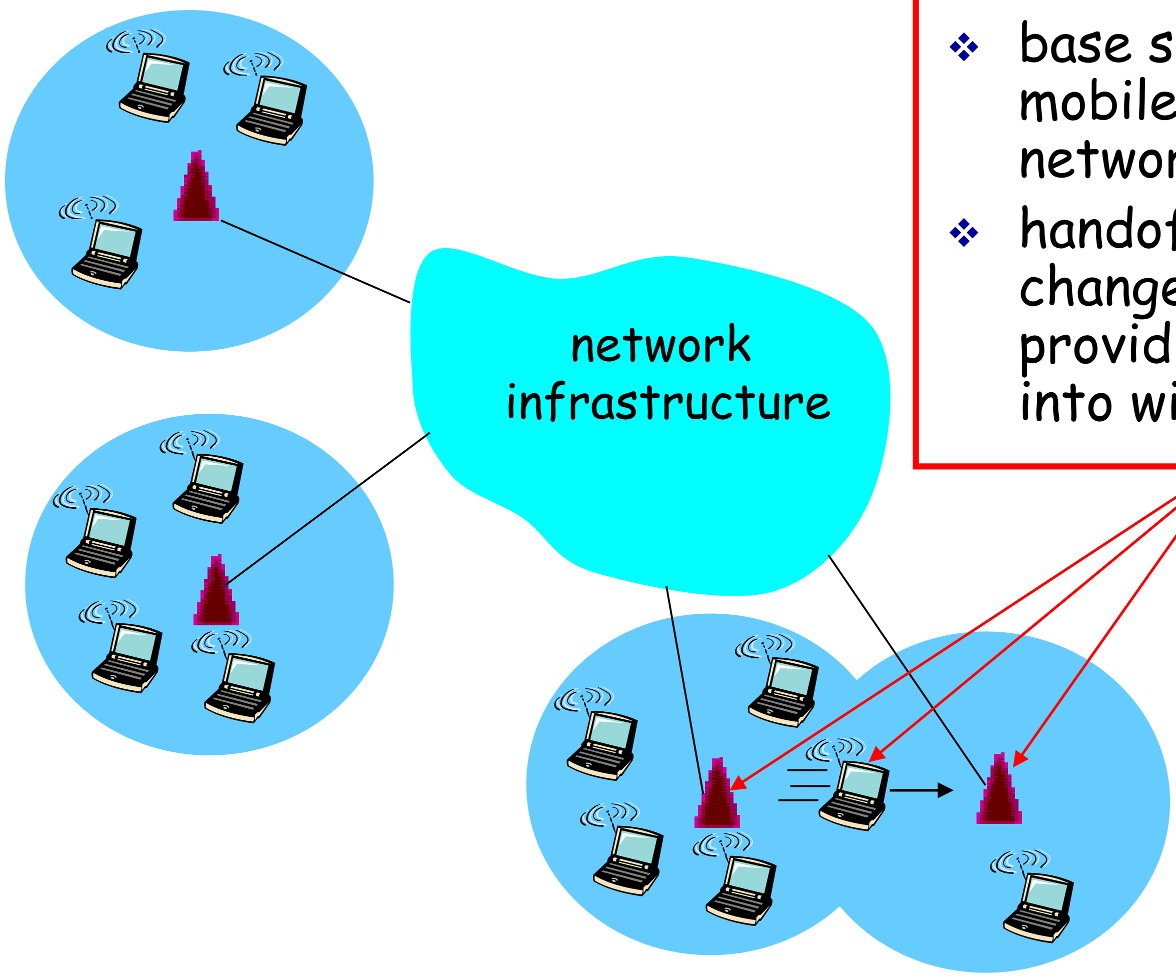
wireless link

- 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



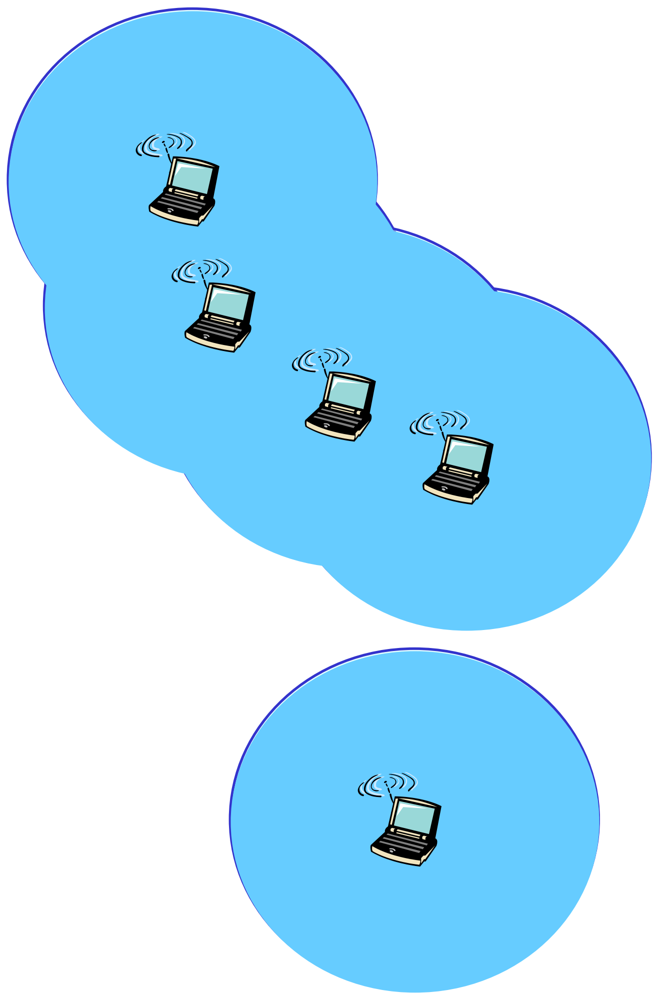
Elements of a wireless network



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 some other nodes to reach a dest. MANET, VANET

Wireless Link Characteristics (1)

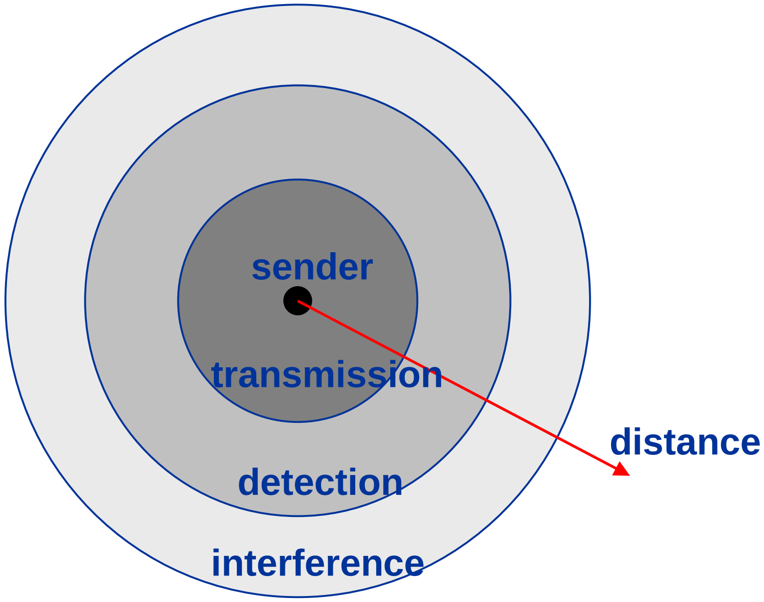
Differences from wired link ….

- 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”

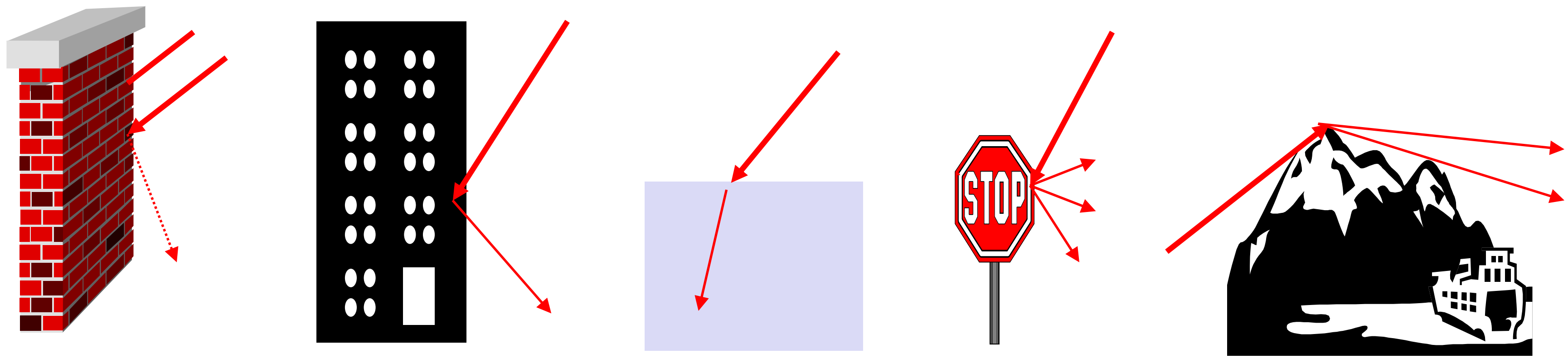
Signal propagation ranges

- **Transmission range**
  - communication possible
  - low error rate
- **Detection range**
  - detection of the signal possible
  - no communication possible
- **Interference range**
  - signal may not be detected
  - signal adds to the background noise



Signal propagation

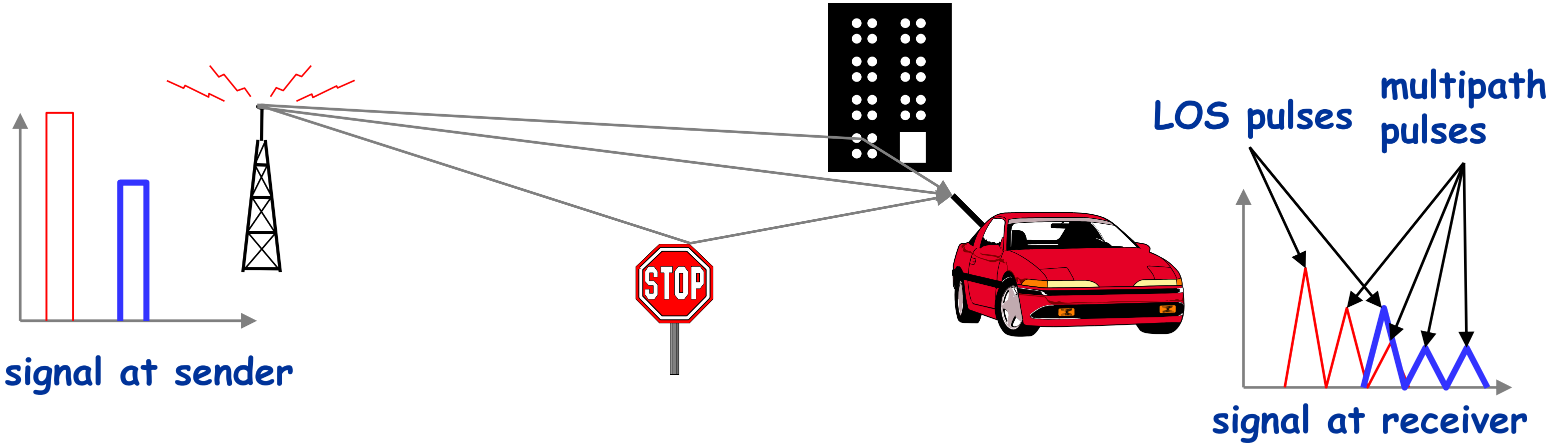
- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$ in vacuum – much more in real environments (d = distance between sender and receiver)
- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges



shadowing reflection refraction scattering diffraction

Multipath propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
  ➔ interference with "neighbor" symbols, **Inter Symbol Interference (ISI)**
- The signal reaches a receiver directly and phase shifted
  ➔ distorted signal depending on the phases of the different parts

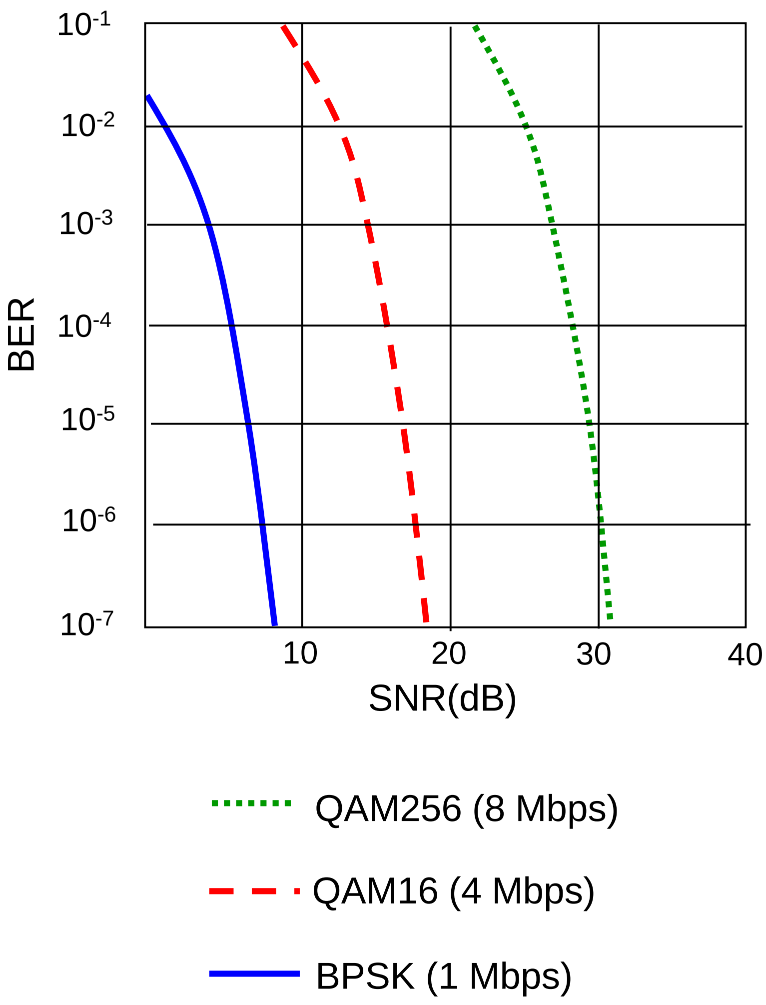
Effects of mobility

- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
    - ➔ quick changes in the power received (**short term fading**)

- Additional changes in
  - distance to sender
  - obstacles further away
    - ➔ slow changes in the average power received (**long term fading**)

Wireless Link Characteristics (2)

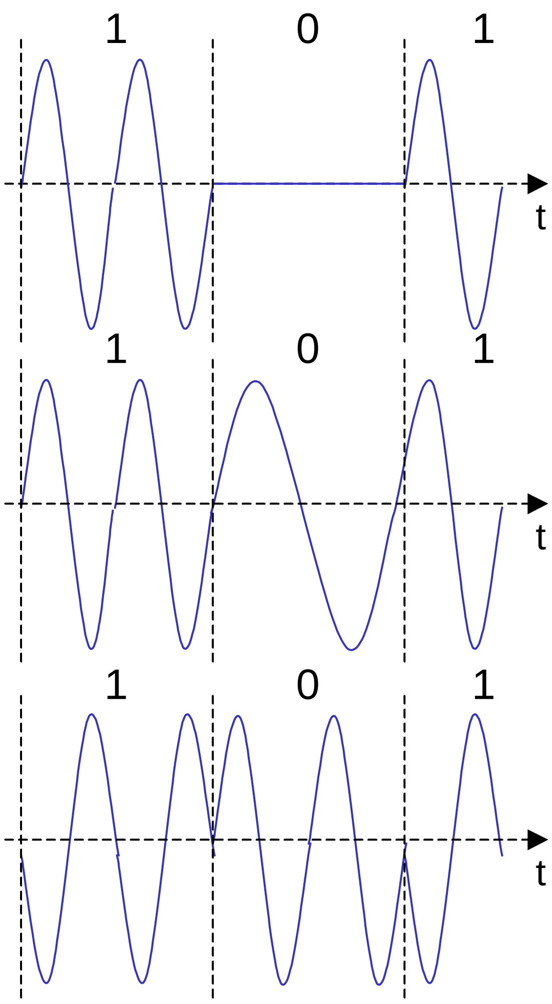
- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a "good thing")
- *SNR versus BER tradeoffs*
  - *given physical layer:* increase power -> increase SNR->decrease BER
  - *given SNR:* choose physical layer that meets BER requirement, giving highest thruput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



Digital modulation

Modulation of digital signals known as **Shift Keying**

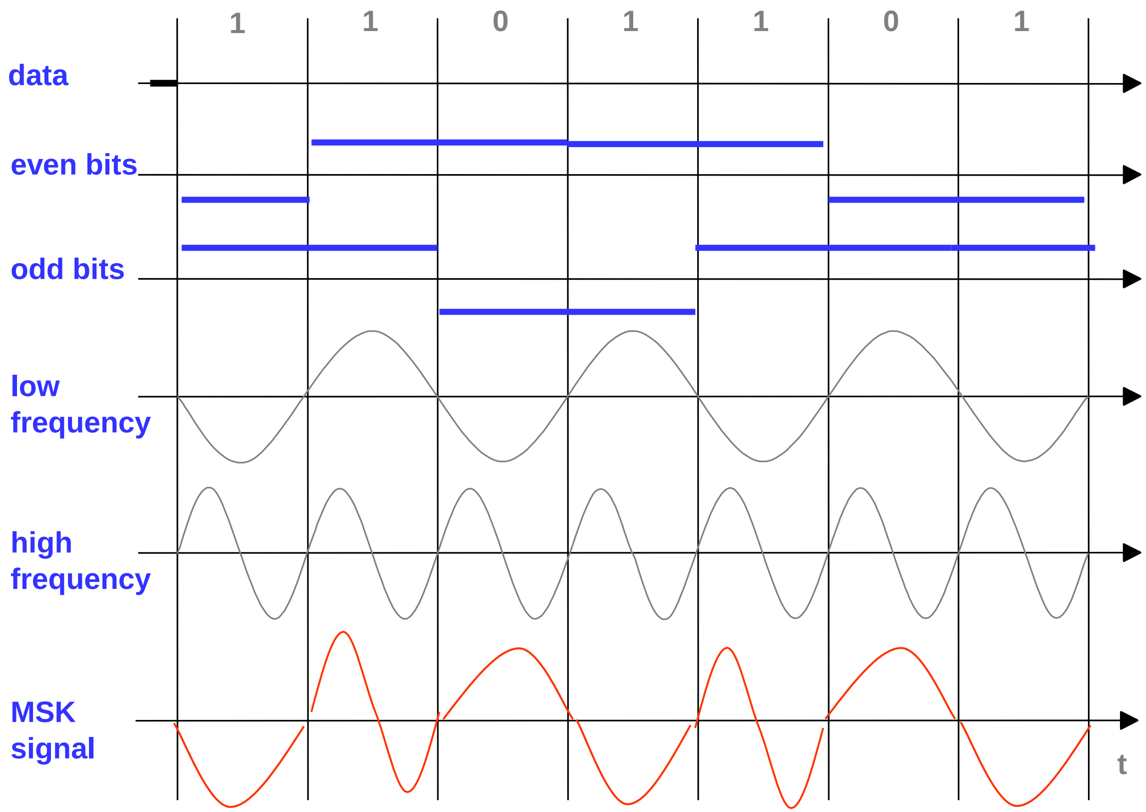
- Amplitude Shift Keying (ASK)
  - very simple
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK)
  - needs larger bandwidth
- Phase Shift Keying (PSK)
  - more complex
  - robust against interference



Advanced Frequency Shift Keying

- special pre-computation avoids sudden phase shifts
  → **MSK (Minimum Shift Keying)**
- bit separated into even and odd bits, the duration of each bit is doubled
- depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
- the frequency of one carrier is twice the frequency of the other (**f2=2f1**)
- even higher bandwidth efficiency using a Gaussian low-pass filter
  → **GMSK (Gaussian MSK)**, used in GSM

Example of MSK

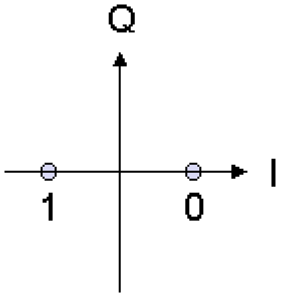


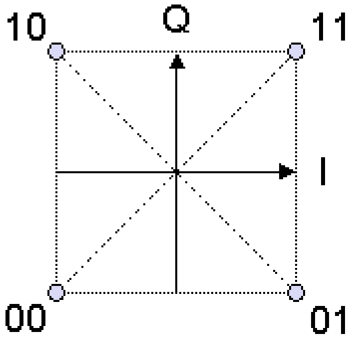
bit	
even	0 1 0 1
odd	0 0 1 1
signal	h n n h
value	- - + +

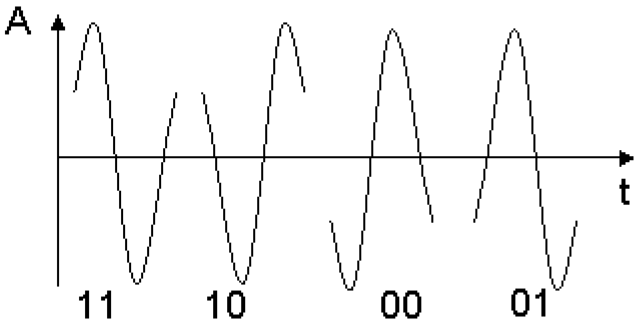
h: high frequency
n: low frequency
+: original signal
-: inverted signal

Advanced Phase Shift Keying

- **BPSK (Binary Phase Shift Keying)**
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used in satellite systems
- **QPSK (Quadrature Phase Shift Keying)**
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex
- **DQPSK - Differential QPSK** (IS-136, PHS)
  - Phase shift is not relative to a reference signal but to the phase of the previous two bits

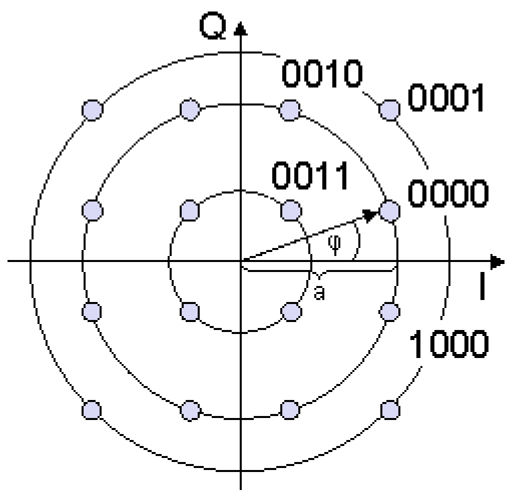






Quadrature Amplitude Modulation

- **Quadrature Amplitude Modulation (QAM):** combines amplitude and phase modulation
  - it is possible to code one symbol using n bits
  - 2^n discrete levels, n=2 identical to QPSK
  - bit error rate increases with n, but less errors compared to comparable PSK schemes



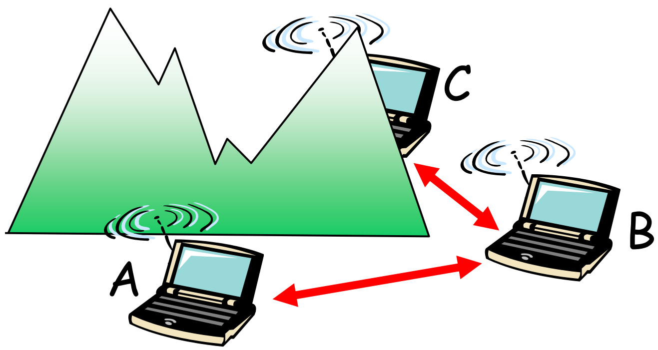
Example: 16-QAM (4 bits = 1 symbol)

- Symbols 0011 and 0001 have the same phase φ, but different amplitude a.
- 0000 and 1000 have different phase, but same amplitude.

→ used in standard 9600 bit/s modems

Wireless network characteristics

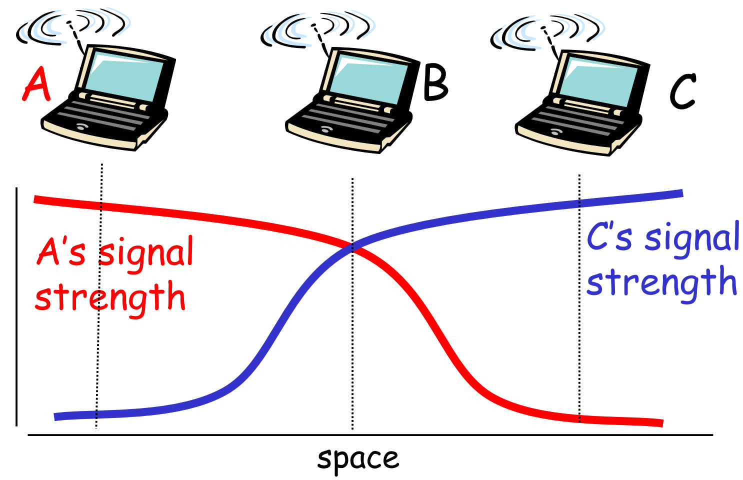
Multiple wireless senders and receivers create additional problems (beyond multiple access):



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

MACA - collision avoidance

MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance

- **RTS (request to send):** a sender request the right to send from a receiver with a short RTS packet before it sends a data packet
- **CTS (clear to send):** the receiver grants the right to send as soon as it is ready to receive

Signaling packets contain

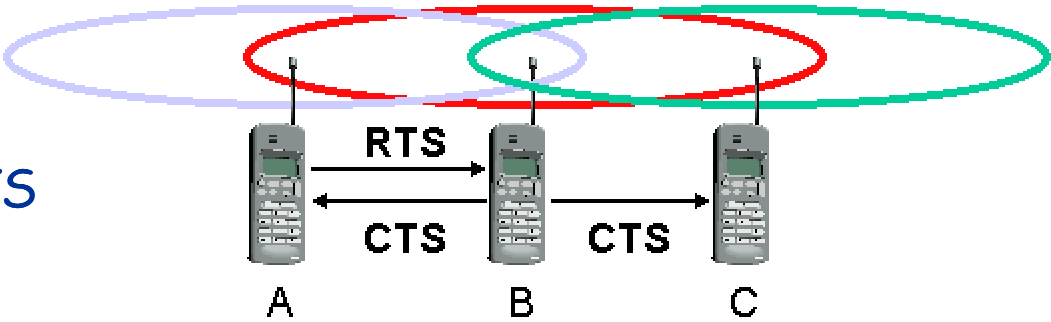
- sender address
- receiver address
- packet size

Variants of this method can be found in IEEE802.11 as DFWMAC (Distributed Foundation Wireless MAC)

MACA examples

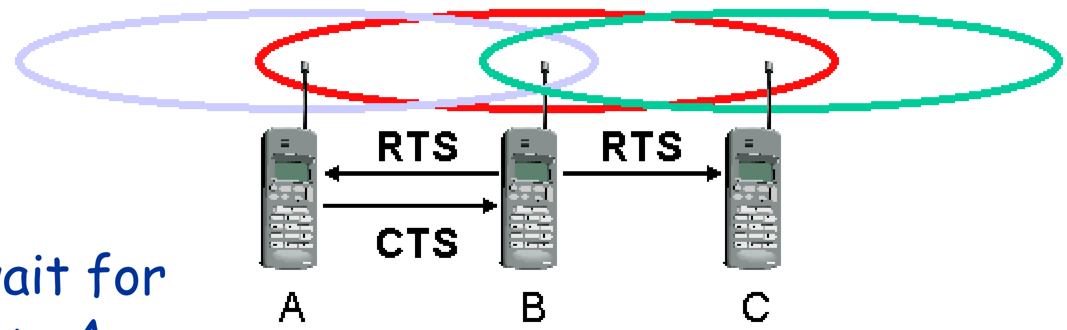
MACA avoids the problem of hidden terminals

- A and C want to send to
- A sends RTS first
- C waits after receiving CTS from B

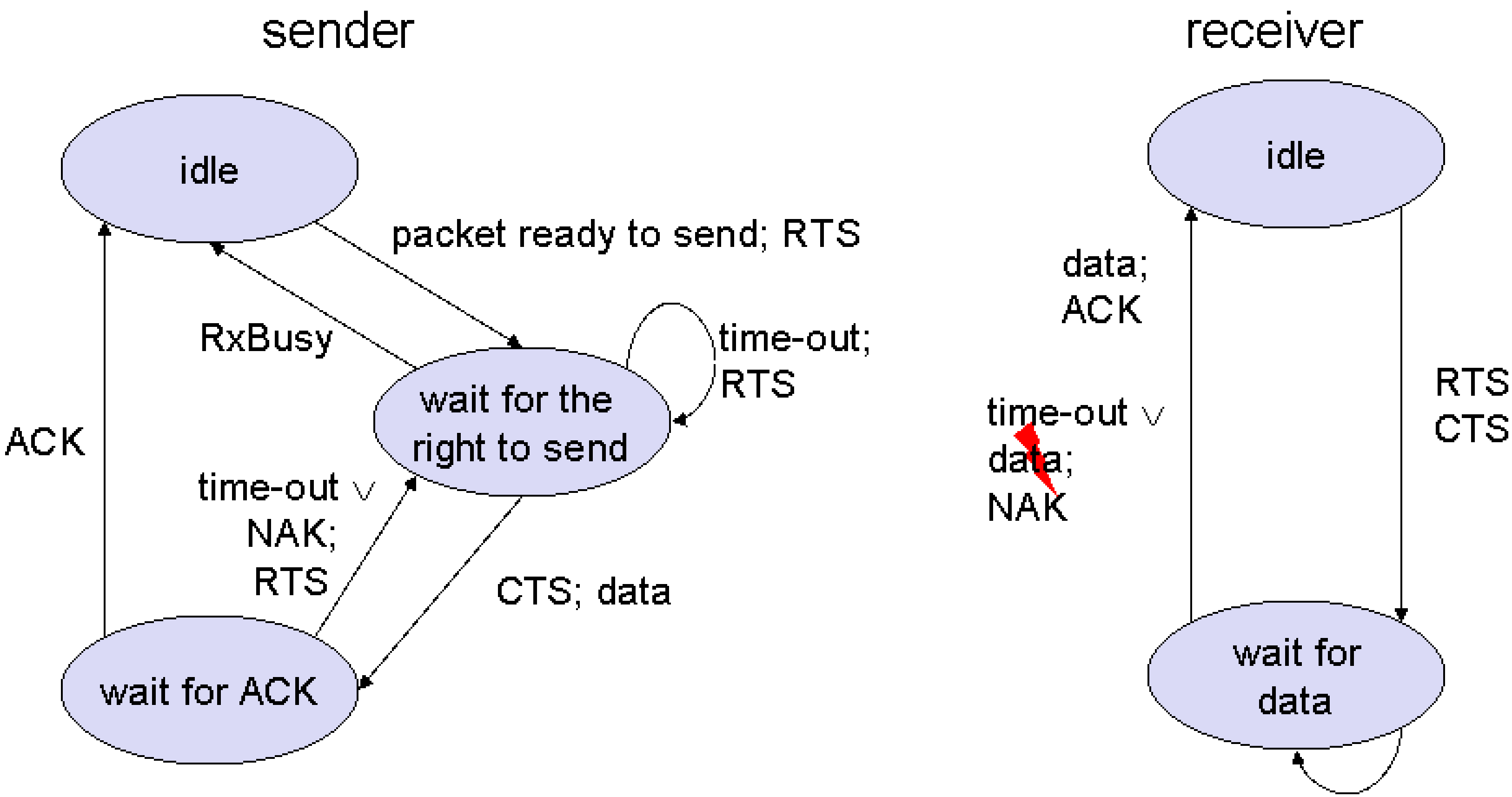


MACA avoids the problem of exposed terminals

- B wants to send to A, C to another terminal
- now C does not have to wait for it cannot receive CTS from A



MACA variant: DFWMAC in IEEE802.11



ACK: positive acknowledgement
NAK: negative acknowledgement

RxBusy: receiver busy

Multiplexing

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)
- Goal: multiple use of a shared medium
- Important: guard spaces needed!

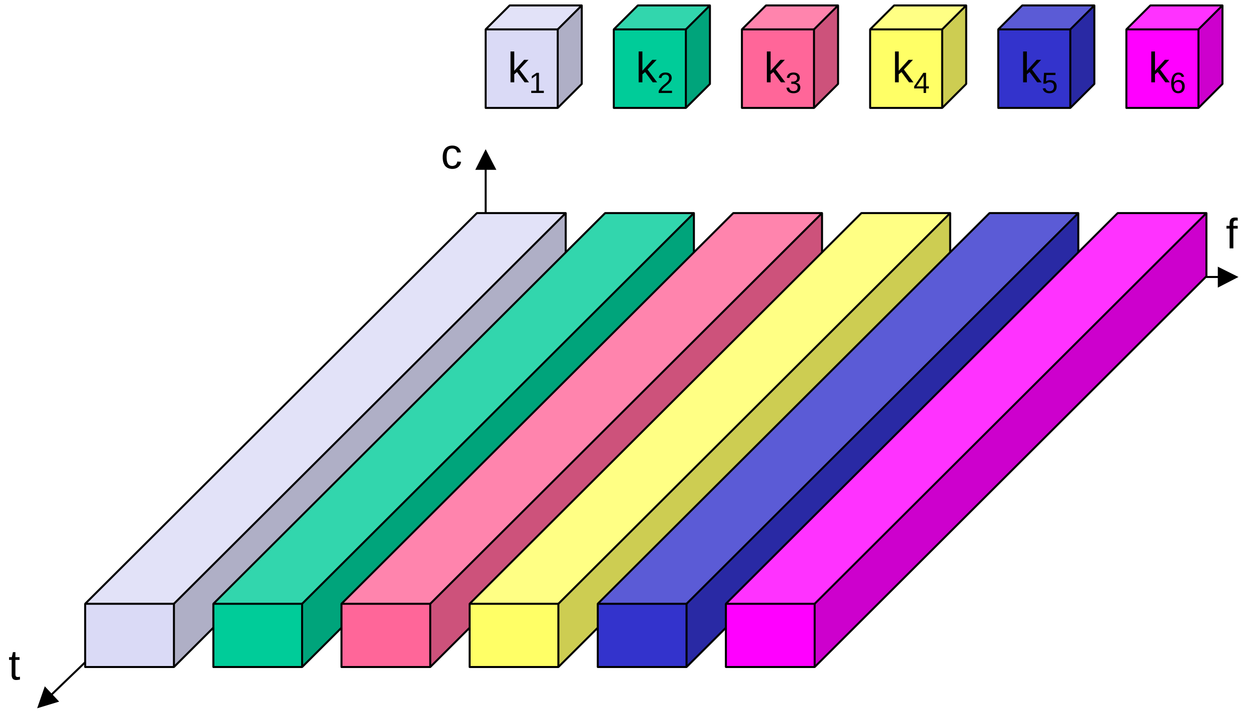
Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands
  A channel gets a certain band of the spectrum for the whole time

- Advantages:
  - no dynamic coordination necessary
  - works also for analog signals

- Disadvantages:
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible
  - guard spaces

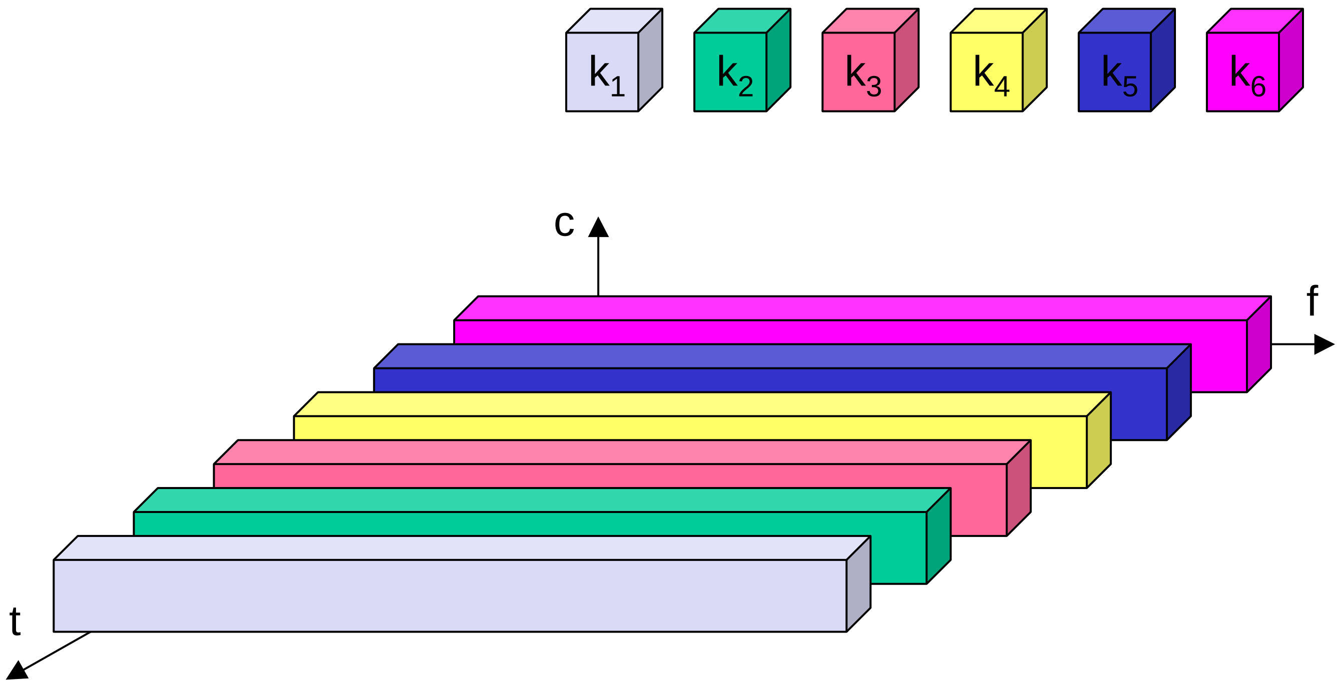
Frequency multiplex



Time multiplex

- A channel gets the whole spectrum for a certain amount of time
- Advantages:
  - only one carrier in the medium at any time
  - throughput high even for many users
- Disadvantages:
  - precise synchronization necessary

Time multiplex

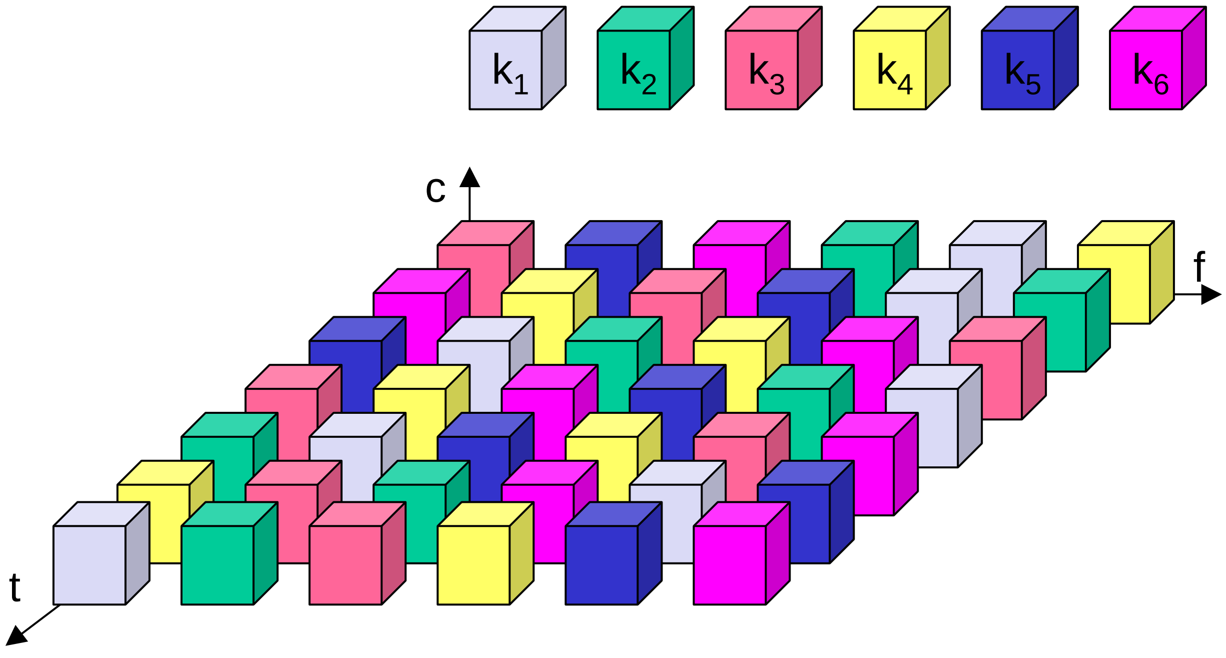


Time and frequency multiplex

- Combination of both methods
  A channel gets a certain frequency band for a certain amount of time
  Example: GSM

- Advantages:
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code multiplex
  - but, precise coordination required

Time and frequency multiplex



Code multiplex

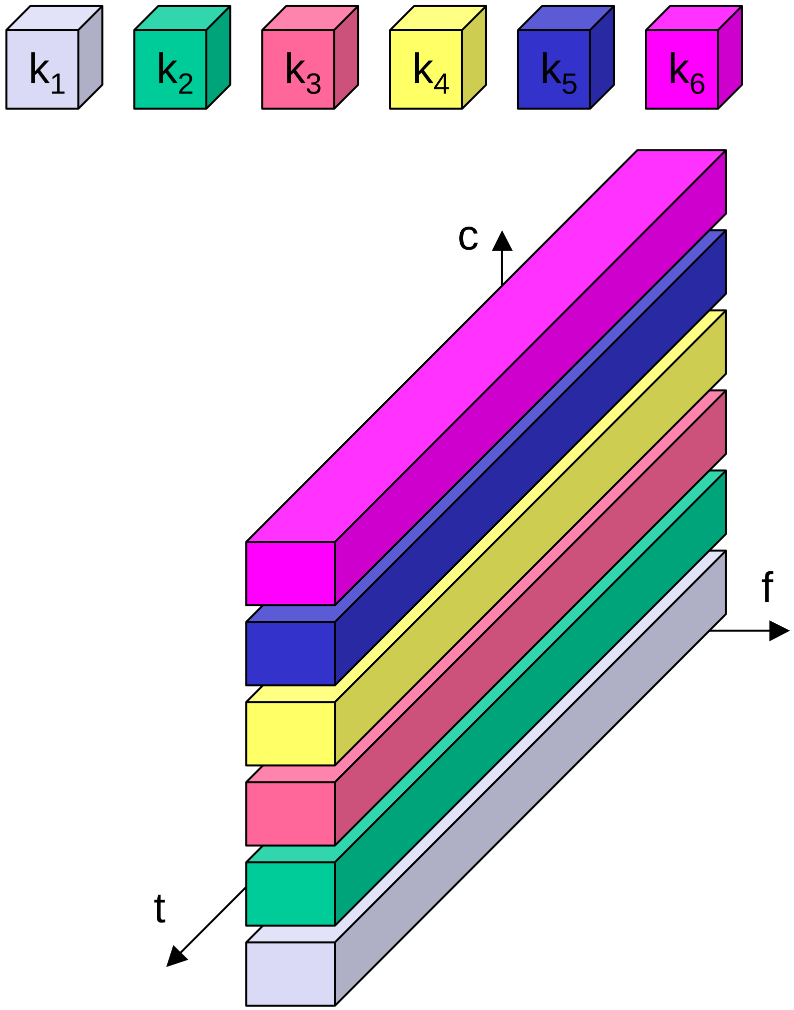
- Each channel has a unique code
- All channels use the same spectrum at the same time

- Advantages:
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping

- Disadvantages:
  - lower user data rates
  - more complex signal regeneration

- Implemented using **spread spectrum technology**

Code Multiplex



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")

Advantages:

- all terminals can use the same frequency, no planning needed
- huge code space (e.g. 2^{32}) compared to frequency space
- interferences (e.g. white noise) is not coded
- forward error correction and encryption can be easily integrated

Disadvantages:

- Higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
- All signals should have the same strength at a receiver

- **Good code for CDMA?**
  - Should be **orthogonal** to other codes
  - Should have a good **autocorrelation**

- Two vectors are called orthogonal if their inner product is 0.

1) Vectors (2, 5, 0) and (0, 0, 17) → Orthogonal

$$(2, 5, 0) \bullet (0, 0, 17) = 0 + 0 + 0 = 0$$

Vectors (3, -2, 4) and (-2, 3, 3) → Orthogonal

$$(3, -2, 4) \bullet (-2, 3, 3) = -6 - 6 + 12 = 0$$

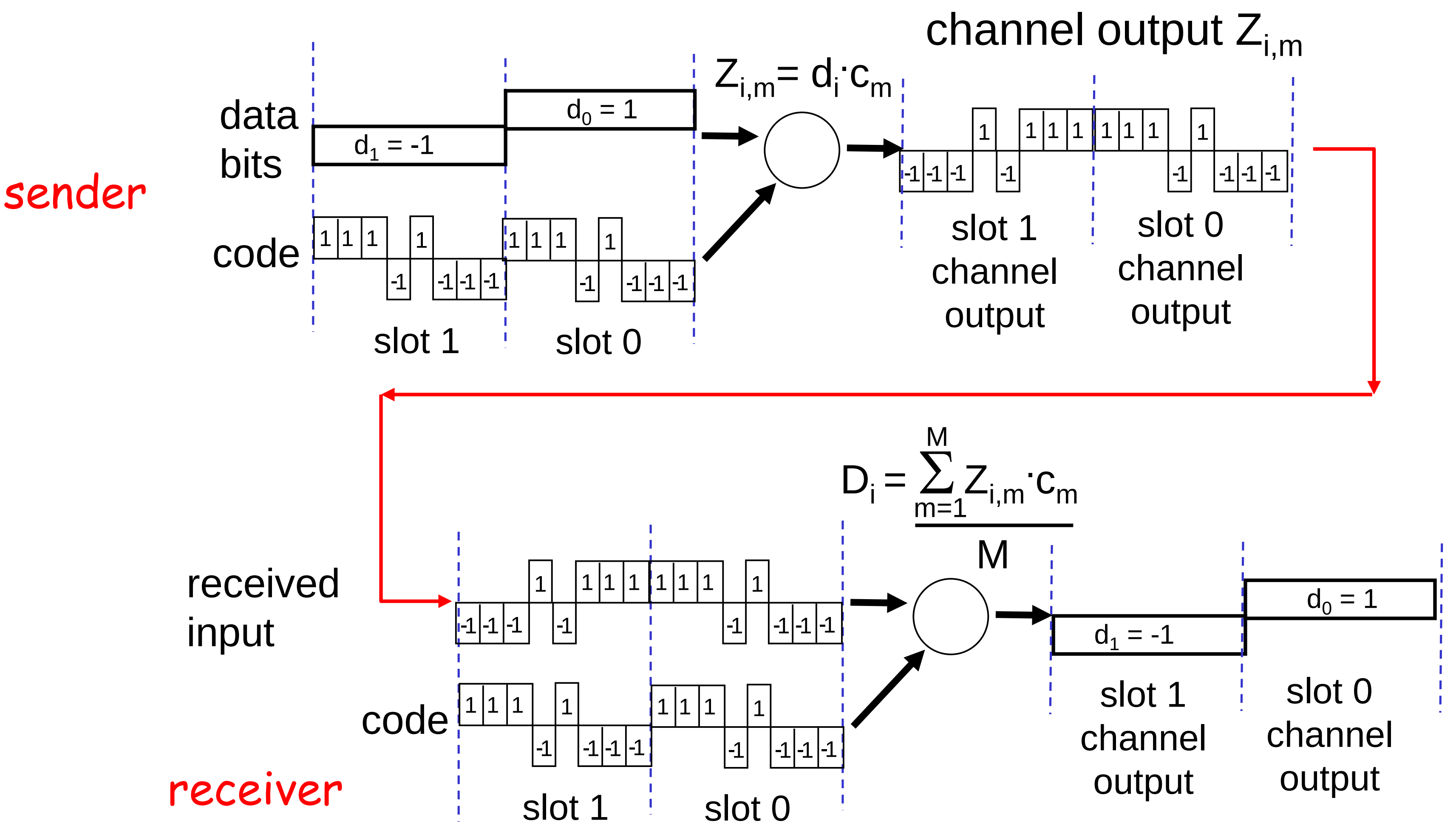
2) Vectors (1, 2, 3) and (4, 2, -6) → Not orthogonal

$$(1, 2, 3) \bullet (4, 2, -6) = 4 + 4 - 18 = -10 \neq 0$$

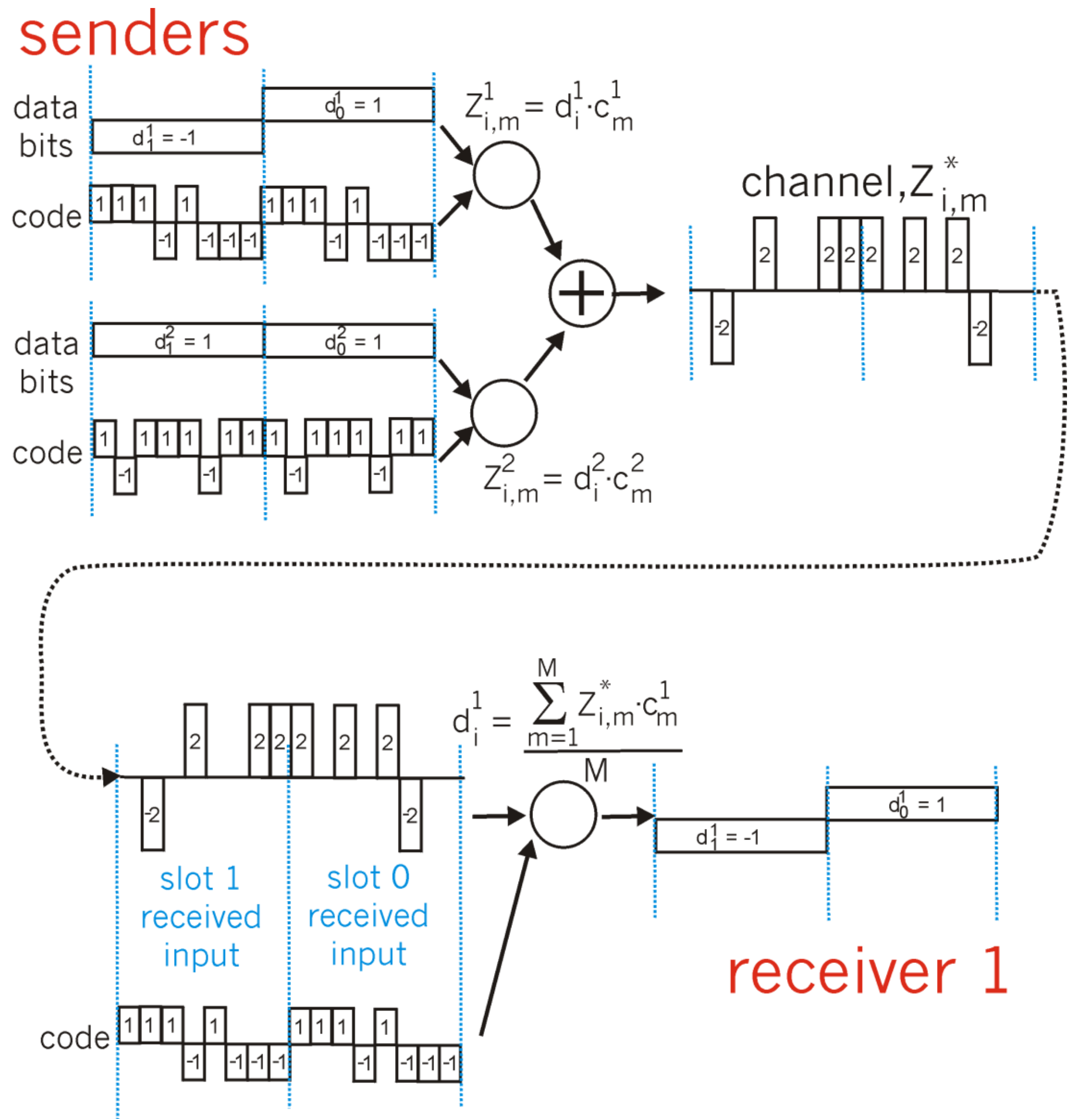
3) Vectors (1, 2, 3) and (4, 2, -3) → Almost orthogonal

$$(1, 2, 3) \bullet (4, 2, -3) = 4 + 4 - 9 = -1 \approx 0$$

CDMA Encode/Decode



CDMA: two-sender interference



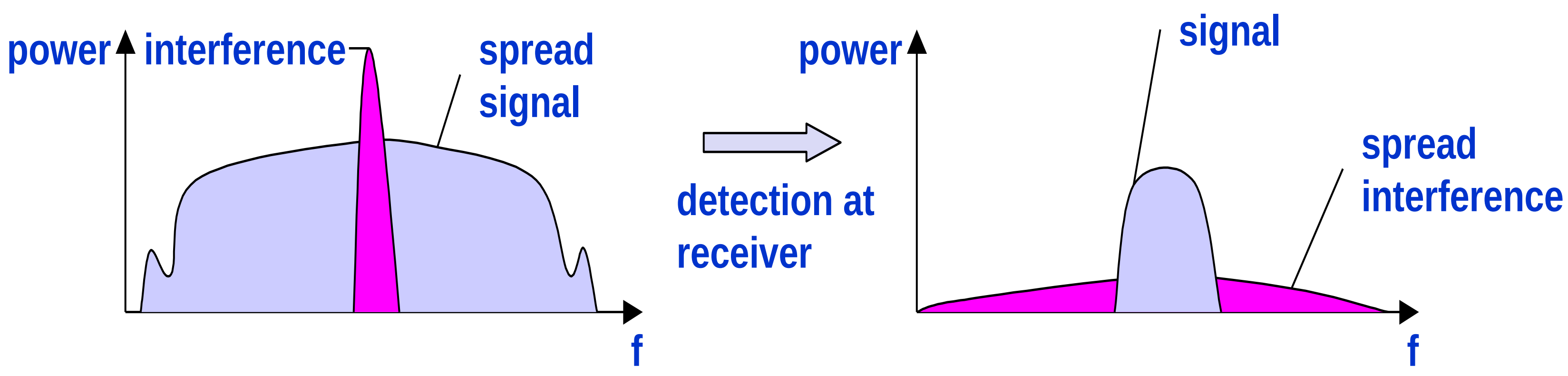
Spread spectrum technology

Problem of radio transmission:

- frequency dependent fading can wipe out narrow band signals for duration of the interference

Solution:

- spread the narrow band signal into a broad band signal using a special code
- protection against narrow band interference



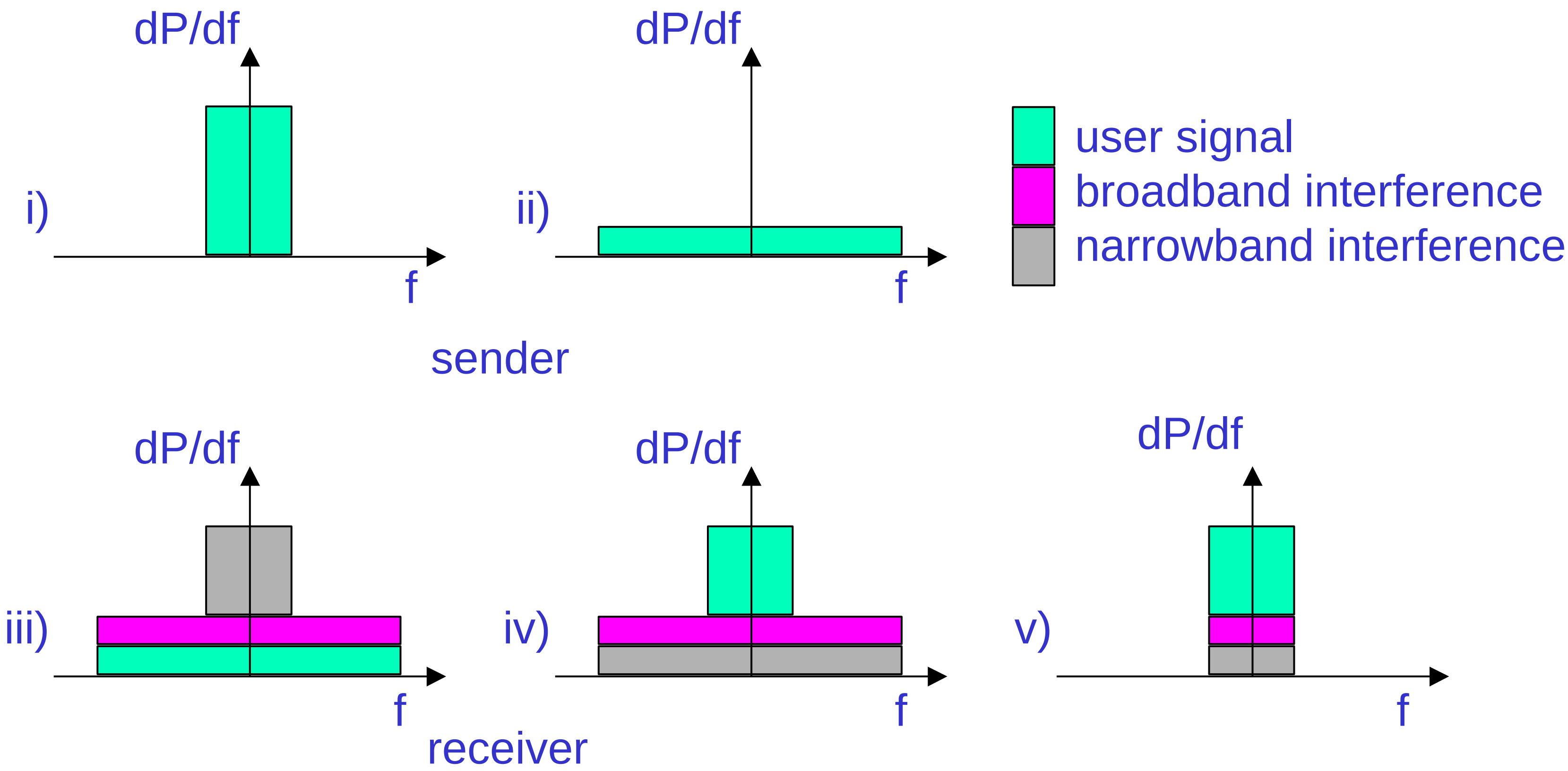
Spread spectrum technology

Side effects:

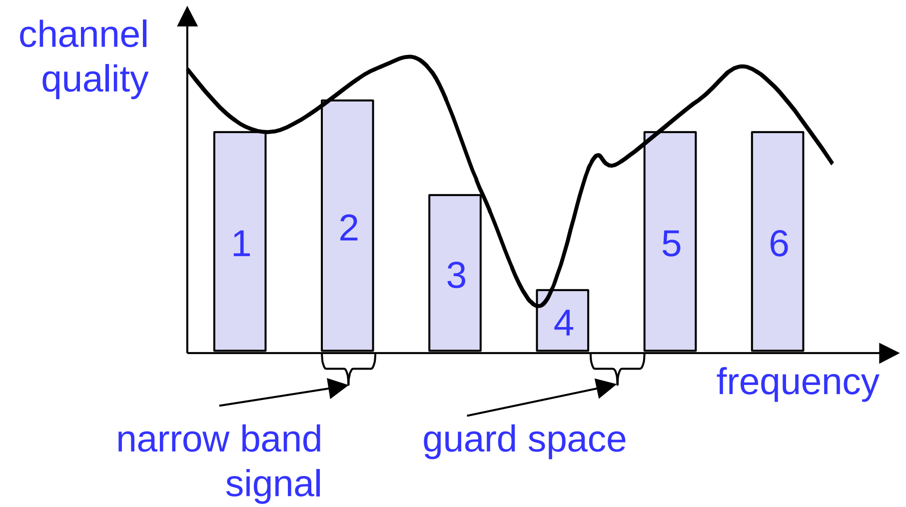
- coexistence of several signals without dynamic coordination
- tap-proof

Alternatives: Direct Sequence, Frequency Hopping

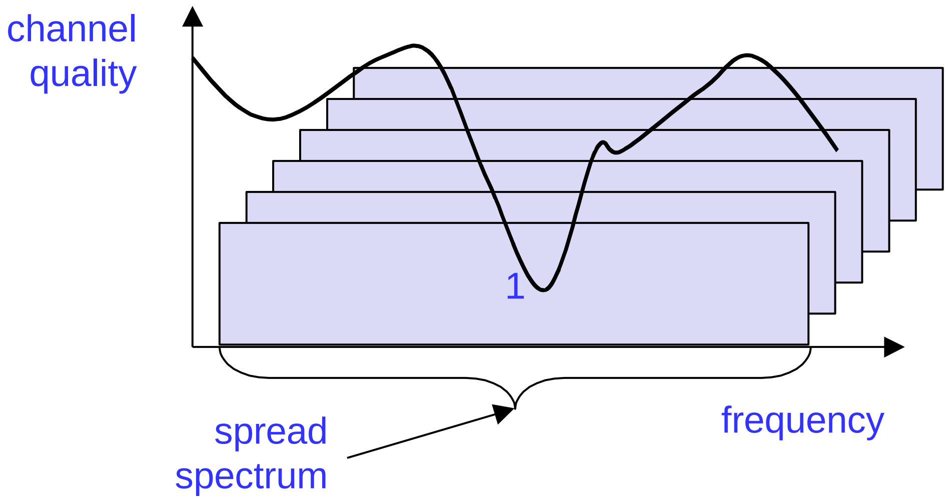
Effects of spreading and interference



Spreading and frequency selective fading



narrowband channels



spread spectrum channels

DSSS (Direct Sequence Spread Spectrum)

XOR of the signal with pseudo-random number, chipping sequence

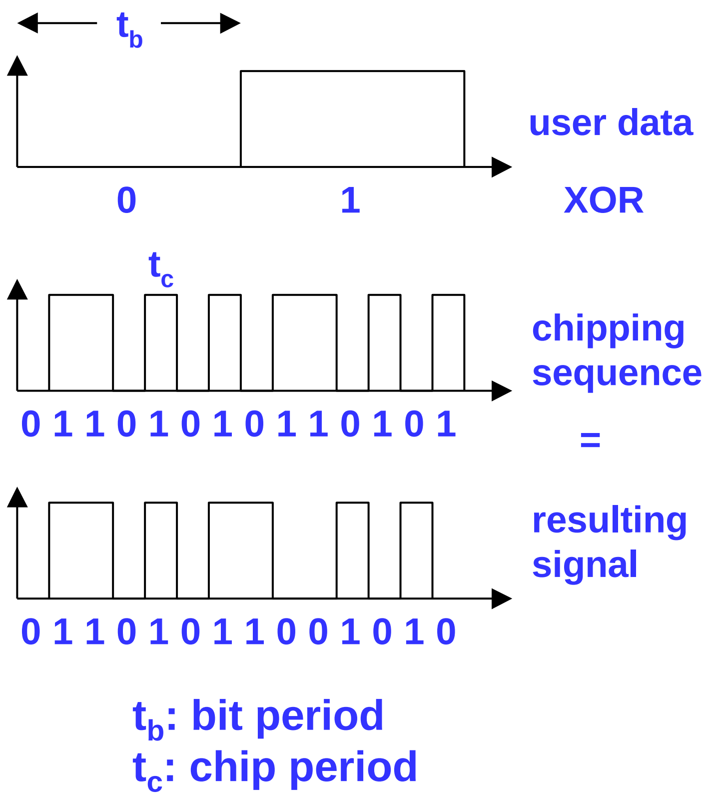
- many chips per bit (e.g., 128) result in higher bandwidth of the signal

Advantages

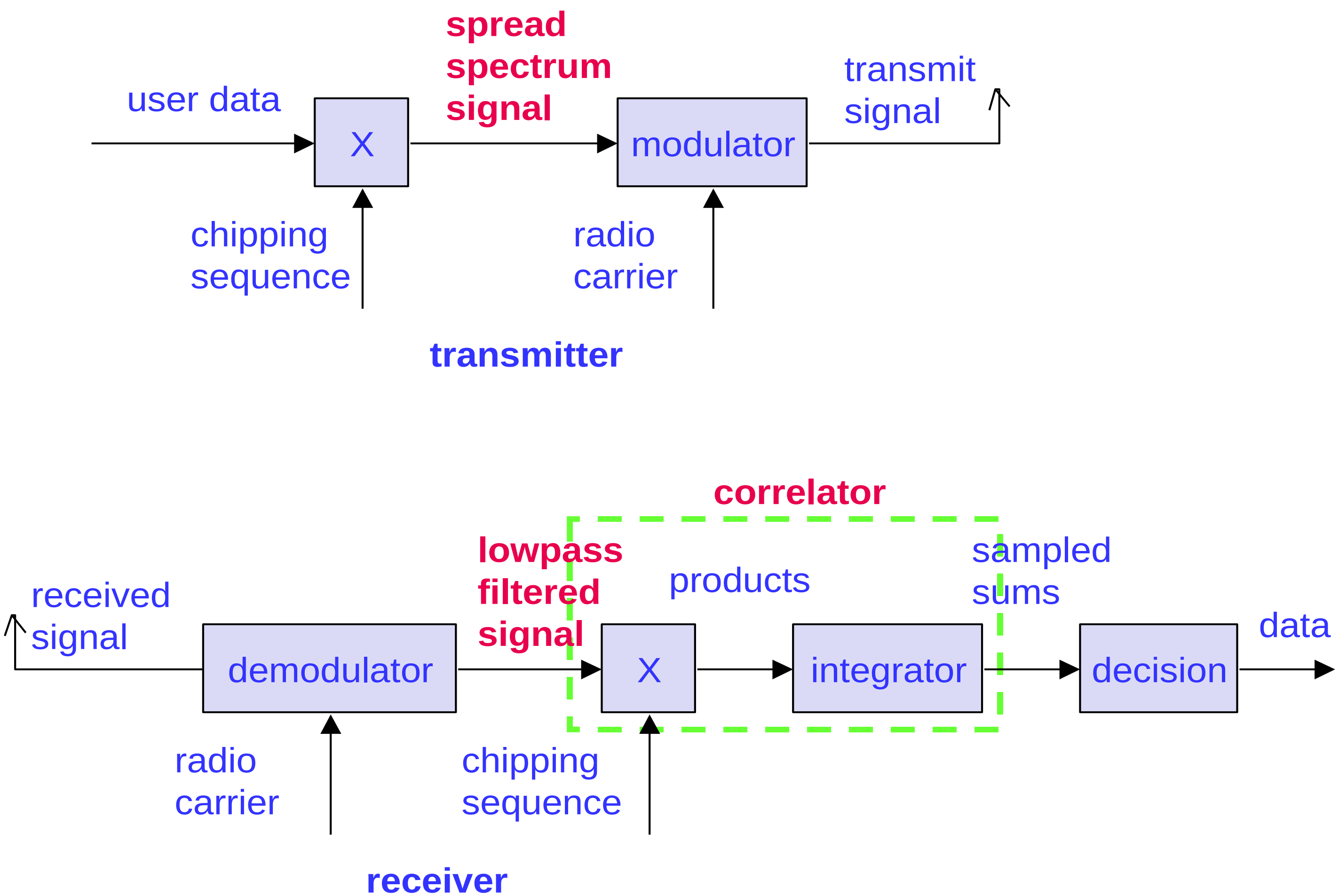
- reduces frequency selective fading
- in cellular networks
  - base stations can use the same frequency range
  - several base stations can detect and recover the signal
  - soft handover

Disadvantages

- precise power control necessary



DSSS (Direct Sequence Spread Spectrum)



FHSS (Frequency Hopping Spread Spectrum)

Discrete changes of carrier frequency

- sequence of frequency changes determined via pseudo random number sequence

Two versions

- Fast Hopping: several frequencies per user bit
- Slow Hopping: several user bits per frequency

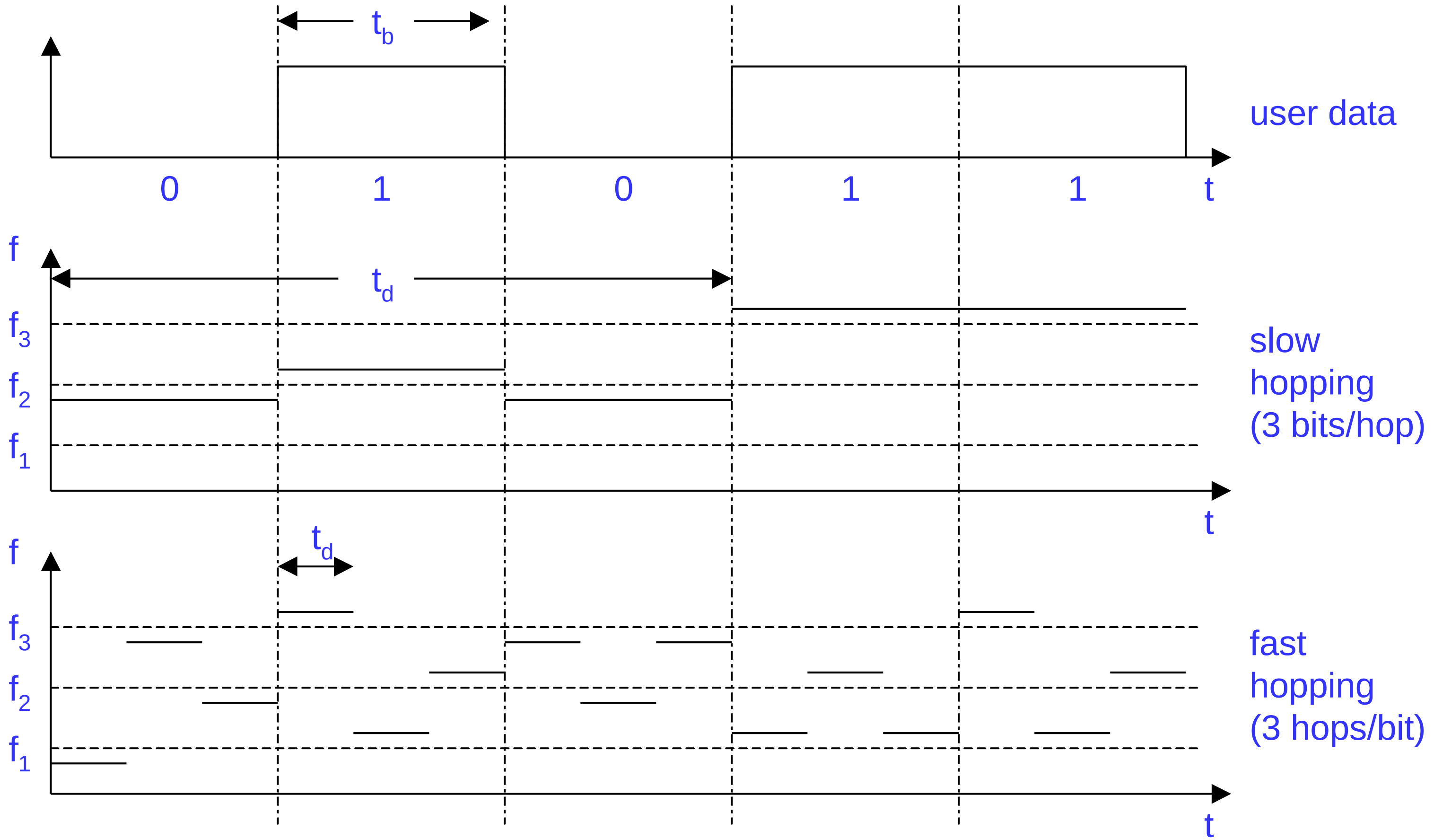
Advantages

- frequency selective fading and interference limited to short period
- simple implementation
- uses only small portion of spectrum at any time

Disadvantages

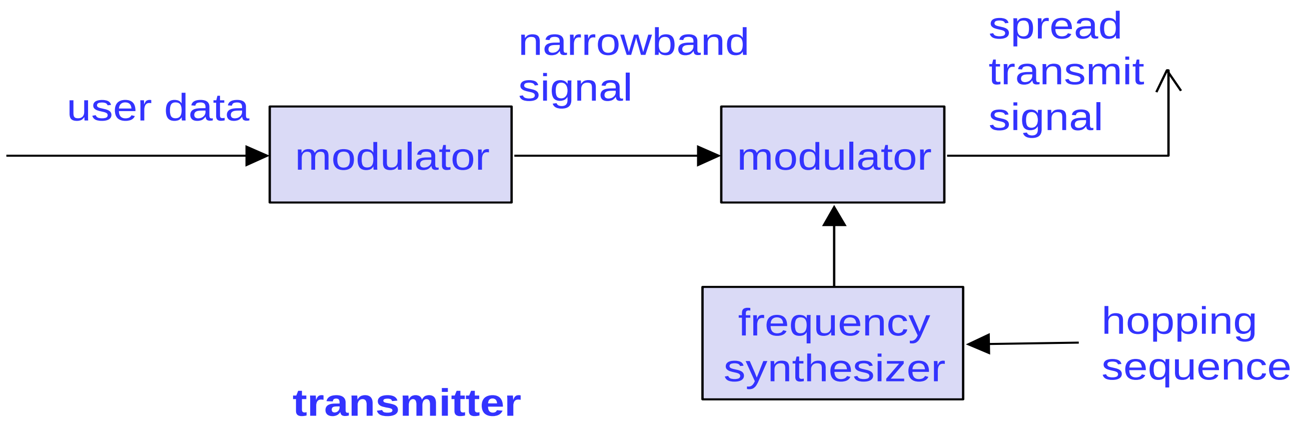
- not as robust as DSSS
- simpler to detect

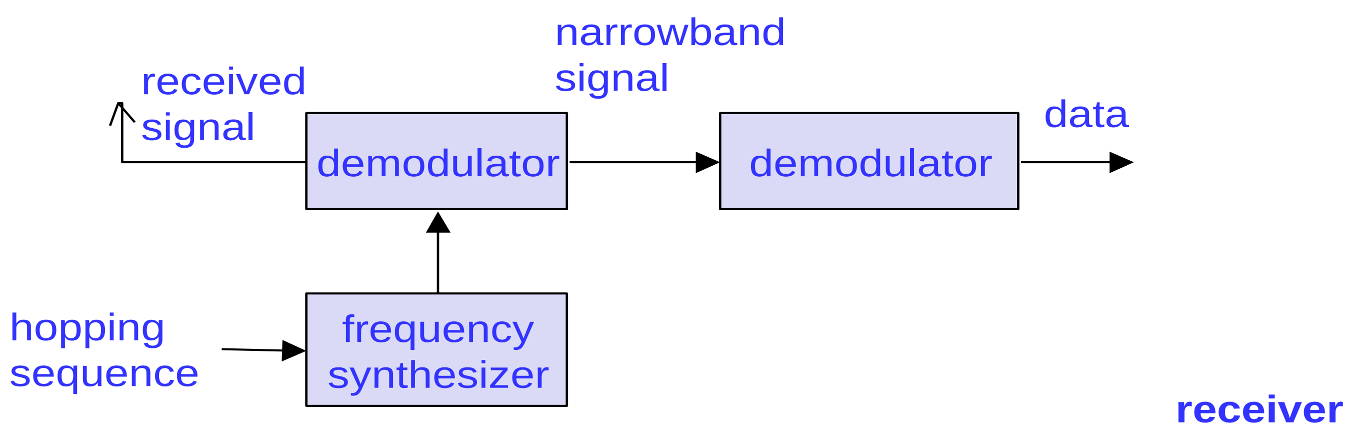
FHSS (Frequency Hopping Spread Spectrum)



t_b: bit period t_d: dwell time

FHSS (Frequency Hopping Spread Spectrum)



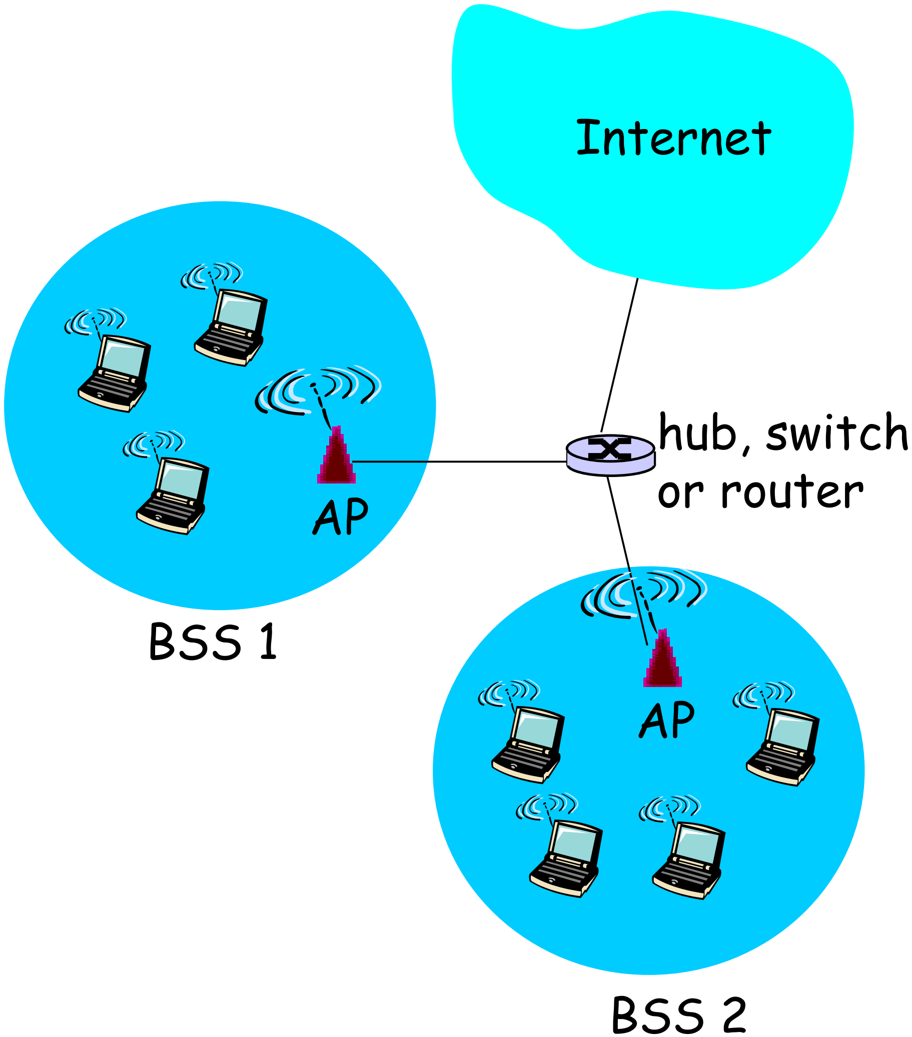


IEEE 802.11 Wireless LAN

- 802.11b
  - 2.4 GHz unlicensed spectrum
  - up to 11 Mbps
  - direct sequence spread spectrum (DSSS) in physical layer
    - all hosts use same chipping code
- 802.11a
  - 5 GHz range
  - up to 54 Mbps
- 802.11g
  - 2.4 GHz range
  - up to 54 Mbps
- 802.11n: multiple antennae
  - 2.4-5 GHz range
  - up to 200 Mbps

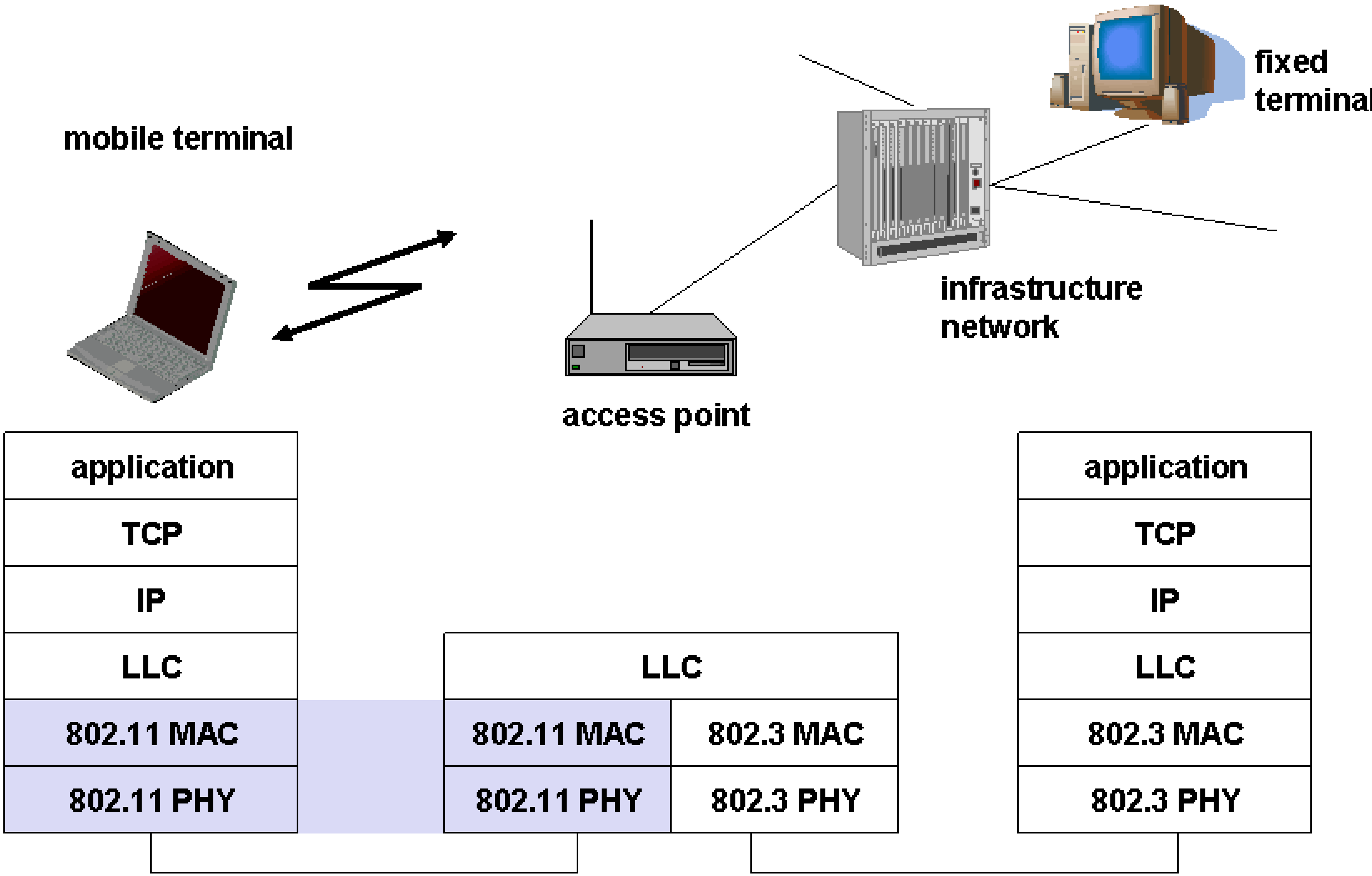
- all use CSMA/CA for multiple access
- all have base-station and ad-hoc network versions

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

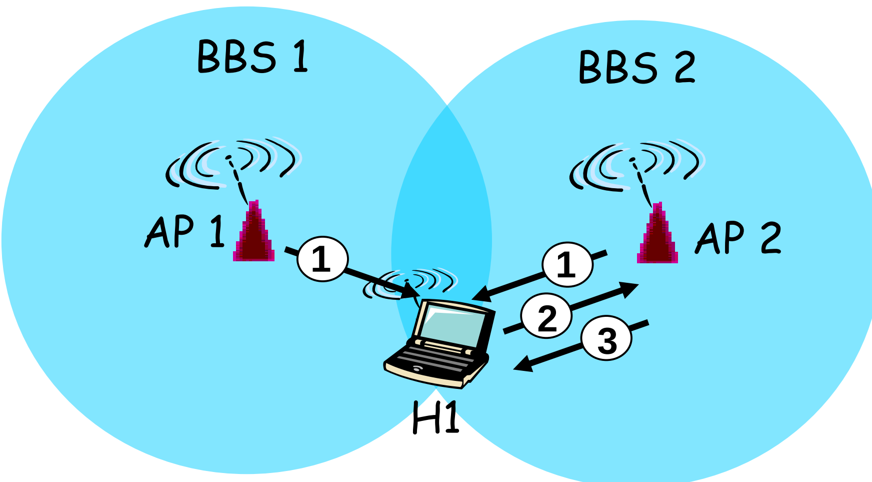
IEEE standard 802.11

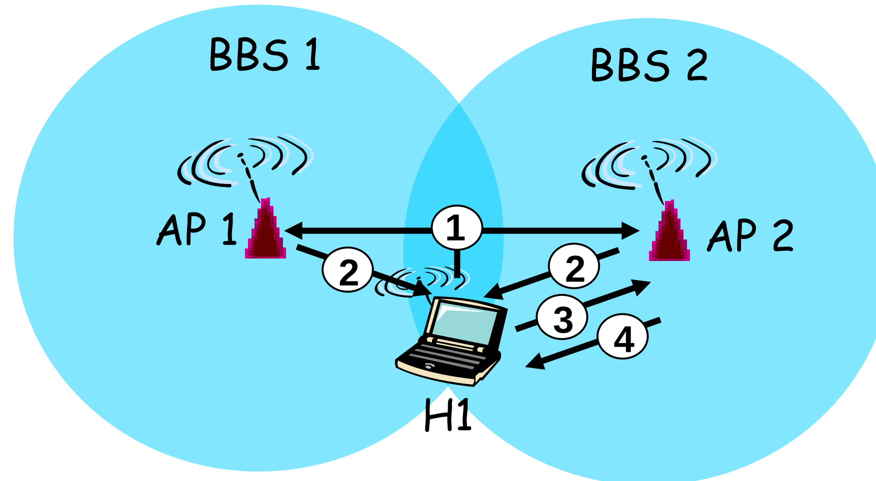


802.11: Channels, association

- 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
  - will typically run DHCP to get IP address in AP's subnet

802.11: passive/active scanning





Passive Scanning:

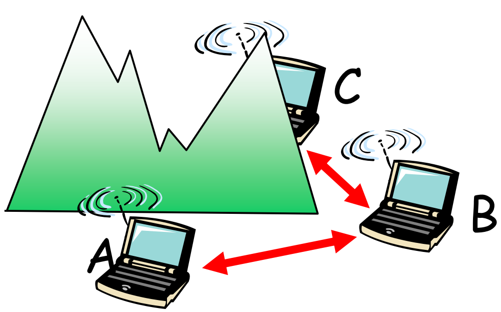
(1) beacon frames sent from APs
(2) association Request frame sent: H1 to selected AP
(3) association Response frame sent: selected AP to H1

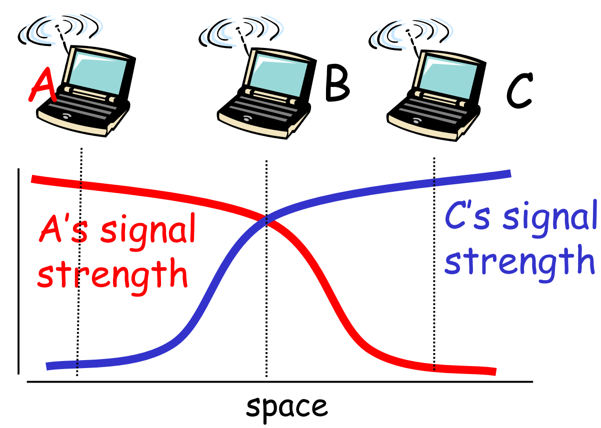
Active Scanning:

(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: 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)





IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

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

transmit entire frame (no CD)

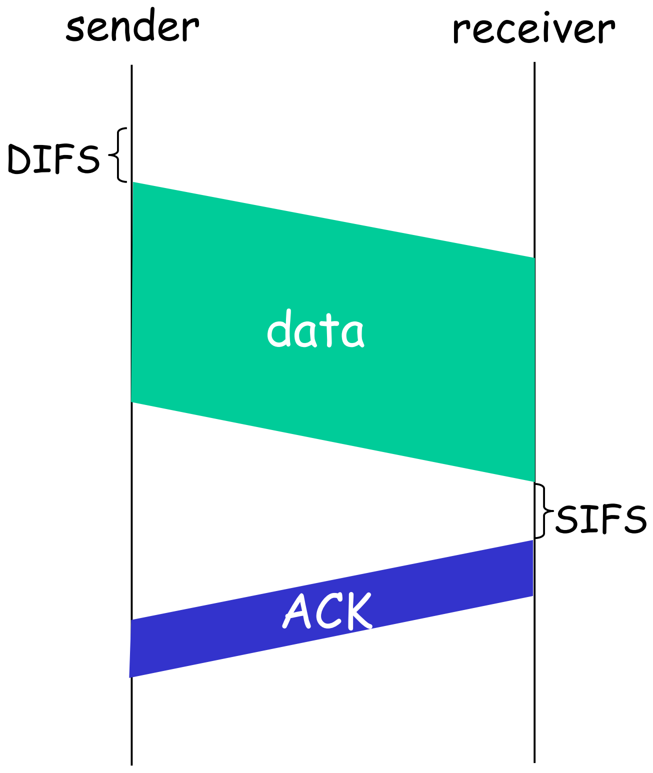
2 if sense channel busy then

start random backoff time

timer counts down while channel idle

transmit when timer expires

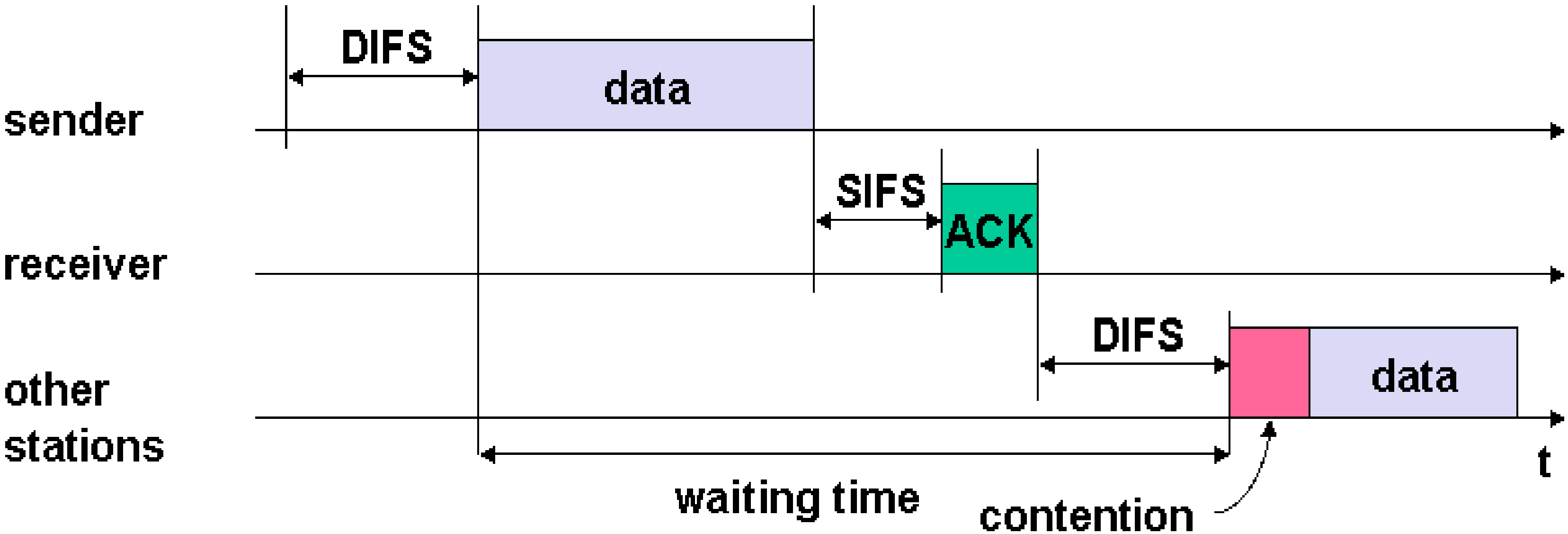
if no ACK, increase random backoff interval, repeat 2



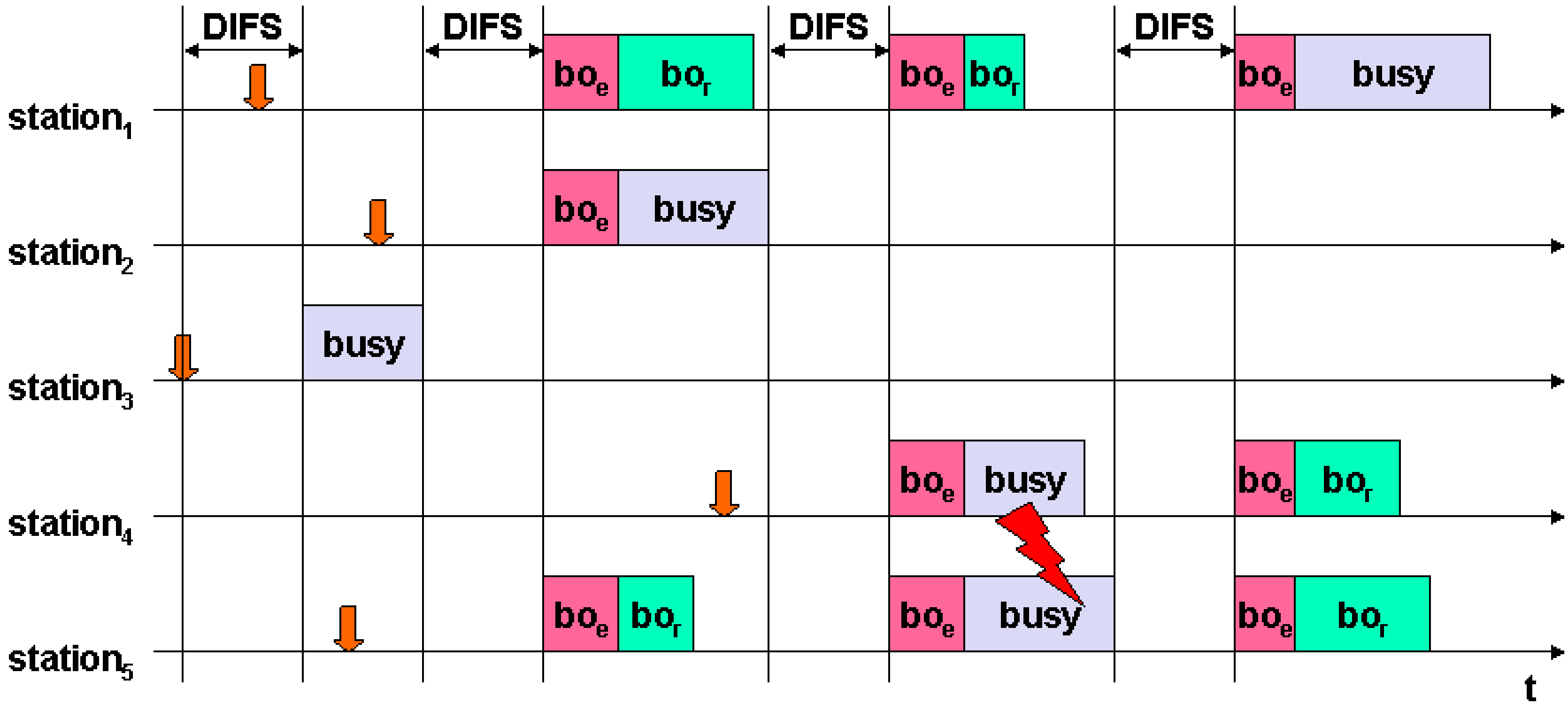
802.11 receiver

- if frame received OK

return ACK after **SIFS** (ACK needed due to hidden terminal problem)


DIFS
data
sender
SIFS
ACK
receiver
DIFS
data
other
stations
t
waiting time
contention

802.11 - competing stations - simple version



busy — medium not idle (frame, ack etc.)

packet arrival at MAC

boe — elapsed backoff time

bor — residual backoff time

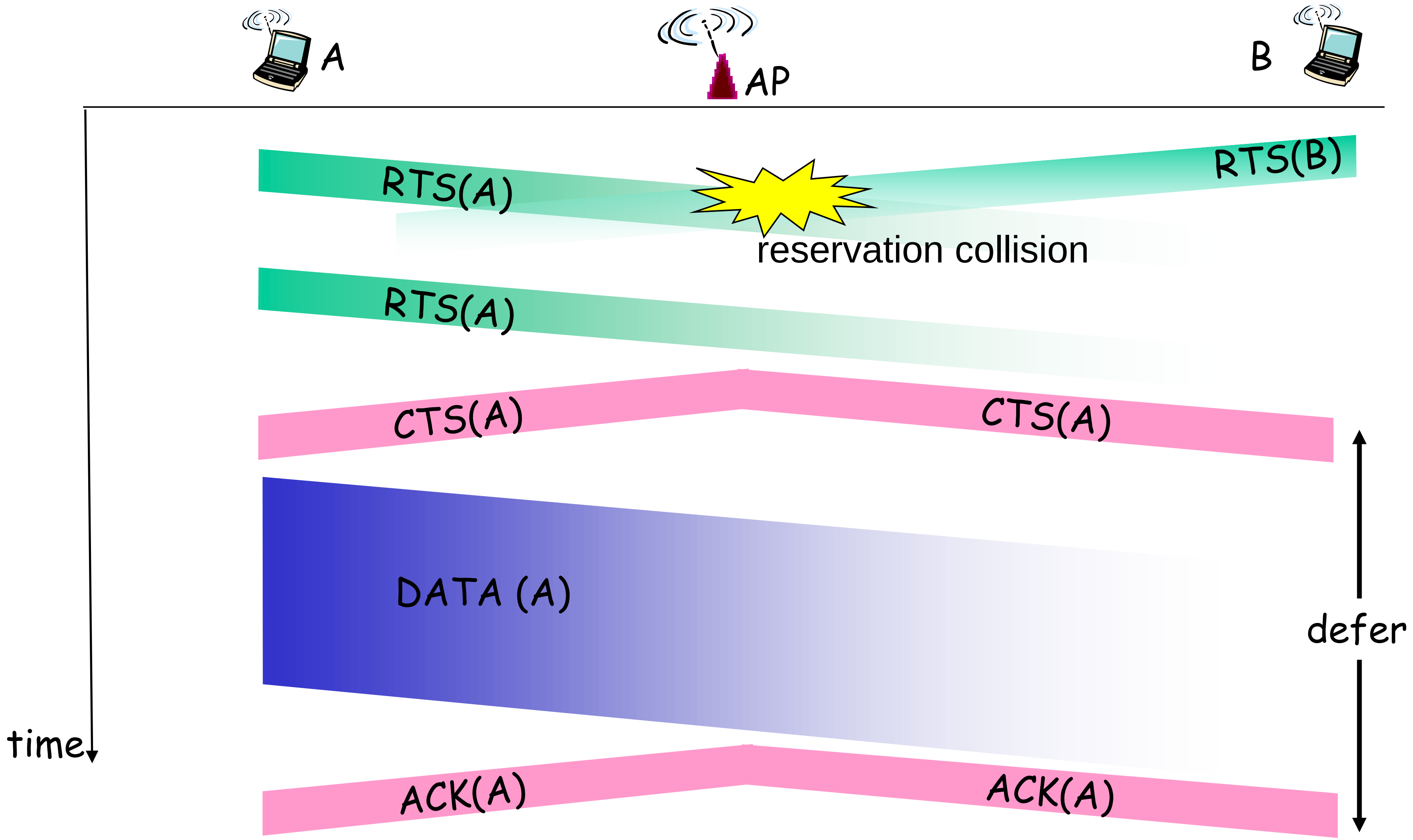
Avoiding collisions (more)

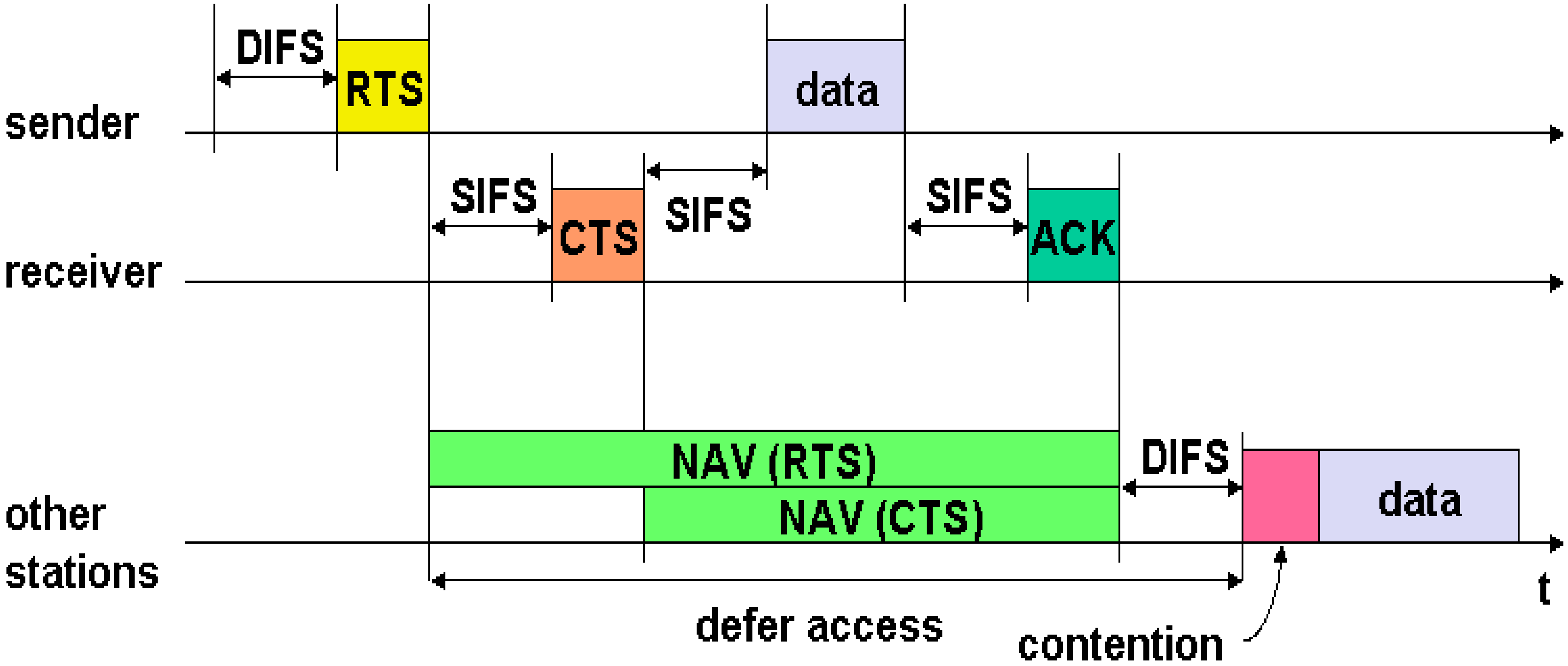
idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

- 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!

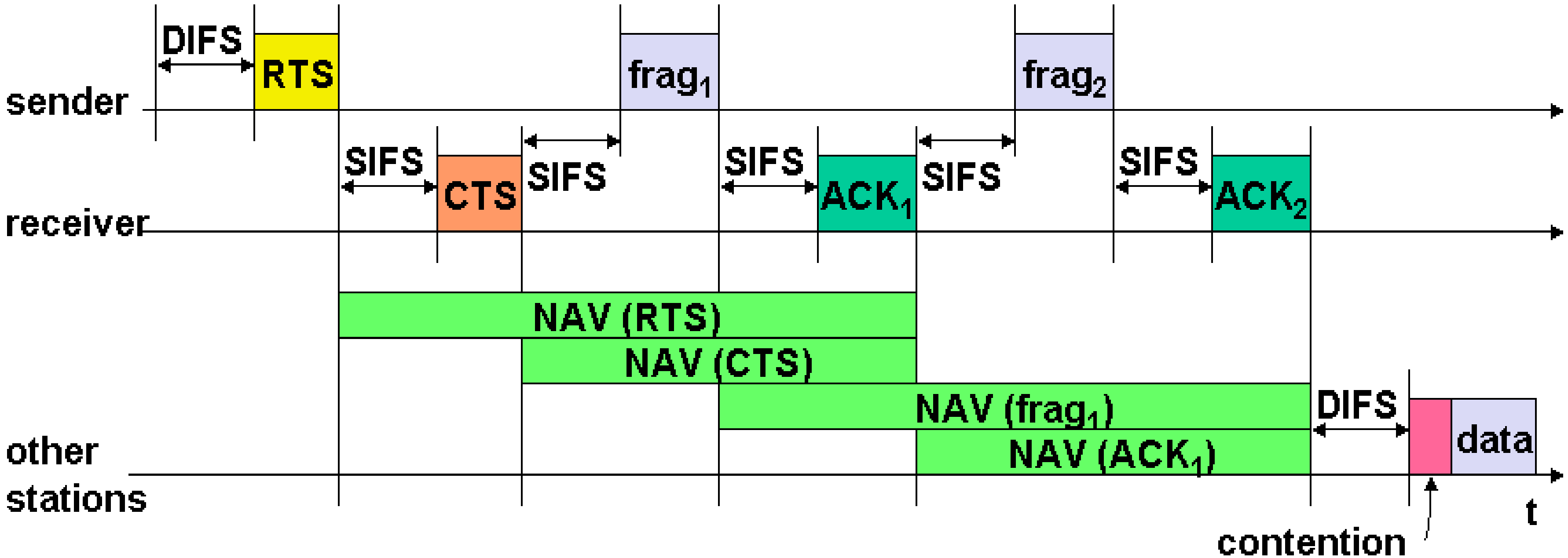
Collision Avoidance: RTS-CTS exchange





DIFS
RTS
data
sender
SIFS
CTS
SIFS
SIFS
ACK
receiver
NAV (RTS)
DIFS
NAV (CTS)
data
other
stations
t
defer access
contention

Fragmentation



802.11 frame: addressing

duration of reserved transmission time (RTS/CTS)

frame seq # (for RDT)

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

Protocol version	Type	Subtype	To DS	From DS	More frag	Retry	Power mgt	More data	WEP	Rsvd
2	2	4	1	1	1	1	1	1	1	1

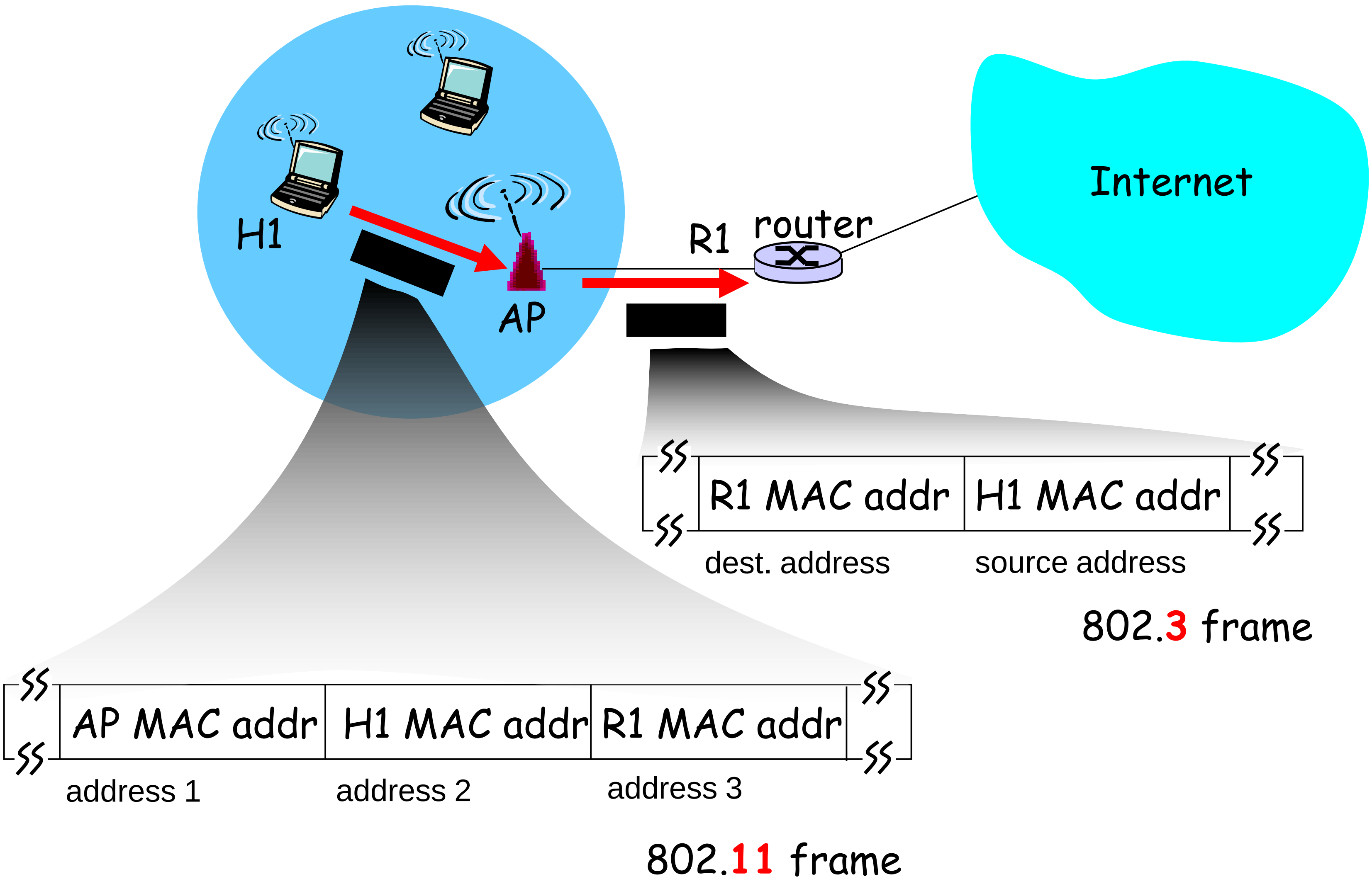
frame type (RTS, CTS, ACK, data)

MAC address format

scenario	to DS	from DS	address 1	address 2	address 3	address 4
ad-hoc network	0	0	DA	SA	BSSID	-
infrastructure network, from AP	0	1	DA	BSSID	SA	-
infrastructure network, to AP	1	0	BSSID	SA	DA	-
infrastructure network, within DS	1	1	RA	TA	DA	SA

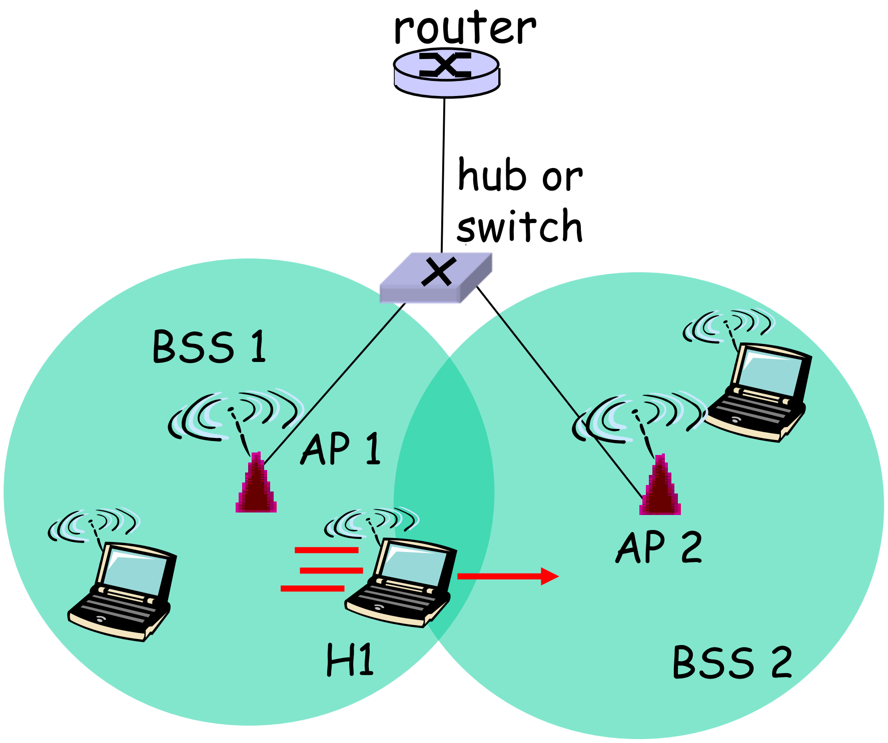
DS: Distribution System
AP: Access Point
DA: Destination Address
SA: Source Address
BSSID: Basic Service Set Identifier
RA: Receiver Address
TA: Transmitter Address

802.11 frame: addressing



802.11: mobility within same subnet

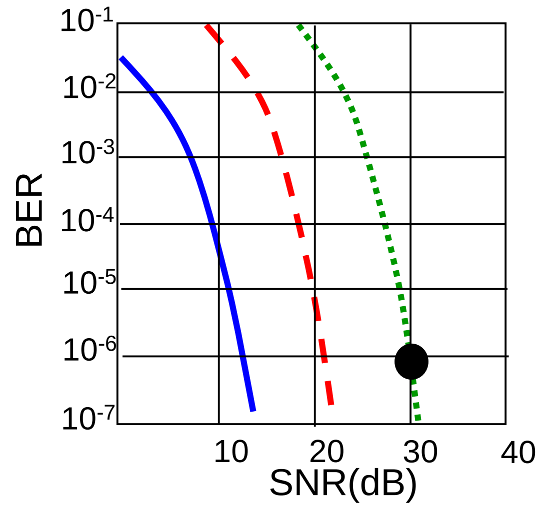
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - **self-learning** : switch will see frame from H1 and "remember" which switch port can be used to reach H1

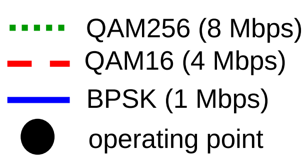


802.11: advanced capabilities

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

Power management

Idea: switch the transceiver off if not needed

States of a station: sleep and awake

Timing Synchronization Function (TSF)

- stations wake up at the same time

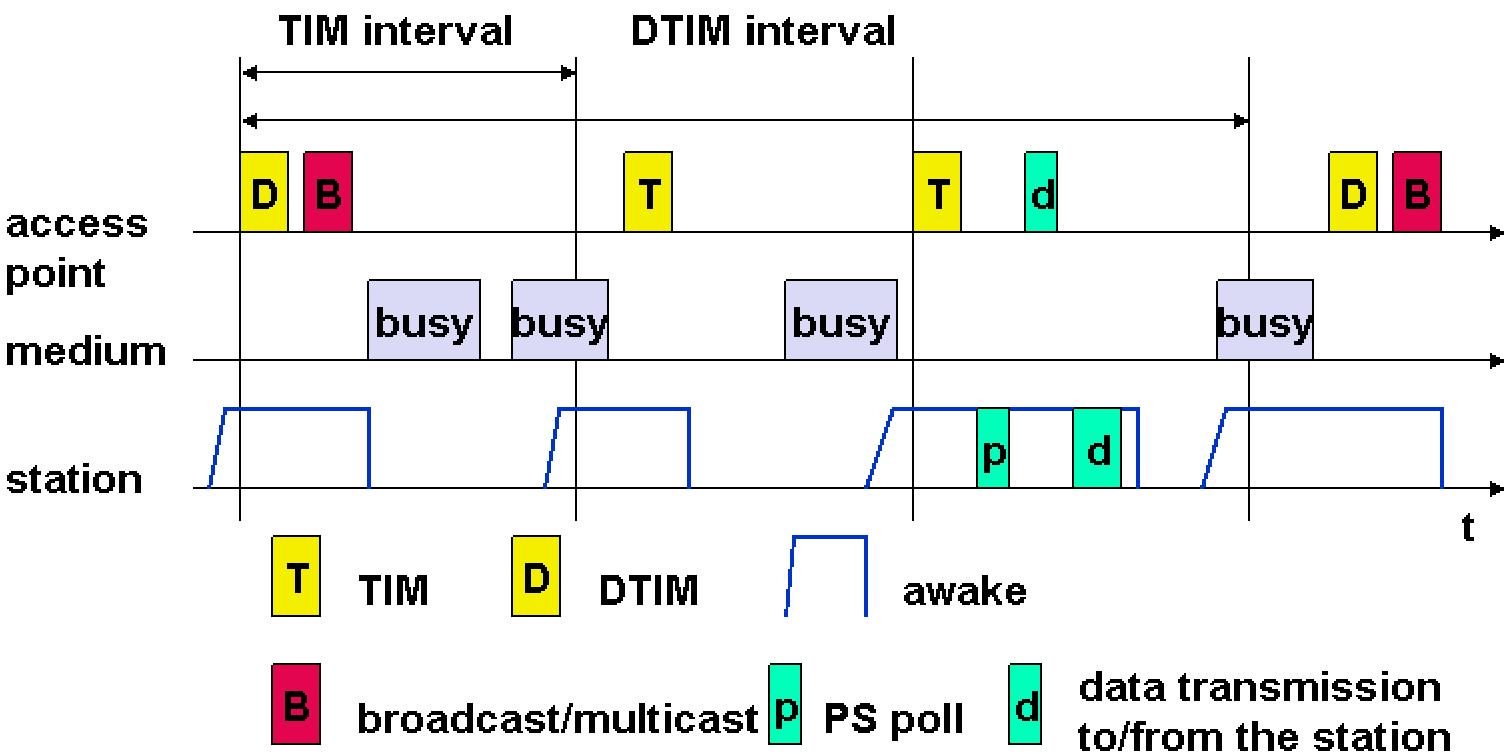
Infrastructure

- Traffic Indication Map (TIM)
  - list of unicast receivers transmitted by AP
- Delivery Traffic Indication Map (DTIM)
  - list of broadcast/multicast receivers transmitted by AP

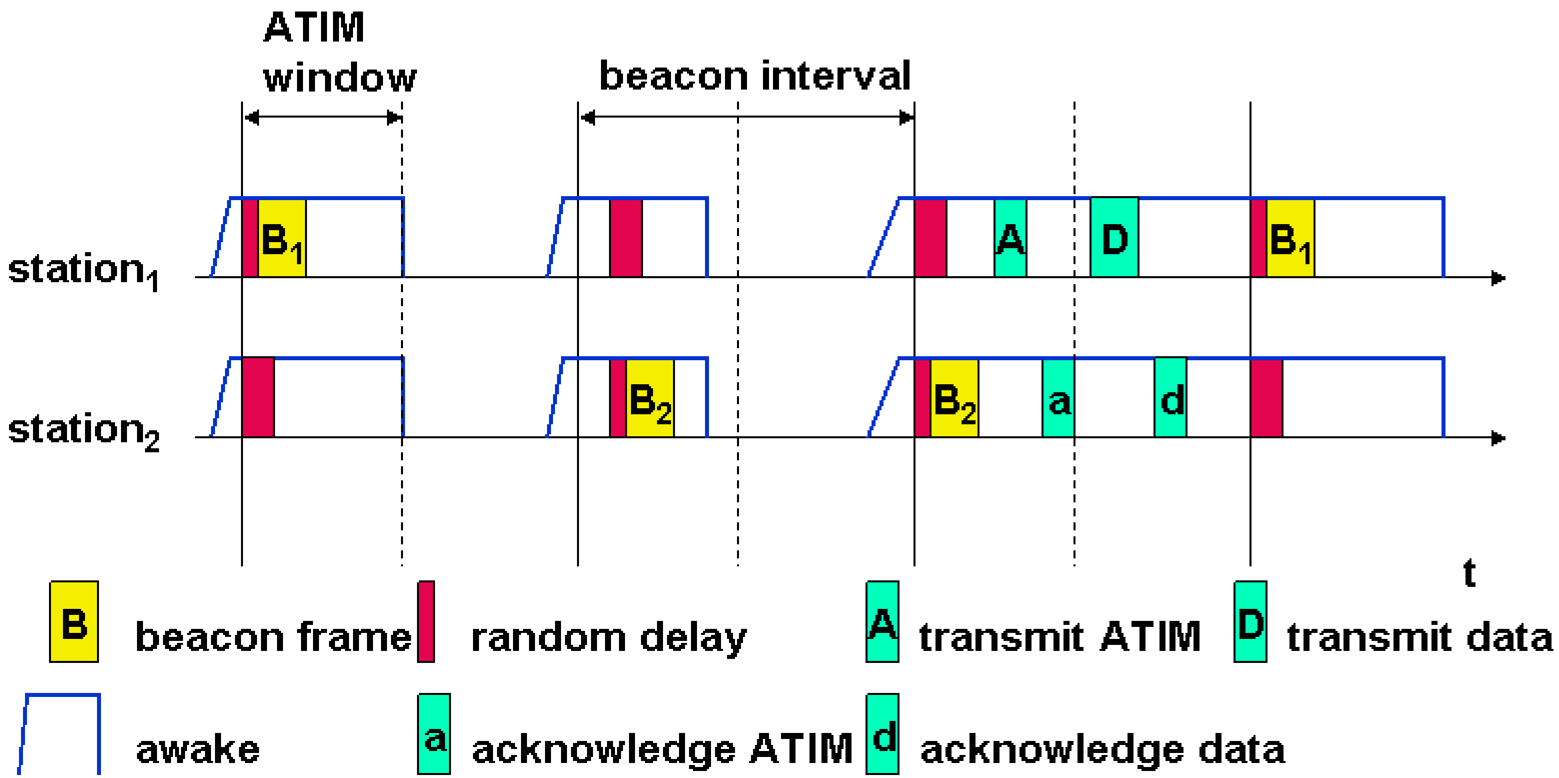
Ad-hoc

- Ad-hoc Traffic Indication Map (ATIM)
  - announcement of receivers by stations buffering frames
  - more complicated - no central AP
  - collision of ATIMs possible (scalability?)

Power saving with wake-up patterns (infrastructure)

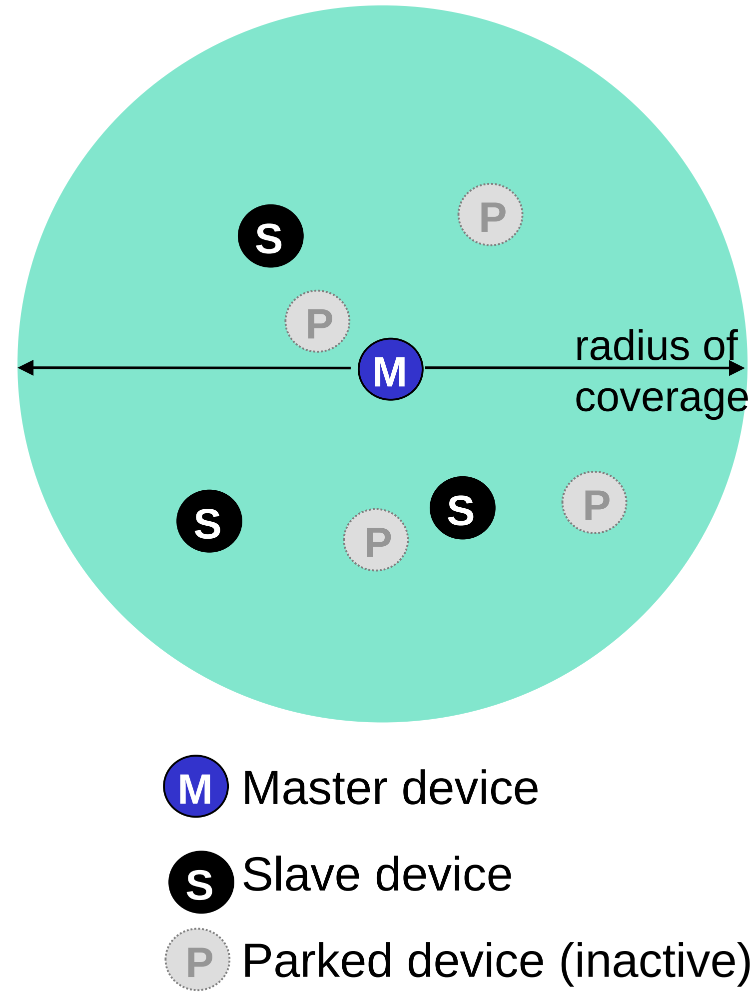


Power saving with wake-up patterns (ad-hoc)



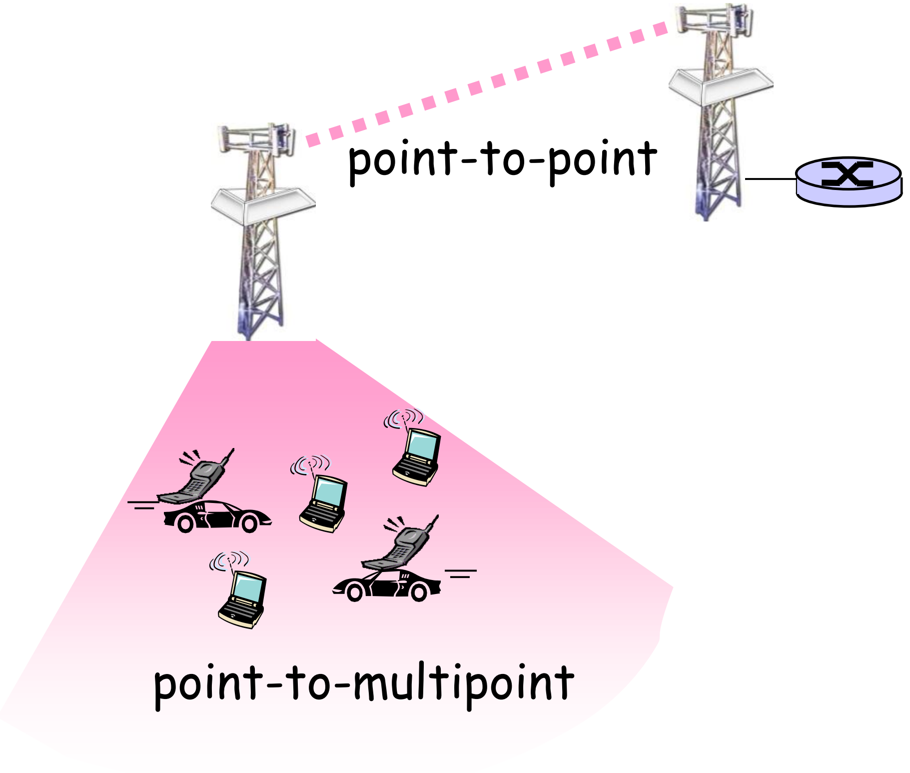
802.15: personal area network

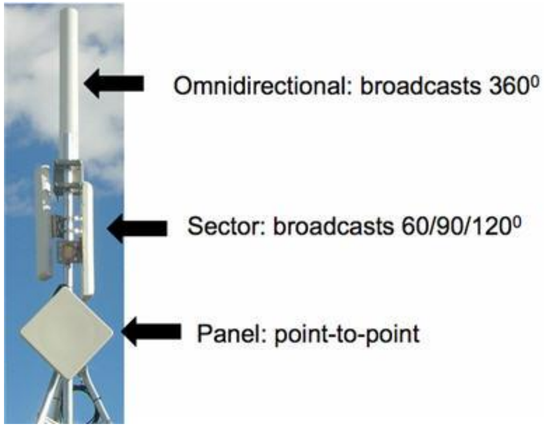
- less than 10 m diameter
- replacement for cables (mouse, keyboard, headphones)
- ad hoc: no infrastructure
- master/slaves:
  - slaves request permission to send (to master)
  - master grants requests
- 802.15: evolved from Bluetooth specification
  - 2.4-2.5 GHz radio band
  - up to 721 kbps



802.16: WiMAX

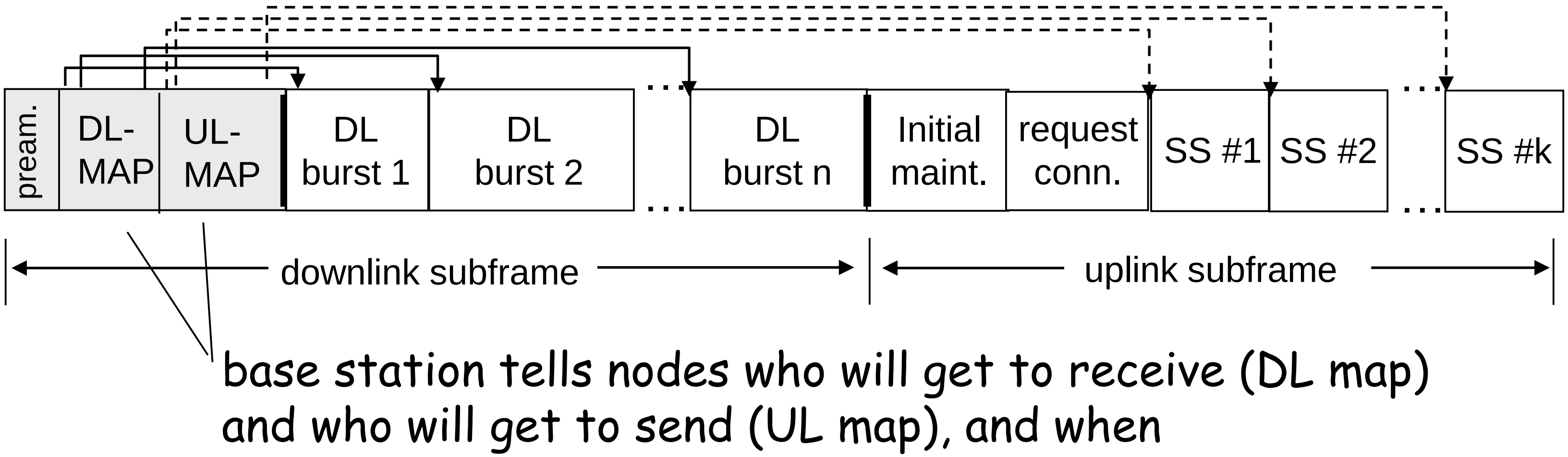
- like 802.11 & cellular: base station model
  - transmissions to/from base station by hosts with omnidirectional antenna
  - base station-to-base station backhaul with point-to-point antenna
- unlike 802.11:
  - range ~ 6 miles ("city rather than coffee shop")
  - ~14 Mbps





802.16: WiMAX: downlink, uplink scheduling

- transmission frame
  - down-link subframe: base station to node
  - uplink subframe: node to base station

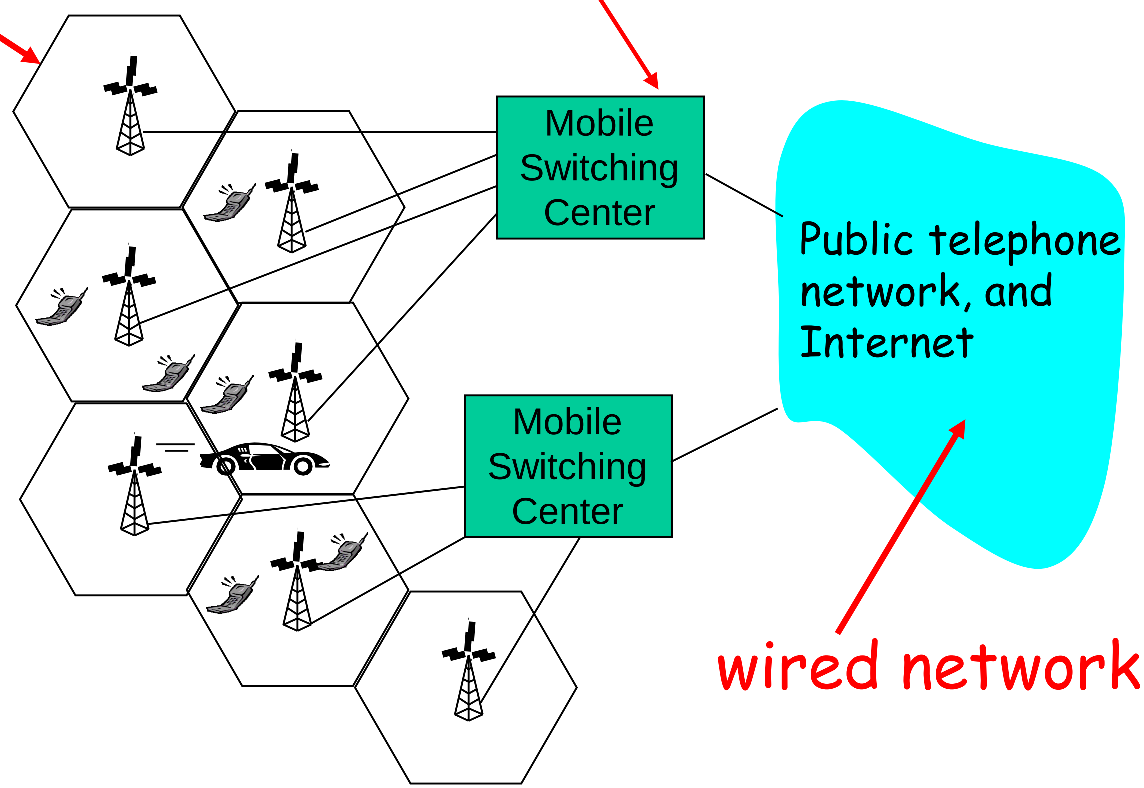


- WiMAX standard provide mechanism for scheduling, but not scheduling algorithm

Components of cellular network architecture

MSC
- connects cells to wide area net
- manages call setup (more later!)
- handles mobility (more later!)

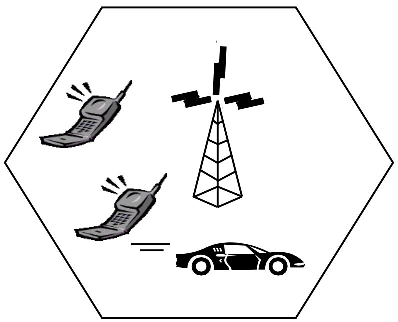
cell
- covers geographical region
- *base station* (BS) analogous to 802.11 AP
- *mobile users* attach to network through BS
- *air-interface:* physical and link layer protocol between mobile and BS

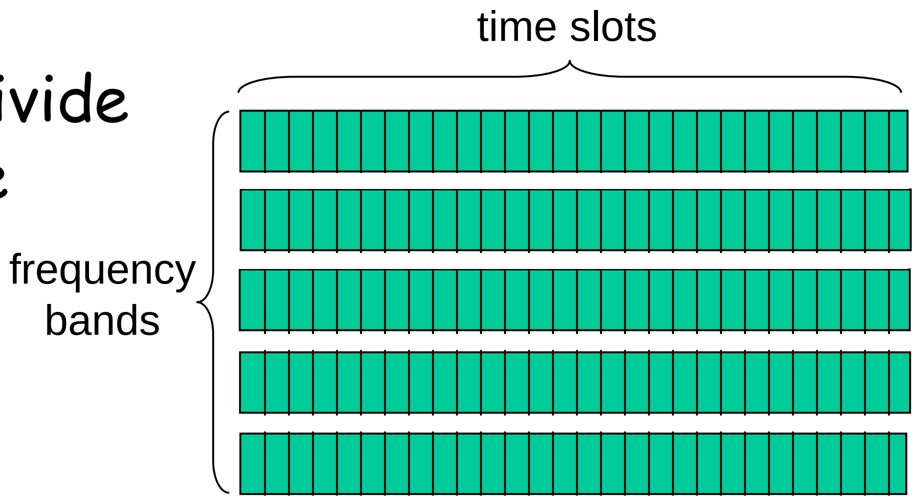


Cellular networks: the first hop

Two techniques for sharing mobile-to-BS radio spectrum

- combined FDMA/TDMA: divide spectrum in frequency channels, divide each channel into time slots
- CDMA: code division multiple access

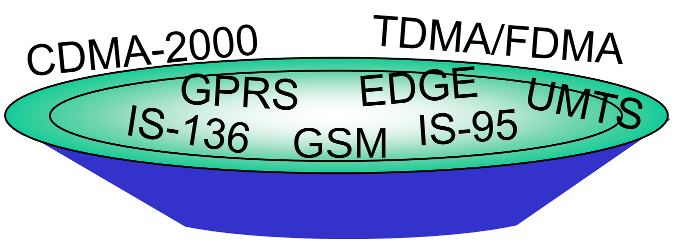




Cellular standards: brief survey

2G systems: voice channels

- IS-136 TDMA: combined FDMA/TDMA (North America)
- GSM (global system for mobile communications): combined FDMA/TDMA
  - most widely deployed
- IS-95 CDMA: code division multiple access



Don't drown in a bowl of alphabet soup: use this for reference only

Cellular standards: brief survey

2.5 G systems: voice and data channels

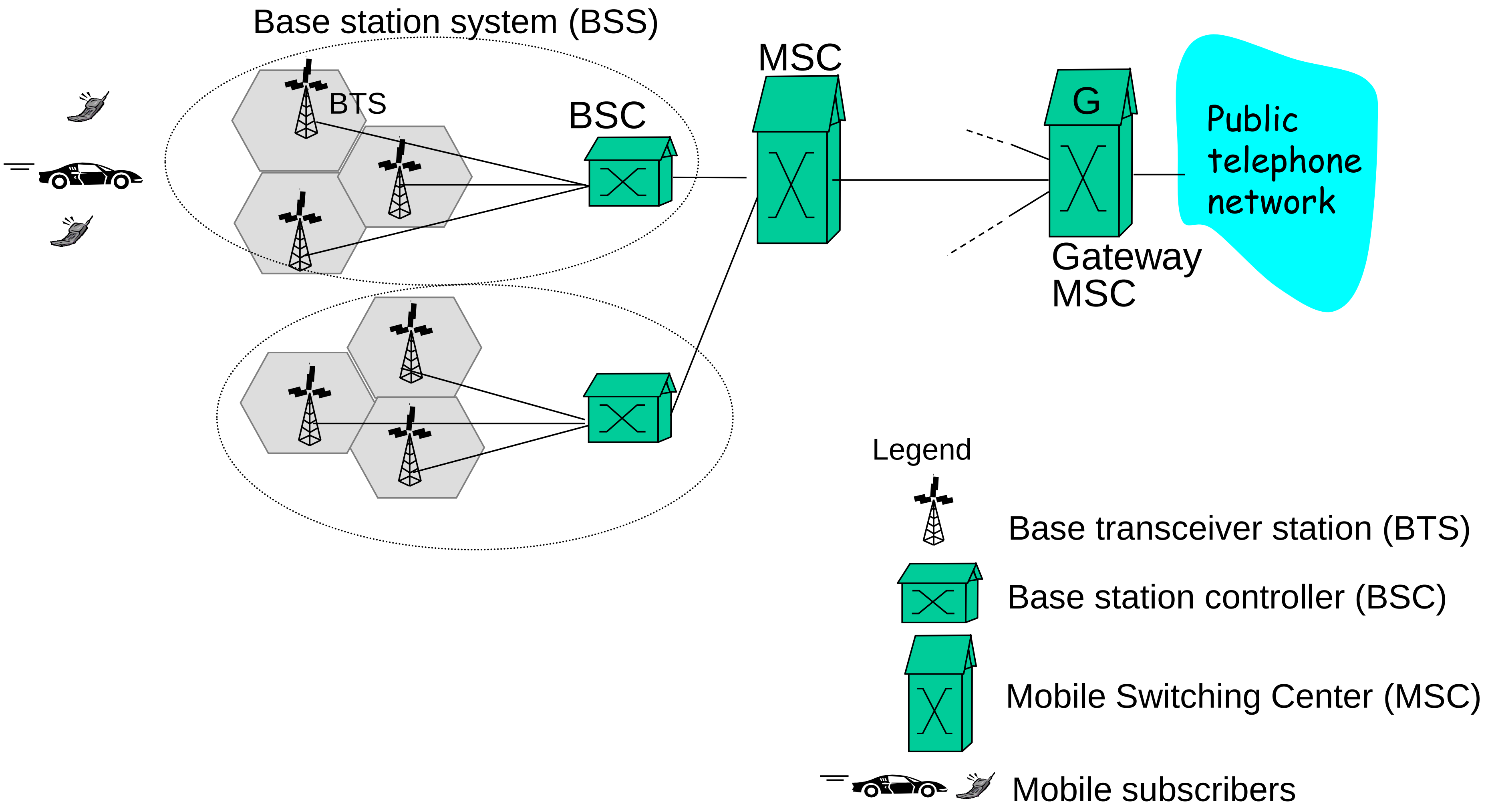
- for those who can't wait for 3G service: 2G extensions
- general packet radio service (GPRS)
  - evolved from GSM
  - data sent on multiple channels (if available)
- enhanced data rates for global evolution (EDGE)
  - also evolved from GSM, using enhanced modulation
  - data rates up to 384K
- CDMA-2000 (phase 1)
  - data rates up to 144K
  - evolved from IS-95

Cellular standards: brief survey

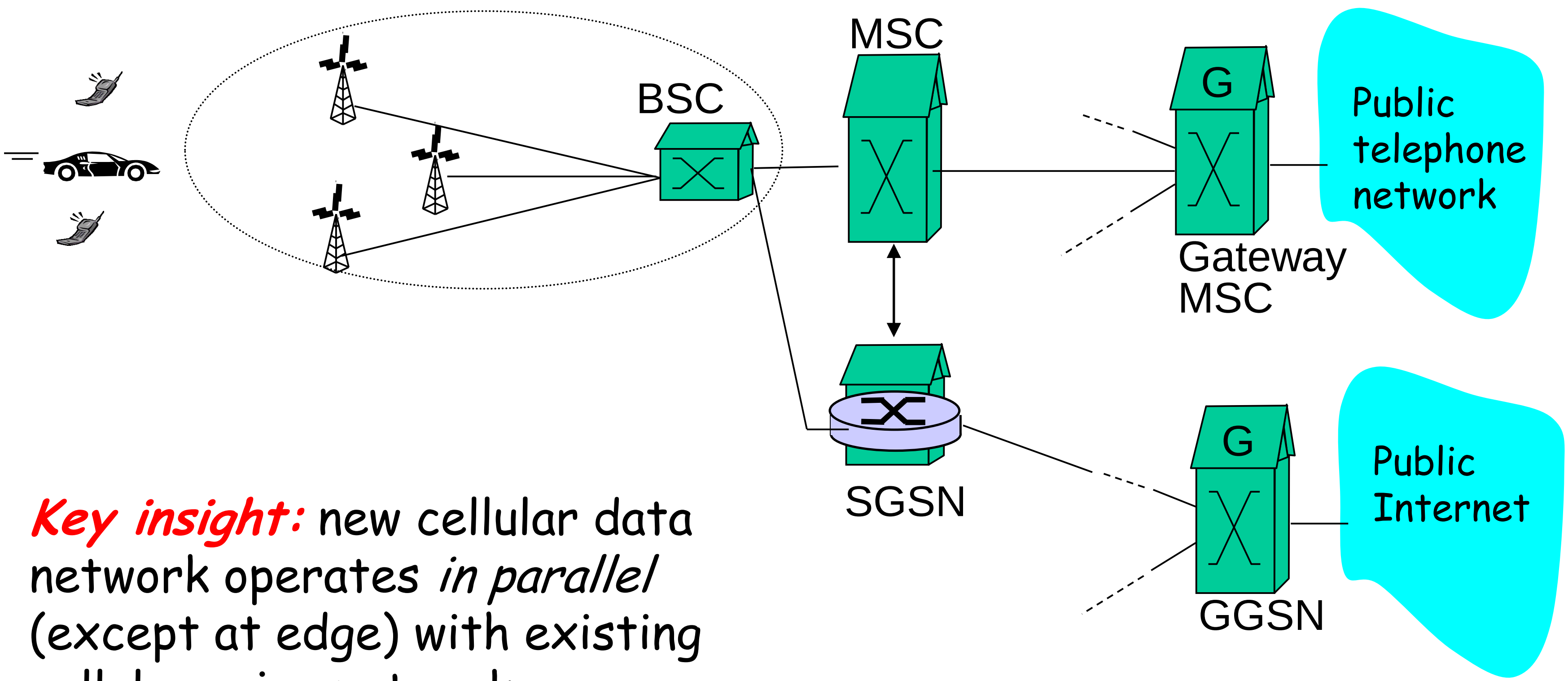
3G systems: voice/data

- Universal Mobile Telecommunications Service (UMTS)
  - data service: High Speed Uplink/Downlink packet Access (HSDPA/HSUPA)
  - CDMA-2000: CDMA in TDMA slots
    data service: 1xEvolution Data Optimized (1xEVDO)
    up to 14 Mbps

2G (voice) network architecture

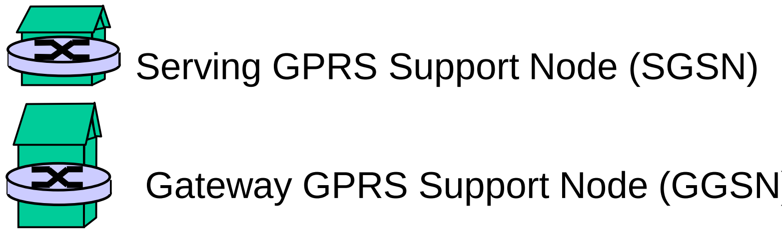


2.5G (voice+data) network architecture



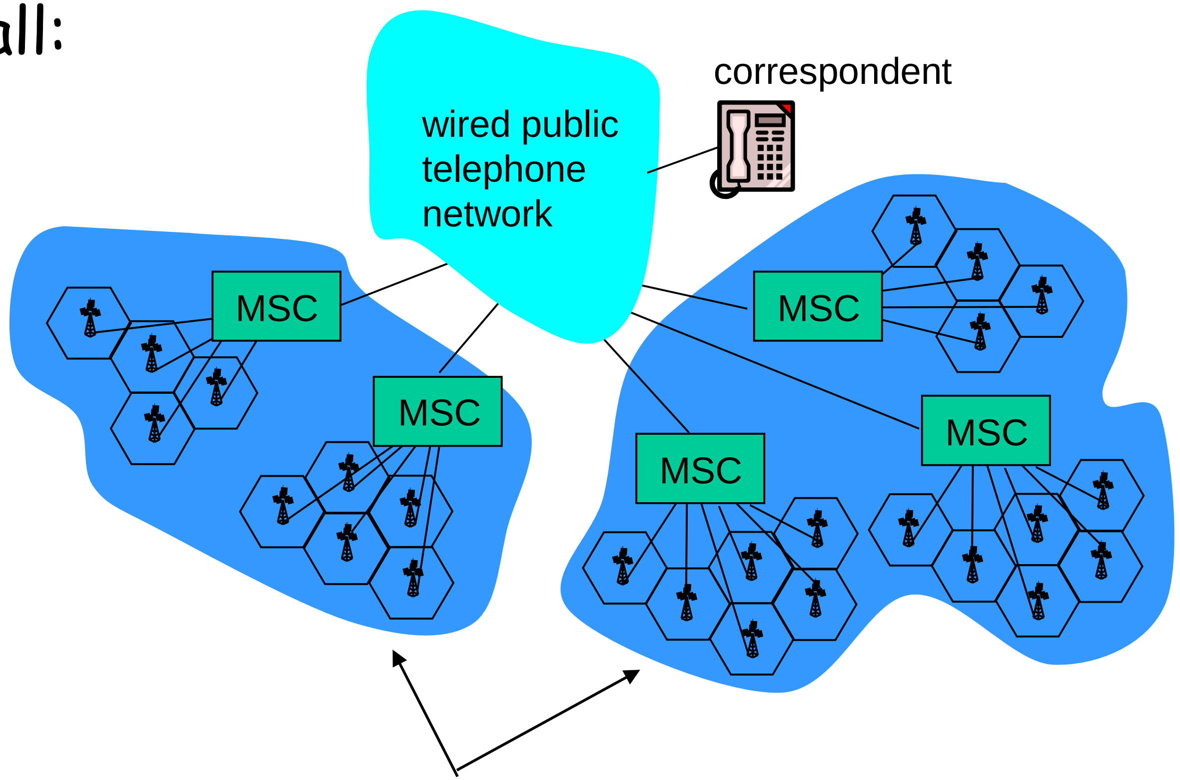
Key insight: new cellular data network operates *in parallel* (except at edge) with existing cellular voice network

- voice network unchanged in core
- data network operates in parallel



Components of cellular network architecture

recall:

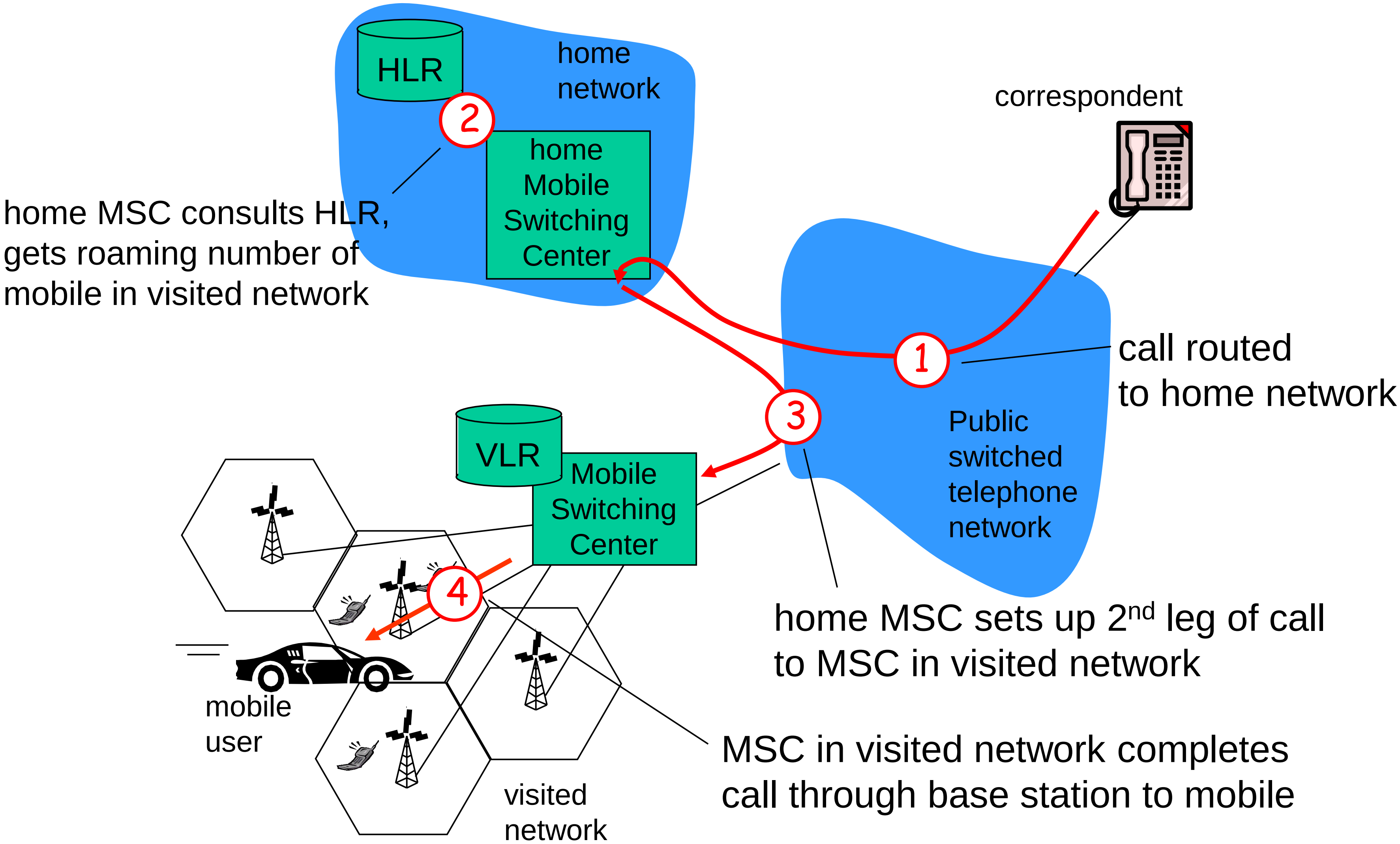


different cellular networks, operated by different providers

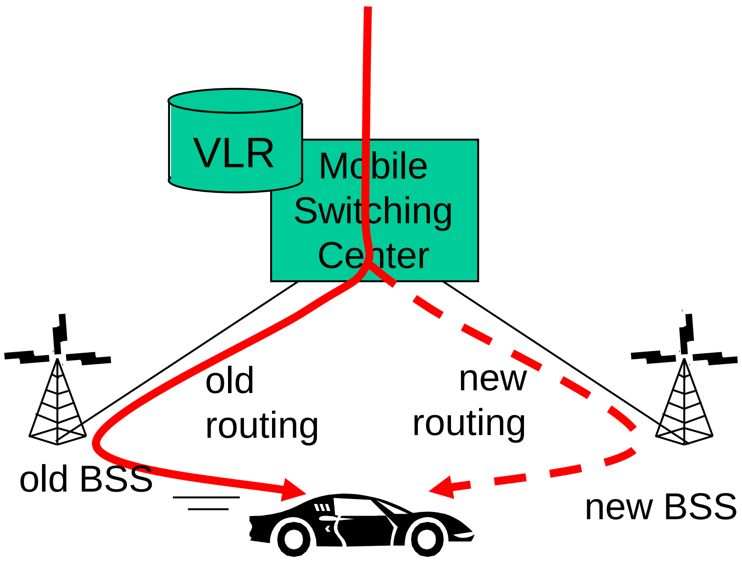
Handling mobility in cellular networks

- *home network:* network of cellular provider you subscribe to (e.g., Sprint PCS, Verizon)
  - *home location register (HLR):* database in home network containing permanent cell phone #, profile information (services, preferences, billing), information about current location (could be in another network)
- *visited network:* network in which mobile currently resides
  - *visitor location register (VLR):* database with entry for each user currently in network
  - could be home network

GSM: indirect routing to mobile

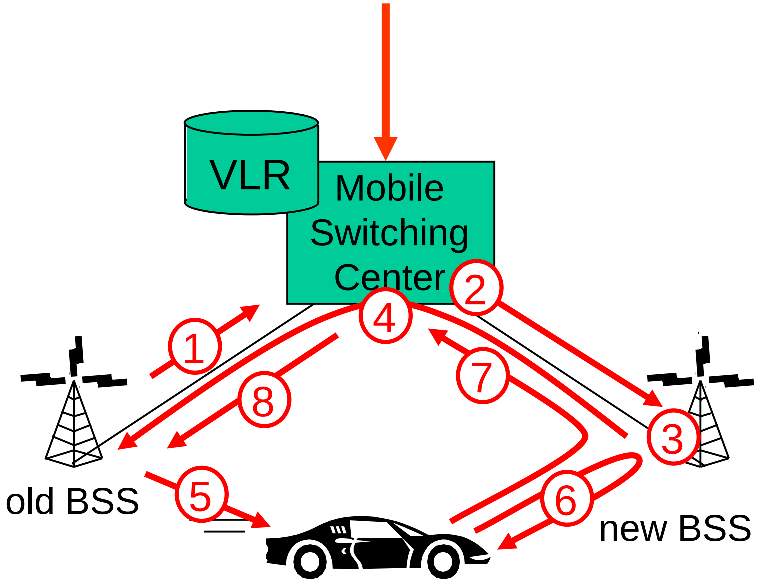


GSM: handoff with common MSC



- Handoff goal: route call via new base station (without interruption)
- reasons for handoff:
  - stronger signal to/from new BSS (continuing connectivity, less battery drain)
  - load balance: free up channel in current BSS
  - GSM doesn't mandate why to perform handoff (policy), only how (mechanism)
- handoff initiated by old BSS

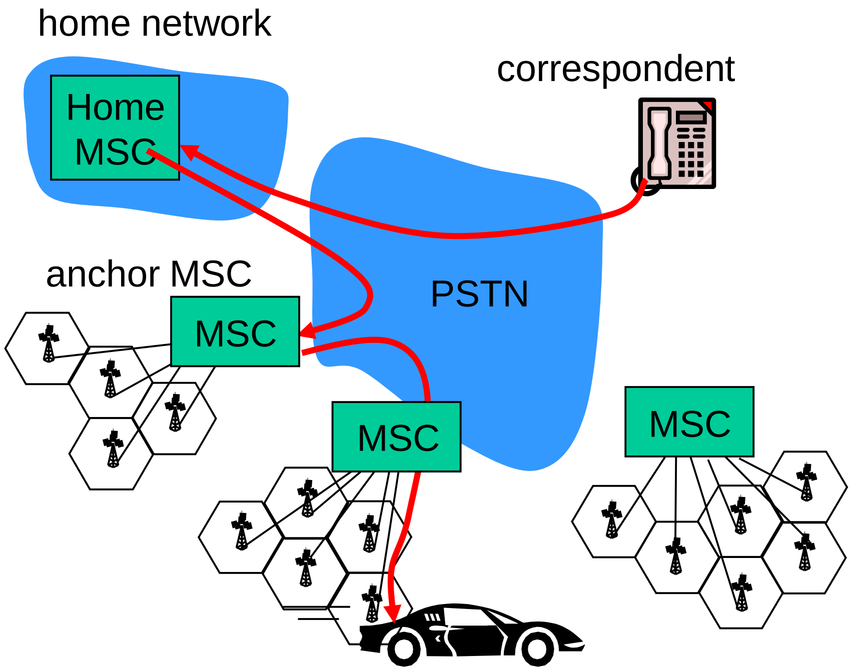
GSM: handoff with common MSC



1. old BSS informs MSC of impending handoff, provides list of 1$^+$ new BSSs
2. MSC sets up path (allocates resources) to new BSS
3. new BSS allocates radio channel for use by mobile
4. new BSS signals MSC, old BSS: ready
5. old BSS tells mobile: perform handoff to new BSS
6. mobile, new BSS signal to activate new channel
7. mobile signals via new BSS to MSC: handoff complete. MSC reroutes call

8 MSC-old-BSS resources released

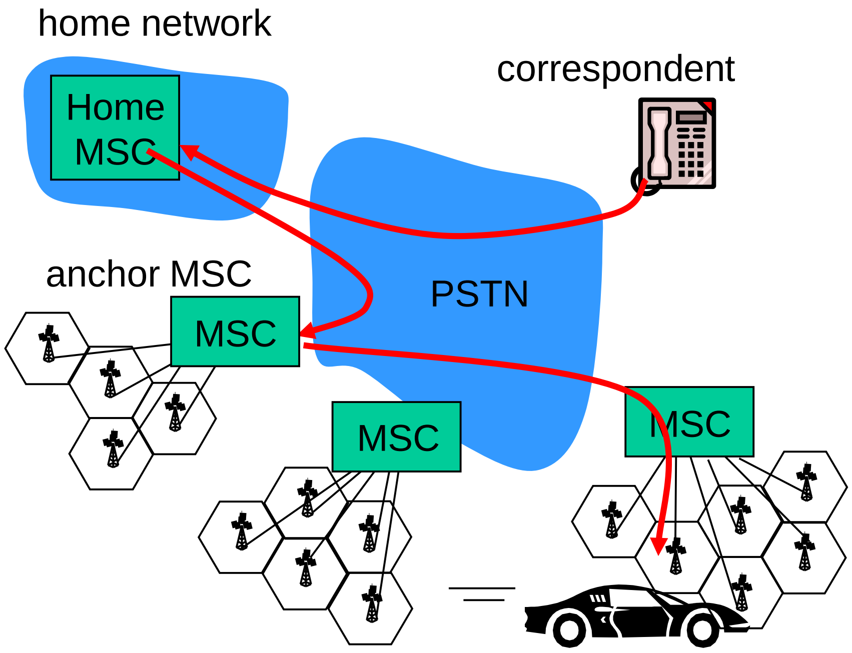
GSM: handoff between MSCs



(a) before handoff

- *anchor MSC:* first MSC visited during cal
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain

GSM: handoff between MSCs



(b) after handoff

- *anchor MSC:* first MSC visited during cal
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain