UiO : Faculty of Mathematics and Natural Sciences
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Department of Informatics
Networks and Distributed Systems (ND) group

INF 3190
(mostly) Wireless Communication

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Wireless: not exactly a minor side topic…

- Cellular Networks (3G/4G/LTE), WLAN, WPAN, WMAN, Software-Defined / Cognitive Radios, Smart Antennas / MIMO Systems, Ad-hoc Wireless Networks, Wireless Mesh Networks, Wireless Sensor Networks, Vehicular Networks, Satellites (GEOs, LEOs, MEOs), ….
  - and usage scenarios! Context-Aware Services, Ubiquitous Computing, Smart Spaces, Delay-Tolerant Networking, …
  - and issues! Cross-layering (e.g. “TCP-over-X”), efficient routing, energy saving, …

- Hence, can only provide:
  - Some technical foundations that are common to many systems above
    - Translates into: layers 1-2
    - We’ll focus on layer 2
  - A brief overview of some examples

Technical foundations and WLANs

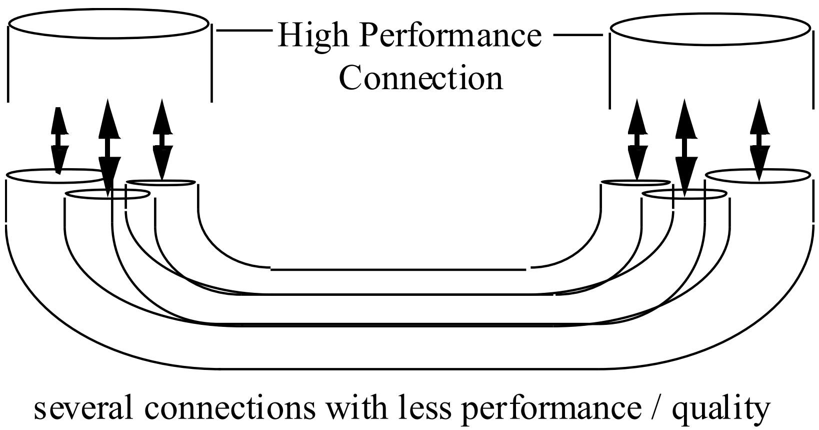
Channel Access: Frequency Hopping Spread Spectrum (FHSS)

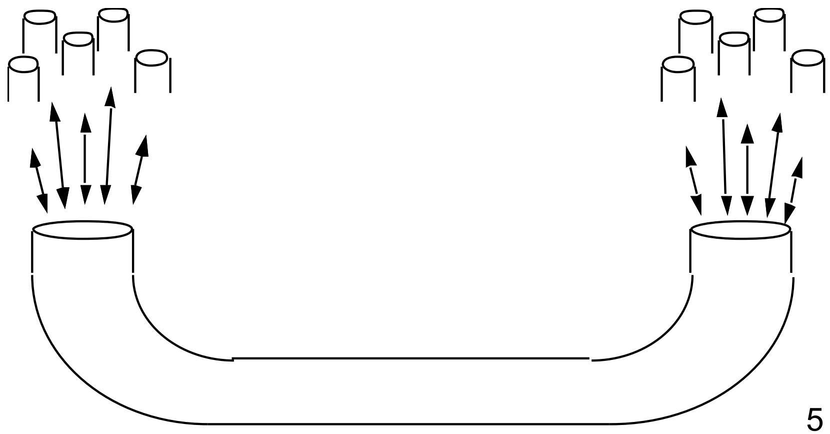
- Signal broadcast over seemingly random series of frequencies
- Receiver hops between frequencies in sync with transmitter
- Eavesdroppers hear unintelligible blips
- Jamming on one frequency affects only a few bits
- Rate of hopping versus Symbol rate
  - *Fast Frequency Hopping:* One bit transmitted in multiple hops.
  - *Slow Frequency Hopping:* Multiple bits are transmitted in a hopping period
- Adaptive variant (trying to avoid “bad” frequencies) used in Bluetooth (79 channels, 1600 hops/s)

Multiplexing (MUX)

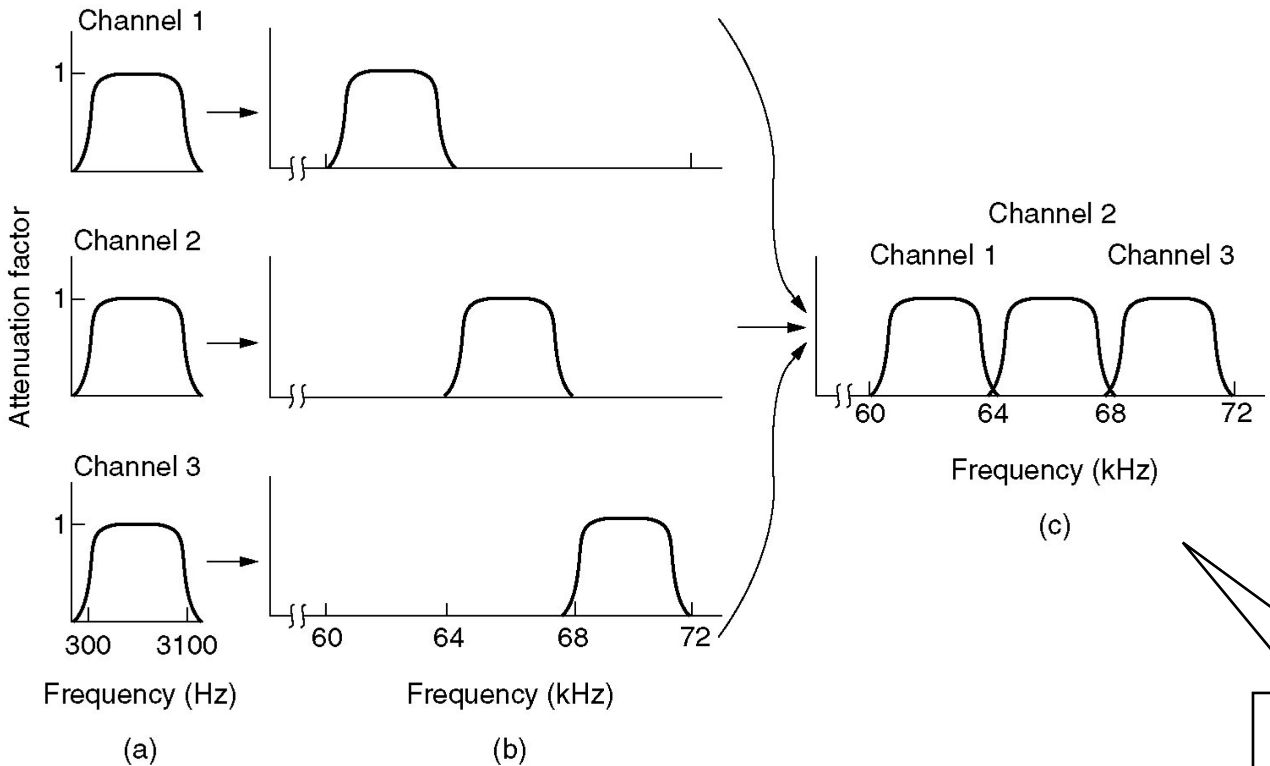
- Transmission of several data flows (logical connections) over one medium
  - Realize individual “connections“, *normally* with deterministic properties (throughput, delay)
  - Terminology: ??M („“.. Multiplexing“) or ??MA (“.. Multiple Access“)

- Also:
  Transmission of one data flow (logical connection) over several media
  - (increase performance and/or reliability)





Frequency Division Multiplexing (FDM(A))



(a) The original bandwidths.

(b) The bandwidths raised in frequency.

(b) The multiplexed channel.

Consider:
radio

- FDM in optical domain: Wavelength Division Multiplexing (WDM)
- FDM with orthogonal signals, allwing closer placement of frequencies: OFDM

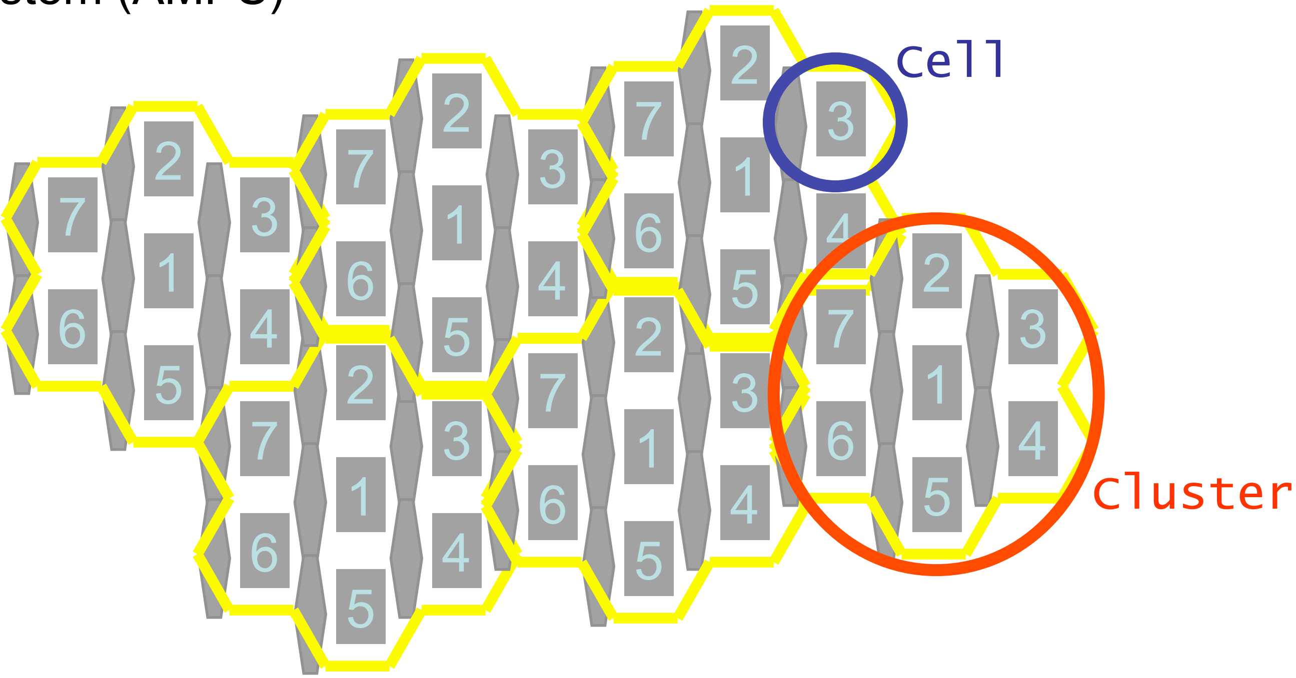
Time Division Multiplexing (TDM(A))

- Time slots used to differentiate between data flows
- can only be used for digital data
- synchronization required; typically: signaling bit(s)
- throughput not always deterministic (statistical TDM)

- TDM formed the basis for ATM
  - Connection oriented behavior emulated via forwarding (“switching”) of fixed-size cells
  - Realized Virtual Paths containing Virtual Channels with various QoS guarantees
  - Not wireless at all (fiber required), but 802.16 (wimax) provides similar QoS services and ATM compatibility…

Space Division Multiplexing (SDM(A))

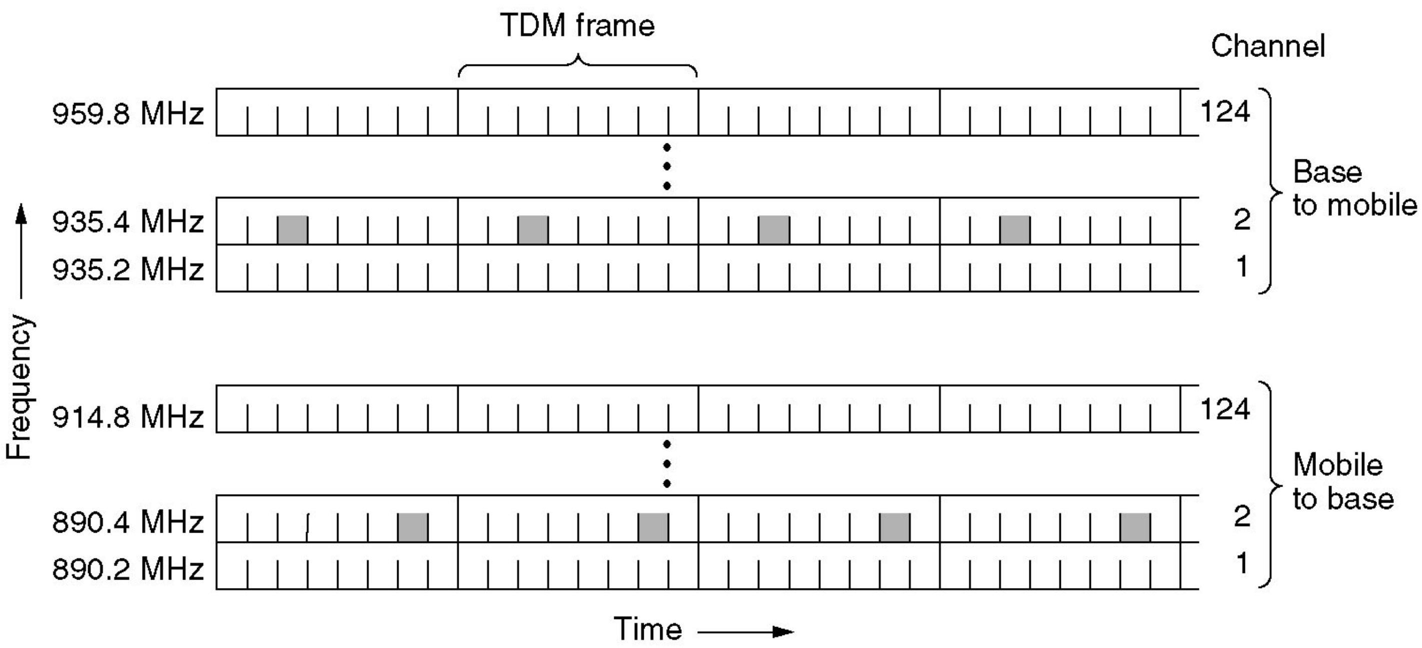
- Wired transmission: multiple cables
- Wireless transmission: reuse of (bunches of) frequencies
  - already used in First-Generation (analog) Advanced Mobile Phone System (AMPS)



Cluster size (No. of cells) *k*, cell radius *r*, distance *d* between base stations sharing the same frequencies: $d = r\sqrt{3k}$

Example: Global System for Mobile Communications (GSM)

- Second Generation (digital voice)
- Cell phone transmits on freq. X, receives on freq. X+55 MHz
  - uses: FDM + TDM (frame hierarchy)



US counterpart: Digital Advanced Mobile Phone System (D-AMPS)

Code Division Multiplexing (CDM(A))

- *Simultaneous* transmission using a *single* frequency!
  - Method explained below is called Direct-Sequence Spread Spectrum (DSSS)

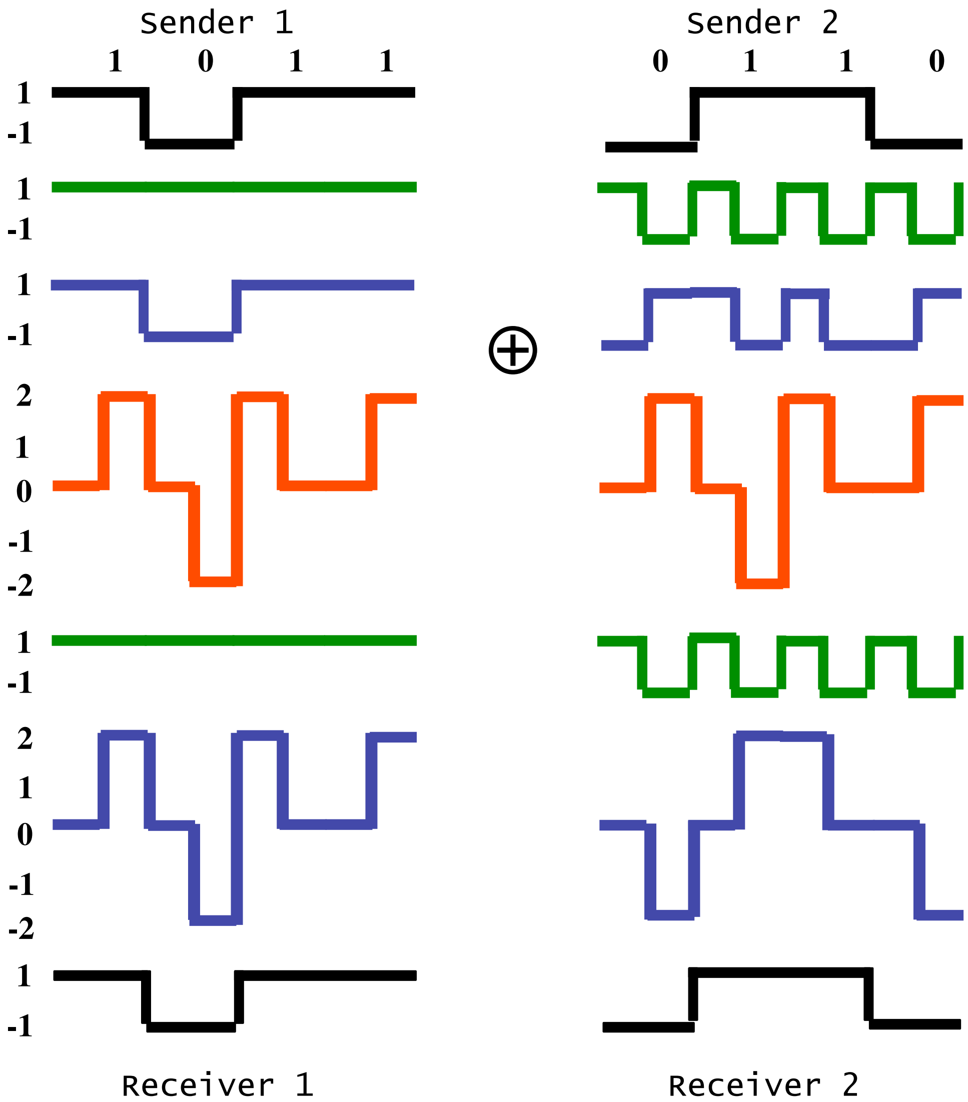
- Signal in bipolar notation: 1 ⇒ 1, 0 ⇒ -1
  - Multiply with individual chip sequence
  - Sequence length = duration of one symbol (1 bit consists of n chips)

- Chip sequences are orthogonal:
  - seq. 1: $\vec{x} = (x_1, x_2, .. x_n)$, seq. 2: $\vec{y} = (y_1, y_2, .. y_n)$ $\sum_{i=1}^{n} x_i y_i = 0$
  - ensures reconstructability!
  - Common choice: Walsh sequence - line of Walsh-Hadamard matrix:
  - $H_1 = [1]$

$$H_n = \begin{bmatrix} H_{n/2} & H_{n/2} \\ H_{n/2} & -H_{n/2} \end{bmatrix}$$

Reconstruction: multiply overlapping signals with chip sequence + integrate

CDMA Example



From H_2:
1,1 1,-1

- Original signals
- Chip sequences
- After multiplication
- Transmitted (overlapped) signal
- Chip sequences
- After multiplication
- After integration

CDMA properties

- Example: 1 signal with 2 symbols ⇒ 2 signals with 3 symbols
- Transmission of chips: higher data rate than bits!
  - more bandwidth required - thus, spread spectrum technology
- Reconstruction requires tight synchronization
- Used within GPS
- Proposal by Ericsson: Wideband CDMA (W-CDMA)
  - 5 MHz bandwidth
  - designed to interwork with GSM networks (not downward compatible, phone can move from GSM to W-CDMA without losing call)
  - used within Universal Mobile Telecommunications System (UMTS)

Multiplexing vs. Multiple Access Control (MUX vs. MAC)

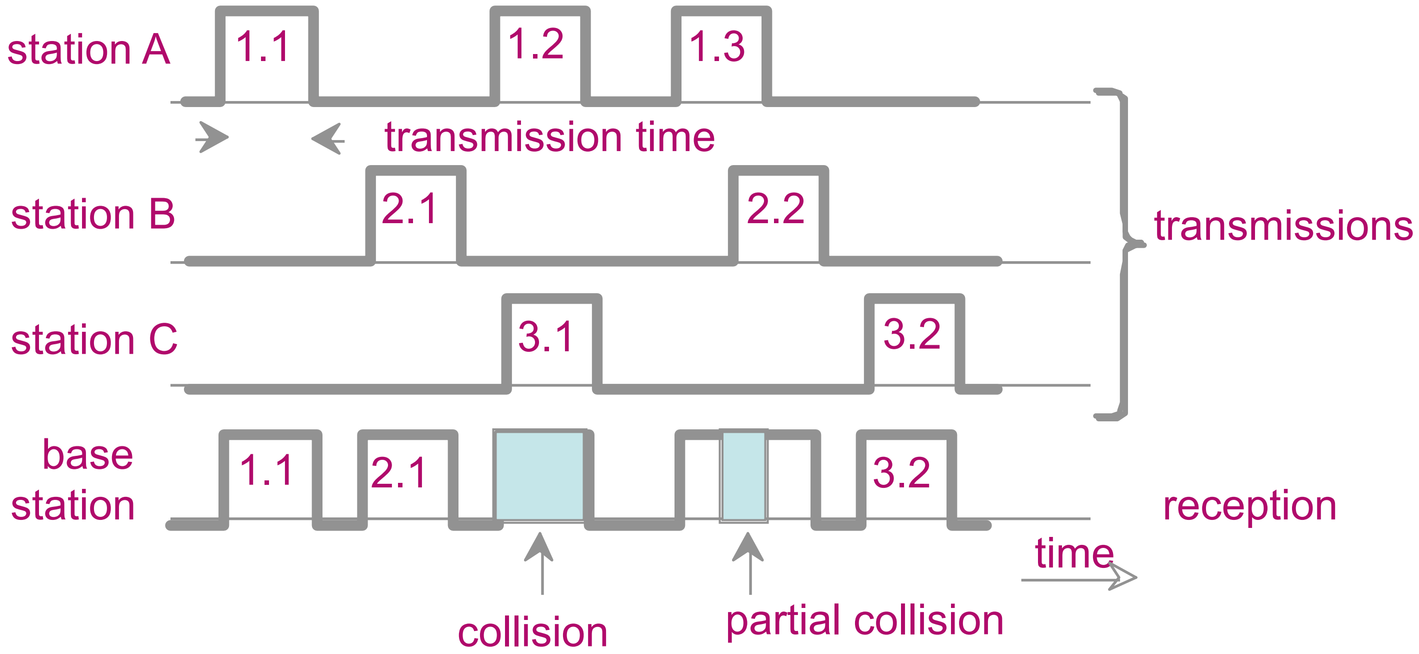
- Multiplexing
  - multiple processes per wire
  - map connections onto connections
  - long-distance “trunk“ wire
- Multiple Access (MA):
  usually, equals “media access“:
  multiple stations per cable / per wireless cell

1. centralized: e.g., host → terminal controllers, master/slave (outdated)
2. decentralized:
   a) concurrent: simpler, good for wireless, few „guarantees“
   b) controlled: next sender „elected“ unambiguously

MA: Aloha

History: wireless ⇒ wired ⇒ wireless :)

- Hawaii 70‘s
- collisions resolved via timeout (base station supposed to ack)



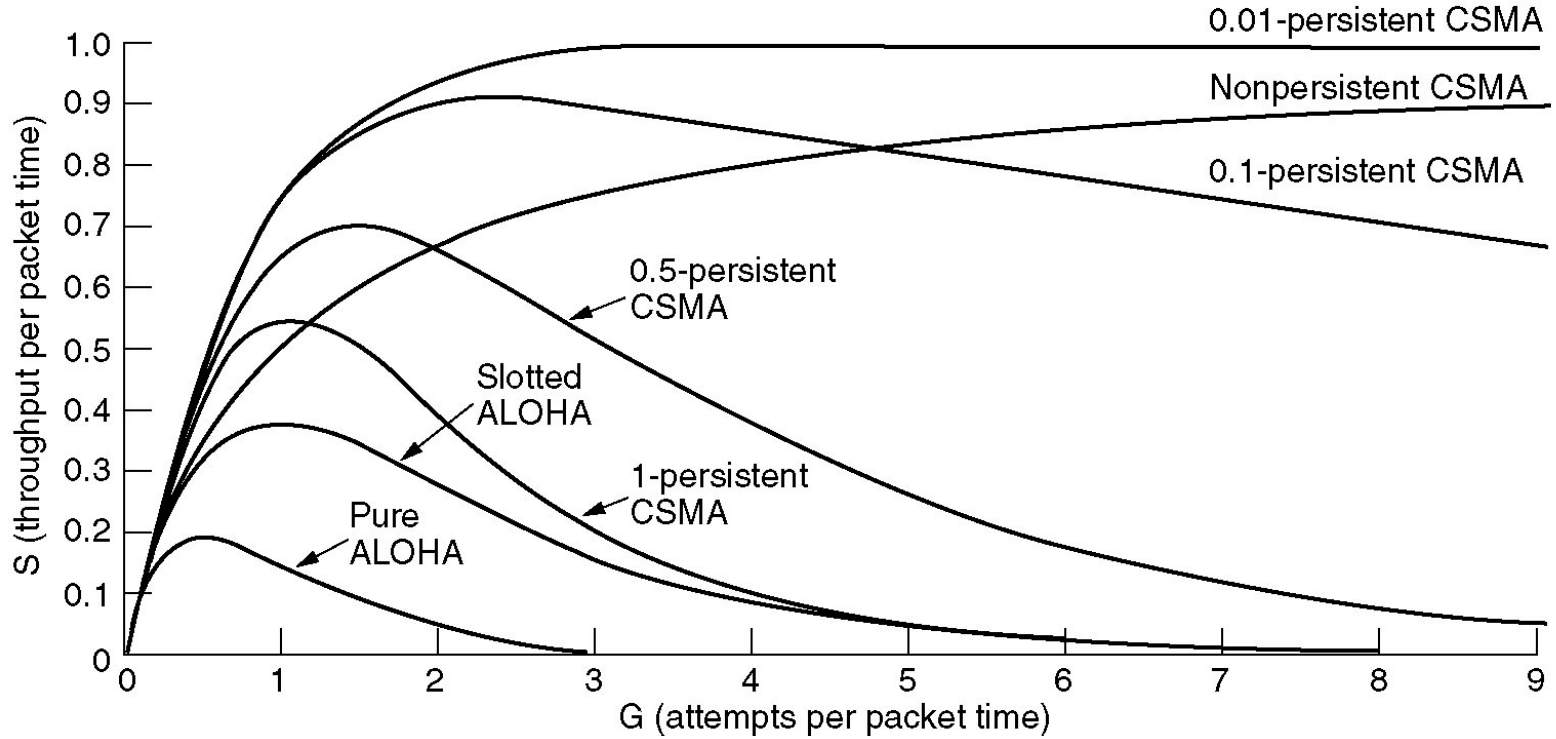
- Variant: slotted Aloha
  - fixed time slots, fixed size frames - no partial collisions

Carrier Sense Multiple Access (CSMA)

What happens if two senders do this?

- Listen (CS) Before Talk (LBT):
  - channel idle: transmit entire frame
  - channel busy: defer transmission
    - 1-Persistent CSMA: retry immediately when channel becomes idle
    - P-Persistent CSMA: retry immediately with probability p when channel becomes idle
    - Non-persistent CSMA: retry after random interval
- Human analogy: don't interrupt others!
  - Politicians are sometimes 1-Persistent…
- Collisions
  - sender 1 may not immediately see 2's transmission (propagation delay)
  - entire frame transmision time wasted

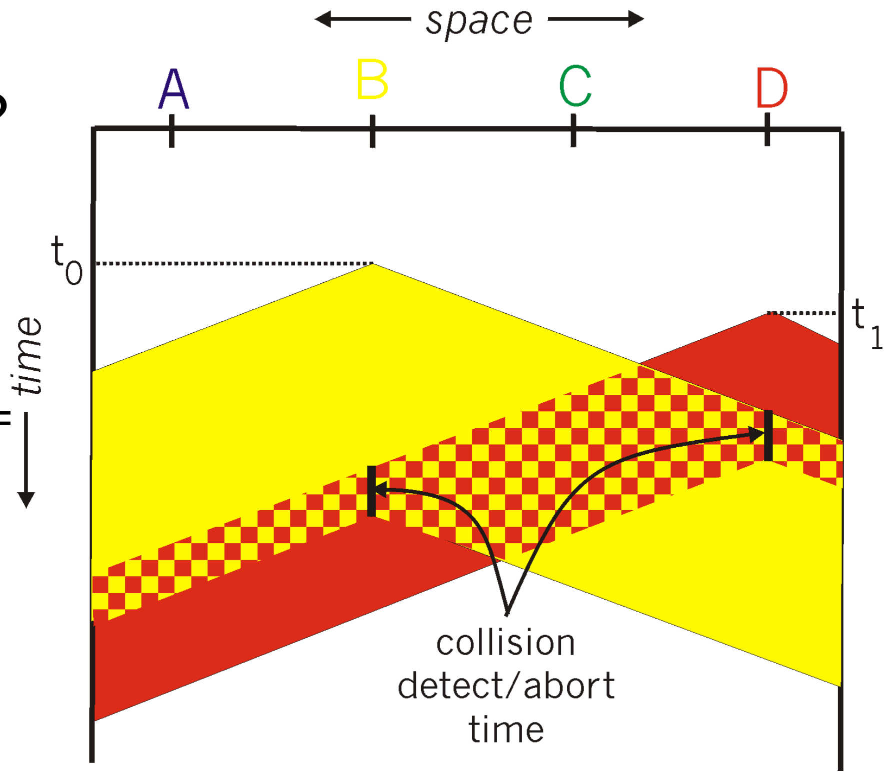
Persistent and Nonpersistent CSMA



Comparison of channel utilization versus load for various random access protocols.

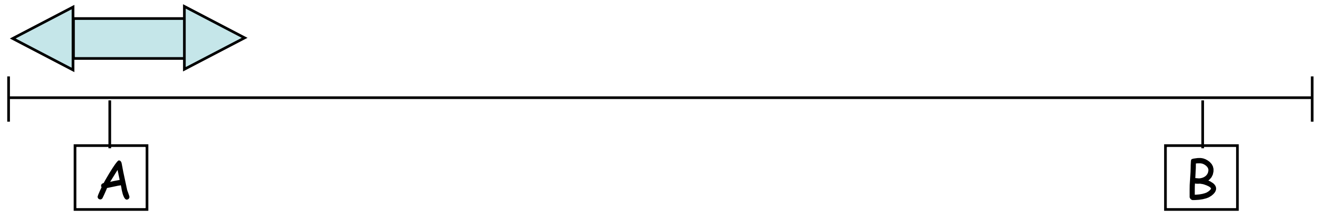
CSMA/CD (Collision Detection): wired only

- CD: signal sent = signal on wire?
  - must Listen While “Talking” (LWT), requires minimum message size
- Colliding transmissions aborted = reducing channel wastage
  - Retry: binary exponential backoff
- Doesn‘t work in wireless
  - a radio can usually not transmit and receive at the same time
  - signal strength decreases proportionally to the square of the distance or even more; not every radio signal is equally strong
  - sender might not “hear” the collision, i.e., CD does not work, e.g. if a terminal is “hidden” (to be explained)

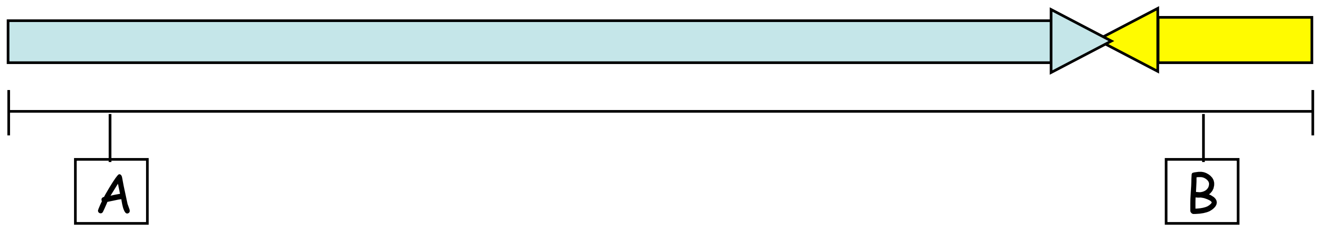


CSMA/CD (2)

A starts transmission (t_0)



B starts transmission (t_0 + t_L - e);
note: after t_0 + t_L, B would not send at all (LBT)



CSMA/CD (3)

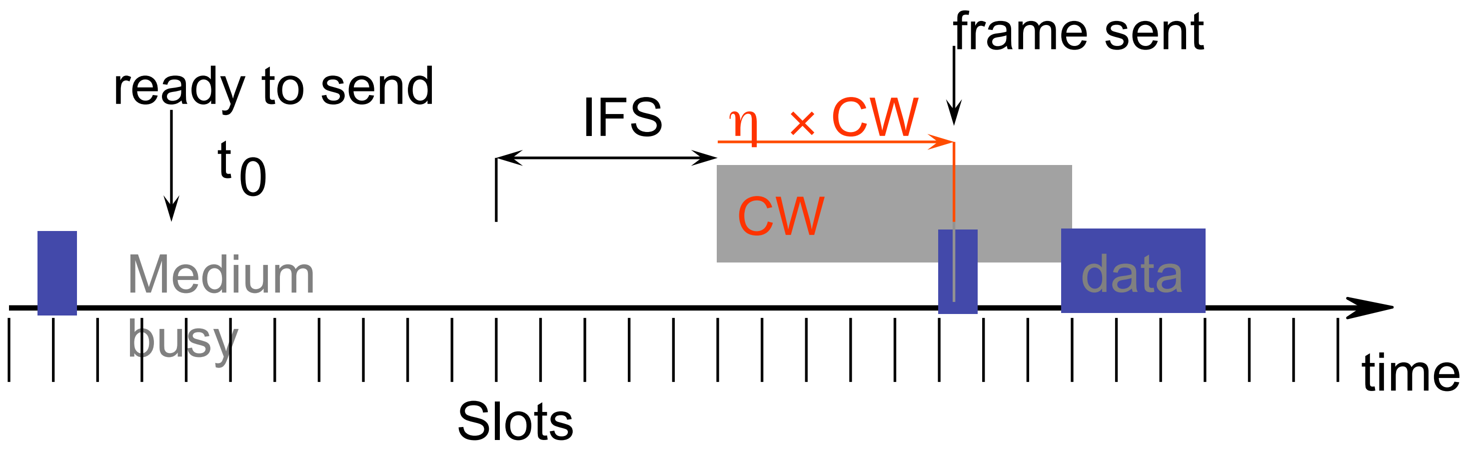
A notes collision (t_0 + 2(t_L - e))

- To notice collision, A must still be sending
- t_L: propagation delay A → B; 2 t_L : round trip delay
- max. distance A-B for „thick" Ethernet ~ 2.5 km, including repeaters (5 segments w/ 500m each)
- roundtrip delay: $5x10^3$ m / (2 x 10^8 m/s) = $2.5x10^{-5}$s (25 µs)
- min. packet size: 10^7 bit/s x $2.5x10^{-5}$s = 250 bit
- repeater delay, security, ... → min. packet size = 512 bit

802.11 DCF: CSMA/CA (Collision Avoidance)

Uses a CW: Contention Window (“dangerous“ time after busy)

- IFS: interframe spacing (3 sub-intervals for short/prio/data msgs.)
- if ready to send, station draws random η from [0,1]
- computes No. of Slots n to wait when medium available: $n = IFS + \eta \times CW$
- decreases n as slots pass by, n=0: transmit!
- if other station precedes (recognized via LBT):
  - keep old n (already decreased)!



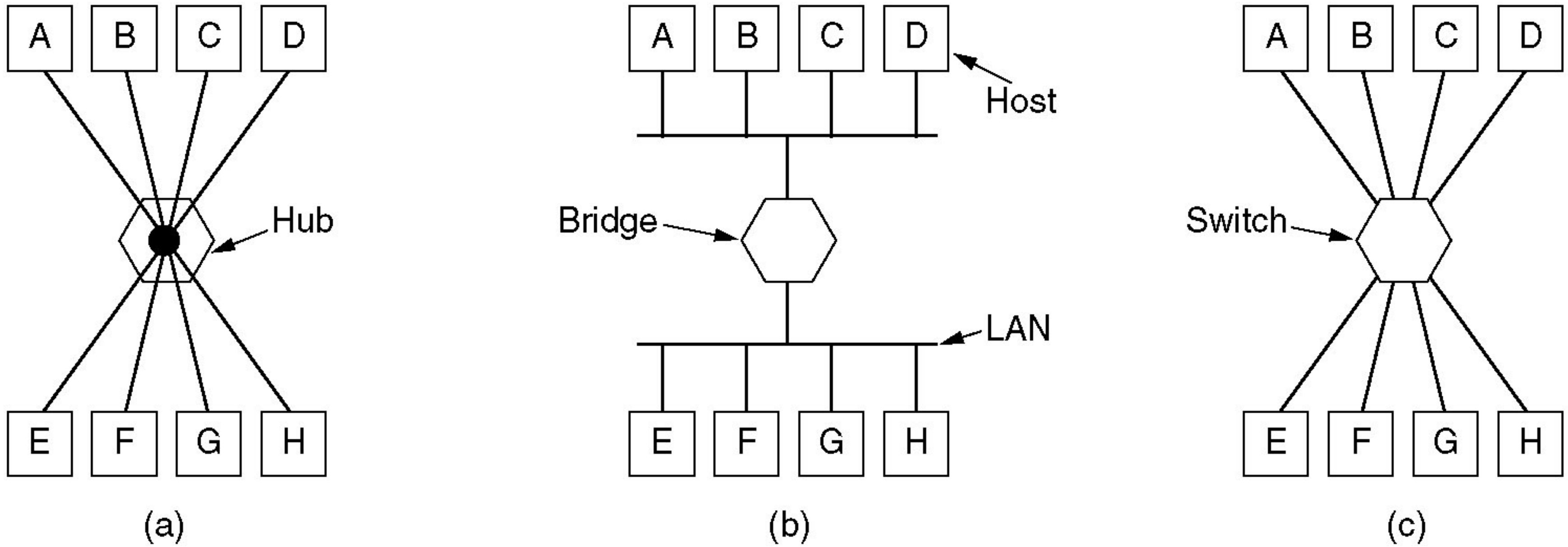
CSMA/CA (2)

- Contention Window
  - small: greater chance of collision, but high throughput when small load
  - large: smaller chance of collision, but less throughput

- CSMA/CA reduces chance of collision, but cannot prevent it
  - Exponential backoff: CW duplicated in response to error

- Collision detected via acknowledgement
  - Receiver sends ACK when frame arrives (sender timeout = error)
  - ACK has high priority (smaller IFS), but can also collide

Collision domains in wired topologies

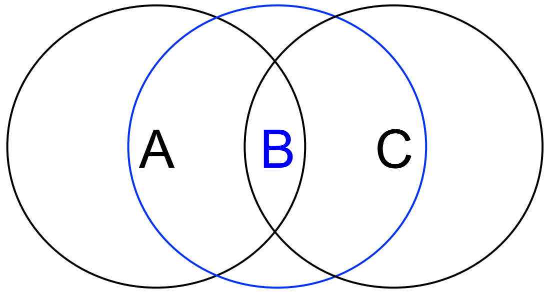


- (a) Hub: Physical layer device (i.e. unaware of + unnoticed by frames)
  - received bits on one interface copied to all other interfaces
  - Emulates bus (collisions)! cheap device
  - Can be arranged in a hierarchy, with backbone hub at its top
- (b) Bridge: Link layer device (i.e. unaware of + unnoticed by (e.g., IP) packets)
  - Isolates collision domains, selectively forwards using buffer
- (c) Switch:
  - Similar to bridge, main difference: topology, more common nowadays, new features

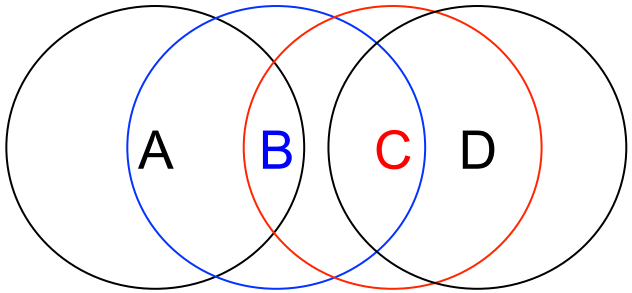
Switch, Gateway, Router: ambiguous terminology

Collision domains in wireless topologies

- Hidden Terminal problem:
  – A and C send to B. They only see B, but B sees A and C; at B, A‘s traffic can collide with C‘s traffic.



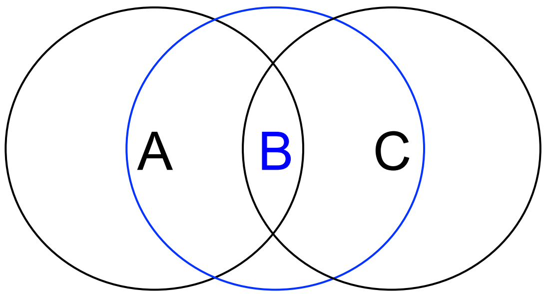
- Exposed Terminal problem:
  – B wants to send to A and C wants to send to D; one of them must unnecessarily (!) wait because traffic collides between B and C only.



- Optional fix for both (but overhead):
  Request to Send (RTS) / Clear to Send (CTS) frames

Network coding

- Based on linear combinations of orthogonal vectors in finite fields
  - Commonly explained with XOR
- Various applications; in wireless, exploits overhearing
- Major gains claimed... but: significant overhead
  - Decoding: Inverting m x m-matrix (m = size of variable vector)
  - this needs time $O(m^3)$ and memory $O(m^2)$



A, C: hosts
B: base station

Example - goal: A => C and C => A

Without NC:
1. A => B
2. B => C (A hears this)
3. C => B
4. B => A (C hears this)

With NC:
1. A => B
2. C => B
3. B broadcasts A's msg. XOR C's msg.

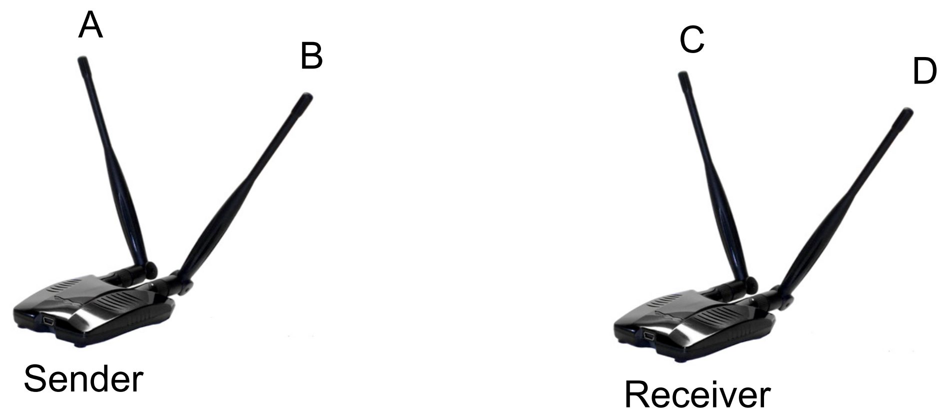
802.11 Rate Adaptation

- Wireless channel characteristics: noise, interference, fading, short-term variation in channel condition (bursty bit errors)

- Lower PHY transmission rate => more robust to noise
  - 802.11b: 1 – 11 Mbit/s (4 PHY rates)
  - 802.11g: 6 – 54 Mbit/s (8 PHY rates)

- Rate Adaptation (RA) method left to the vendor;
  various schemes exist
    - based on PHY (e.g. SNR or Received Signal Strength Indication (RSSI)) or link layer metrics
    - Common: Auto-Rate Fallback (ARF) and derivatives:
      assumes that consecutive packet loss = probably not due to collision

802.11n Features

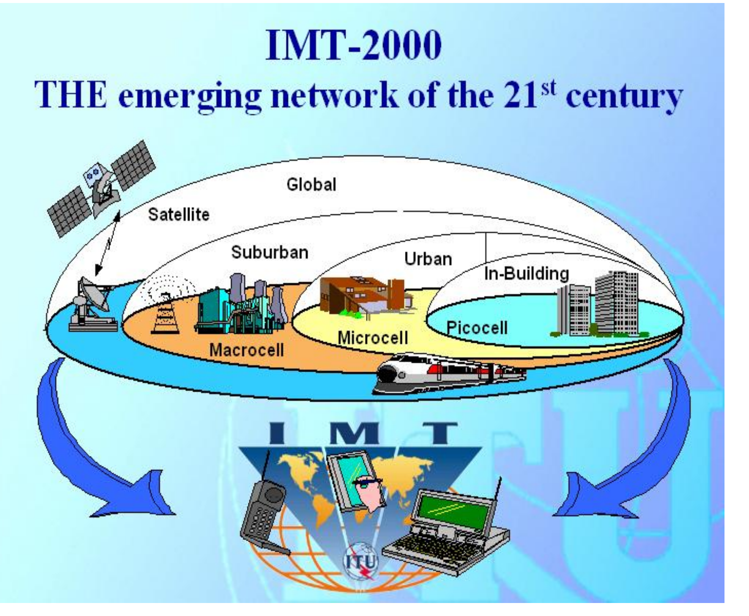


- MIMO
  - Because signals
    A=>C, A=>D, B=>C, B=>D will be phase shifted, cumulative signal can be de-multiplexed at the receiver

- Frame aggregation
  - Consider e.g. only one sender transmitting 3 frames in a row: contention period between frames is a waste of time
  - Better to transfer them as a single “superframe”
    (but limited in max size for fairness reasons)
  - (“Block”) ACKs sent in between blocks of the superframe

Some examples of wireless systems

UMTS and all that (2G, 2.5G, 3G, 4G)



- Third Generation Mobile Phones:
  Digital Voice and Data

- ITU-Standard "International Mobile Telecommunications" (IMT-2000):
  - High-quality voice transmission
  - Messaging (replace email, fax, SMS, chat, etc.)
  - Multimedia (music, videos, films, TV, etc.)
  - Internet access (web surfing + multimedia)

- Single worldwide technology envisioned by ITU, but:
  - **Europe:** GSM-based UMTS
  - **US:** IS-95 based CDMA2000 (different chip rate, frame time, spectrum, ..)

- Intermediate solutions (2.5G):
  - Enhanced Data rates for GSM Evolution (EDGE): GSM with more bits per baud
  - General Packet Radio Service (GPRS): packet network over D-AMPS or GSM

- Now there's also 4G, based on the Open Wireless Architecture (OWA)
  - 3GPP Long Term Evolution (LTE) is based on GSM/EDGE and UMTS/HSPA; sometimes called 3.9G because it doesn't satisfy 4G requirements. LTE Advanced does

WiMAX (802.16)

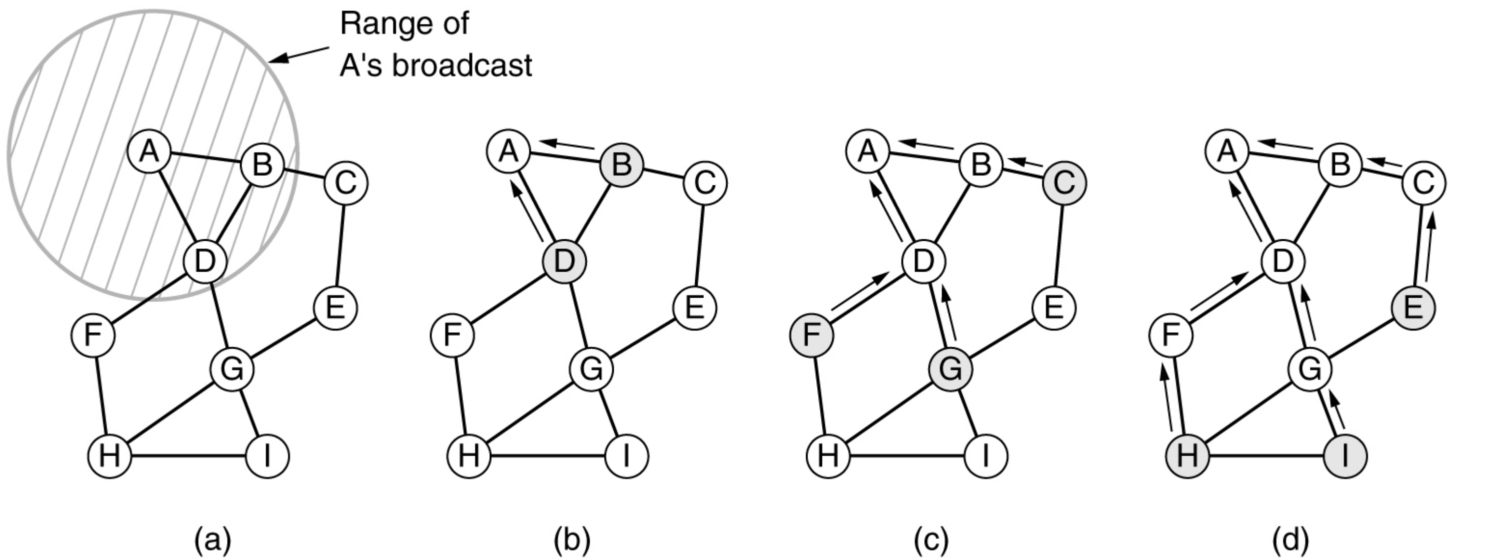
- MAN technology, but frequencies auctioned off country wide in many cases
=> eliminates main business case?

- Connection oriented
  - QoS per connection; all services applied to connections
  - managed by mapping connections to “service flows”
  - bandwidth requested via signaling
- Three management connections per direction, per station
  - basic connection: short, time-critical MAC / RLC messages
  - primary management connection: longer, delay-tolerant messages
authentication, connection setup
  - secondary management connection: e.g. DHCP, SNMP
- Transport connections
  - unidirectional; different parameters per direction
- Convergence sublayers map connections to upper technology
  - two sublayers defined: ATM and “packet“ (Ethernet, VLAN, IP, ..)

Mobile Ad Hoc Networks (MANETs)

- Mobile devices, also acting as routers
- Memory and CPU restrictions
- Flexible environment, changing topology
- Proactive routing
  - continuously make routing decisions
  - numerous efforts - examples: DBF, DSDV, WRP, ..
- Reactive routing
  - determine routes when needed
  - numerous efforts - examples: TORA, DSR, ABR, RDMAR, AODV, ..

Example: Ad hoc On-Demand Distance Vector (AODV) algorithm - route discovery



- (a) Range of A's broadcast.
- (b) After B and D have received A's broadcast.
- (c) After C, F, and G have received A's broadcast.
- (d) After E, H, and I have received A's broadcast.

Shaded nodes are new recipients. Arrows show possible reverse routes.

From MANETs to WMN…

- MANET used to be a hype, is now a “cold topic”
- Not too many realistic usage scenarios
  - When do you not have a base station but want to connect anyway?
    - Military battlefield was a common example scenario – is it the only real use case?
    - For anything else, what’s the user incentive for type of net?
  - Better to incorporate base stations and consider the (somewhat less mobile) network formed by the heterogeneous equipment connected in this way
    - Wireless Mesh Network (WMN)

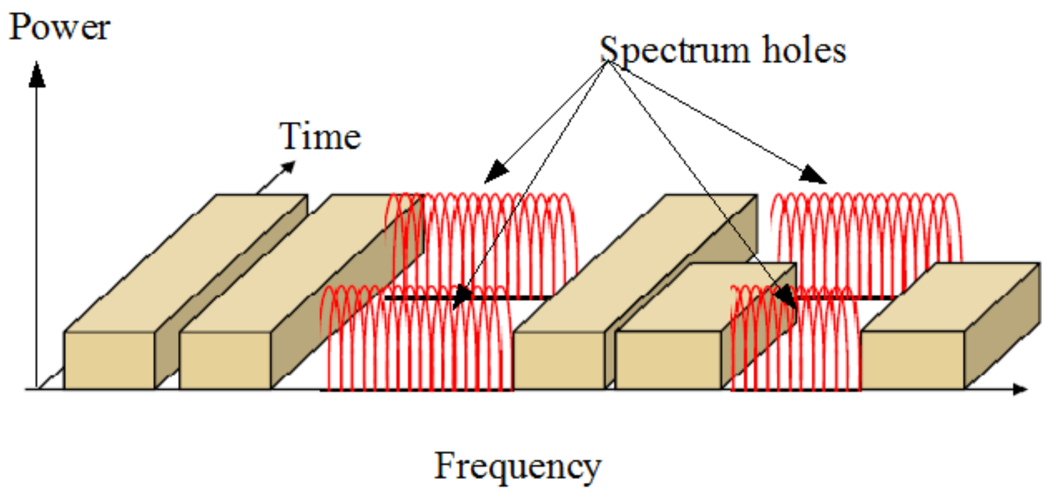
… and DTN

- Real "ad hoc" situations are often intermittent
  - We meet in the hallway and talk for 5 minutes
  - You then meet a common friend 2 hours later
    - There will never be e.g. a TCP connection between me and this friend … but your device could still carry my packets, like you could deliver a letter for me?

- DTN was originally "Interplanetary Internet"
  - intermittent connectivity inherent, e.g. moon not always visible…
  - On earth, DTN has been proposed for rural connectivity (the bus or a motorcycle carry packets) - e.g. KioskNet: http://blizzard.cs.uwaterloo.ca/tetherless/index.php/KioskNet

Cognitive Radio

- Spectrum utilization depends strongly on time and place
  - Could do better than always use the same allocated frequencies
- Idea: let unlicensed ("secondary") users access licensed bands without interfering with licensed ("primary") users
  - Ideally, access a database which maintains a common view of who uses which spectrum
  - Many issues (e.g. security, incentives for cooperating, ..)



Wireless Sensor Networks (WSNs)

- Based on 802.15.4
  - Some devices: ZigBee (802.15.4 PHY+MAC + layers 3 / 7)
  - uses CSMA/CA
  - Many devices can run TinyOS or Contiki OSes

- Specific scenarios – alarm based systems, regular measurements, ... => specific improvements possible
  - e.g. static topology, regular updates: can do special routing; can put nodes to sleep when they don't communicate
  - transport: sometimes per-hop reliability
  - often: one static sink => "funneling effect" of traffic going "up the tree", earlier battery depletion of nodes near the sink
  - Solution: mobile sink (e.g. radio controlled helicopter)