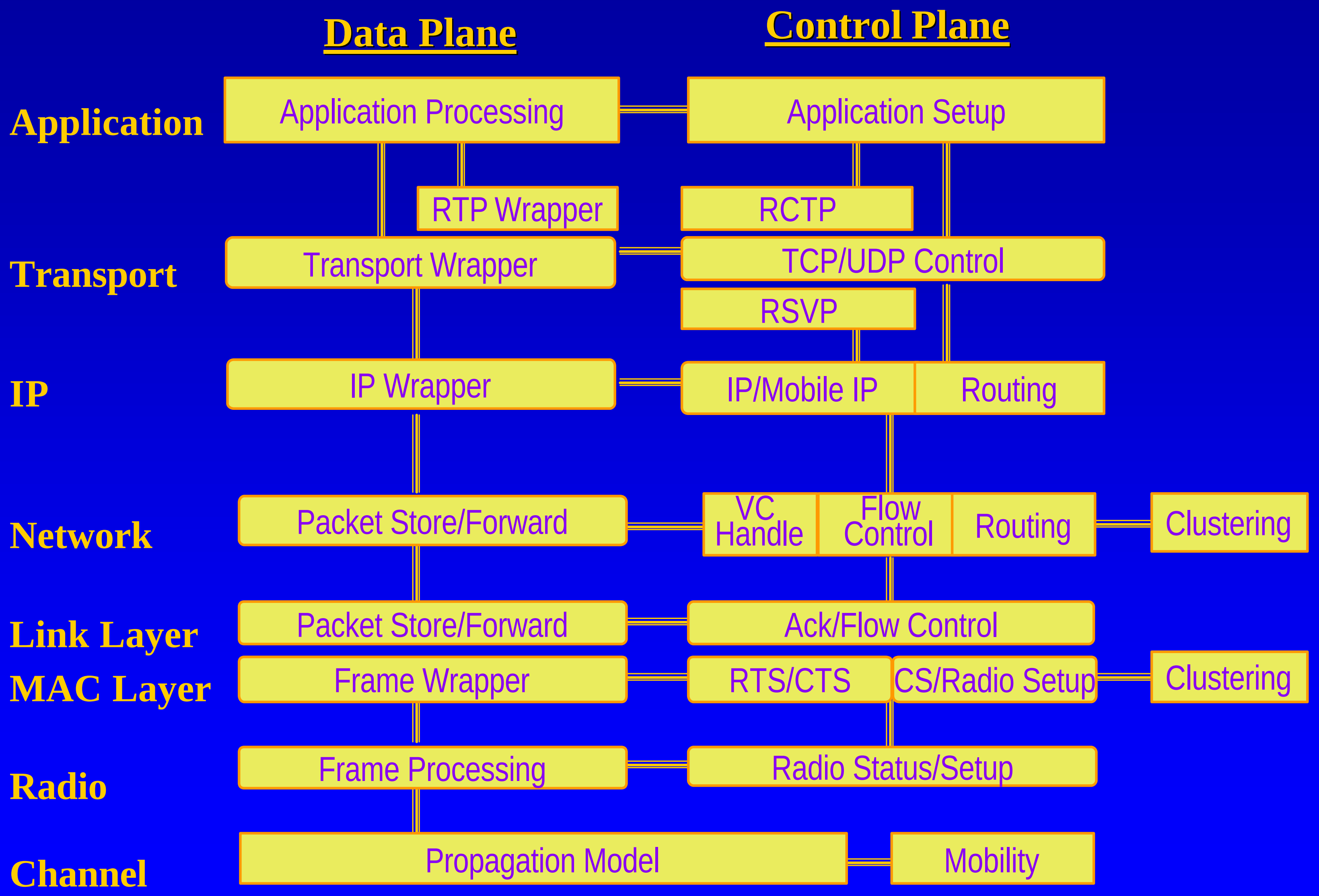
Wireless Nets – the MAC layer
Part I

- FDMA/TDMA/CDMA
- MAC Protocols Overview
- MAC layer in the DARPA Packet Radio testbed
- MAC in wireless LANs (MACA and IEEE 802.11)

Wireless Protocol Layers



MAC Layer

- **Media Access Control protocol: coordination and scheduling of transmissions among competing neighbors**
- **Goals: low latency, good channel utilization; best effort + real time support**
- **MAC layer clustering: aggregation of nodes in a cluster (= cell) for MAC enhancement; different from network layer clustering/partitioning such as used for routing.**

MAC protocols reviewed

- FDMA/TDMA/CDMA
- ALOHA
- CSMA (Packet Radio Net)
- IEEE 802.11
- Bluetooth

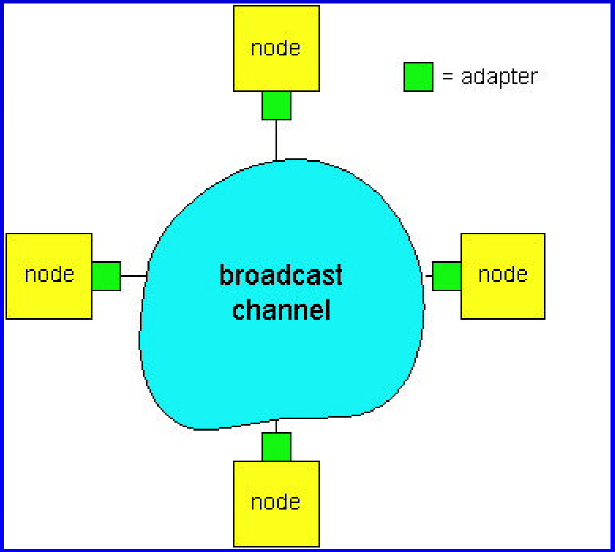
If time permits…

- Cluster TDMA
- MACA/PR
- Ad Hoc MAC
- SCOPE

Multiple Access Control (MAC) Protocols

- **MAC protocol: coordinates transmissions from different stations in order to minimize/avoid collisions**
- **(a)** Channel Partitioning **MAC protocols: TDMA, FDMA, CDMA**
- **(b)** Random Access **MAC protocols: CSMA, MACA**
- **(c) "**Taking turns**" MAC protocols: polling**

- **Goal:** efficient, fair, simple, decentralized



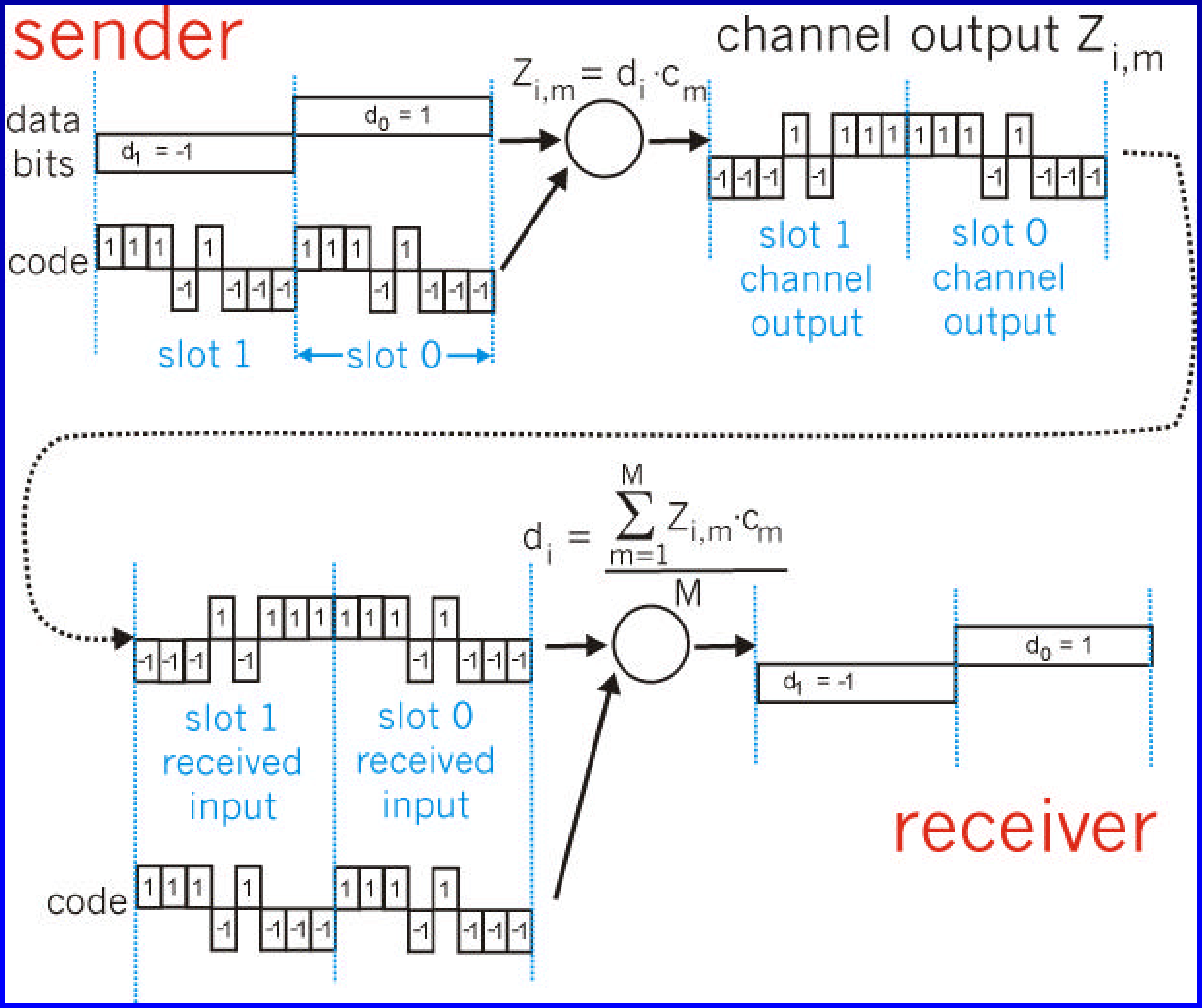
Channel Partitioning (CDMA)

- CDMA (Code Division Multiple Access)**: exploits** spread spectrum **(DS or FH) encoding scheme**
- **unique "code" assigned to each user; ie,** code set **partitioning**
- **Used mostly in** wireless **broadcast channels (cellular, satellite,etc)**
- **All users share the** same frequency**, but each user has** own "chipping" sequence **(ie, code)**

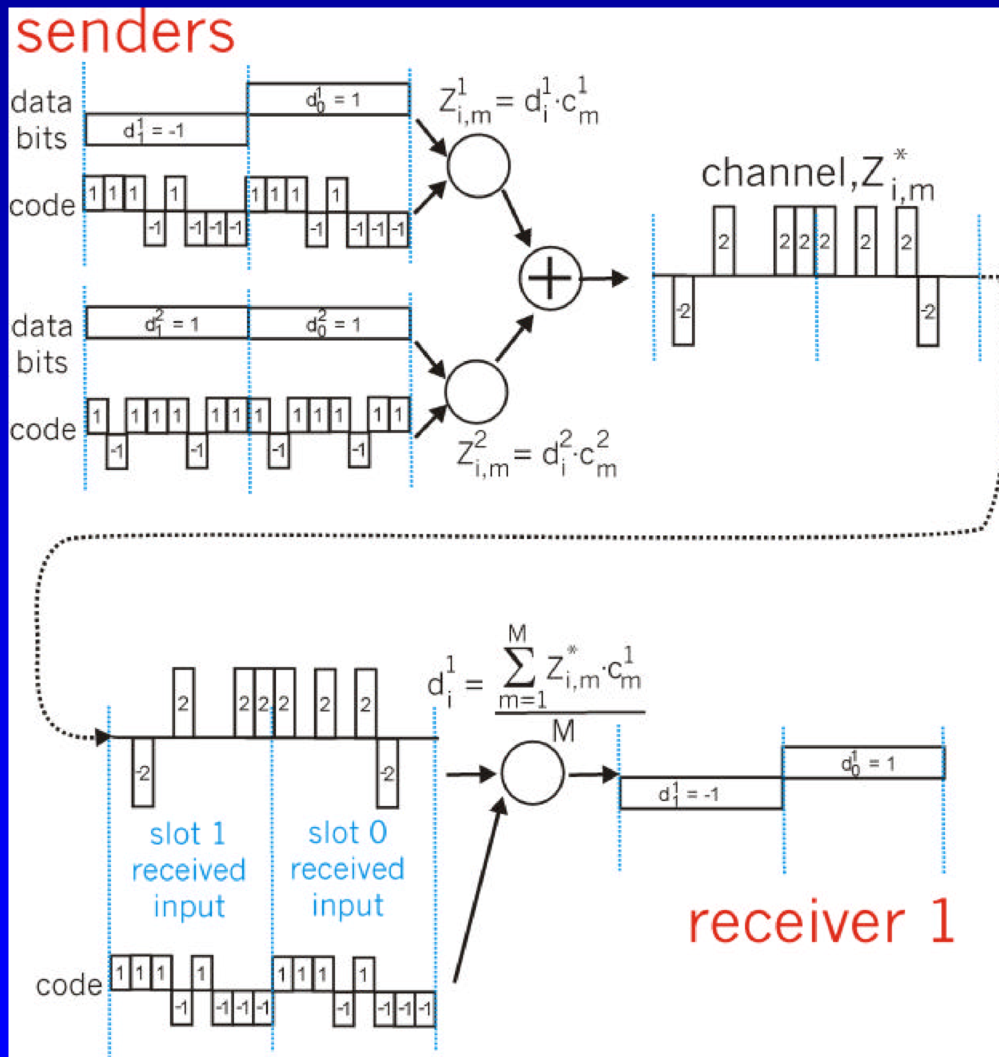
Channel Partitioning (CDMA)

- **Chipping sequence like a** mask**: used to** encode **the signal**
- encoded signal **= (original signal) X (chipping sequence)**
- decoding**: innerproduct of encoded signal and chipping sequence (note, the innerproduct is the sum of the component-by-component products)**
- **To make CDMA work, chipping sequences must be chosen orthogonal to eachother (ie, innerproduct = 0)**

CDMA Encode/Decode



CDMA: two-sender interference



CDMA (cont)

CDMA Properties:

- protects users from interference and jamming (used in WW II)
- protects users from radio multipath fading
- allows multiple users to “coexist” and transmit simultaneously with minimal interference (if codes are “orthogonal”)
- requires “chip synch” acquisition before demodulation
- requires careful transmit power control to avoid “capture” by near stations in near-far situations
- FAA requires use of SS (with limits on tx power) in the Unlicensed Spectrum region (ISM), ie .9 , 2.4 and 5.7 Ghz (WaveLANs)
- CDMA used in Qualcomm cell phones (channel efficiency improved by factor of 4 with respect to TDMA)

Frequency Hopping (FH)

- Frequency spectrum sliced into frequency subbands (eg, 125 subbands in a 25 Mhz range)
- Time is subdivided into slots; each slot can carry several bits (slow FH)
- A typical packet covers several time slots (up to 5 slots in Bluetooth)
- A transmitter changes frequency slot by slot (frequency hopping) according to unique, predefined sequence; all users are clock and slot synchronized
- Ideally, hopping sequences are “orthogonal” (ie, non overlapped); in practice, some conflicts may occur

Random Access protocols

- A node transmits at random (ie, no a priory coordination among nodes) at full channel data rate R.
- If two or more nodes "collide", they retransmit at random times
- The random access MAC protocol specifies how to detect collisions and how to recover from them (via delayed retransmissions, for example)
- Examples of random access MAC protocols:

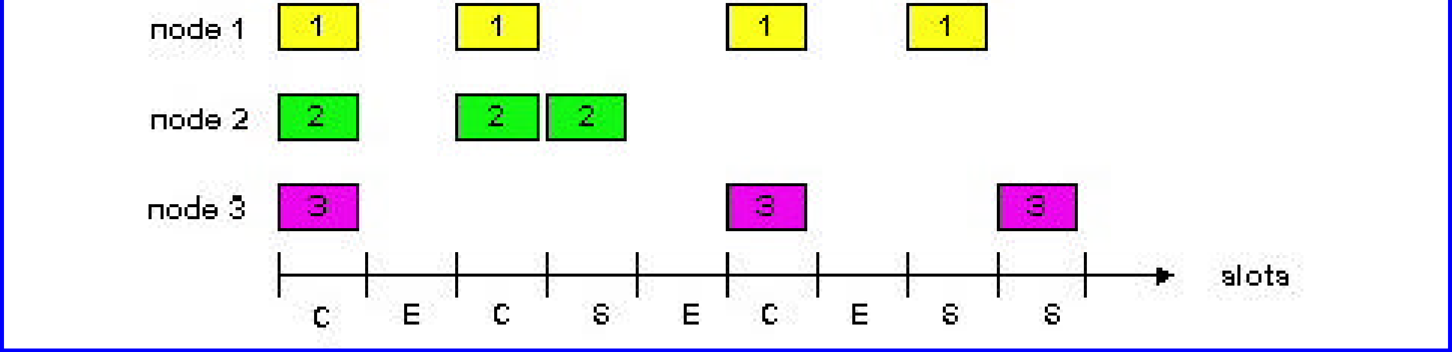
(a) SLOTTED ALOHA

(b) ALOHA

(c) CSMA and CSMA/CD

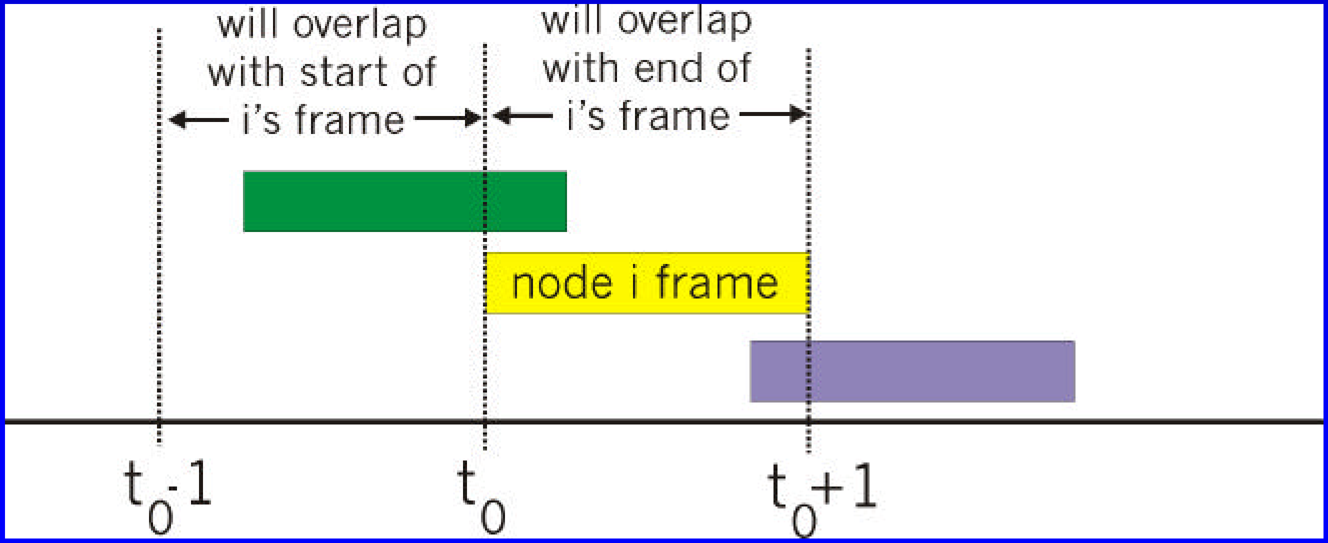
Slotted Aloha

- Time is divided into equal size slots (= full packet size)
- a newly arriving station transmits a the beginning of the next slot
- if collision occurs (assume channel feedback, eg the receiver informs the source of a collision), the source retransmits the packet at each slot with probability P, until successful.
- Success (S), Collision (C), Empty (E) slots
- S-ALOHA is fully decentralized
- Throughput efficiency = 1/e



Pure (unslotted) ALOHA

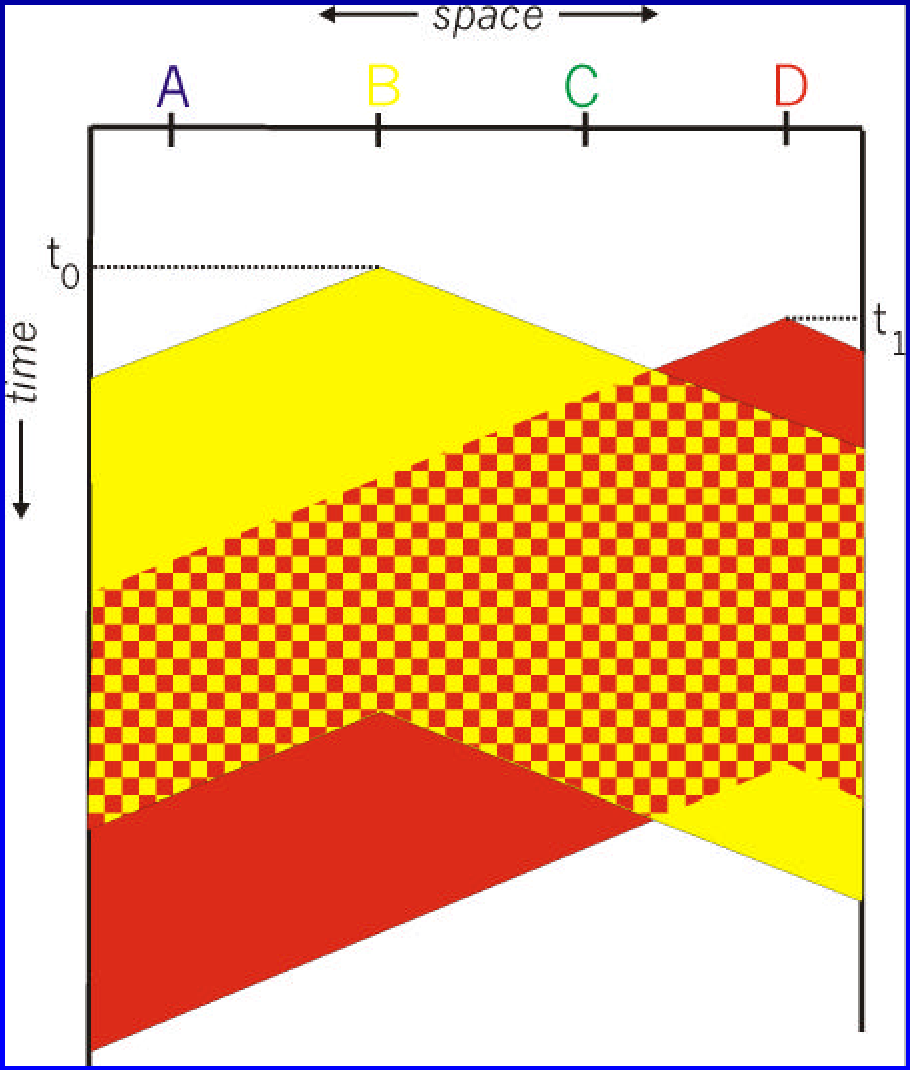
- Slotted ALOHA requires slot synchronization
- A simpler version, pure ALOHA, does not require slots
- A node transmits without awaiting for the beginning of a slot
- Collision probability increases (packet can collide with packets transmitted in a “vulnerable” window twice as large as in S-Aloha)
- Throughput is reduced by one half, ie S= 1/2e



CSMA (Carrier Sense Multiple Access)

- CSMA: **listen before transmit. If channel is sensed busy, defer transmission**
- Persistent **CSMA: retry immediately when channel becomes idle (this may cause instability)**
- Non persistent CSMA**: retry after random interval**
- **Note: collisions may still exist, since two stations may sense the channel idle at the same time (or better, within a "vulnerable" window = round trip delay)**
- **In case of collision, the entire pkt transmission time is wasted**

CSMA collisions

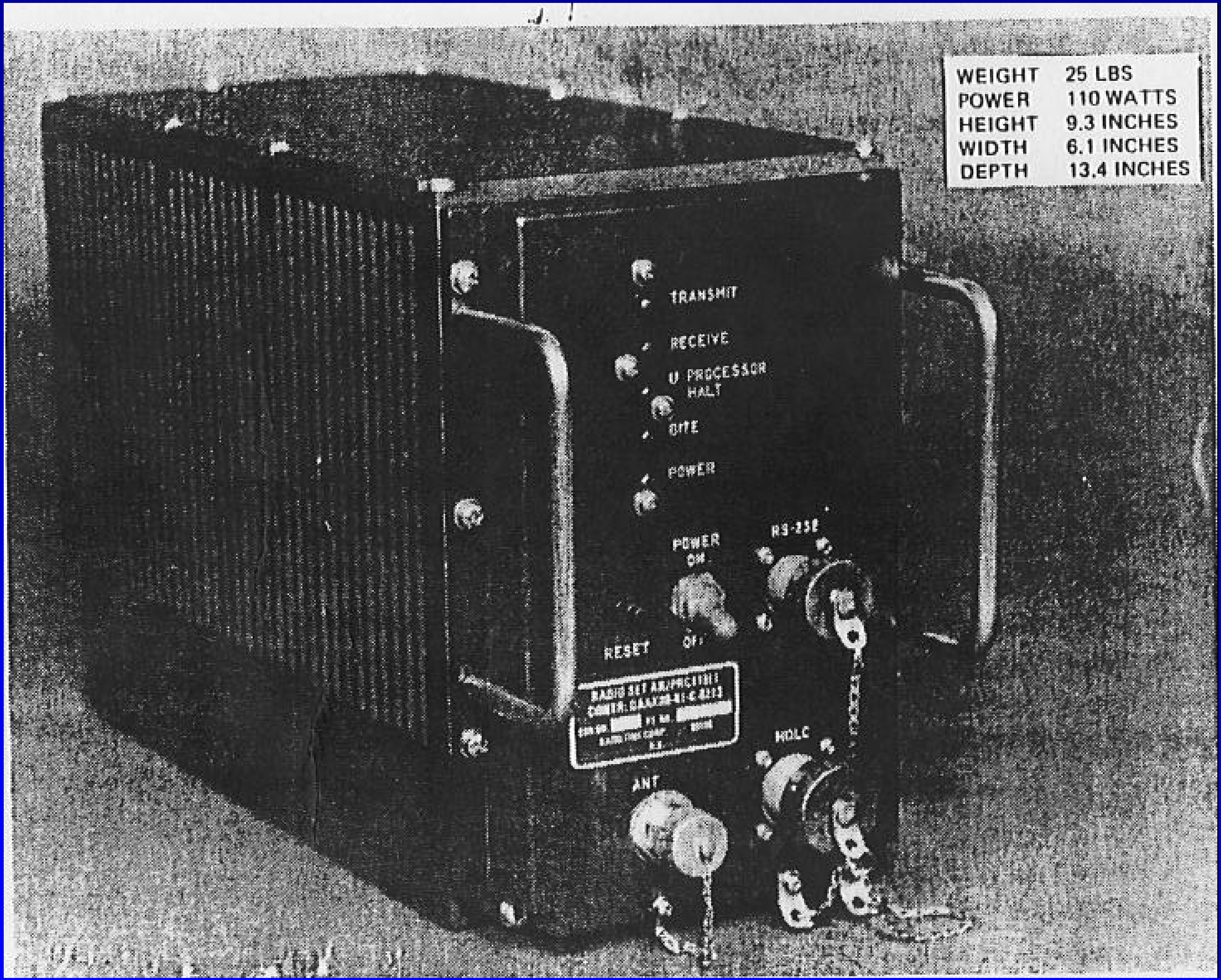


CSMA/CD (Collision Detection)

- CSMA/CD: carrier sensing and deferral like in CSMA. But, collisions are detected within a few bit times.
- Transmission is then aborted, reducing the channel wastage considerably.
- Typically, persistent transmission is implemented
- CSMA/CD can approach channel utilization =1 in LANs (low ratio of propagation over packet transmission time)
- Collision detection is easy in wired LANs (eg, E-net): can measure signal strength on the line, or code violations, or compare tx and receive signals
- Collision detection cannot be done in wireless LANs (the receiver is shut off while transmitting, to avoid damaging it with excess power)

DARPA Packet Radio Project (1973-1985)

- **Goals:**
  - extend P/S to mobile environment
  - provide network access to mobile terminals
  - quick (re) deployment
- **Fully distributed design philosophy:**
  - self initialization
  - dynamic reconfiguration
  - dynamic routing
  - automated network management
- **PR NET components:**
  - packet radio
  - user device (connected to radio via Network Interface Unit)



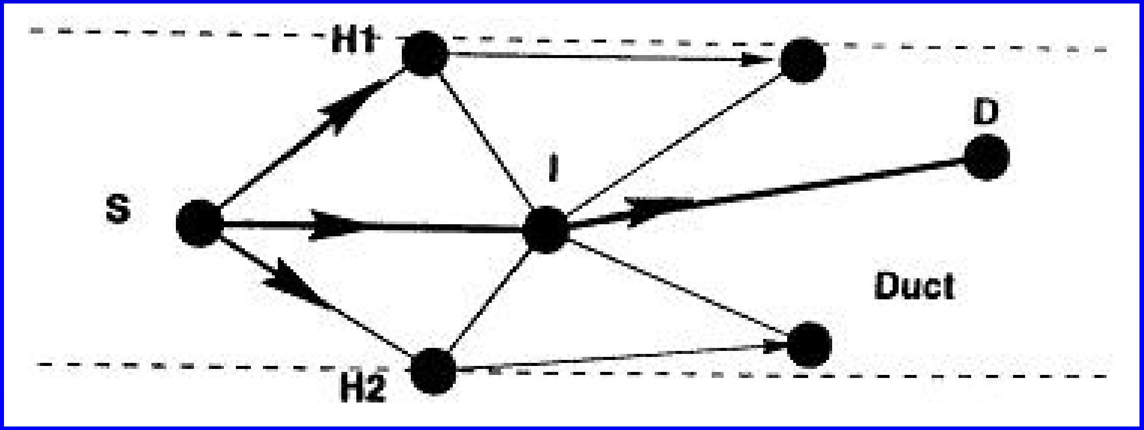
WEIGHT 25 LBS
POWER 110 WATTS
HEIGHT 9.3 INCHES
WIDTH 6.1 INCHES
DEPTH 13.4 INCHES
TRANSMIT
RECEIVE
PROCESSOR
HALT
POWER
POWER
ON
RESET
ANT
HDLC

Radio channel characteristics

- Band of operation: 1718.4 to 1840 MHz
- Number of channels: 10 (preselectable)
- Channel bandwidth: 12 MHz
- Data rate: 100 Kbps or 400 Kbps (preselectable)
- Modulation: Direct Sequence Spread Spectrum
- chip rate: 12.8 Megachips/sec
- Preamble 28 bits
- Forward Error correction: variable rates (1/2, 2/3, 7/8)
- Multiple access techniques: CSMA, CDMA
- Transmit power: 5W (adjustable: 0 to 24 dB att.)
- Range: 10Km (with omnidirectional antenna 1.5m above ground).

Packet Forwarding

- **Acknowledgements: active/passive**
- **Retransmission (after time out; retx up to 6 times)**
- **Error Control: FEC (1/2 rate) and CRC**
- **Alternate routing:**
  - after 3 unsuccessful attempts, alt-route flag set in packet header. Any neighbor can pick up packet (“Duct Routing”)
- **Duplicate filtering:**
  - UPI (unique Packet ID = source PR ID and seq. number) used to discard duplicates.



IEEE 802.11 and Wireless LANs

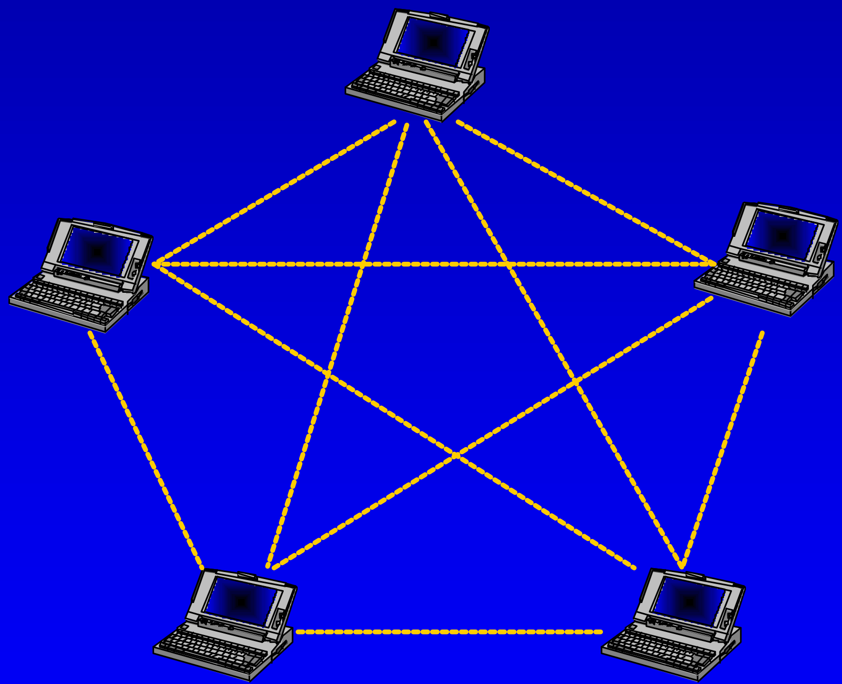
- **Wireless LANs**
  - mostly indoor
  - base station (like cellular); or ad hoc networking (mostly point to point)
  - standards: IEEE802.11 (various versions); HyperLAN (ETSI); Bluetooth

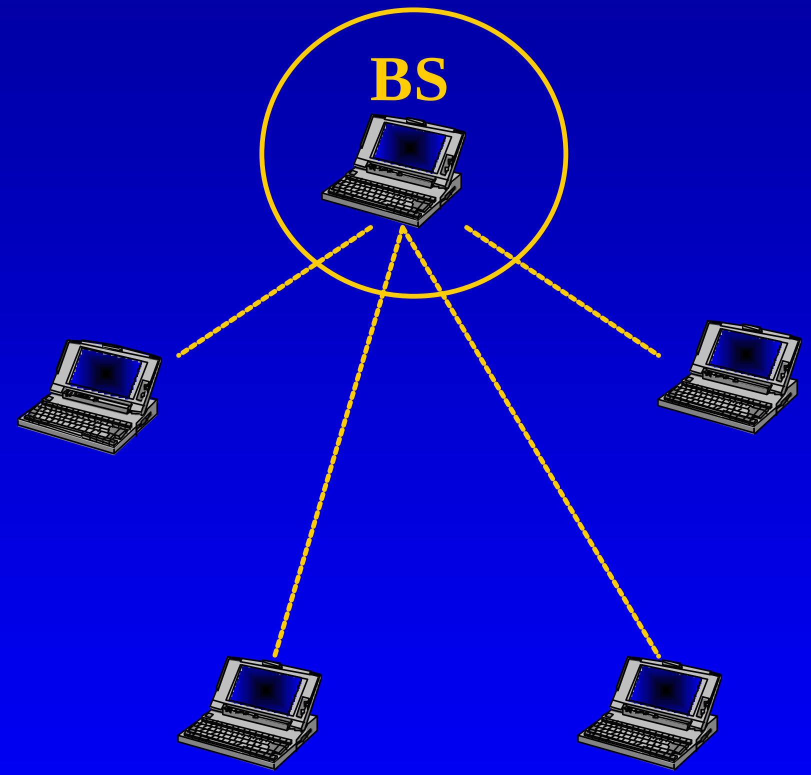
M. Veeraraghavan, N. Cocker, and T. Moors, "Support of Voice Services in IEEE 802.11 Wireless LANs," In Proceedings of Infocom 2001, Anchorage, AK, 2001.

Also, see the set of TUTORIAL slides in the class readings

Wireless LAN Configurations

Peer-to-peer Networking
Ad-hoc Networking

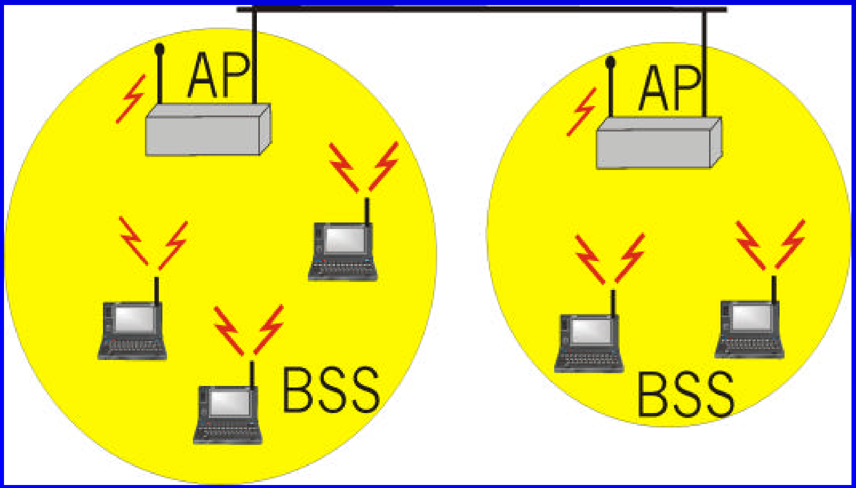




With or without control (base) station

IEEE 802.11 Wireless LAN

- **Applications: nomadic Internet access, portable computing, ad hoc networking (multihopping)**
- **IEEE 802.11 standards define MAC protocol; unlicensed frequency spectrum bands: 900Mhz, 2.4Ghz**
- **Like a bridged LAN (flat MAC address)**



IEEE 802.11 MAC Protocol

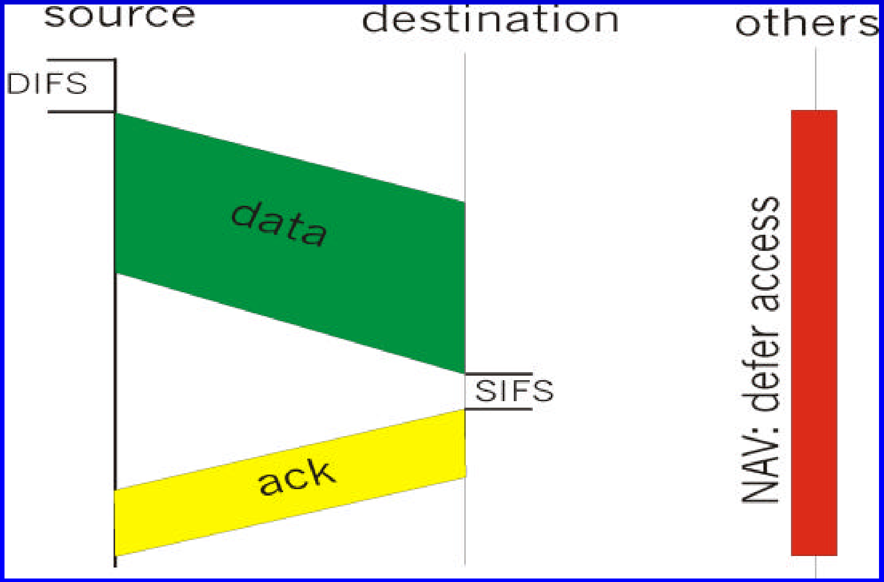
CSMA Version of the Protocol:

sense channel idle for DISF sec (Distributed Inter Frame Space)

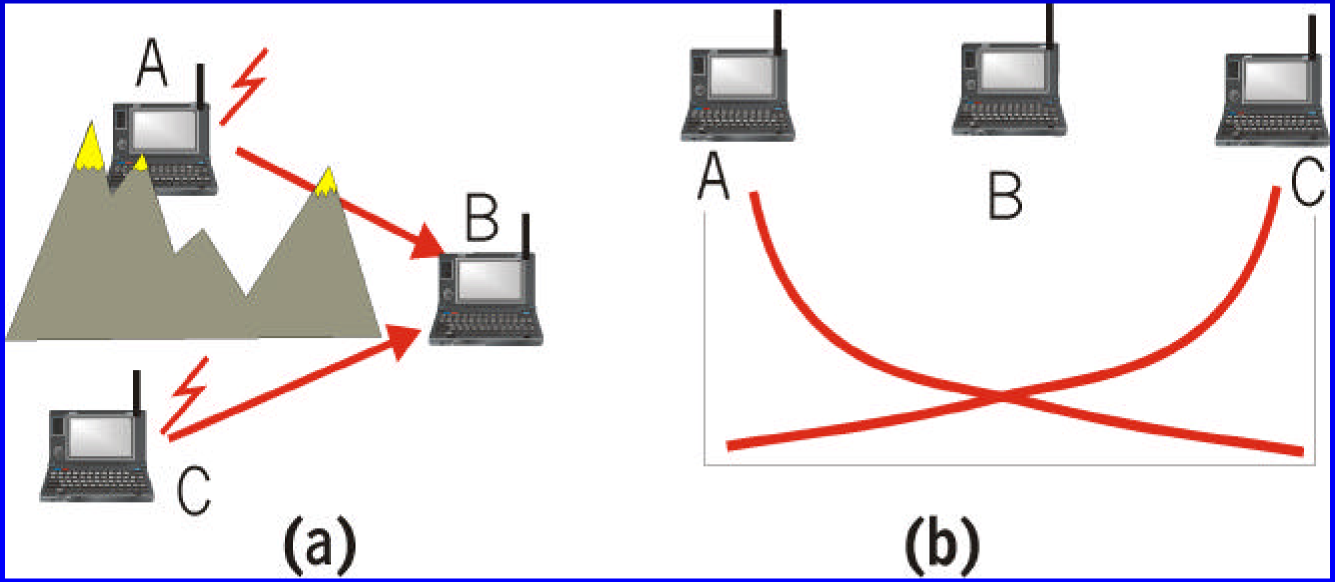
- **transmit frame (no Collision Detection)**
- **receiver returns ACK after SIFS (Short Inter Frame Space)**

if channel sensed busy => binary backoff

NAV: Network Allocation Vector (min time of deferral)

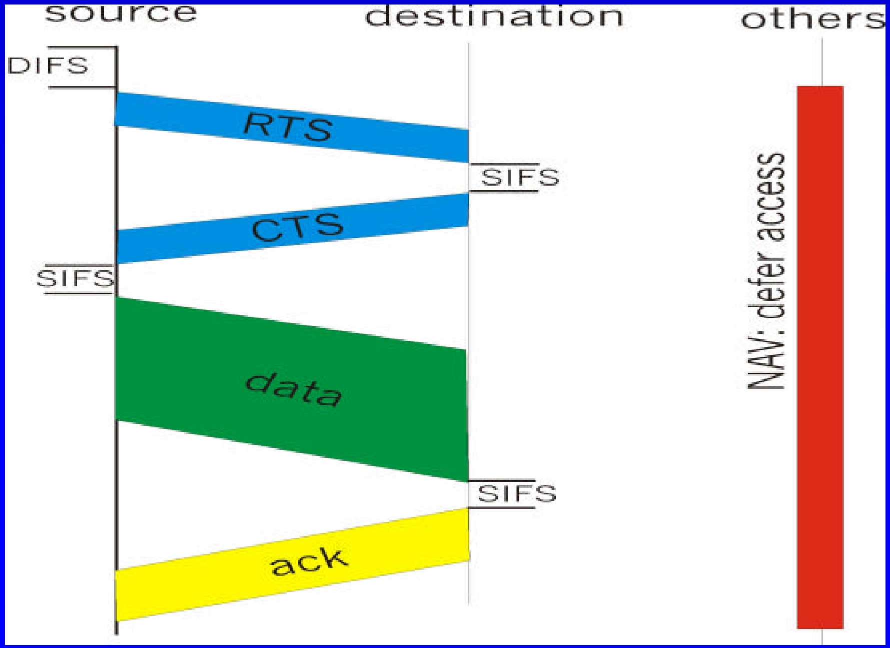


Hidden Terminal effect

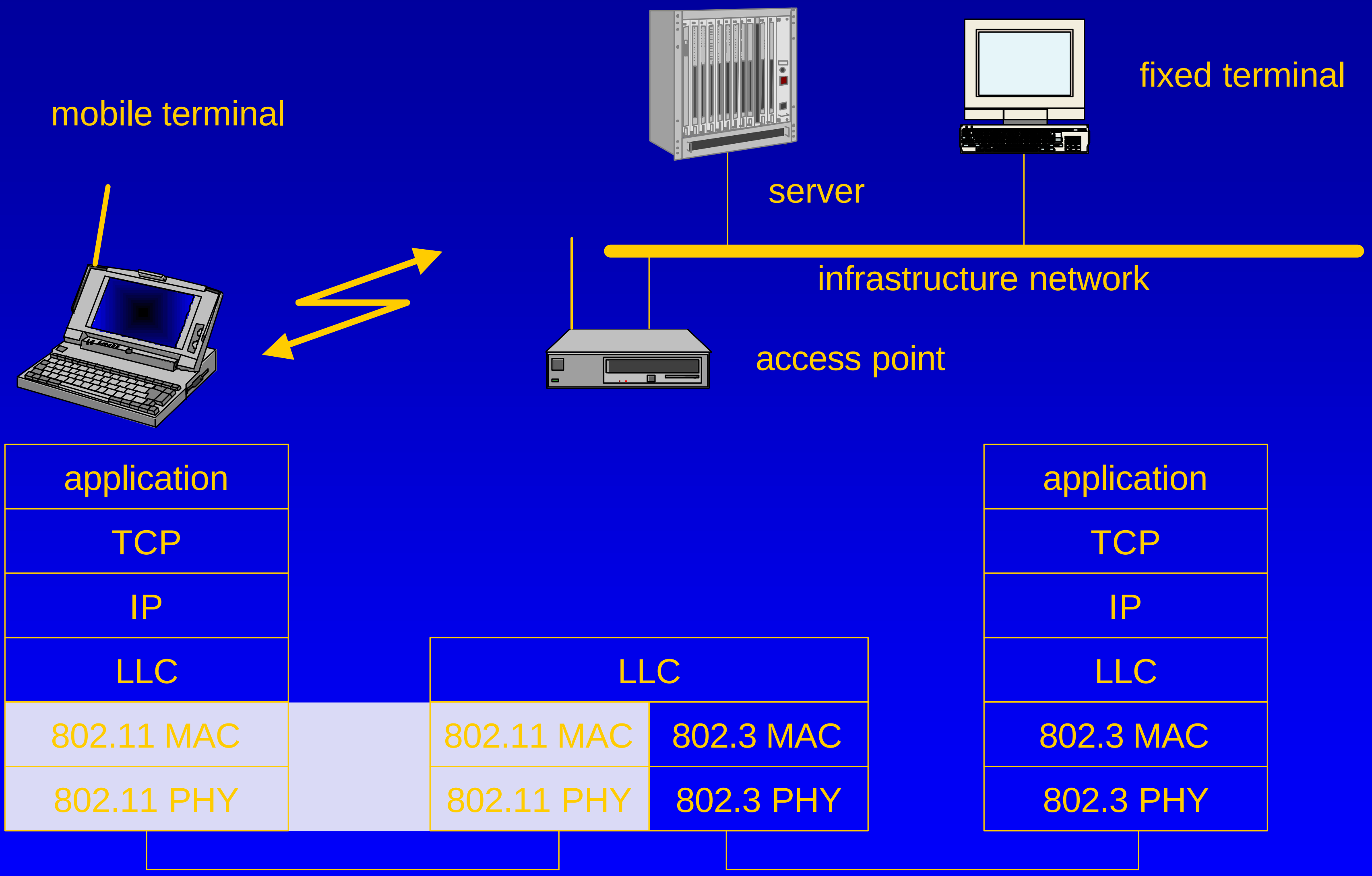
- **CSMA inefficient in presence of hidden terminals**
- **Hidden terminals: A and B cannot hear each other because of obstacles or signal attenuation; so, their packets collide at B**
- **Solution?** CSMA/CA
- 

Collision Avoidance

- RTS freezes stations near the transmitter
- CTS "freezes" stations within range of receiver (but possibly hidden from transmitter); this prevents collisions by hidden station during data transfer
- RTS and CTS are very short: collisions during data phase are thus very unlikely (similar effect as Collision Detection)
- Note: IEEE 802.11 allows CSMA, CSMA/CA and "polling" from AP



IEEE standard: 802.11



802.11 - Physical layer

- **3 versions: 2 radio (.9, 2.4, 5.7 GHz), 1 IR**

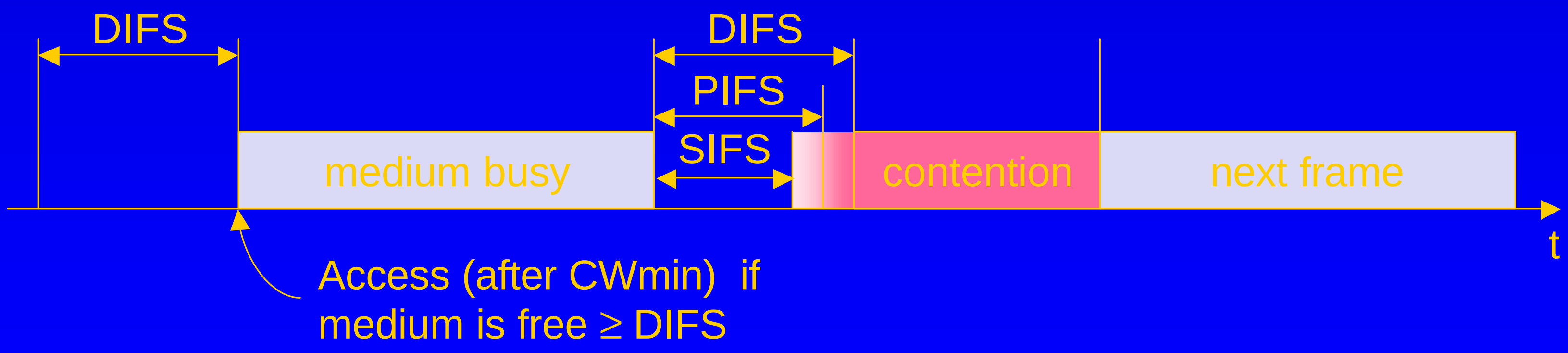
- **FHSS (Frequency Hopping Spread Spectrum)**
  - spreading, despreading, signal strength, typ. 1 Mbit/s
  - min. 2.5 frequency hops/s (USA), two-level GFSK modulation
- **DSSS (Direct Sequence Spread Spectrum)**
  - DBPSK modulation for 1 Mbit/s (Differential Binary Phase Shift Keying), DQPSK for 2 Mbit/s (Differential Quadrature PSK)
  - preamble and header of a frame is always transmitted with 1 Mbit/s, rest of transmission 1 or 2 Mbit/s
  - max. radiated power 1 W (USA), 100 mW (EU), min. 1mW
- **Infrared**
  - 850-950 nm, diffuse light, typ. 10 m range
  - carrier detection, energy detection, synchronization

802.11 - MAC layer

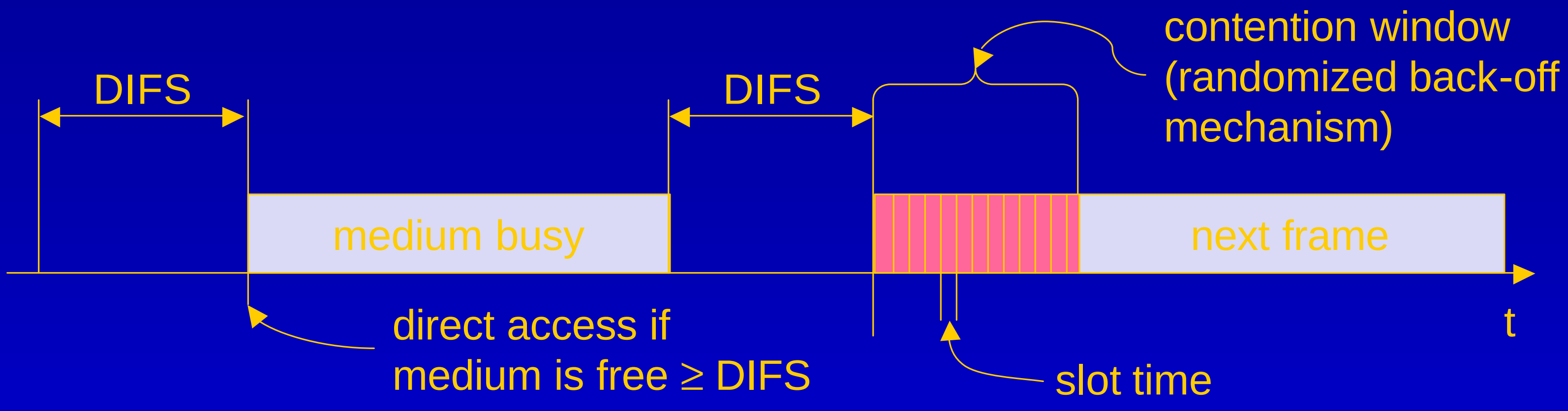
- Access methods
  - MAC-DCF CSMA/CA (mandatory)
    - collision avoidance via randomized „back-off“ mechanism
    - minimum distance between consecutive packets
    - ACK packet for acknowledgements (not for broadcasts)
  - MAC-DCF w/ RTS/CTS (optional)
    - Distributed Foundation Wireless MAC
    - avoids hidden terminal problem
  - MAC- PCF (optional)
    - access point polls terminals according to a list

802.11 - MAC layer (cont)

- **Priorities**
  - defined through different inter frame spaces
  - no guaranteed, hard priorities
  - SIFS (Short Inter Frame Spacing)
    - highest priority, for ACK, CTS, polling response
  - PIFS (PCF IFS)
    - medium priority, for time-bounded service using PCF
  - DIFS (DCF, Distributed Coordination Function IFS)
    - lowest priority, for asynchronous data service



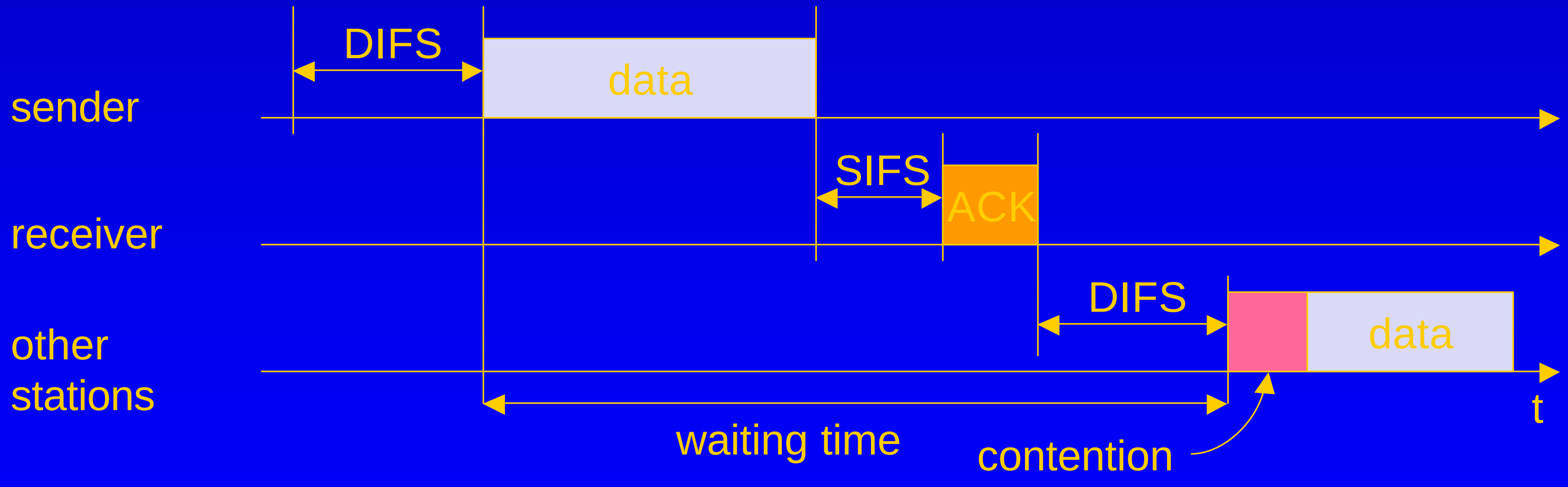
802.11 - CSMA/CA basic access method



- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending after CWmin (IFS depends on packet type)
- if the medium is busy, the station has to wait for a free IFS, then the station must additionally wait a random back-off time (collision avoidance, multiple of slot-time)
- if another station occupies the medium during the back-off time of the station, the back-off timer stops (fairness)

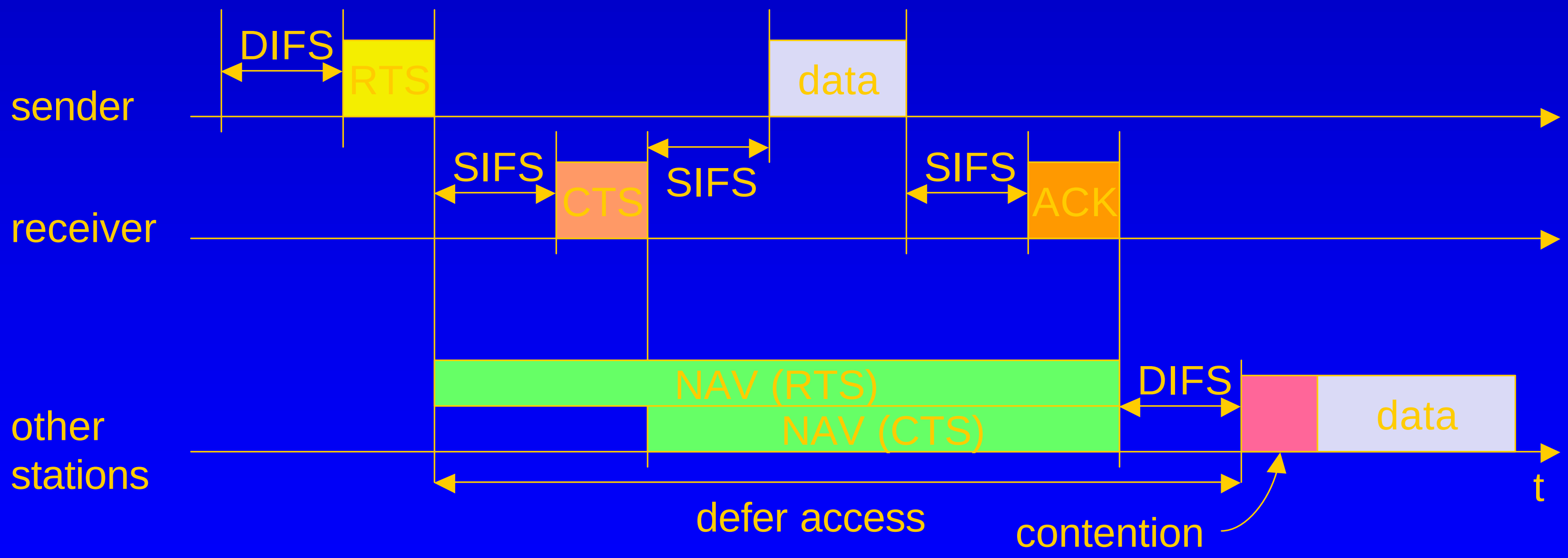
802.11 - CSMA/CA (cont)

- **Sending unicast packets**
  - station has to wait for DIFS (and CWmin) before sending data
  - receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
  - automatic retransmission of data packets in case of transmission errors

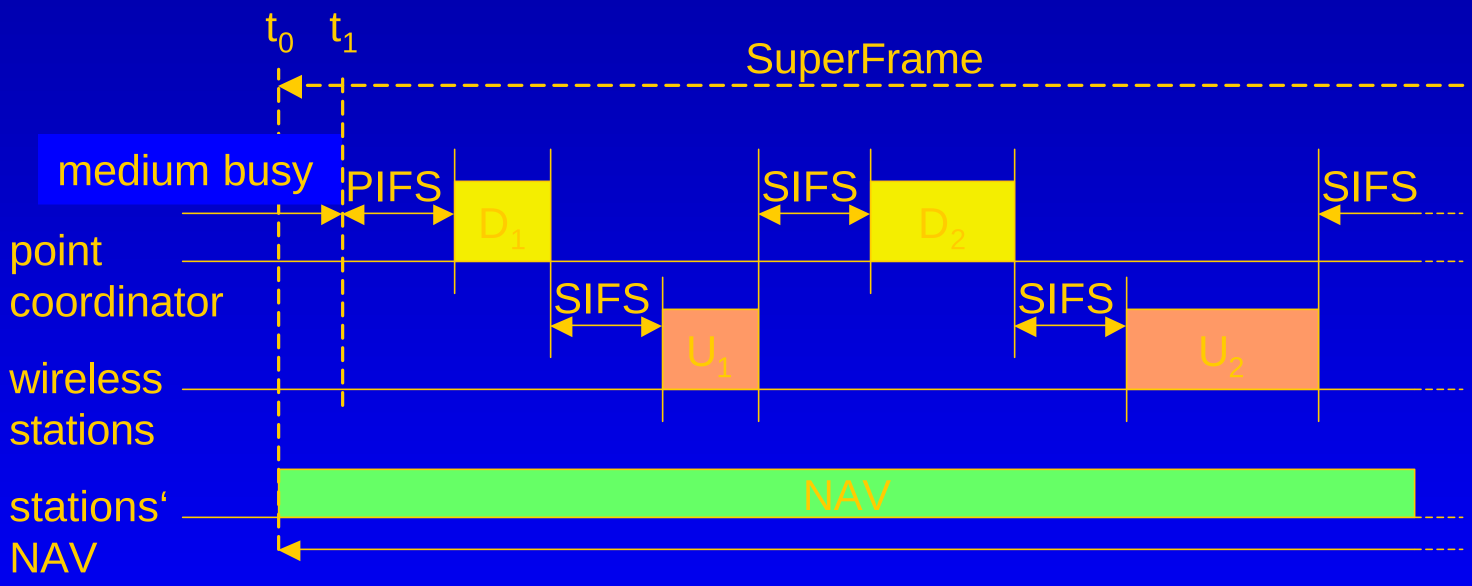


802.11 - CSMA/CA with RTS/CTS

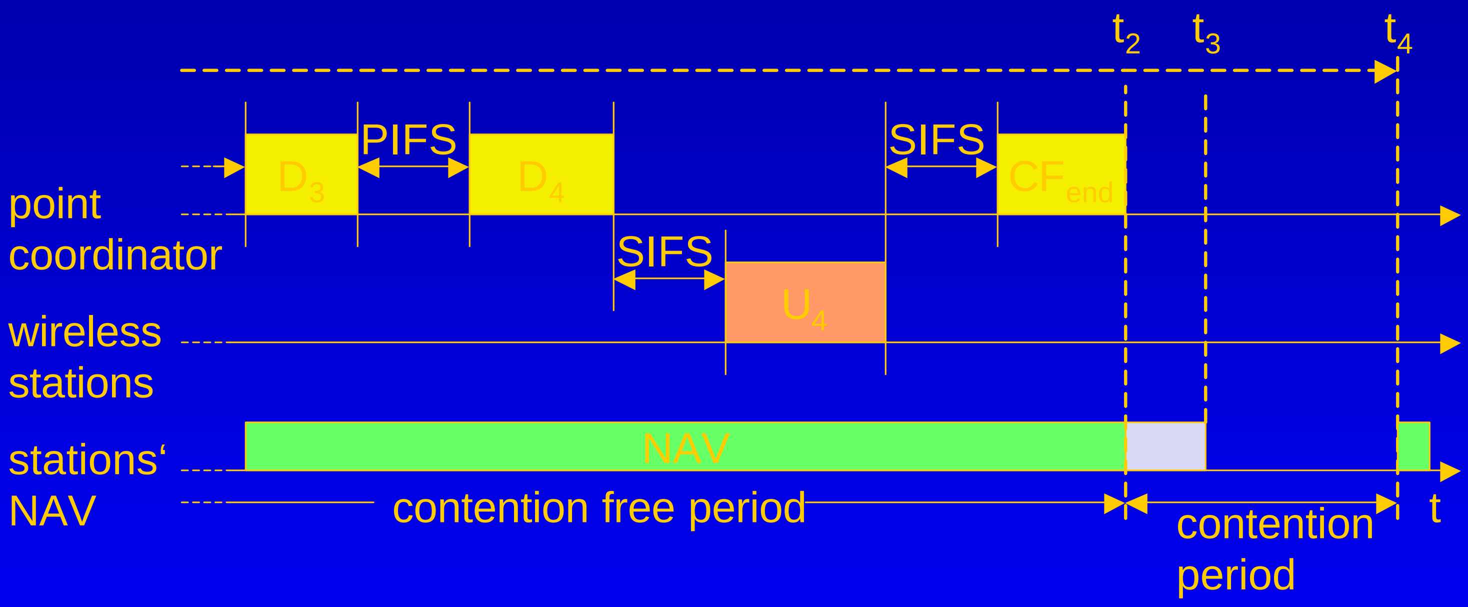
- **Sending unicast packets**
  - station can send RTS with reservation parameter after waiting for DIFS (reservation declares amount of time the data packet needs the medium)
  - acknowledgement via CTS after SIFS by receiver (if ready to receive)
  - sender can now send data at once, acknowledgement via ACK
  - other stations store medium reservations distributed via RTS and CTS



MAC-PCF (Point Coordination Function) like polling



MAC-PCF (cont)


t2
t3
t4
PIFS
SIFS
D3
D4
CFend
point coordinator
SIFS
U4
wireless stations
stations' NAV
NAV
contention free period
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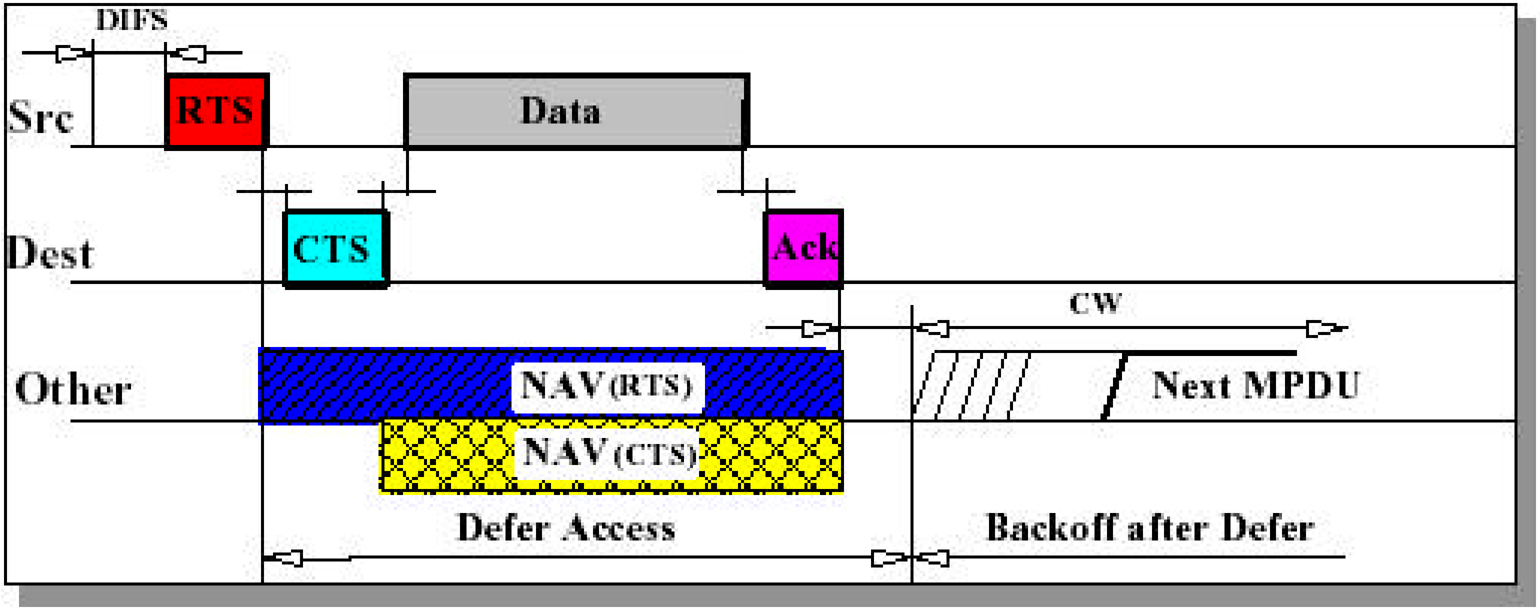
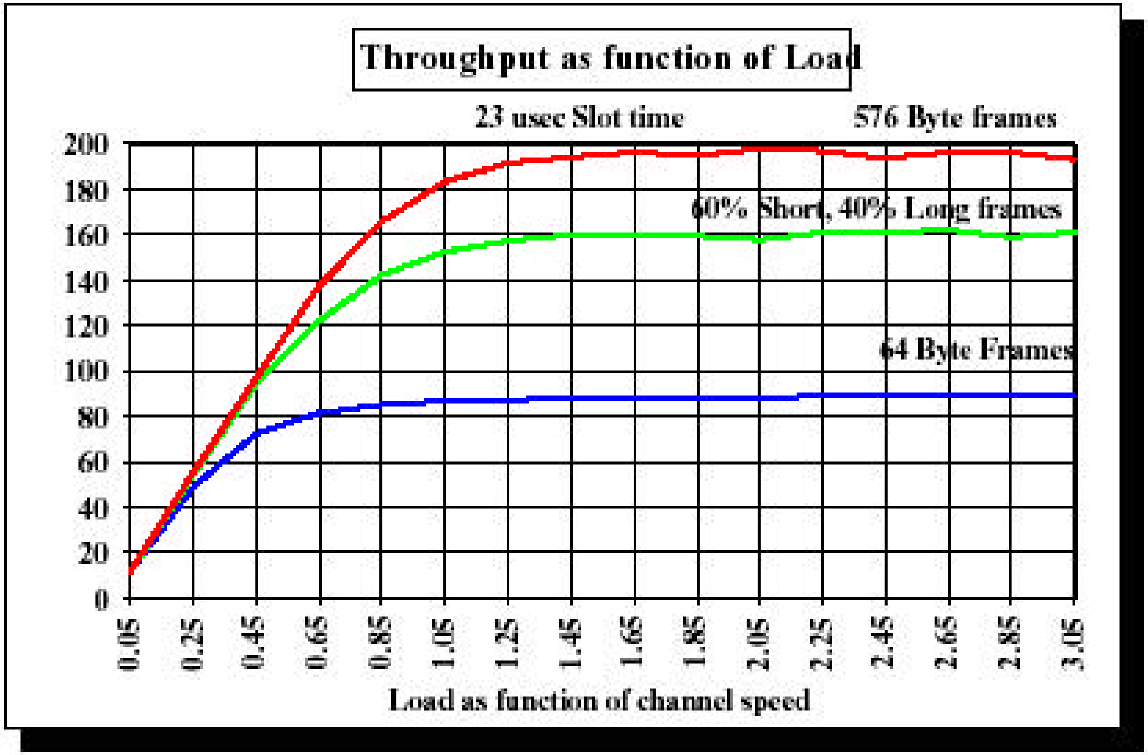
t

"Hidden Node" Provisions



- *Duration* field in RTS and CTS frames distribute *Medium Reservation* information which is stored in a ***Net Allocation Vector (NAV)***.
- Defer on either NAV or "CCA" indicating ***Medium Busy***.
- Use of RTS / CTS is optional but must be implemented.
- Use is controlled by a *RTS_Threshold* parameter per station.
  - To limit overhead for short frames.

Throughput Efficiency



- Efficient and stable throughput.
  - Stable throughput at overload conditions.
  - To support "Bursty Traffic" characteristics.

Frame Formats

Bytes:	2	2	6	6	6	2	6	0-2312	4
	Frame Control	Duration ID	Addr 1	Addr 2	Addr 3	Sequence Control	Addr 4	Frame Body	CRC

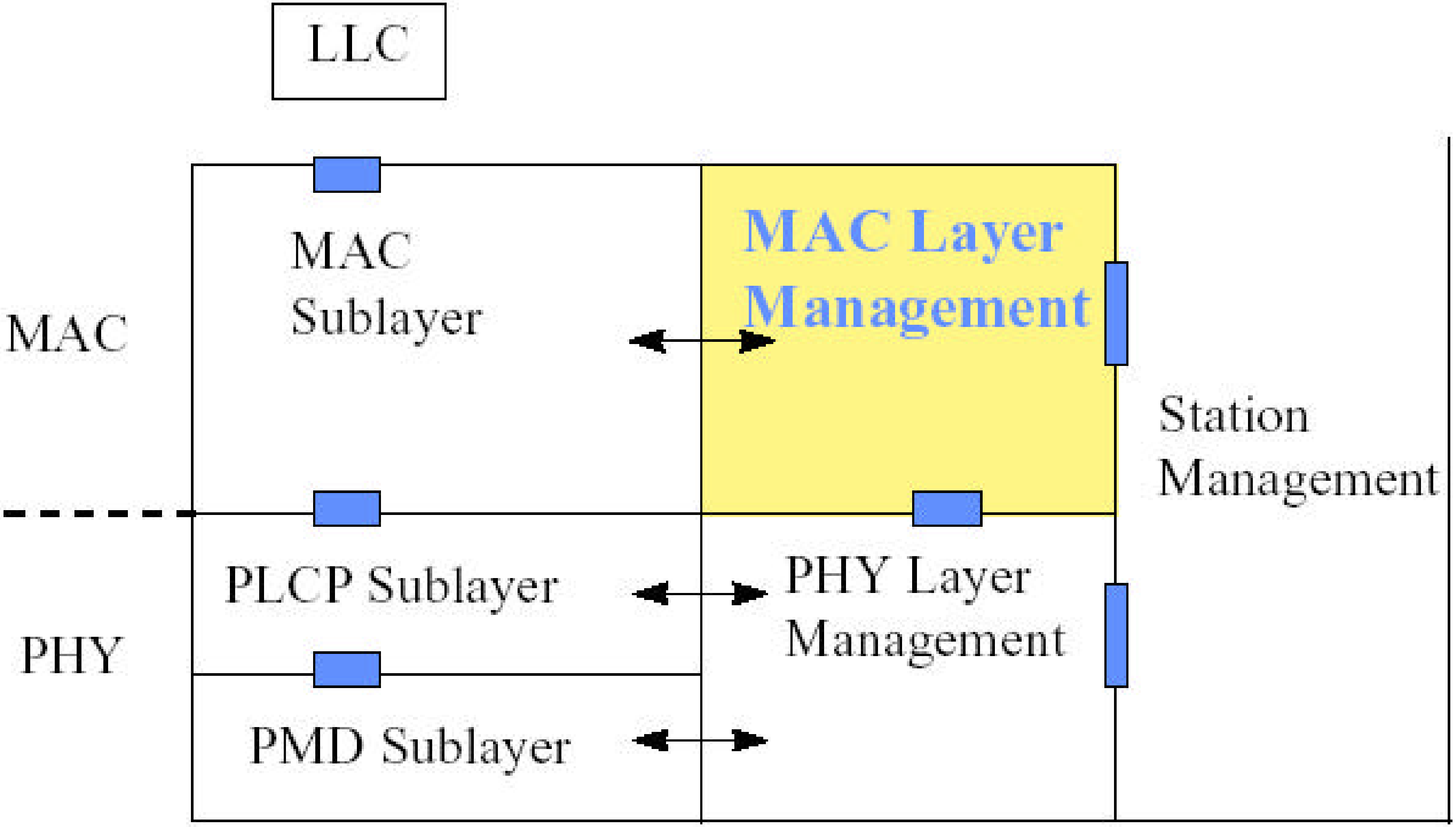
802.11 MAC Header

Bits:	2	2	4	1	1	1	1	1	1	1	1
	Protocol Version	Type	SubType	To DS	From DS	More Frag	Retry	Pwr Mgt	More Data	WEP	Rsvd

Frame Control Field

- MAC Header format differs per Type:
  - Control Frames (several fields are omitted)
  - Management Frames
  - Data Frames
- Includes Sequence Control Field for filtering of duplicate caused by ACK mechanism.

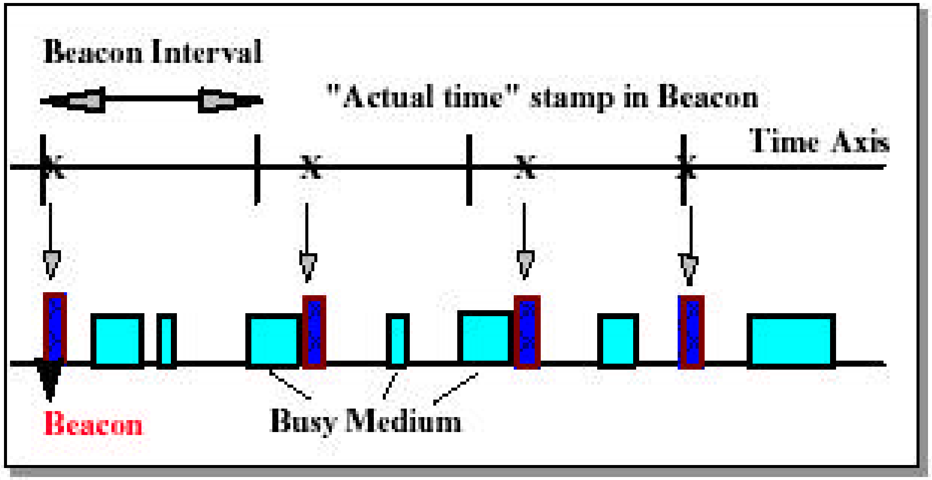
Support for Mobility



Synchronization in 802.11

- Timing Synchronization Function (TSF)
- Used for Power Management
  - Beacons sent at well known intervals
  - All station timers in BSS are synchronized
- Used for Point Coordination Timing
  - TSF Timer used to predict start of Contention Free burst
- Used for Hop Timing for FH PHY
  - TSF Timer used to time Dwell Interval
  - All Stations are synchronized, so they hop at same time.

Infrastructure Beacon Generation

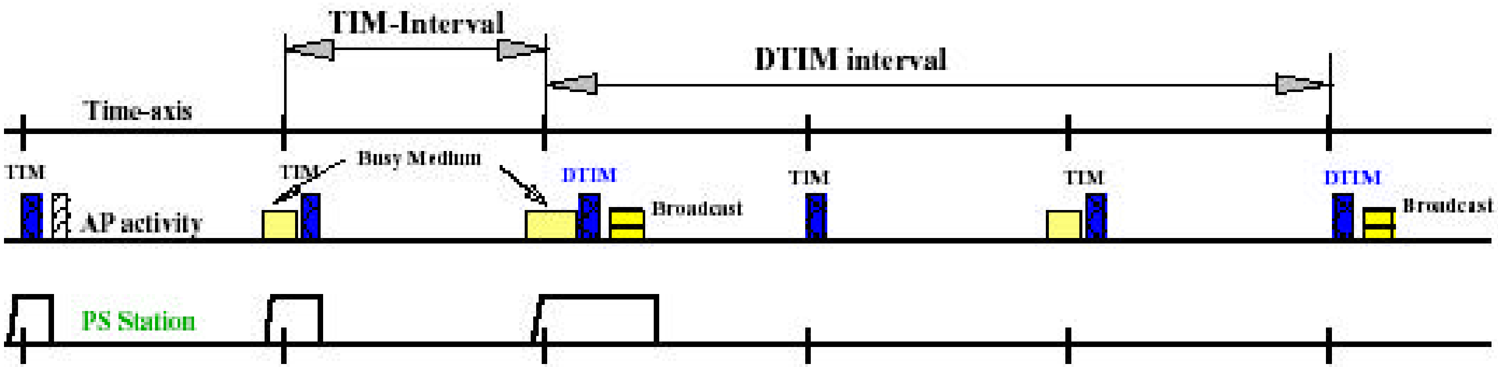


- APs send Beacons in infrastructure networks.
- Beacons scheduled at Beacon Interval.
- Transmission may be delayed by CSMA deferral.
  - subsequent transmissions at expected Beacon Interval
  - not relative to last Beacon transmission
  - next Beacon sent at Target Beacon Transmission Time
- Timestamp contains timer value at transmit time.

Power Management Approach

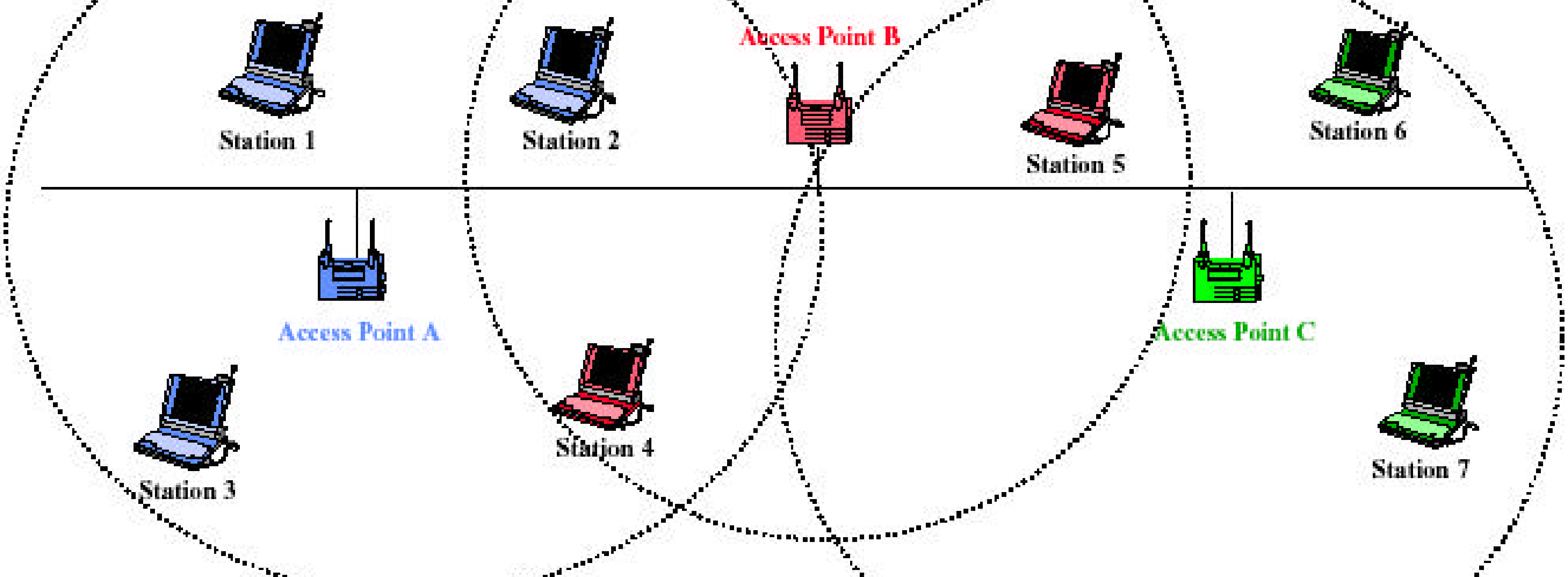
- **Allow idle stations to go to sleep**
  - station's power save mode stored in AP
- **APs buffer packets for sleeping stations.**
  - AP announces which stations have frames buffered
  - Traffic Indication Map (TIM) sent with every Beacon
- **Power Saving stations wake up periodically**
  - listen for Beacons
- **TSF assures AP and Power Save stations are synchronized**
  - stations will wake up to hear a Beacon
  - TSF timer keeps running when stations are sleeping
  - synchronization allows extreme low power operation
- **Independent BSS also have Power Management**
  - similar in concept, distributed approach

Infrastructure Power Management



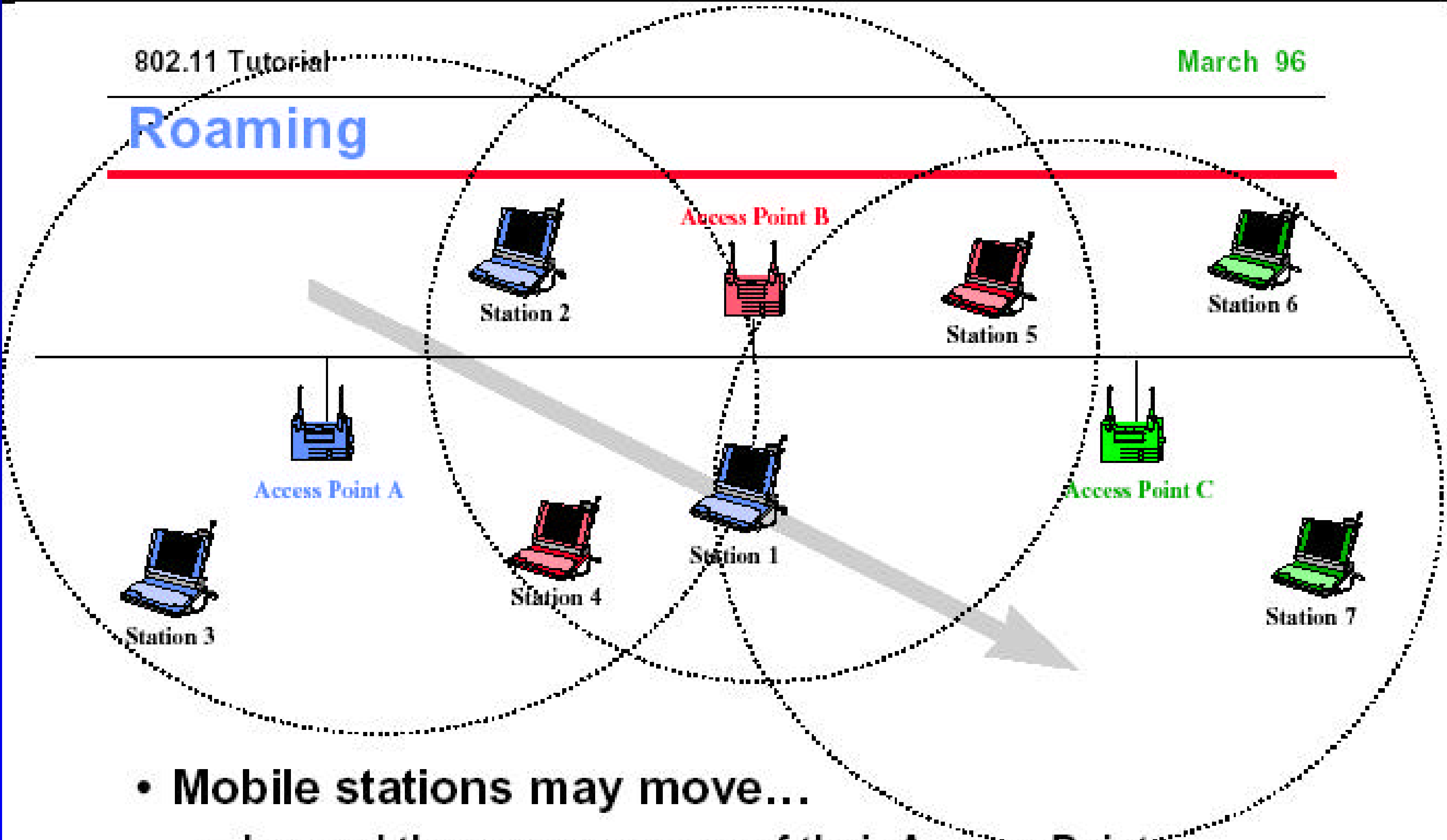
- Broadcast frames are also buffered in AP.
  - all broadcasts/multicasts are buffered
  - broadcasts/multicasts are only sent after DTIM
  - DTIM interval is a multiple of TIM interval
- Stations wake up prior to an expected (D)TIM.

Wireless LAN Infrastructure Network



- Each Station is Associated with a particular AP
  - Stations 1, 2, and 3 are associated with Access Point A
  - Stations 4 and 5 are associated with Access Point B
  - Stations 6 and 7 are associated with Access Point C

Roaming

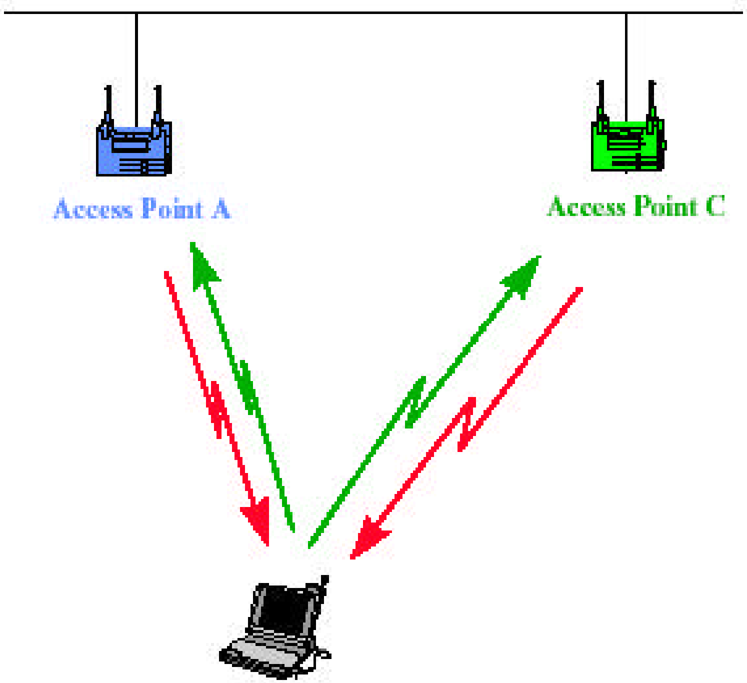


- Mobile stations may move...
  - beyond the coverage area of their Access Point

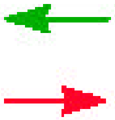
Scanning

- Scanning required for many functions.
  - finding and joining a network
  - finding a new AP while roaming
  - initializing an Independent BSS (ad hoc) network
- 802.11 MAC uses a common mechanism for all PHY.
  - single or multi channel
  - passive or active scanning
- Passive Scanning
  - Find networks simply by listening for Beacons
- Active Scanning
  - On each channel
    - » Send a Probe, Wait for a Probe Response
- Beacon or Probe Response contains information necessary to join new network.

Active Scanning Example



Steps to Association:

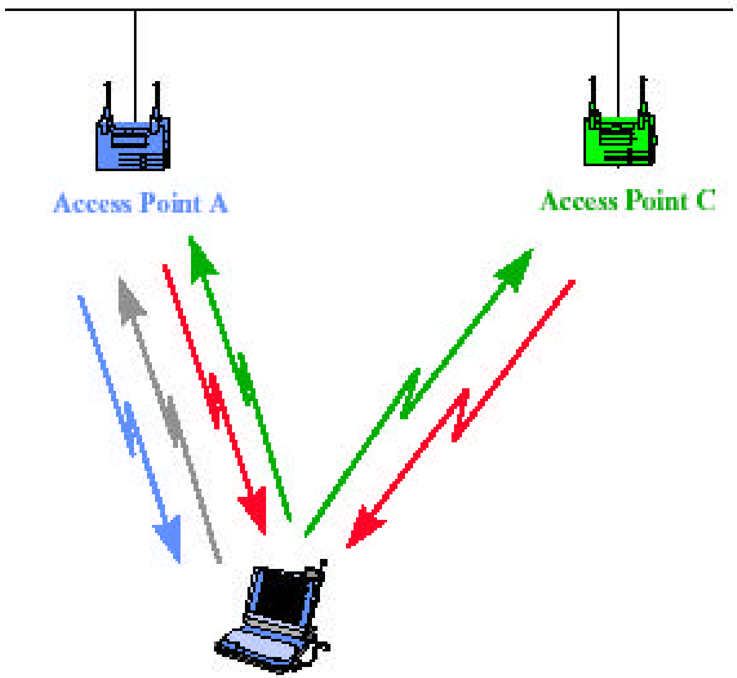


Station sends Probe.

APs send Probe Response.

Initial connection to an Access Point

Active Scanning Example



Steps to Association:

- Station sends Probe.
- APs send Probe Response.
- Station selects best AP.
- Station sends Association Request to selected AP.
- AP sends Association Response.

Initial connection to an Access Point
- ReAssociation follows a similar process

Voice support in IEEE 802.11 (Sobrinho, Krishnakumar Globcom 96)

- DCF mode, with CSMA
- voice has priority over data (short IFS)
- voice users transmit staggered "black bursts", of length proportional to waiting time (ie, speech bytes in buffer)
- voice user who waited longest wins (longest black burst)
- positive ACK guarantees success (no hidden term.)
- voice connections tend to evenly spread out in time frame

Possible Improvement:

- instead of pos ACK, neg ACK (less OH)
- receiver "invites" the sender with neg ACK if did not receive pkt after time out

Higher Speeds?

- **IEEE 802.11a**
  - compatible MAC, but now 5.8 GHz ISM band
  - transmission rates up to 50 Mbit/s
  - close cooperation with BRAN (ETSI Broadband Radio Access Network)
- **IEEE 802.11 g: up to 50Mbps, in the 2.5 range**
- **IEEE 802.11 n: up to 100 Mbps, using OFDM and MIMO technologies**

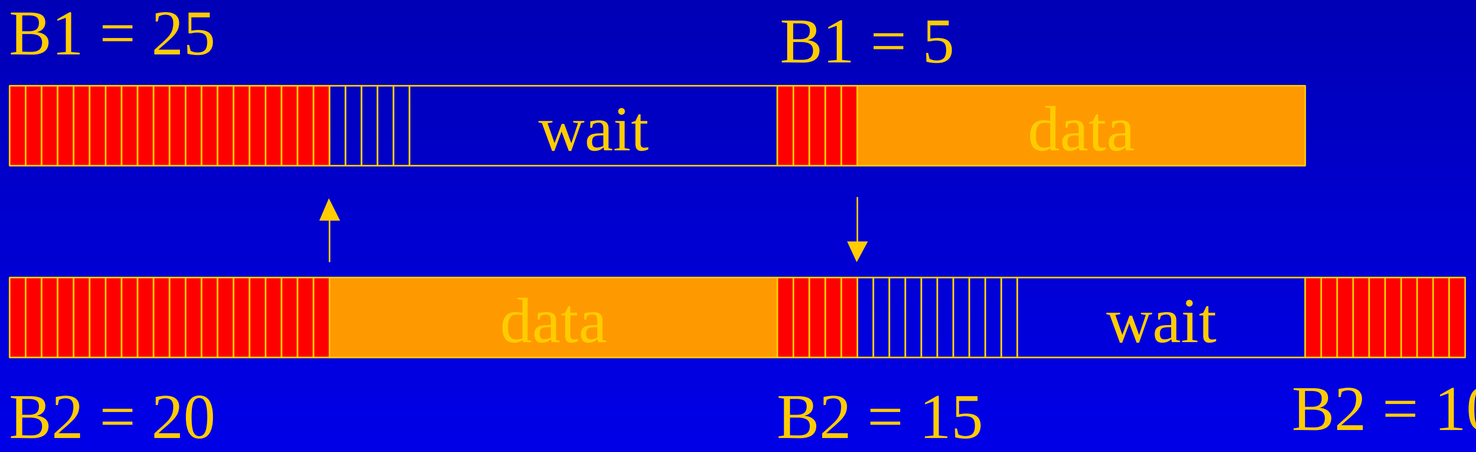
CSMA/CA Protocol: congestion control and fairness

Congestion Avoidance:
IEEE 802.1 DCF

- **Before transmitting a packet, randomly choose a backoff interval in the range [0,cw]**
  - cw is the contention window
- **"Count down" the backoff interval when medium is idle**
  - Count-down is suspended if medium becomes busy
- **When backoff interval reaches 0, transmit packet (or RTS)**

DCF Example

Let cw = 31



B1 and B2 are backoff intervals at nodes 1 and 2

Congestion Avoidance

- The time spent counting down backoff intervals contributes to MAC overhead

- Choosing a *large cw* leads to large backoff intervals and can result in larger overhead

- Choosing a *small cw* leads to a larger number of collisions (more likely that two nodes count down to 0 simultaneously)

Congestion Control

- **Since the number of nodes attempting to transmit simultaneously may change with time, some mechanism to manage congestion is needed**

- **IEEE 802.11 DCF: Congestion control achieved by dynamically adjusting the contention window *cw***

Binary Exponential Backoff in DCF

- **When a node fails to receive CTS in response to its RTS, it increases the contention window**
  - *cw* is doubled (up to an upper bound – typically 5 times)
- **When a node successfully completes a data transfer, it restores *cw* to CW_{min}**

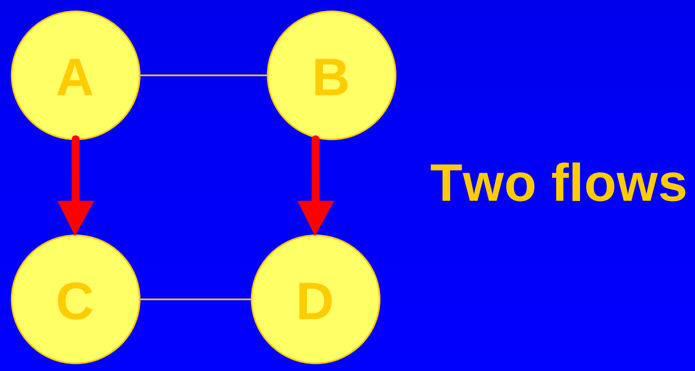
MILD Algorithm in MACAW [Bharghavan94Sigcomm]

- **When a node fails to receive CTS in response to its RTS, it multiplies *cw* by 1.5**
  - Less aggressive than 802.11, which multiplies by 2
- **When a node successfully completes a transfer, it reduces *cw* by 1**
  - More conservative than 802.11, where cw is restored to Cw_{min}
  - 802.11 reduces cw much faster than it increases it
  - MACAW: cw reduction slower than the increase

    Exponential Increase Linear Decrease
- **MACAW can avoid wild oscillations of cw when congestion is high**

Fairness Issue

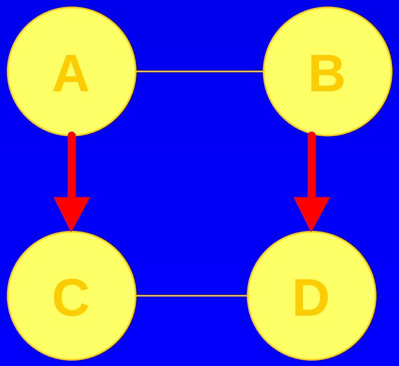
- Many definitions of fairness plausible
- Simplest definition: All nodes should receive *equal* bandwidth



Fairness Issue

- **Assume that initially, A and B both choose a backoff interval in range [0,31] but their RTSs collide**

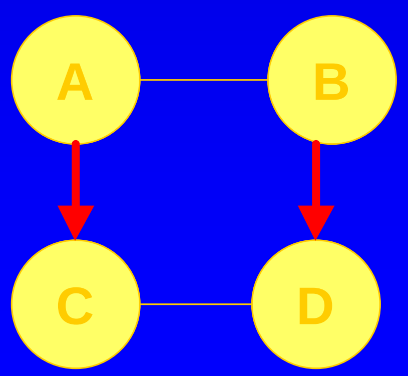
- **Nodes A and B then choose from range [0,63]**
  - Node A chooses 4 slots and B choose 60 slots
  - After A transmits a packet, it next chooses from range [0,31]
  - It is possible that A may transmit several packets before B transmits its first packet



Two flows

Fairness Issue

- Observation: unfairness occurs when one node has backed off much more than some other node



Two flows

MACAW Solution for Fairness

- When a node transmits a packet, it appends its current *cw* value to the packet
- All nodes hearing that *cw* value use it for their future transmission attempts
- The effect is to reset all competing nodes to the same ground rule

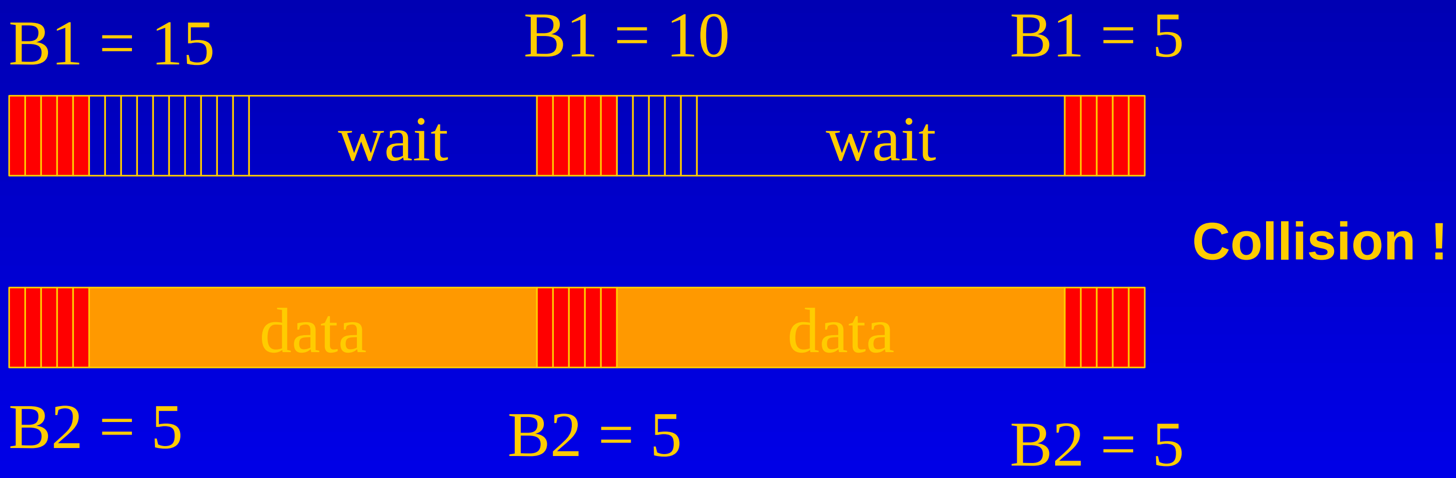
Weighted Fair Queueing

- Assign a weight to each node
- Goal: bandwidth used by each node should be proportional to the weight assigned to the node

Distributed Fair Scheduling (DFS) [Vaidya00Mobicom]

- A fully distributed algorithm for achieving weighted fair queueing
- Chooses backoff intervals proportional to *(packet size / weight)*
- DFS attempts to mimic the centralized Self-Clocked Fair Queueing algorithm [Golestani]
- Works well on a LAN

Distributed Fair Scheduling (DFS)



Weight of node 1 = 1
Weight of node 2 = 3

Assume equal packet size

B1 = 15 **(DFS actually picks a random value with mean 15)**

B2 = 5 **(DFS picks a value with mean 5)**