# Medium Access Control

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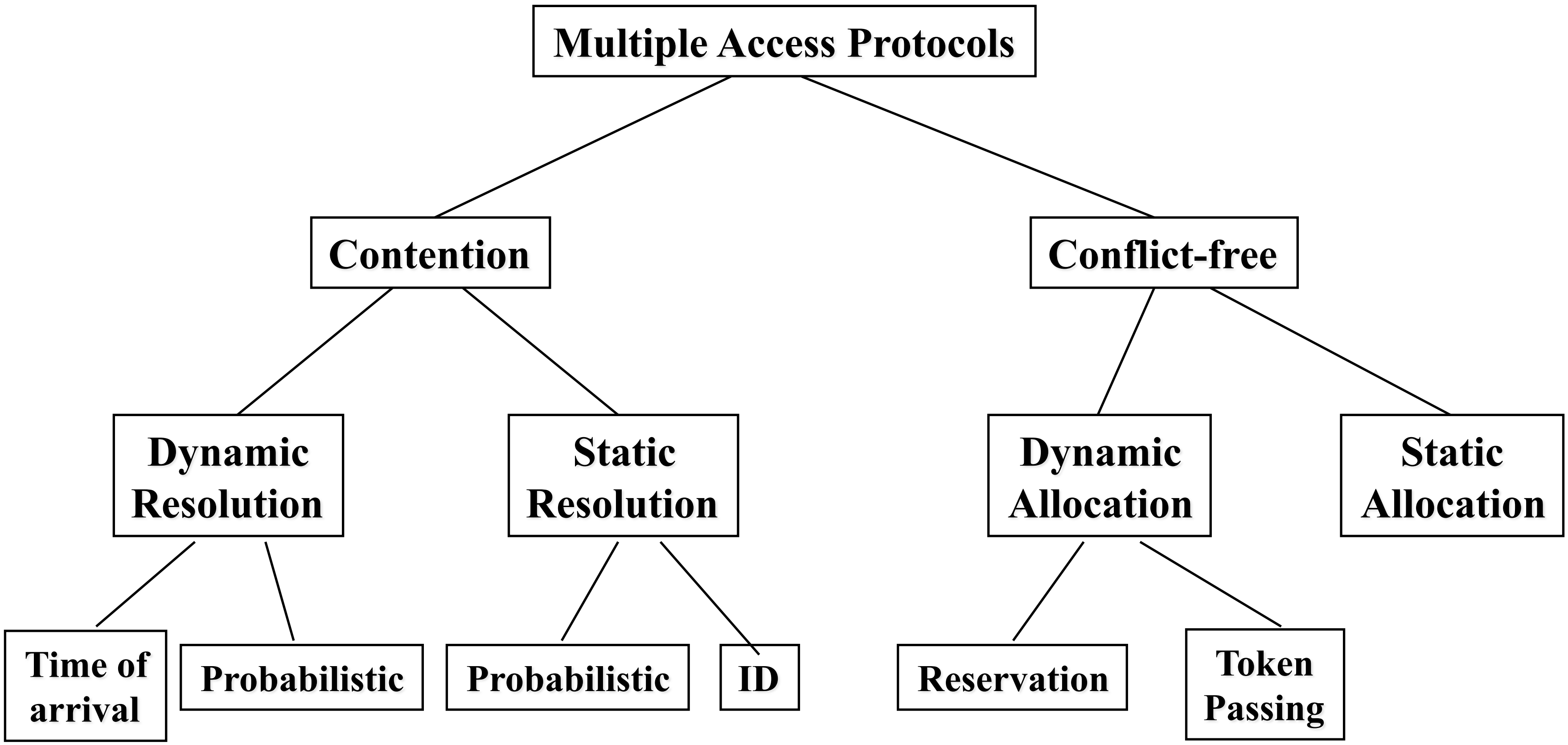
CS4700 CS5700

# Multiple Access Schemes: Summary

- Stations can communicate if they use different combinations of: frequency, time slot, code, location, polarization
  - Note: it is not always possible to implement all these access schemes
- An atomic resource can be defined as:
  - (freq, time-slot, code, location, polarization)
  - The simultaneous use of an atomic resource results in a "collision" and loss of packets
- Medium Access Protocols define the rules for stations to share these resources
- Algorithms for MAC can be used in other contexts
  - distributed systems (*e.g.,* databases)

# Medium Access Control Protocols



# MAC Protocols: Evaluation

- Throughput
- Delay
- Buffering
- Stability

We also generally assume that:

- – channel is errorless
- – a feedback is available

# Slotted Aloha [Abramson1970]

- History: developed by the University of Hawaii to connect data terminals to a central computer using radio channels
- Assumptions on an ideal *slotted* multi-access model:
  - Slotted system (discrete system, no sensing)
  - Poisson arrivals on each node: $\lambda/m$ ($m$ is the number of nodes)
    - Prob(i arrivals within t units of time) = $(\lambda t)^i e^{-\lambda i}/i!$
    - Poisson process is basically a Bernouilli trial in the limit
  - Collision or perfect reception
  - Feedback: 0, 1, collision; no sensing
  - Retransmissions: colliding packets are retransmitted until successfully received ( => backlogged nodes)
  - Buffering options:
    - No buffering: packets arriving at backlogged nodes are discarded
    - Infinite set of nodes ($m \rightarrow \infty$): packets always arrive at new nodes

# Slotted Aloha Algorithm

- Unbacklogged nodes transmit a newly arriving packet in the first slot after the packet arrival

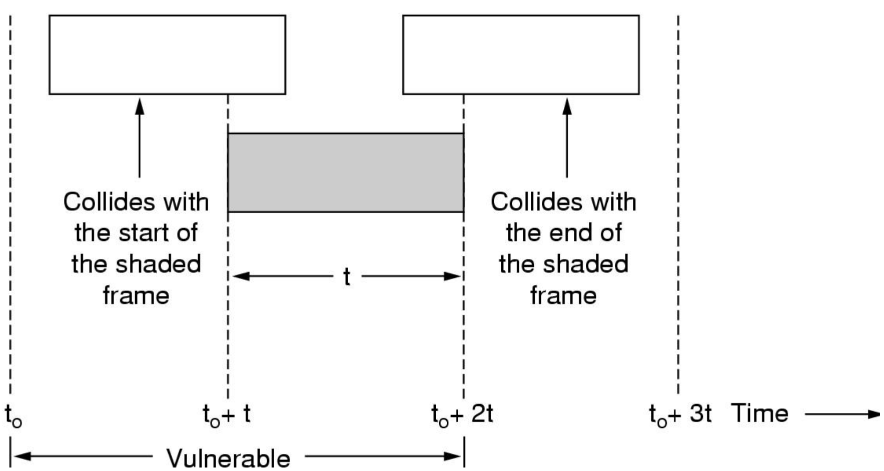
- When a collision occurs, each node sending one of the colliding packets becomes backlogged. Backlogged nodes wait for a random number of slots before retransmitting. Full analysis considers separate retransmissions probability

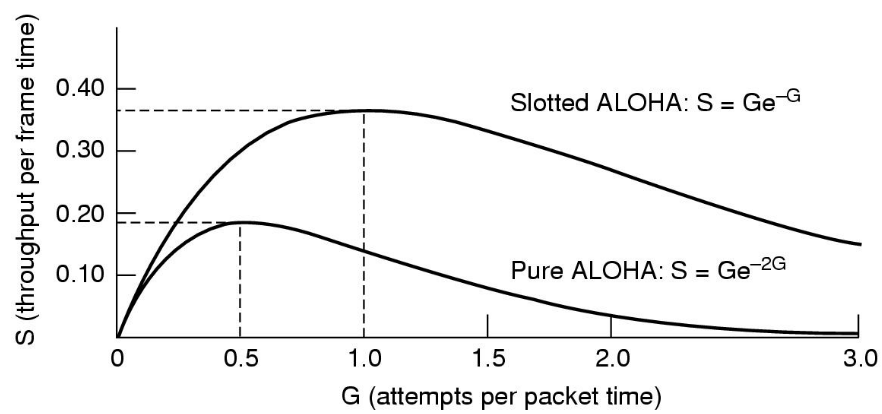
# Performance of Slotted Aloha

- Simplified analysis:
  - Assumption: retransmissions from backlogged nodes are sufficiently randomized to approximate the total transmission by a Poisson process of rate $G > \lambda$.
  - Probability of successful transmission: $Ge^{-G}$
  - In equilibrium: arrival rate should be equal to departure rate
  - Maximum possible departure rate occurs at $G = 1$ => departure rate = $1/e$.
- This analysis doesn't take into account the dynamic of the system: $G$ changes as a function of the number of backlogged nodes. However it correctly identifies the maximum achievable throughput, and optimum value for $G$.

# Pure Aloha Protocol

- Packets arrive according to a Poisson process
- Throughput = $Ge^{-2G}$
- Maximum: 1/2e



# Carrier Sense Protocols

Use the fact that in some networks you can *sense* the medium to check whether it is currently free

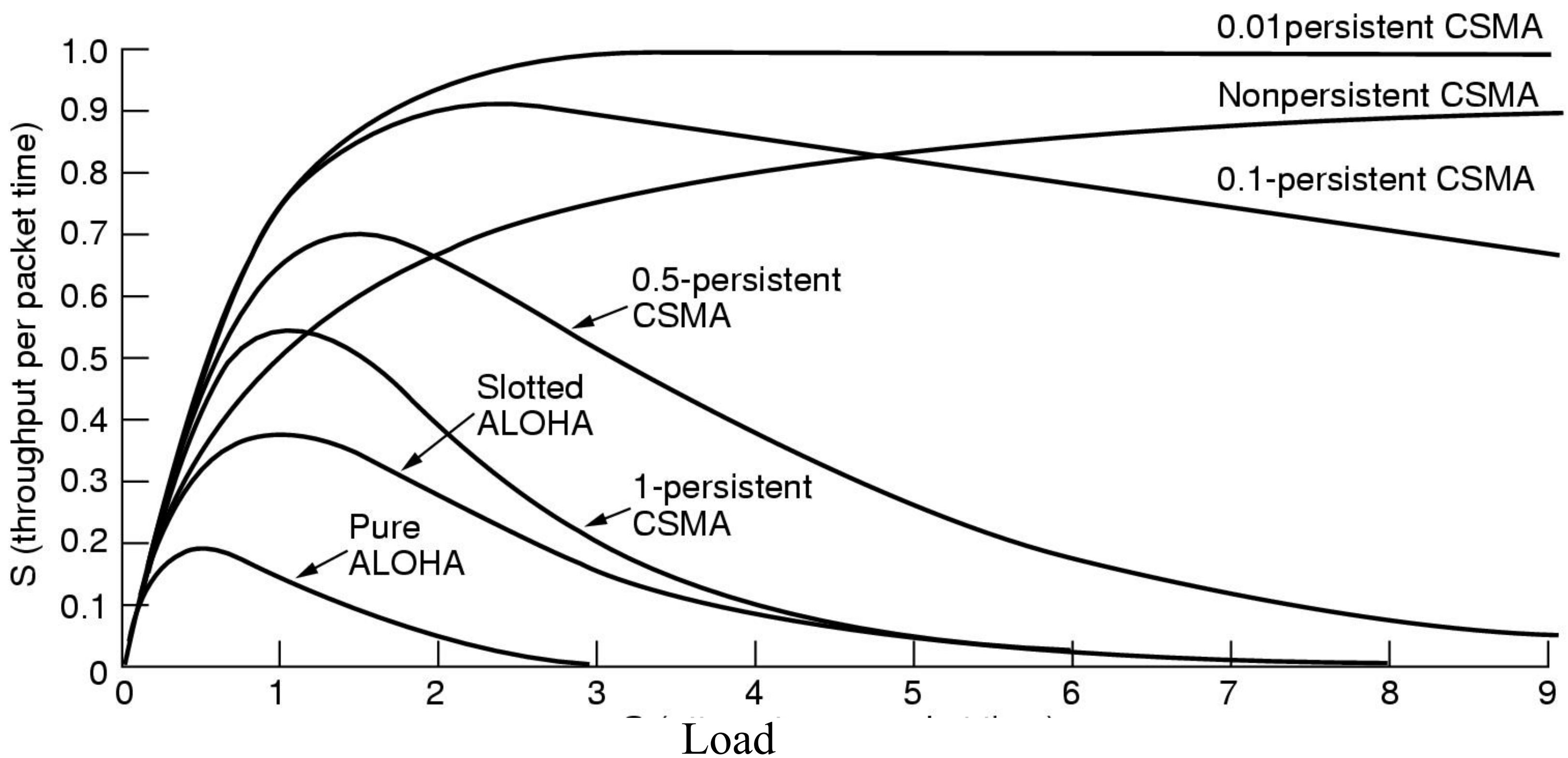
- 1-persistent CSMA
- non-persistent CSMA
- p-persistent protocol
- CSMA with collision Detection (CSMA/CD)

- 1-persistent CSMA
  - when a station has a packet:
    - it waits until the medium is free to transmit the packet
    - if a collision occurs, the station waits a random amount of time
  - first transmission results in a collision if several stations are waiting for the channel

# Carrier Sense Protocols (*Cont'd*)

- non-persistent CSMA
  - when a station has a packet:
    - if the medium is free, transmit the packet
    - otherwise wait for a random period of time and repeat the algorithm
  - higher delays, but better performance than pure ALOHA
- p-persistent protocol
  - when a station has a packet wait until the medium is free:
    - transmit the packet with probability *p*
    - wait for next slot with probability 1-*p*
  - better throughput than other schemes but higher delay
- CSMA with collision Detection (CSMA/CD)
  - stations abort their transmission when they detect a collision
  - e.g., Ethernet, IEEE802.3

# Comparison



0.01persistent CSMA
Nonpersistent CSMA
0.1-persistent CSMA
0.5-persistent
CSMA
Slotted
ALOHA
1-persistent
CSMA
Pure
ALOHA
S (throughput per packet time)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
Load

# Throughputs of Some Random Access Protocols

| **Protocol** | **Throughput** |
|---|---|
| **Pure-ALOHA** | $S = Ge^{-2G}$ |
| **Slotted-ALOHA** | $S = Ge^{-G}$ |
| **Non slotted 1-persistent** | $S = \frac{G[1 + G + aG(1 + G + aG/2)]e^{-G(1+2a)}}{G(1 + 2a) - (1 - e^{-aG}) + (1 + aG)e^{-G(1+a)}}$ |
| **Slotted 1-persistent CSMA** | $S = \frac{G[1 + G - e^{-aG}]e^{-G(1+a)}}{(1 + a) - (1 - e^{-aG}) + ae^{-G(1+a)}}$ |
| **Nonpersistent non slotted CSMA** | $S = \frac{Ge^{-aG}}{(1 + 2a) + e^{-aG}}$ |
| **Nonpersistent slotted CSMA** | $S = \frac{aGe^{-aG}}{1 - e^{-aG} + a}$ |

*G:* load (includes both successful transmissions and retransmissions)

*S*: successful transmission

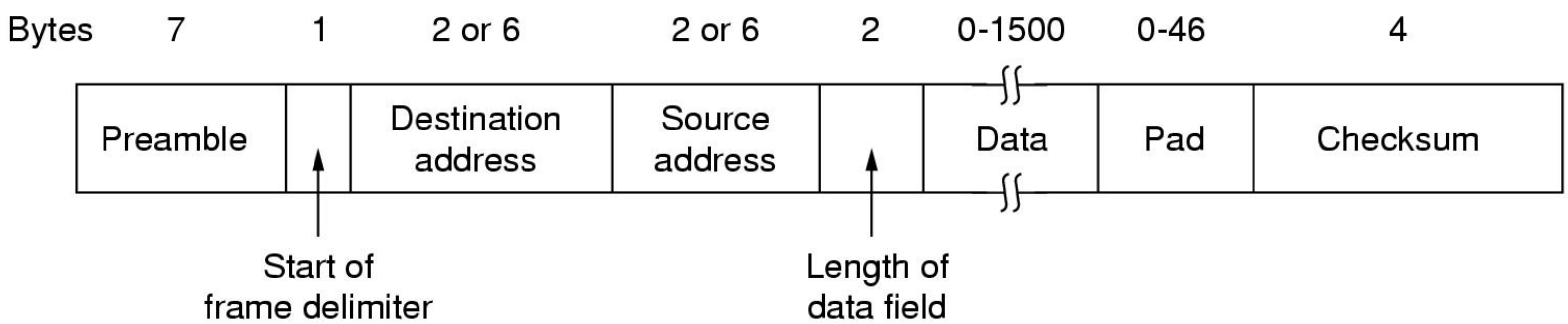
*a:* ratio of propagation delay to the packet transmission delay

# Ethernet

- History: evolution from Aloha, CSMA, CSMA/CD (by Xerox PARC) => Ethernet, => IEEE802.3 (Digital, Intel, Xerox)
  - There are slight differences between Ethernet and 802.3 (e.g., 802.3 length field is used for packet type in Ethernet, various transmission speeds for 802.3 from 1 Mbps to beyond 10 Gbps)
- Physical layer (10Mbps Ethernet):
  - Manchester encoding (bit syncro, no-dc component)
  - Cabling: maximum 500 meters with up to 4 repeaters (max 2500m)

- Physical layer evolved to
  - 100Mbps, 1Gbps, 10Gbps, … 100Gbps
  - Auto-negotiation capability
  - Can also carry power

# Frame Format (IEEE802.3)

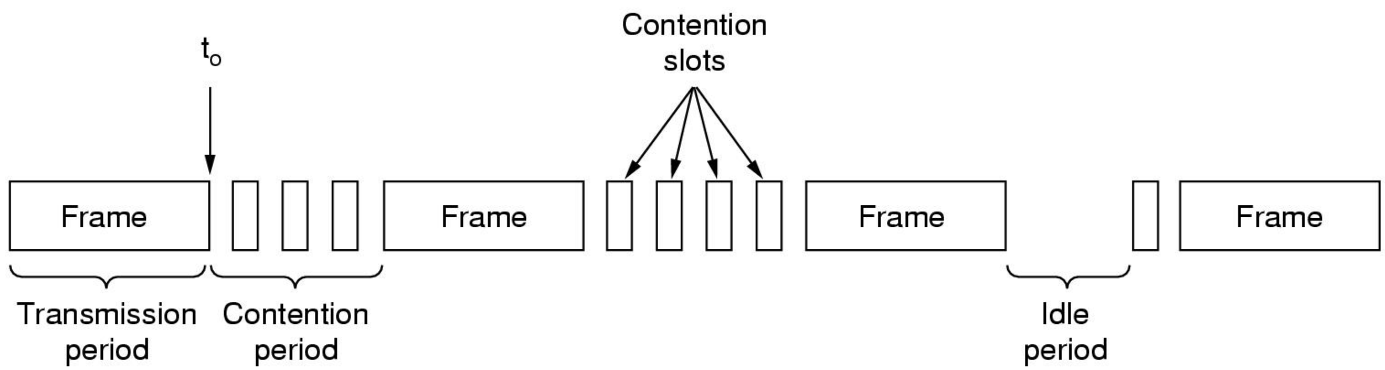



- Preamble : 7x10101010… (allows the receiver's clock to synchronize)
- SF: 10101011
- 10Mbps has only 6 bytes addresses:
  - Unicast: unique per adaptor (ranges are allocated to manufacturers)
  - Broadcast: FF:FF:FF:FF:FF:FF
  - Multicast: first address bit = 1
  - Internet Multicast: 01:00:5e:00:00:00 -to- 01:00:5e:7f:ff:ff
- Pad: minimum frame length of 64 bytes

# Ethernet Algorithm

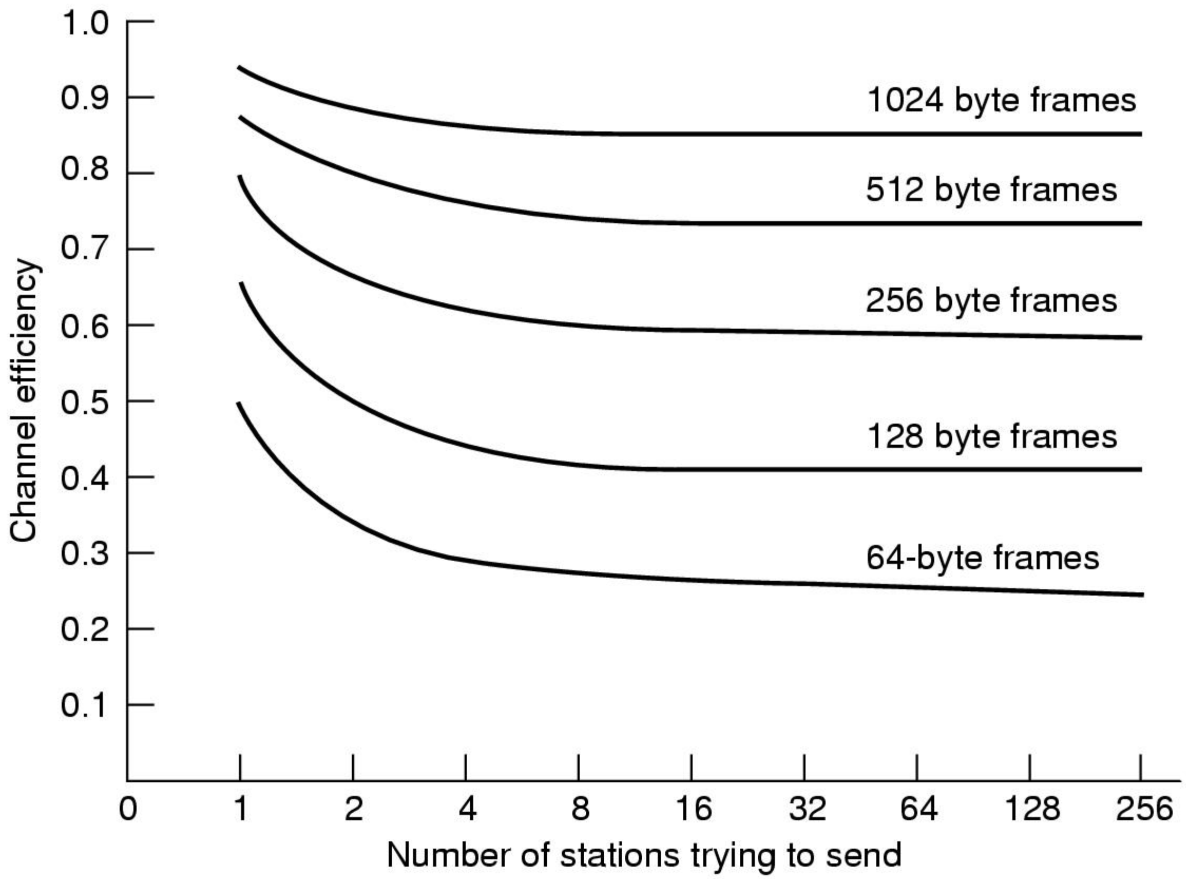
- Receiver: accepts frames with a correct CRC
- Sender: CSMA/CD 1-persistent algorithm
  - If the adaptor has a frame and the line is idle: transmit, otherwise wait until idle line then transmit
  - If a collision occurs:
    - When detected a 32-bit jamming sequence is sent
    - Binary exponential backoff: select a random number $\in [0, 2^i-1]$
    - After ten collisions the randomization interval is frozen to max 1023
    - After 16 collisions the controller throws away the frame
- What is the reasons for having a minimal frame length? (Hint RTT: 51.2$\mu$s)

# Ethernet Performance




- Assume that retransmissions occur with probability *p, k* stations ready to transmit:
  - Probability that a station acquires the channel: $A=kp(1-p)^{k-1}$
  - Maximum: when $p=1/k$, $k\text{->}\infty$ $A\text{->}1/e$
  - Probability that a contention interval has exactly *j* slots is: $A(1-A)^{j-1}$
  - Mean number of slots per contention is: $1/A$
  - Slot duration: $2\tau = 51.2\mu s$
  - Channel efficiency: $P/(P+2\tau/A)$

# Ethernet Performance



# Ethernet Capture Effect

- A and B have a large queue of packets
- There exists a situation were B will keep increasing its backoff interval (and finally dropping its packet) while A is transmitting its packets

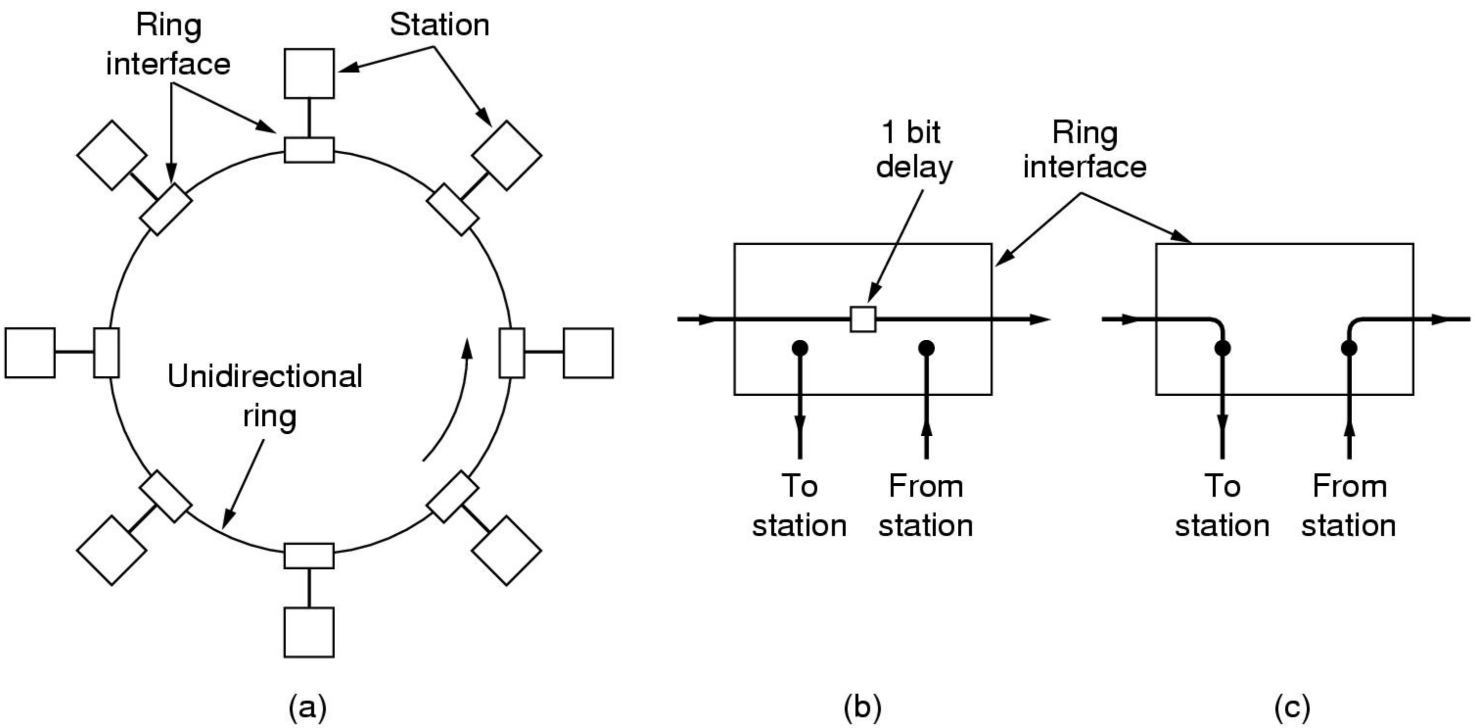
# Token Ring

HERE'S YOUR PROBLEM. THE CONNECTION TO THE NETWORK IS BROKEN.
UH-OH. IT'S A "TOKEN RING" LAN. THAT MEANS THE TOKEN FELL OUT AND IT'S IN THIS ROOM SOMEPLACE.
YOU ARE THE WIND BENEATH MY WINGS.
I'LL WAIT A WEEK THEN TELL HIM THE TOKEN MUST BE IN THE "ETHERNET."
S.Adams E-mail: SCOTTADAMS@AOL.COM
5/2/96 © 1996 United Feature Syndicate, Inc.(NYC)

# Token Passing MAC

- Token Bus (IEEE802.4):
  - broadcast bus
  - logical ring
  - token: special control frame
  - only the token holder station can transmit frames
  - 0, 2, 4, 6: traffic priority classes
- Token Ring (initiated by IBM => IEEE802.5 => Fiber Distributed Data Interface):
  - token regenerated/modified at each node
  - stations have two modes:
    - listen (forwards bits with delay 1)
    - transmit (seizes the first token by transforming into the start of frame)
- Resilient Packet Ring (IEEE802.17)

# Token Ring



Ring interface
Station
Unidirectional ring
1 bit delay
Ring interface
To station
From station
To station
From station
(a)
(b)
(c)

# Token Ring (cont)

- Idea
  - Frames flow in one direction: upstream to downstream
  - special bit pattern (token) rotates around ring
  - must capture token before transmitting
  - release token after done transmitting
    - immediate release
    - delayed release
  - remove your frame when it comes back around
  - stations get round-robin service
- Frame Format

| 8 | 8 | 48 | 48 | | 32 | 8 | 24 |
|---|---|---|---|---|---|---|---|
| Start of frame | Control | Dest addr | Src addr | Body | CRC | End of frame | Status |

# Fiber Distributed Data Interface

- Evolution of IEEE802.5
- Designed for fiber (100Mbps) but also supports coax and twisted pair
- Architecture: dual ring
  - Tolerates one broken link or one station failure
- Stations buffer at least 9 bits and at most 80 bits
- Uses 4B/5B encoding
- Specific Timed-Token Algorithm

# Timed Token Algorithm

- Token Holding Time (THT)
  - upper limit on how long a station can hold the token
- Token Rotation Time (TRT)
  - how long it takes the token to traverse the ring.
  - **`TRT`** <= **`ActiveNodes`** x **`THT`** + **`RingLatency`**
- Target Token Rotation Time (TTRT)
  - agreed-upon upper bound on TRT

# Algorithm (cont)

- Each node measures TRT between successive tokens
  - if measured-TRT > TTRT: token is late so don't send
  - if measured-TRT < TTRT: token is early so OK to send
- Two classes of traffic
  - synchronous: can always send
  - asynchronous: can send only if token is early
- Worse case: 2xTTRT between seeing token
- Back-to-back 2xTTRT rotations not possible

# Token Maintenance

- Lost Token
  - no token when initializing ring
  - bit error corrupts token pattern
  - node holding token crashes
- Generating a Token (and agreeing on TTRT)
  - execute when join ring or suspect a failure
  - send a *claim frame* that includes the node's TTRT *bid*
  - when receive claim frame, update the bid and forward
  - if your claim frame makes it all the way around the ring:
    - your bid was the lowest
    - everyone knows TTRT
    - you insert new token

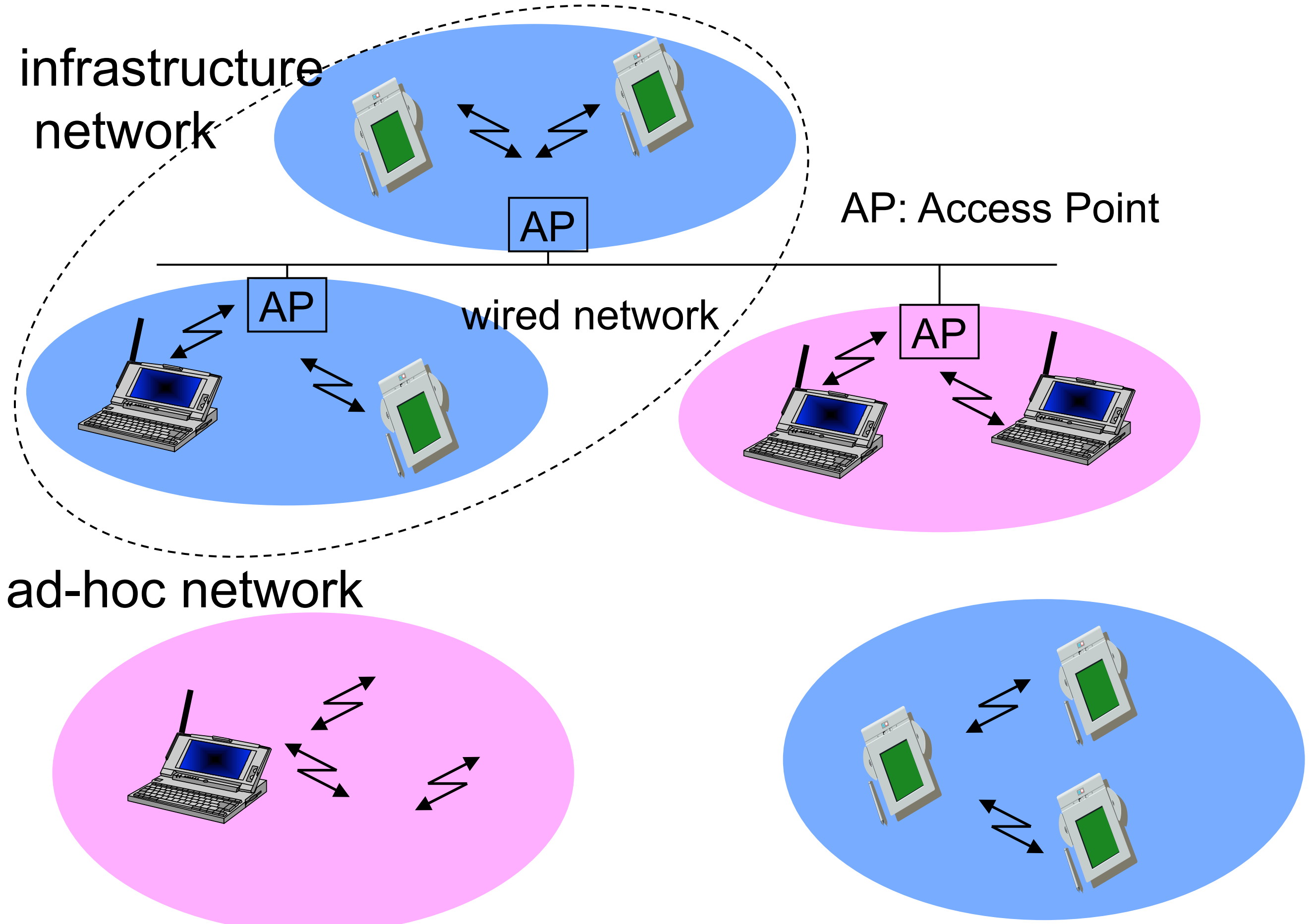
# Maintenance (cont)

- Monitoring for a Valid Token
  - should periodically see valid transmission (frame or token)
  - maximum gap = ring latency + max frame < = 2.5ms
  - set timer at 2.5ms and send claim frame if it fires

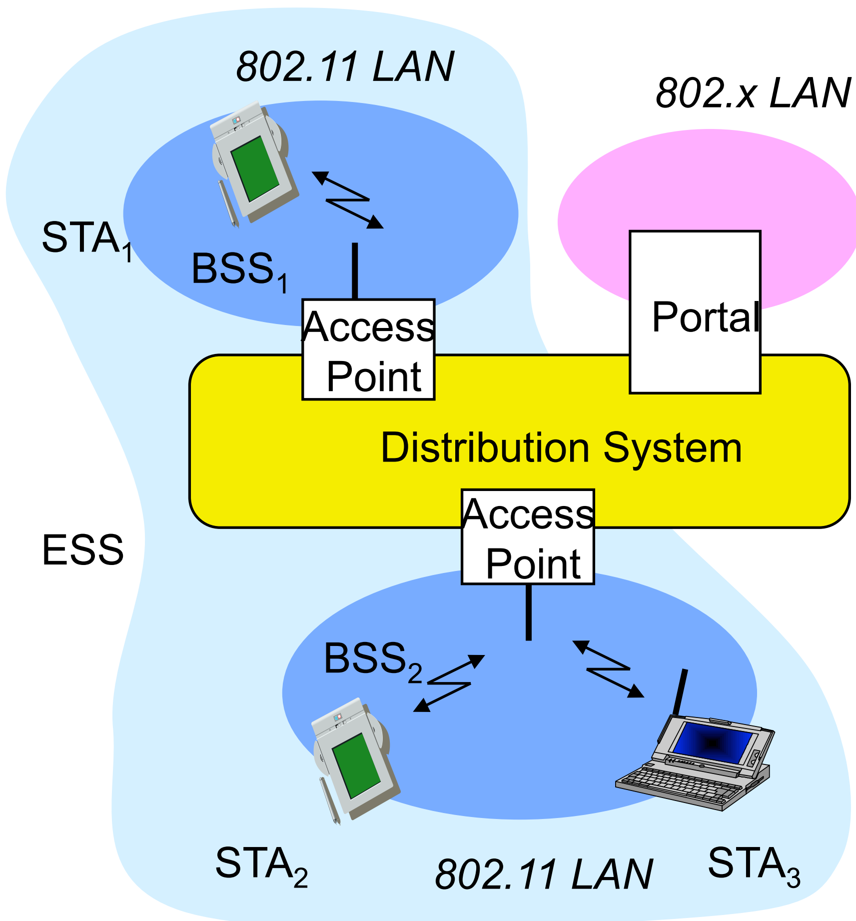
# Multiple Access with Collision Avoidance (MACA 1990)

- In wireless networks, collision happen at receiver, difficult to sense from the transmitter side
- MACA is designed for ad-hoc wireless networks
- When a station $S_1$ has a packet to transmit to station $S_2$
  - $S_1$ senses the channel. If the channel is busy defers the transmission until idle
  - if channel is idle $S_1$ sends a special packet called Request-To-Send (RTS) to the $S_2$
  - (if the RTS is correctly received by $S_2$) $S_2$ sends a Clear-To-Send (CTS), CTS includes the frame length
  - (if the CTS is correctly received by $S_1$) $S_1$ starts the data transmission
- Stations which sense:
  - RTS: defer transmission until after CTS
  - CTS: defer transmission until the transmission of data completes
- If a station does not receive CTS in response to its RTS, it invokes an exponential backoff

# IEEE802.11

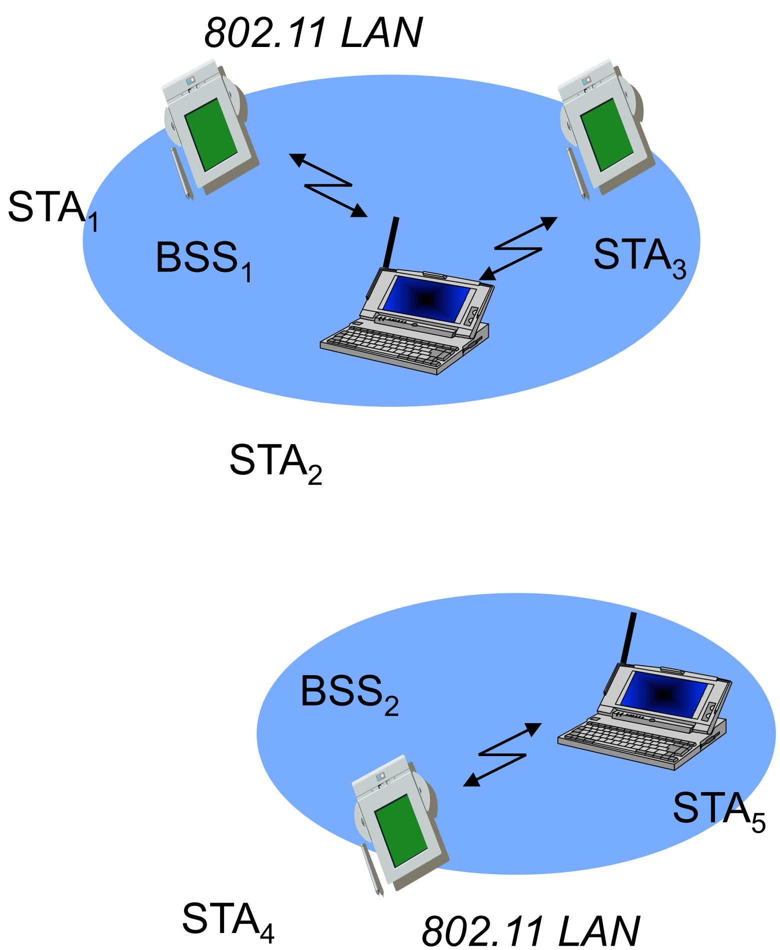

infrastructure
network
AP
AP: Access Point
AP
wired network
AP
ad-hoc network

# 802.11 - Architecture of an infrastructure network



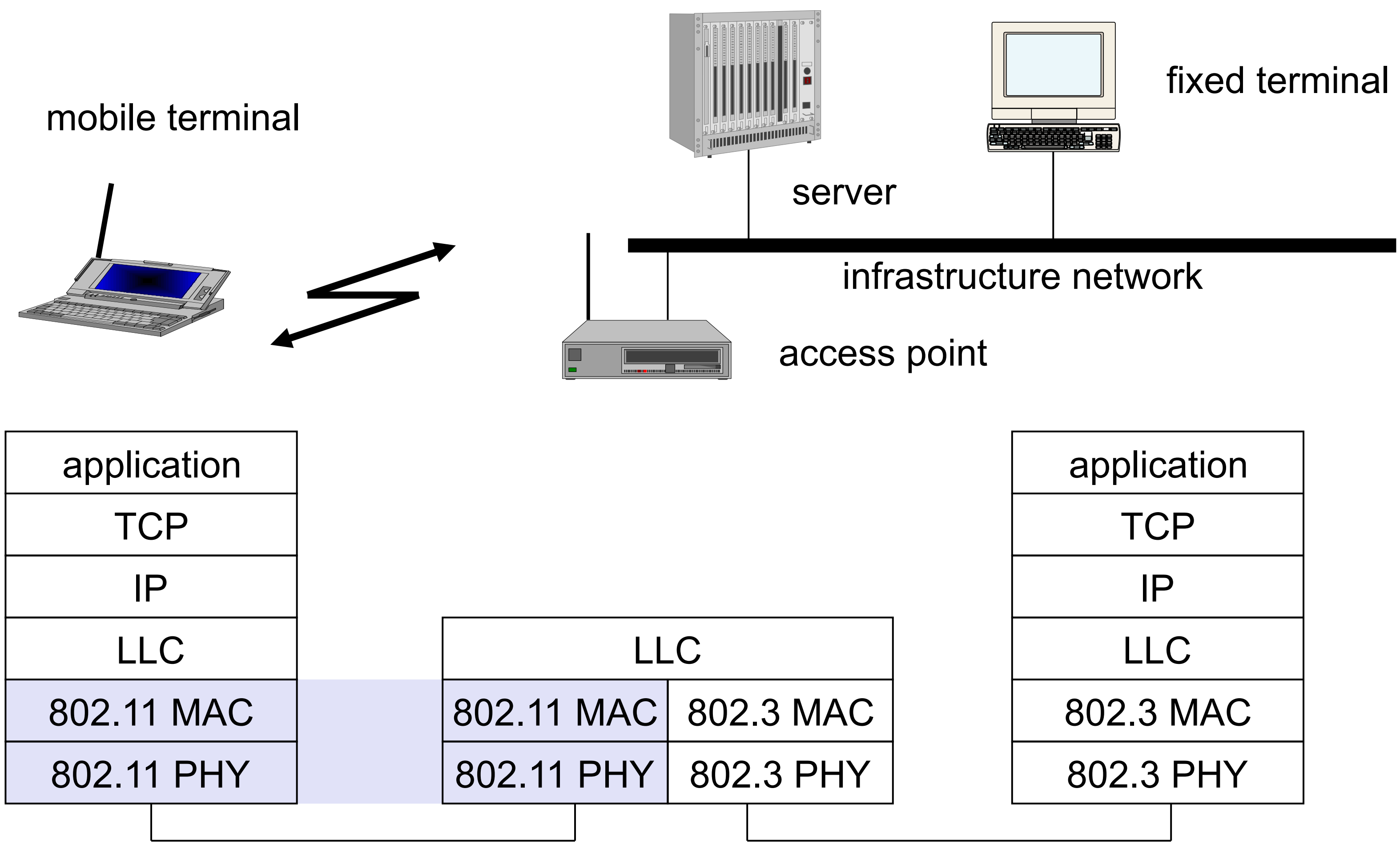

- Station (STA)
  - terminal with access mechanisms to the wireless medium and radio contact to the access point
- Basic Service Set (BSS)
  - group of stations using the same radio frequency
- Access Point
  - station integrated into the wireless LAN and the distribution system
- Portal
  - bridge to other (wired) networks
- Distribution System
  - interconnection network to form one logical network (EES: Extended Service Set) based on several BSS

# 802.11 - Architecture of an Ad Hoc Network



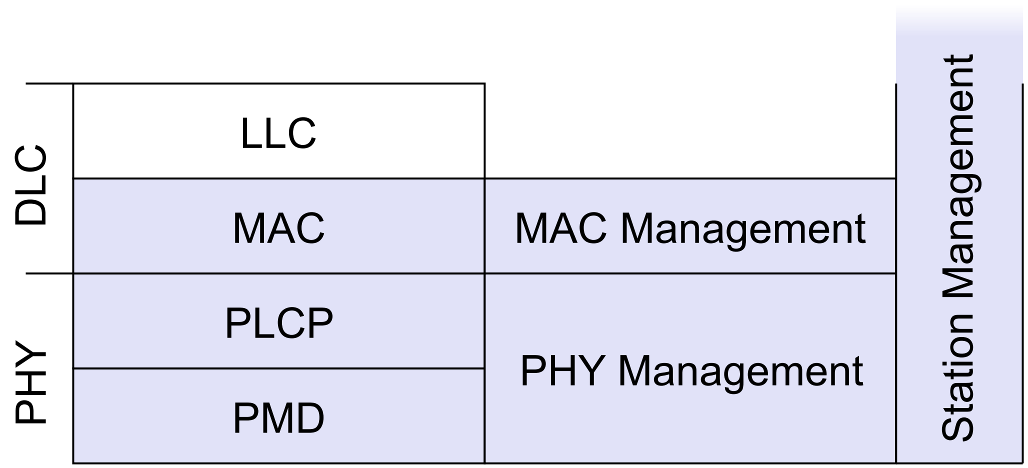

- Direct communication within a limited range
  - Station (STA): terminal with access mechanisms to the wireless medium
  - Basic Service Set (BSS): group of stations using the same radio frequency

# IEEE Standard 802.11



# 802.11 - Layers and functions

- MAC
  - access mechanisms, fragmentation, encryption
- MAC Management
  - synchronization, roaming, MIB, power management
- PLCP Physical Layer Convergence Protocol
  - clear channel assessment signal (carrier sense)
- PMD Physical Medium Dependent
  - modulation, coding
- PHY Management
  - channel selection, MIB
- Station Management
  - coordination of all management functions



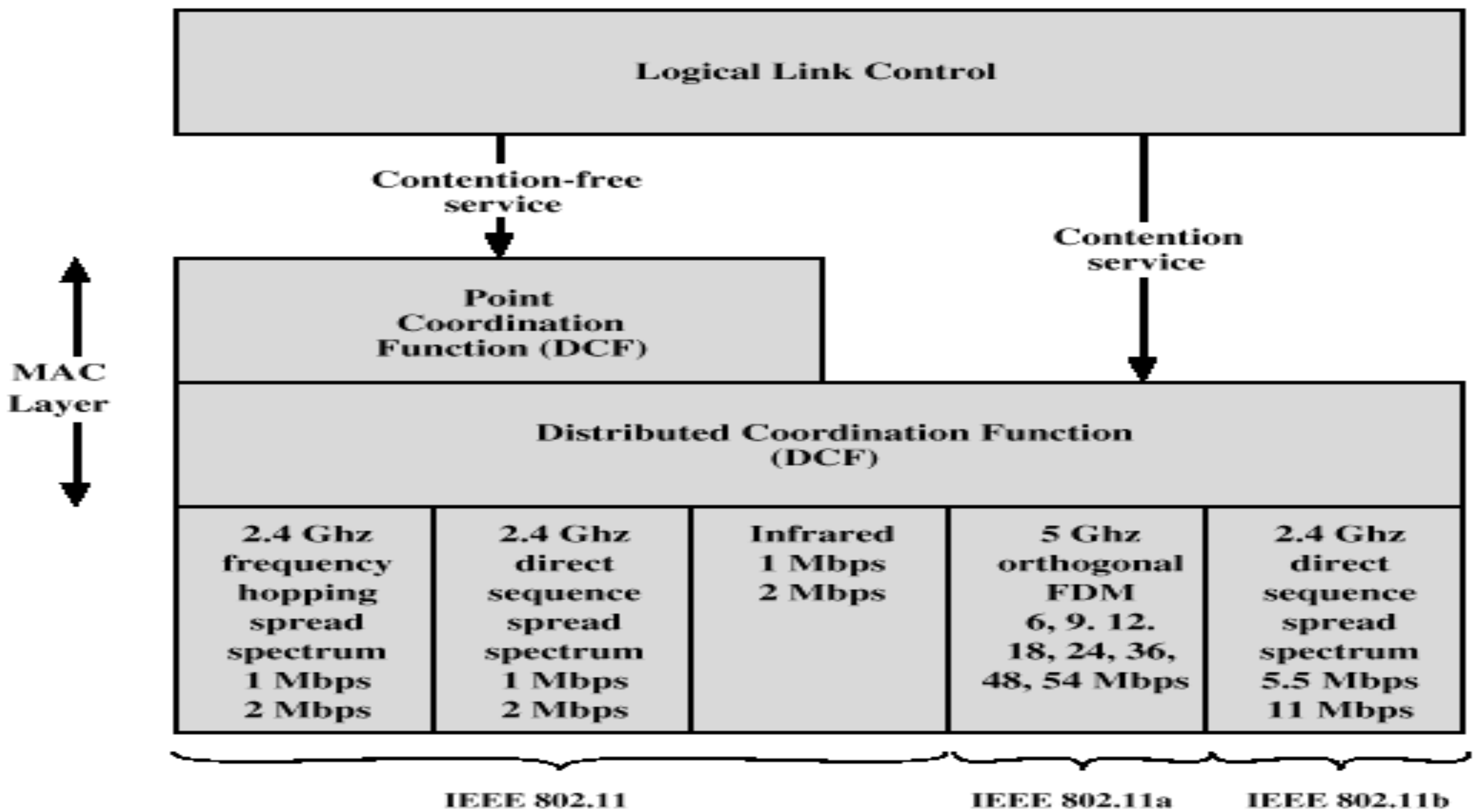



**Figure 14.5 IEEE 802.11 Protocol Architecture**

# 802.11 - Physical layer

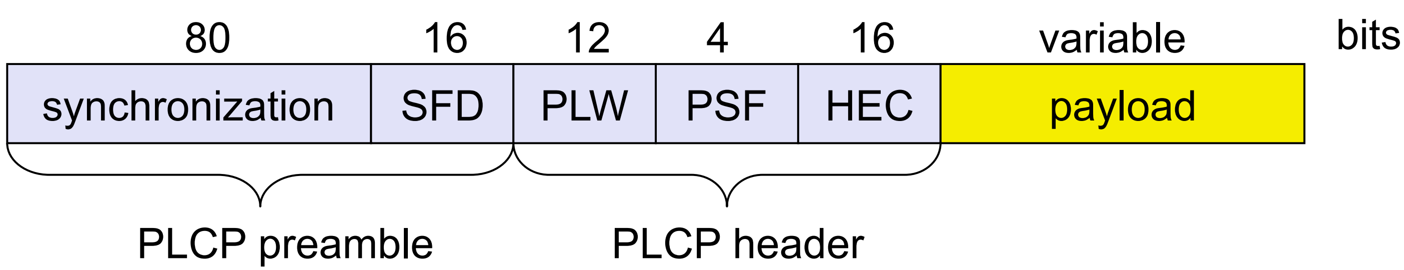
- 5 versions: 2 radio (typ. 2.4 GHz), 1 IR
  - data rates 1 or 2 Mbit/s
- FHSS (Frequency Hopping Spread Spectrum) 2.4 GHz
  - spreading, despreading, signal strength, typ. 1 Mbit/s
  - min. 2.5 frequency hops/s (USA), two-level GFSK modulation
- DSSS (Direct Sequence Spread Spectrum) 2.4GHz
  - DBPSK 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
  - chipping sequence: +1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1 (Barker code)
  - 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

# IEEE 802.11abgn

- IEEE 802.11a
  - Makes use of 5-GHz band
  - Provides rates of 6, 9 , 12, 18, 24, 36, 48, 54 Mbps
  - Uses orthogonal frequency division multiplexing (OFDM)
  - Subcarrier modulated using BPSK, QPSK, 16-QAM or 64-QAM
- IEEE 802.11b
  - Provides data rates of 5.5 and 11 Mbps
  - Complementary code keying (CCK) modulation scheme
- IEEE 802.11g
  - Mix of a & b on 2.4Ghz
- IEEE802.11n
  - Multiple Input Multiple Output
- Higher rates are not achieved for free
  - There are assumptions about range, channel, power

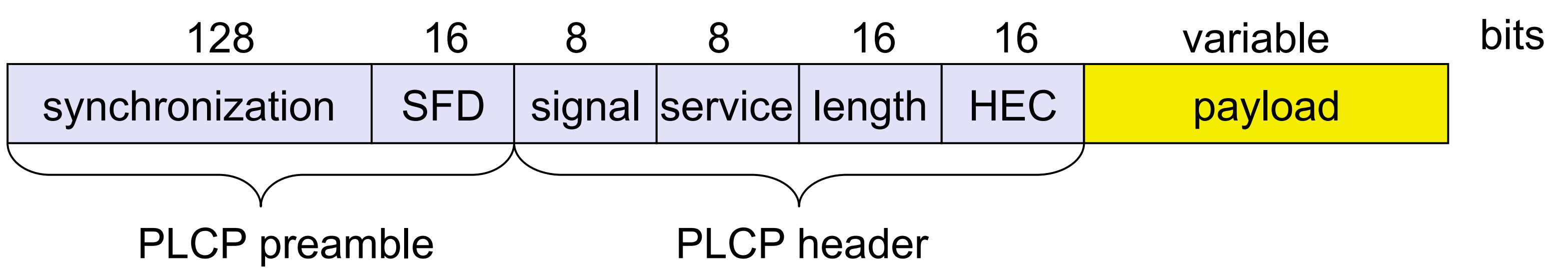
# FHSS PHY packet format

- Synchronization
  - synch with 010101... pattern
- SFD (Start Frame Delimiter)
  - 0000110010111101 start pattern
- PLW (PLCP_PDU Length Word)
  - length of payload incl. 32 bit CRC of payload, PLW < 4096
- PSF (PLCP Signaling Field)
  - data rate of payload (1 or 2 Mbit/s)
- HEC (Header Error Check)
  - CRC with $x^{16}+x^{12}+x^5+1$



# DSSS PHY packet format

- Synchronization
  - synch., gain setting, energy detection, frequency offset compensation
- SFD (Start Frame Delimiter)
  - 1111001110100000
- Signal
  - data rate of the payload (0A: 1 Mbit/s DBPSK; 14: 2 Mbit/s DQPSK)
- Service
  - future use, 00: 802.11 compliant
- Length
  - length of the payload
- HEC (Header Error Check)
  - protection of signal, service and length, $x^{16}+x^{12}+x^5+1$

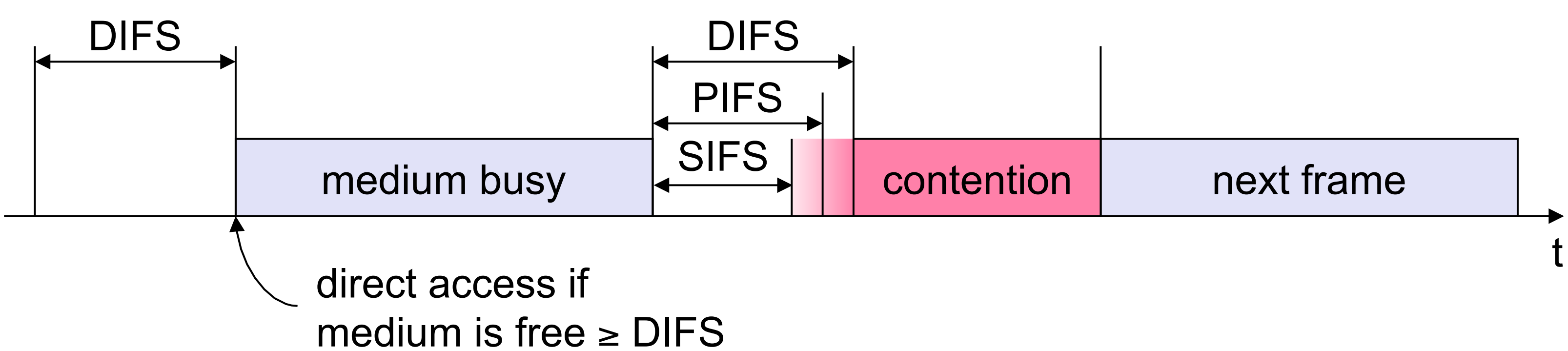


# 802.11 - MAC layer I – DFWMAC Distributed Foundation Wireless MAC

- Traffic services
  - Asynchronous Data Service (mandatory)
    - exchange of data packets based on “best-effort”
    - support of broadcast and multicast
  - Time-Bounded Service (optional)
    - implemented using PCF (Point Coordination Function)
- Access methods
  - DFWMAC-DCF CSMA/CA (mandatory)
    - collision avoidance via randomized “back-off” mechanism
    - minimum distance between consecutive packets
    - ACK packet for acknowledgements (not for broadcasts)
  - DFWMAC-DCF w/ RTS/CTS (optional)
    - Distributed Foundation Wireless MAC
    - avoids hidden terminal problem
  - DFWMAC- PCF (optional)
    - access point polls terminals according to a list

# 802.11 - MAC layer II

- Priorities
  - defined through different inter frame spaces
  - 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

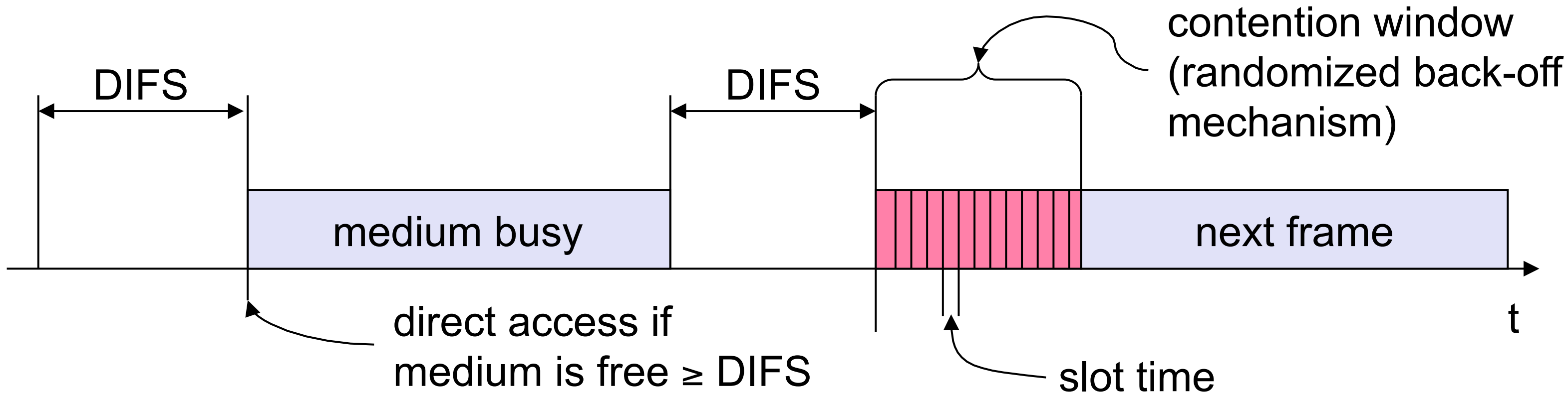


# IFS Timing

- aSIFSTime = aRxRFDelay + aRxPLCPDelay + aMACProcessingDelay + aRxTxTurnaroundTime.
- aSlotTime = aCCATime + aRxTxTurnaroundTime + aAirPropagationTime + aMACProcessingDelay.

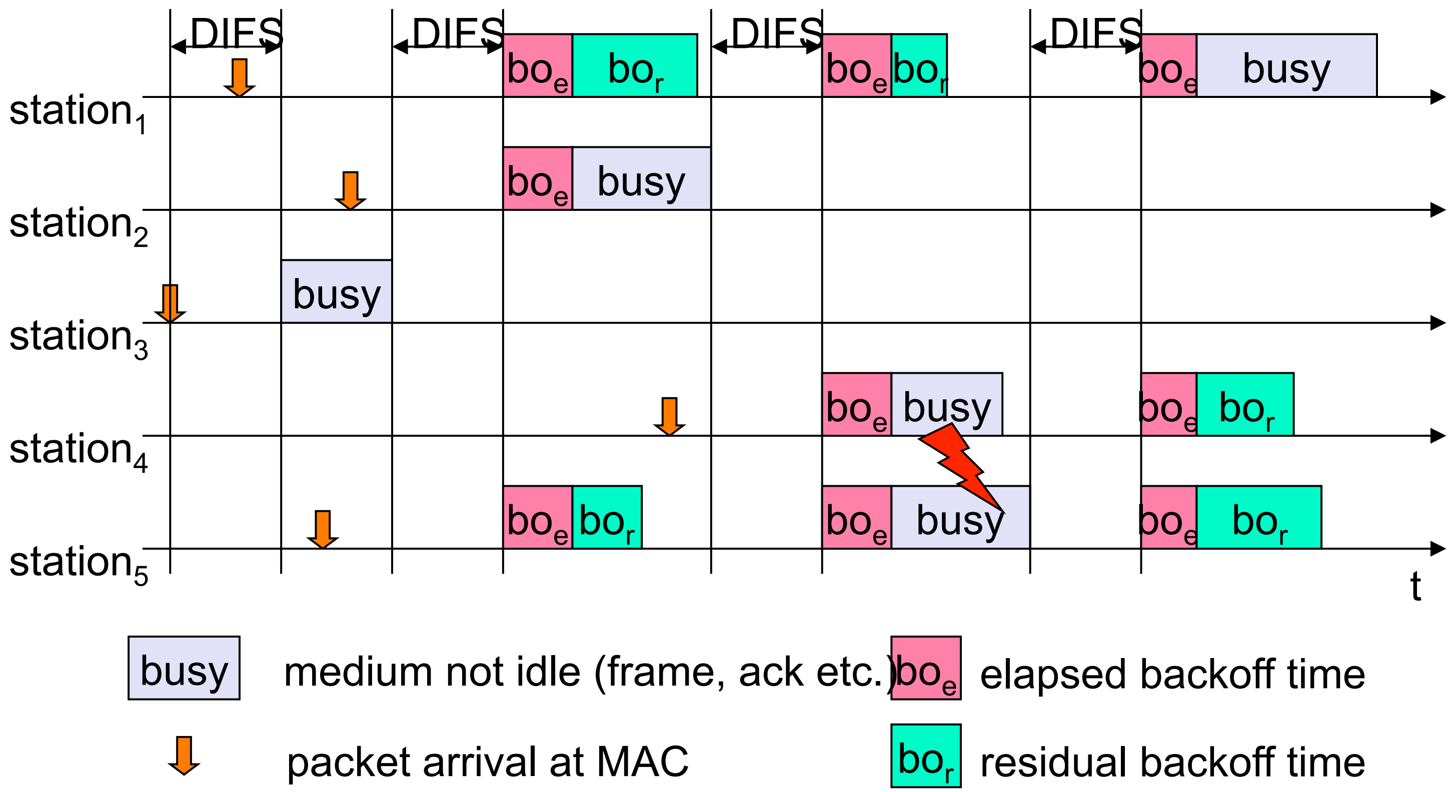
- PIFS = aSIFSTime + aSlotTime
- DIFS = aSIFSTime + 2∗aSlotTime
- EIFS = aSIFSTime + (8 × ACKSize) + aPreambleLength + aPLCPHeaderLngth+ DIFS
- For Direct Sequence Spread Spectrum physical layer:
  - aSlotTime 20 μs
  - aSIFSTime 10 μs
  - aCCATime < 15 μs
  - aRxTxTurnaroundTime <5 μs

# 802.11 - CSMA/CA access method I



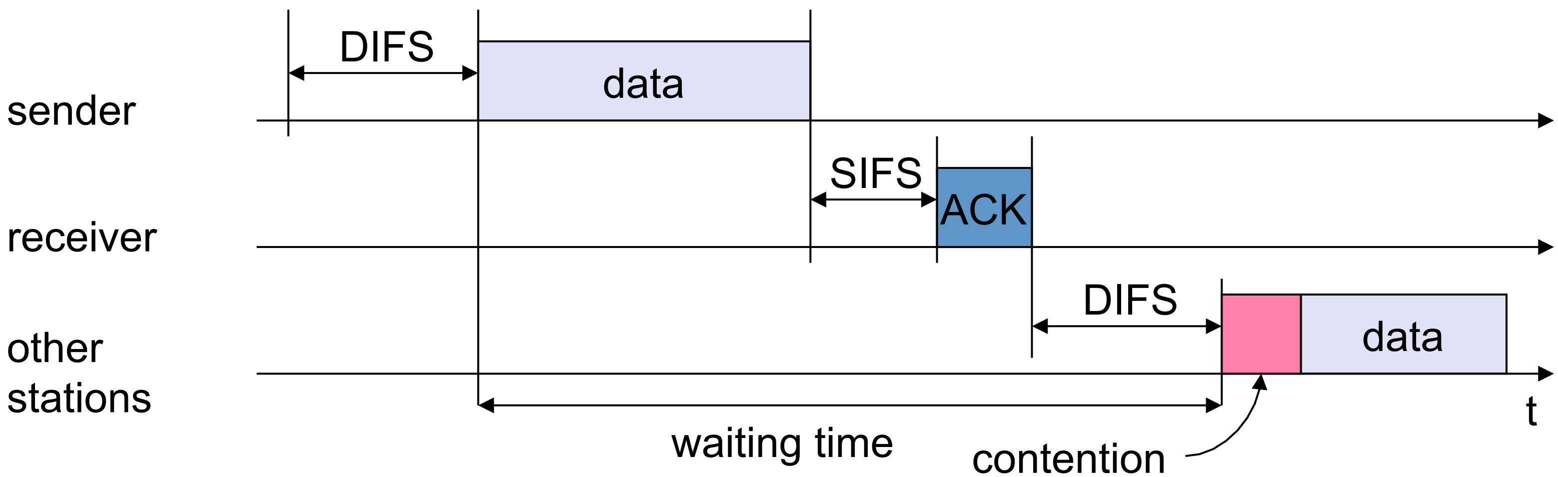

- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- if the medium is busy, the station has to wait for a free IFS, 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 - competing stations - simple version



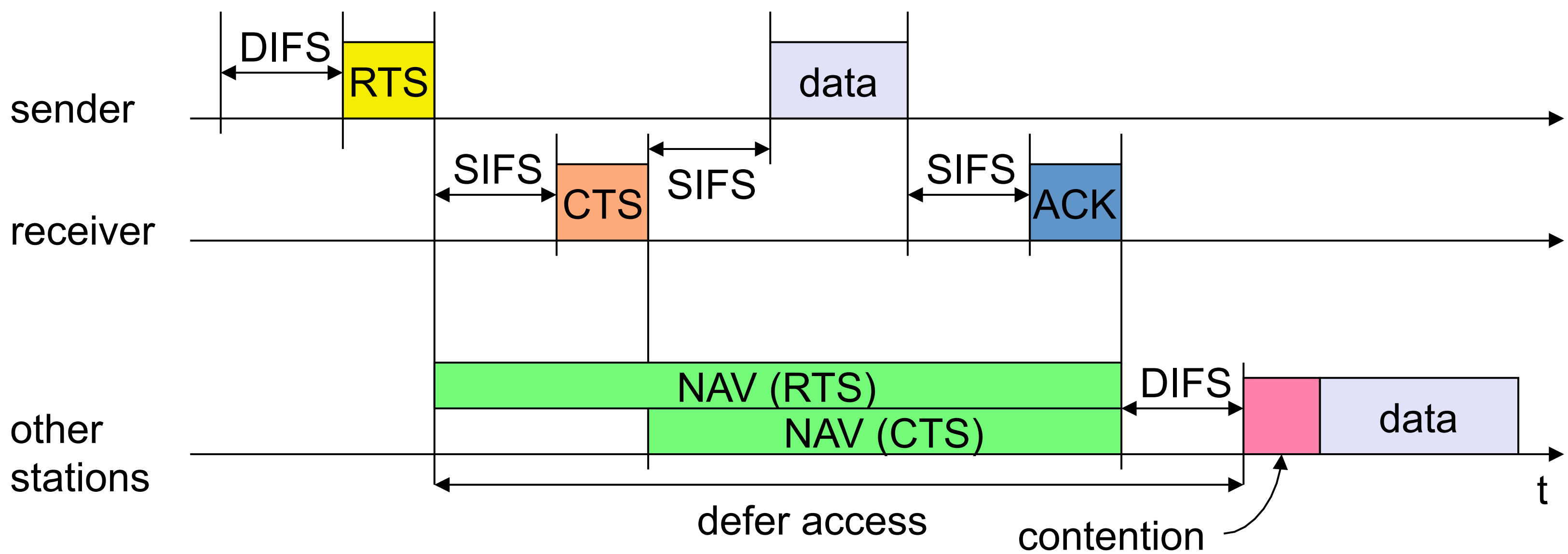
# 802.11 - CSMA/CA access method II

- Sending unicast packets
  - station has to wait for DIFS 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

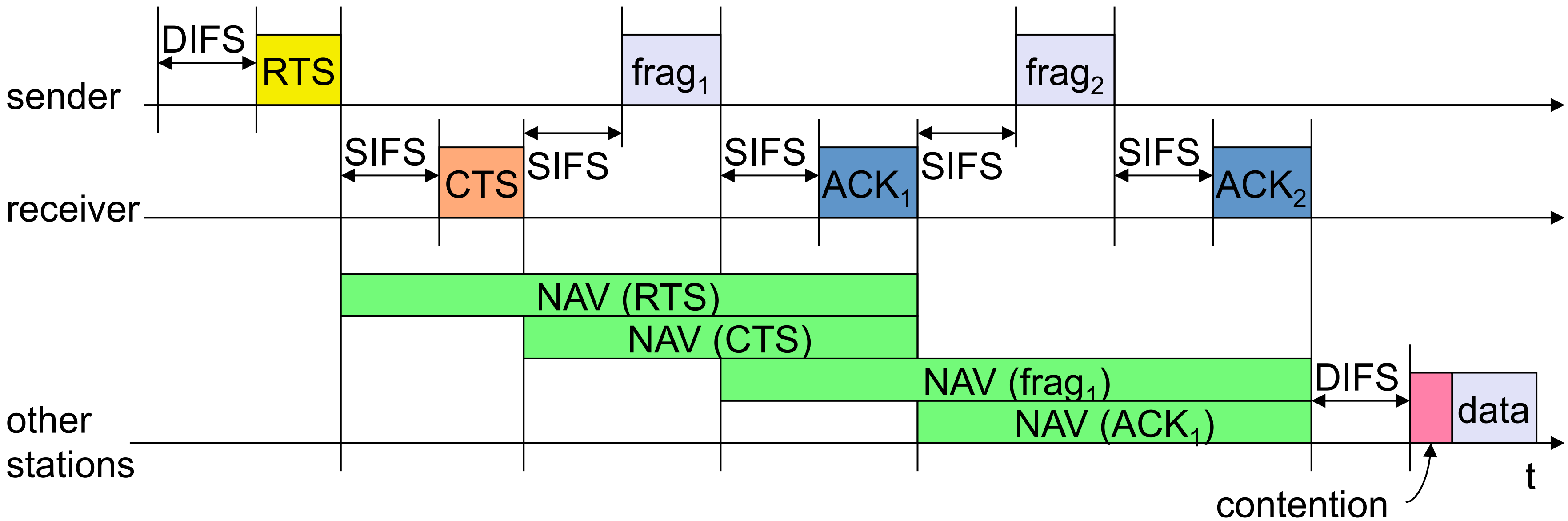


# 802.11 - DFWMAC

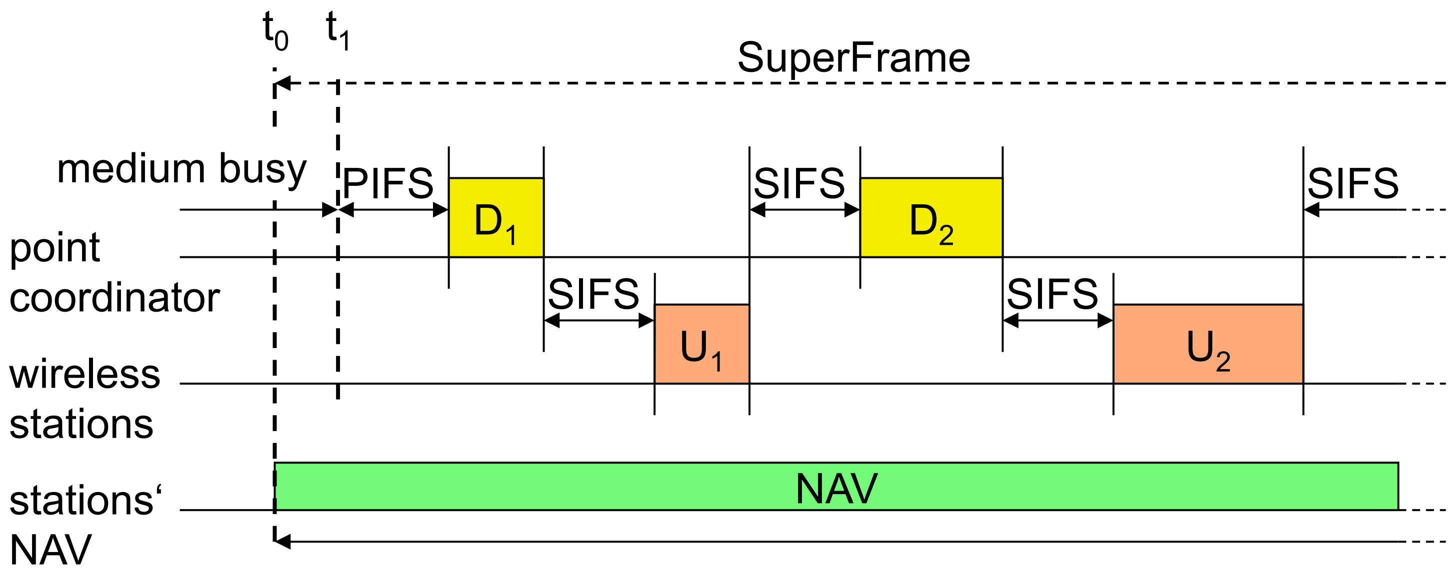
- Sending unicast packets
  - station can send RTS with reservation parameter after waiting for DIFS (reservation determines amount of time the data packet needs the medium)
  - acknowledgement via CTS after SIFS by receiver (if ready to receive)
  - sender can now send data at once, acknowledgement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



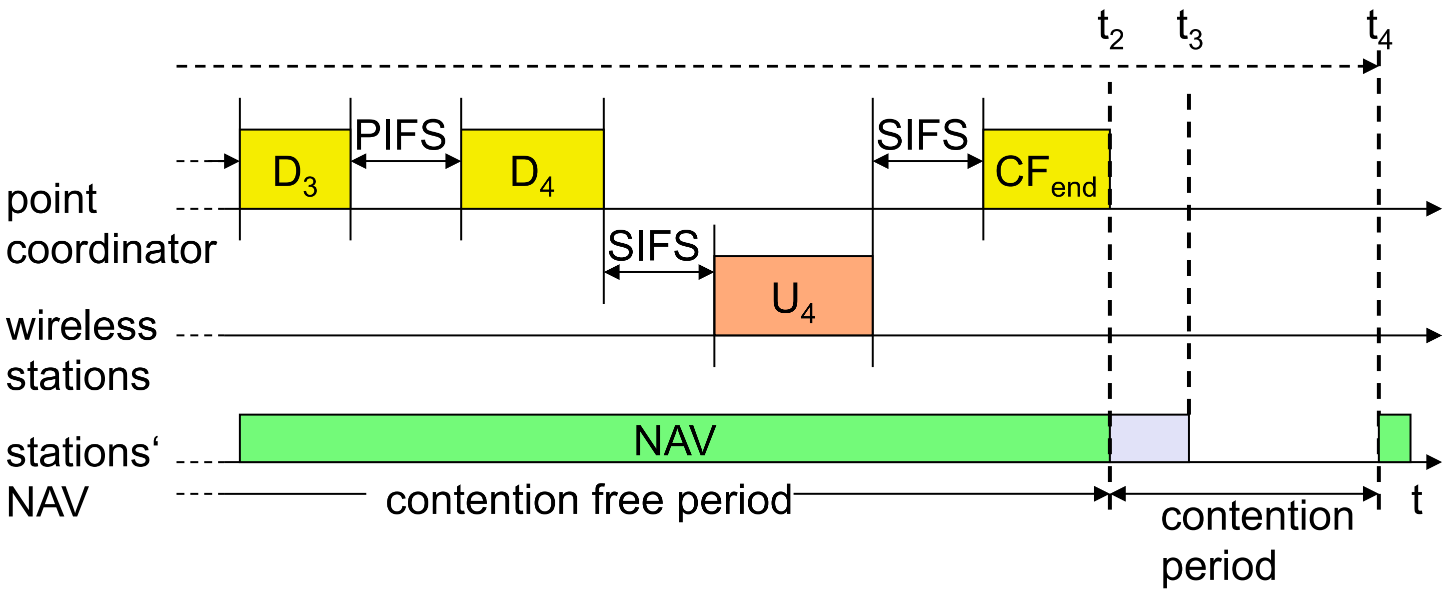
# Fragmentation



# DFWMAC-PCF I


t0
t1
SuperFrame
medium busy
PIFS
D1
SIFS
D2
SIFS
point coordinator
SIFS
U1
SIFS
U2
wireless stations
stations' NAV
NAV

# DFWMAC-PCF II




7.20.1

# 802.11 - Frame format

- Types
  - control frames, management frames, data frames
- Sequence numbers
  - important against duplicated frames due to lost ACKs
- Addresses
  - receiver, transmitter (physical), BSS identifier, sender (logical)
- Miscellaneous
  - sending time, checksum, frame control, data

| bytes | 2 | 2 | 6 | 6 | 6 | 2 | 6 | 0-2312 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| | Frame Control | Duration ID | Address 1 | Address 2 | Address 3 | Sequence Control | Address 4 | Data | CRC |

Frame Control: Version, Type, Subtype, To DS, From DS, More Fragments, Retry, Power Management, More Data, Wired Equivalent Privacy (WEP), and Order

# MAC address format

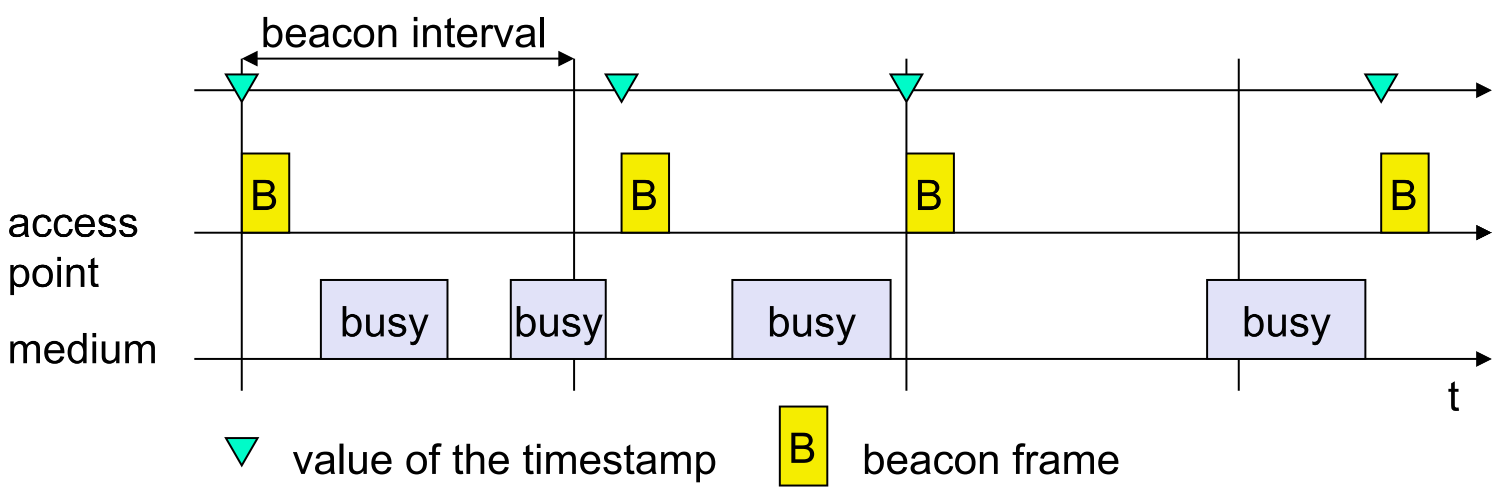
| scenario | to DS | from DS | address 1 | address 2 | address 3 | address 4 |
|---|---|---|---|---|---|---|
| ad-hoc network | 0 | 0 | DA | SA | BSSID | - |
| infrastructure network, from AP | 0 | 1 | DA | BSSID | SA | - |
| infrastructure network, to AP | 1 | 0 | BSSID | SA | DA | - |
| infrastructure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

DS: Distribution System
AP: Access Point
DA: Destination Address (final recipient)
SA: Source Address (initiator)
BSSID: Basic Service Set Identifier
RA: Receiver Address (immediate recipient)
TA: Transmitter Address (immediate sender)

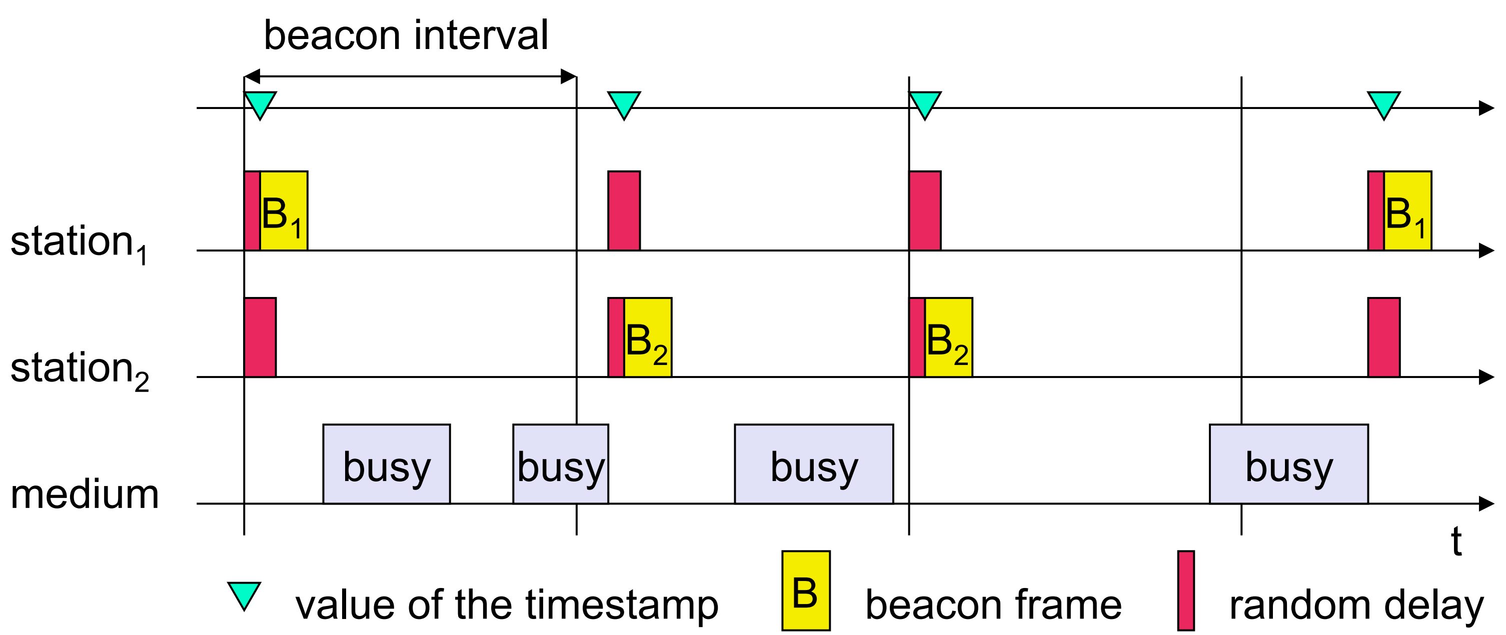
# 802.11 - MAC management

- Synchronization
  - try to find a LAN, try to stay within a LAN
  - timer etc.
- Power management
  - sleep-mode without missing a message
  - periodic sleep, frame buffering, traffic measurements
- Association/Reassociation
  - integration into a LAN
  - roaming, i.e. change networks by changing access points
  - scanning, i.e. active search for a network
- MIB - Management Information Base
  - managing, read, write

# Synchronization using a Beacon (infrastructure)



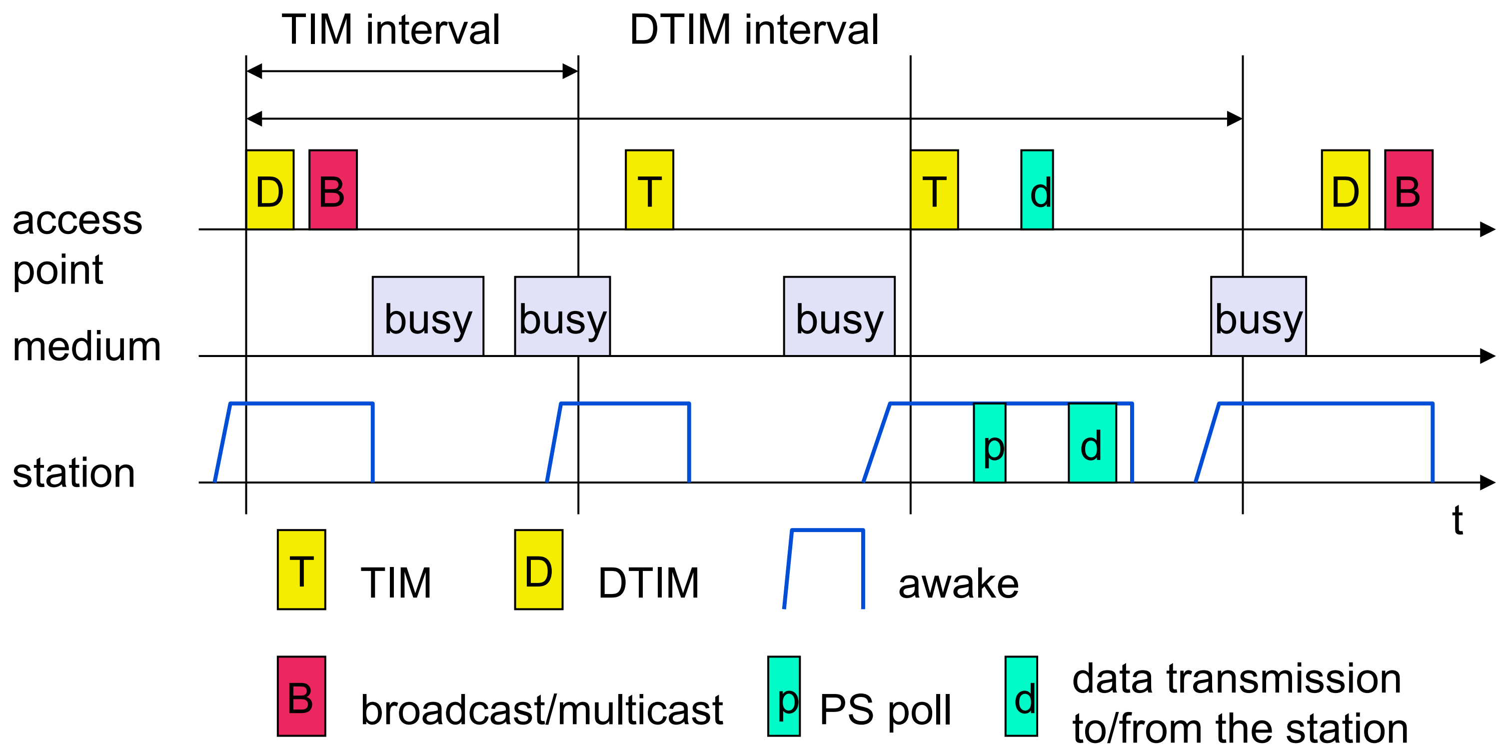
# Synchronization using a Beacon (ad-hoc)



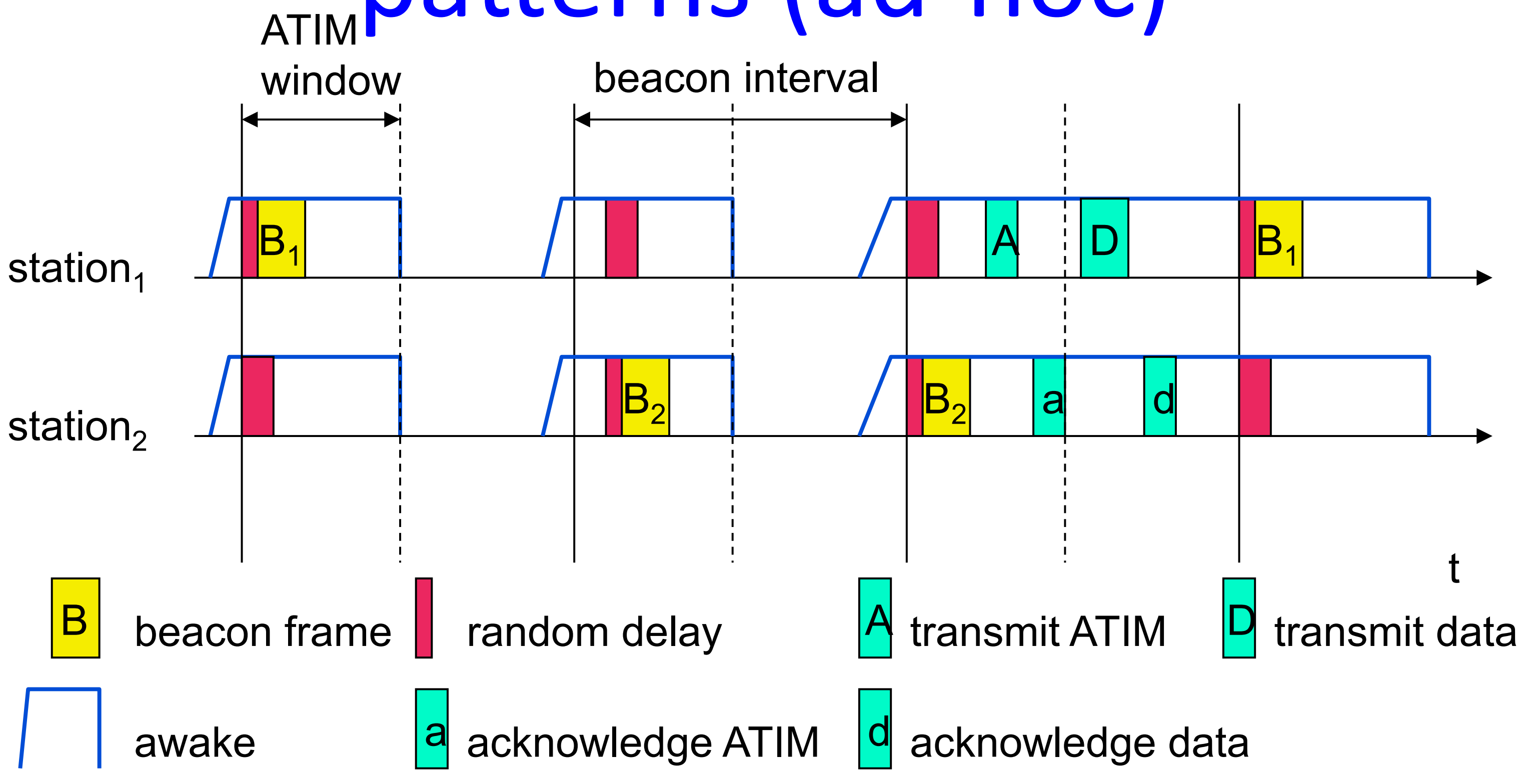
# Power management

- 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)



# 802.11 - Roaming

- No or bad connection? Then perform:
- Scanning
  - scan the environment, i.e., listen into the medium for beacon signals (passive) or send probes (active) into the medium and wait for an answer
- Reassociation Request
  - station sends a request to one or several AP(s)
- Reassociation Response
  - success: AP has answered, station can now participate
  - failure: continue scanning
- AP accepts Reassociation Request
  - signal the new station to the distribution system
  - the distribution system updates its data base (i.e., location information)
  - typically, the distribution system now informs the old AP so it can release resources