Medium Access Control (MAC) and Wireless LANs

Outline

- Wireless LAN Technology
- Medium Access Control for Wireless
- IEEE 802.11

Wireless LAN Applications

- LAN Extension
- Cross-building interconnect
- Nomadic Access
- Ad hoc networking

LAN Extension

- Wireless LAN linked into a wired LAN on same premises
  - Wired LAN
    - Backbone
    - Support servers and stationary workstations
  - Wireless LAN
    - Stations in large open areas
    - Manufacturing plants, stock exchange trading floors, and warehouses

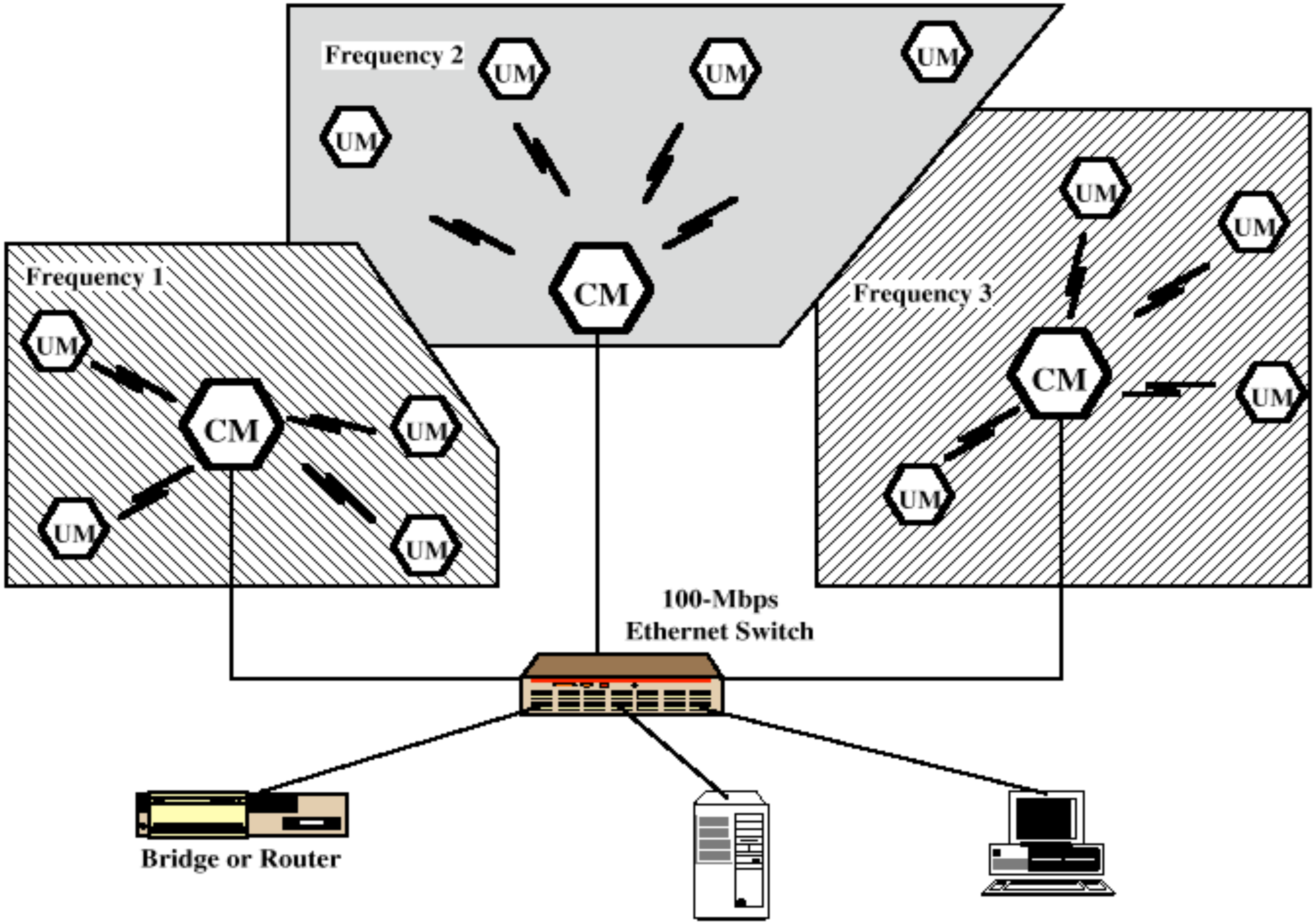


Figure 13.2 Example Multiple-Cell Wireless LAN Configuration

Cross-Building Interconnect

- Connect LANs in nearby buildings
  - Wired or wireless LANs
- Point-to-point wireless link is used
- Devices connected are typically bridges or routers

Nomadic Access

- Wireless link between LAN hub and mobile data terminal equipped with antenna

- Uses:
  - Transfer data from portable computer to office server
  - Extended environment such as campus

Ad Hoc Networking

- Temporary peer-to-peer network set up to meet immediate need
- Example:
  - Group of employees with laptops convene for a meeting; employees link computers in a temporary network for duration of meeting
  - Military applications
  - Disaster scenarios

Wireless LAN Parameters

- Throughput
- Number of nodes
- Connection to backbone LAN
- Service area
- Battery power consumption
- Transmission robustness and security
- Collocated network operation
- License-free operation
- Handoff/roaming
- Dynamic configuration

Wireless LAN Categories

- Infrared (IR) LANs
- Spread spectrum LANs
- Narrowband microwave

Strengths of Infrared Over Microwave Radio

- Spectrum for infrared virtually unlimited
  - Possibility of high data rates
- Infrared spectrum unregulated
- Equipment inexpensive and simple
- Reflected by light-colored objects
  - Ceiling reflection for entire room coverage
- Doesn’t penetrate walls
  - More easily secured against eavesdropping
  - Less interference between different rooms

Drawbacks of Infrared Medium

- Indoor environments experience infrared background radiation
  - Sunlight and indoor lighting
  - Ambient radiation appears as noise in an infrared receiver
  - Transmitters of higher power required
    - Limited by concerns of eye safety and excessive power consumption
  - Limits range

Spread Spectrum LANs

- Multiple cell arrangement
- Most popular type of wireless LAN
- Two configurations:
  - Hub topology: infrastructure mode
  - Peer-to-peer topology: multi-hop ad hoc network

Spread Spectrum LAN configurations

- Hub topology:
  - Mounted on the ceiling and connected to backbone
  - Need MAC protocol
  - May act as multiport repeater
  - Automatic handoff of mobile stations
  - Stations in cell either:
    - Transmit to / receive from hub only
    - Broadcast using omnidirectional antenna
- Peer-to-peer mode:
  - No hub
  - Need a distributed MAC protocol

Narrowband Microwave LANs

- Use of a microwave radio frequency band for signal transmission
- Relatively narrow bandwidth
- Licensed & unlicensed

Medium Access Control Protocols

- Schedule-based: Establish transmission schedules statically or dynamically
  - TDMA
  - FDMA
  - CDMA
- Contention-based:
  - Let the stations contend for the channel
  - Random access protocols
- Reservation-based:
  - Reservations made during a contention phase
  - Size of packet in contention phase much smaller than a data packet
- Space-division multiple access:
  - Serve multiple users simultaneously by using directional antennas

Schedule-based access methods

- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel between a sender and a receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- TDMA (Time Division Multiple Access)
  - assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time
- CDMA (Code Division Multiple Access)
  - signals are spread over a wideband using pseudo-noise sequences
  - codes generate signals with "good-correlation" properties
  - signals from another user appear as "noise"
  - the receiver can "tune" into this signal if it knows the pseudo random number, tuning is done via a correlation function

Contention-based protocols

- Aloha
- CSMA (Carrier-sense multiple access)
  - Ethernet
- MACA (Multiple access collision avoidance)
- MACAW
- CSMA/CA and IEEE 802.11

Ingredients of MAC Protocols

- Carrier sense (CS)
  - Hardware capable of sensing whether transmission taking place in vicinity
- Collision detection (CD)
  - Hardware capable of detecting collisions
- Collision avoidance (CA)
  - Protocol for avoiding collisions
- Acknowledgments
  - When collision detection not possible, link-layer mechanism for identifying failed transmissions
- Backoff mechanism
  - Method for estimating contention and deferring transmissions

Carrier Sense Multiple Access

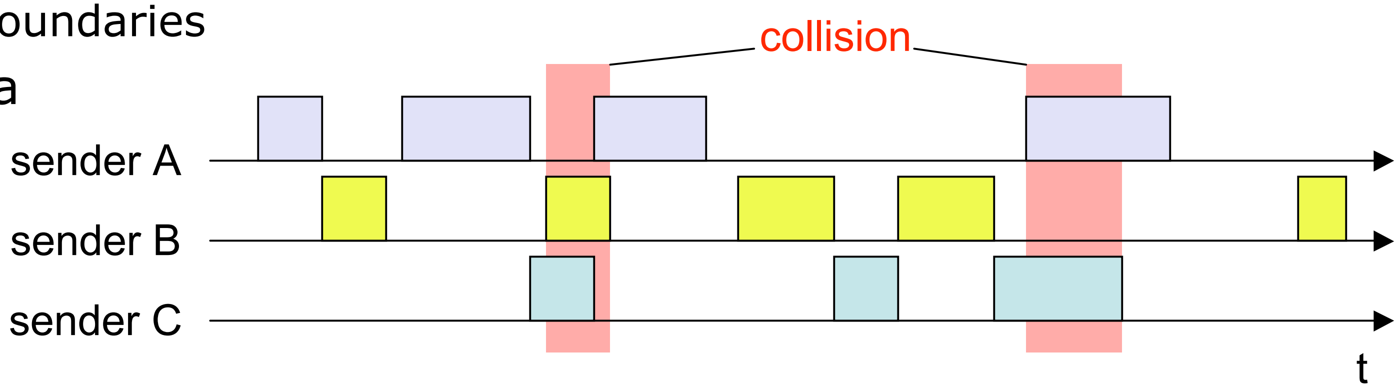
- Every station senses the carrier before transmitting
- If channel appears free
  - Transmit (with a certain probability)
- Otherwise, wait for some time and try again
- Different CSMA protocols:
  - Sending probabilities
  - Retransmission mechanisms

Aloha

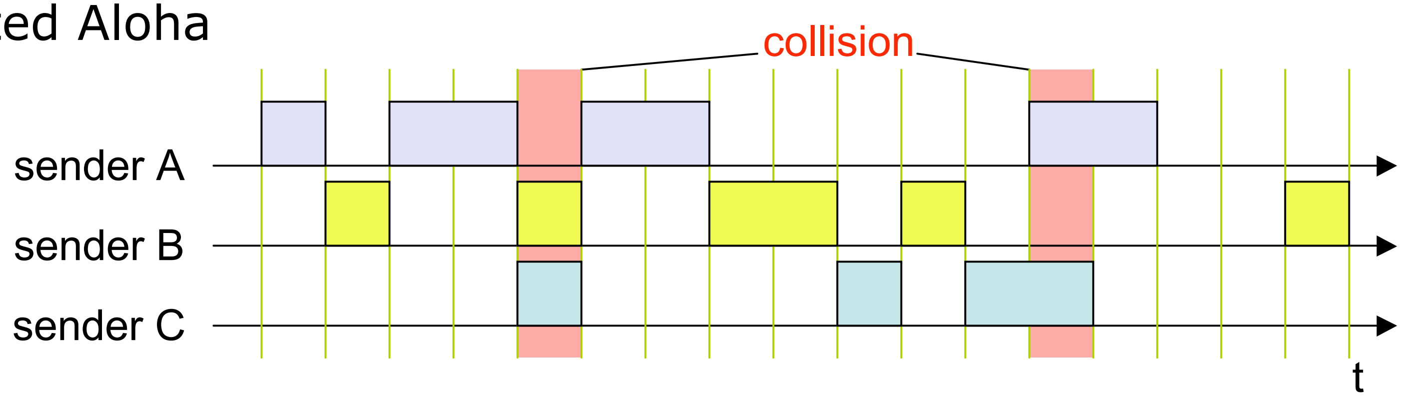
- Proposed for packet radio environments where every node can hear every other node
- Assume collision detection
- In Slotted Aloha, stations transmit at the beginning of a slot
- If collision occurs, then each station waits a random number of slots and retries
  - Random wait time chosen has a geometric distribution
  - Independent of the number of retransmissions
- Analysis in standard texts on networking theory

Aloha/Slotted aloha

- Mechanism
  - random, distributed (no central arbiter), time-multiplexed
  - Slotted Aloha additionally uses time-slots, sending must always start at slot boundaries
- Aloha



- Slotted Aloha



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): not applicable to wireless systems
- 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

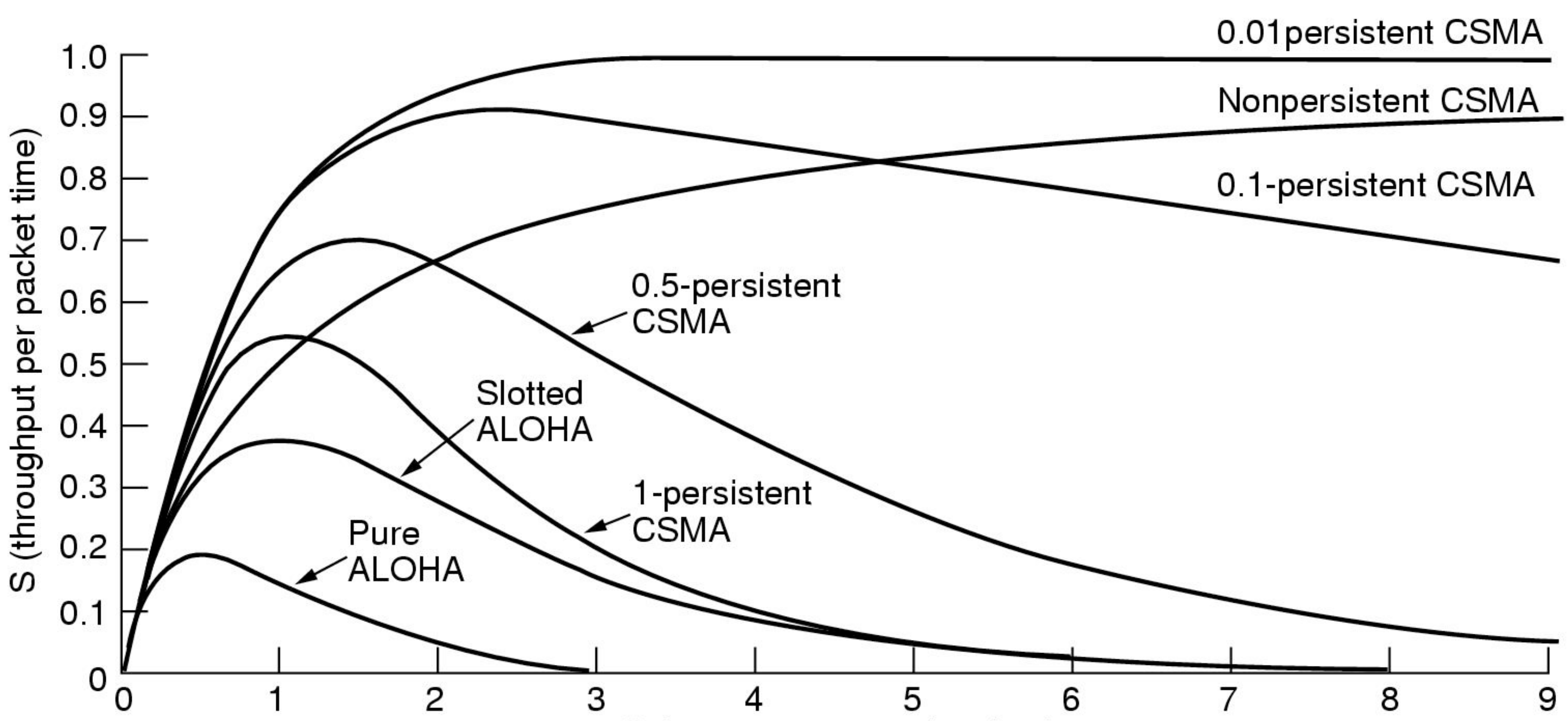
Carrier Sense Protocols (*Cont'd*)

- Non-persistent CSMA
  - o 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
  - o higher delays, but better performance than pure ALOHA
- p-persistent protocol
  - o 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*
  - o better throughput than other schemes but higher delay
- CSMA with collision Detection (CSMA/CD)
  - o stations abort their transmission when they detect a collision
  - o e.g., Ethernet, IEEE802.3 but not applicable to wireless systems

Ethernet

- CSMA with collision detection (CSMA/CD)
- If the adaptor has a frame and the line is idle: transmit
- Otherwise wait until idle line then transmit
- If a collision occurs:
    - Binary exponential backoff: wait for a random number $\in [0, 2^i-1]$ of slots before transmitting
    - After ten collisions the randomization interval is frozen to max 1023
    - After 16 collisions the controller throws away the frame

Comparison of MAC Algorithms

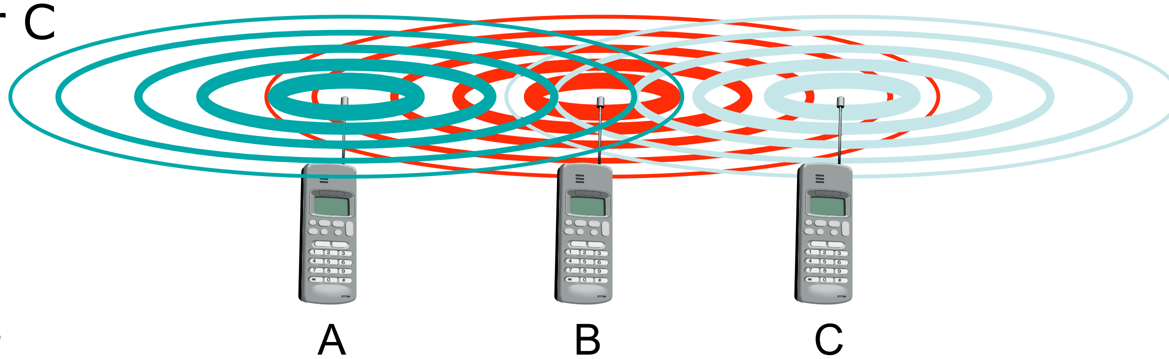


Motivation for Wireless MAC

- Can we apply media access methods from fixed networks?
- Example CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)
- Problems in wireless networks
  - signal strength decreases proportional to the square of the distance
  - the sender would apply CS and CD, but the collisions happen at the receiver
  - it might be the case that a sender cannot “hear” the collision, i.e., CD does not work
  - furthermore, CS might not work if, e.g., a terminal is “hidden”

Hidden and exposed terminals

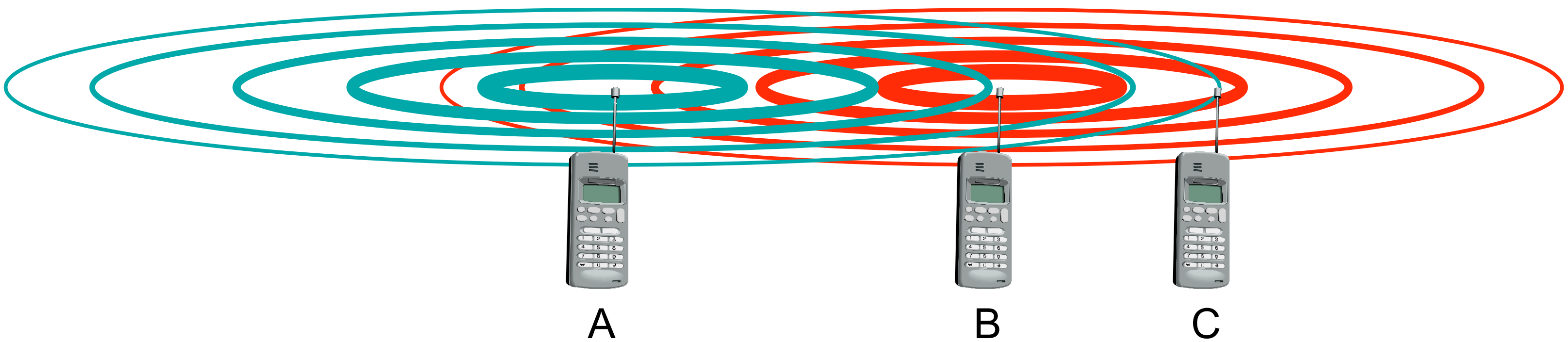
- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a “free” medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is “hidden” for C



- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A/B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is “exposed” to B

Near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases proportional to the square of the distance
  - the signal of terminal B therefore drowns out A’s signal
  - C cannot receive A



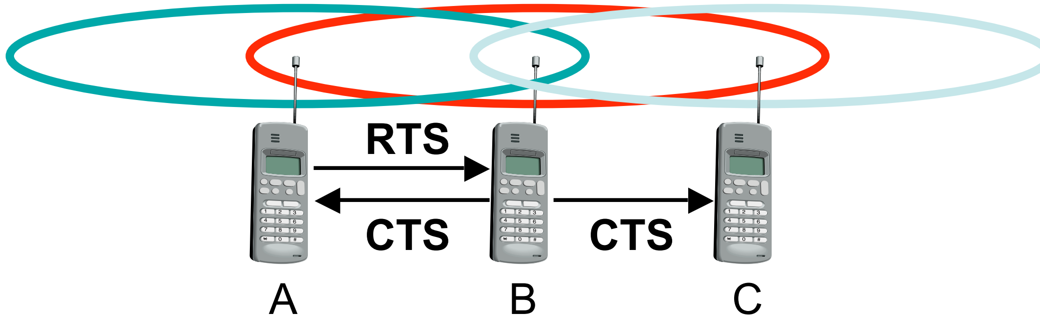
- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Also severe problem for CDMA-networks - precise power control needed!

MACA - collision avoidance

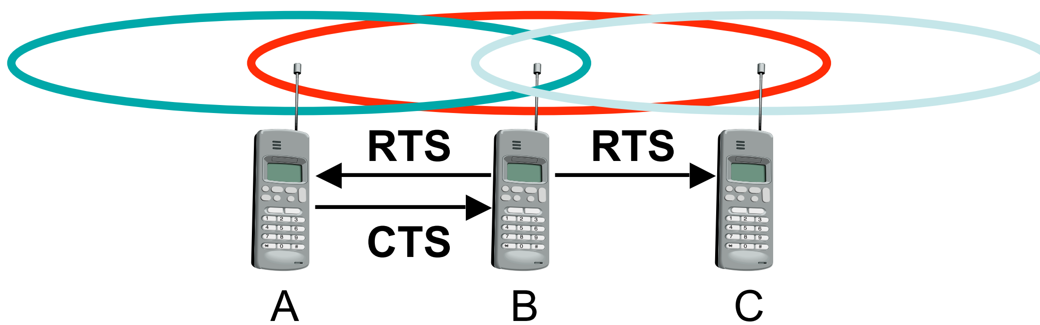
- No carrier sense (CS)
- MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance
  - RTS (request to send): sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
  - CTS (clear to send): the receiver grants 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 IEEE 802.11.

MACA examples

- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B

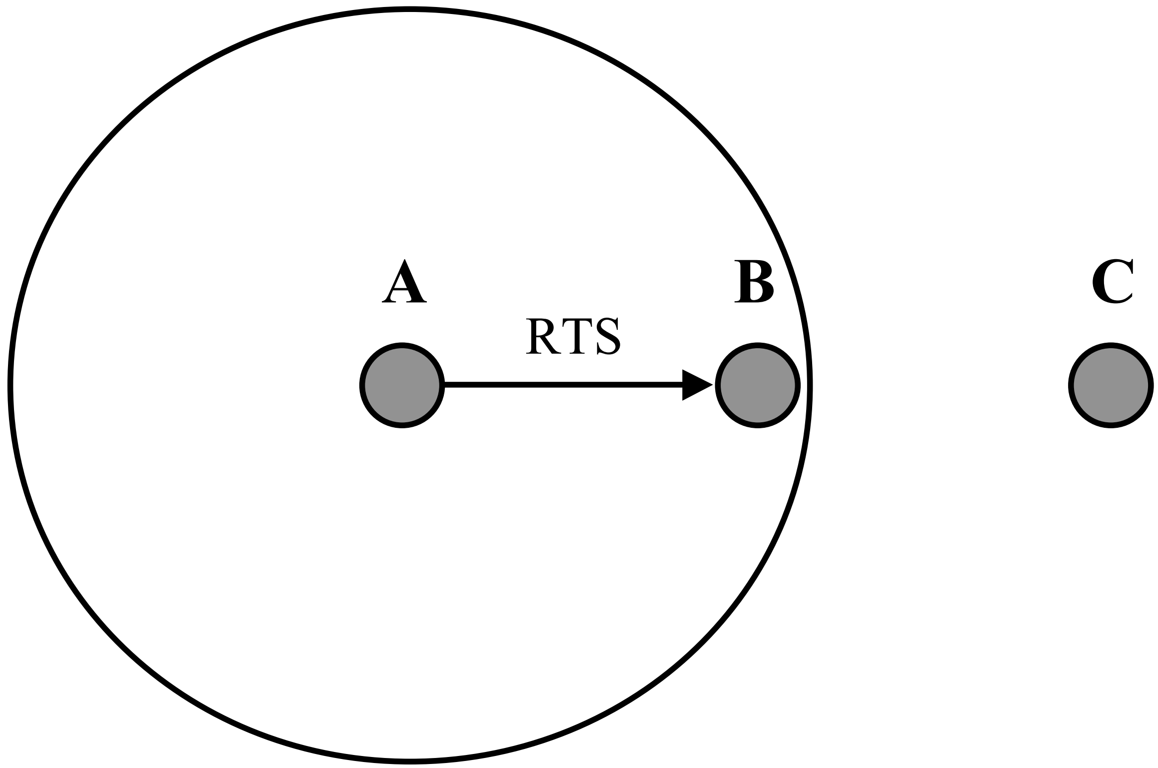


- MACA avoids the problem of exposed terminals?
  - B wants to send to A, C to another terminal
  - now C does not have to wait for it cannot receive CTS from A



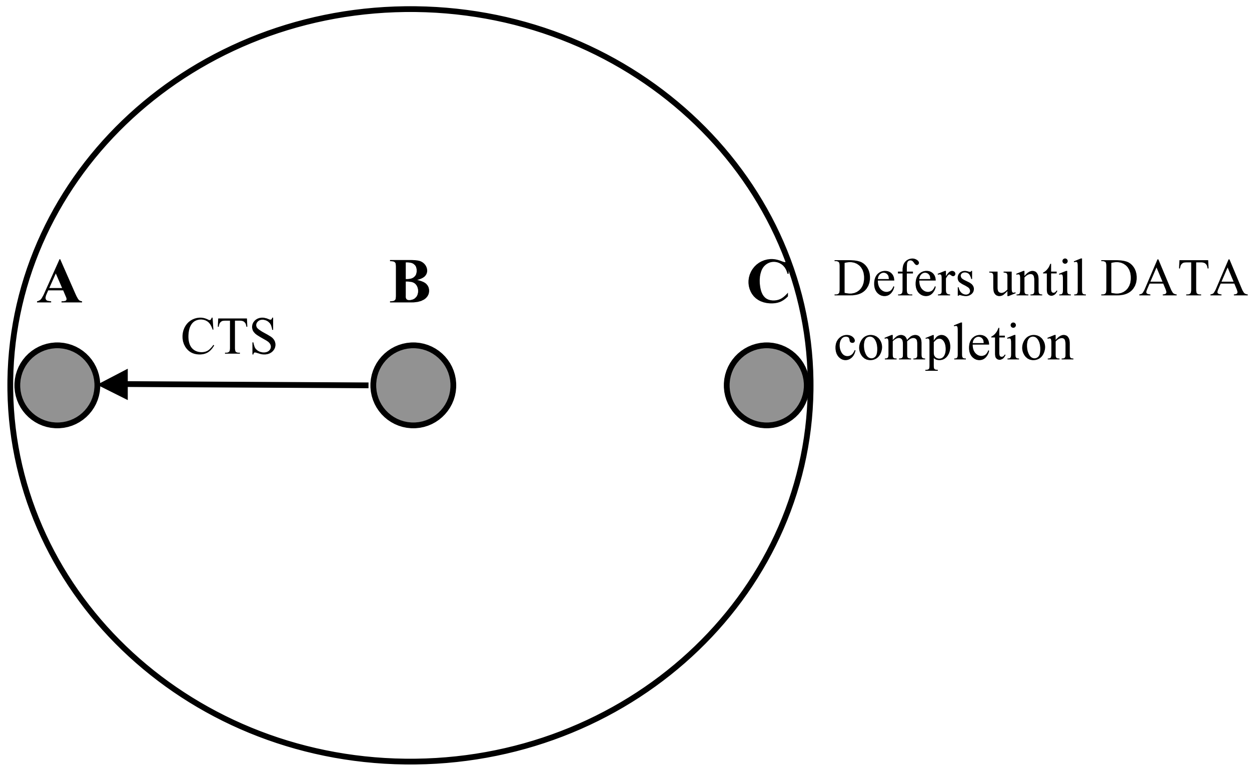
MACA in Action

- If C also transmits RTS, collision at B



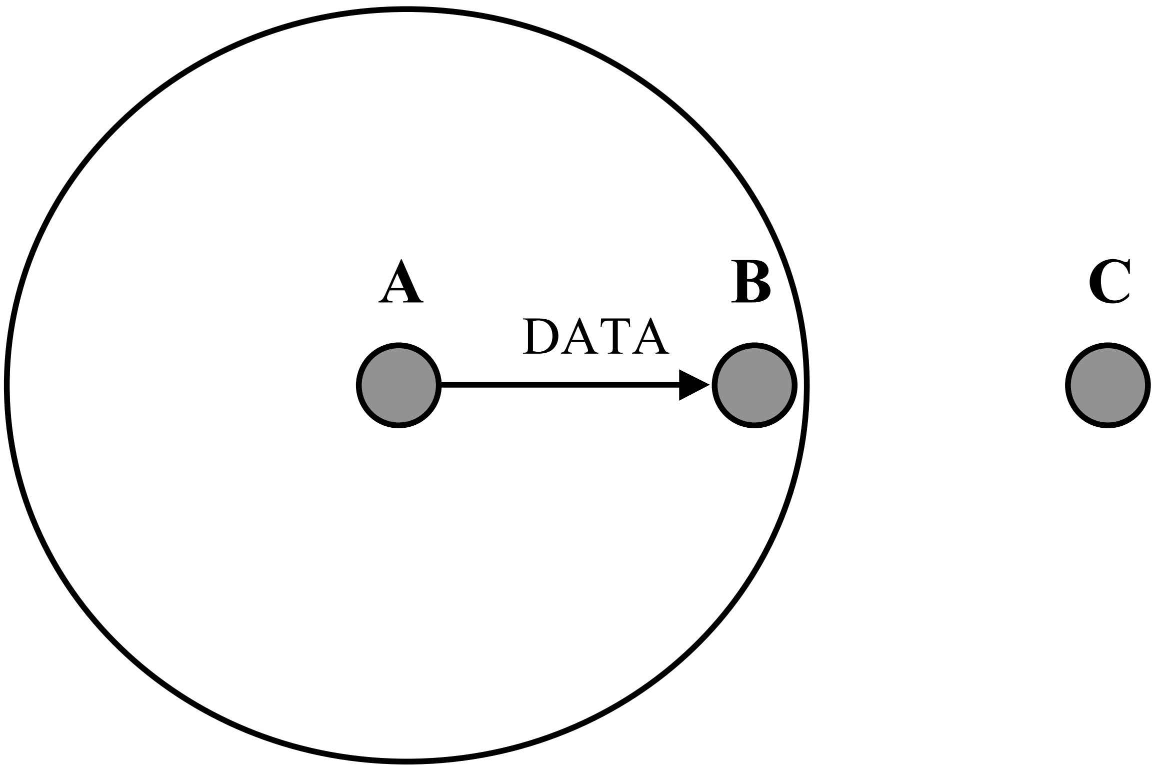
MACA in Action

- C knows the expected DATA length from CTS



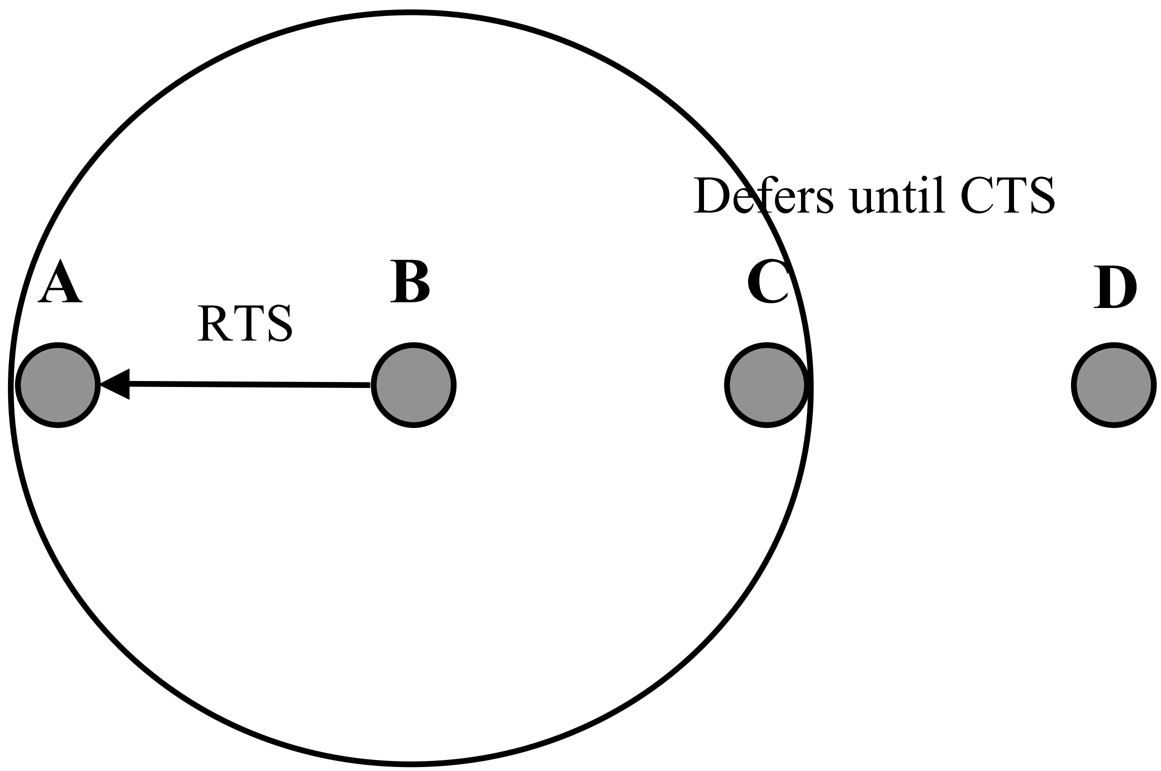
MACA in Action

- Avoids the hidden terminal problem



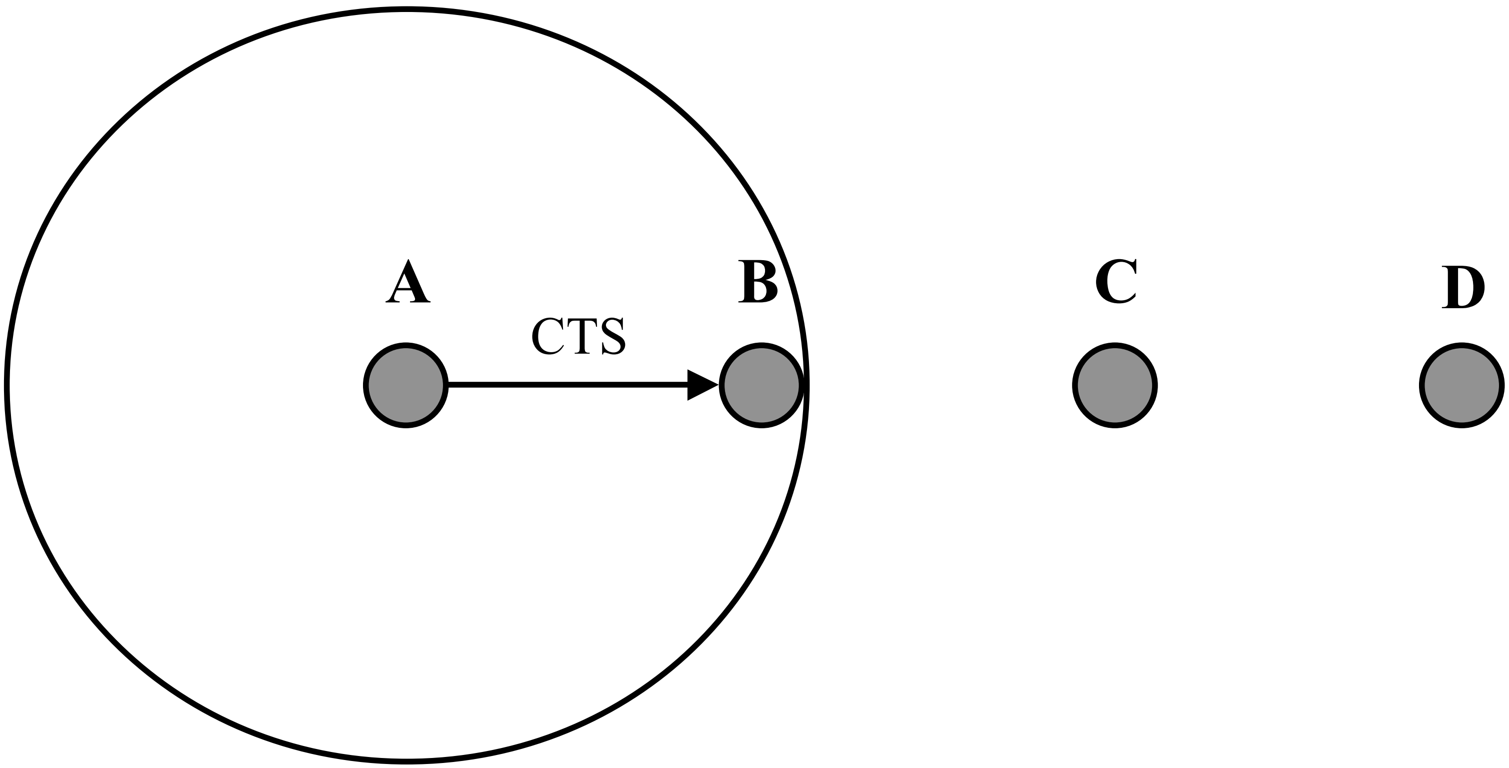
MACA in Action

- CTS packets have fixed size



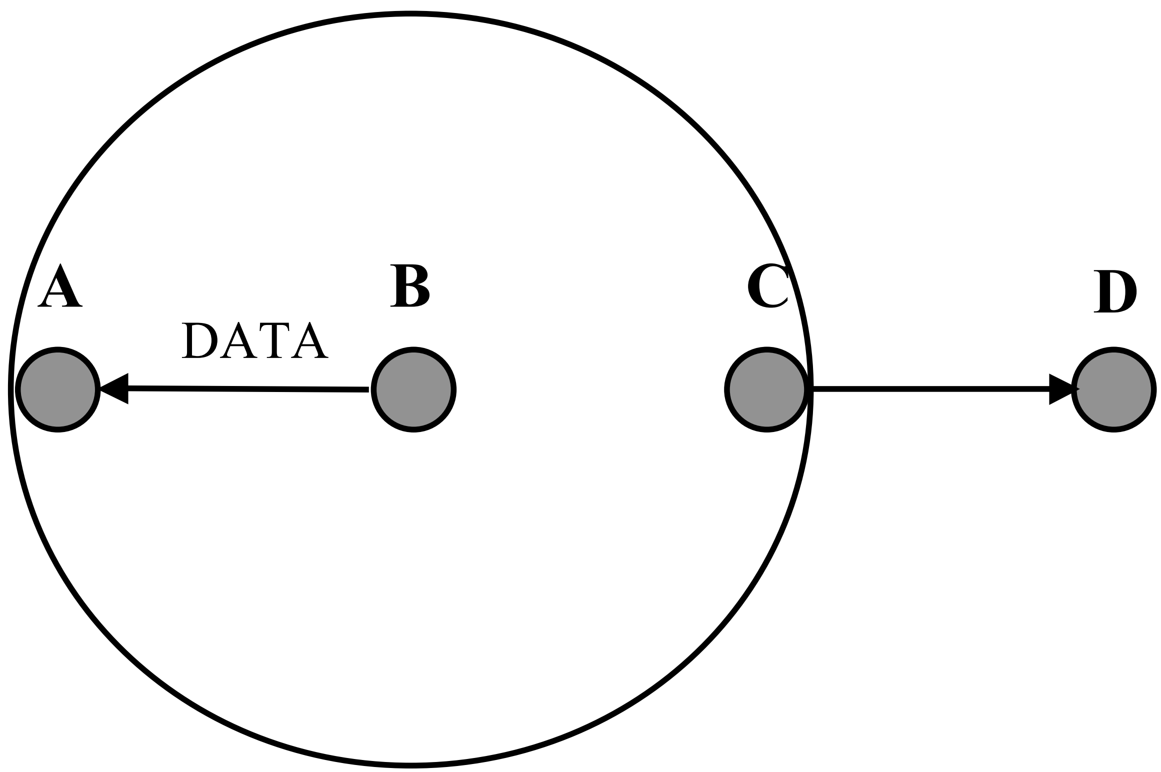
MACA in Action

- C does not hear a CTS



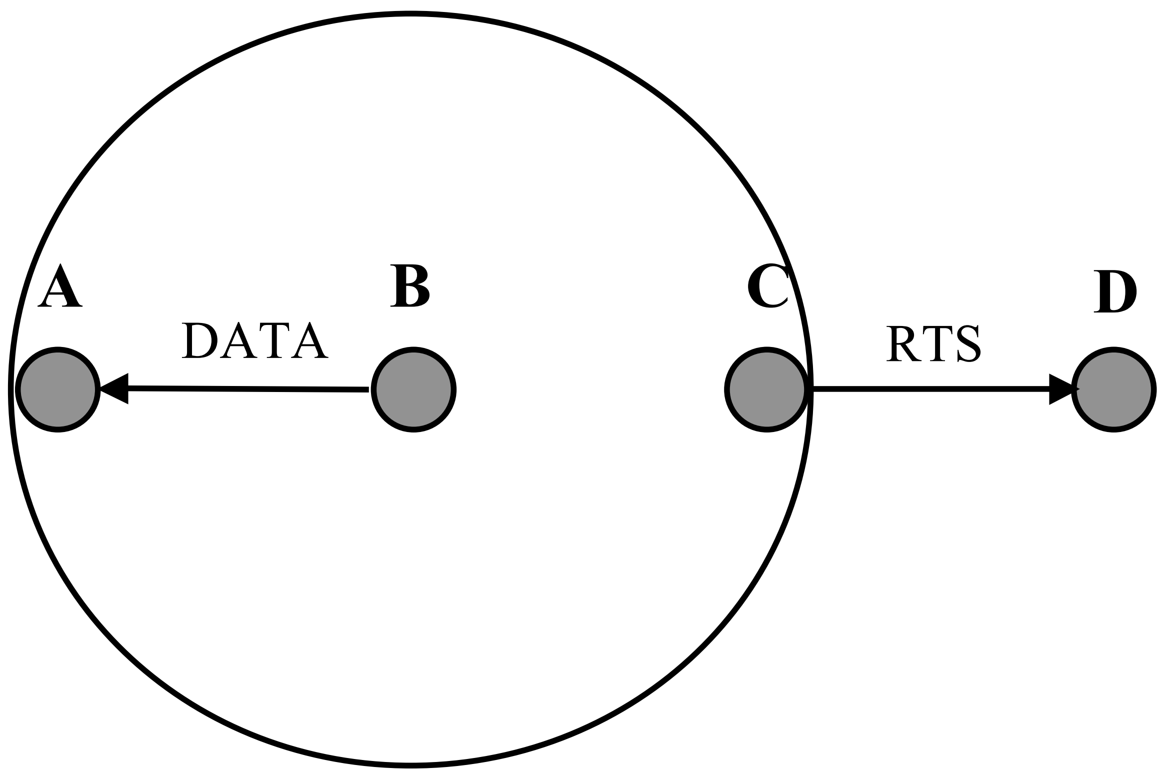
MACA in Action

- C is free to send to D; no exposed terminal



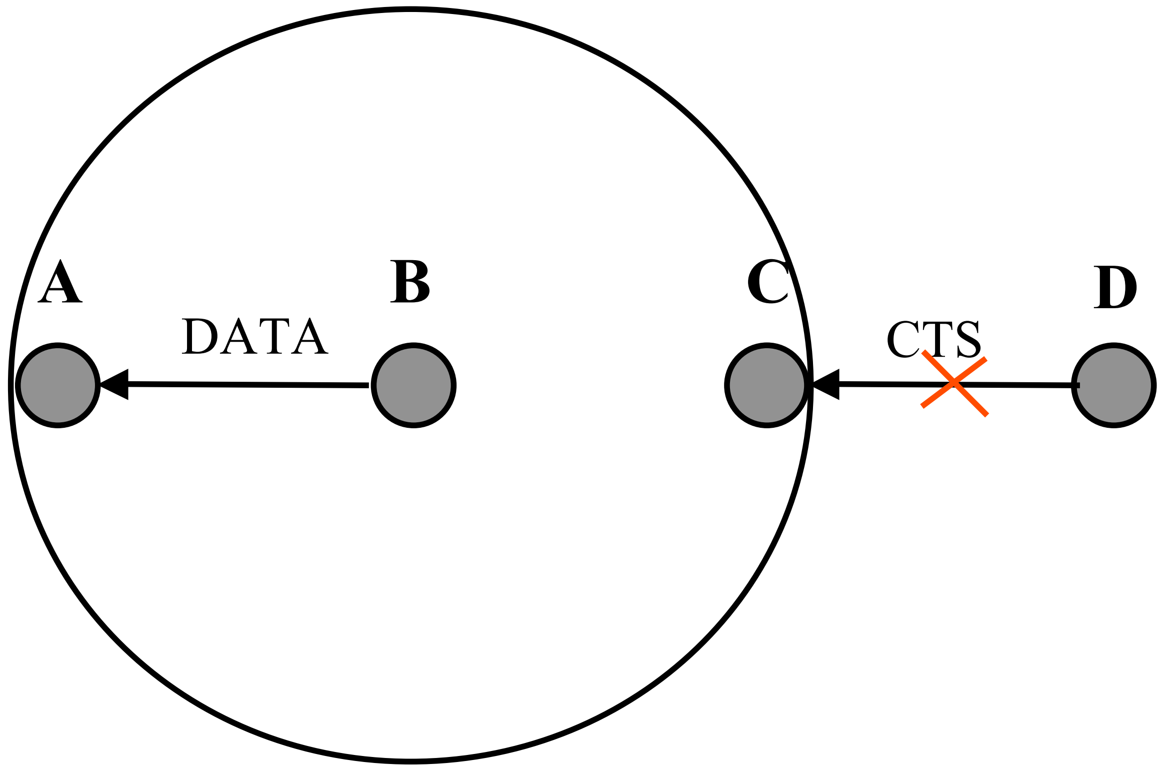
MACA in Action

- Is C really free to send to D?



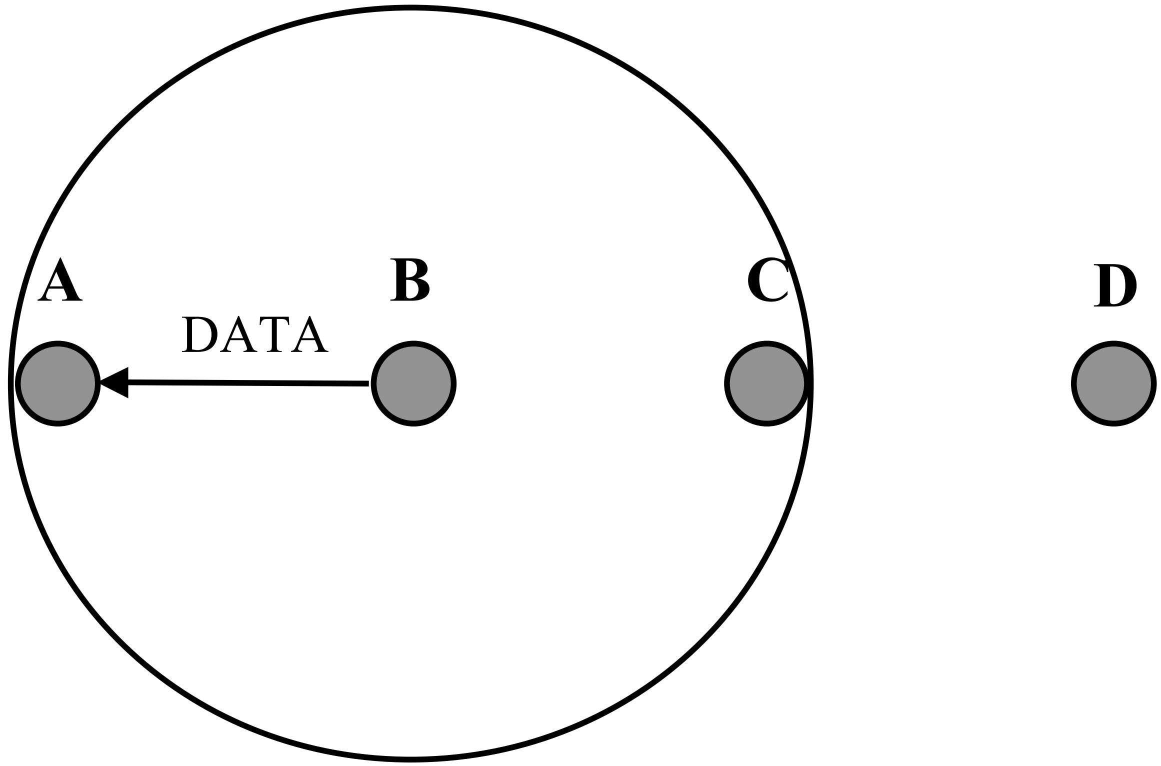
MACA in Action

- In fact, C increases its backoff counter!



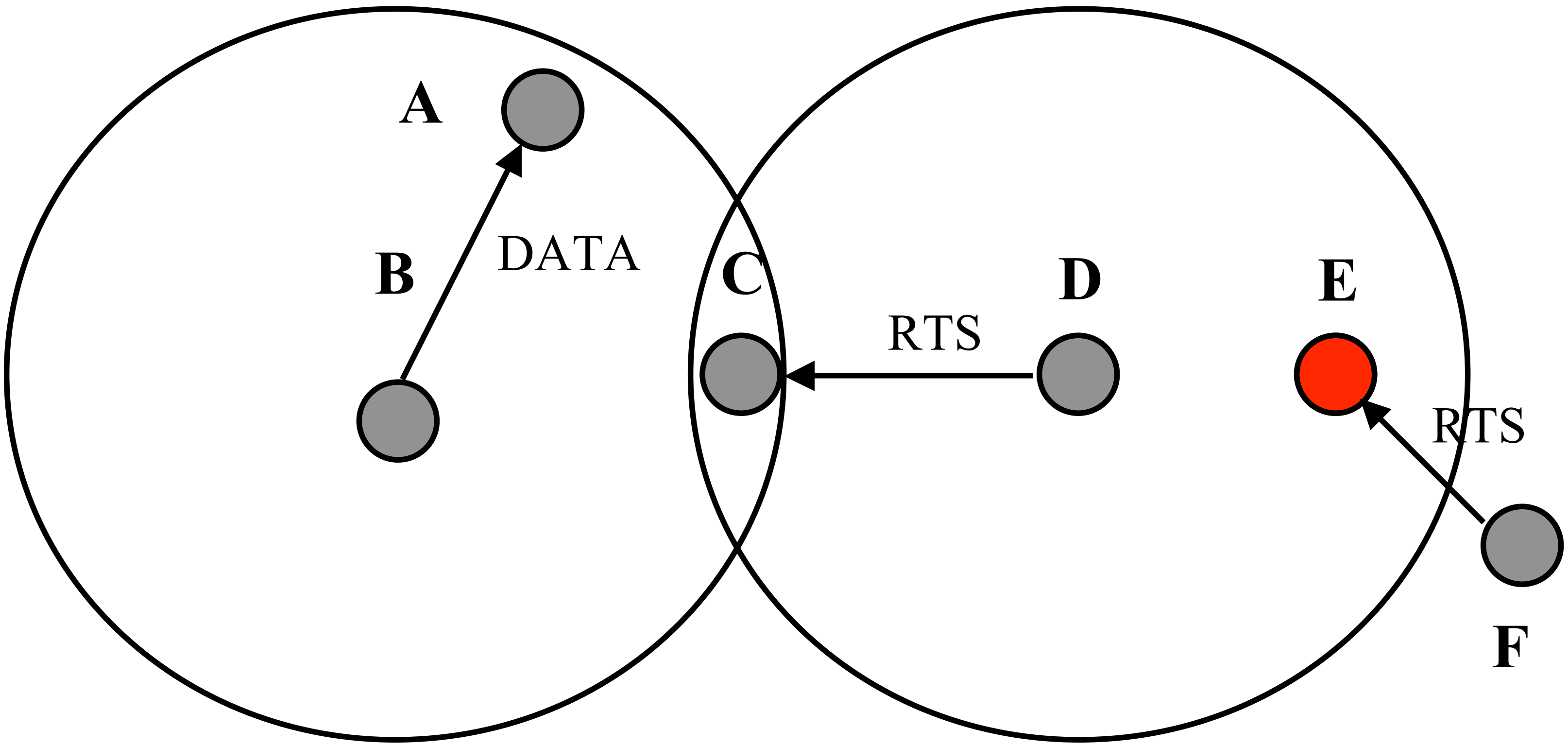
The CSMA/CA Approach

- Add carrier sense; C will sense B's transmission and refrain from sending RTS



False Blocking

- F sends RTS to E; D sends RTS to C
- E is falsely blocked



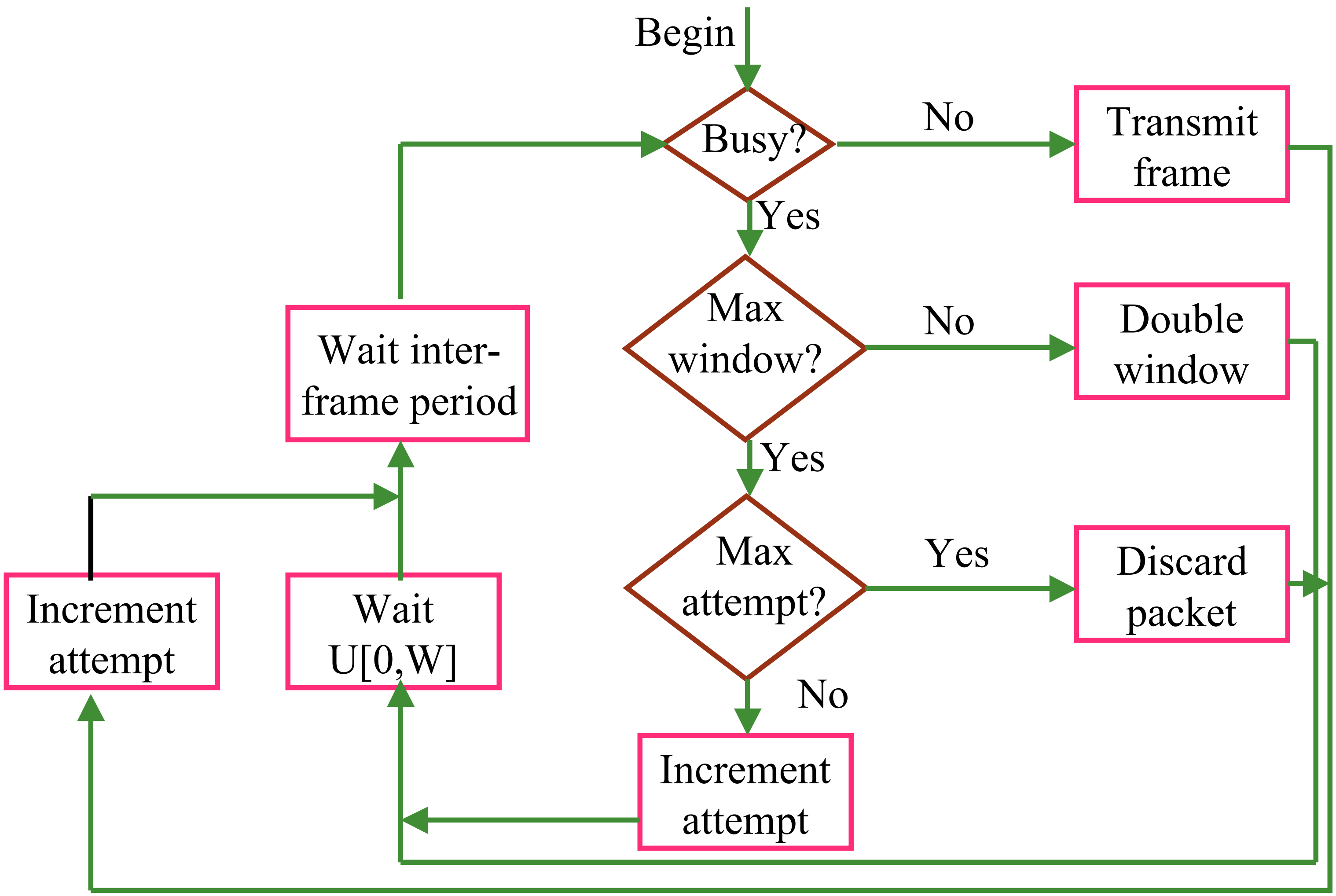
Alternative Approach: MACAW

- No carrier sense, no collision detection
- Collision avoidance:
  - Sender sends RTS
  - Receiver sends CTS
  - Sender sends DS
  - Sender sends DATA
  - Receiver sends ACK
  - Stations hearing DS defer until end of data transmission
- Backoff mechanism:
  - Exponential backoff with significant changes for improving fairness and throughput

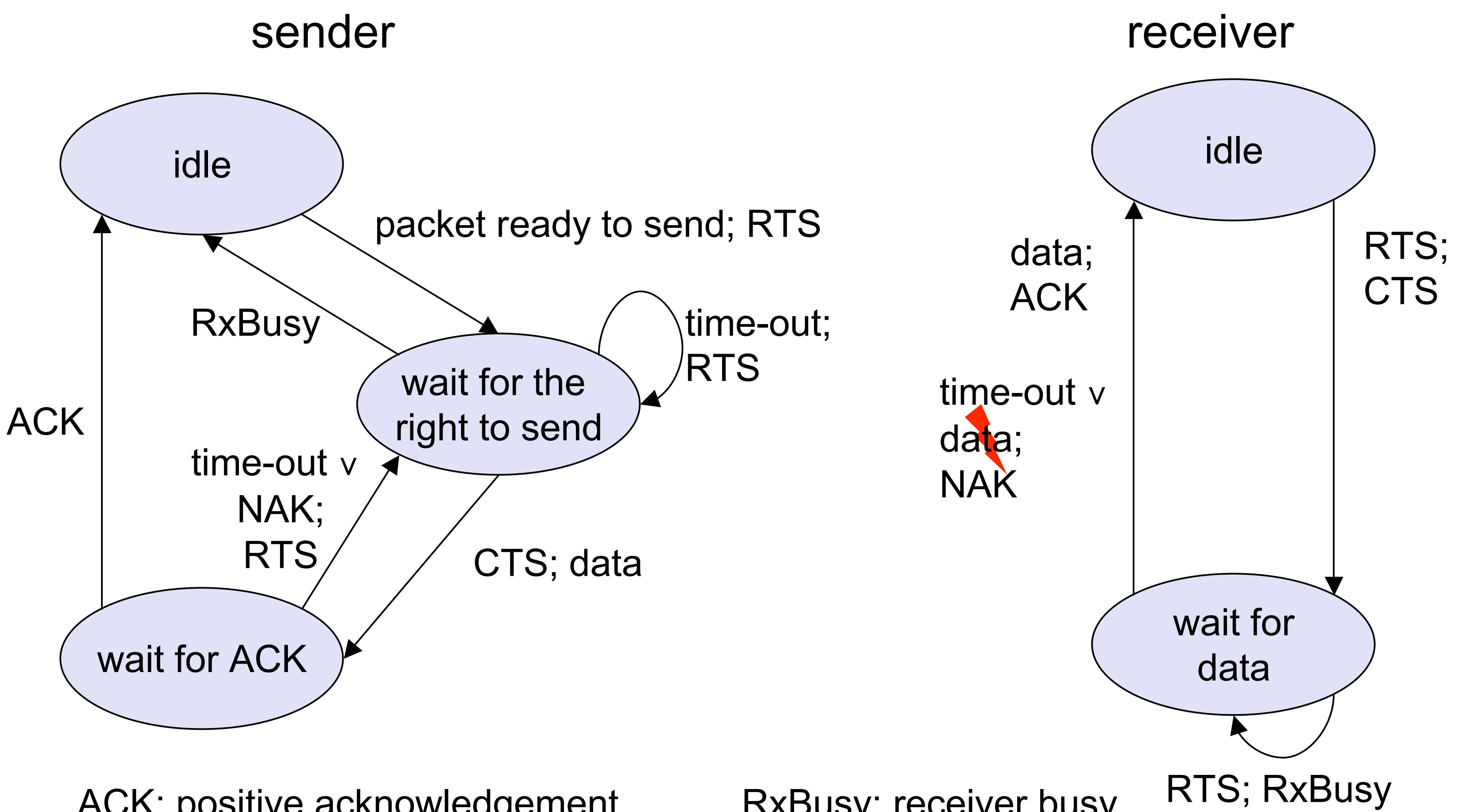
The IEEE 802.11 Protocol

- Two medium access schemes
- Point Coordination Function (PCF)
  - Centralized
  - For infrastructure mode
- Distributed Coordination Function (DCF)
  - For ad hoc mode
  - CSMA/CA
  - Exponential backoff

CSMA/CA with Exponential Backoff



MAC in IEEE 802.11



ACK: positive acknowledgement
NAK: negative acknowledgement

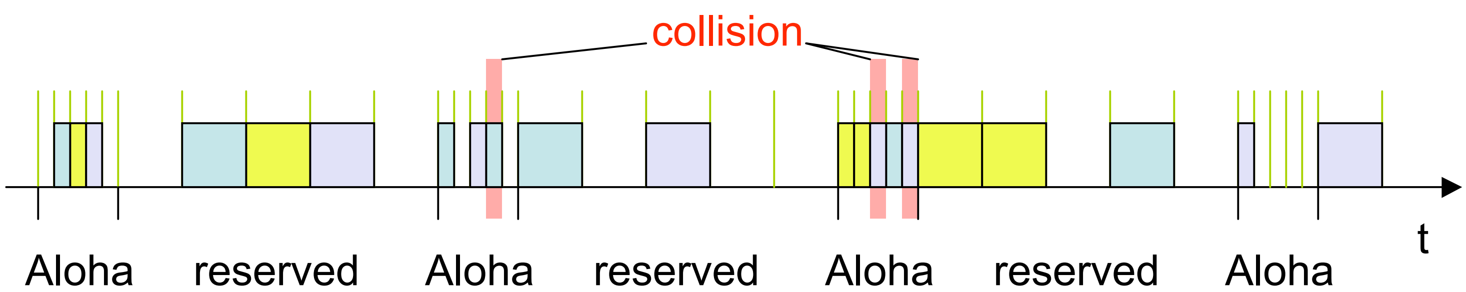
RxBusy: receiver busy

Demand Assigned Multiple Access

- Channel efficiency only 18% for Aloha, 36% for Slotted Aloha (assuming Poisson distribution for packet arrival and packet length)
- Reservation can increase efficiency to 80%
  - a sender *reserves* a future time-slot
  - sending within this reserved time-slot is possible without collision
  - reservation also causes higher delays
  - typical scheme for satellite links
- Examples for reservation algorithms:
  - *Explicit Reservation (Reservation-ALOHA)*
  - *Implicit Reservation (PRMA)*
  - *Reservation-TDMA*

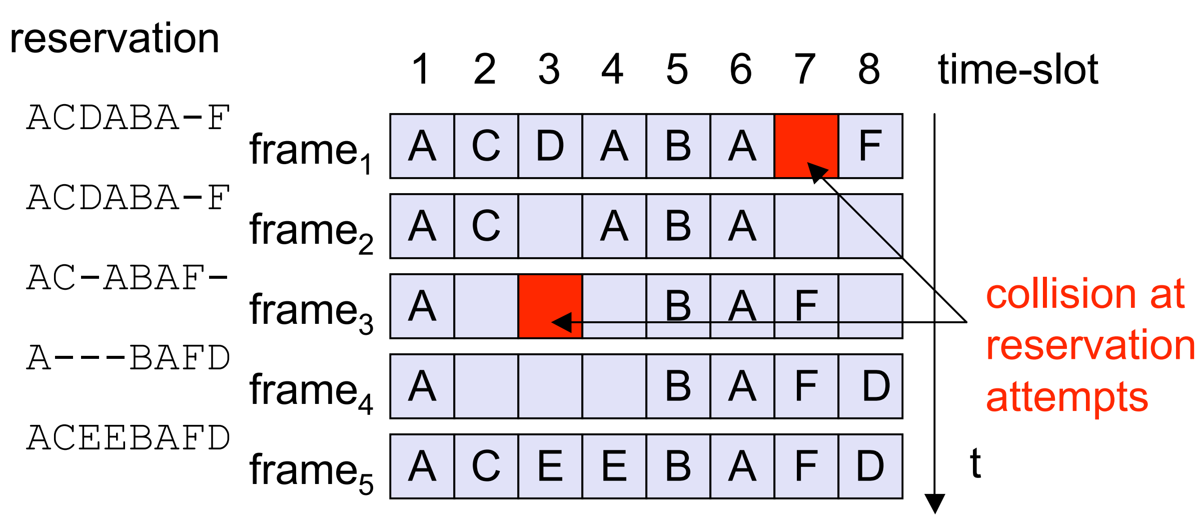
DAMA: Explicit Reservation

- Explicit Reservation (Reservation Aloha):
  - two modes:
    - *ALOHA mode* for reservation:
      competition for small reservation slots, collisions possible
    - *reserved mode* for data transmission within successful reserved slots (no collisions possible)
  - it is important for all stations to keep the reservation list consistent at any point in time and, therefore, all stations have to synchronize from time to time



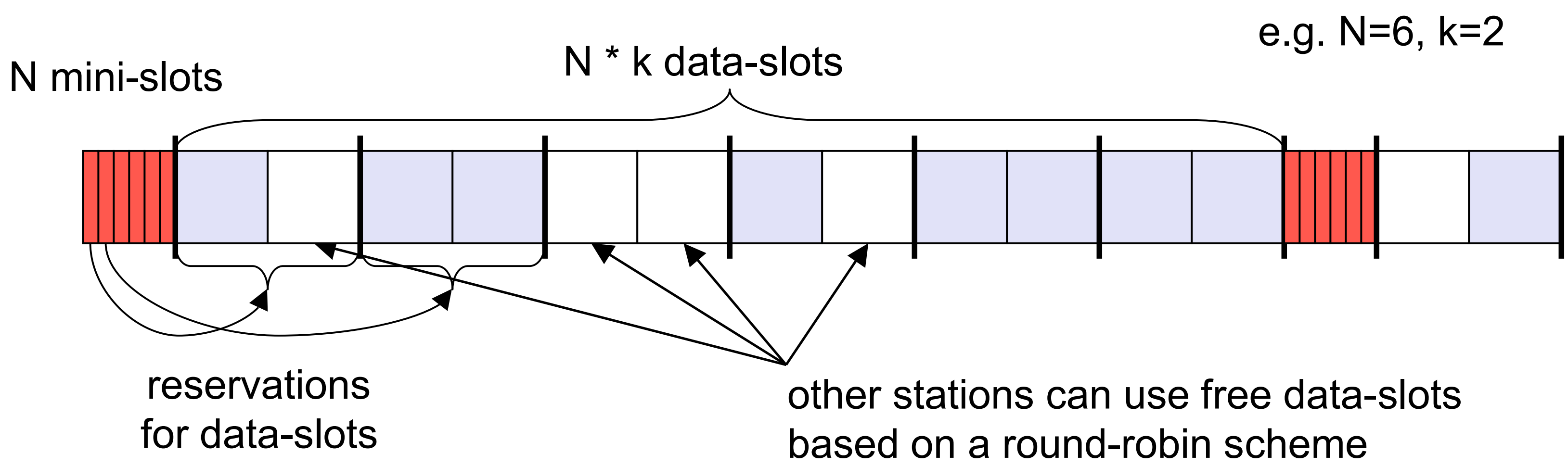
DAMA: PRMA

- Implicit reservation (PRMA - Packet Reservation MA):
  - a certain number of slots form a frame, frames are repeated
  - stations compete for empty slots according to the slotted aloha principle
  - once a station reserves a slot successfully, this slot is automatically assigned to this station in all following frames as long as the station has data to send
  - competition for this slots starts again as soon as the slot was empty in the last frame



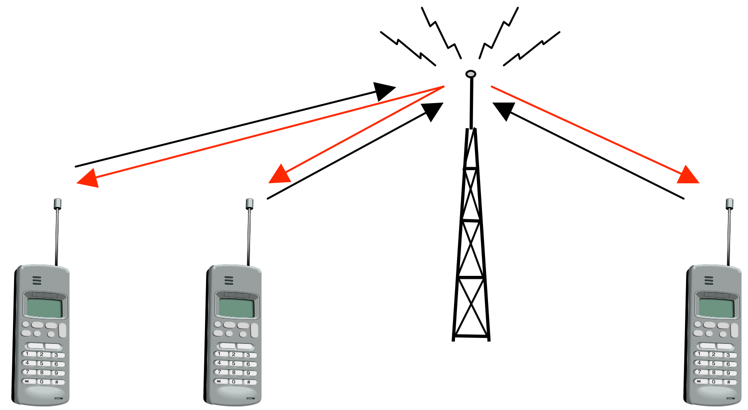
DAMA: Reservation-TDMA

- Reservation Time Division Multiple Access
  - o every frame consists of N mini-slots and x data-slots
  - o every station has its own mini-slot and can reserve up to k data-slots using this mini-slot (i.e. x = N * k).
  - o other stations can send data in unused data-slots according to a round-robin sending scheme (best-effort traffic)

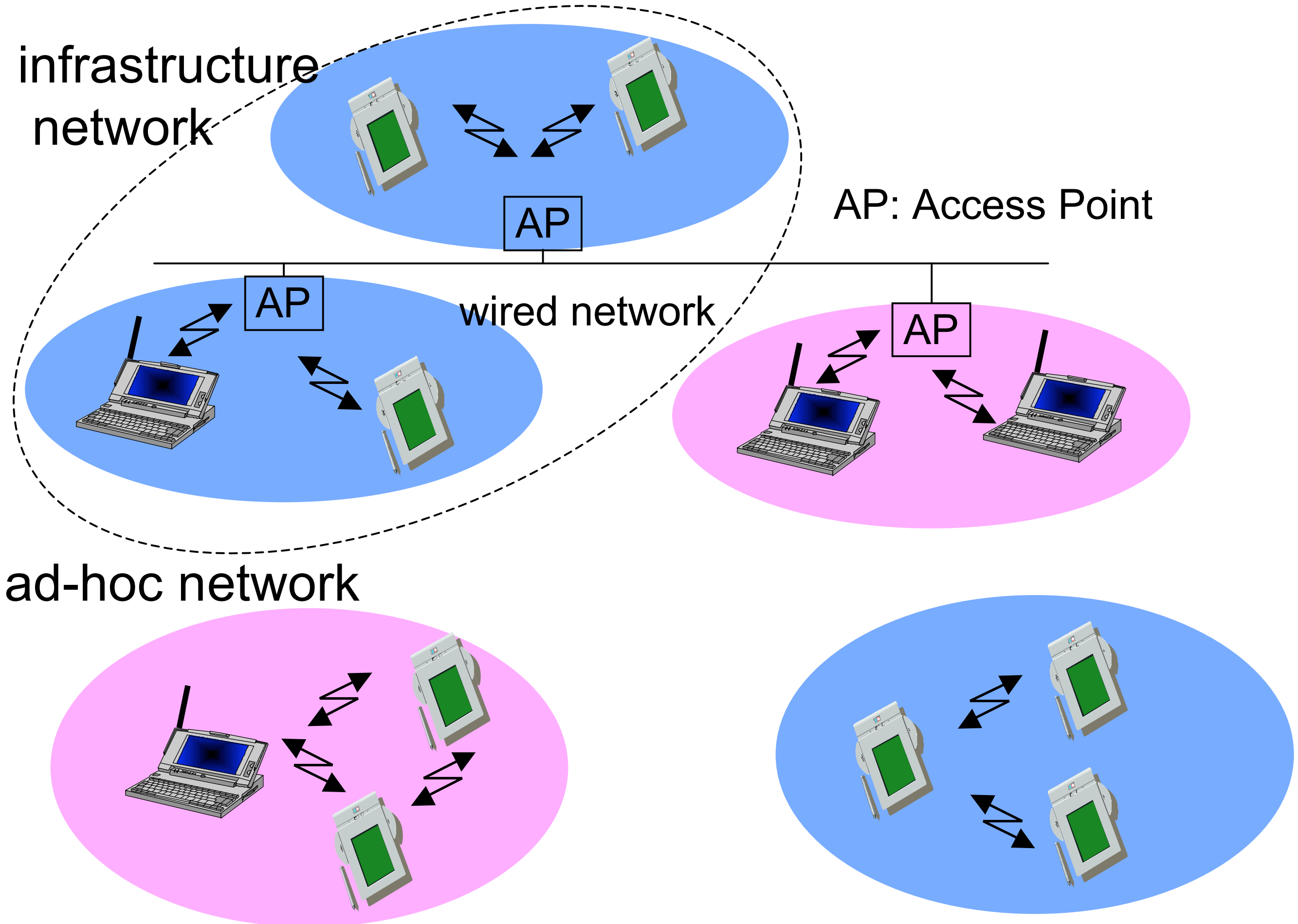


ISMA (Inhibit Sense)

- Current state of the medium is signaled via a "busy tone"
  - the base station signals on the downlink (base station to terminals) if the medium is free or not
  - terminals must not send if the medium is busy
  - terminals can access the medium as soon as the busy tone stops
  - the base station signals collisions and successful transmissions via the busy tone and acknowledgements, respectively (media access is not coordinated within this approach)
  - mechanism used, e.g., for CDPD (USA, integrated into AMPS)

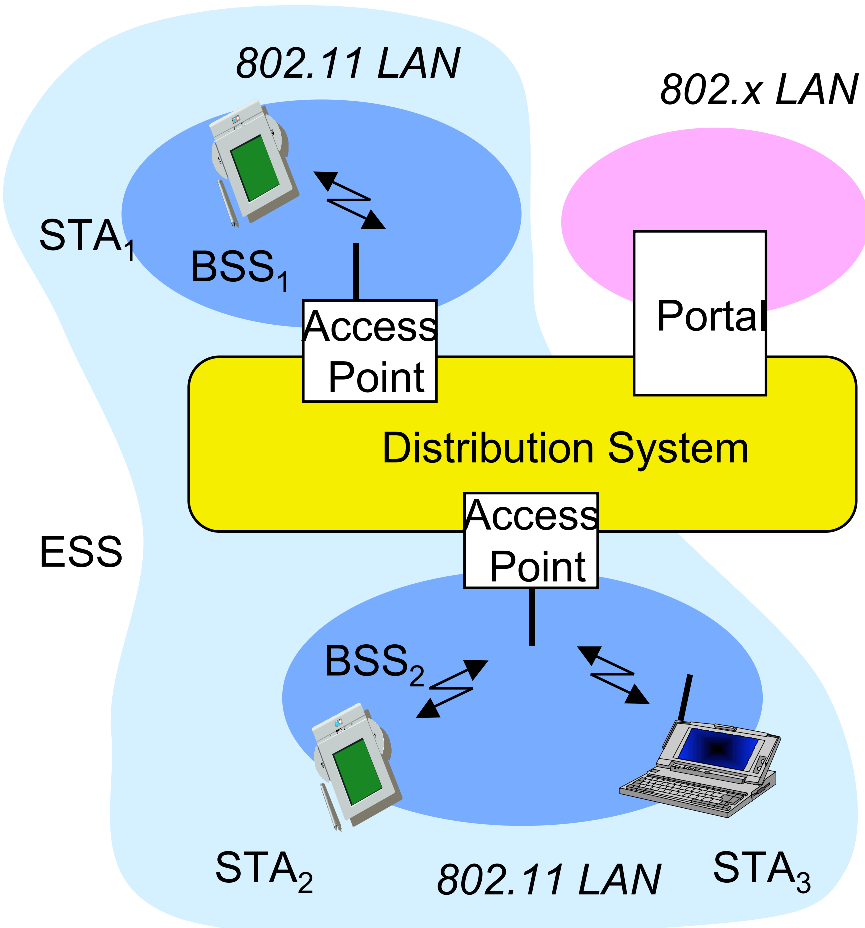


IEEE802.11



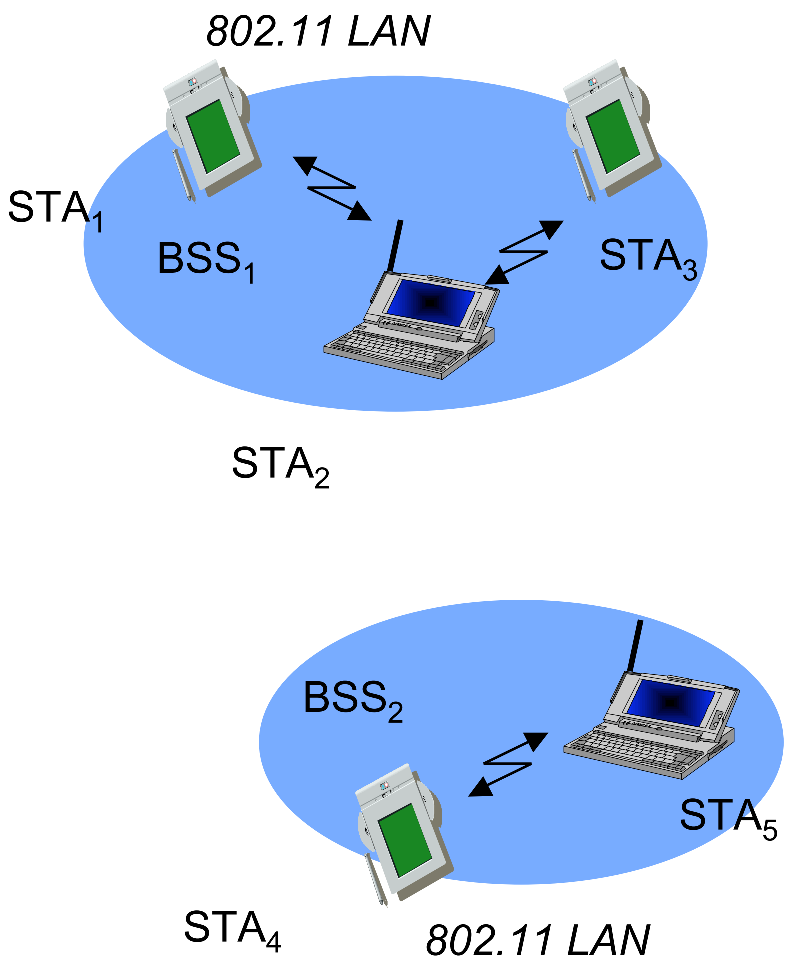
infrastructure network
AP
AP: Access Point
AP
wired network
AP
ad-hoc network

802.11 infrastructure mode



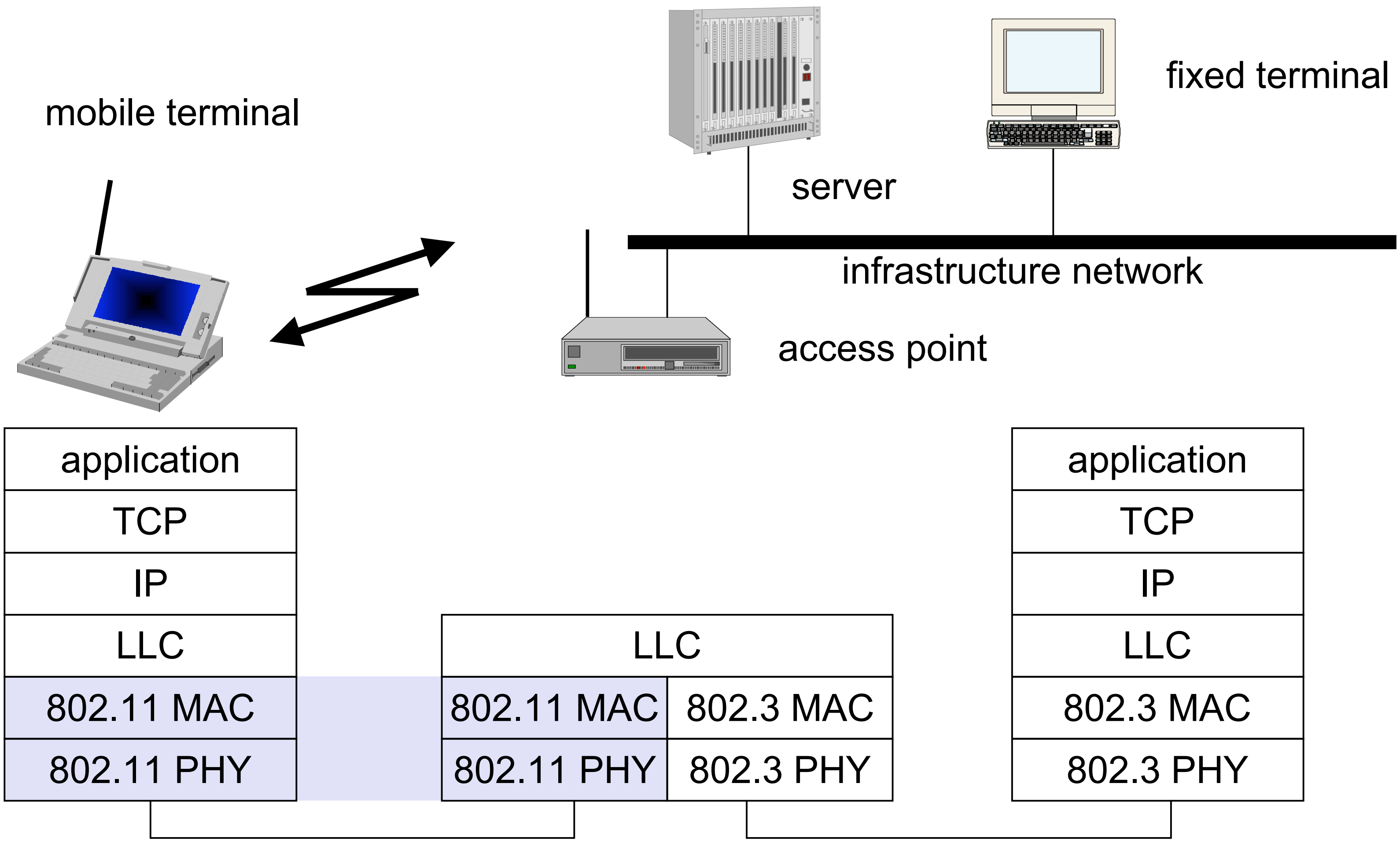
- Station (STA)
  - terminal with access mechanisms to the wireless medium and radio contact to the access point
- Basic Service Set (BSS)
  - group of stations using the same radio frequency
- Access Point
  - station integrated into the wireless LAN and the distribution system
- Portal
  - bridge to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

802.11: ad-hoc mode



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

IEEE standard 802.11



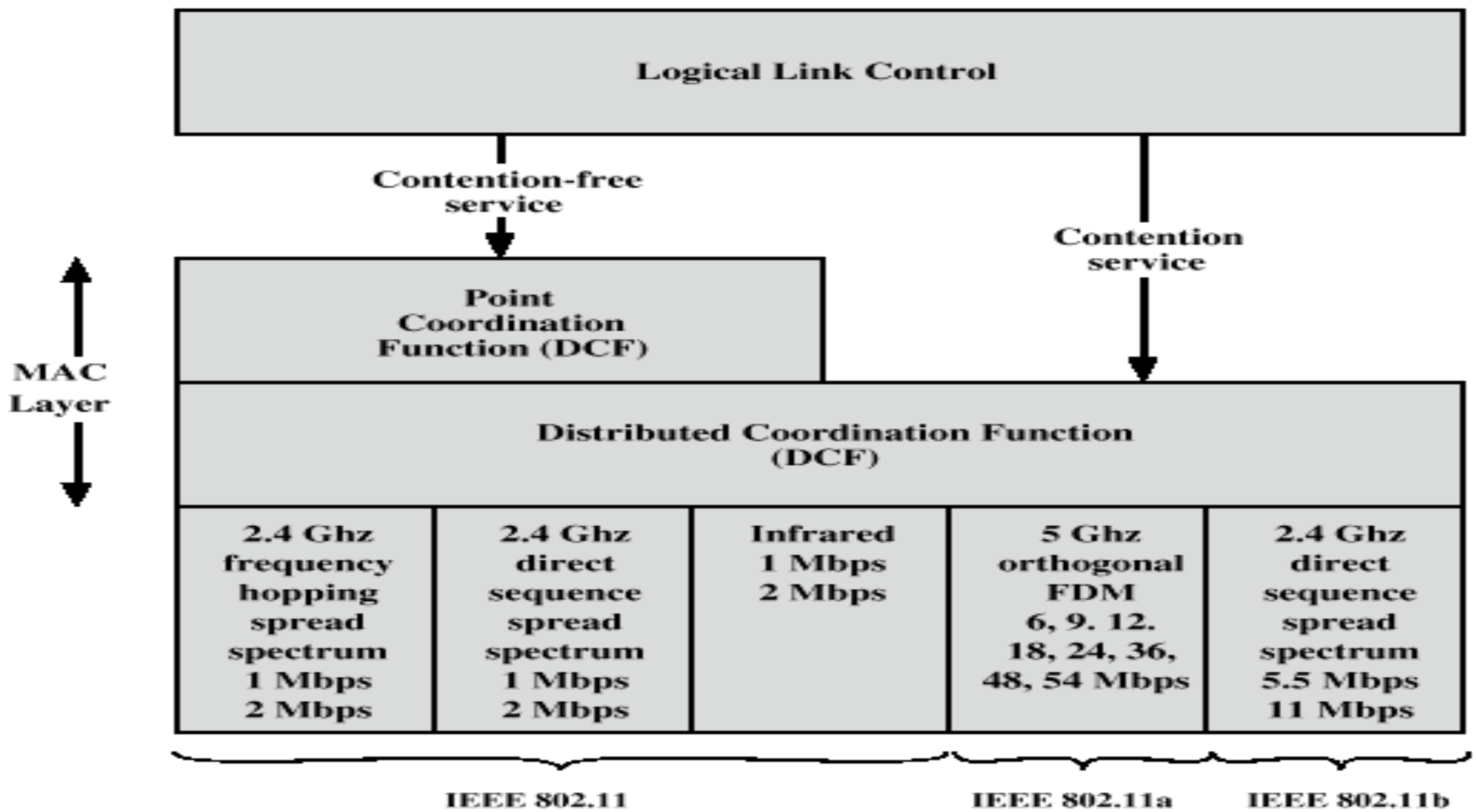


Figure 14.5 IEEE 802.11 Protocol Architecture

802.11 - Physical layer

- 2 radio ranges (2.4 GHz and 5 GHz), 1 IR
  - data rates ranging from 1 Mbps to 54 Mbps
- FHSS (Frequency Hopping Spread Spectrum) 2.4 GHz
  - spreading, de-spreading, signal strength, typically 1 Mbit/s
  - min. 2.5 frequency hops/s (USA), two-level GFSK modulation
- DSSS (Direct Sequence Spread Spectrum) 2.4 GHz
  - DBPSK or DQPSK modulation (Differential Binary Phase Shift Keying or Differential Quadrature PSK)
  - Chipping sequence: +1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1 (Barker code)
  - Maximum radiated power 1 W (USA), 100 mW (EU), min. 1mW
- Infrared
  - 850-950 nm, diffuse light, typically 10 m range
  - Data rates 1-2 Mbps

IEEE 802.11a and IEEE 802.11b

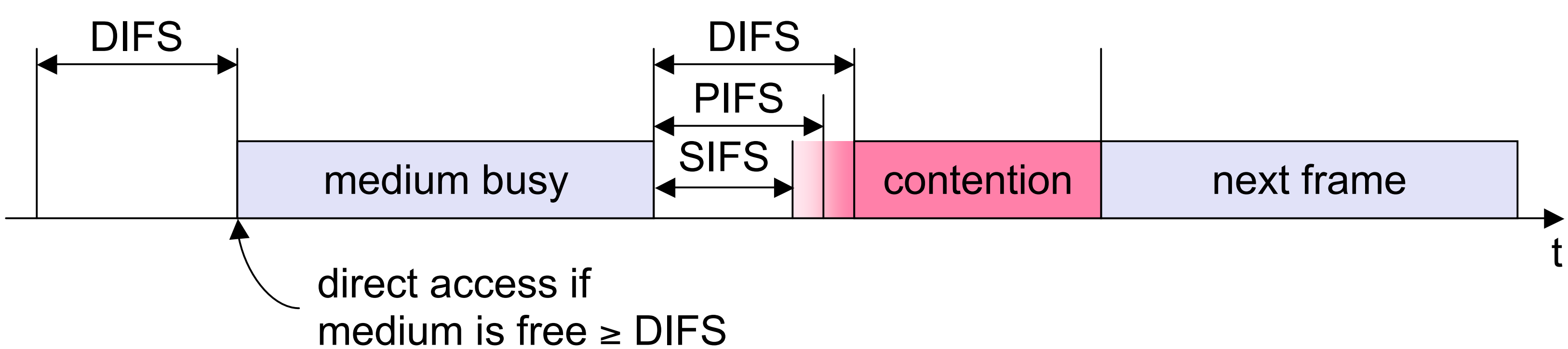
- IEEE 802.11a
  - Makes use of 5-GHz band
  - Provides rates of 6, 9 , 12, 18, 24, 36, 48, 54 Mbps
  - Uses orthogonal frequency division multiplexing (OFDM)
  - Sub-carrier modulated using BPSK, QPSK, 16-QAM or 64-QAM
- IEEE 802.11b
  - Provides data rates of 5.5 and 11 Mbps
  - DSSS and complementary code keying (CCK) modulation
- IEEE 802.11g
  - Extends data rates to up to 54 Mbps
  - Uses OFDM, in the 2.4 GHz band

802.11 - MAC layer

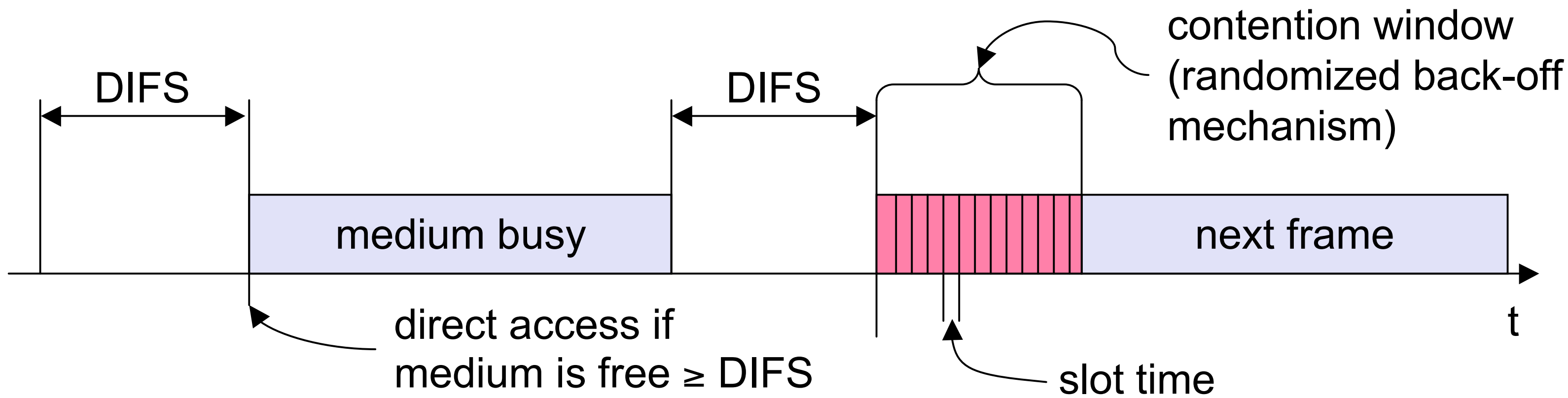
- Traffic services
  - Asynchronous Data Service (mandatory)
    - exchange of data packets based on “best-effort”
    - support of broadcast and multicast
  - Time-Bounded Service (optional)
    - implemented using PCF (Point Coordination Function)
- Access methods
  - DCF CSMA/CA (mandatory)
    -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

802.11 - MAC layer

- 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

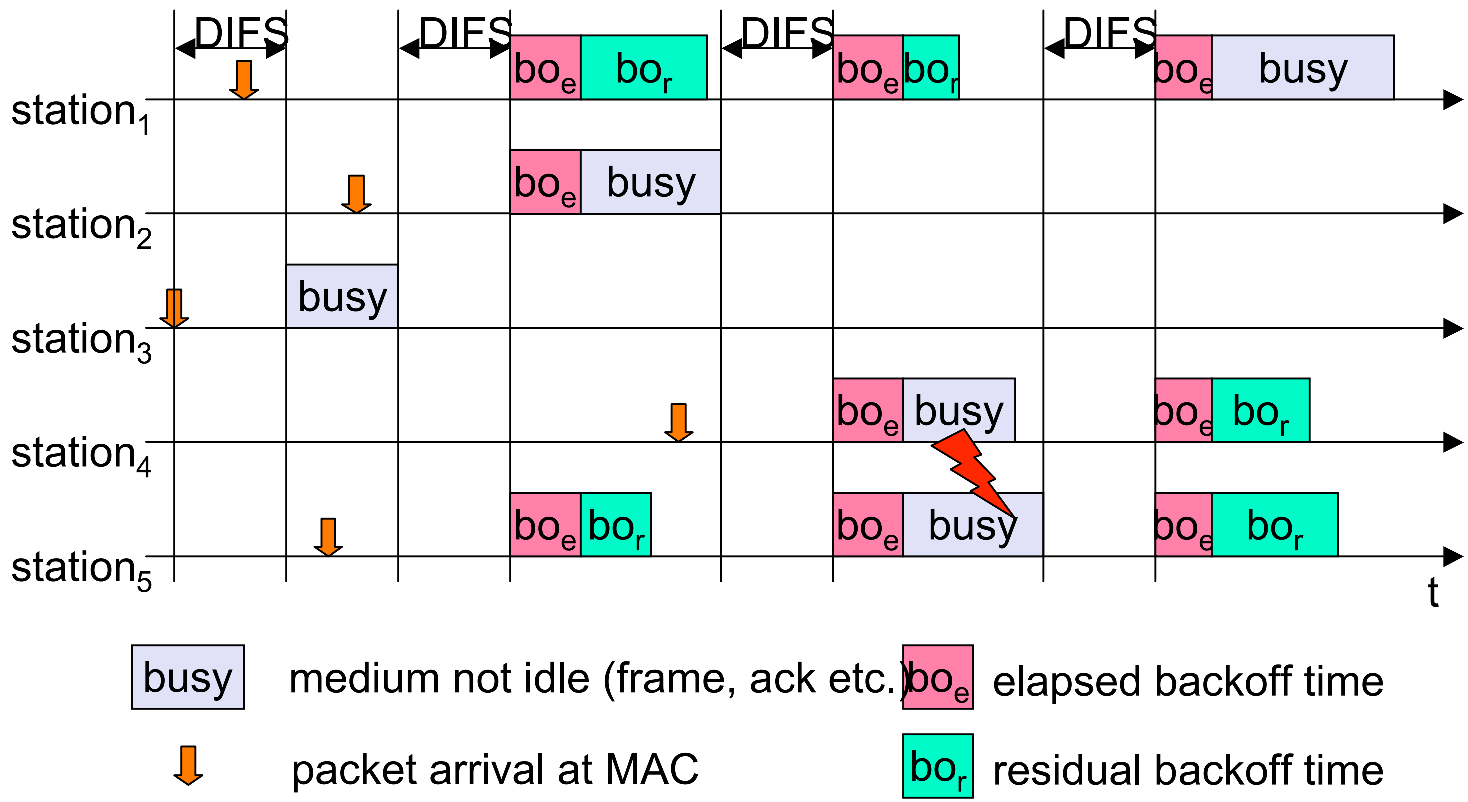


CSMA/CA access method



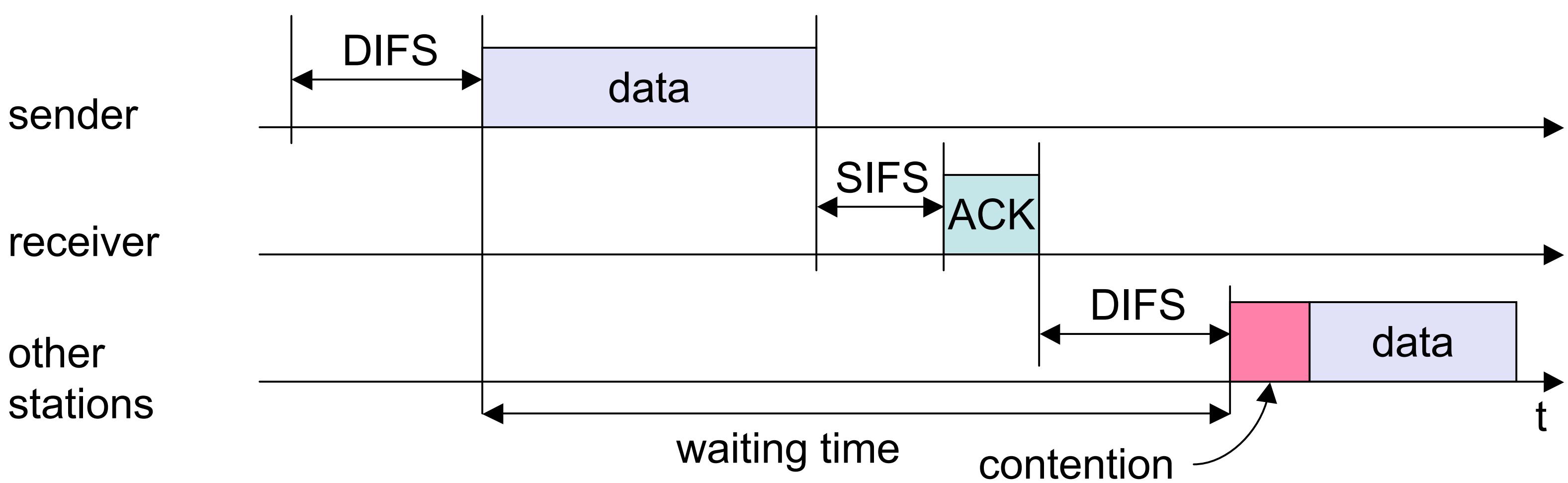
- Station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- If the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- If the medium is busy, the station has to wait for a free IFS,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

Contending stations



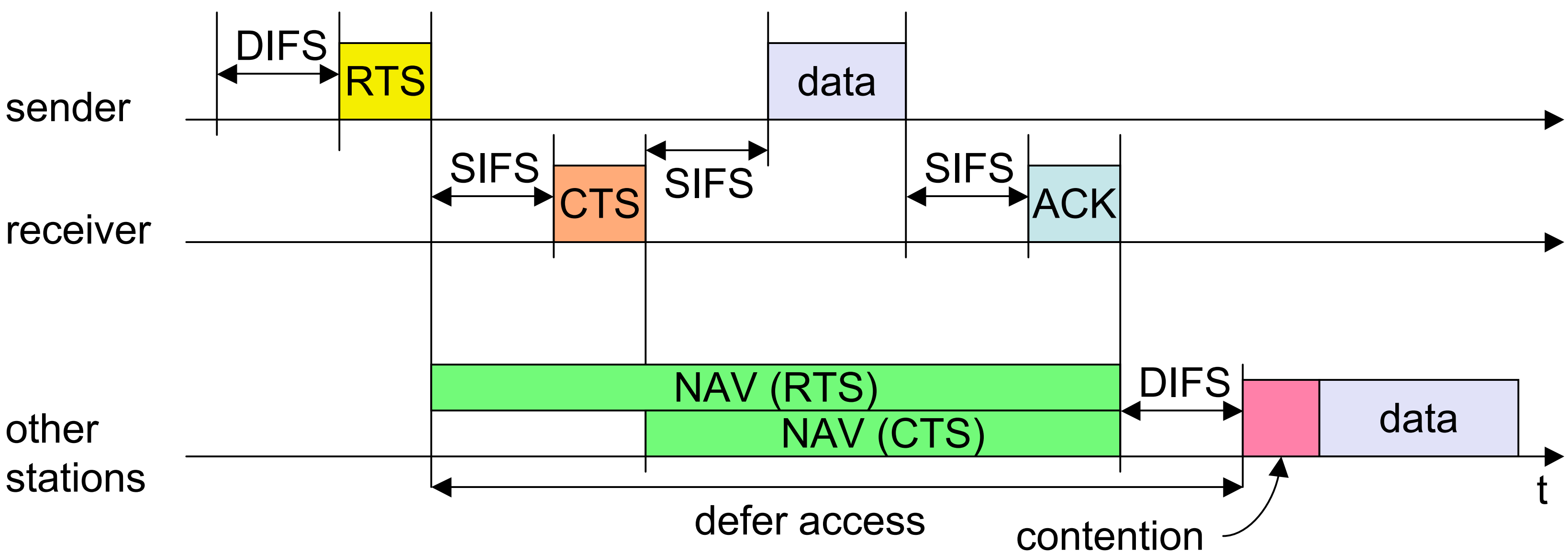
802.11 access scheme details

- 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

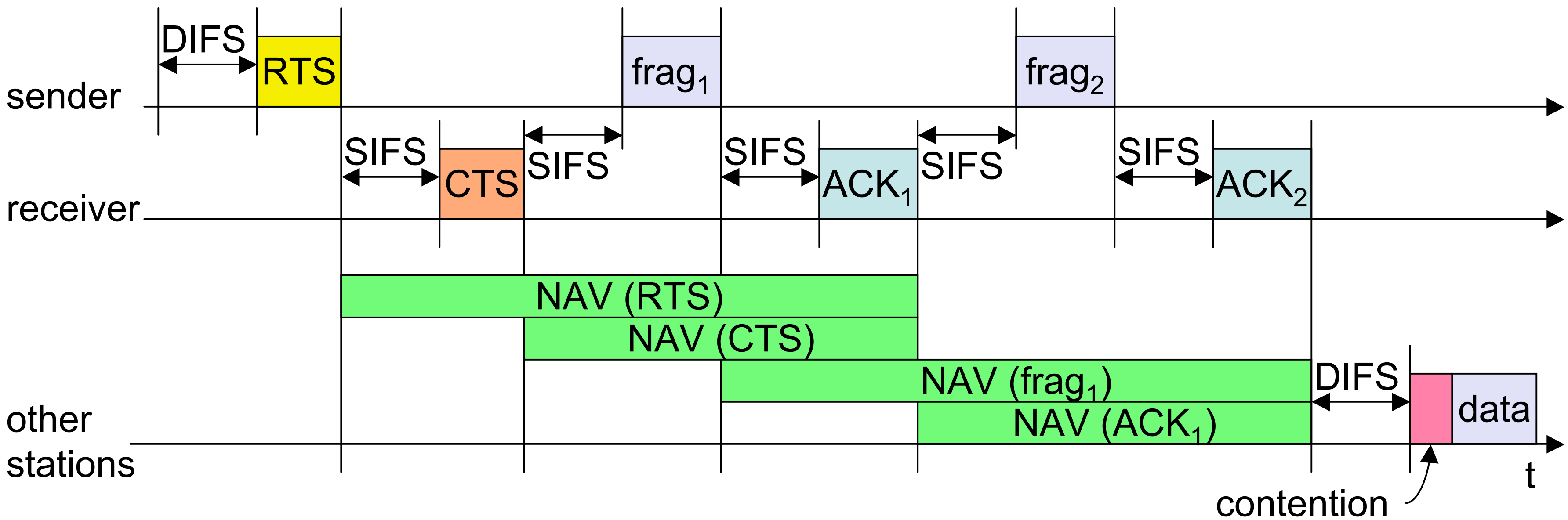


802.11 access scheme details

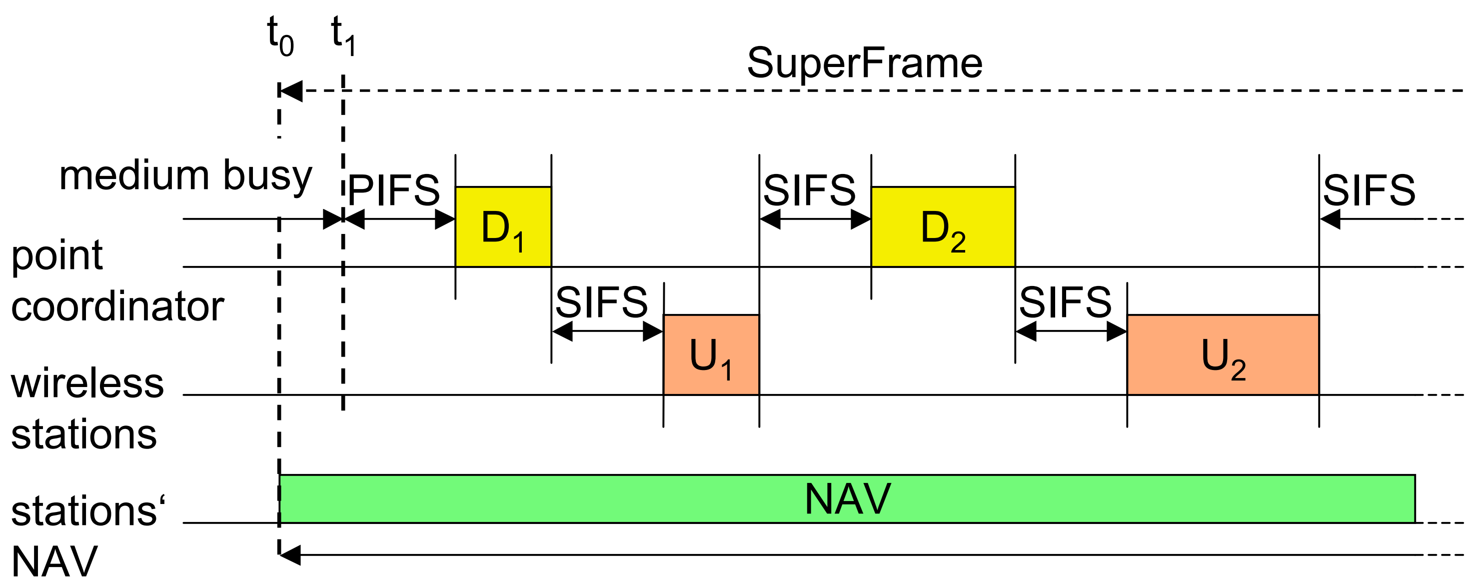
- Sending unicast packets
  - station can send RTS with reservation parameter after waiting for DIFS (reservation determines amount of time the data packet needs the medium)
  - ack via CTS after SIFS by receiver (if ready to receive)
  - sender can now send data at once, acknowledgement via ACK
  -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



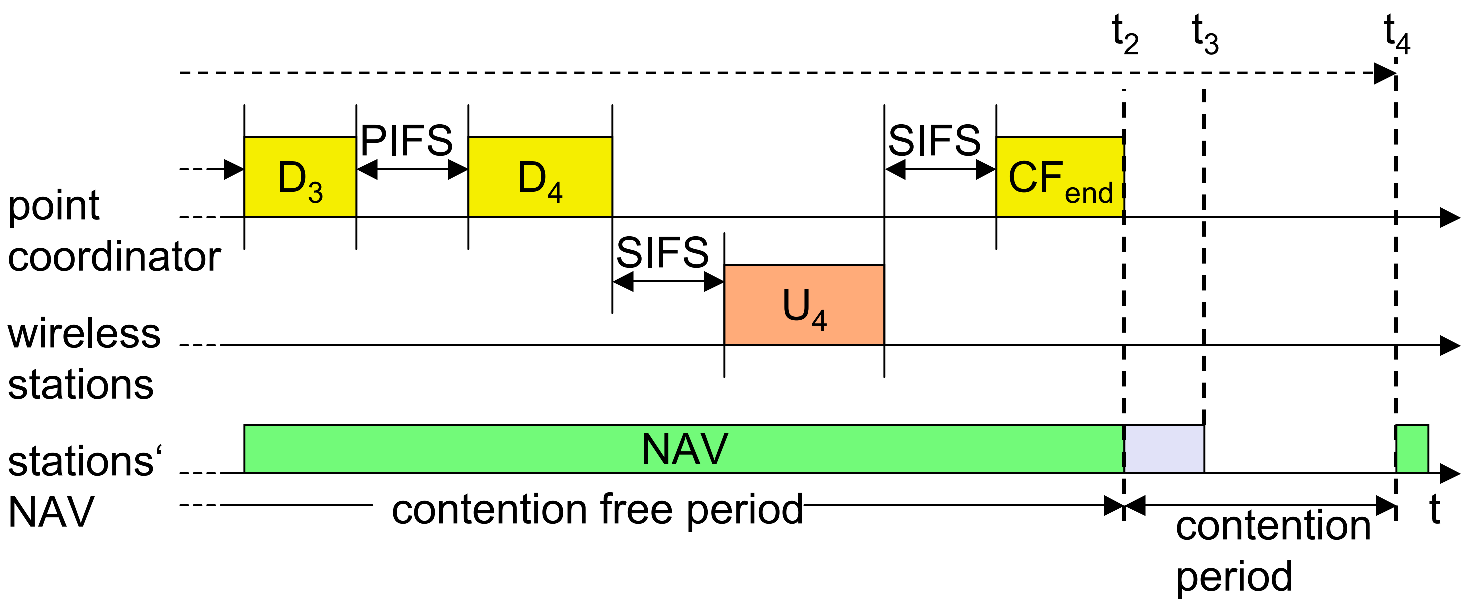
Fragmentation



Point Coordination Function



Point Coordination Function



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

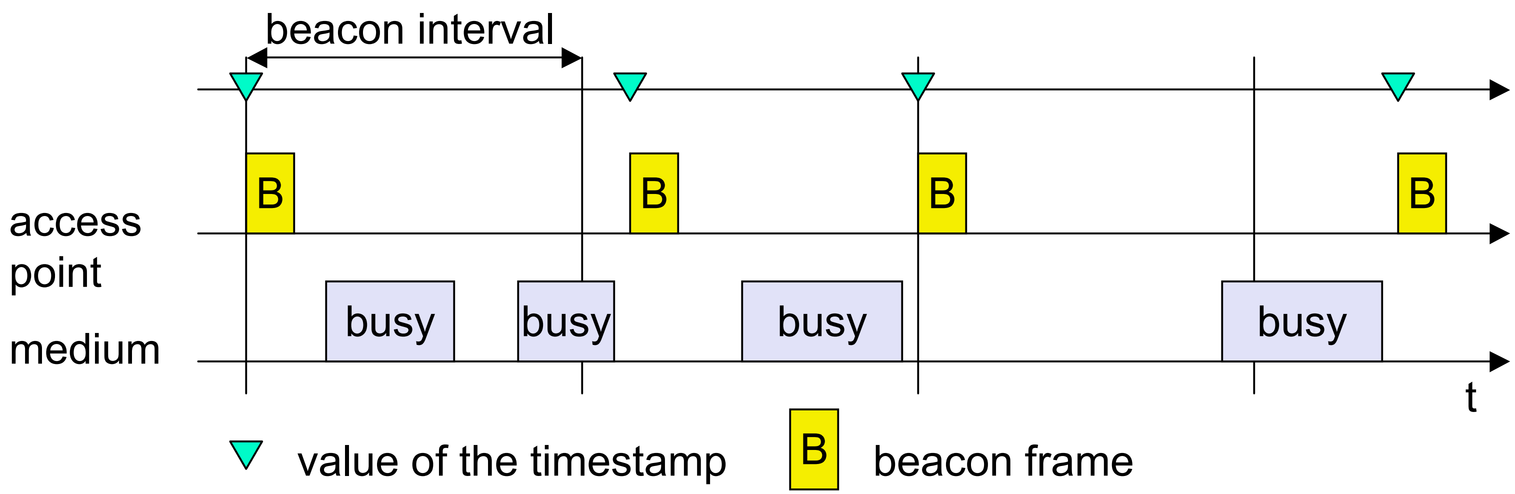
bytes	2	2	6	6	6	2	6	0-2312	4
	Frame Control	Duration ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Data	CRC

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

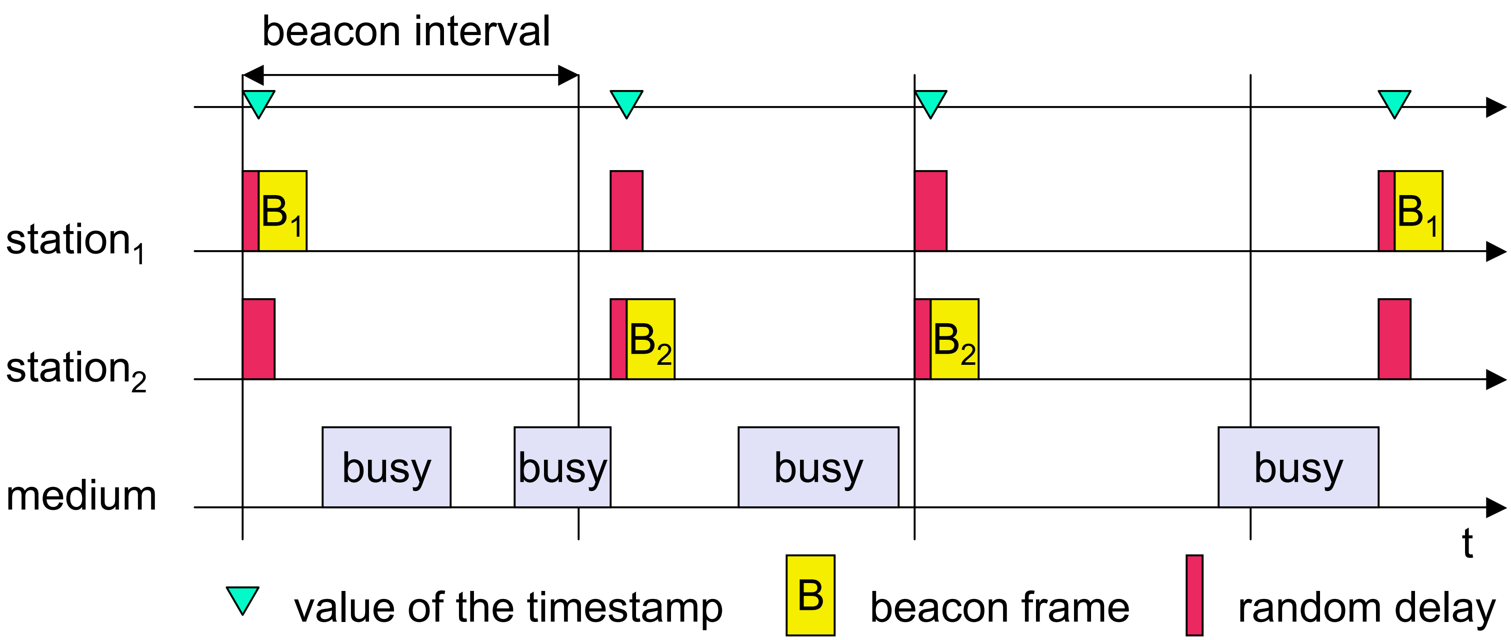
802.11 MAC management

- 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 (infrastructure)



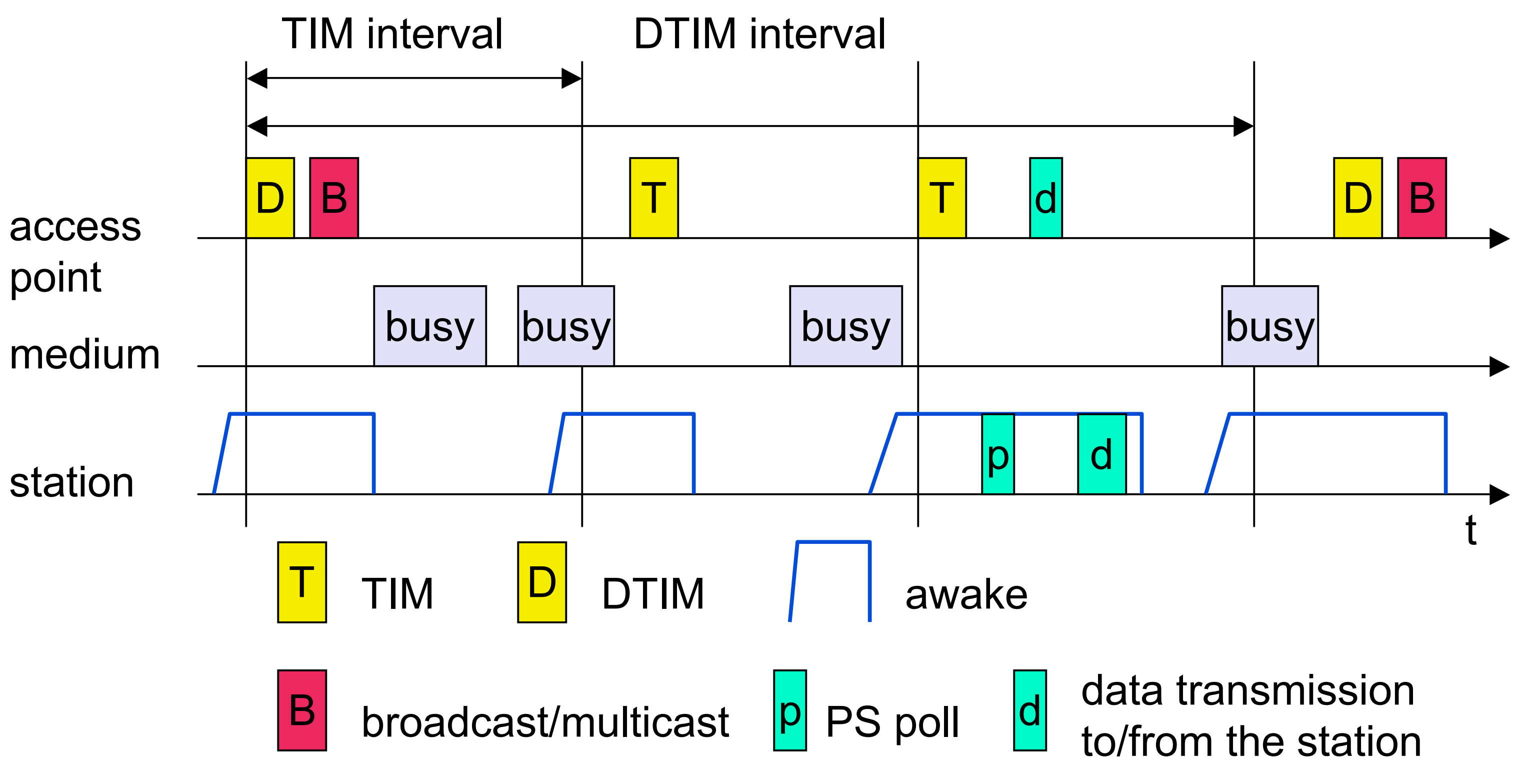
Synchronization (ad-hoc)



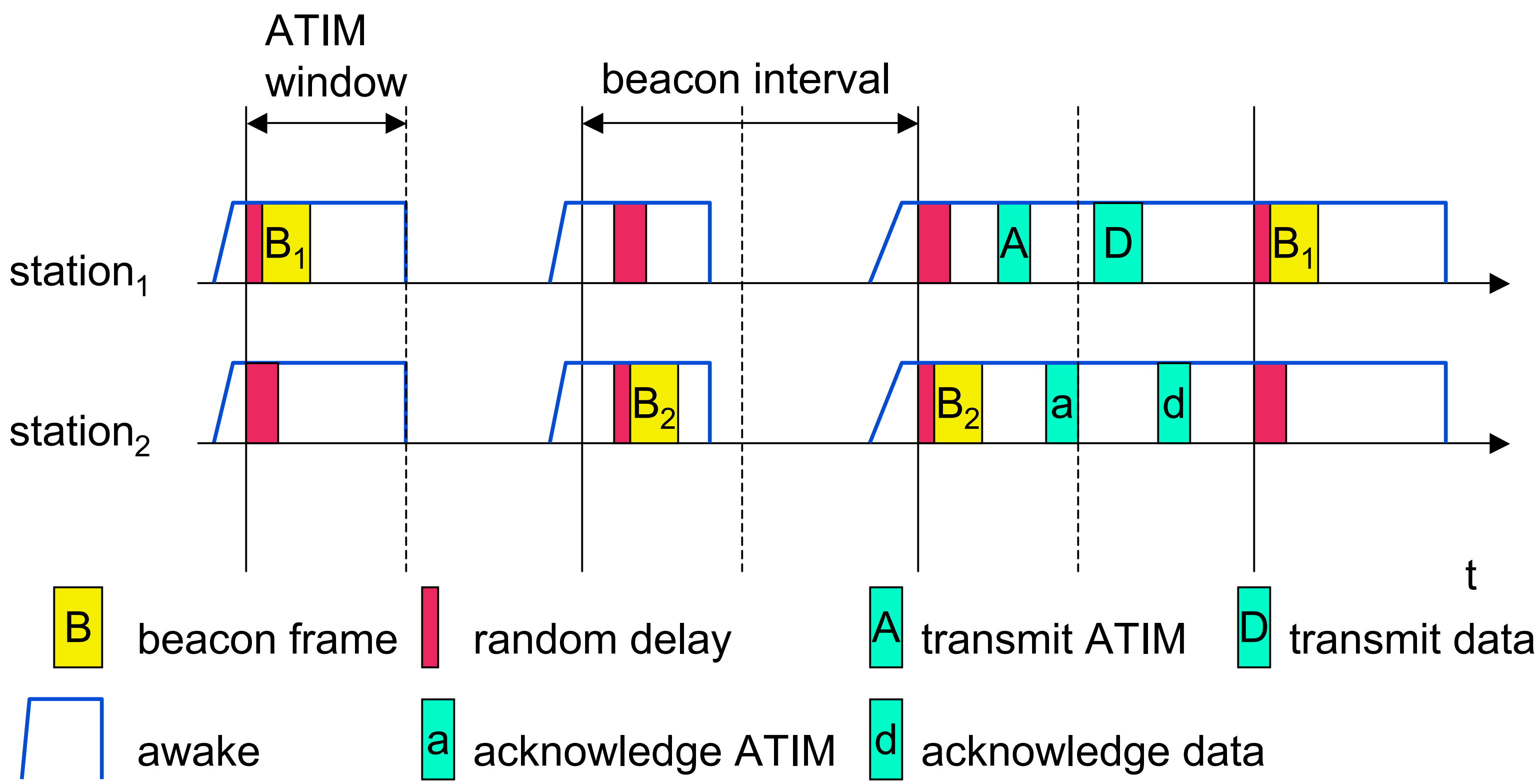
Power management

- 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

Power saving (infrastructure)



Power saving (ad-hoc)



802.11 - Roaming

- No or bad connection?
- 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

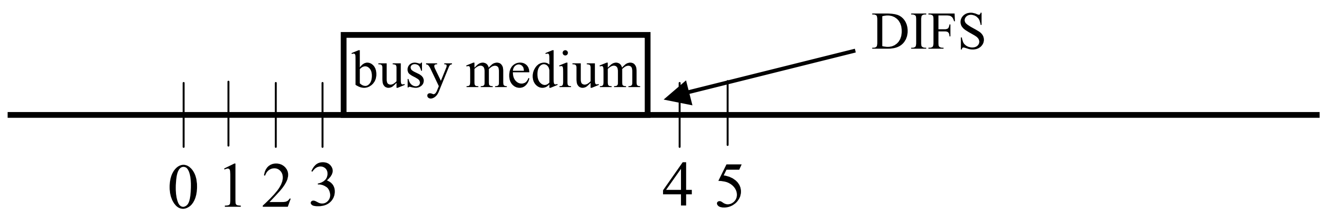
Performance Analysis of 802.11

- Markov chain models for DCF
- Throughput:
  - Saturation throughput: maximum load that the system can carry in stable conditions
- Focus on collision avoidance and backoff algorithms

Analysis of Saturation Throughput

- Model assumptions [Bianchi 00]:
  - No hidden terminal: all users can hear one another
  - No packet capture: all receive powers are identical
  - Saturation conditions: queue of each station is always nonempty
- Parameters:
  - Packet lengths (headers, control and data)
  - Times: slots, timeouts, interframe space
- [Bianchi 00] Performance Analysis of the IEEE 802.11 Distributed Coordination Function, *IEEE Journal on Selected Areas in Communication*, Vol 18, No. 3, March 2000

A Stochastic Model for Backoff

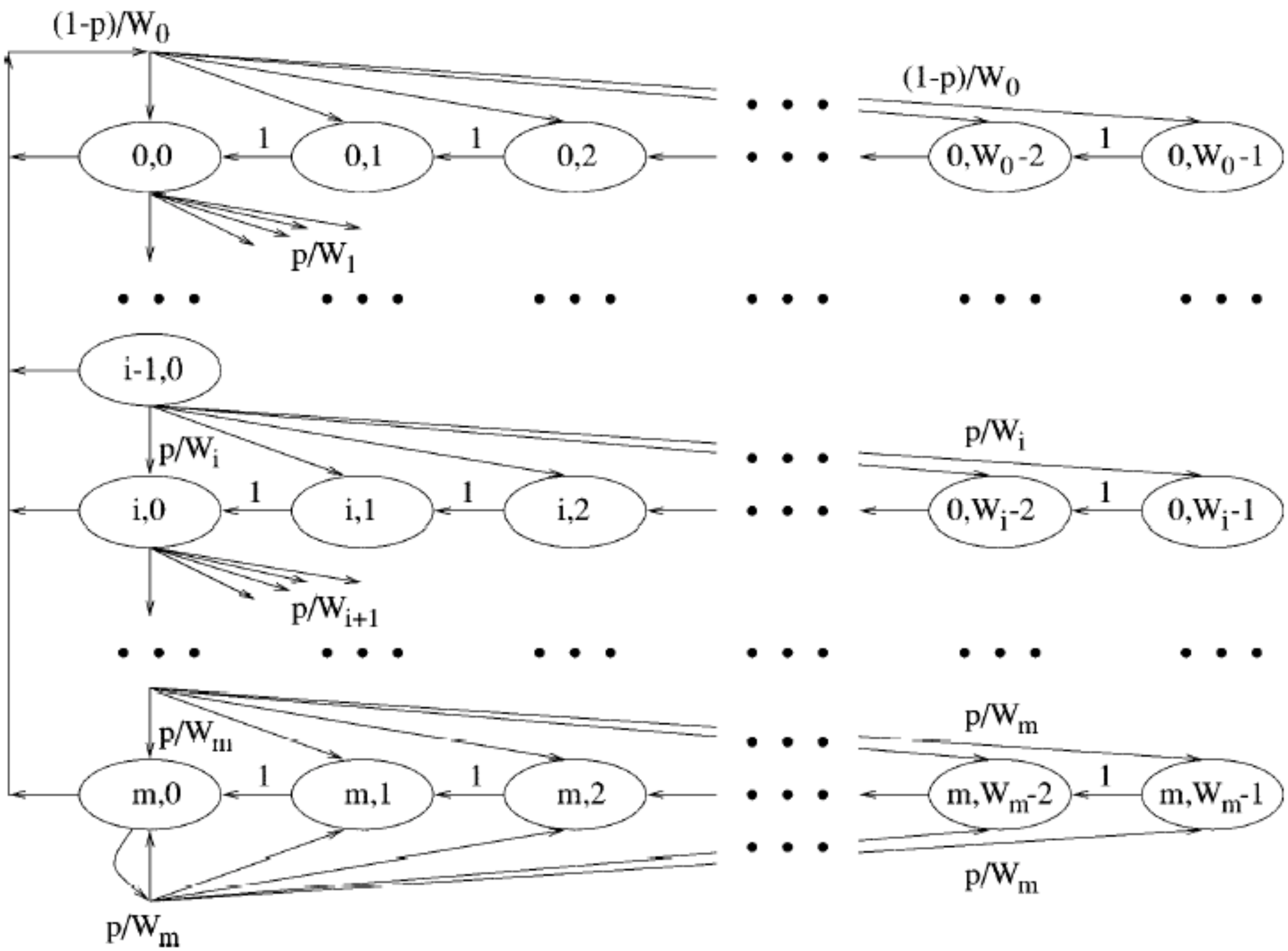


- Let $b(t)$ denote the backoff time counter for a given node at slot t
  - o Slot: constant time period σ if the channel is idle, and the packet transmission period, otherwise
  - o Note that t is not the same as system time
- The variable $b(t)$ is non-Markovian
  - o Its transitions from a given value depend on the number of retransmissions

A Stochastic Model for Backoff

- Let $s(t)$ denote the backoff stage at slot t
  - In the set $\{0,\ldots,m\}$, where m is the maximum number of backoffs
- Is $(s(t), b(t))$ Markovian?
- Unfortunately, no!
  - The transition probabilities are determined by collision probabilities
  - The collision probability may in turn depend on the number of retransmissions suffered
- Independence Assumption:
  - Collision probability is constant and independent of number of retransmissions

Markov Chain Model



Bianchi 00

Steady State Analysis

- Two probabilities:
  - Transmission probability τ
  - Collision probability p
- Analyzing the Markov chain yields an equation for τ in terms of p
- However, we also have

$$p = 1 - (1 - \tau)^{n-1}$$

- Solve for τ and p

Saturation Throughput Calculation

- Probability of at least one transmission

$$P_{tr} = 1 - (1 - \tau)^n$$

- Probability of a successful slot

$$P_s = \frac{n\tau(1 - \tau)^{n-1}}{1 - (1 - \tau)^n}$$

- Throughput: (packet length L)

$$\frac{P_s P_{tr} L}{(1 - P_{tr})\sigma + P_{tr} L}$$

Analysis vs. Simulations

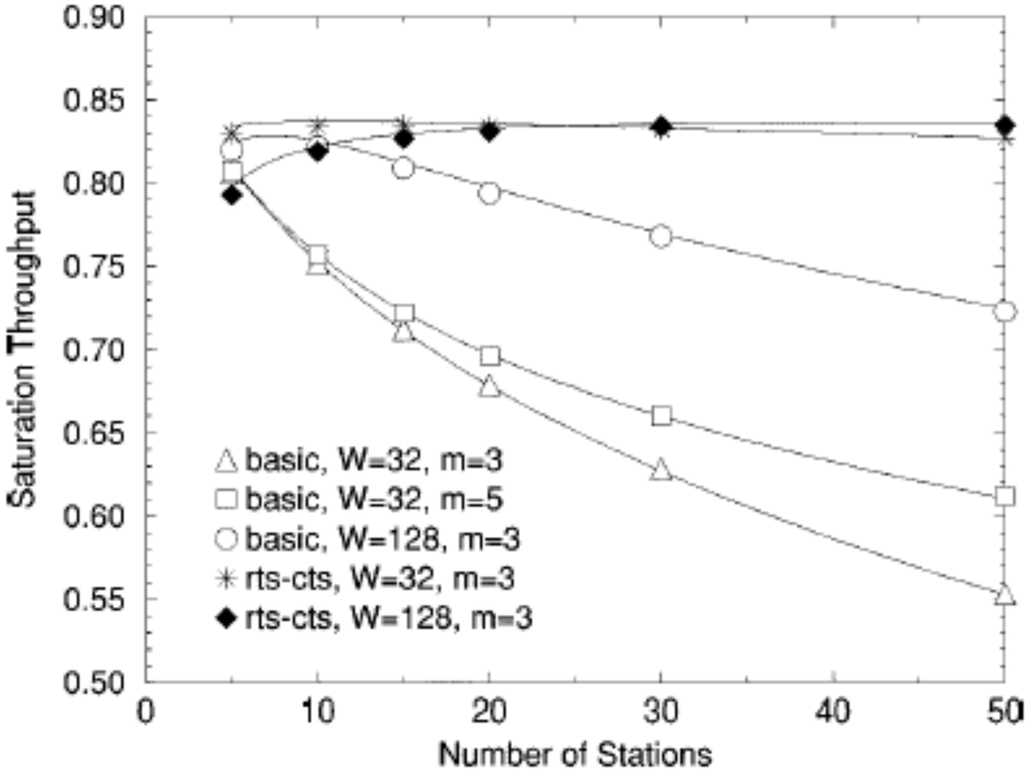


Fig. 6. Saturation Throughput: analysis versus simulation.

	analysis	simulation
n=2, BAS	0.8473	0.846 ± 0.001
n=2, RTS	0.8198	0.817 ± 0.001
n=3, BAS	0.8368	0.835 ± 0.001
n=3, RTS	0.8279	0.823 ± 0.001

Bianchi 00