

# Medium Access Control (MAC) and Wireless LANs

NTT EX2012  
MediaTek v. NTT  
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# Outline

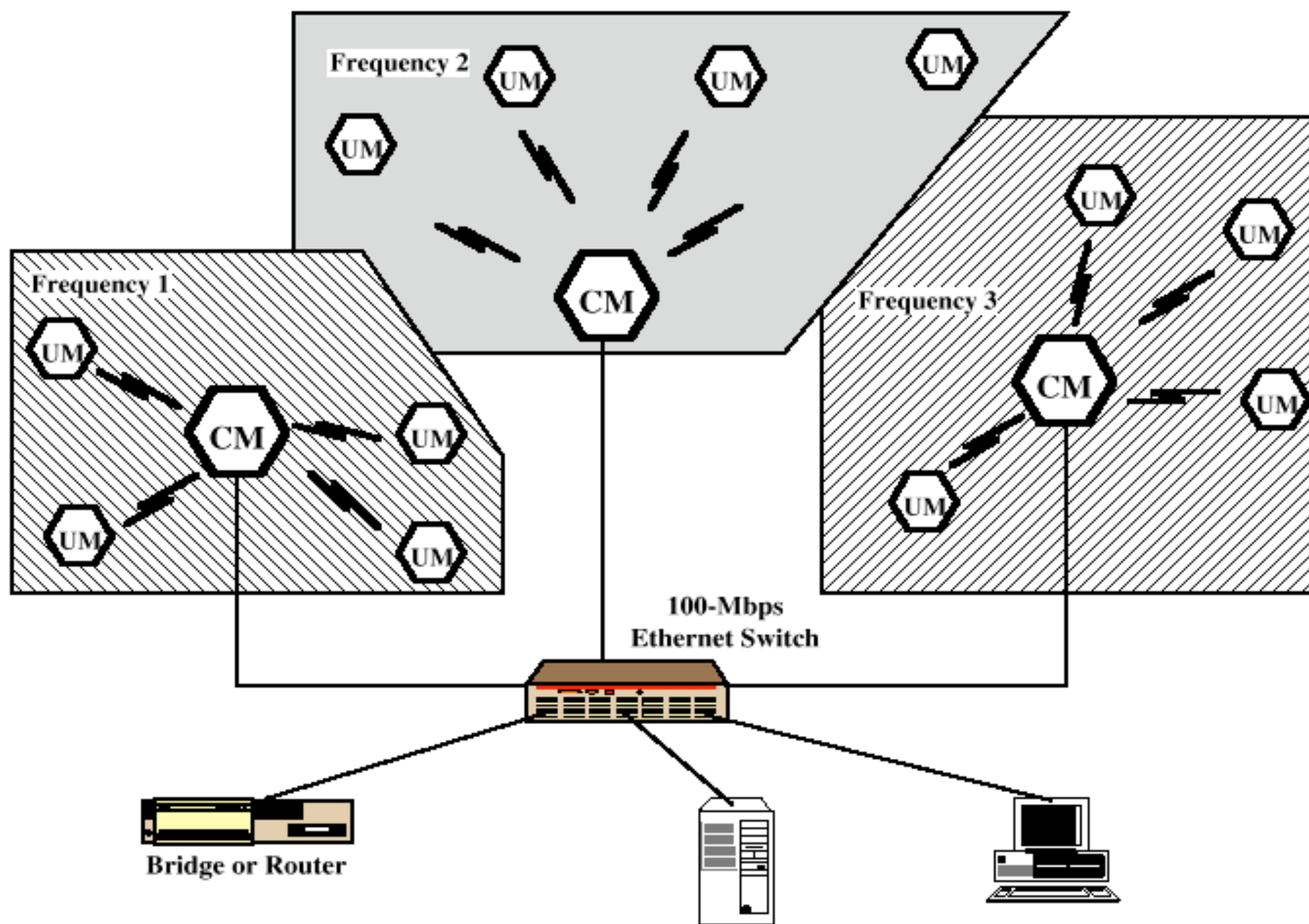
- ❑ Wireless LAN Technology
- ❑ Medium Access Control for Wireless
- ❑ IEEE 802.11

# 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
  - o Wired LAN
    - Backbone
    - Support servers and stationary workstations
  - o 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
  - o 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:
  - o Transfer data from portable computer to office server
  - o Extended environment such as campus

# Ad Hoc Networking

- ❑ Temporary peer-to-peer network set up to meet immediate need
- ❑ Example:
  - o Group of employees with laptops convene for a meeting; employees link computers in a temporary network for duration of meeting
  - o Military applications
  - o 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
  - o Possibility of high data rates
- ❑ Infrared spectrum unregulated
- ❑ Equipment inexpensive and simple
- ❑ Reflected by light-colored objects
  - o Ceiling reflection for entire room coverage
- ❑ Doesn't penetrate walls
  - o More easily secured against eavesdropping
  - o Less interference between different rooms

## Drawbacks of Infrared Medium

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

# Spread Spectrum LANs

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

# Spread Spectrum LAN configurations

## ❑ Hub topology:

- o Mounted on the ceiling and connected to backbone
- o Need MAC protocol
- o May act as multiport repeater
- o Automatic handoff of mobile stations
- o Stations in cell either:
  - Transmit to / receive from hub only
  - Broadcast using omnidirectional antenna

## ❑ Peer-to-peer mode:

- o No hub
- o 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
  - o TDMA
  - o FDMA
  - o CDMA
- ❑ Contention-based:
  - o Let the stations contend for the channel
  - o Random access protocols
- ❑ Reservation-based:
  - o Reservations made during a contention phase
  - o Size of packet in contention phase much smaller than a data packet
- ❑ Space-division multiple access:
  - o Serve multiple users simultaneously by using directional antennas



# Schedule-based access methods

- ❑ FDMA (Frequency Division Multiple Access)
  - o assign a certain frequency to a transmission channel between a sender and a receiver
  - o permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- ❑ TDMA (Time Division Multiple Access)
  - o 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)
  - o signals are spread over a wideband using pseudo-noise sequences
  - o codes generate signals with “good-correlation” properties
  - o signals from another user appear as “noise”
  - o 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)
  - o Ethernet
- ❑ MACA (Multiple access collision avoidance)
- ❑ MACAW
- ❑ CSMA/CA and IEEE 802.11

# Ingredients of MAC Protocols

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

# Carrier Sense Multiple Access

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

# Aloha

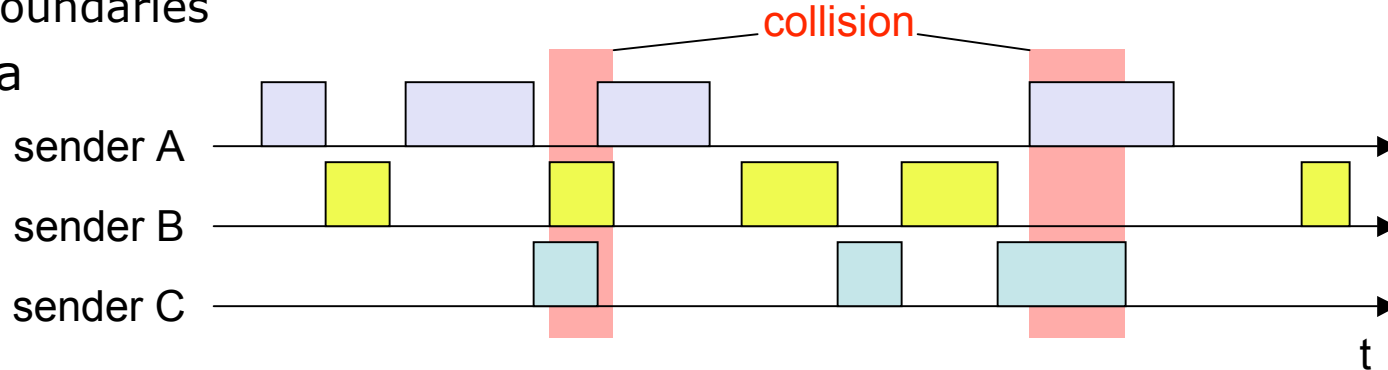
- ❑ Proposed for packet radio environments where every node can hear every other node
- ❑ Assume collision detection
- ❑ In Slotted Aloha, stations transmit at the beginning of a slot
- ❑ If collision occurs, then each station waits a random number of slots and retries
  - o Random wait time chosen has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

# Aloha/Slotted aloha

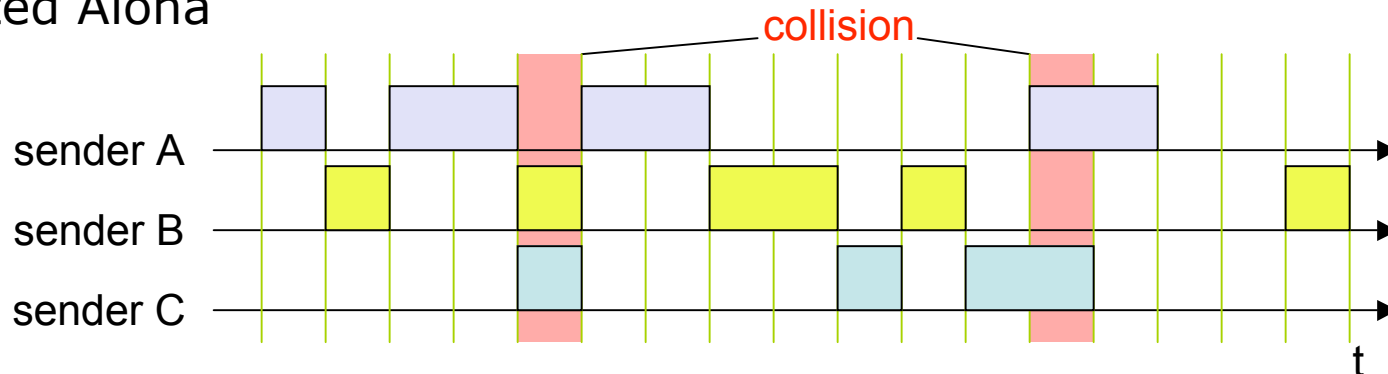
## ❑ Mechanism

- o random, distributed (no central arbiter), time-multiplexed
- o 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
  - o 1-persistent CSMA
  - o non-persistent CSMA
  - o p-persistent protocol
  - o CSMA with collision detection (CSMA/CD): not applicable to wireless systems
- ❑ 1-persistent CSMA
  - o 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
  - o 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

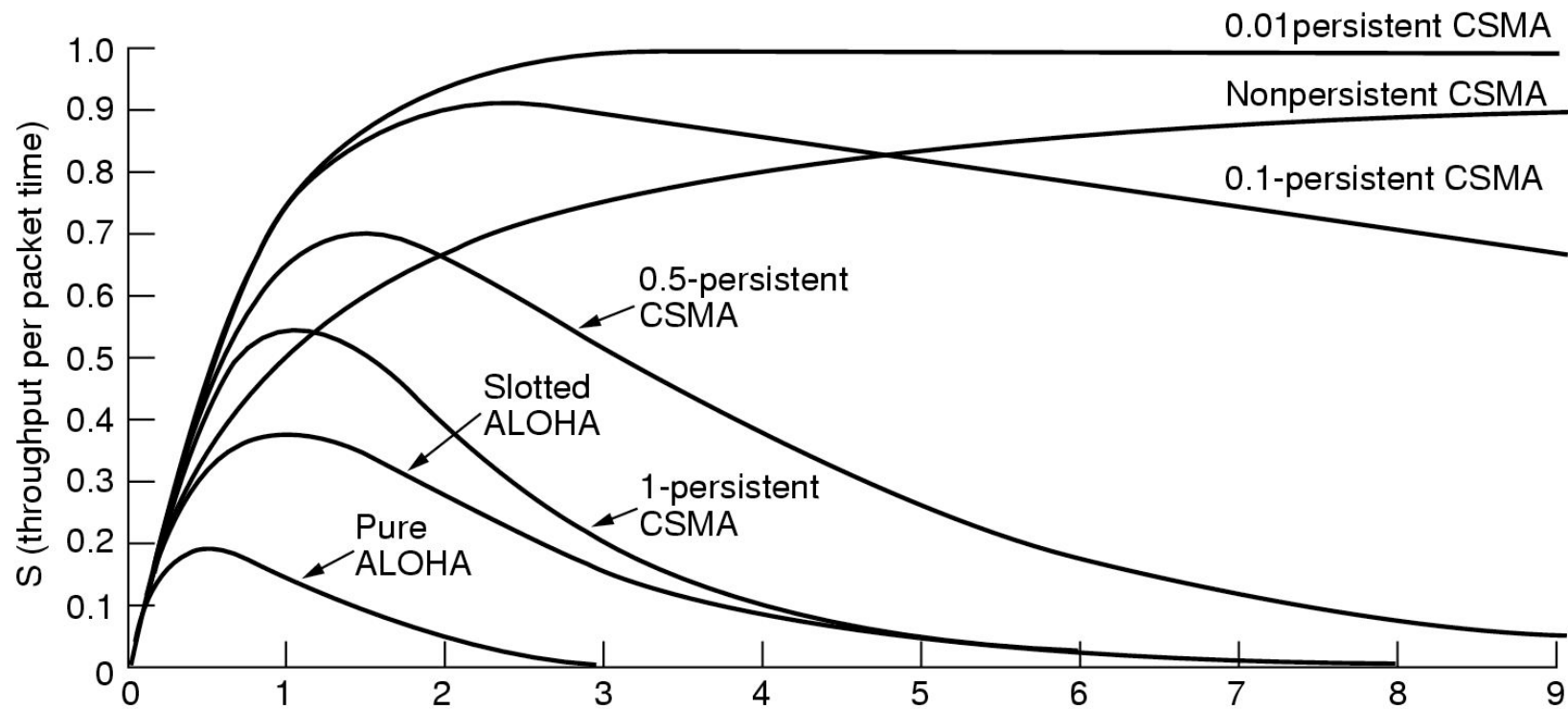
- o e.g., Ethernet, IEEE802.3 but not applicable to wireless systems



# 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:
  - o Binary exponential backoff: wait for a random number  $\in [0, 2^i - 1]$  of slots before transmitting
  - o After ten collisions the randomization interval is frozen to max 1023
  - o After 16 collisions the controller throws away the frame

# Comparison of MAC Algorithms



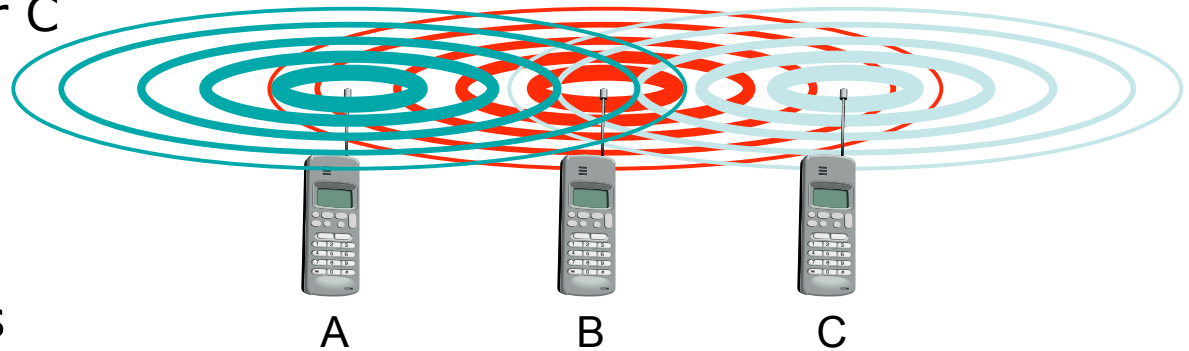
# Motivation for Wireless MAC

- ❑ Can we apply media access methods from fixed networks?
- ❑ Example CSMA/CD
  - o **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - o 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
  - o signal strength decreases proportional to the square of the distance
  - o the sender would apply CS and CD, but the collisions happen at the receiver
  - o it might be the case that a sender cannot “hear” the collision, i.e., CD does not work
  - o furthermore, CS might not work if, e.g., a terminal is “hidden”

# Hidden and exposed terminals

## ❑ Hidden terminals

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

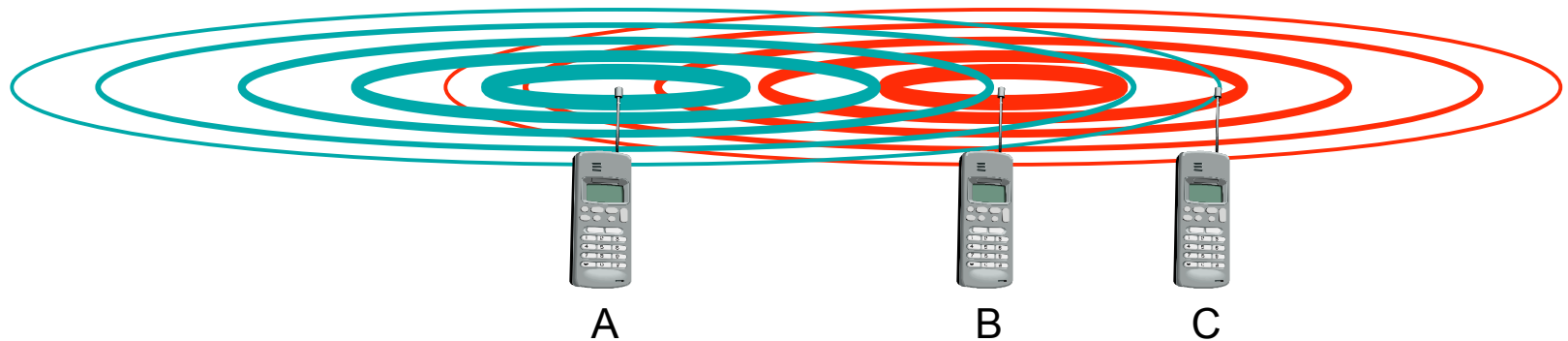


## ❑ Exposed terminals

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

# Near and far terminals

- ❑ Terminals A and B send, C receives
  - o signal strength decreases proportional to the square of the distance
  - o the signal of terminal B therefore drowns out A's signal
  - o 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!

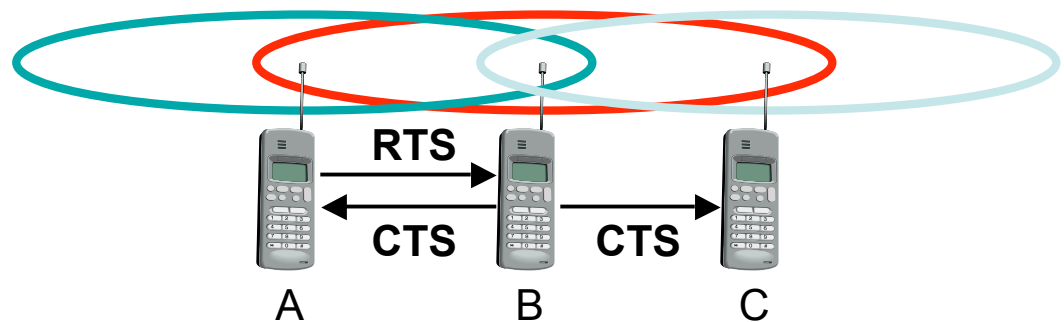
# MACA - collision avoidance

- ❑ No carrier sense (CS)
- ❑ MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance
  - o RTS (request to send): sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
  - o CTS (clear to send): the receiver grants the right to send as soon as it is ready to receive
- ❑ Signaling packets contain
  - o sender address
  - o receiver address
  - o packet size
- ❑ Variants of this method can be found in IEEE 802.11.

# MACA examples

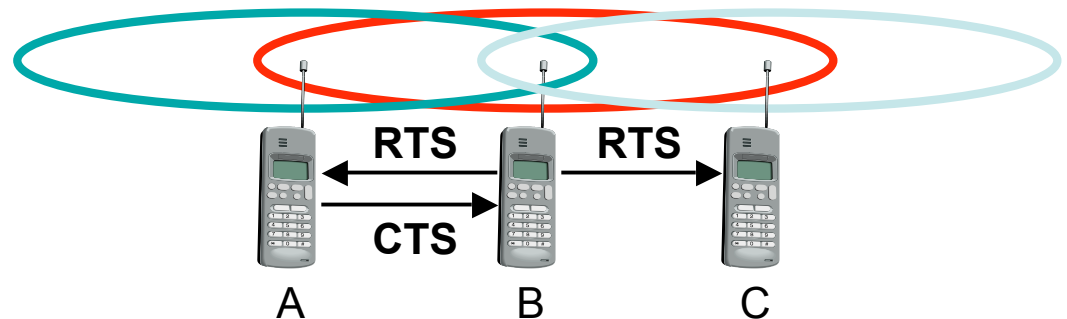
## ❑ MACA avoids the problem of hidden terminals

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



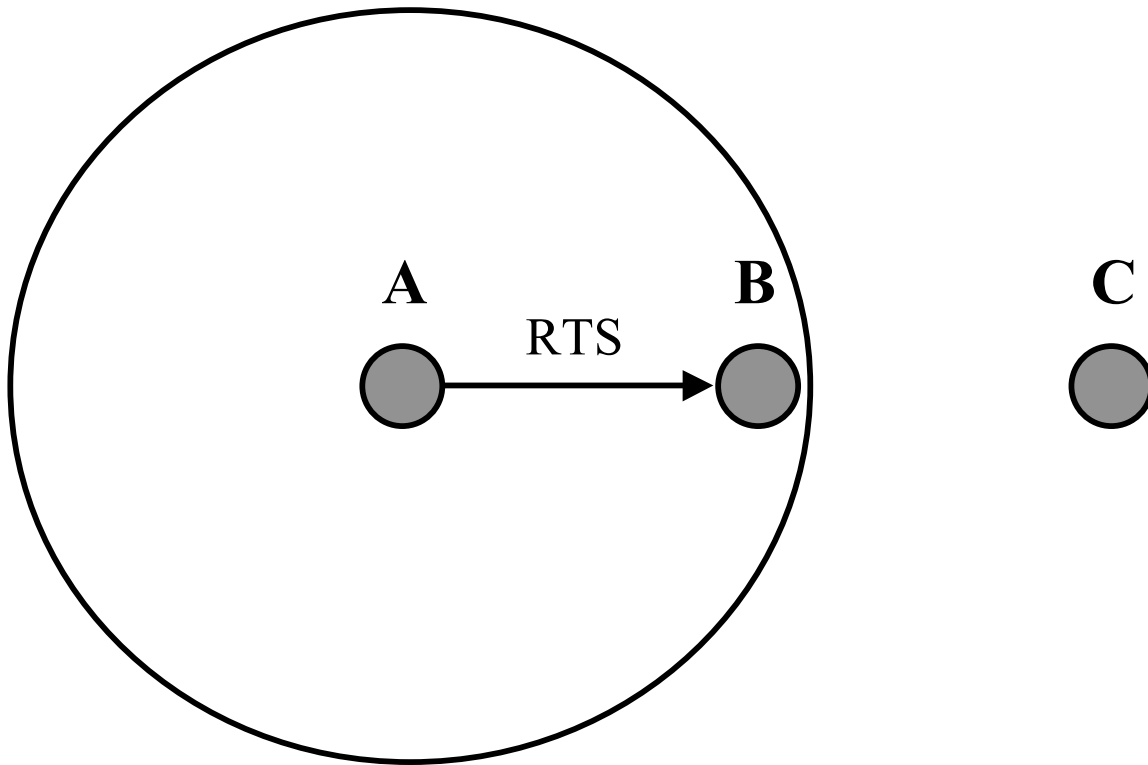
## ❑ MACA avoids the problem of exposed terminals?

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



## MACA in Action

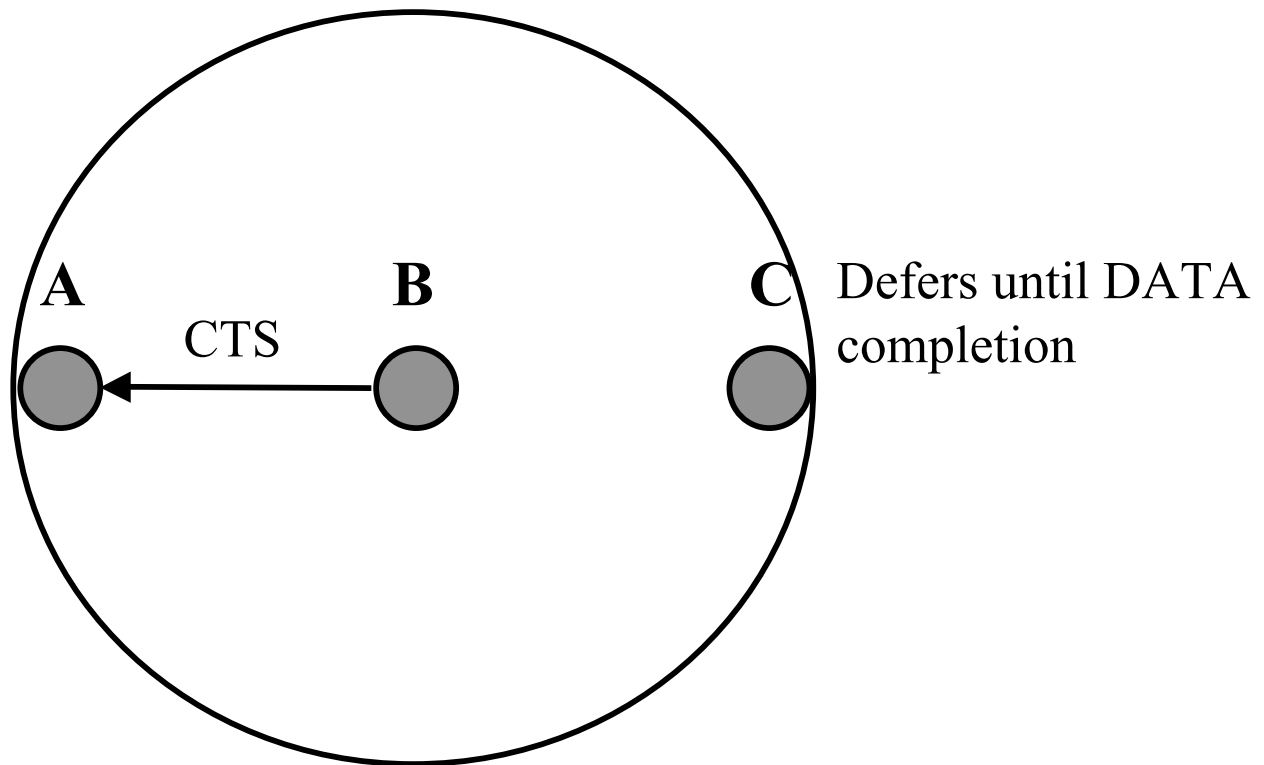
- ❑ If C also transmits RTS, collision at B





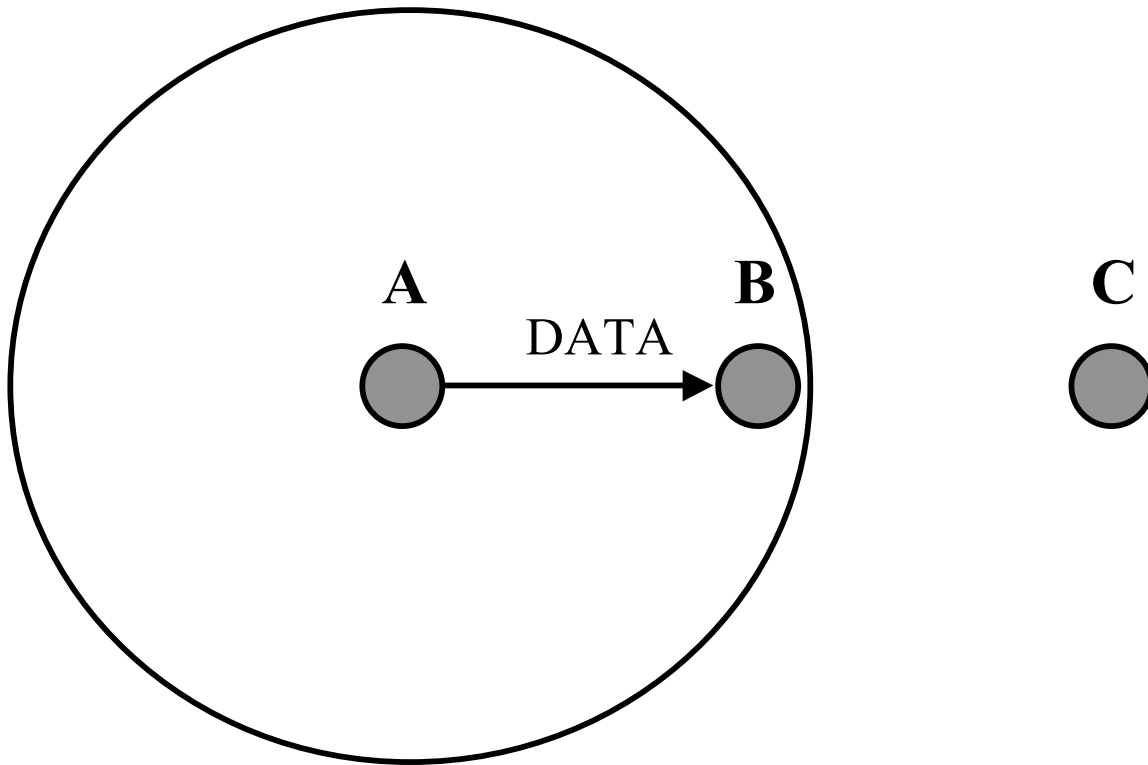
## MACA in Action

- ❑ C knows the expected DATA length from CTS



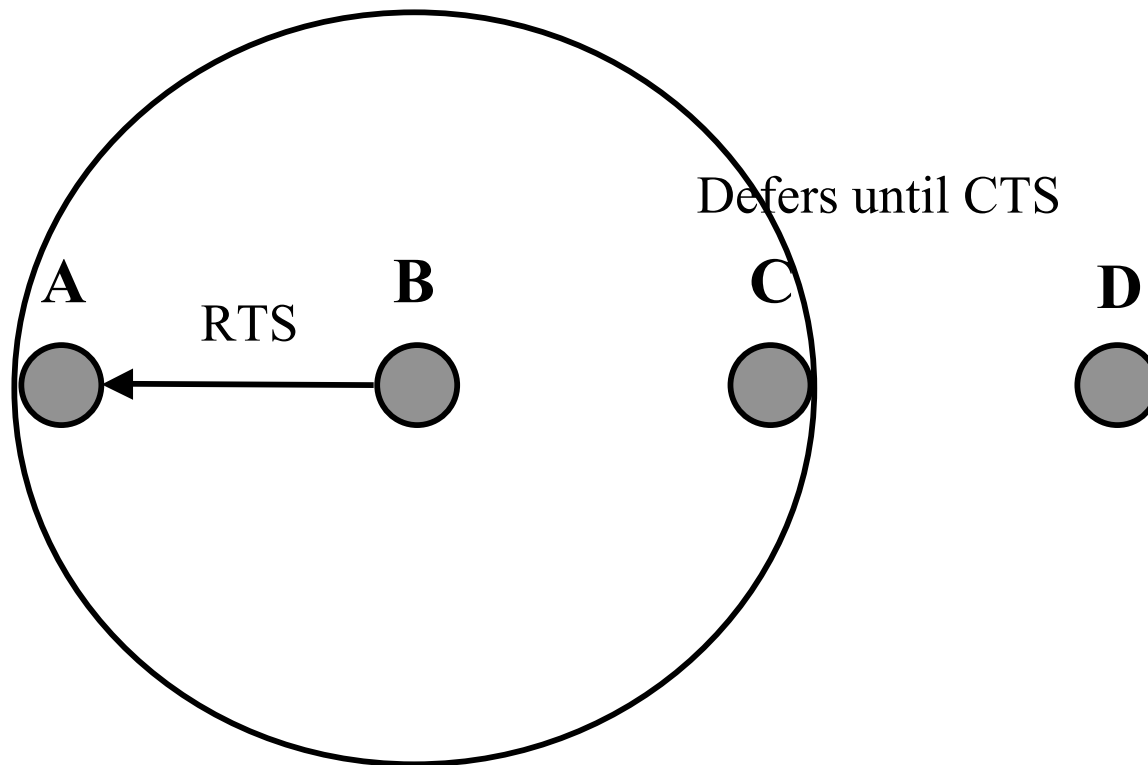
## MACA in Action

- ❑ Avoids the hidden terminal problem



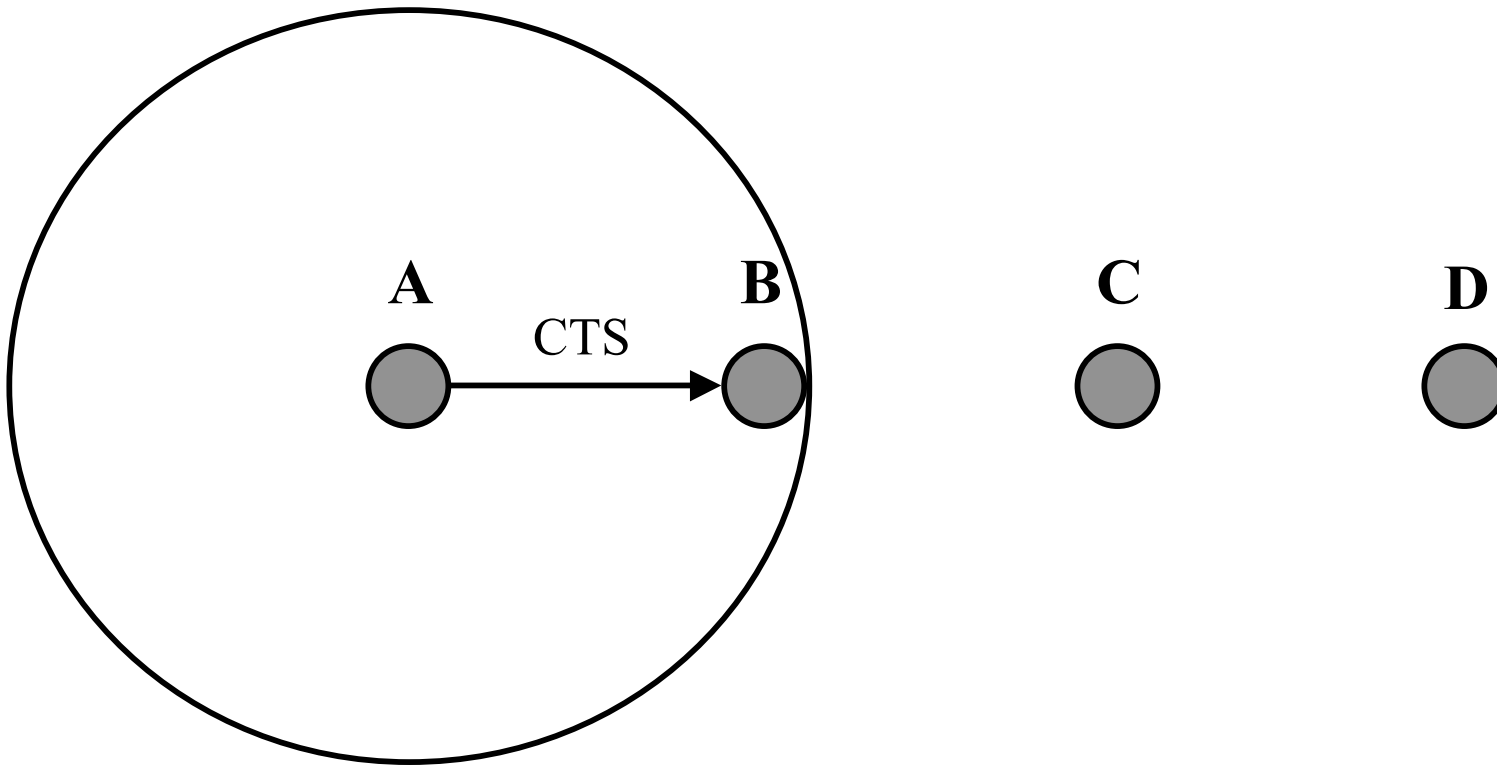
# MACA in Action

- ❑ CTS packets have fixed size



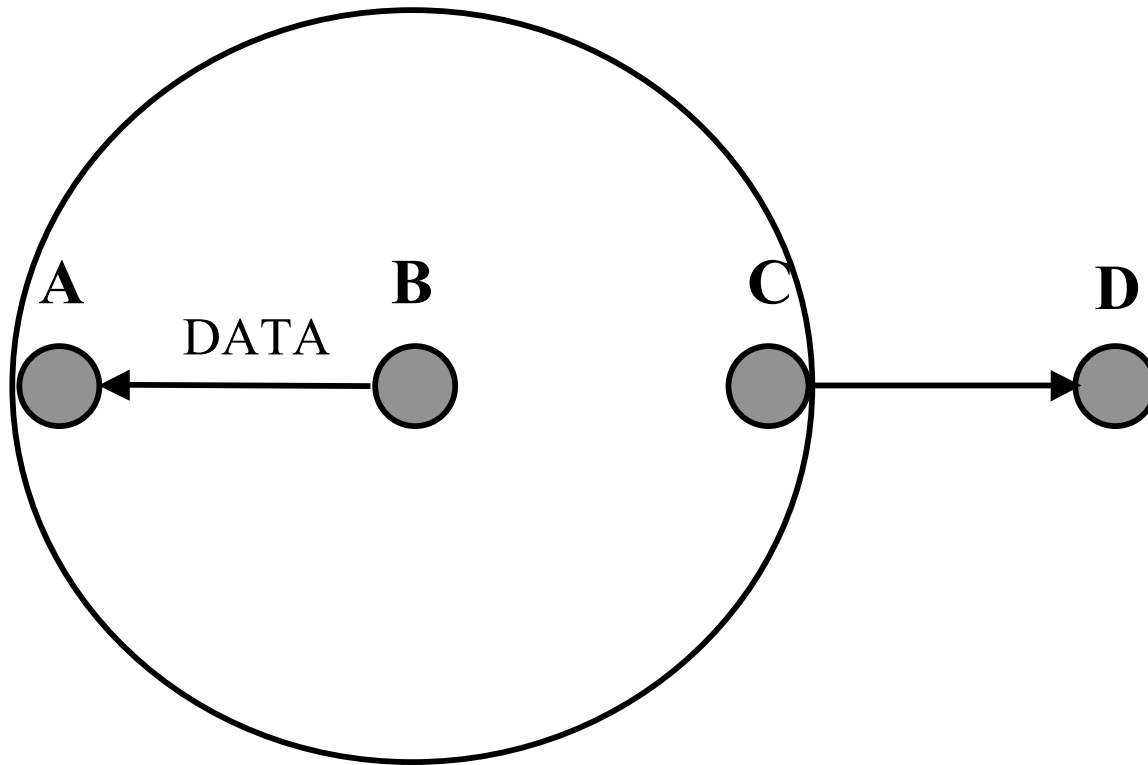
## MACA in Action

- ❑ C does not hear a CTS



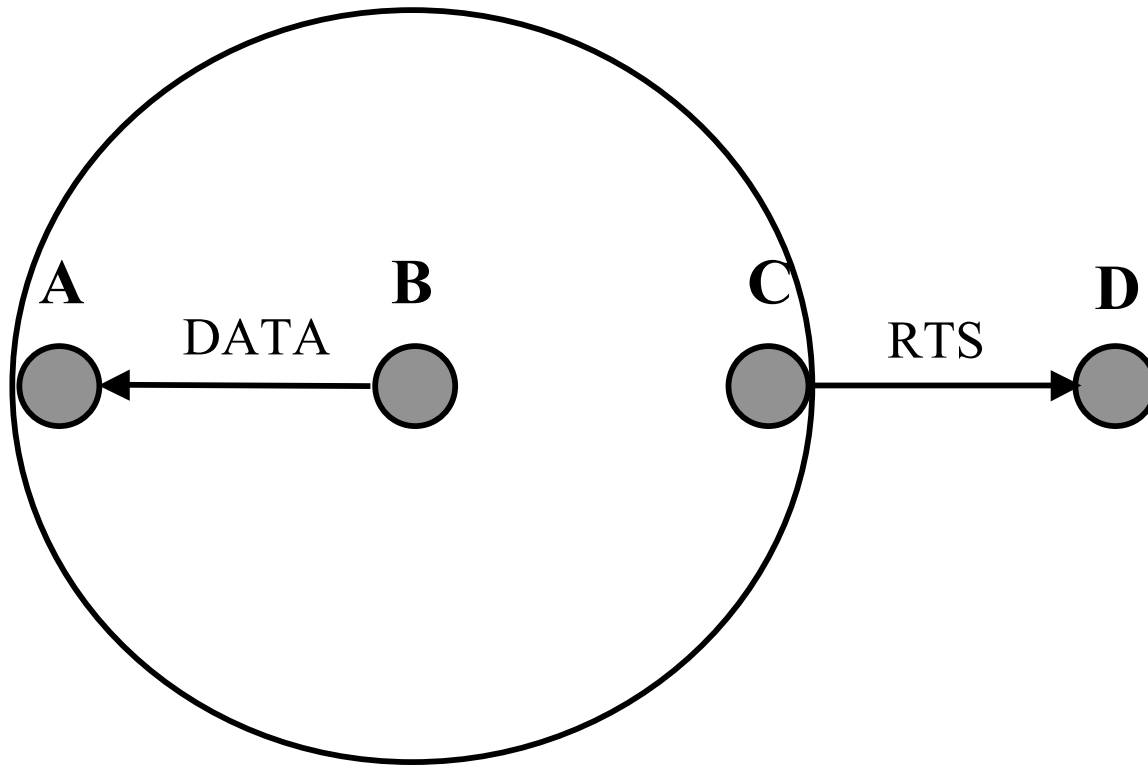
## MACA in Action

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



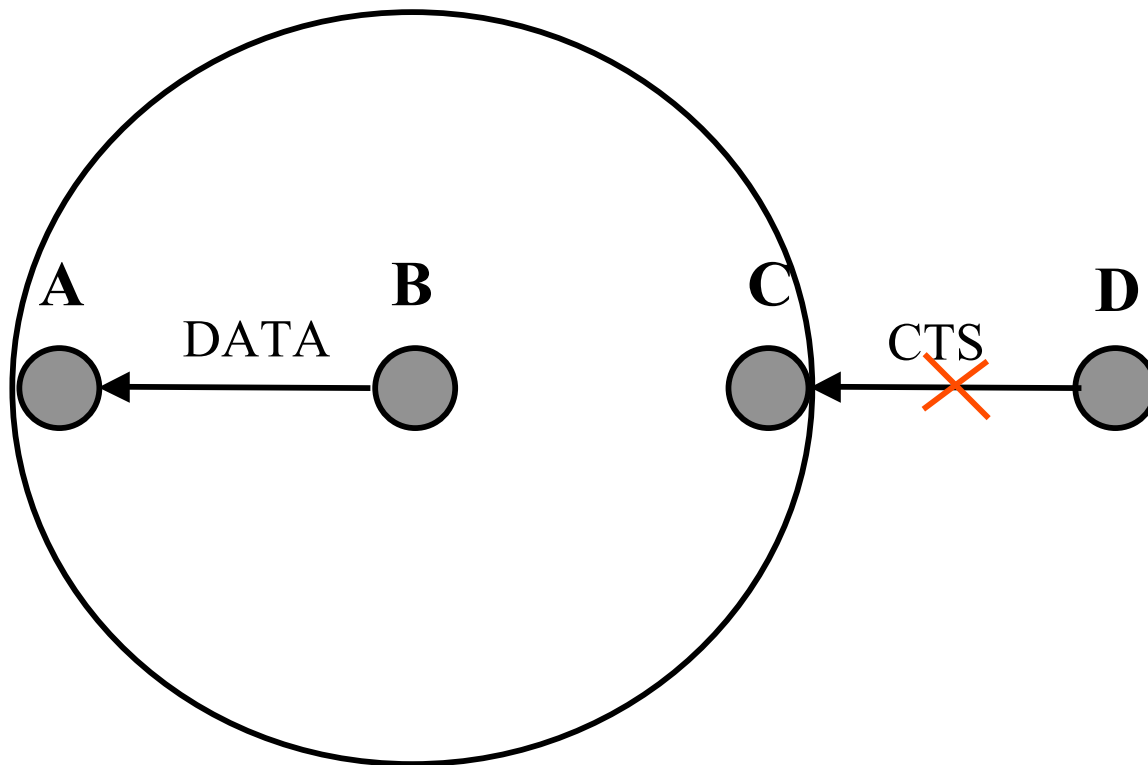
## MACA in Action

❑ Is C really free to send to D?



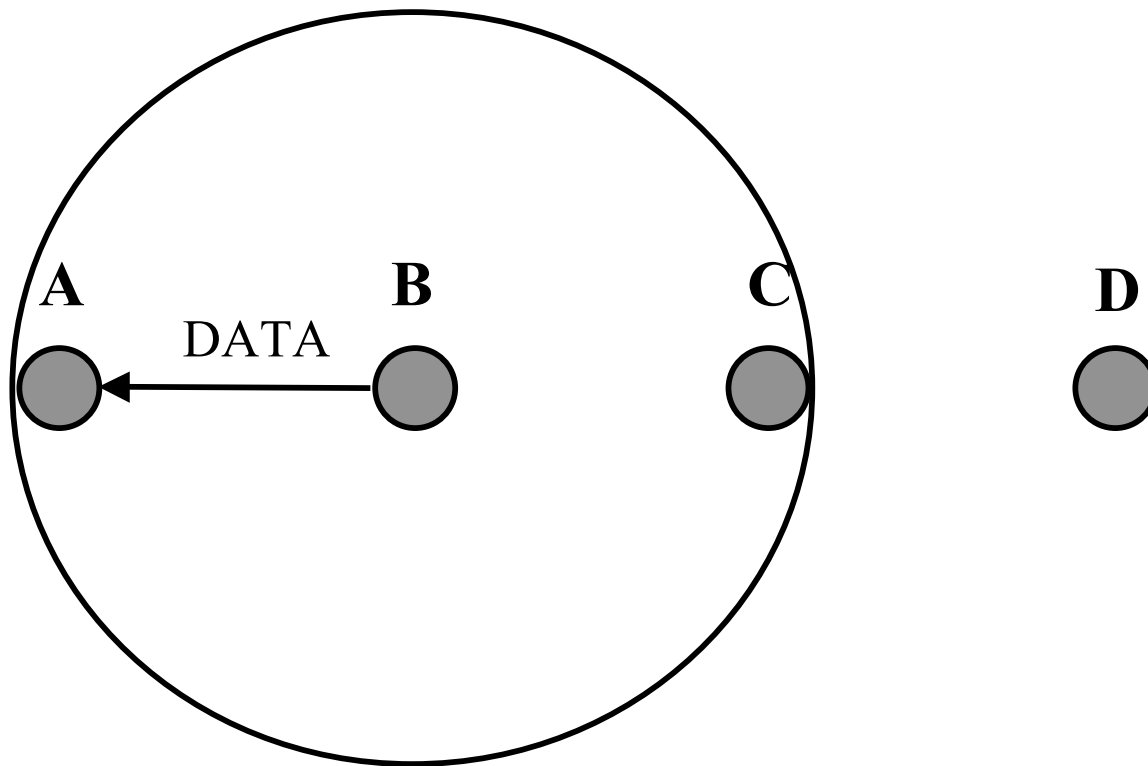
## MACA in Action

- ❑ In fact, C increases its backoff counter!



# The CSMA/CA Approach

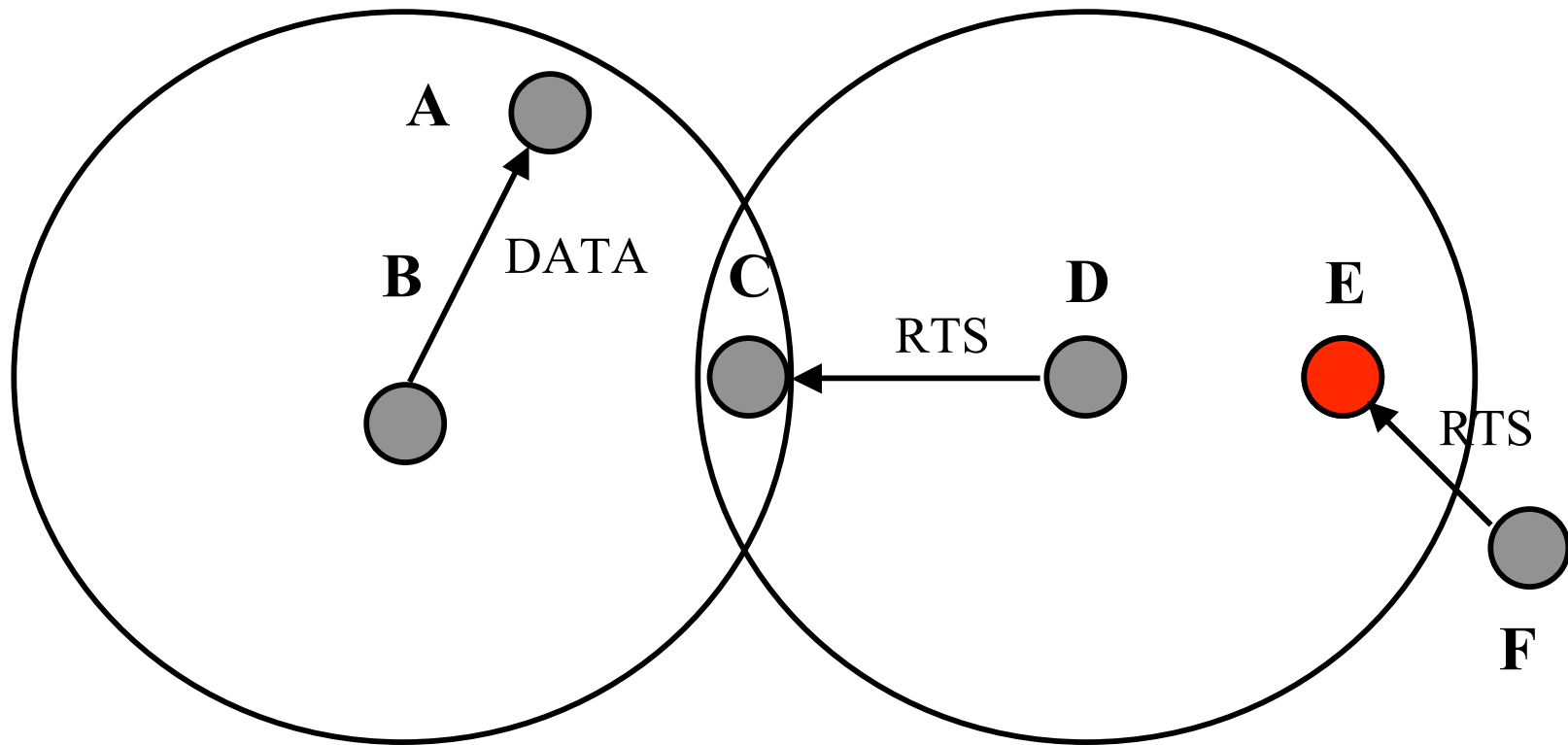
- ❑ Add **carrier sense**; C will sense B's transmission and refrain from sending RTS





# False Blocking

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



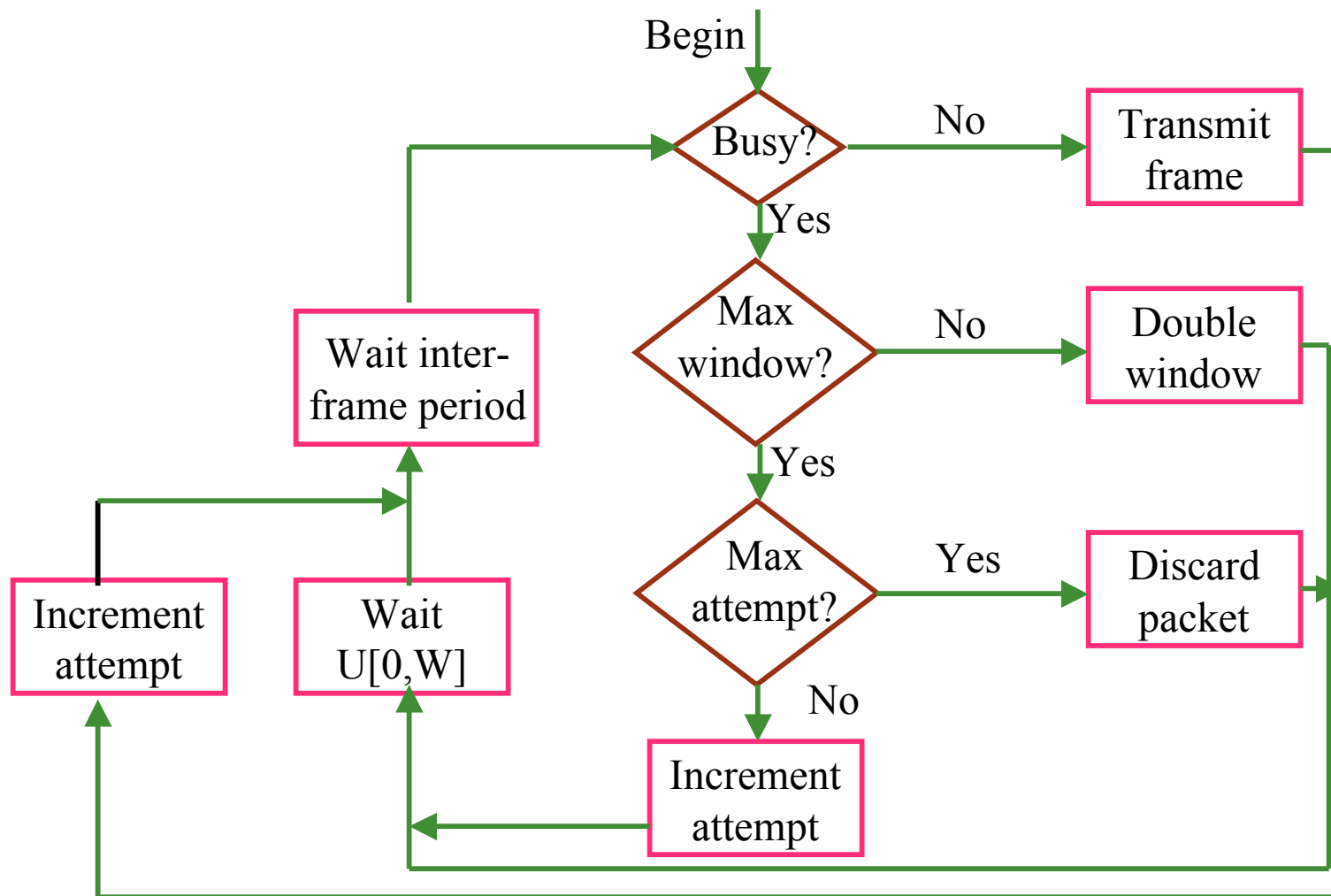
# Alternative Approach: MACAW

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

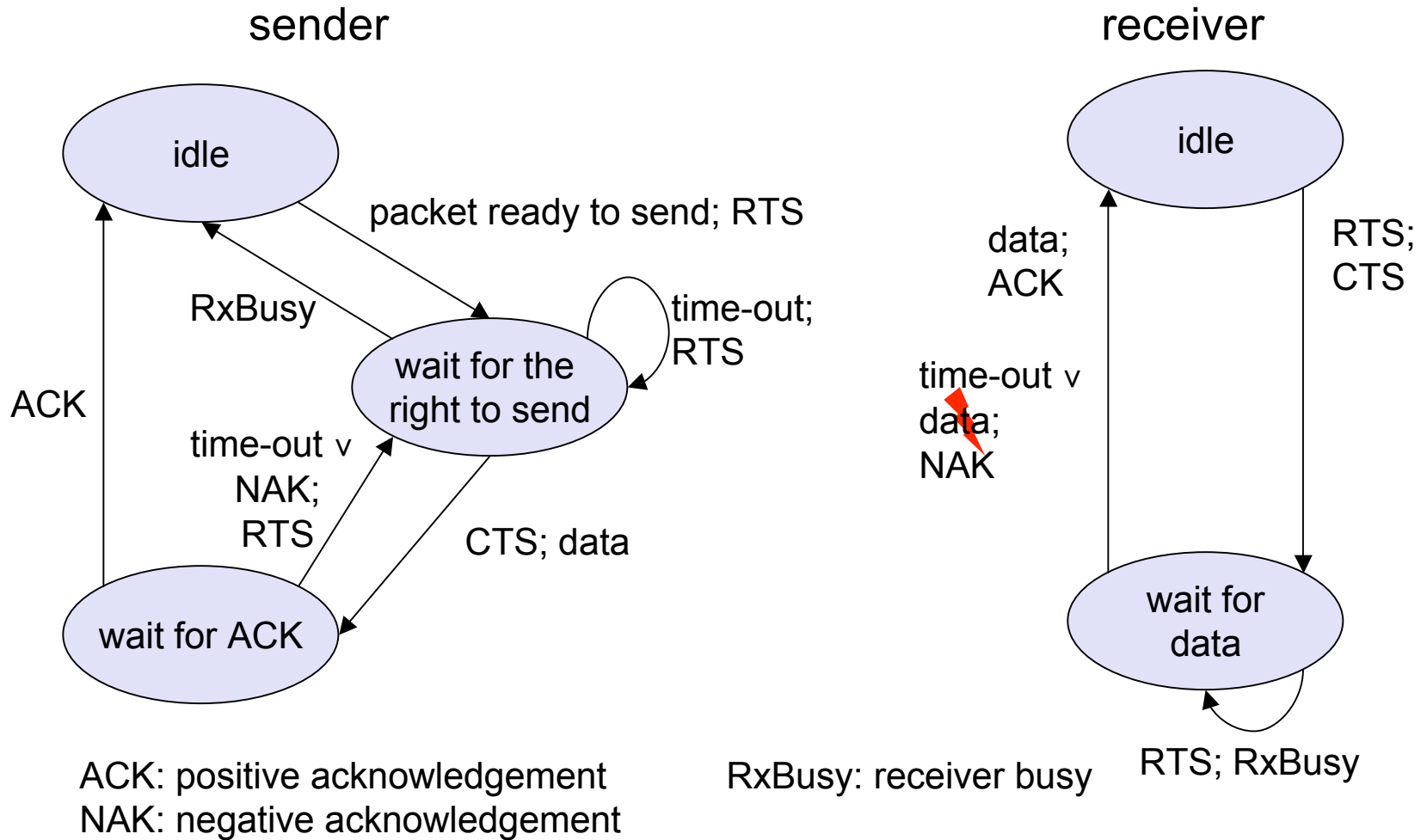
## The IEEE 802.11 Protocol

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

## CSMA/CA with Exponential Backoff



# MAC in IEEE 802.11



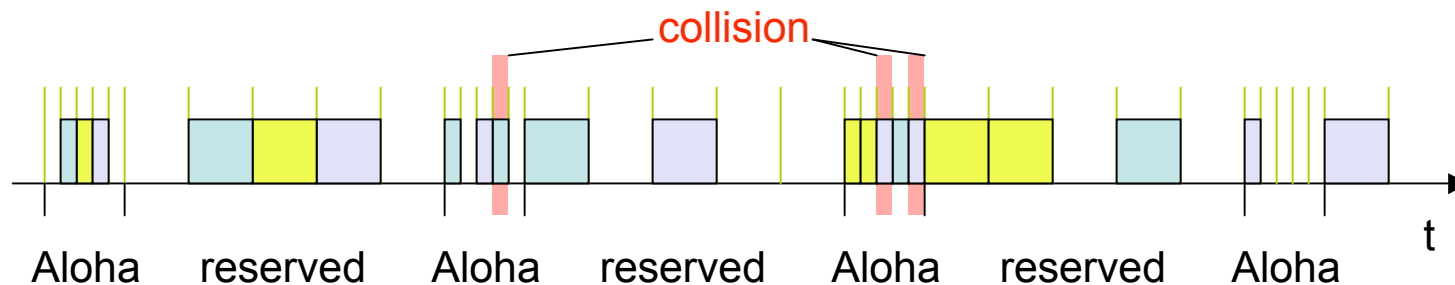
# Demand Assigned Multiple Access

- ❑ 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%
  - o a sender *reserves* a future time-slot
  - o sending within this reserved time-slot is possible without collision
  - o reservation also causes higher delays
  - o typical scheme for satellite links
- ❑ Examples for reservation algorithms:
  - o *Explicit Reservation (Reservation-ALOHA)*
  - o *Implicit Reservation (PRMA)*
  - o *Reservation-TDMA*

# DAMA: Explicit Reservation

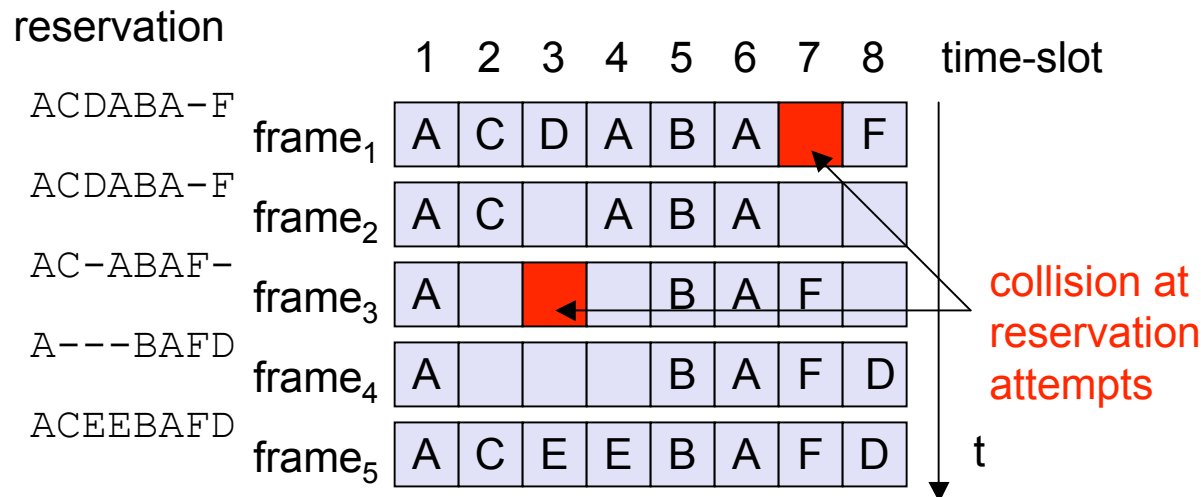
## □ Explicit Reservation (Reservation Aloha):

- o 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)
- o 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):
  - o a certain number of slots form a frame, frames are repeated
  - o stations compete for empty slots according to the slotted aloha principle
  - o 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
  - o competition for this slots starts again as soon as the slot was empty in the last frame

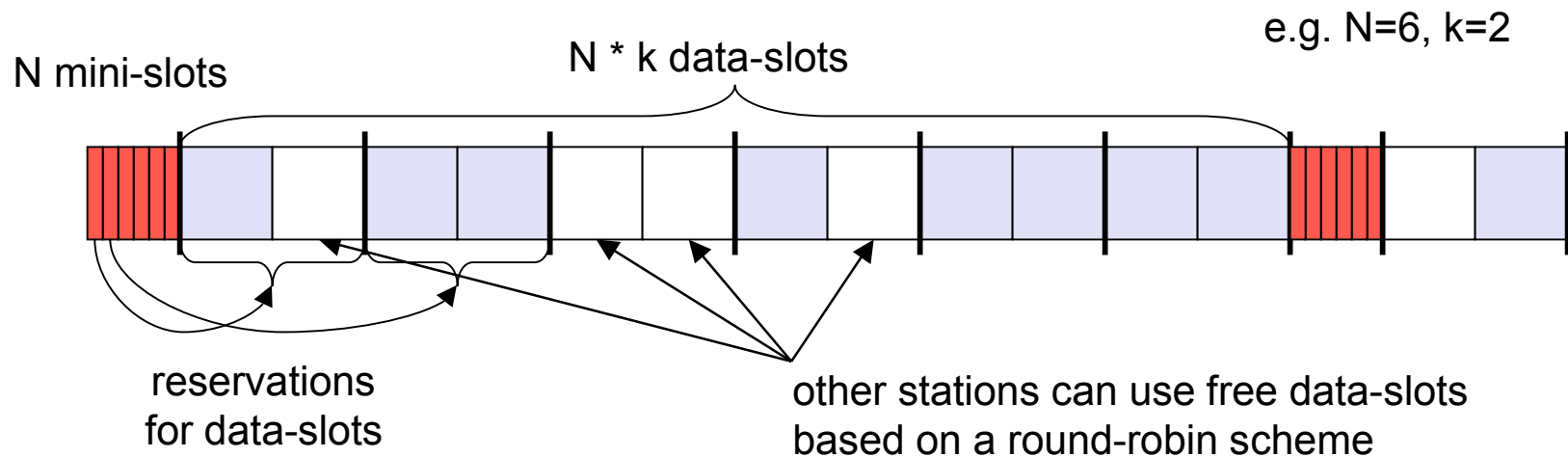




# DAMA: Reservation-TDMA

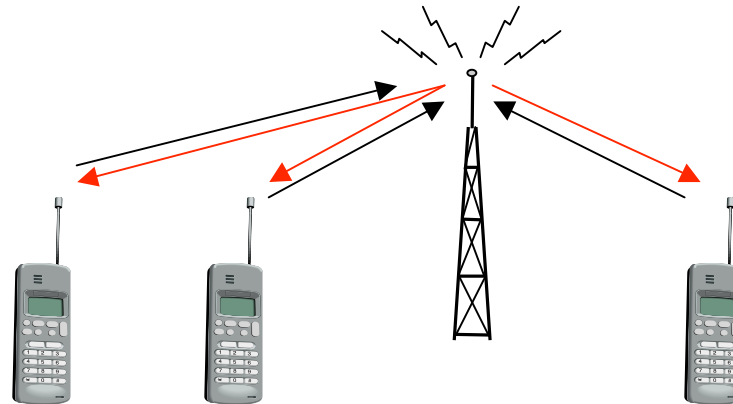
## ❑ Reservation Time Division Multiple Access

- 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)

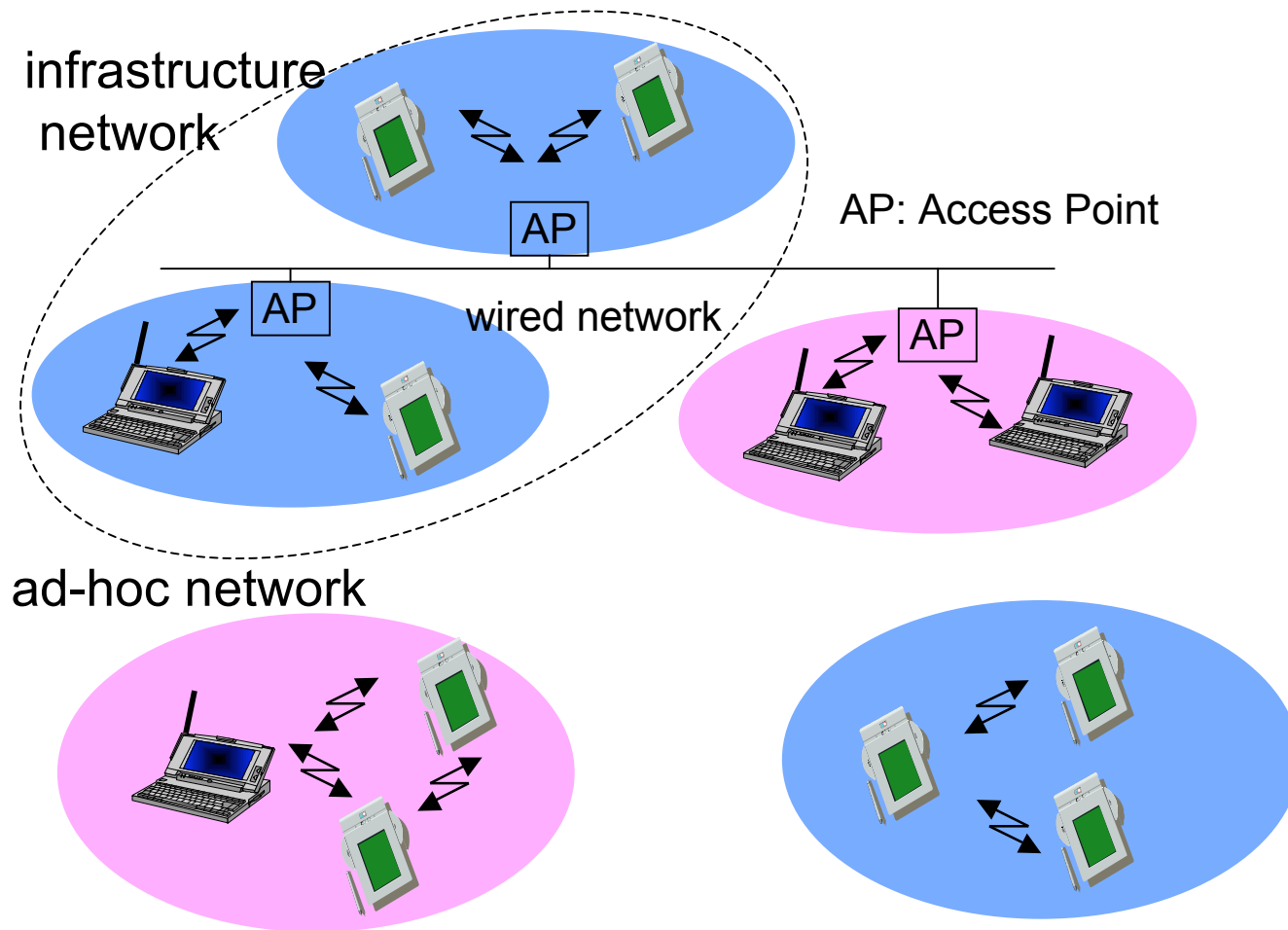


# ISMA (Inhibit Sense)

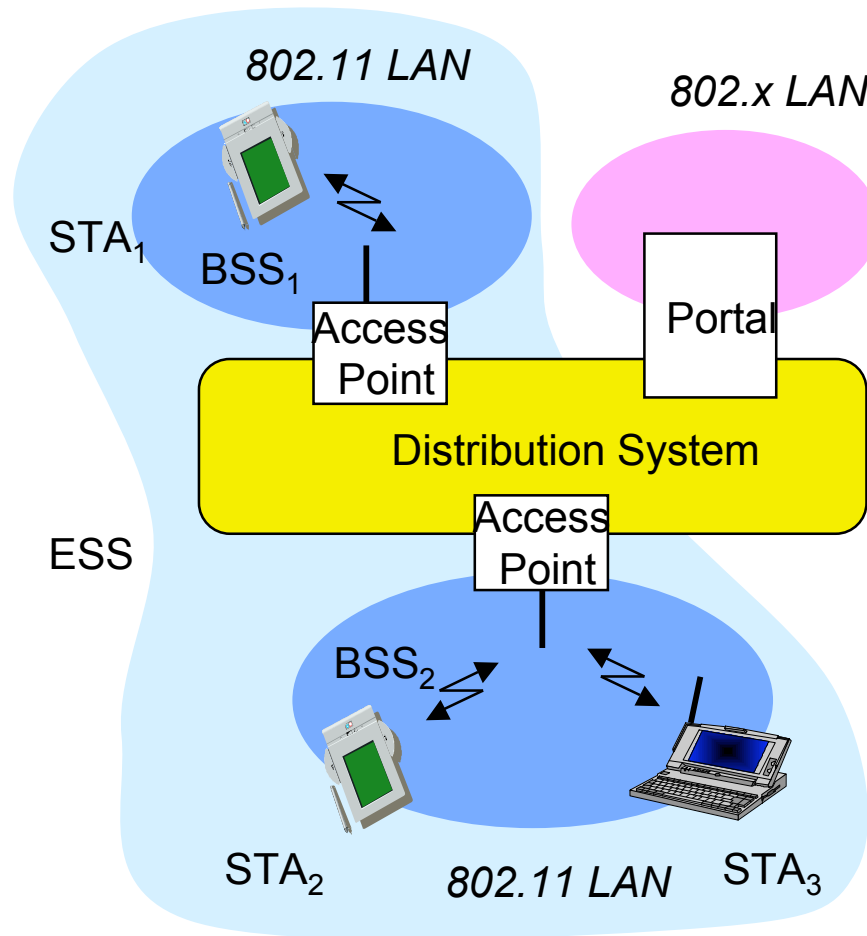
- ❑ Current state of the medium is signaled via a “busy tone”
  - o the base station signals on the downlink (base station to terminals) if the medium is free or not
  - o terminals must not send if the medium is busy
  - o terminals can access the medium as soon as the busy tone stops
  - o the base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



# IEEE802.11



# 802.11 infrastructure mode



## ❑ Station (STA)

- o terminal with access mechanisms to the wireless medium and radio contact to the access point

## ❑ Basic Service Set (BSS)

- o group of stations using the same radio frequency

## ❑ Access Point

- o station integrated into the wireless LAN and the distribution system

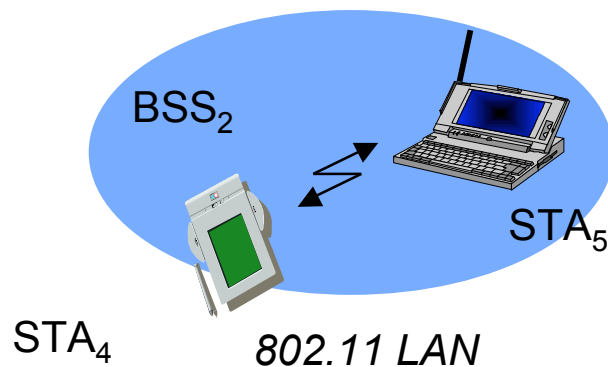
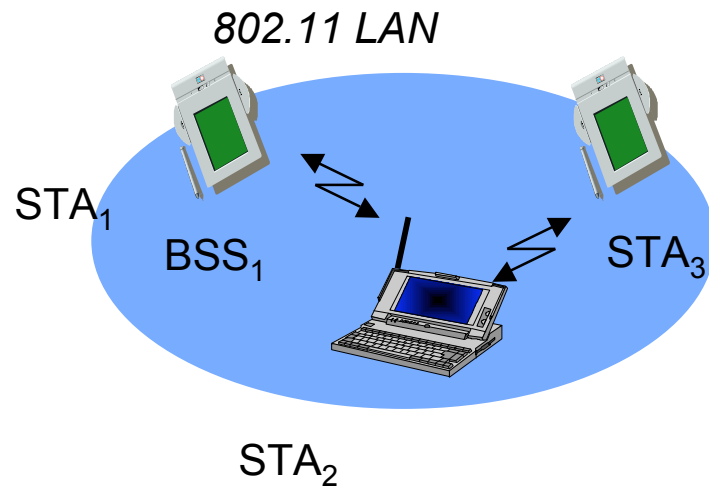
## ❑ Portal

- o bridge to other (wired) networks

## ❑ Distribution System

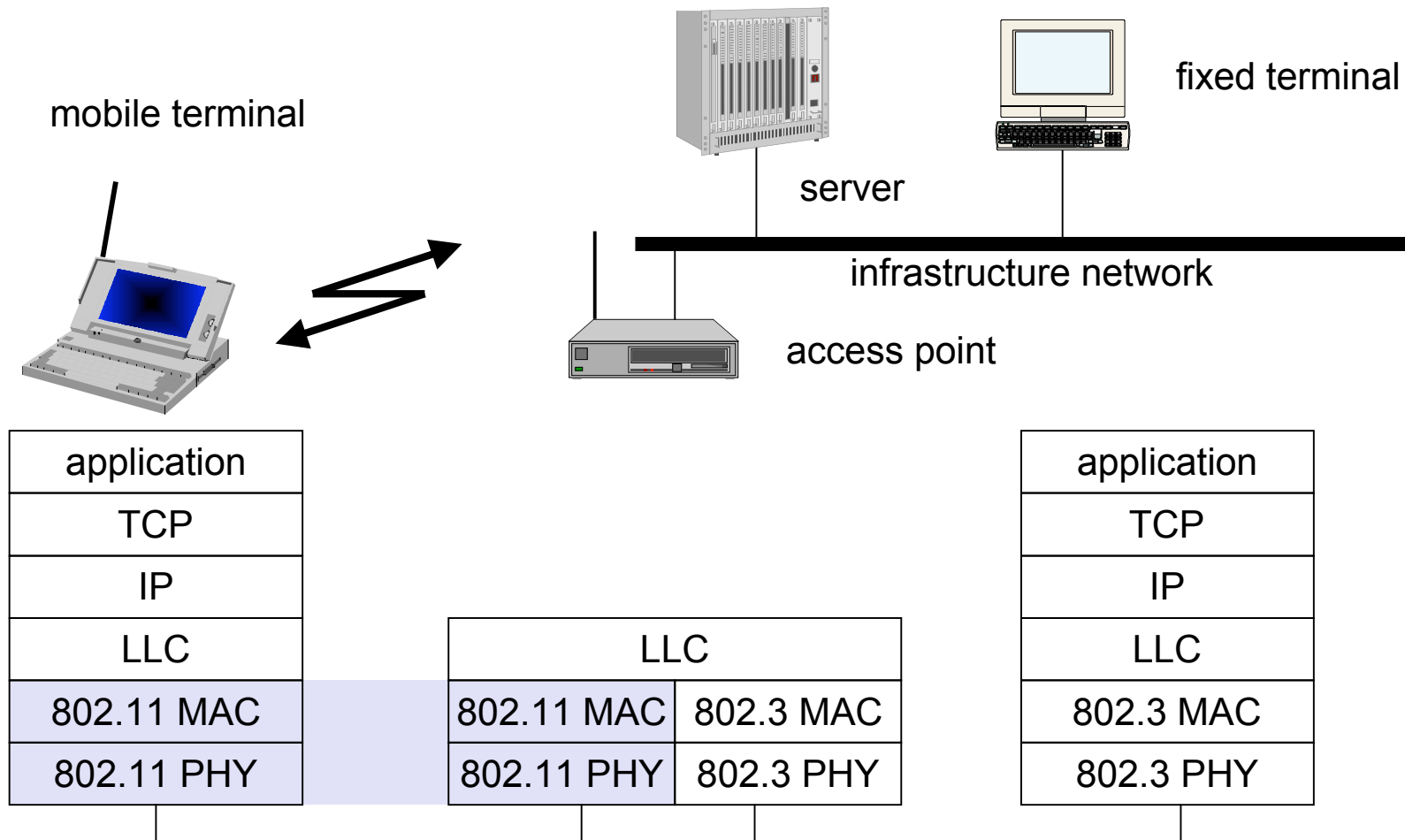
- o interconnection network to form one logical network (ESS: Extended Service Set) based on several BSS

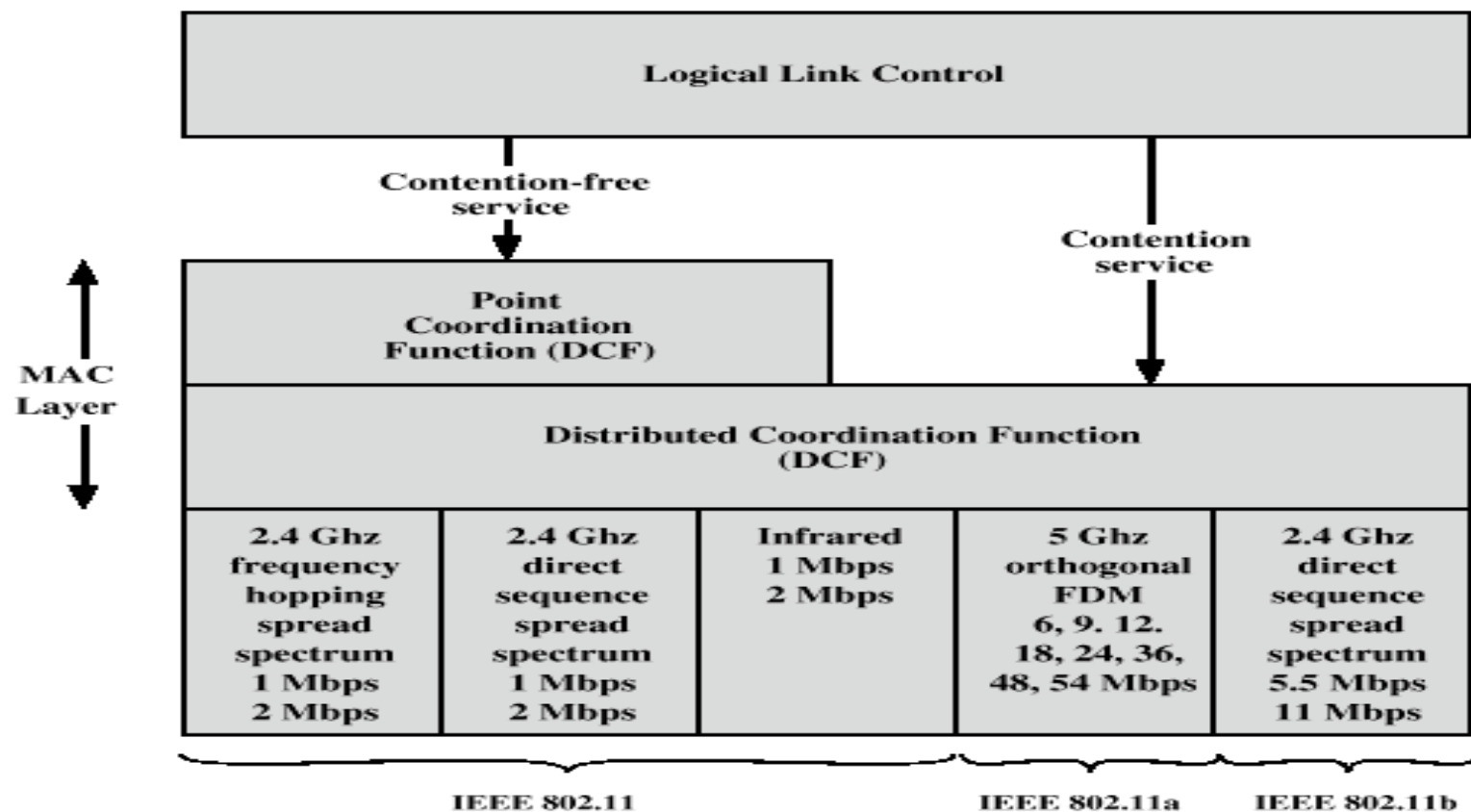
# 802.11: ad-hoc mode



- ❑ Direct communication within a limited range
  - o Station (STA): terminal with access mechanisms to the wireless medium
  - o 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
  - o data rates ranging from 1 Mbps to 54 Mbps
- ❑ FHSS (Frequency Hopping Spread Spectrum) 2.4 GHz
  - o spreading, de-spreading, signal strength, typically 1 Mbit/s
  - o min. 2.5 frequency hops/s (USA), two-level GFSK modulation
- ❑ DSSS (Direct Sequence Spread Spectrum) 2.4 GHz
  - o DBPSK or DQPSK modulation (Differential Binary Phase Shift Keying or Differential Quadrature PSK)
  - o Chipping sequence: +1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1 (Barker code)
  - o Maximum radiated power 1 W (USA), 100 mW (EU), min. 1mW
- ❑ Infrared
  - o 850-950 nm, diffuse light, typically 10 m range
  - o Data rates 1-2 Mbps



# IEEE 802.11a and IEEE 802.11b

## ❑ IEEE 802.11a

- o Makes use of 5-GHz band
- o Provides rates of 6, 9 , 12, 18, 24, 36, 48, 54 Mbps
- o Uses orthogonal frequency division multiplexing (OFDM)
- o Sub-carrier modulated using BPSK, QPSK, 16-QAM or 64-QAM

## ❑ IEEE 802.11b

- o Provides data rates of 5.5 and 11 Mbps
- o DSSS and complementary code keying (CCK) modulation

## ❑ IEEE 802.11g

- o Extends data rates to up to 54 Mbps
- o Uses OFDM, in the 2.4 GHz band

# 802.11 - MAC layer

## ❑ Traffic services

- o Asynchronous Data Service (mandatory)
  - exchange of data packets based on “best-effort”
  - support of broadcast and multicast
- o Time-Bounded Service (optional)
  - implemented using PCF (Point Coordination Function)

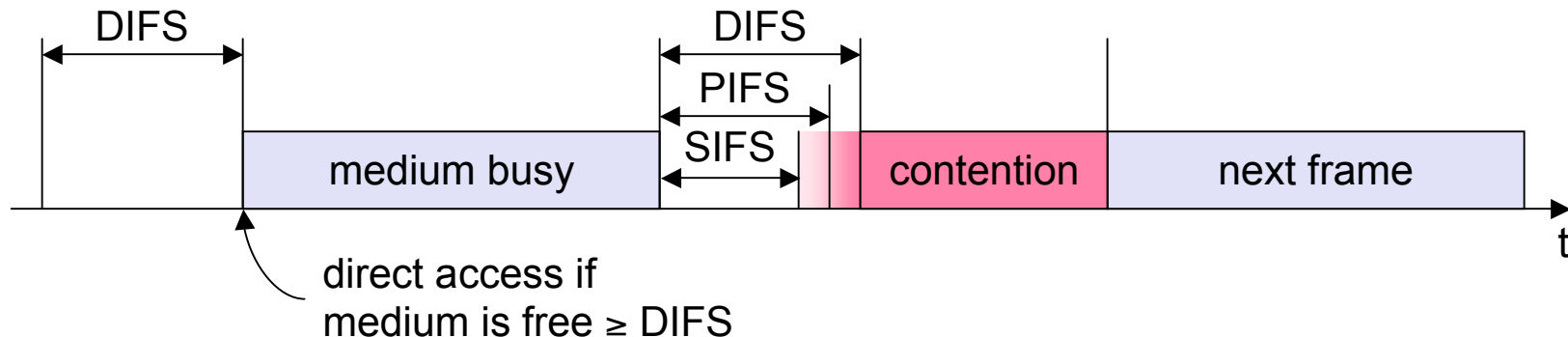
## ❑ Access methods

- o DCF CSMA/CA (mandatory)
  - collision avoidance via exponential backoff
  - Minimum distance (IFS) between consecutive packets
  - ACK packet for acknowledgements (not for broadcasts)
- o DCF with RTS/CTS (optional)
  - Distributed Foundation Wireless MAC
  - avoids hidden terminal problem
- o PCF (optional)
  - access point polls terminals according to a list

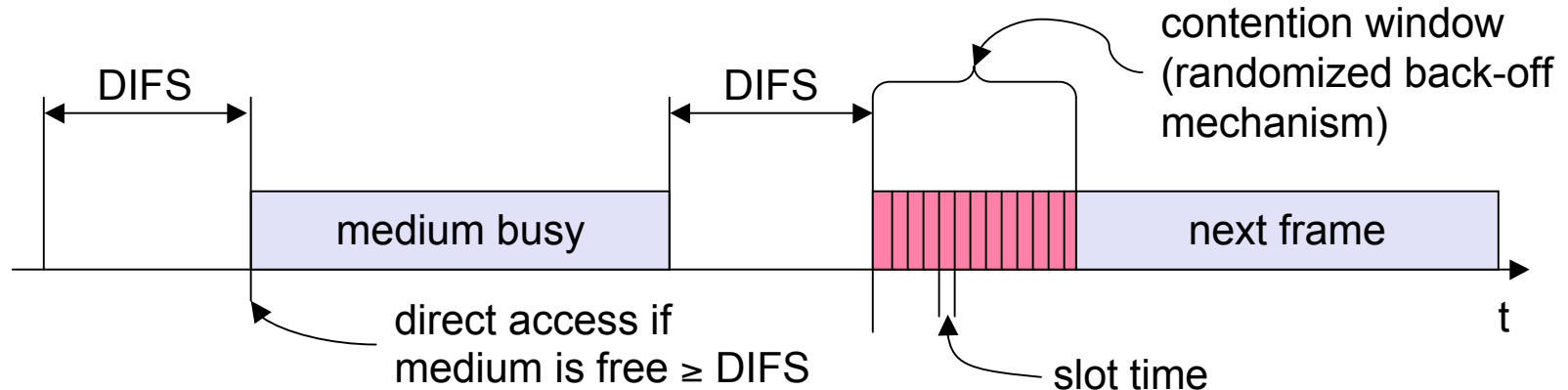
# 802.11 - MAC layer

## □ Priorities

- o defined through different inter frame spaces
- o SIFS (Short Inter Frame Spacing)
  - highest priority, for ACK, CTS, polling response
- o PIFS (PCF IFS)
  - medium priority, for time-bounded service using PCF
- o DIFS (DCF, Distributed Coordination Function IFS)
  - lowest priority, for asynchronous data service

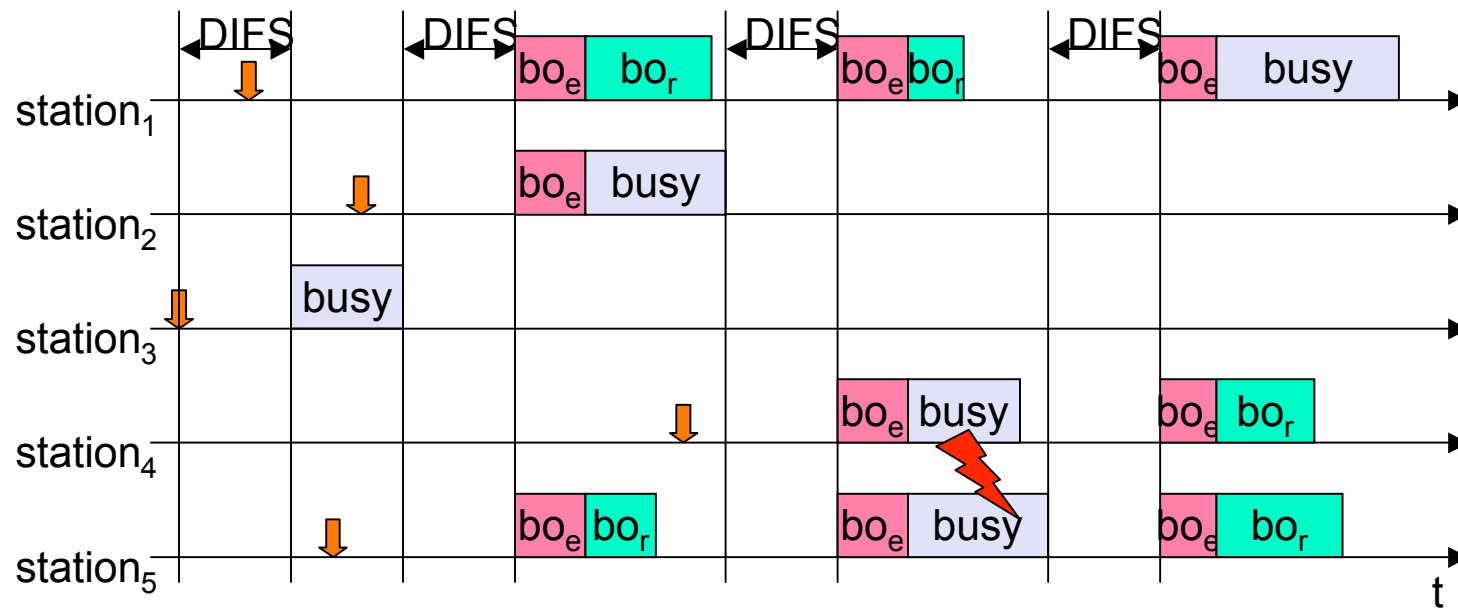


# CSMA/CA access method



- ❑ 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



busy

medium not idle (frame, ack etc.)

$bo_e$

elapsed backoff time



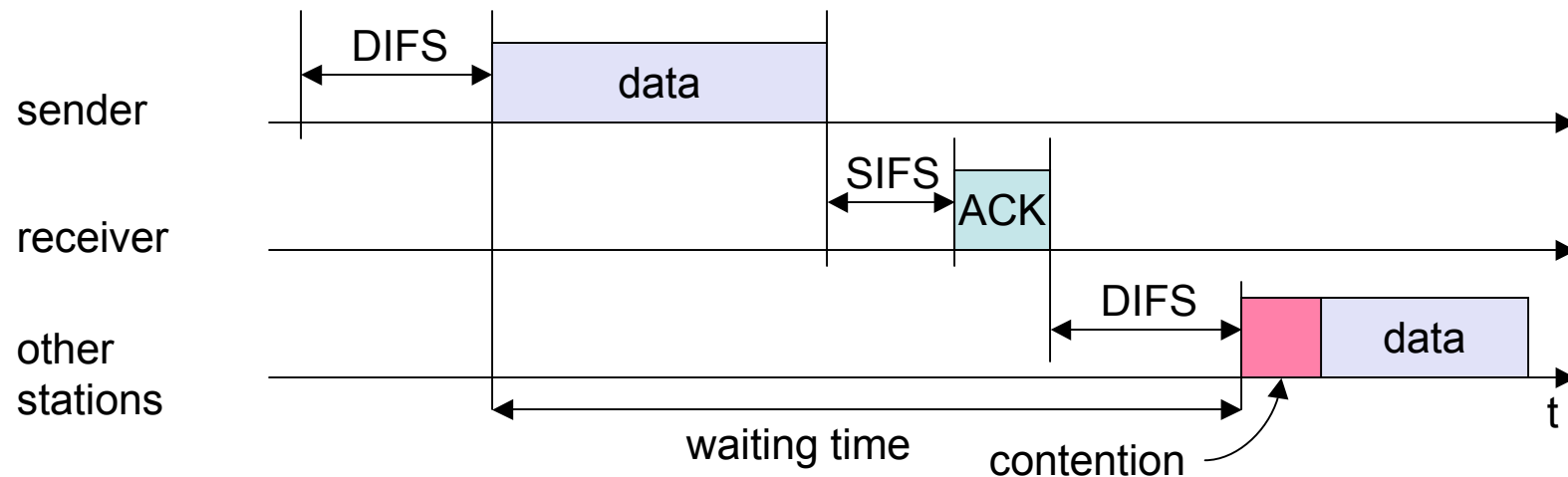
packet arrival at MAC

$bo_r$

residual backoff time

# 802.11 access scheme details

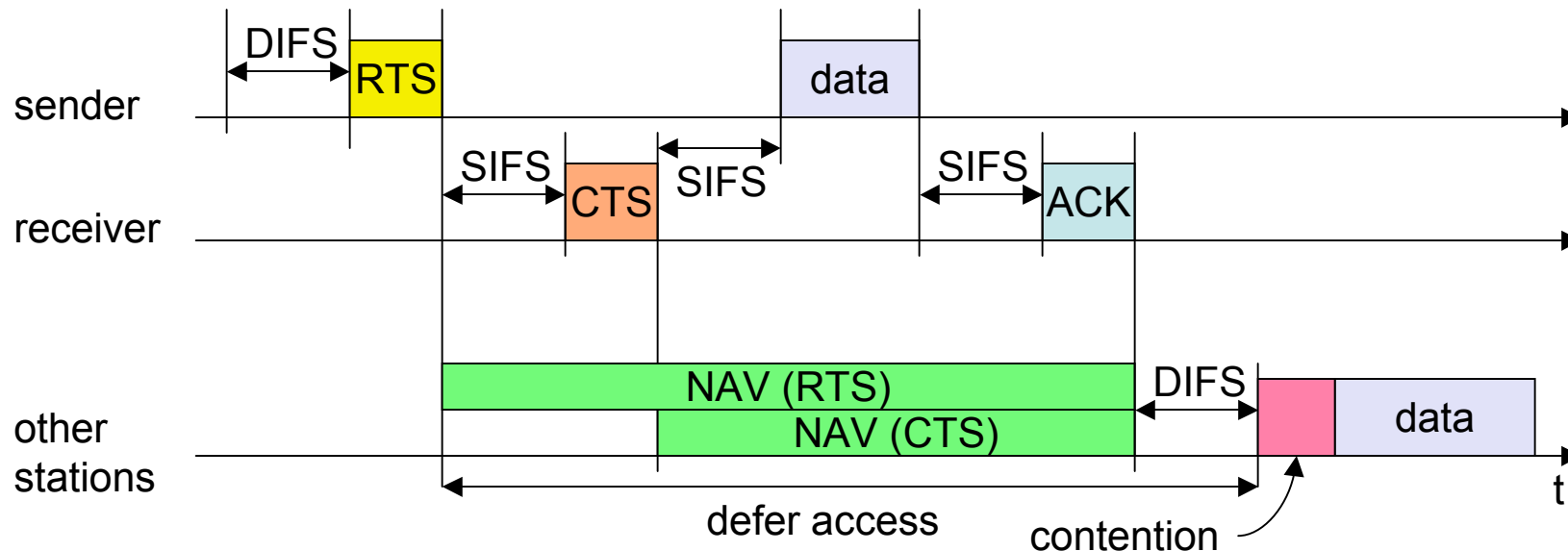
- ❑ Sending unicast packets
  - o station has to wait for DIFS before sending data
  - o receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
  - o automatic retransmission of data packets in case of transmission errors



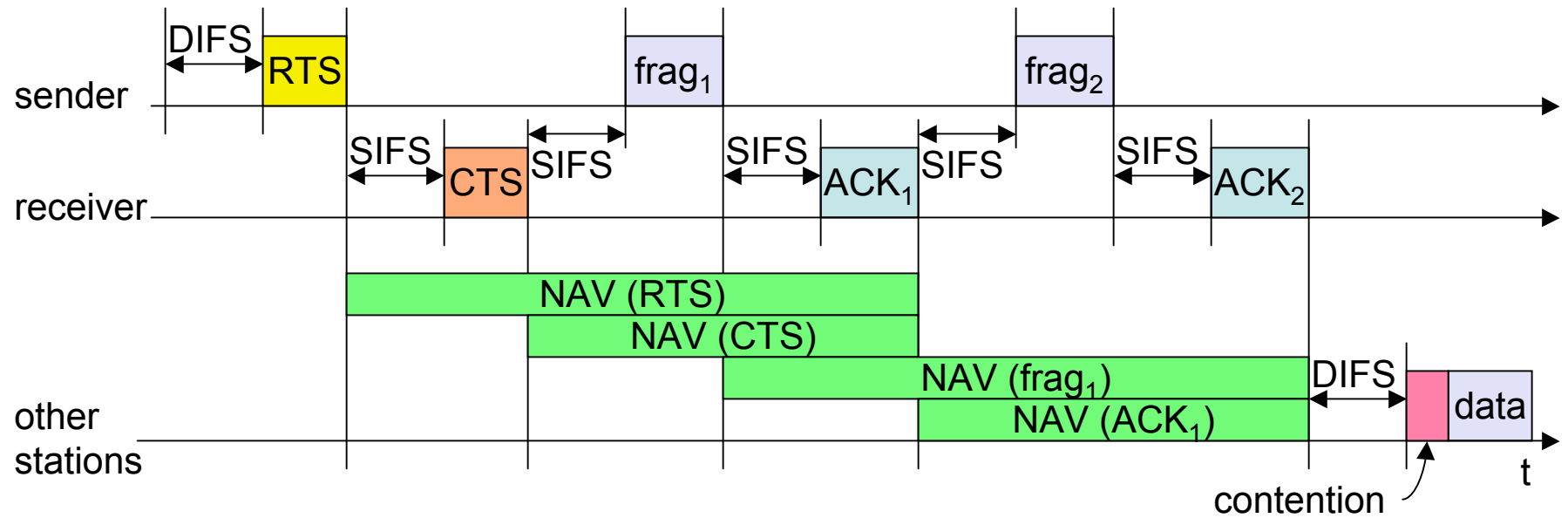
# 802.11 access scheme details

## ❑ Sending unicast packets

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

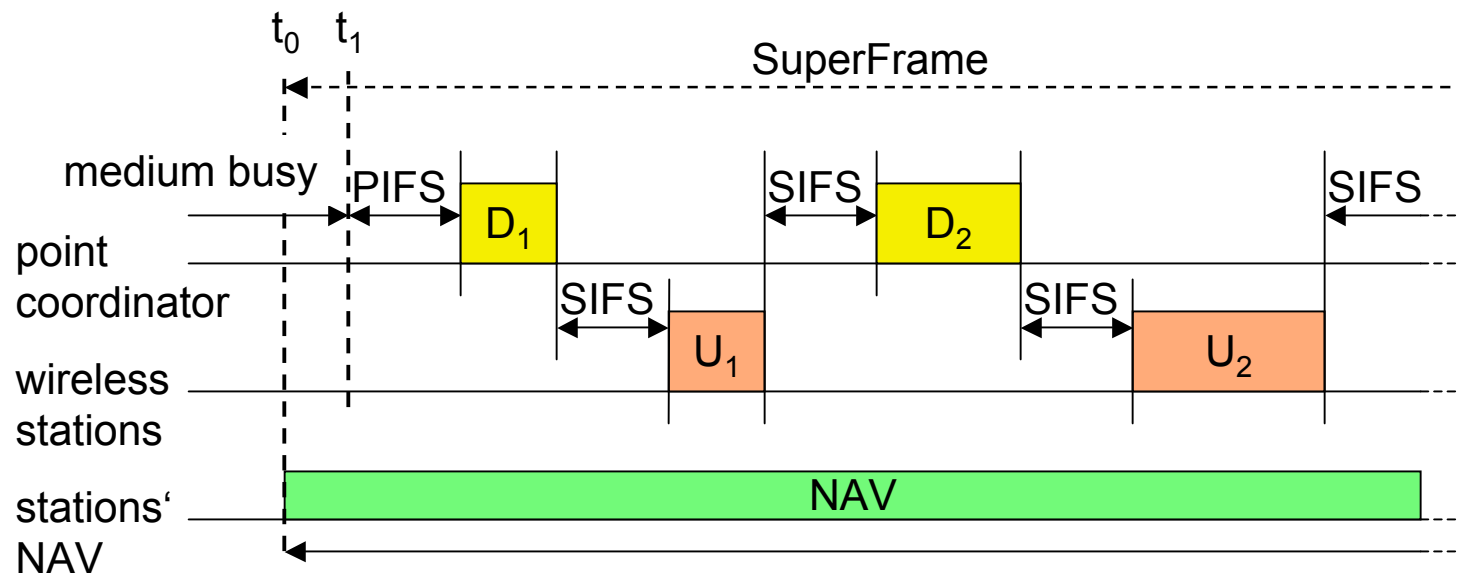


# Fragmentation

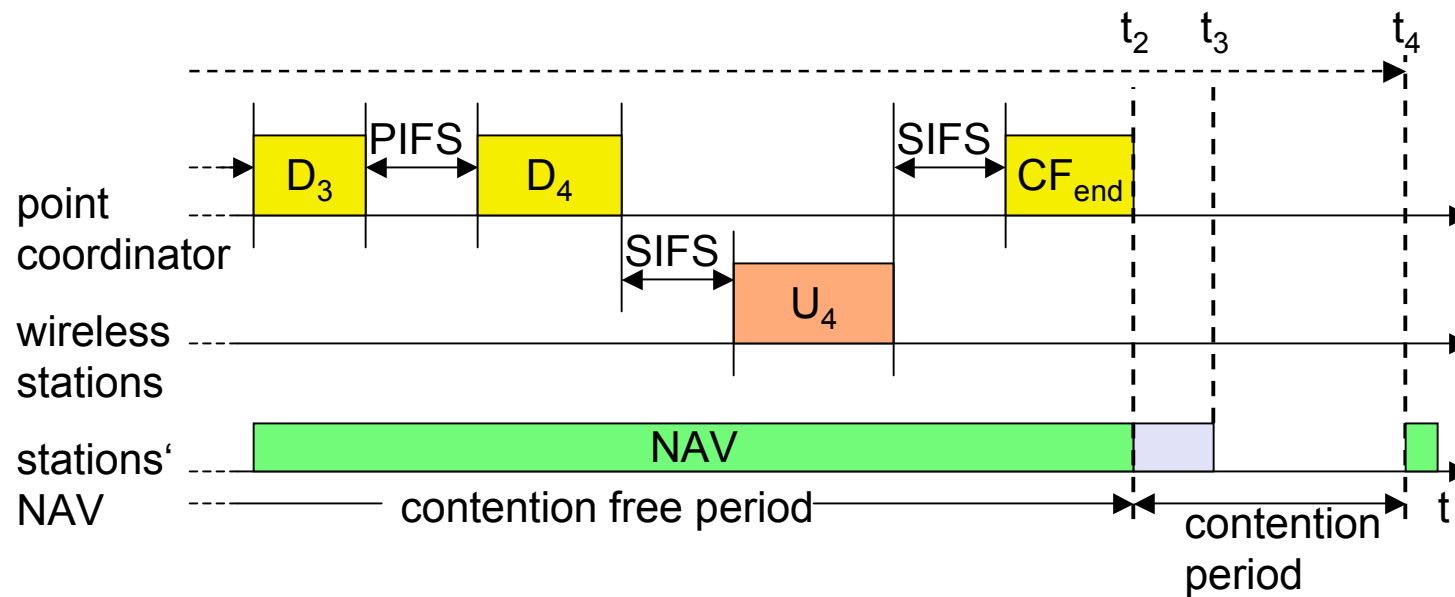




# Point Coordination Function

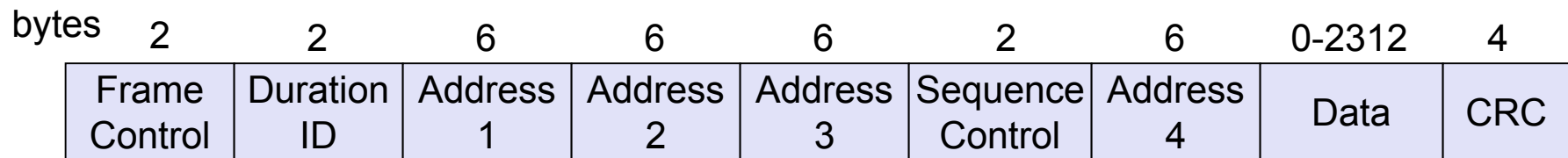


# Point Coordination Function



# 802.11 - Frame format

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

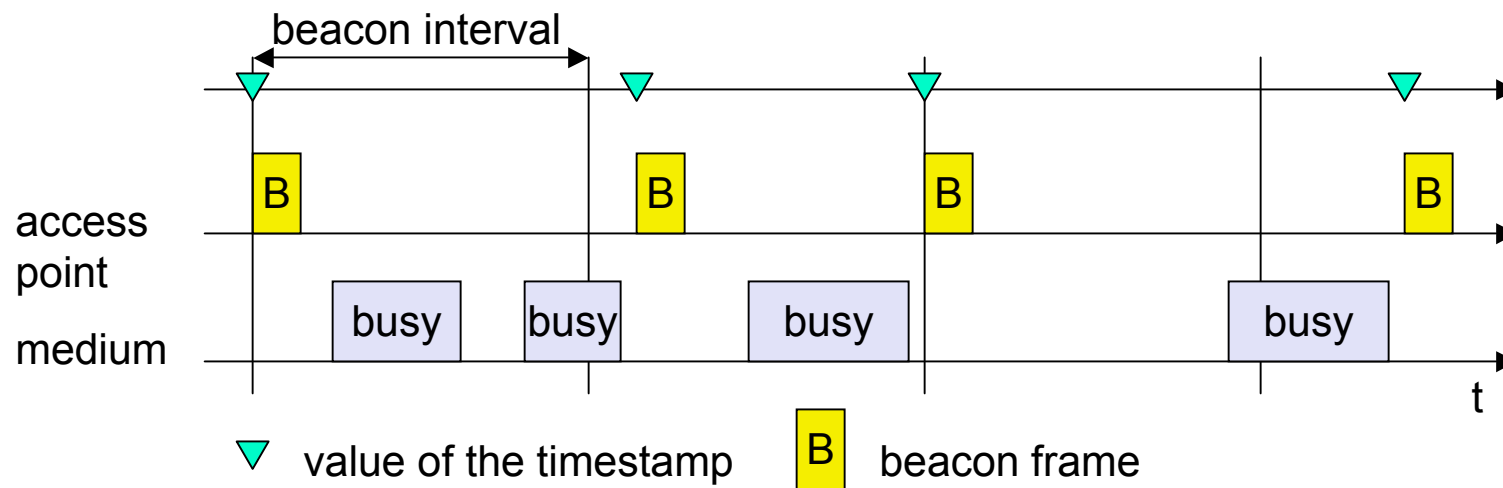


Version, Type, Subtype, To DS, From DS, More Fragments, Retry, Power Management, More Data, Wired Equivalent Privacy (WEP), and Order

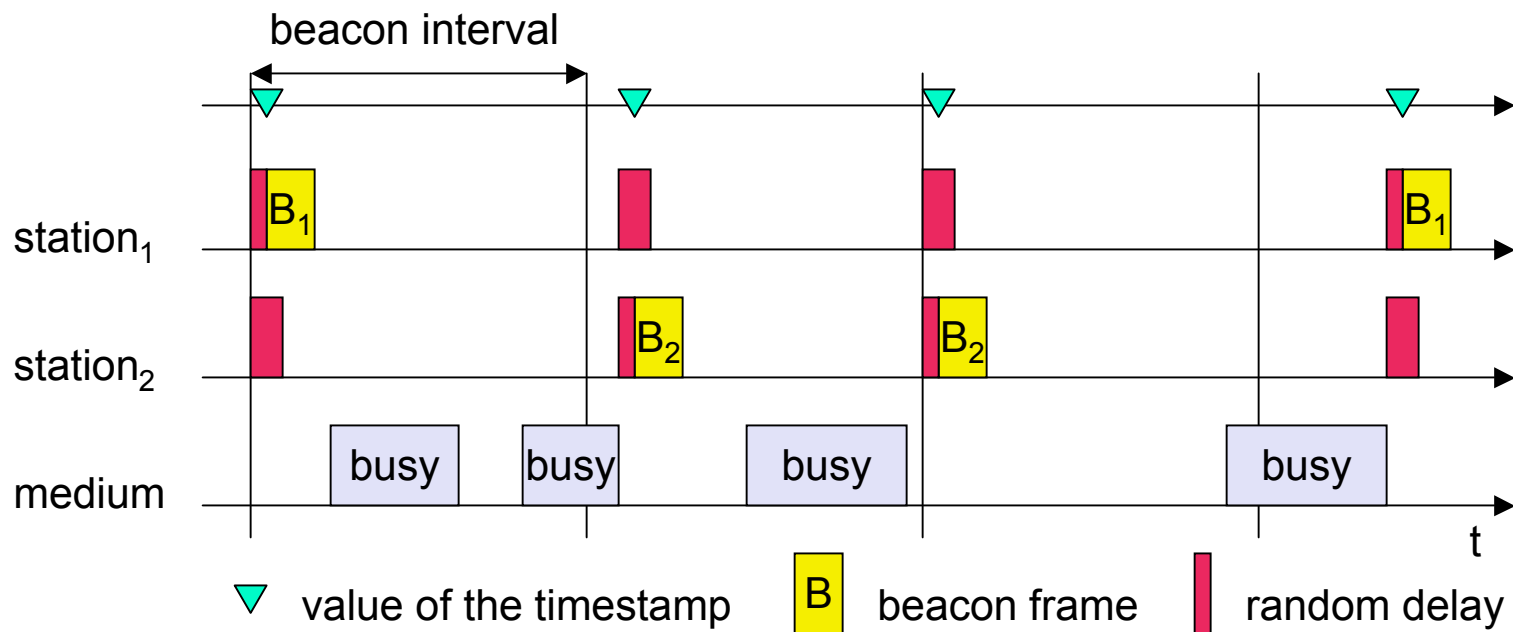
# 802.11 MAC management

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

# Synchronization (infrastructure)



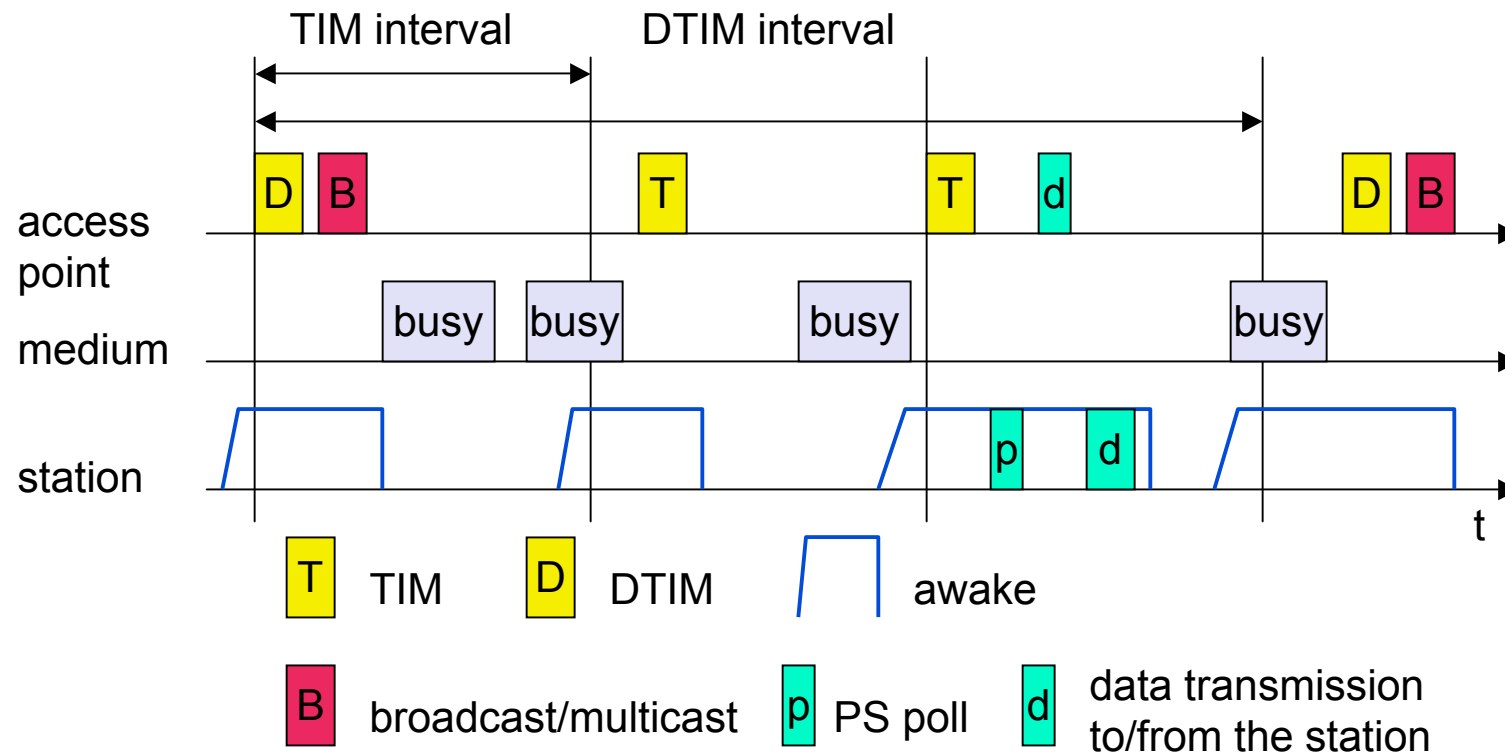
# Synchronization (ad-hoc)



# Power management

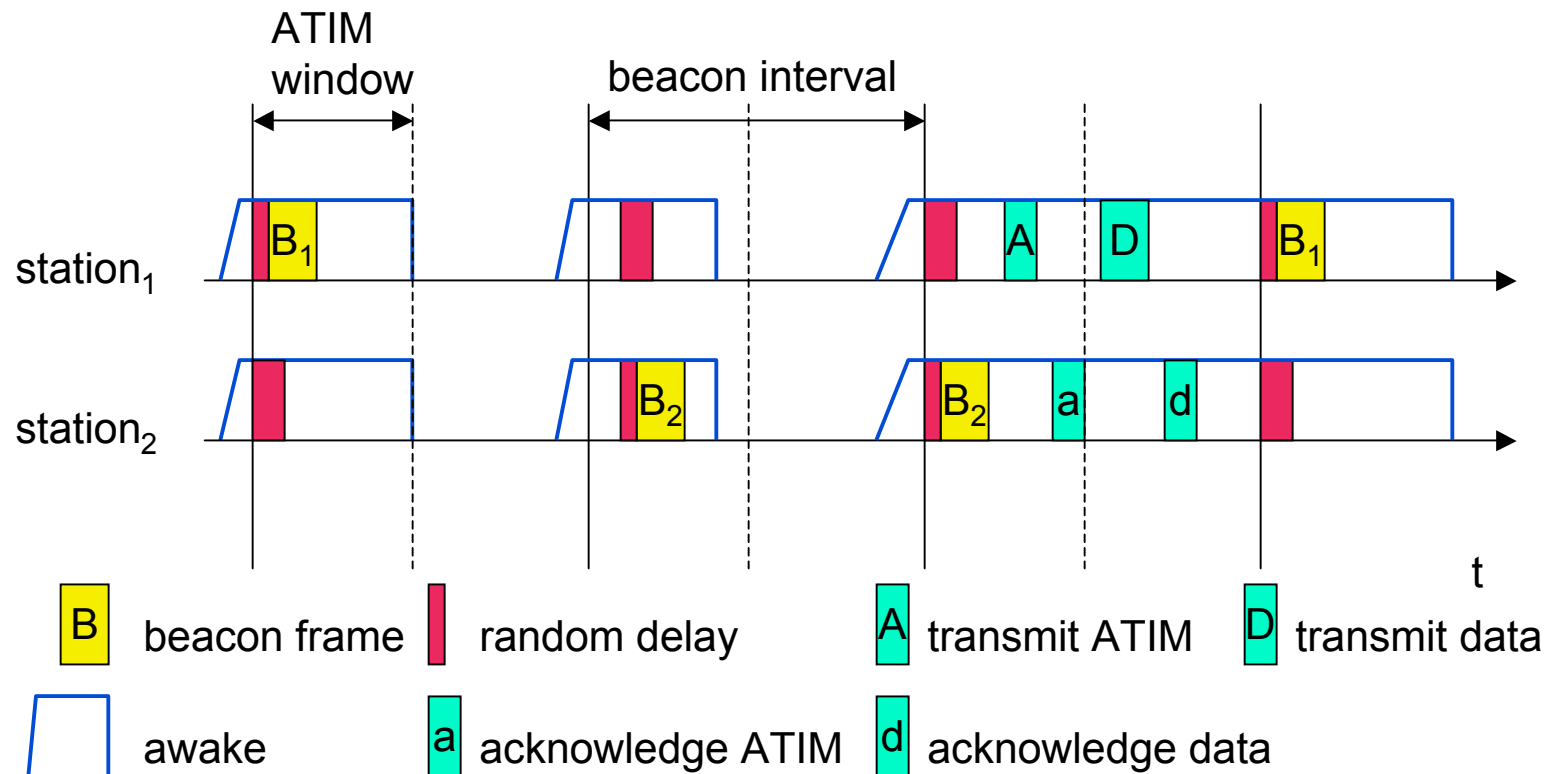
- ❑ Idea: switch the transceiver off if not needed
- ❑ States of a station: sleep and awake
- ❑ Timing Synchronization Function (TSF)
  - o stations wake up at the same time
- ❑ Infrastructure
  - o Traffic Indication Map (TIM)
    - list of unicast receivers transmitted by AP
  - o Delivery Traffic Indication Map (DTIM)
    - list of broadcast/multicast receivers transmitted by AP
- ❑ Ad-hoc
  - o 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
  - o 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
  - o station sends a request to one or several AP(s)
- ❑ Reassociation Response
  - o success: AP has answered, station can now participate
  - o failure: continue scanning
- ❑ AP accepts Reassociation Request
  - o signal the new station to the distribution system
  - o the distribution system updates its data base (i.e., location information)
  - o typically, the distribution system now informs the old AP so it can release resources

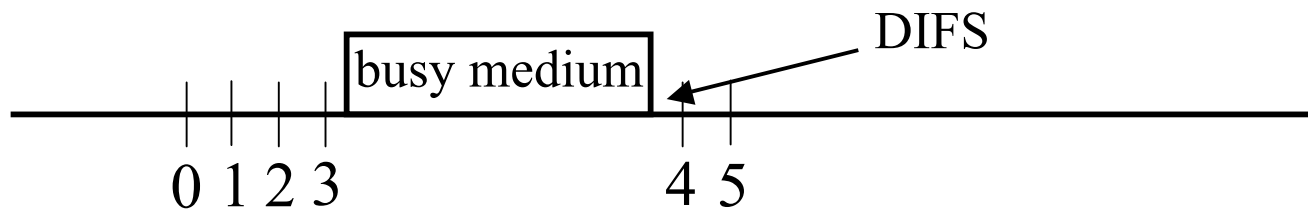
# Performance Analysis of 802.11

- ❑ Markov chain models for DCF
- ❑ Throughput:
  - o 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]:
  - o No hidden terminal: all users can hear one another
  - o No packet capture: all receive powers are identical
  - o Saturation conditions: queue of each station is always nonempty
- ❑ Parameters:
  - o Packet lengths (headers, control and data)
  - o 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

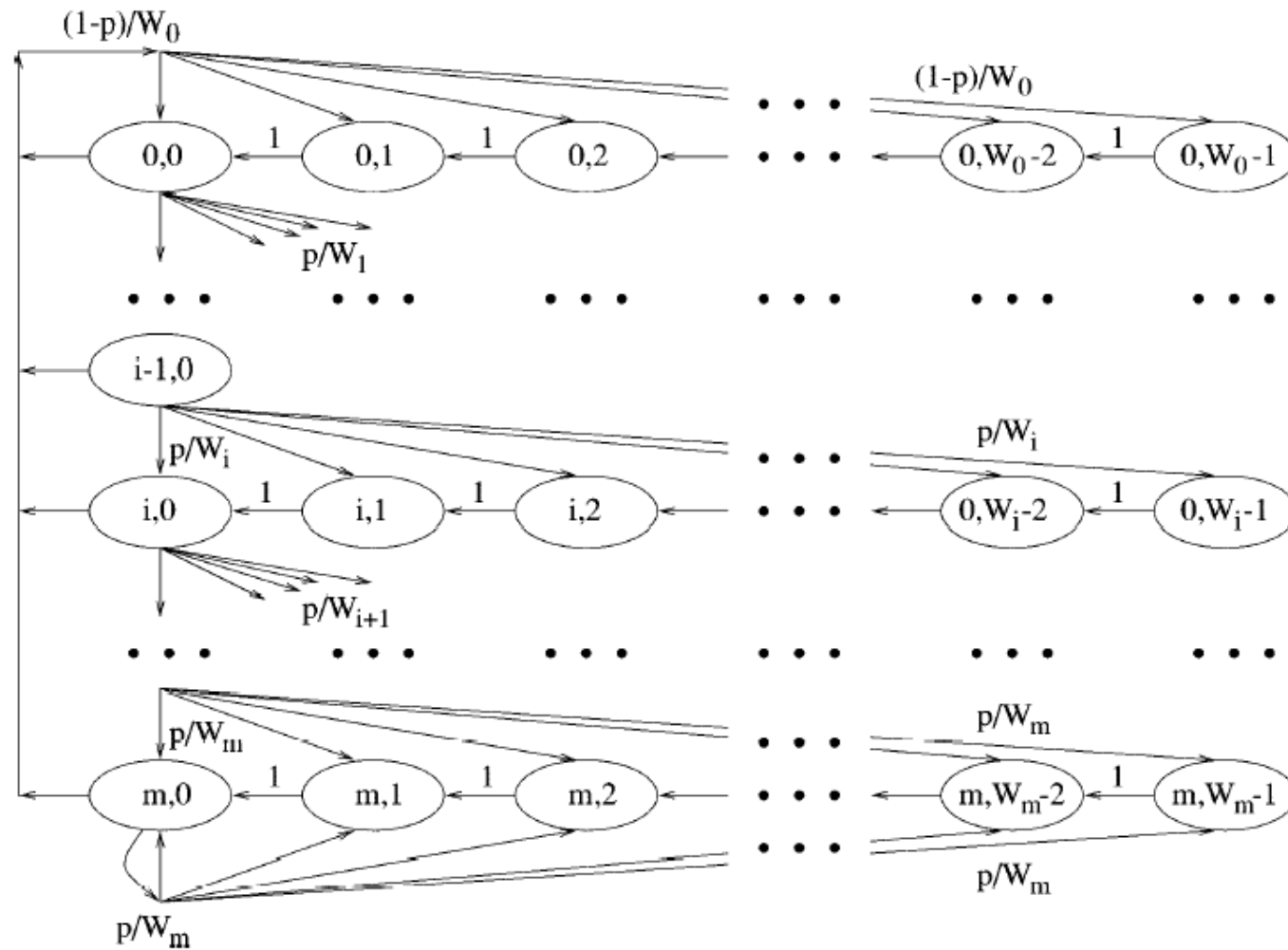


- ❑ Let  $b(t)$  denote the backoff time counter for a given node at slot  $t$ 
  - o Slot: constant time period  $\sigma$  if the channel is idle, and the packet transmission period, otherwise
  - o Note that  $t$  is not the same as system time
- ❑ The variable  $b(t)$  is non-Markovian
  - o Its transitions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

# A Stochastic Model for Backoff

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

# Markov Chain Model



Bianchi 00

# Steady State Analysis

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

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

- ❑ Solve for  $\tau$  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

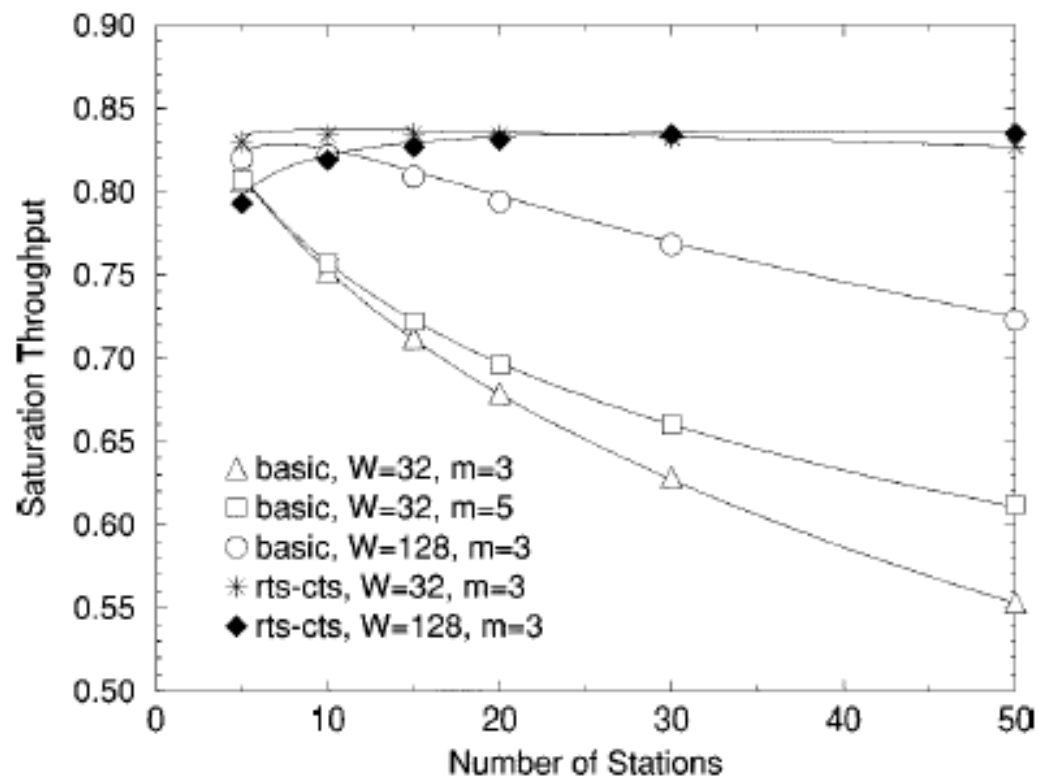


Fig. 6. Saturation Throughput: analysis versus simulation.

	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