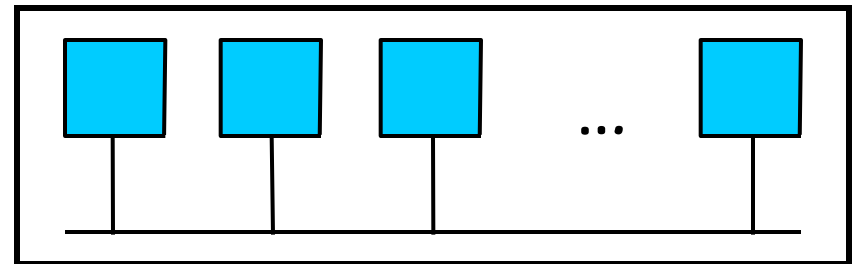# CS/ECE 439: Wireless Networking

MAC Layer – Road to Wireless

Multiple Access Media

▸ ## Media access

  ▸ Controlling which frame should be sent over the link next

    ▸ Easy for point-to-point links; half versus full duplex
    ▸ Harder for multi-access links: who gets to send?

▸ ## Multiple senders on some media

  ▸ Buses (Ethernet)
  ▸ Radio, Satellite

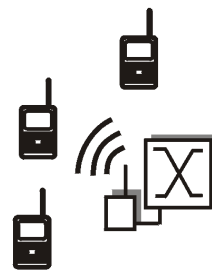▸ ## Goals

  ▸ Fair arbitration
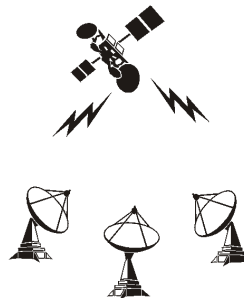 ▸ Good performance

Point-to-Point vs. Broadcast Media

▸ **Point-to-point: dedicated pairwise communication**

  ▸ Long-distance fiber link

  ▸ Point-to-point link between Ethernet switch and host

▸ **Broadcast: shared wire or medium**

  ▸ Traditional Ethernet

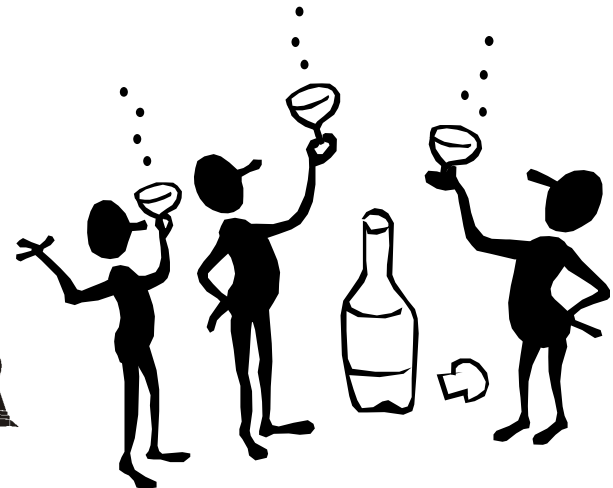 ▸ 802.11 wireless LAN
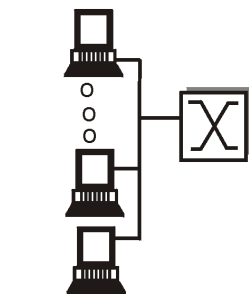
shared wire
(e.g. Ethernet) 　　shared wireless
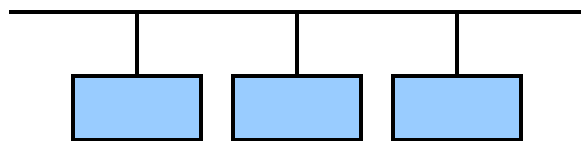(e.g. Wavelan) 　　satellite 　　cocktail party

Types of Shared Link Networks

Bus Topology: Shared

Ethernet, Token Bus

Ring Topology: Multihop

FDDI, IEEE 802.5

Star Topology: Active or Passive Hub

ATM
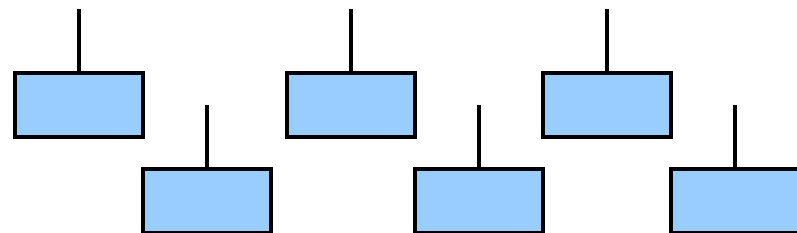
Wireless: Shared

IEEE 802.11

Multiple Access Algorithm

▶ **Single shared broadcast channel**

  ▶ Must avoid having multiple nodes speaking at once

  ▶ Otherwise, collisions lead to garbled data

  ▶ Need distributed algorithm for sharing the channel

  ▶ Algorithm determines which node can transmit

▶ **Typical assumptions**

  ▶ Communication needs vary

    ▶ Over time

    ▶ Between hosts

  ▶ Network is not fully utilized

Multiple Access Media

▸ ## Which kind of multiplexing is best?
  ▸ ### Channel partitioning: divide channel into pieces
    ▸ Frequency-division multiplexing (FDM, separate bands)
  ▸ ### Taking turns: scheme for trading off who gets to transmit
    ▸ Time-division multiplexing (TDM, synchronous time slots)
    ▸ Statistical time-division multiplexing (STDM, time slots on demand)

▸ ## These techniques are useful
  ▸ ### But they have a number of limitations
  ▸ ### They do not support bursty traffic efficiently
    ▸ Lots of unused capacity, …
    ▸ … while active users squeeze their bit stream through a very thin pipe
  ▸ ### Work best in a provisioned service
    ▸ Management of frequencies, time slots, placement of devices, etc.

Multiple Access Media: Random Access

▸ **Random access**
  ▸ Allow collisions, and then recover
  ▸ Optimize for the common case (no collision)
  ▸ Don't avoid collisions, just recover from them….

▸ **When node has packet to send**
  ▸ Transmit at full channel data rate
  ▸ No a priori coordination among nodes

▸ **Two or more transmitting nodes** $\Rightarrow$ **collision**
  ▸ Data lost

▸ **Random access MAC protocol specifies**
  ▸ How to detect collisions
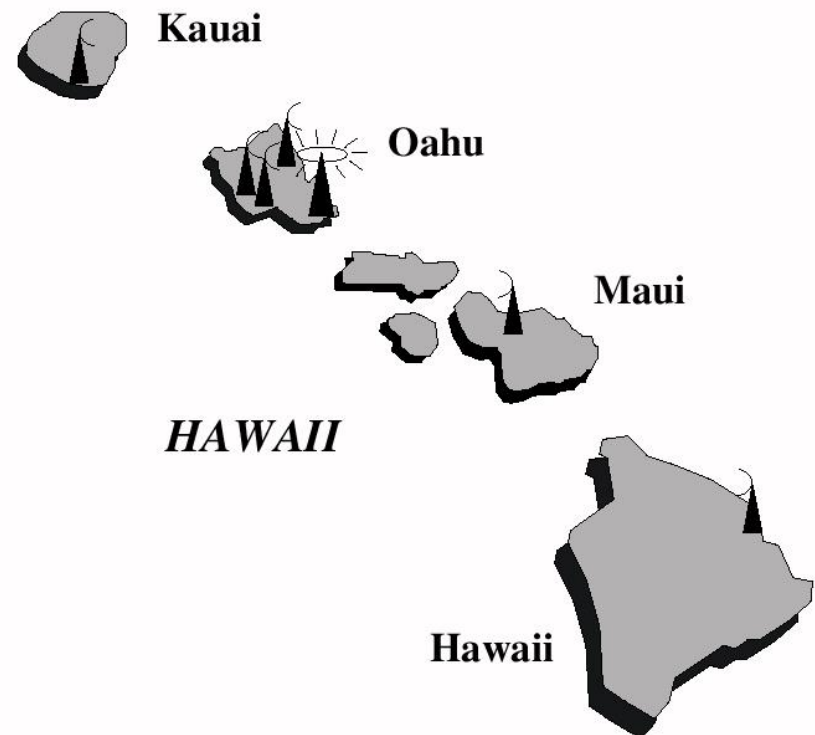 ▸ How to recover from collisions

Carrier Sense Multiple Access with Collision Detection (CSMA/CD)

- ▶ Aloha Packet Radio Network
  - ▶ First data communication system for Hawaiian islands
  - ▶ Hub at U. Hawaii, Oahu
  - ▶ Two radio channels
    - ▶ Random access: for sites sending data
    - ▶ Broadcast for hub rebroadcasting data
- ▶ Ethernet
  - ▶ CSMA/CD for LANs

Pure ALOHA

▸ Developed in University of Hawaii in early 1970's
▸ Keep it simple
  ▸ User transmits at will
  ▸ If two or more messages overlap in time → collision
    ▸ Receiver cannot decode packets
  ▸ Wait roundtrip time plus a fixed increment → collision
    ▸ Lack of ACK
  ▸ After a collision
    ▸ Colliding stations retransmit
    ▸ Stagger attempts randomly to reduce repeat collisions
  ▸ After several attempts, senders give up
▸ Simple but wasteful
  ▸ Max efficiency of at most $1/(2e) = 18\%$!

Pure ALOHA

▸ ## User model

  ▸ ### N transmitters

    ▸ Each transmitter hooked to one terminal
    ▸ One person at each terminal

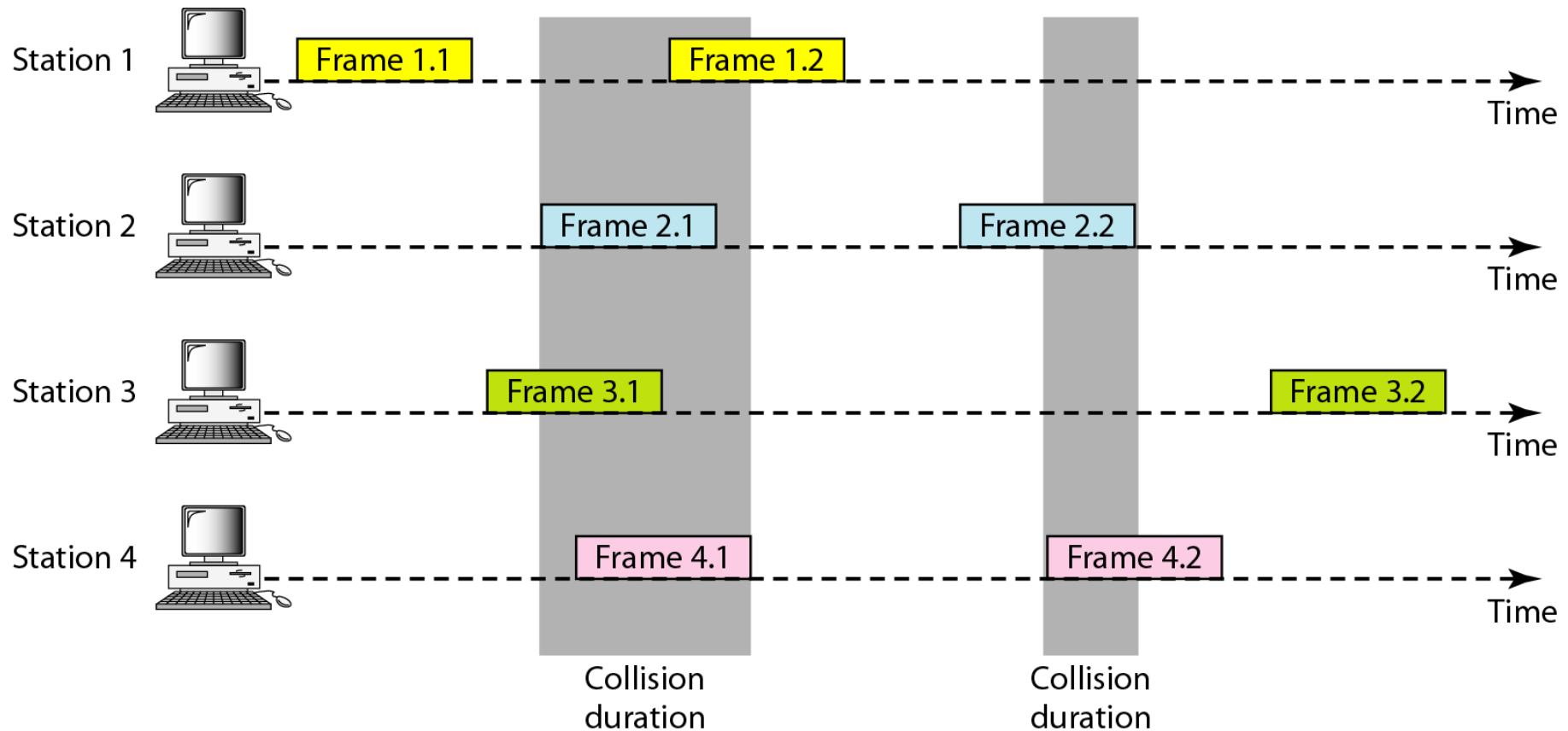 ▸ ### Person types a line, presses return

    ▸ Transmitter sends line
    ▸ Each station transmits λ packets/sec on average based on a Poisson arrival process

  ▸ ### Checks for success (no interference)

  ▸ ### If collision occurred, wait random time and resend

Pure ALOHA

Pure ALOHA

▸ Collisions

  ▸ A frame not will suffer a collision if no other frames are sent within one frame time of its start

  ▸ Let t = time to send a frame

  ▸ If any other user has generated a frame between time t_0 and time $t_0 + t$, the end of that frame will collide with the beginning of our frame

  ▸ Similarly, any other frame started between time $t_0 + t$ and time $t_0 + 2t$ will collide with the end of our frame

Pure ALOHA
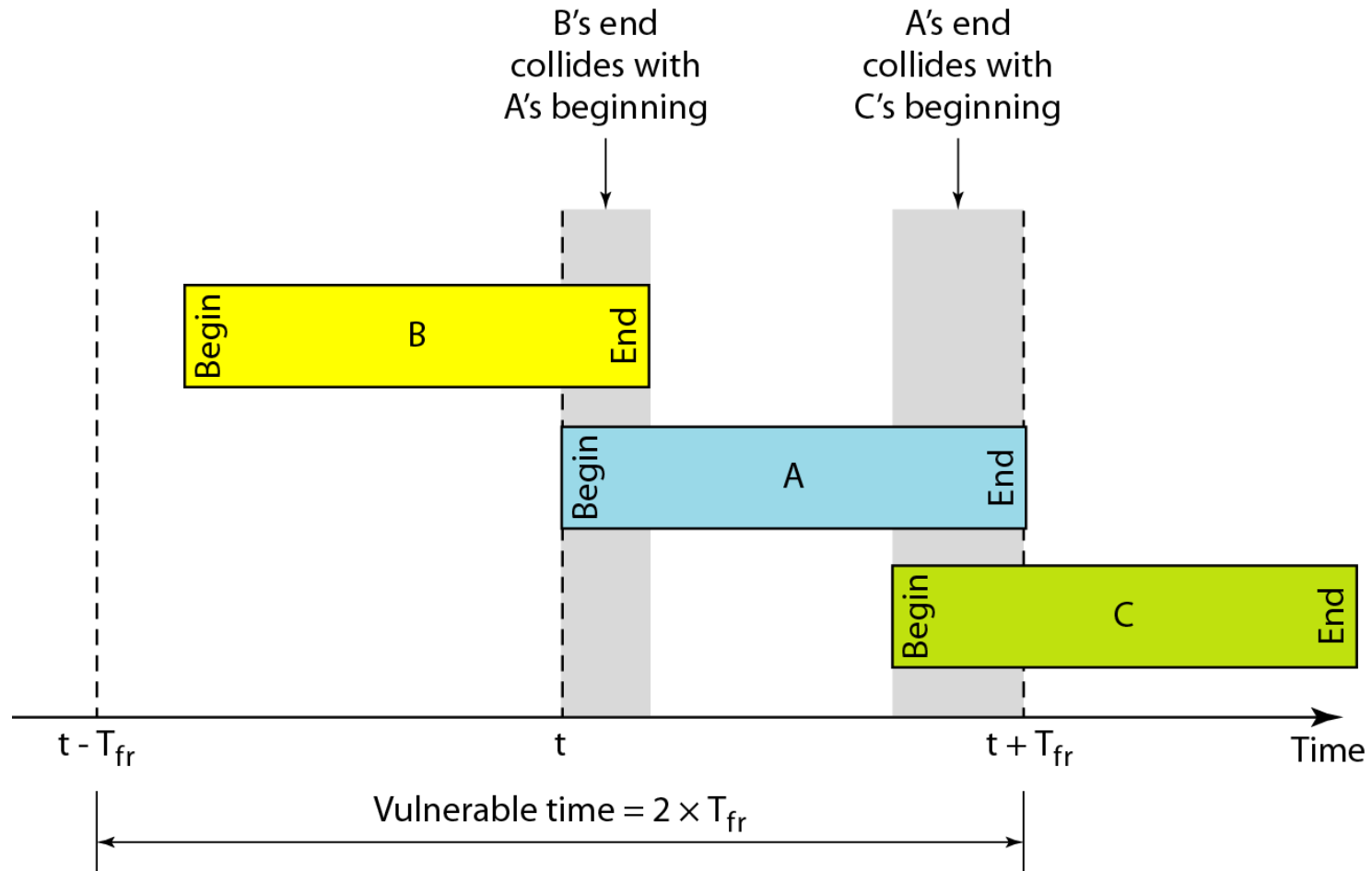
Pure ALOHA

- Also assume fixed packet sizes (maximizes throughput)
- Arrival and success rates
  - Frames generated at rate S
    - In steady state, must leave at S as well
  - Some frames retransmitted
    - Assume also Poisson with rate G, $G > S$
- $S = G\ P_0$
  - P_0 is the probability of successful transmission

Pure Aloha Analysis

▸ **Maximum throughput**

  ▸ *G = 0.5*

  ▸ *S = 1⁄2e*

■ Utilization

  ○ Maximum of 0.184!
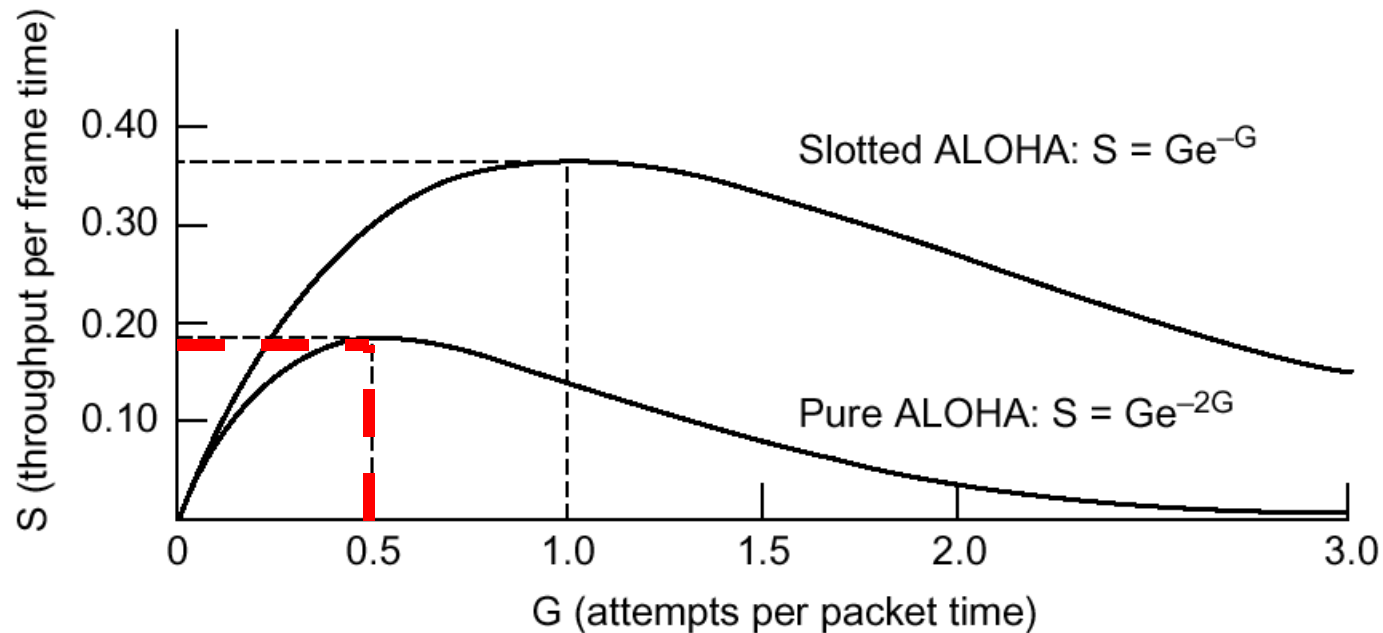
Slotted ALOHA

▸ **Hosts wait for next slot to transmit**
  ▸ Slot time units = *m* (message length)
  ▸ Modify Aloha by allowing users to attempt transmission at the beginning of a time slot only
  ▸ All users need to be synchronized in time.

▸ **Vulnerable period is now cut in half (*T*)**
  ▸ Doubles max throughput
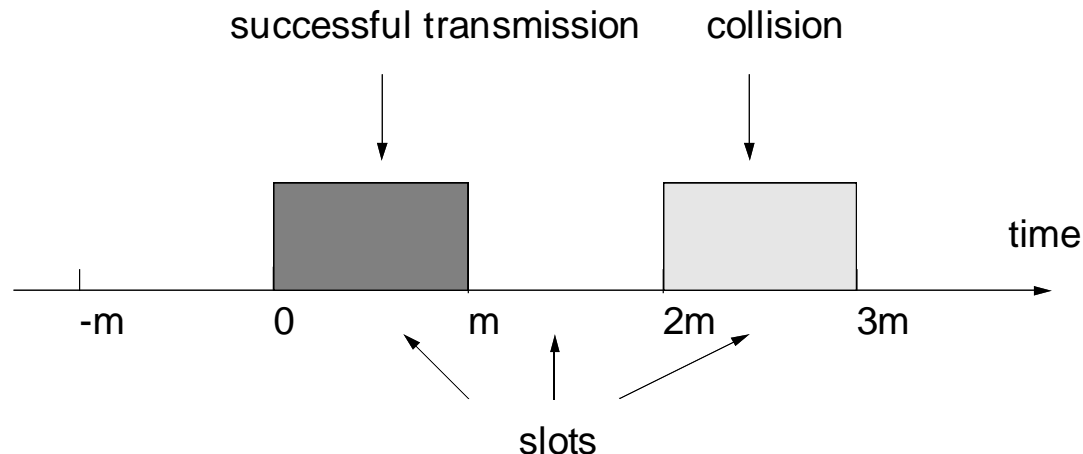
Slotted Aloha
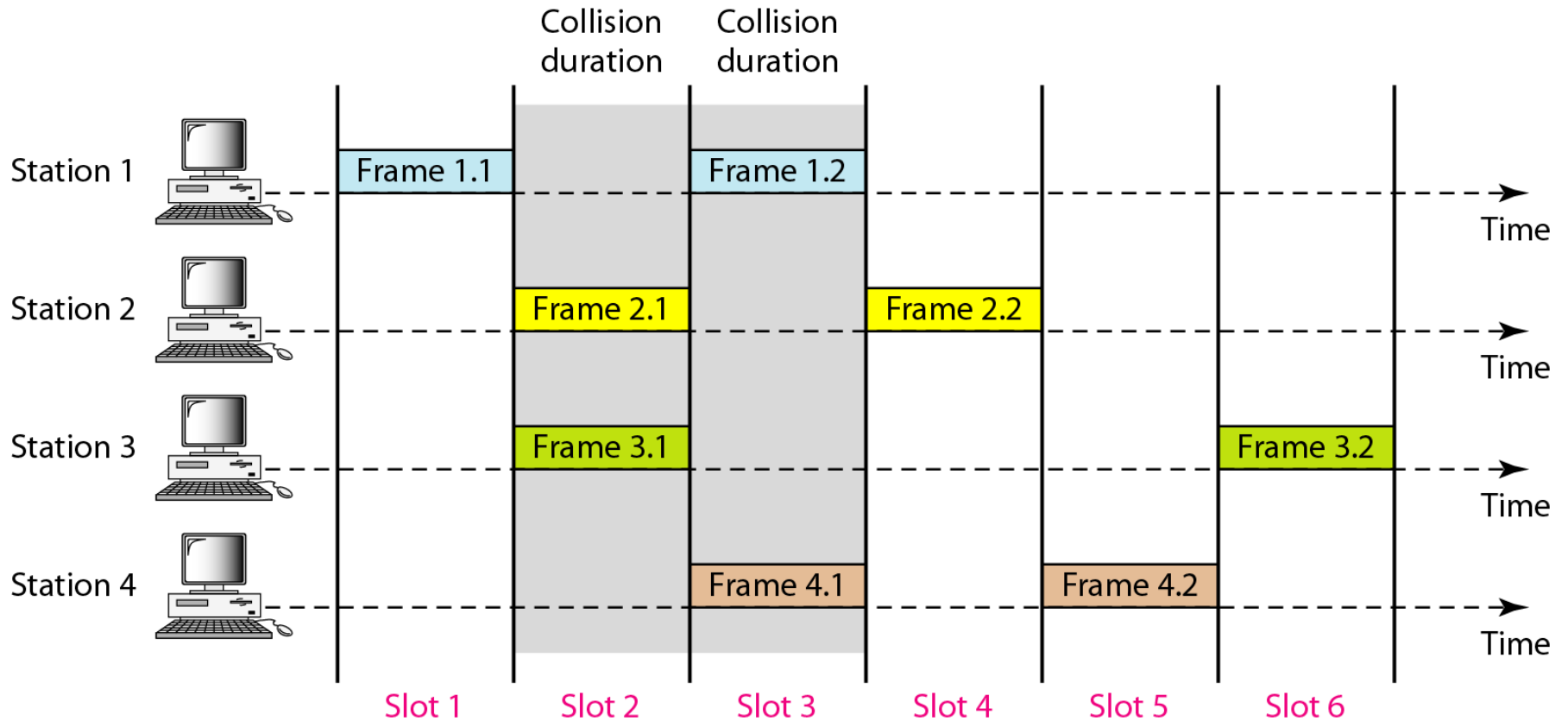
Slotted ALOHA

- ## In each interval *m*
  - Mean number of frames generated is **G**
  - The probability of no other traffic being generated during the entire vulnerable period is
    - $P_0 = e^{-G}$
    - $S = Ge^{-G}$

Note: Not 2G

- ## Max S 1/e = 0.368
  - at G = 1.

Slotted ALOHA

- **Maximum throughput**
  - *G = 1*
  - *S = 1/e*

- Utilization
  - Maximum of 0.368!
  - 37% empty slots
  - 37% successes
  - 26% collisions

Slotted ALOHA: $S = Ge^{-G}$

Pure ALOHA: $S = Ge^{-2G}$

x-axis: G (attempts per packet time)
y-axis: S (throughput per frame time)
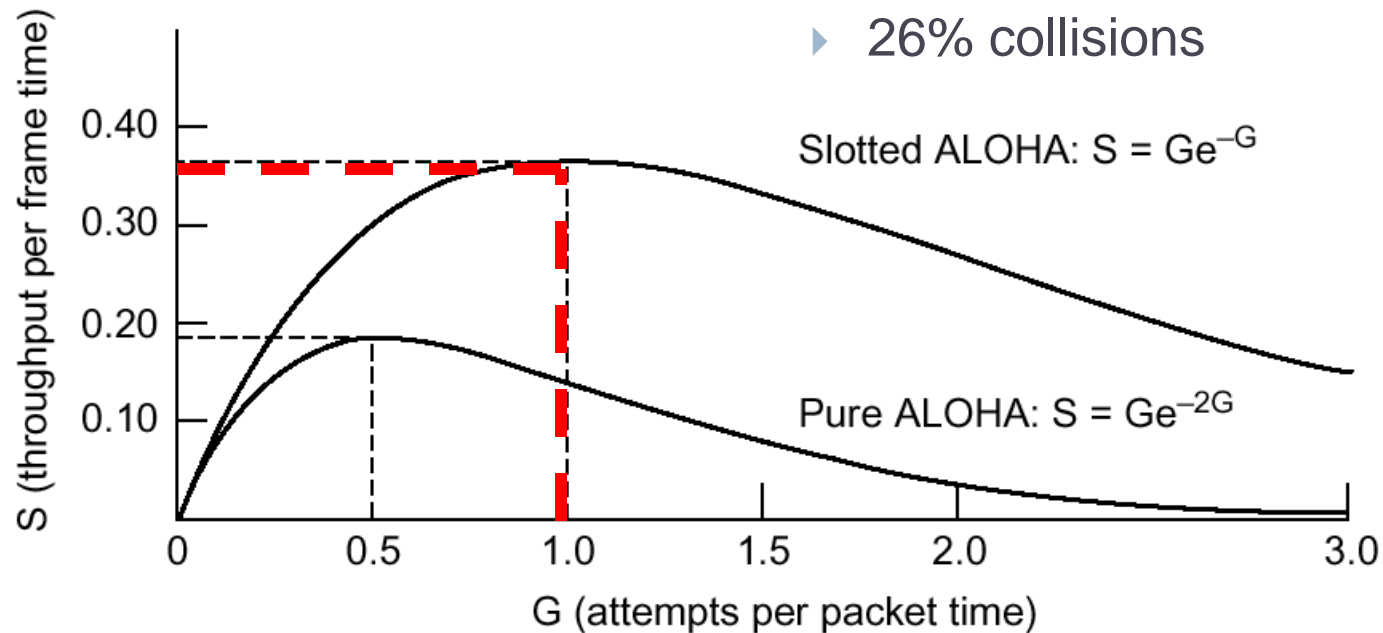
Slotted ALOHA

▸ Pros
  ▸ Single active node can continuously transmit at full rate of channel
  ▸ Highly decentralized: only need slot synchronization
  ▸ Simple
▸ Cons
  ▸ Wasted slots:
    ▸ Idle
    ▸ Collisions
  ▸ Nodes should detect collision in less than time to transmit packet
  ▸ Clock synchronization

Slotted ALOHA

- Performance
  - Higher values of *G*
    - Reduces the number of empty slots
    - Increases the number of collisions exponentially
  - Small increases in channel load can drastically reduce performance
- Limitations
  - Slotted Alohas has twice the performance of basic Aloha, but performance is still poor
    - Slotted design is also not very efficient when carrying variable sized packets!
    - Also (slightly) longer delay than pure Aloha
  - Still, not bad for an absolutely minimal protocol!
  - How do we go faster?

ALOHA Analysis

- ## Tradeoff
  - Pure ALOHA provides smaller delays
  - Slotted ALOHA provides higher throughput

From Aloha comes Ethernet

▸ Ethernet - CSMA/CD

▸ CS – Carrier Sense

  ▸ Nodes can distinguish between an idle and a busy link

▸ MA - Multiple Access

  ▸ A set of nodes send and receive frames over a shared link

▸ CD – Collision Detection

  ▸ Nodes listen during transmission to determine if there has been interference

Ethernet MAC Algorithm

Node A

Node B

At time almost T, node A's message has almost arrived

Node A starts transmission at time 0

Node B starts transmission at time T
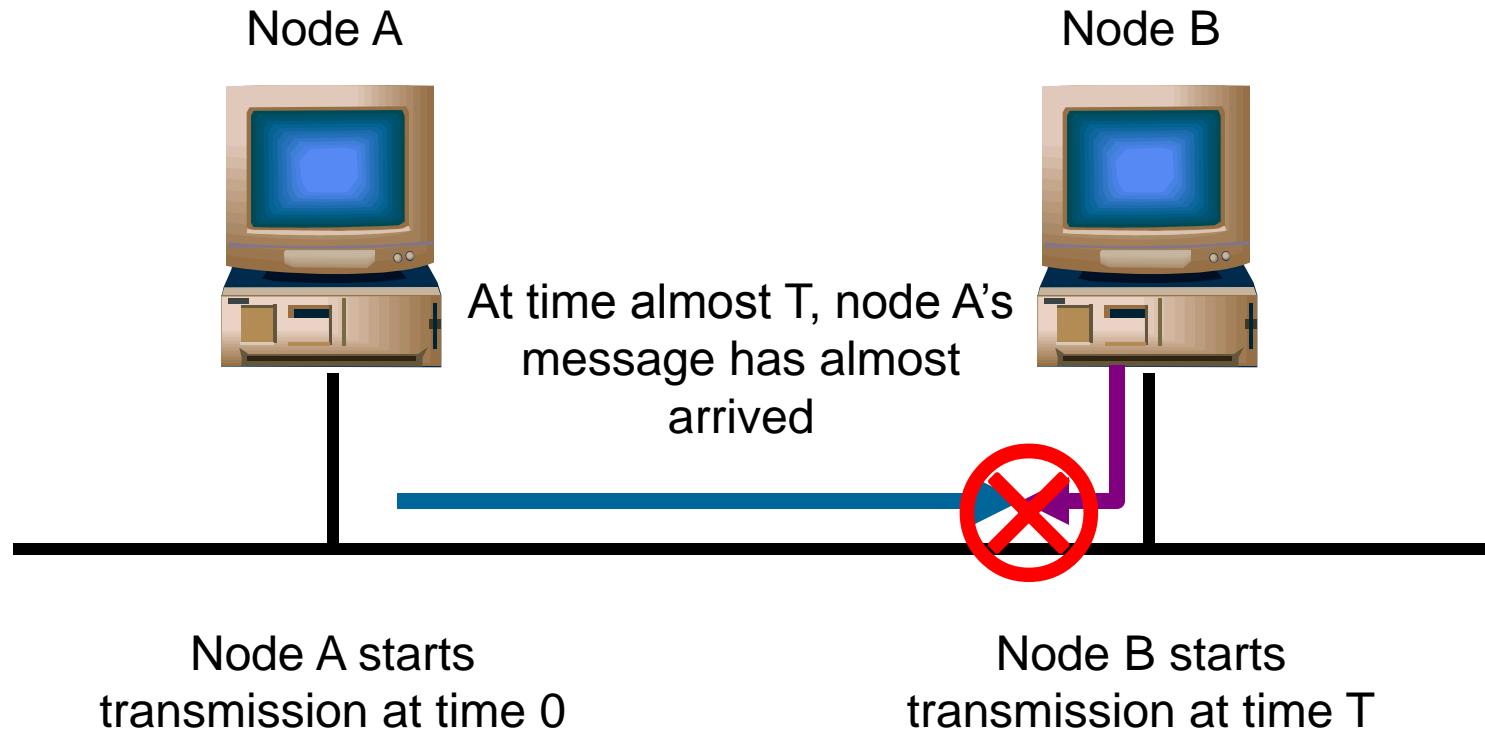
How can we ensure that A knows about the collision?

Collision Detection

- ▶ Problem
  - ▶ How can A detect a collision?

- ▶ Solution
  - ▶ A must still be transmitting when it receives B's transmission!

- ▶ Example
  - ▶ Node A's message reaches node B at time T
  - ▶ Node B's message reaches node A at time 2T
  - ▶ For node A to detect a collision, node A must still be transmitting at time 2T

Ethernet MAC Algorithm

Node A

Node B

At time almost T, node A's message has almost arrived

Node A starts transmission at time 0

Node B starts transmission at time T

At time 2T, A is still transmitting and notices a collision
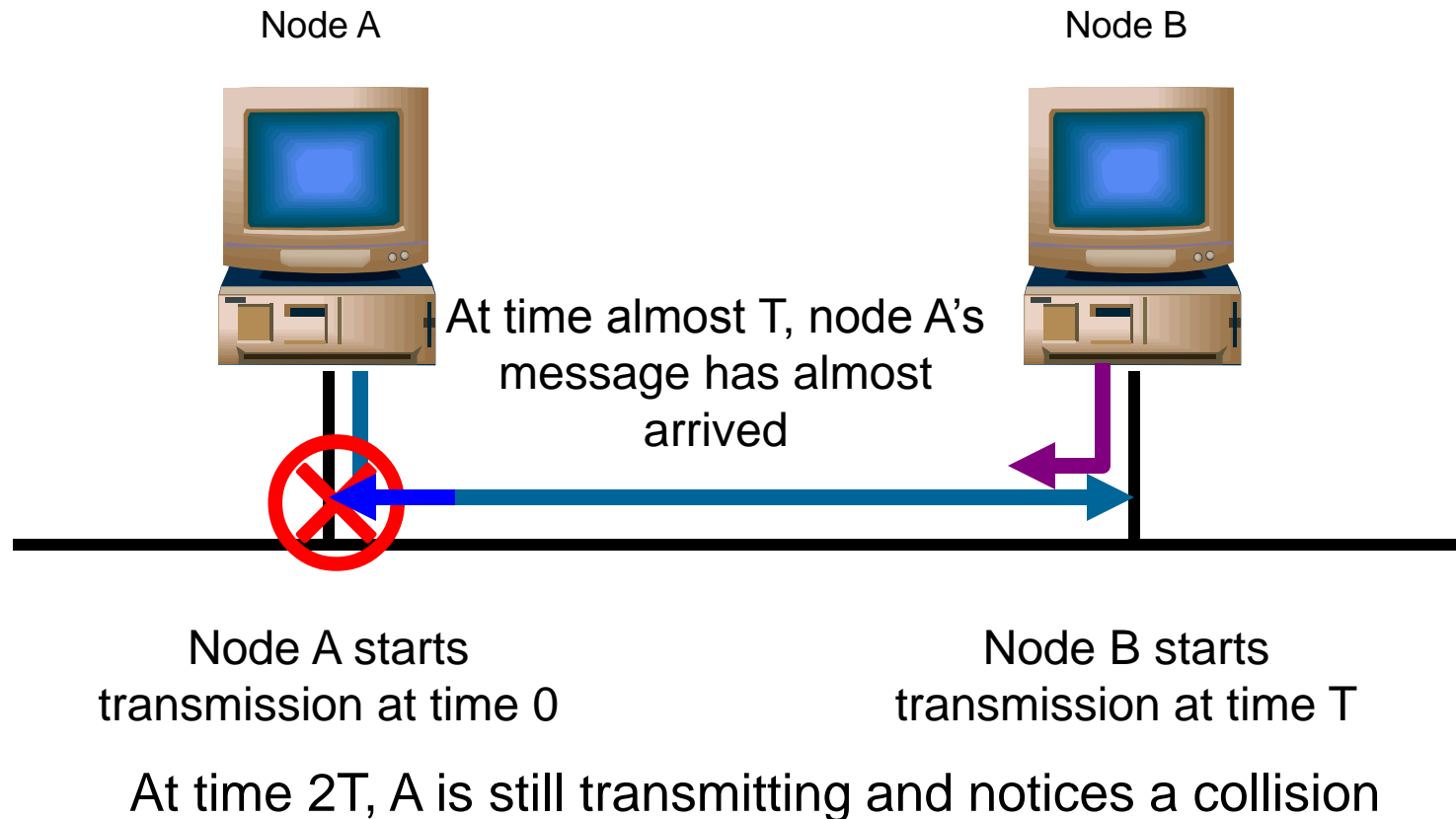
Collision Detection

- IEEE 802.3
  - 2T is bounded to 51.2μs
  - At 10Mbps 51.2μs = 512b or 64 = 512b or 64B
  - Packet length $\geq$ 64B

- Jam after collision
  - Ensures that all hosts notice the collision

Ethernet MAC Algorithm

▶ ## Sender/Transmitter

- ▶ If line is idle (carrier sensed)
  - ▶ Send immediately
  - ▶ Send maximum of 1500B data (1527B total)
  - ▶ Wait 9.6 μs before sending again
- ▶ If line is busy (no carrier sense)
  - ▶ Wait until line becomes idle
  - ▶ Send immediately (1-persistent)
- ▶ If collision detected
  - ▶ Stop sending and jam signal
  - ▶ Try again later

Why have a max size?

Want to prevent one node from taking over completely

Why 9.6 μs?

Too long: wastes time
Too short: doesn't allow other nodes to transmit (fairness)
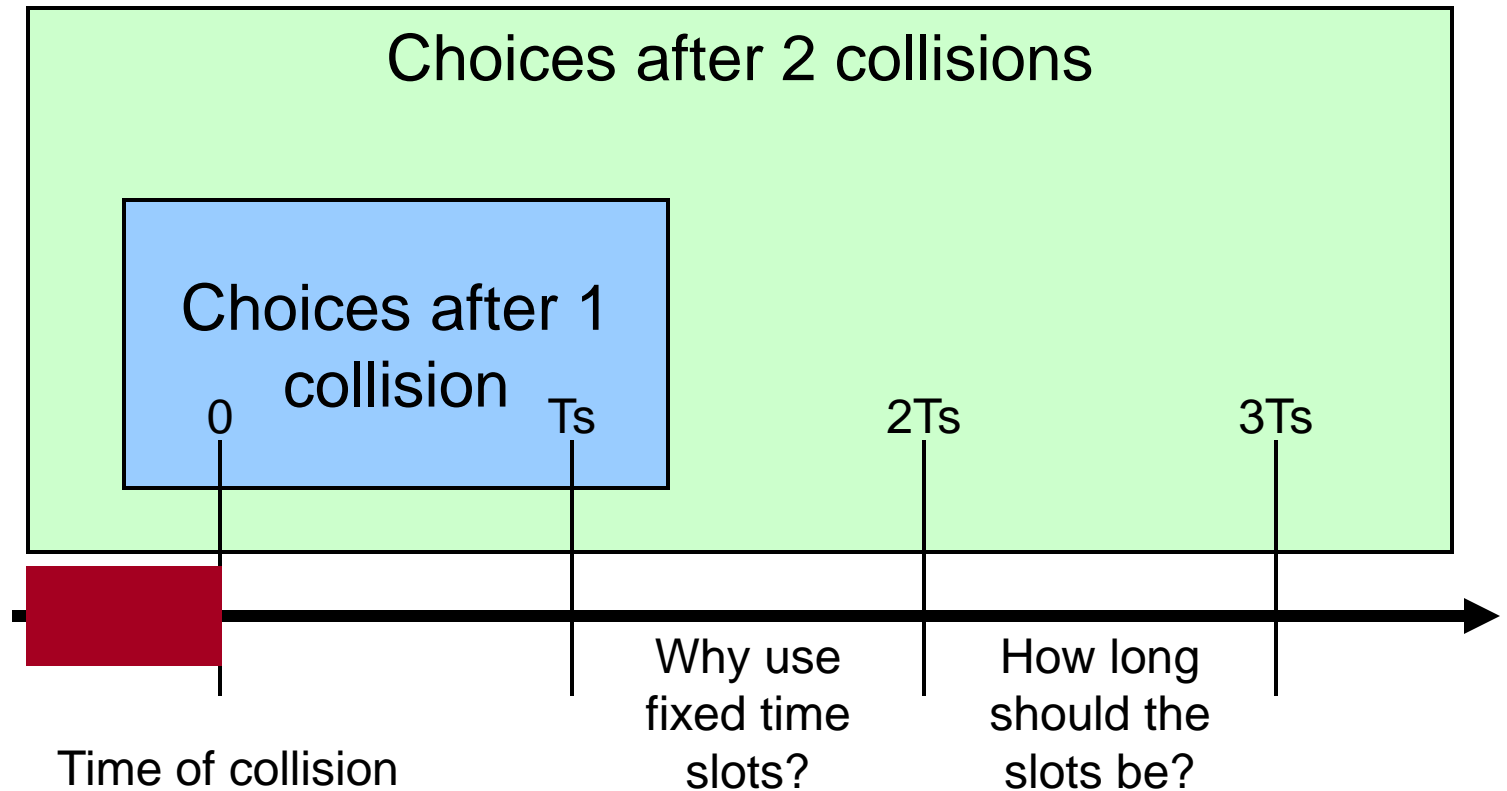
Incoming signal ≠ outgoing signal!

Retransmission

▸ How long should a host wait to retry after a collision?

▸ What happens if the host waits too long?

  ▸ Wasted bandwidth

▸ What happens if the host doesn't wait long enough?

  ▸ More collisions

▸ Ethernet Solution

  ▸ Binary exponential backoff

    ▸ Maximum backoff doubles with each failure

    ▸ After N failures, pick an N-bit number

    ▸ 2^N discrete possibilities from 0 to maximum

Binary Exponential Backoff

Choices after 2 collisions

Choices after 1 collision

0   Ts   2Ts   3Ts

Time of collision   Why use fixed time slots?   How long should the slots be?

Binary Exponential Backoff

‣ For IEEE 802.3, T = 51.2 μs

‣ Consider the following

  ‣ *k* hosts collide

  ‣ Each picks a random number from *0* to *2$^{(N-1)}$*

  ‣ If the minimum value is unique

    ‣ All other hosts see a busy line

    ‣ Note: Ethernet RTT < 51.2 μs

  ‣ If the minimum value is not unique

    ‣ Hosts with minimum value slot collide again!

    ‣ Next slot is idle

    ‣ Consider the next smallest backoff value

Binary Exponential backoff algorithm

▸ When collision first occurs

  ▸ Send a jamming signal to prevent further data being sent

▸ Resend a frame

  ▸ After either *0* or *T* seconds, chosen at random

▸ If resend fails, resend the frame again

  ▸ After either *0*, *T*, *2T*, or *3T* seconds.

  ▸ In other words, send after *kT* seconds, where k is a random integer with $0 \leq k < 2^2$

▸ If that still doesn't work, resend the frame again

  ▸ After *kT*, where k is a random number with $0 \leq k < 2^3$

▸ In general, after the nth failed attempt, resend the frame after *kT*, where *k* is a random number and $0 \leq k < 2^n$

Medium Access Control

▸ ## IEEE 802.11

▸ A physical and multiple access layer standard for wireless local area networks (WLAN)

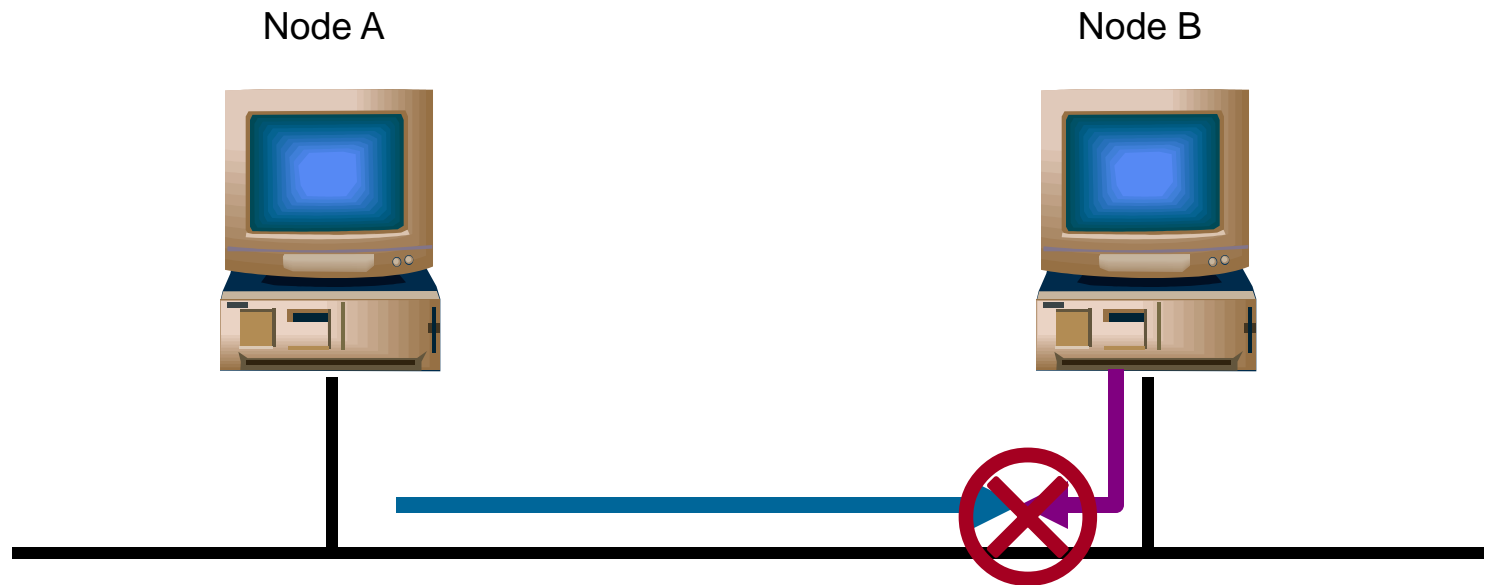Ad Hoc Network: no servers or access points

Client Server Network
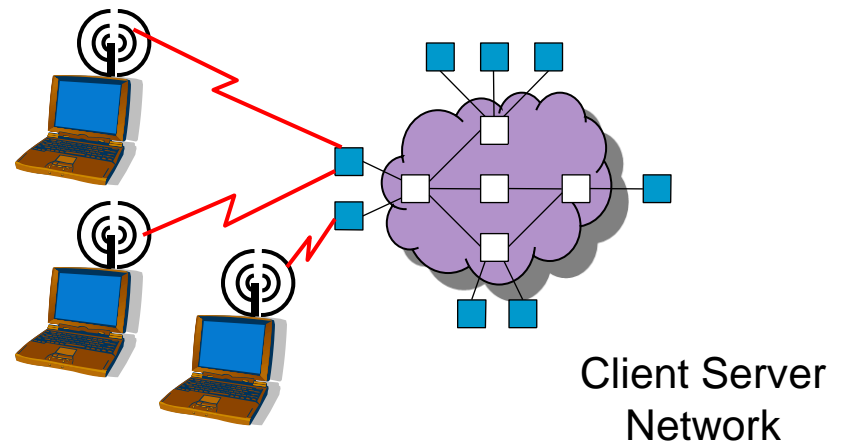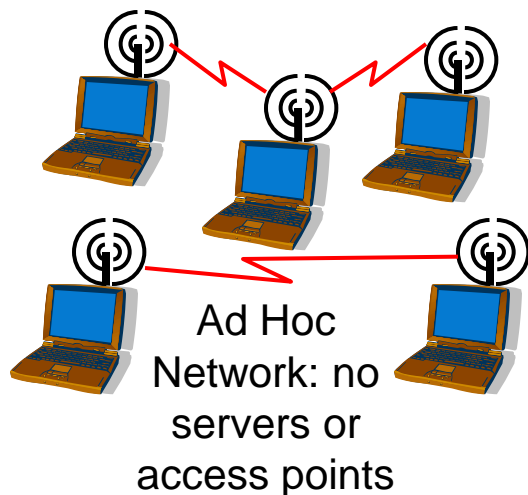
Medium Access Control

- Wireless channel is a shared medium

- Need access control mechanism to avoid interference

- Why not CSMA/CD?

# Ethernet MAC Algorithm

Node A   Node B

- Listen for carrier sense before transmitting
- Collision: What you hear is not what you sent!

CSMA/CD in WLANs?

- Most radios are functionally half-duplex
  - Listening while transmitting is not possible
  - Ratio of transmitted signal power to received power is too high at the transmitter
  - Transmitter cannot detect competing transmitters (is deaf while transmitting)
- Collision might not occur at sender
  - Collision at receiver might not be detected by sender!

A   B
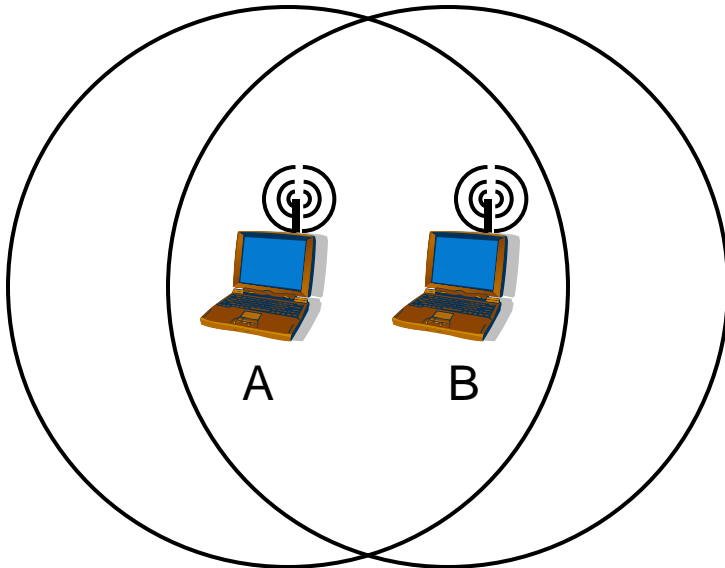
- Why do collisions happen?
  - Near simultaneous transmissions
    - Period of vulnerability: propagation delay

Wireless Ethernet - CSMA/CA

▸ ## CS – Carrier Sense

  ▸ Nodes can distinguish between an idle and a busy link

▸ ## MA - Multiple Access

  ▸ A set of nodes send and receive frames over a shared link

▸ ## CD – Collision Detection

  ▸ Nodes listen during transmission to determine if there has been interference

Wireless Ethernet - CSMA/CA

▶ ## CS – Carrier Sense

  ▶ Nodes can distinguish between an idle and a busy link

▶ ## MA - Multiple Access

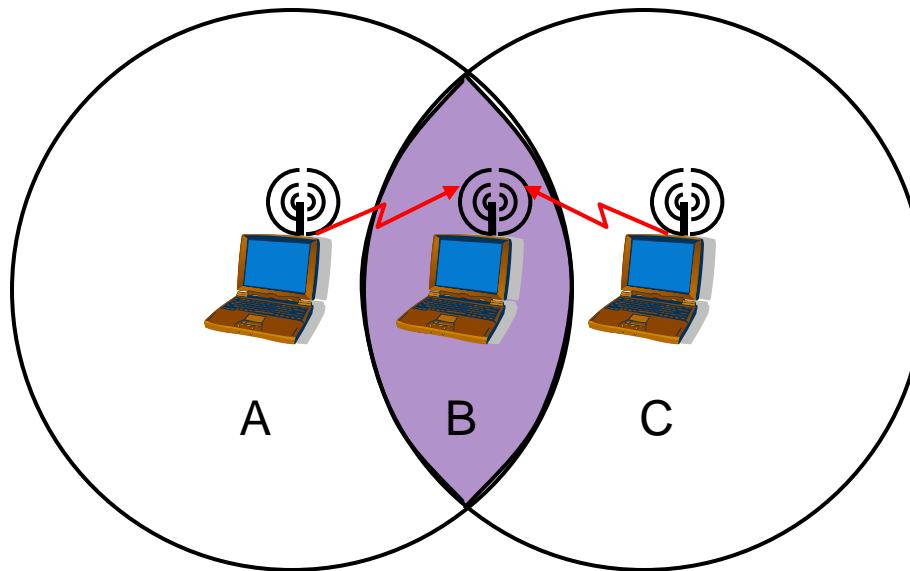 ▶ A set of nodes send and receive frames over a shared link

▶ ## CA – Collision Avoidance

 ▶ Nodes use protocol to prevent collisions from occurring

IEEE 802.11 MAC Layer Standard

▶ Similar to Ethernet

▶ But consider the following:

Hidden Terminal Problem

▶ Node B can communicate with both A and C

▶ A and C cannot hear each other

▶ When A transmits to B, C cannot detect the transmission using the carrier sense mechanism

▶ If C transmits, collision will occur at node B

DATA   **DATA**

A   B   C
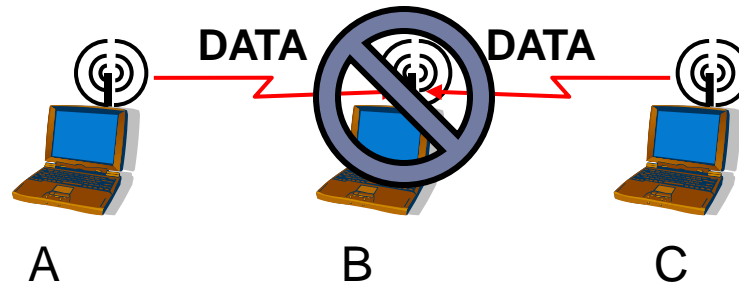
MACA Solution for Hidden Terminal Problem

▸ When node A wants to send a packet to node B

  ▸ Node A first sends a Request-to-Send (RTS) to A

▸ On receiving RTS

  ▸ Node A responds by sending Clear-to-Send (CTS)

  ▸ provided node A is able to receive the packet

▸ When a node C overhears a CTS, it keeps quiet for the duration of the transfer

RTS

CTS   **CTS**

A   B   C
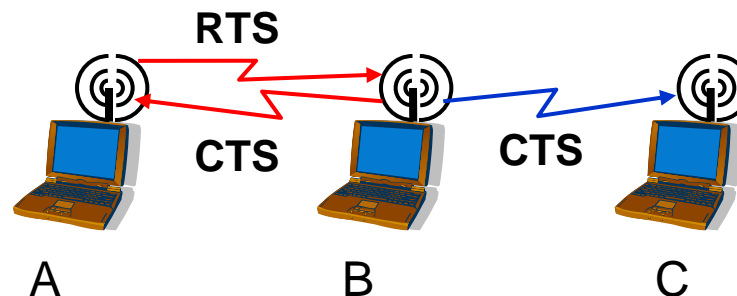
IEEE 802.11 MAC Layer Standard

▸ But we still have a problem
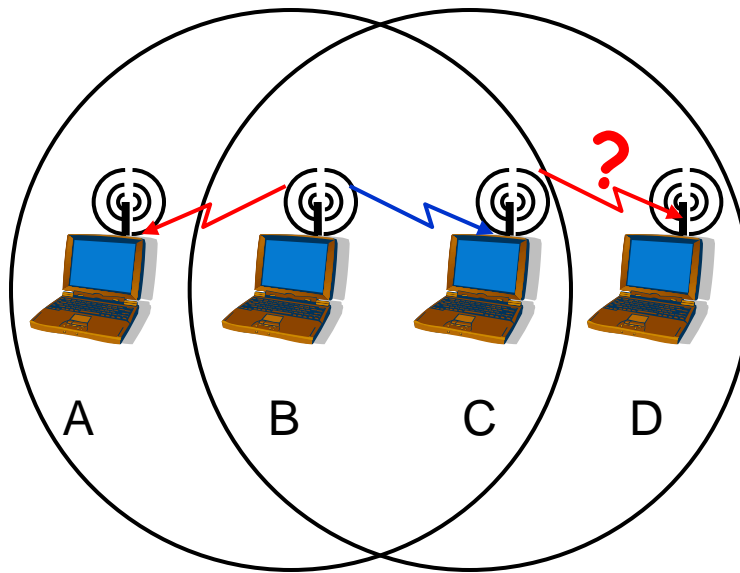
Exposed Terminal Problem

▸ B talks to A

▸ C wants to talk to D

▸ C senses channel and finds it to be busy

▸ C stays quiet (when it could have ideally transmitted)
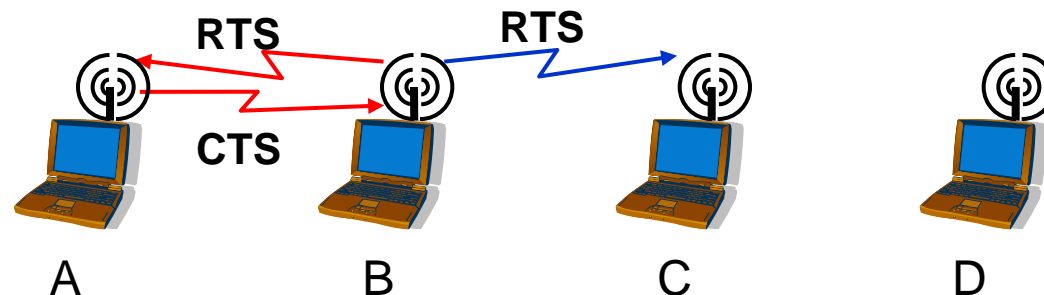
MACA Solution for Exposed Terminal Problem

▸ Sender transmits Request to Send (RTS)

▸ Receiver replies with Clear to Send (CTS)

▸ Neighbors

  ▸ See CTS - Stay quiet

  ▸ See RTS, but no CTS - OK to transmit
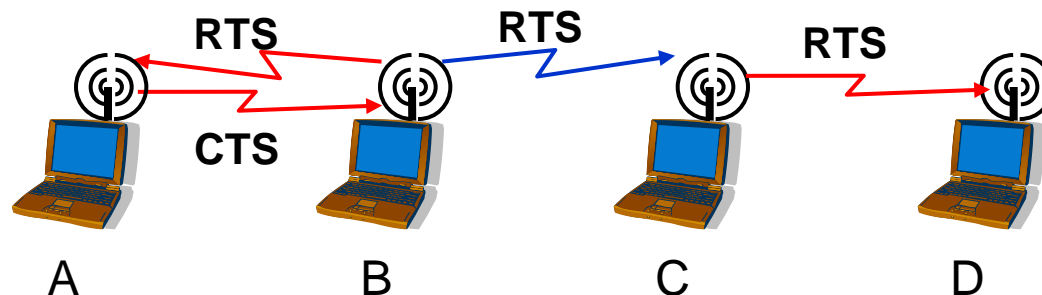
Capture Effect

- ▸ C will almost always "win" if there is a collision at B
  - ▸ Can lead to extreme unfairness and even starvation
- ▸ Solution is power control
  - ▸ Very difficult to manage in a non-provisioned environment!

A   B   C
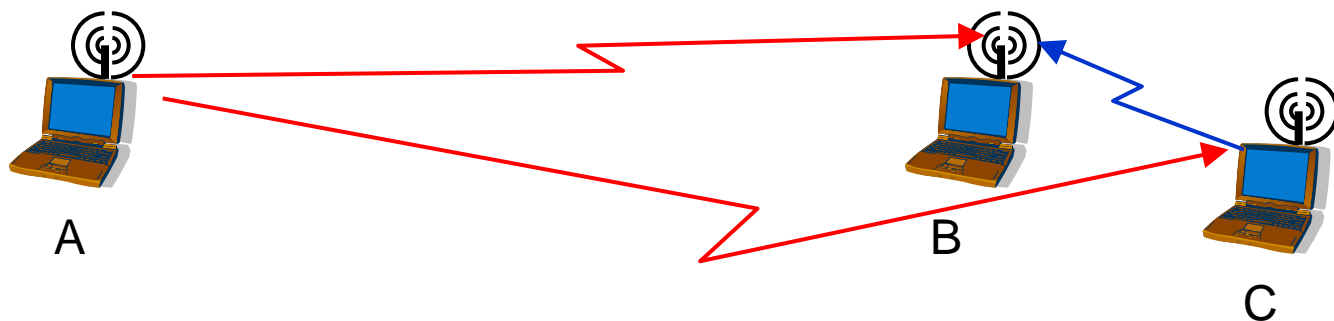
IEEE 802.11 MAC Layer Standard

- ▸ MACAW – Multiple Access with Collision Avoidance for Wireless
  - ▸ Sender transmits Request to Send (RTS)
  - ▸ Receiver replies with Clear to Send (CTS)
  - ▸ Neighbors
    - ▸ See CTS
      - □ Stay quiet
    - ▸ See RTS, but no CTS
      - □ OK to transmit
  - ▸ Receiver sends ACK for frame
    - ▸ Neighbors stay silent until they hear ACK

Collisions

▸ **Still possible**
  ▸ RTS packets can collide!

▸ **Binary exponential backoff**
  ▸ Backoff counter doubles after every collision and reset to minimum value after successful transmission
  ▸ Performed by stations that experience RTS collisions

▸ **RTS collisions not as bad as data collisions in CSMA**
  ▸ Since RTS packets are typically much smaller than DATA packets

# Reliability

- Wireless links are prone to errors
  - High packet loss rate detrimental to transport-layer performance
- Mechanisms needed to reduce packet loss rate experienced by upper layers

A Simple Solution to Improve Reliability - MACAW

▸ When node B receives a data packet from node A, node B sends an Acknowledgement (ACK)

▸ If node A fails to receive an ACK

  ▸ Retransmit the packet
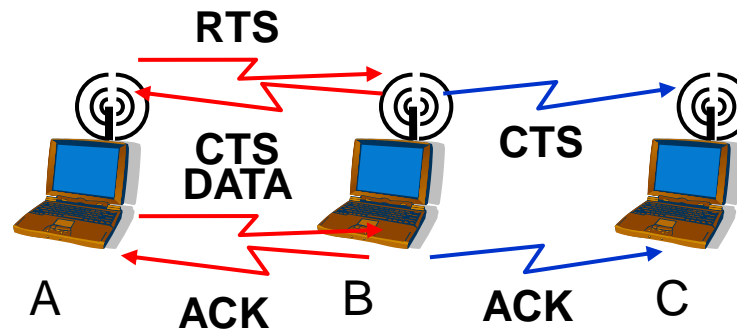
Revisiting the Exposed Terminal Problem

▸ ## Problem
  ▸ Exposed terminal solution doesn't consider CTS at node C

▸ ## With RTS-CTS, C doesn't wait since it doesn't hear A's CTS
  ▸ With B transmitting DATA, C can't hear intended receiver's CTS
  ▸ C trying RTS while B is transmitting is useless

Revisiting the Exposed Terminal Problem - MACAW

▸ **One solution**

  ▸ Have C use carrier sense before RTS

▸ **Alternative**

  ▸ B sends DS (data sending) packet before DATA

    ▸ Short packet lets C know that B received A's CTS

    ▸ Includes length of B's DATA so C knows how long to wait

Backoff Algorithm

▸ Binary exponential backoff (BEB)

  ▸ Backoff counter doubles after every collision and reset to minimum value after successful transmission

▸ Unfair channel allocation!

  ▸ Successful transmitters reset backoff counter to minimum value

    ▸ It is more likely that successful transmitters continue to be successful

  ▸ If there is no maximum backoff

    ▸ One station can get the entire channel bandwidth

▸ Ideally

  ▸ The backoff counter should reflect the ambient congestion level which is the same for all stations involved!

Deafness

▸ **For the scenario below**

  ▸ Node A sends an RTS to B

    ▸ While node C is receiving from D,

  ▸ Node B cannot reply with a CTS

    ▸ B knows that D is sending to C

    ▸ A keeps retransmitting RTS and increasing its own BO timeout

Revisiting the Exposed Terminal Problem - MACAW

- ▶ **One solution**
  - ▶ Have C use carrier sense before RTS
- ▶ **Alternative**
  - ▶ B sends DS (data sending) packet before DATA
    - ▶ Short packet lets C know that B received A's CTS
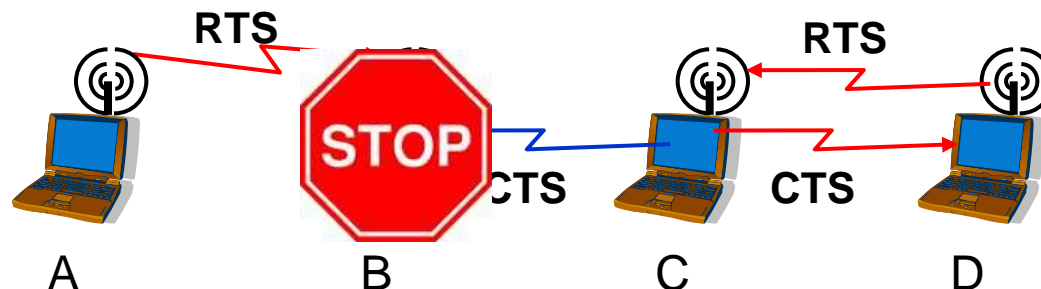   - ▶ Includes length of B's DATA so C knows how long to wait

Backoff Algorithm

‣ **Binary exponential backoff (BEB)**

  ‣ Backoff counter doubles after every collision and reset to minimum value after successful transmission

‣ **Unfair channel allocation!**

  ‣ Successful transmitters reset backoff counter to minimum value

    ‣ It is more likely that successful transmitters continue to be successful

  ‣ If there is no maximum backoff

    ‣ One station can get the entire channel bandwidth

‣ **Ideally**

  ‣ The backoff counter should reflect the ambient congestion level which is the same for all stations involved!

Deafness

- For the scenario below
  - Node A sends an RTS to B
    - While node C is receiving from D,
  - Node B cannot reply with a CTS
    - B knows that D is sending to C
    - A keeps retransmitting RTS and increasing its own BO timeout

RTS   RTS

STOP

CTS   CTS

A   B   C   D

Request for RTS - MACAW

▸ Have B do contention on behalf of A

  ▸ If B receives RTS for which it must defer CTS reply

  ▸ Then B later sends RRTS to A when it can send

  ▸ A responds by starting normal RTS-CTS

  ▸ Others hearing RRTS defer long enough for RTS-CTS
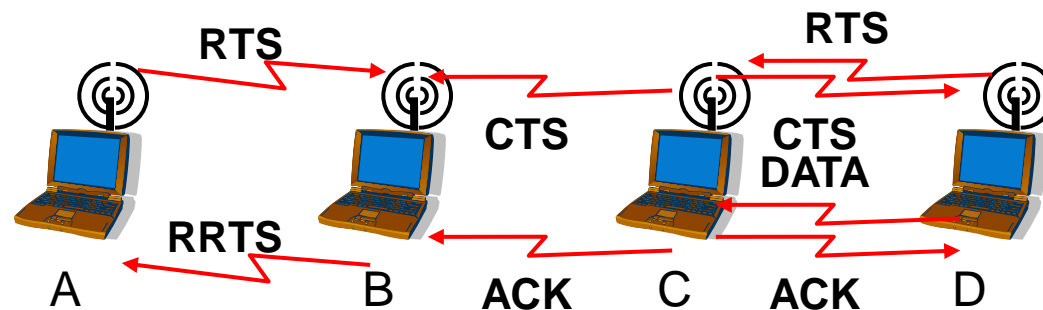
Another MACAW Proposal

▶ This approach, however, does not work in the scenario below

  ▶ Node B may not receive the RTS from A at all, due to interference with transmission from C
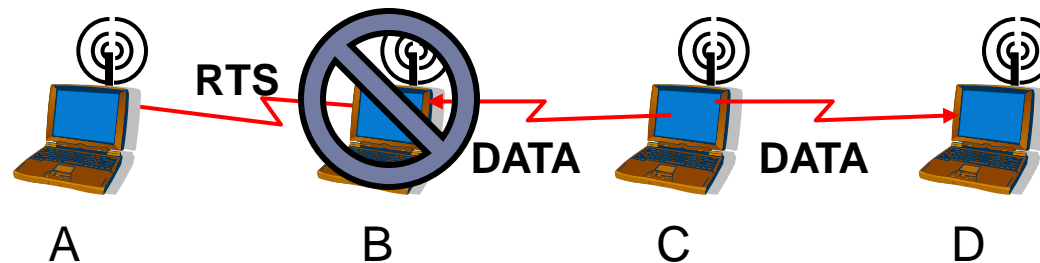
Broadcast/Multicast

▸ Problem

  ▸ Basic RTS-CTS only works for unicast transmissions

▸ For multicast

  ▸ RTS would get CTS from each intended receiver

  ▸ Likely to cause (many) collisions back at sender

Multicast - MACAW

▶ **Sort-of solution**
  ▶ Don't use CTS for multicast data

▶ **Receivers recognize multicast destination in RTS**
  ▶ Don't return CTS
  ▶ Sender follows RTS immediately by DATA
  ▶ After RTS, all receivers defer for long enough for DATA

▶ **Helps, but doesn't fully solve problem**
  ▶ Like normal CSMA, only those in range of sender will defer
  ▶ Others in range of receiver will not defer

IEEE 802.11

- MAC functionality
    - Addressing
    - CSMA/CA
- Error detection (FCS)
- Error correction (ACK frame)
- Flow control: stop-and-wait
- Fragmentation (More Frag)
- Collision Avoidance (RTS-CTS)

IEEE 802.11 Wireless MAC

▸ Distributed and centralized MAC components

  ▸ Distributed Coordination Function (DCF)

  ▸ Point Coordination Function (PCF)

▸ DCF suitable for multi-hop ad hoc networking

▸ DCF is a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol

IEEE 802.11 DCF

- Uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer
- Uses ACK to achieve reliability
- Any node receiving the RTS cannot transmit for the duration of the transfer
  - To prevent collision with ACK when it arrives at the sender
  - When B is sending data to C, node A keeps quite
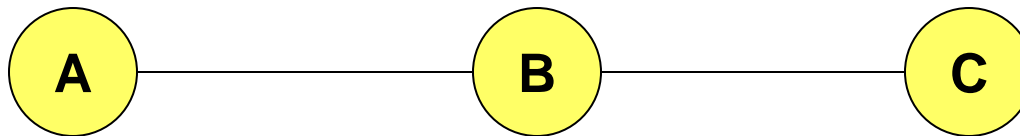
IEEE 802.11 CSMA/CA

- ▶ Nodes stay silent when carrier sensed
  - ▶ Physical carrier sense
  - ▶ Virtual carrier sense
    - ▶ Network Allocation Vector (NAV)
    - ▶ NAV is updated based on overheard RTS/CTS/DATA/ACK packets, each of which specified duration of a pending transmission

- ▶ Backoff intervals used to reduce collision probability

IEEE 802.11 Physical Carrier Sense

Interference range

Carrier sense range

Packet

(A) (B) (C) → (D) (E) (F)

Transmit range

IEEE 802.11 Virtual Carrier Sense

RTS = Request-to-Send

RTS

A B C → D E F

Pretending a circular range
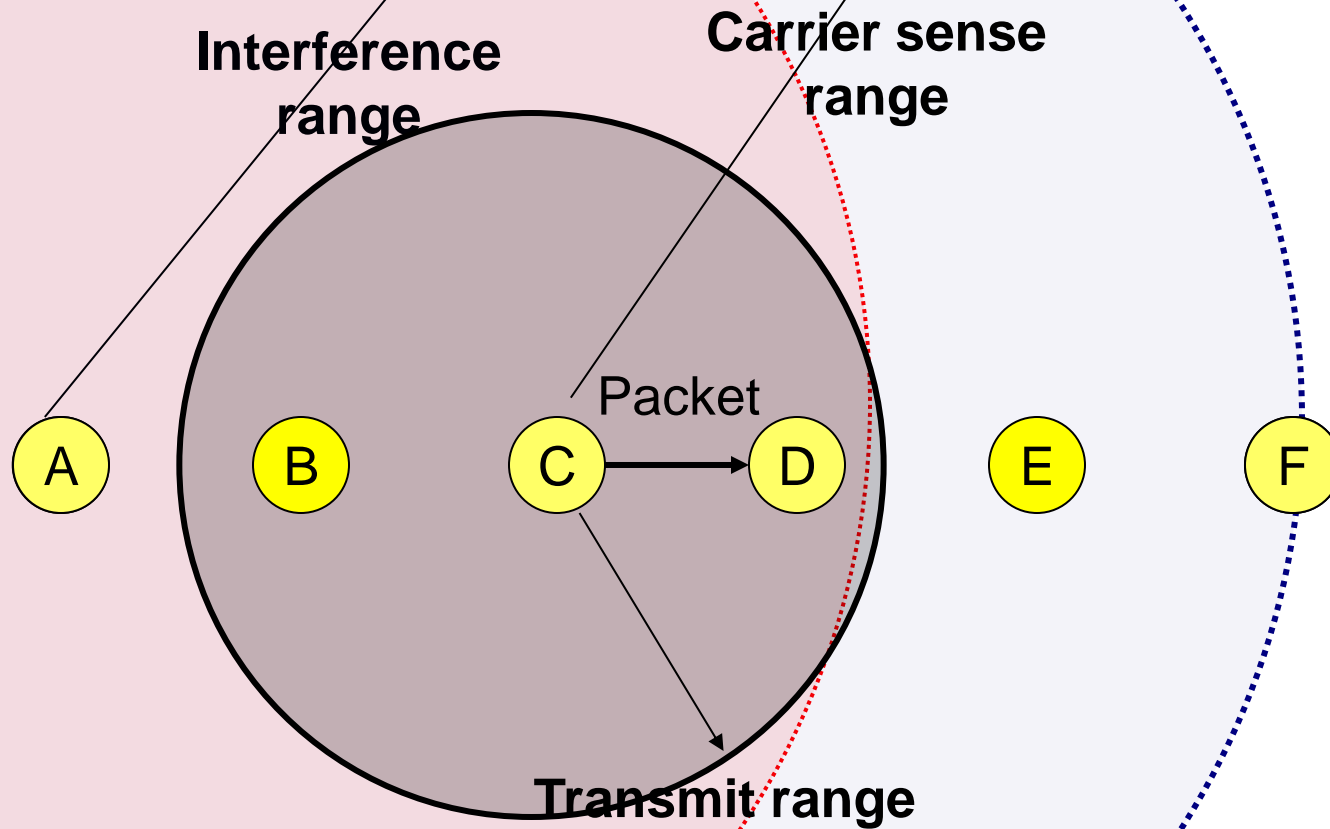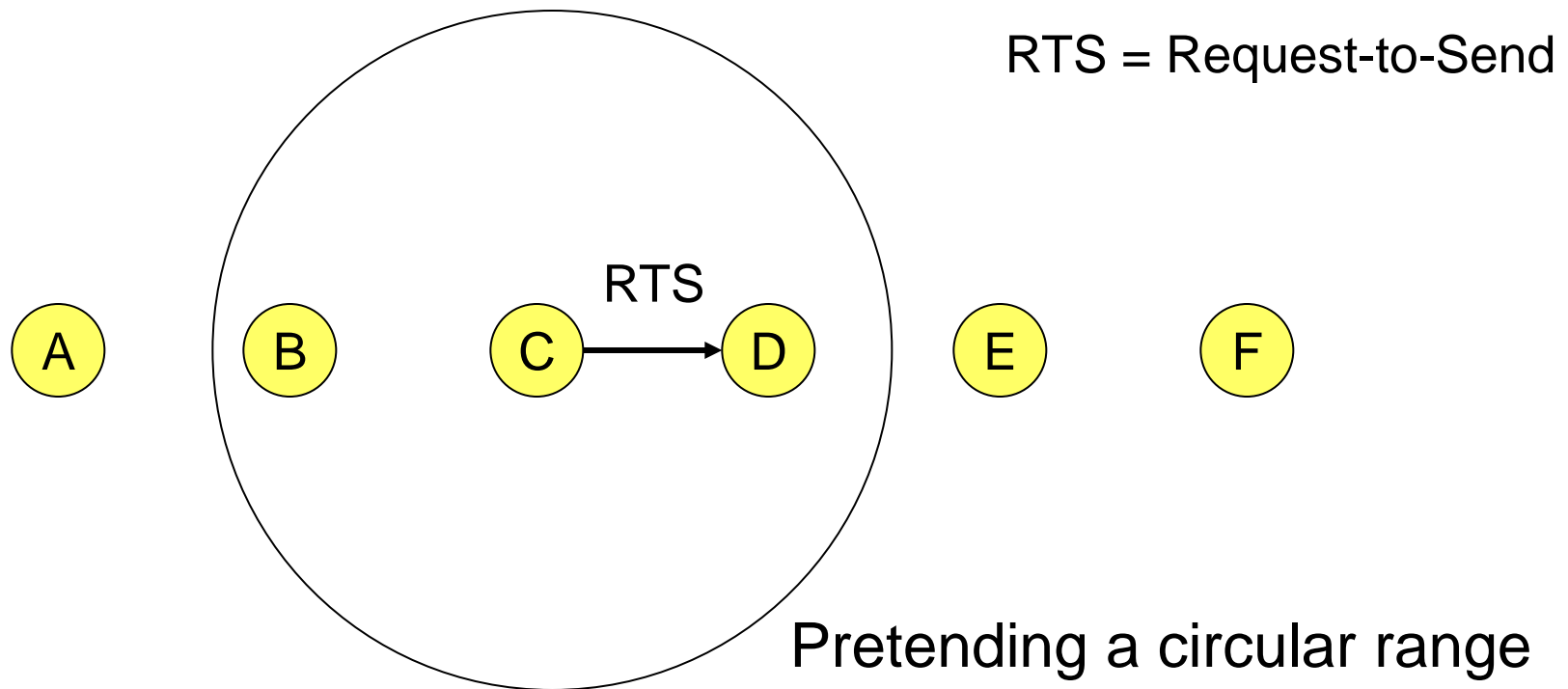
IEEE 802.11 Virtual Carrier Sense

NAV = remaining duration to keep quiet

RTS = Request-to-Send
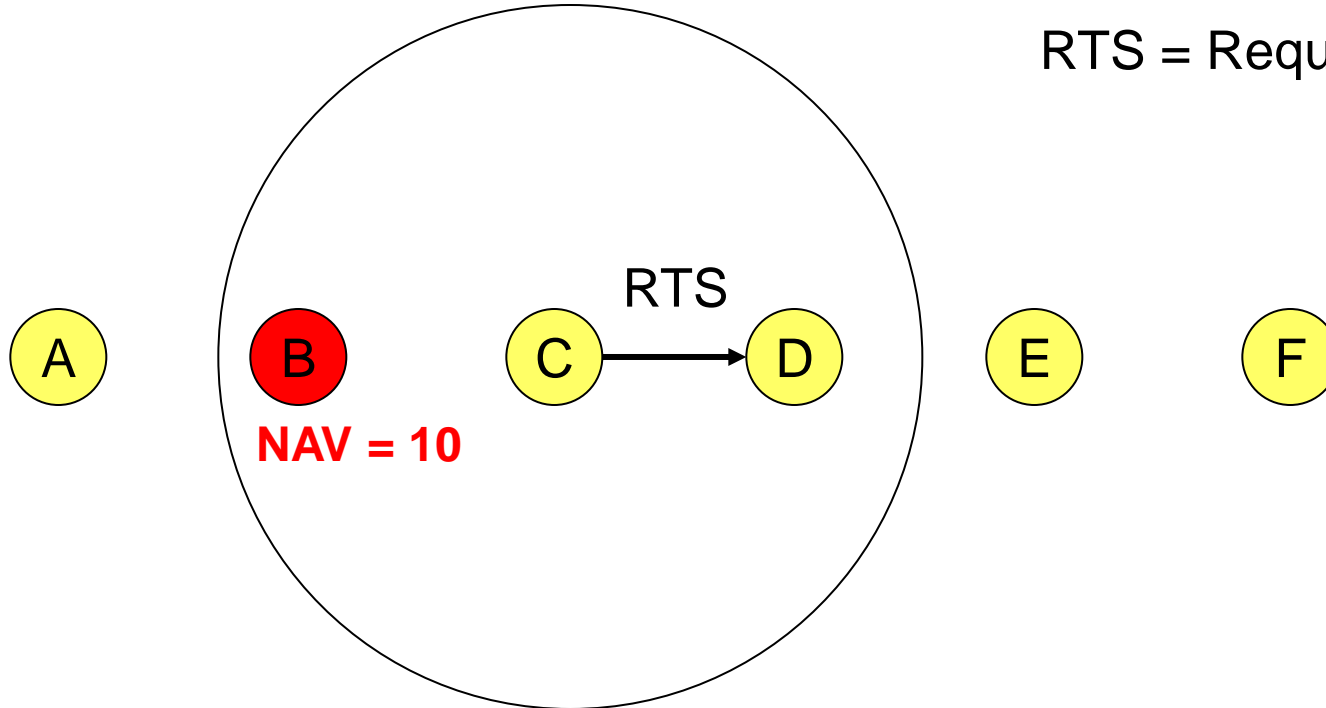
A   B   RTS   C → D   E   F

NAV = 10

IEEE 802.11 Virtual Carrier Sense

CTS = Clear-to-Send

CTS

A   B   C ← D   E   F

IEEE 802.11 Virtual Carrier Sense

CTS = Clear-to-Send

CTS

A B C ← D E F

NAV = 8
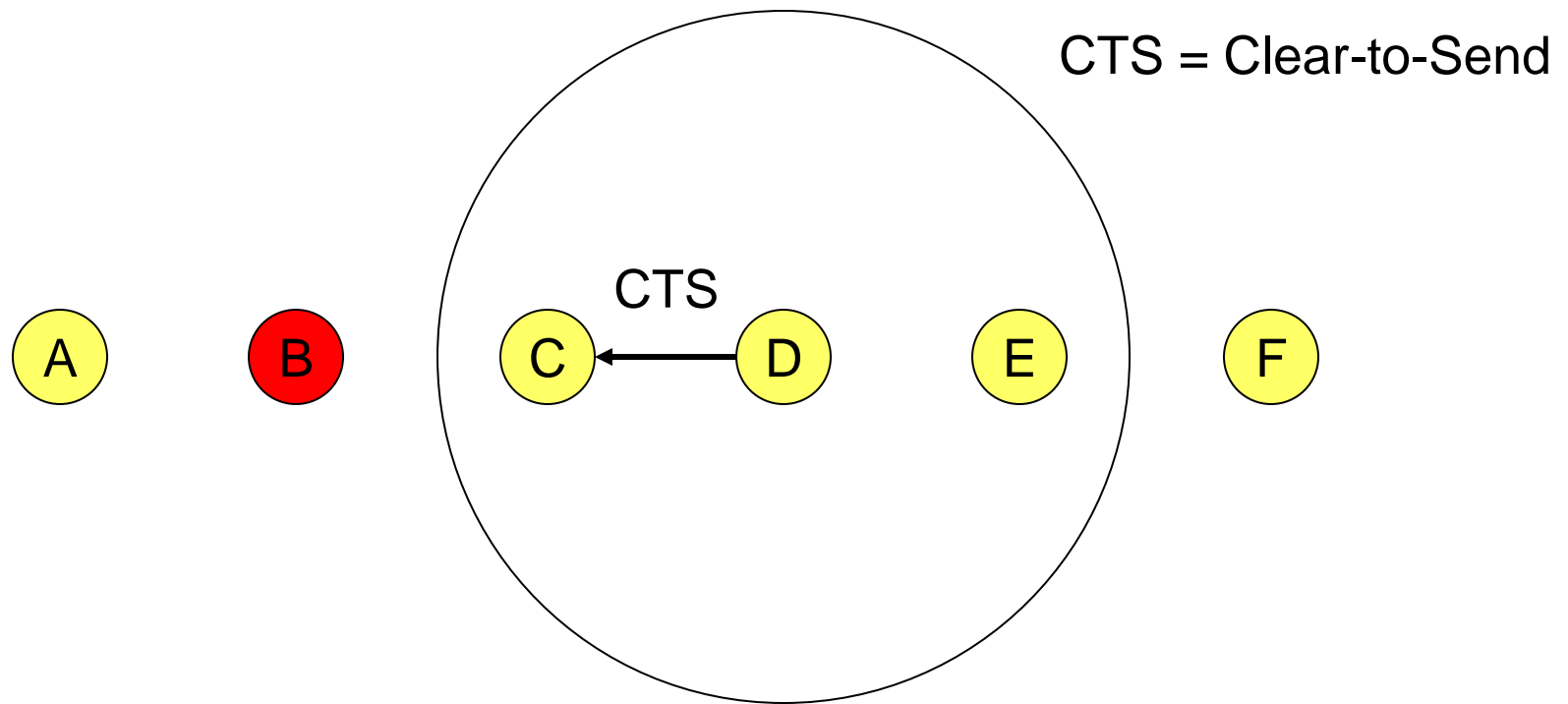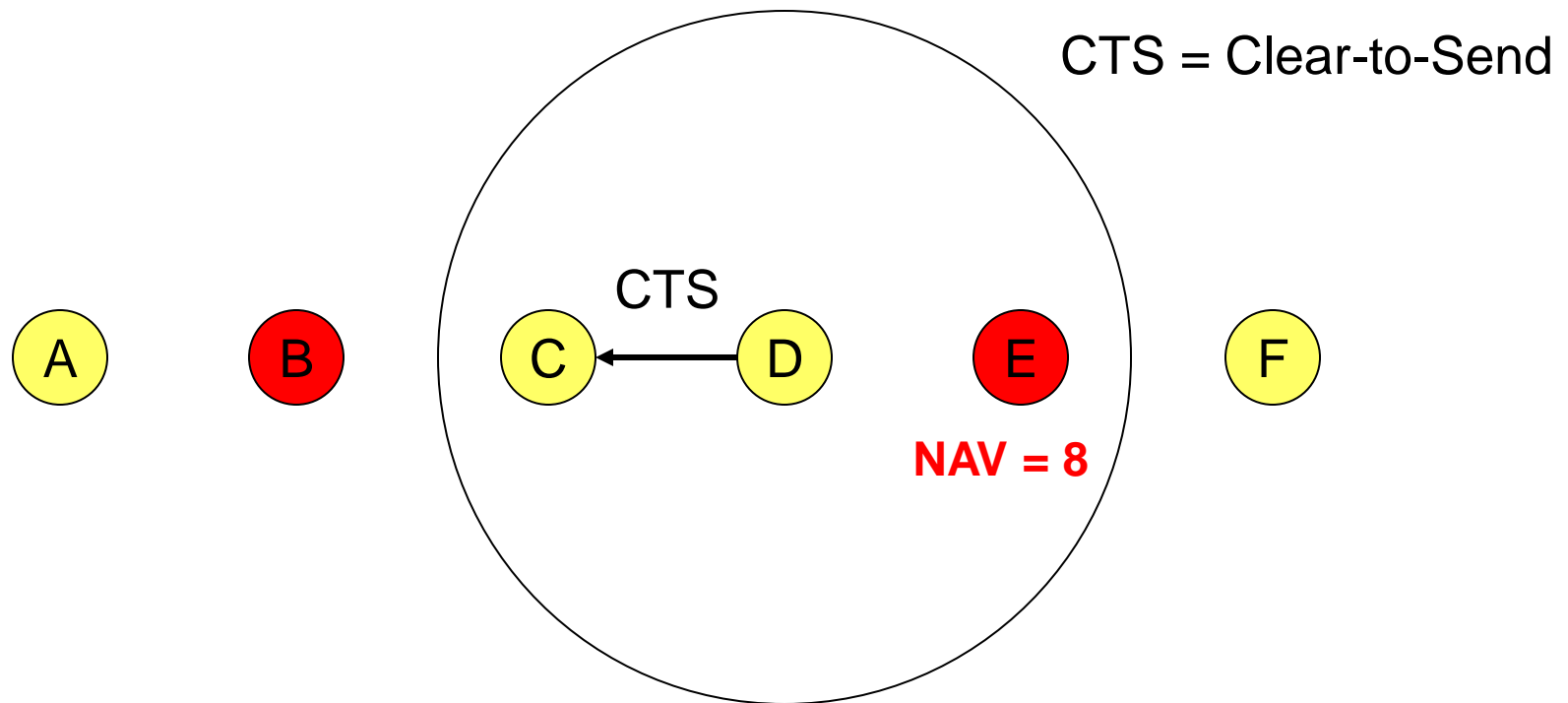
IEEE 802.11 Virtual Carrier Sense

▶ DATA packet follows CTS

IEEE 802.11 Virtual Carrier Sense

▸ Successful data reception acknowledged using ACK

IEEE 802.11

Reserved area

ACK

A   B   C   D   E   F
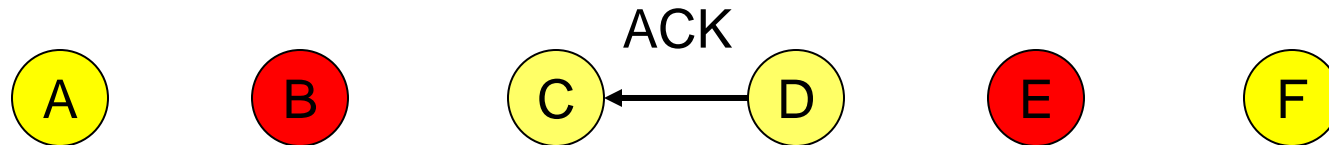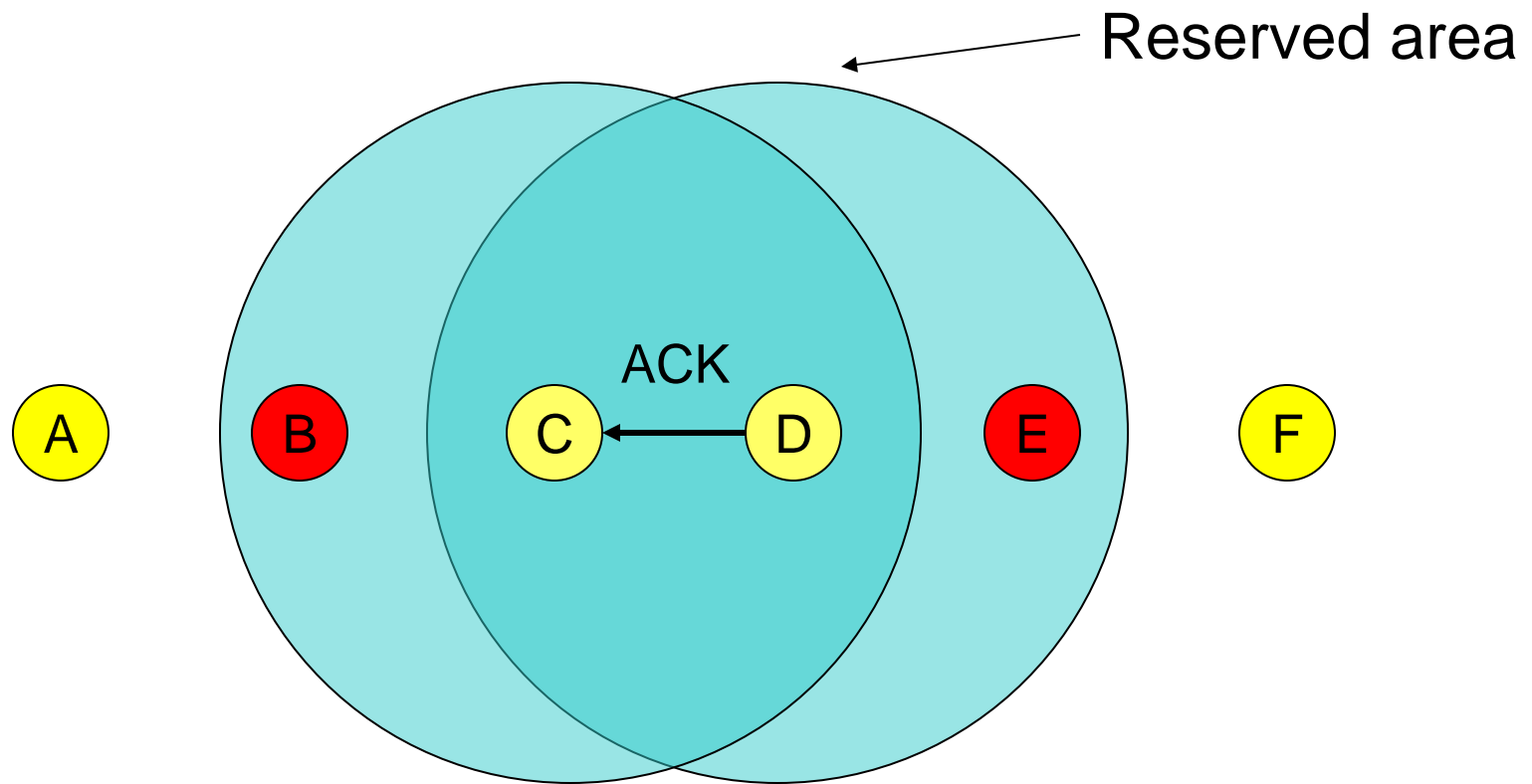
More features

▸ **Use of RTS/CTS is controlled by an RTS threshold**
  ▸ Only used for data packets $>$ threshold
  ▸ Pointless to use RTS/CTS for short data packets
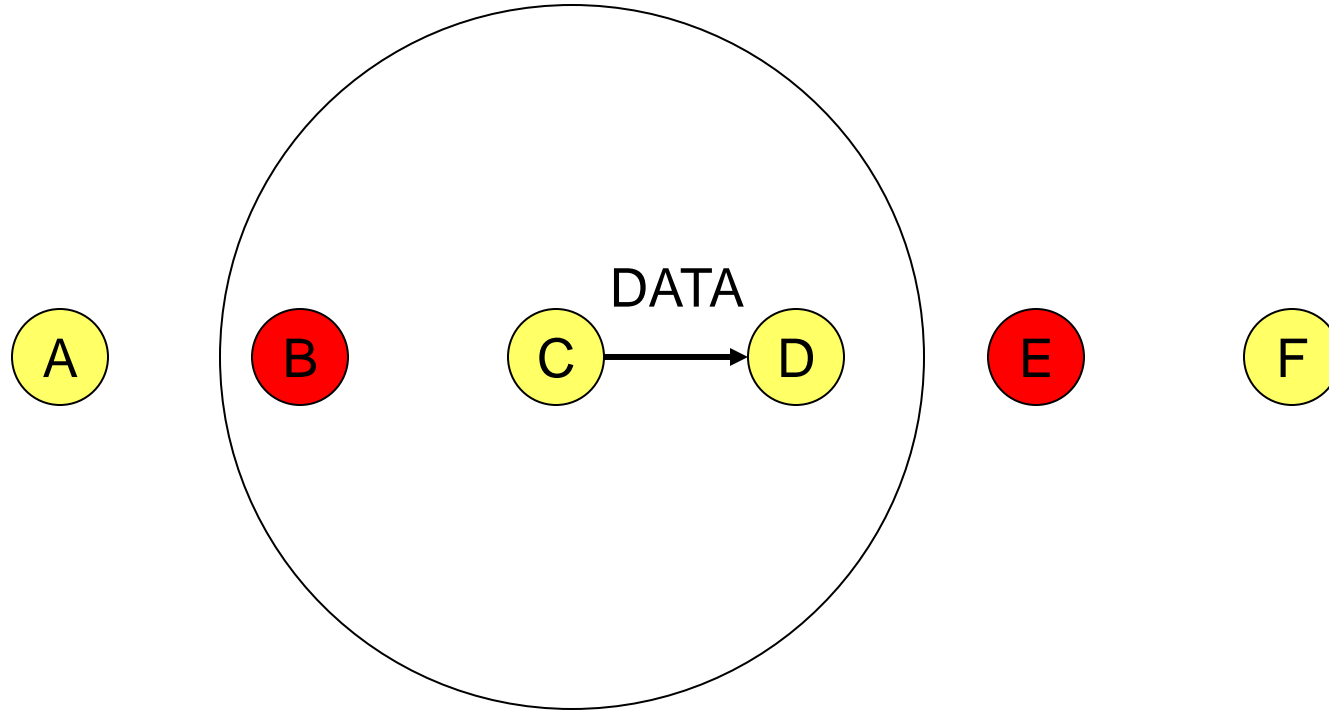   ▸ High overhead!

▸ **Number of retries is limited by a Retry Counter**
  ▸ Short retry counter
    ▸ For packets shorter than RTS threshold
  ▸ Long retry counter
    ▸ For packets longer than RTS threshold

▸ **Packets can be fragmented.**
  ▸ Each fragment is acknowledged
  ▸ But all fragments are sent in one sequence
  ▸ Sending shorter frames can reduce impact of bit errors
  ▸ Lifetime timer: maximum time for all fragments of frame

Ethernet vs. IEEE 802.11

▸ **If carrier is sensed**

- ▸ Send immediately
- ▸ Send maximum of 1500B data (1527B total)
- ▸ Wait 9.6 μs before sending again

▸ **If carrier is sensed**

- ▸ When should a node transmit?

Interframe Spacing

▶ **Interframe spacing**
  ▶ Plays a large role in coordinating access to the transmission medium

▶ **Varying interframe spacings**
  ▶ Creates different priority levels for different types of traffic!

▶ **802.11 uses 4 different interframe spacings**

direct access if
medium is free ≥ DIFS
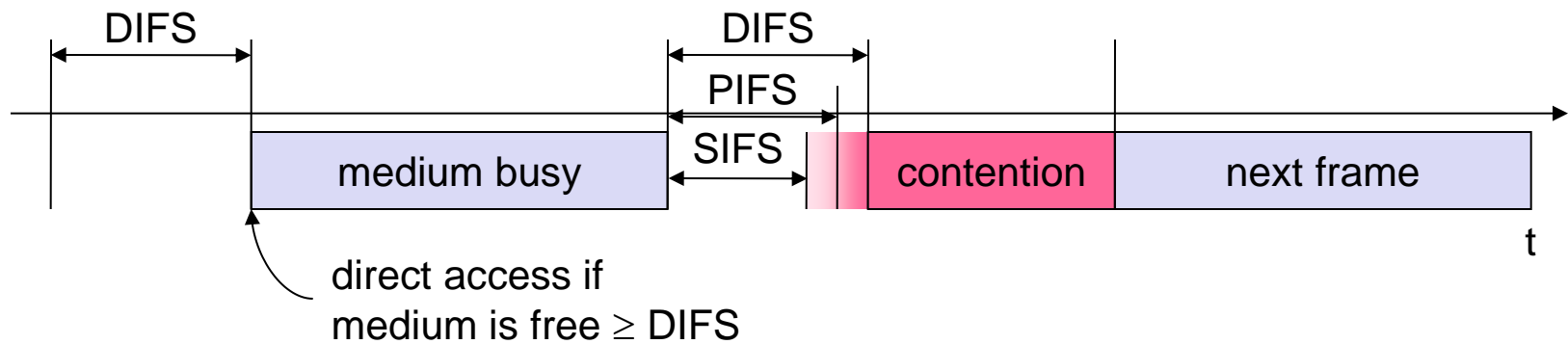
IEEE 802.11 - CSMA/CA

- ▸ Sensing the medium
- ▸ If free for an Inter-Frame Space (IFS)
  - ▸ Station can start sending (IFS depends on service type)
- ▸ If busy
  - ▸ Station waits for a free IFS, then waits a random back-off time (collision avoidance, multiple of slot-time)
- ▸ If another station transmits during back-off time
  - ▸ The back-off timer stops (fairness)

contention window (randomized back-off mechanism)

DIFS

DIFS

medium busy

next frame

direct access if medium is free ≥ DIFS

slot time

t
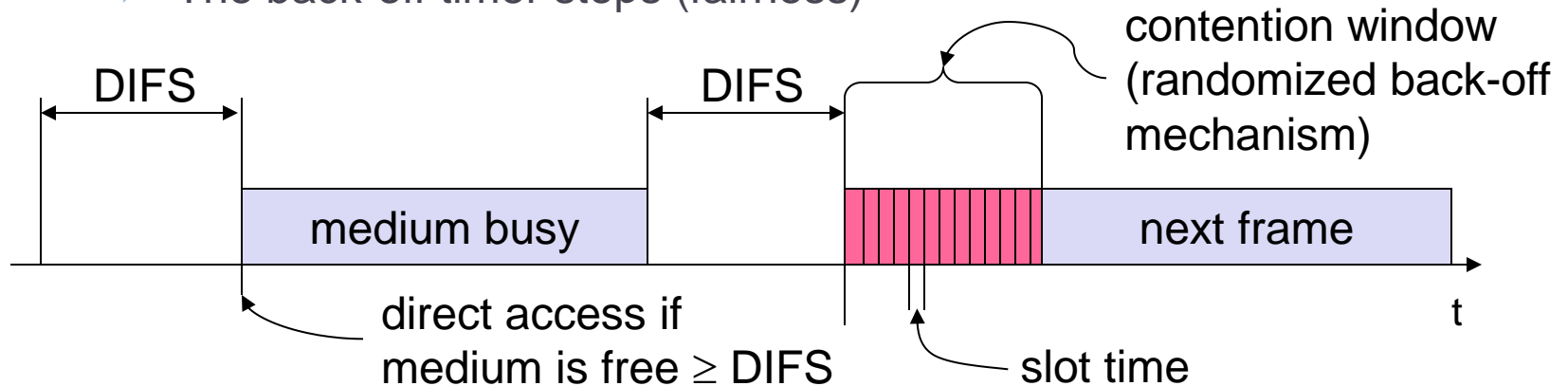
Types of IFS

- ## SIFS
  - Short interframe space
  - Used for highest priority transmissions
  - RTS/CTS frames and ACKs

- ## DIFS
  - DCF interframe space
  - Minimum idle time for contention-based services (> SIFS)

Types of IFS

- ## PIFS
  - PCF interframe space
  - Minimum idle time for contention-free service (>SIFS, <DIFS)

- ## EIFS
  - Extended interframe space
  - Used when there is an error in transmission

IEEE 802.11 - Competing Stations

station$_1$

station$_2$

station$_3$

station$_4$

station$_5$
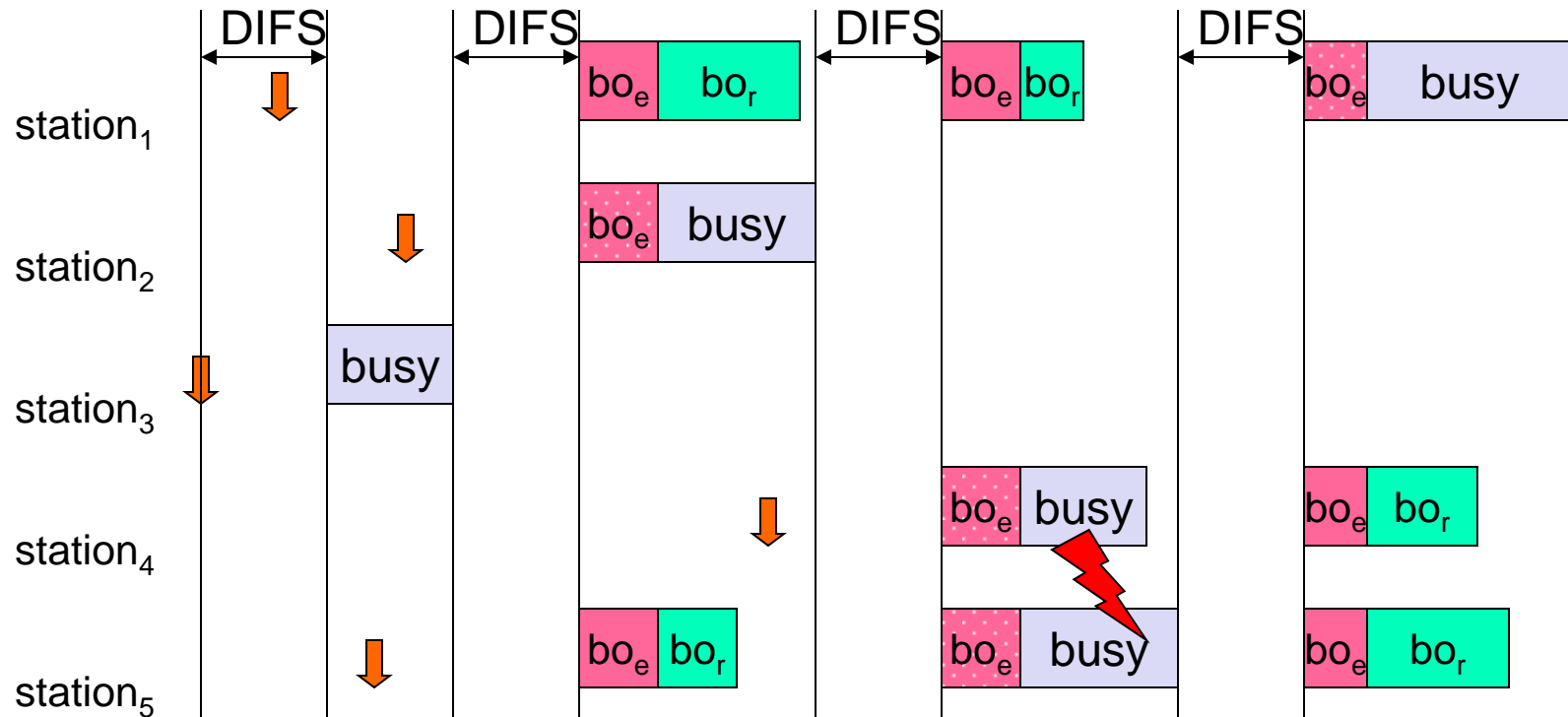
busy	medium not idle (frame, ack etc.)

| | packet arrival at MAC |

bo_e	elapsed backoff time

| bo_r | residual backoff time |

Backoff Interval

- When transmitting a packet, choose a backoff interval in the range [0,CW]
  - CW is contention window
- Count down the backoff interval when medium is idle
  - Count-down is suspended if medium becomes busy
- When backoff interval reaches 0, transmit RTS

DCF Example

B1 = 25

B1 = 5

wait   data

data   wait

B2 = 20

B2 = 15

B2 = 10
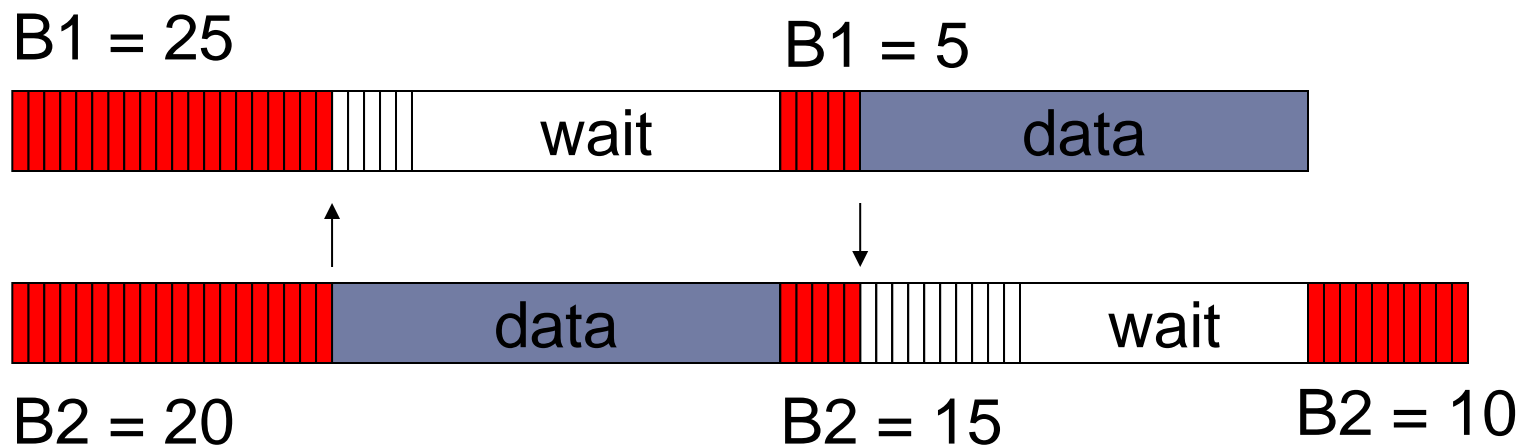
CW = 31

B1 and B2 are backoff intervals
at nodes 1 and 2

Backoff Interval

- The time spent counting down backoff intervals is a part of MAC overhead
- Large CW
  - Large backoff intervals
  - Can result in larger overhead
- Small CW
  - Larger number of collisions (when two nodes count down to 0 simultaneously)

Backoff Interval

- ▸ The number of nodes attempting to transmit simultaneously may change with time
  - ▸ Some mechanism to manage contention is needed
- ▸ IEEE 802.11 DCF
  - ▸ Contention window CW is chosen dynamically depending on collision occurrence

Binary Exponential Backoff in DCF

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

IEEE 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

IEEE 802.11 Data Frame Format

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

bits	2	2	4	1	1	1	1	1	1	1	1
	Protocol version	Type	Subtype	To DS	From DS	More Frag	Retry	Power Mgmt	More Data	WEP	Order
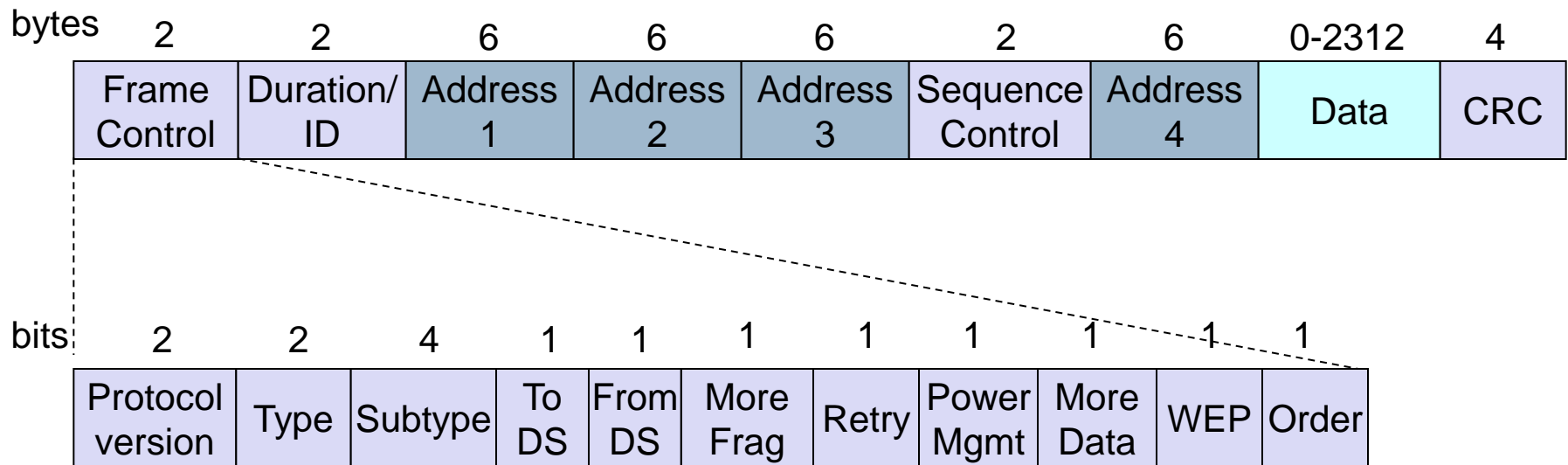
IEEE 802.11 Control Frame Format

▸ Acknowledgement

▸ Request To Send

ACK

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

▸ Clear To Send

RTS

bytes	2	2	6	6	4
	Frame Control	Duration	Receiver Address	Transmitter Address	CRC

CTS

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC
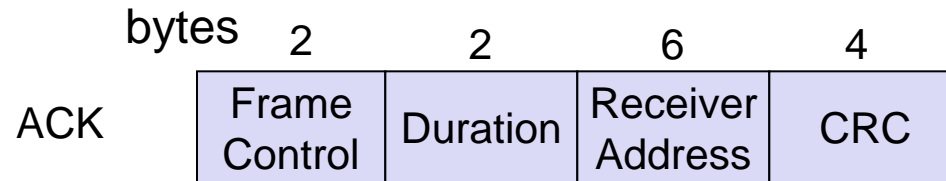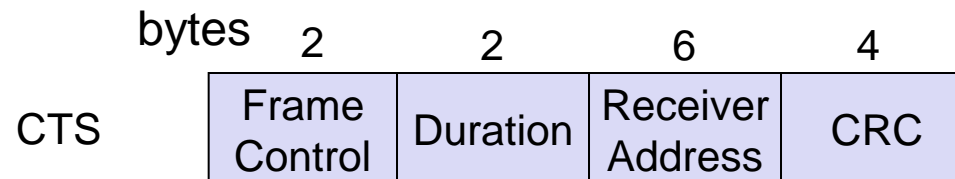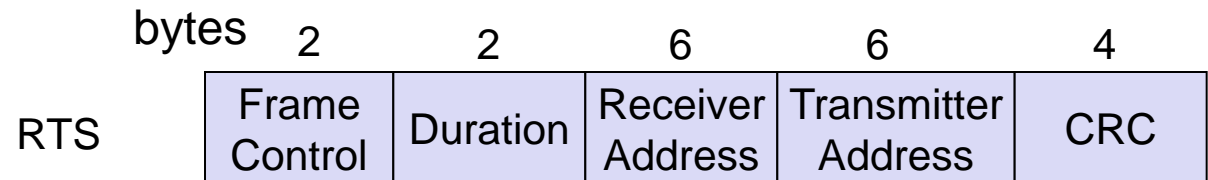
Fairness Issue

▸ Many definitions of fairness plausible

▸ Simplest definition

▸ All nodes should receive equal bandwidth

Two flows

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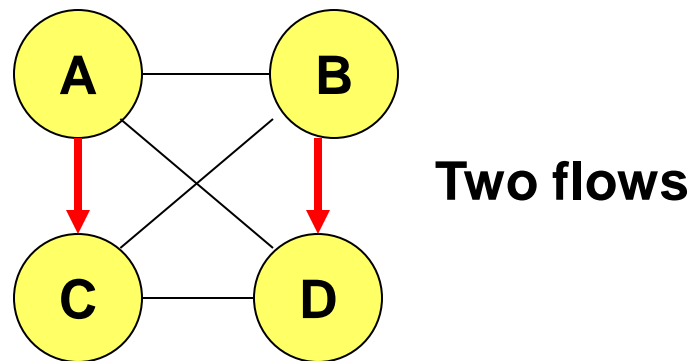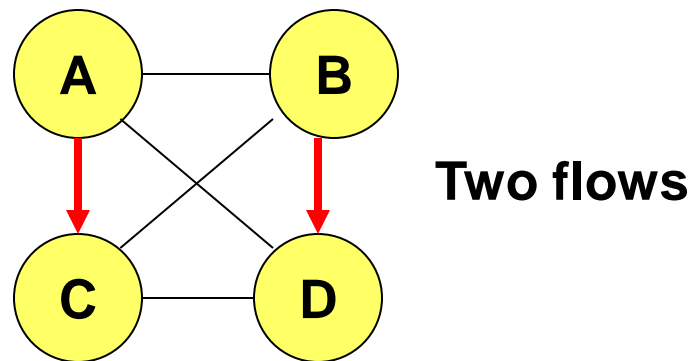
▸ Assume that initially, A and B both choose a backoff interval in range [0,31] but their RTSs collide

▸ Nodes A and B then choose from range [0,63]

  ▸ Node A chooses 4 slots and B choose 60 slots

  ▸ After A transmits a packet, it next chooses from range [0,31]

  ▸ It is possible that A may transmit several packets before B transmits its first packet

Two flows

Fairness Issue

- ## Unfairness
  - When one node has backed off much more than some other node

- ## MACAW Solution
  - When a node transmits a packet
    - Append the CW value to the packet
    - All nodes hearing that CW value use it for their future transmission attempts
  - CW is an indication of the level of congestion in the vicinity of a specific receiver node
    - MACAW proposes maintaining CW independently for each receiver
  - Per-receiver CW is particularly useful in multi-hop environments
    - Congestion level at different receivers can be very different

IEEE 802.11 Amendments

- IEEE 802.11-1997:
  - Originally 1 Mbit/s and 2 Mbit/s
  - 2.4 GHz RF and infrared (IR)
- IEEE 802.11a:
  - 54 Mbit/s, 5 GHz standard (2001)
- IEEE 802.11b:
  - Enhancements to support 5.5 and 11 Mbit/s (1999)
- IEEE 802.11c:
  - Bridge operation procedures;
  - Included in the IEEE 802.1D standard (2001)
- IEEE 802.11d:
  - International (country-to-country) roaming extensions (2001)

- IEEE 802.11e:
  - Enhancements: QoS, including packet bursting (2005)
- IEEE 802.11g:
  - 54 Mbit/s, 2.4 GHz standard (backwards compatible with b) (2003)
- IEEE 802.11h:
  - Spectrum Managed 802.11a (5 GHz) for European compatibility (2004)
- IEEE 802.11i:
  - Enhanced security (2004)
- IEEE 802.11j:
  - Extensions for Japan (2004)
- IEEE 802.11-2007:
  - Updated standard including a, b, d, e, g, h, i and j. (2007)

IEEE 802.11 Amendments

- IEEE 802.11k:
  - Radio resource measurement enhancements (2008)
- IEEE 802.11n:
  - Higher throughput improvements using MIMO (multiple input, multiple output antennas) (September 2009)
- IEEE 802.11p:
  - WAVE—Wireless Access for the Vehicular Environment (such as ambulances and passenger cars) (2010)
- IEEE 802.11r:
  - Fast BSS transition (FT) (2008)
- IEEE 802.11s:
  - Mesh Networking, Extended Service Set (ESS) (2011)

- IEEE 802.11u:
  - Improvements related to HotSpots and 3rd party authorization of clients, e.g. cellular network offload (2011)
- IEEE 802.11v:
  - Wireless network management (2011)
- IEEE 802.11w:
  - Protected Management Frames (2009)
- IEEE 802.11y:
  - 3650–3700 MHz Operation in the U.S. (2008)
- IEEE 802.11z:
  - Extensions to Direct Link Setup (DLS) (2010)

IEEE 802.11 Amendments

- IEEE 802.11-2012:
  - New release including k, n, p, r, s, u, v, w, y and z (2012)
- IEEE 802.11aa:
  - Robust streaming of Audio Video Transport Streams (2012)
- IEEE 802.11ac:
  - Very High Throughput < 6GHz
  - Potential improvements over 802.11n: better modulation scheme (expected ~10% throughput increase), wider channels (estimate in future time 80 to 160 MHz), multi user MIMO (2012)
- IEEE 802.11ae:
  - Prioritization of Management Frames (2012)

In process amendments

- IEEE 802.11ad:
  - Very High Throughput 60 GHz (~ February 2014)
- IEEE 802.11af:
  - TV Whitespace (~ June 2014)
- IEEE 802.11ah:
  - Sub 1 GHz sensor network, smart metering. (~ January 2016)
- IEEE 802.11ai:
  - Fast Initial Link Setup (~ February 2015)

- IEEE 802.11mc:
  - Maintenance of the standard (~ March 2015)
- IEEE 802.11aj:
  - China Millimeter Wave (~ October 2016)
- IEEE 802.11aq:
  - Pre-association Discovery (~ May 2015)
- IEEE 802.11ak:
  - General Links

Other Technologies

- IEEE 802.15 Wireless PAN

- IEEE 802.15.1
  - Bluetooth certification

- IEEE 802.15.2
  - IEEE 802.15 and IEEE 802.11 coexistence

- IEEE 802.15.3
  - High-Rate wireless PAN (e.g., UWB, etc)

- IEEE 802.15.4
  - Low-Rate wireless PAN (e.g., ZigBee, WirelessHART, MiWi, etc.)

- IEEE 802.15.5
  - Mesh networking for WPAN

- IEEE 802.15.6
  - Body area network

- IEEE 802.16
  - Broadband Wireless Access (WiMAX certification)