

CS/ECE 439: Wireless Networking

MAC Layer – Road to Wireless

Multiple Access Media

▶ Media access

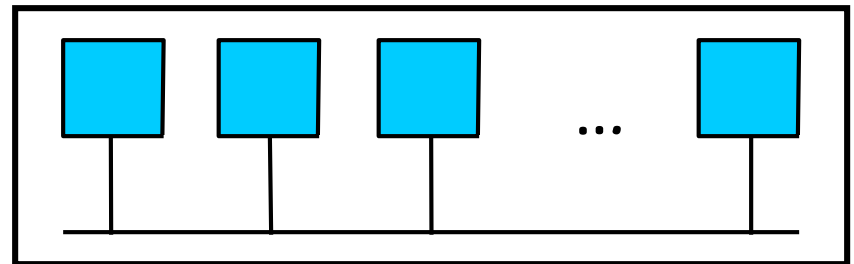
- ▶ Controlling which frame should be sent over the link next
 - ▶ Easy for point-to-point links; half versus full duplex
 - ▶ Harder for multi-access links: who gets to send?

▶ Multiple senders on some media

- ▶ Buses (Ethernet)
- ▶ Radio, Satellite

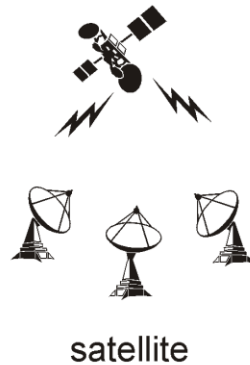
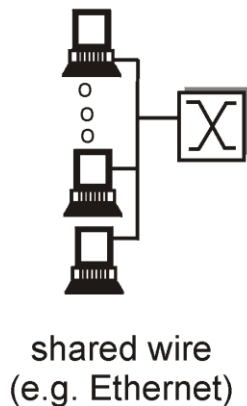
▶ Goals

- ▶ Fair arbitration
- ▶ Good performance

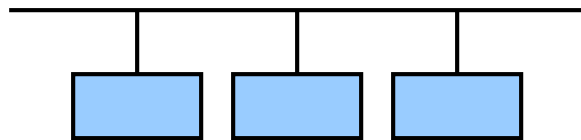


Point-to-Point vs. Broadcast Media

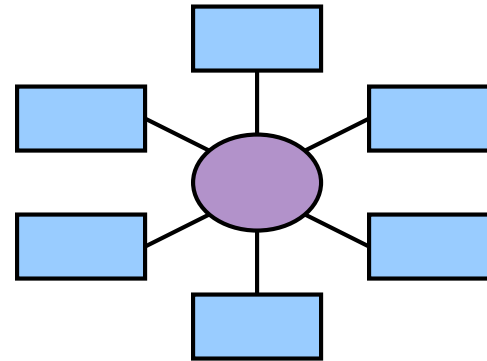
- ▶ **Point-to-point: dedicated pairwise communication**
 - ▶ Long-distance fiber link
 - ▶ Point-to-point link between Ethernet switch and host
- ▶ **Broadcast: shared wire or medium**
 - ▶ Traditional Ethernet
 - ▶ 802.11 wireless LAN



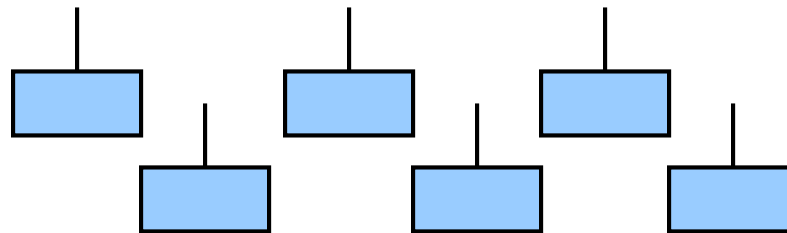
Types of Shared Link Networks



Bus Topology: Shared
Ethernet



Star Topology: Active or Passive Hub



Wireless: Shared
IEEE 802.11, BT, ZigBee

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

- ▶ [video](#)



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.



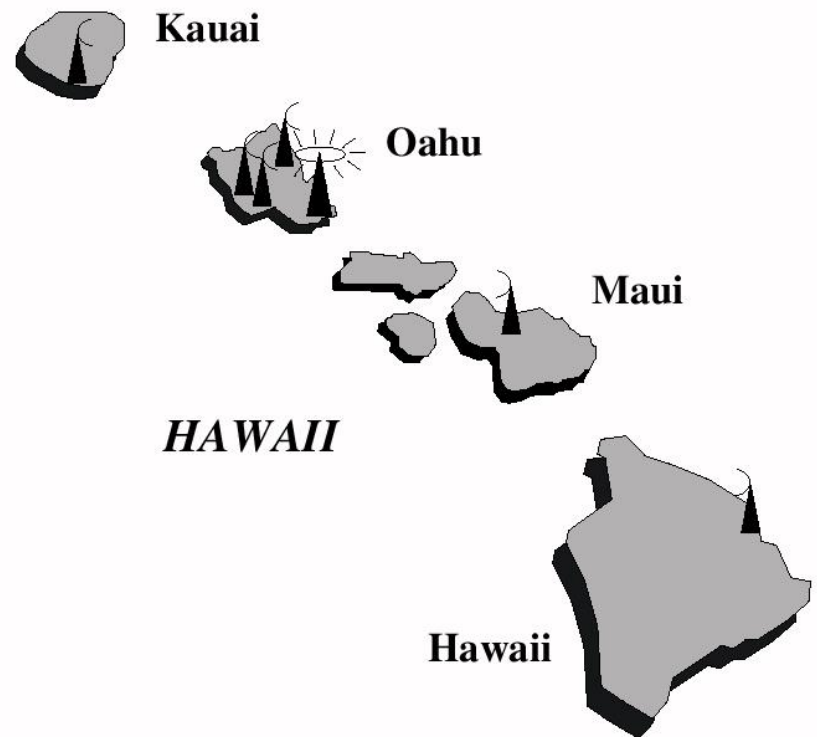
Multiple Access Media: Random Access

- ▶ **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 $1/(2e) = 18\%$!



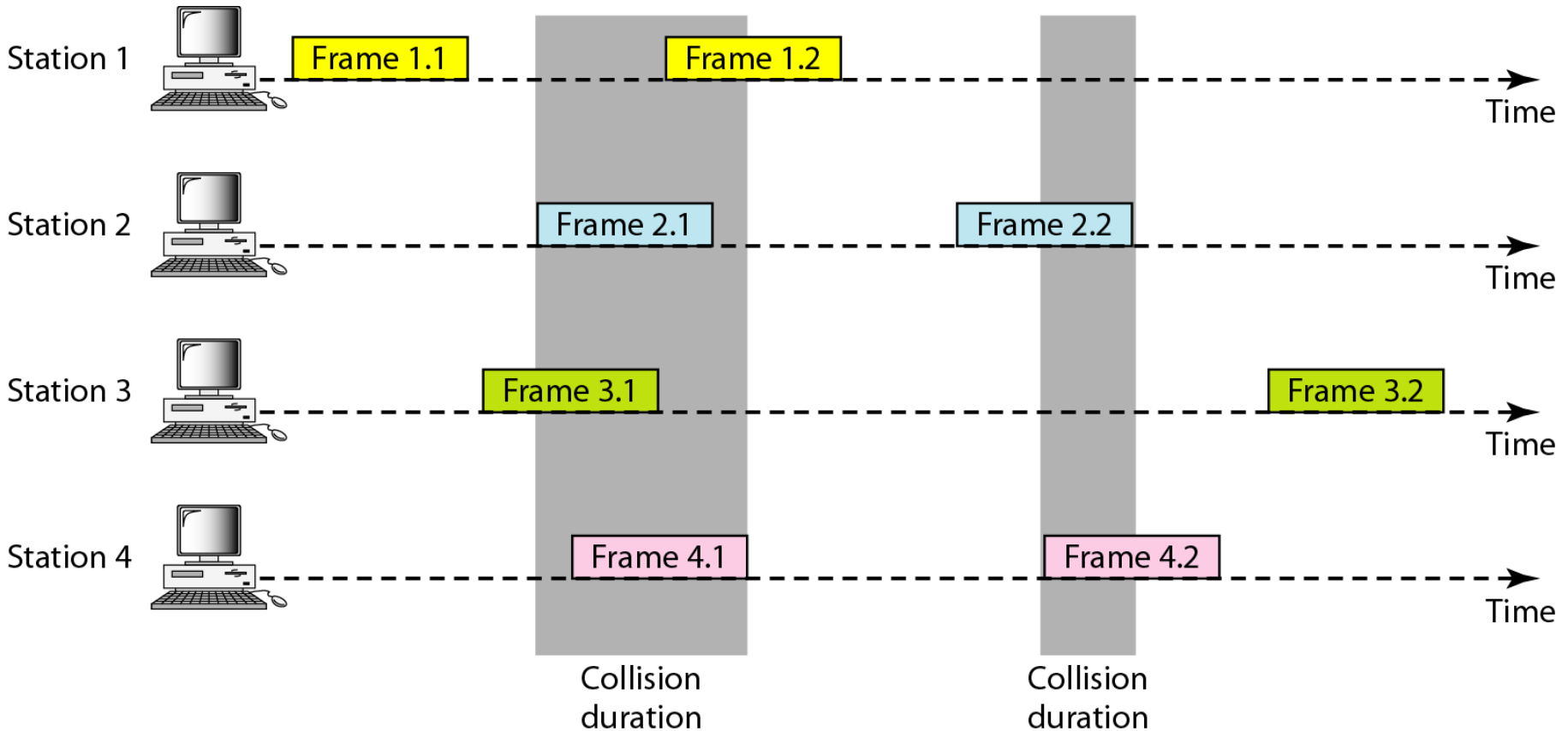
Pure ALOHA

▶ 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



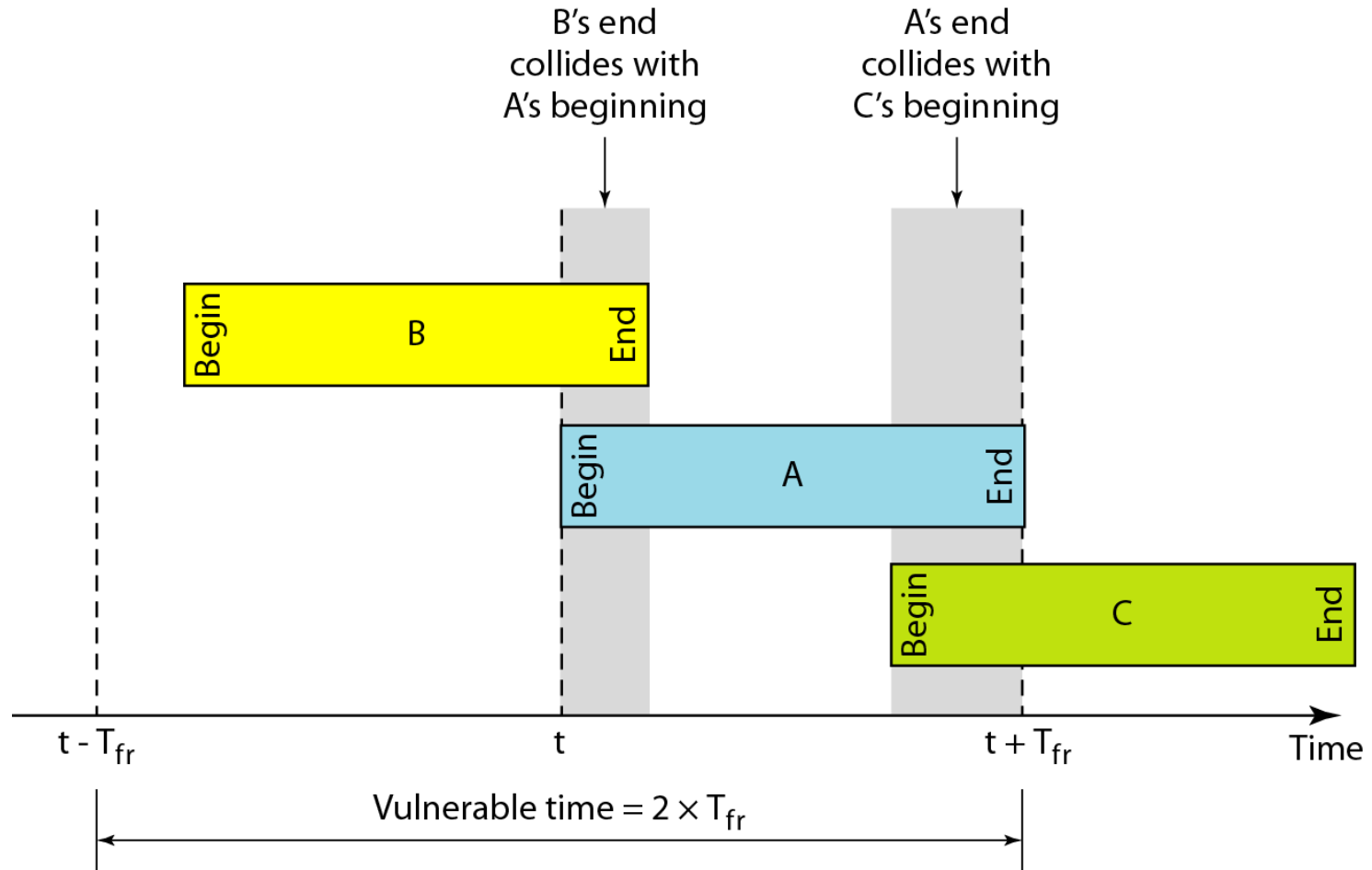
Pure ALOHA

▶ Collisions

- ▶ A frame will not 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

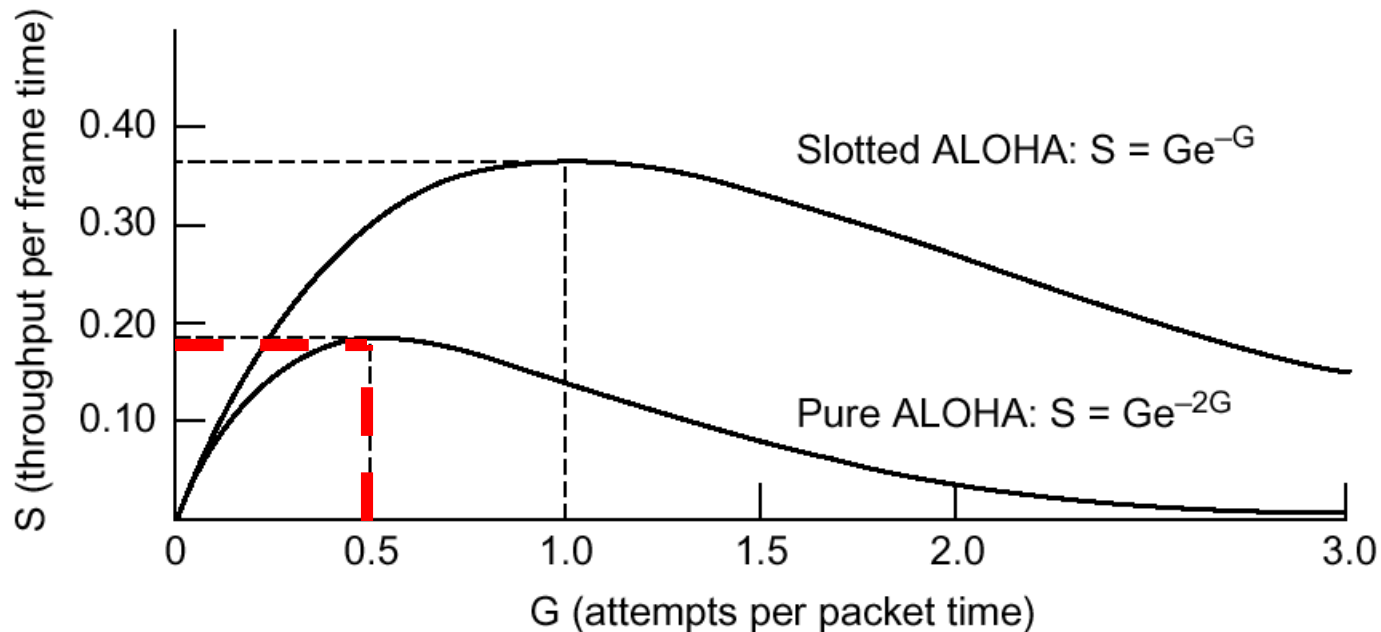
- ▶ Maximum throughput

- ▶ $G = 0.5$

- ▶ $S = 1/2e$

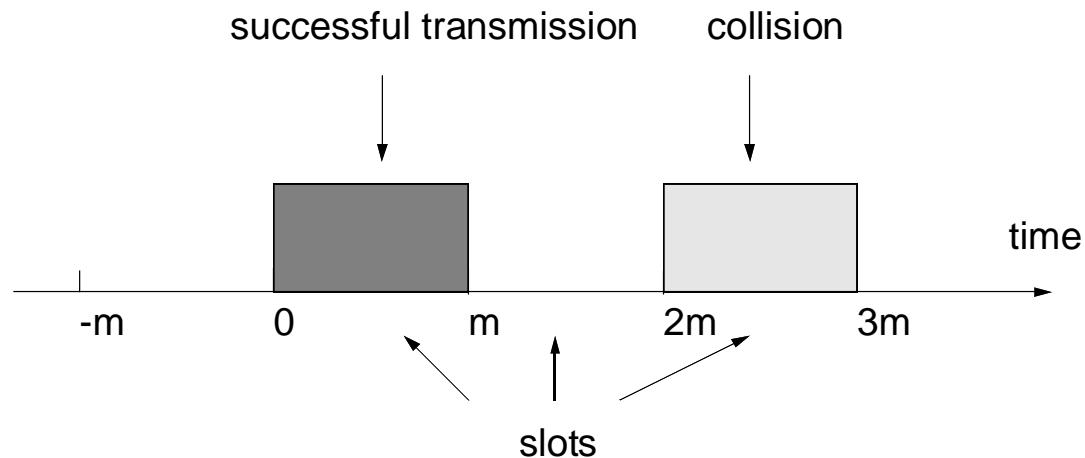
- Utilization

- Maximum of 0.184!

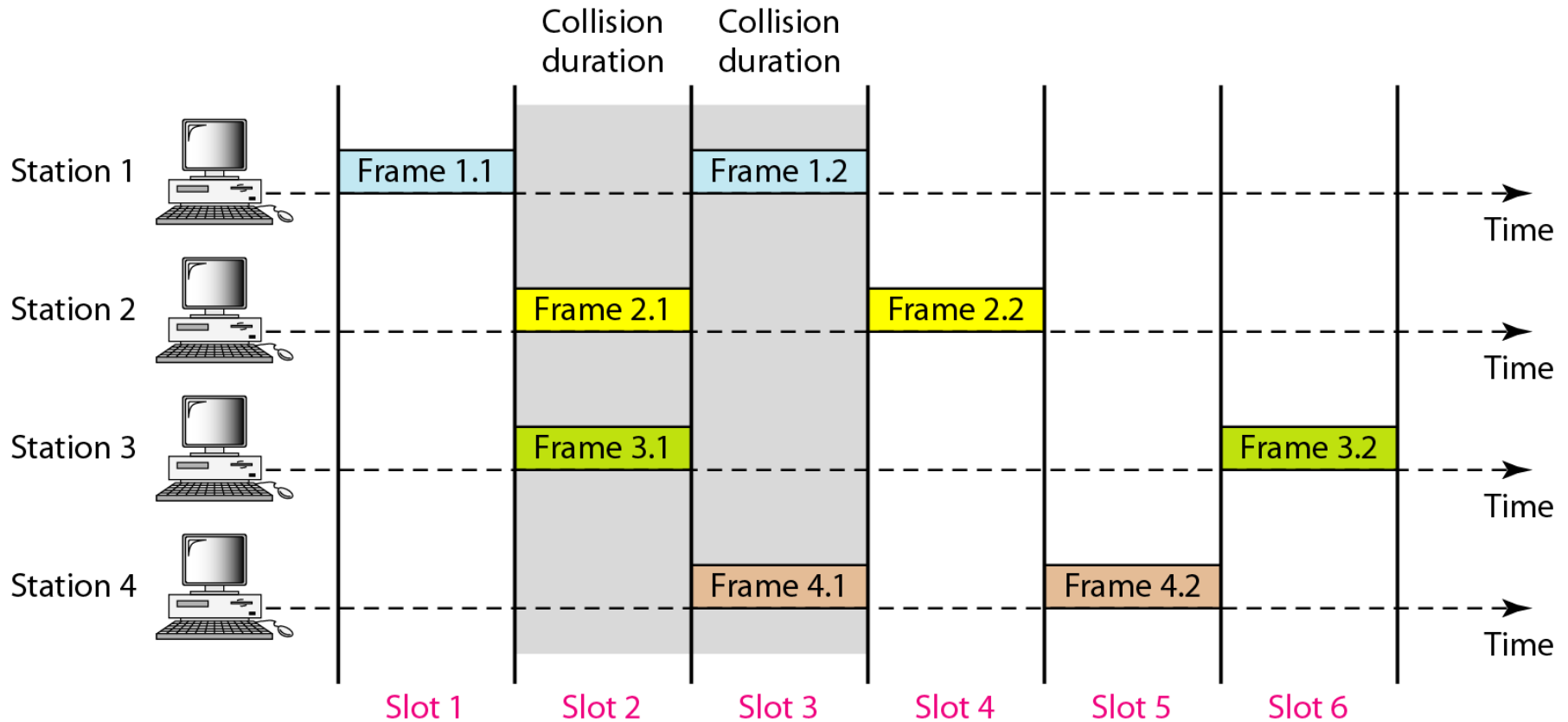


Slotted ALOHA

- ▶ 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 $G = 1$.



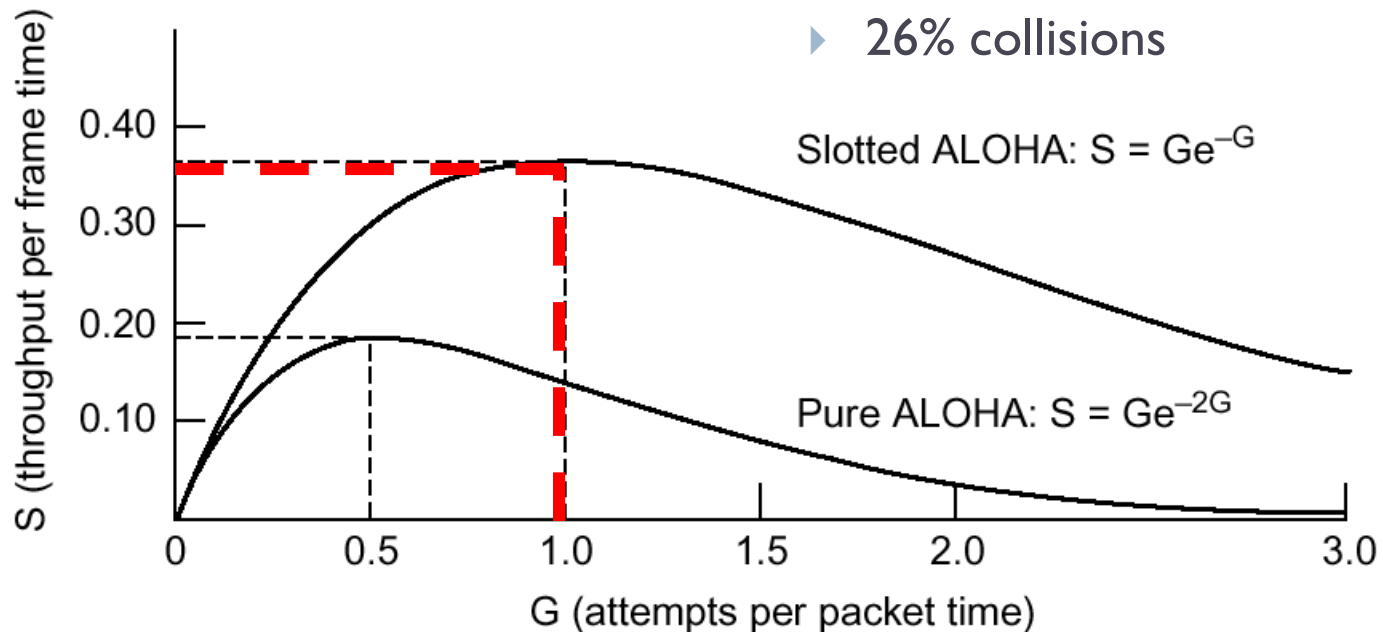
Slotted ALOHA

- ▶ Maximum throughput

- ▶ $G = 1$
- ▶ $S = 1/e$

- ▶ Utilization

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



Slotted ALOHA

▶ 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

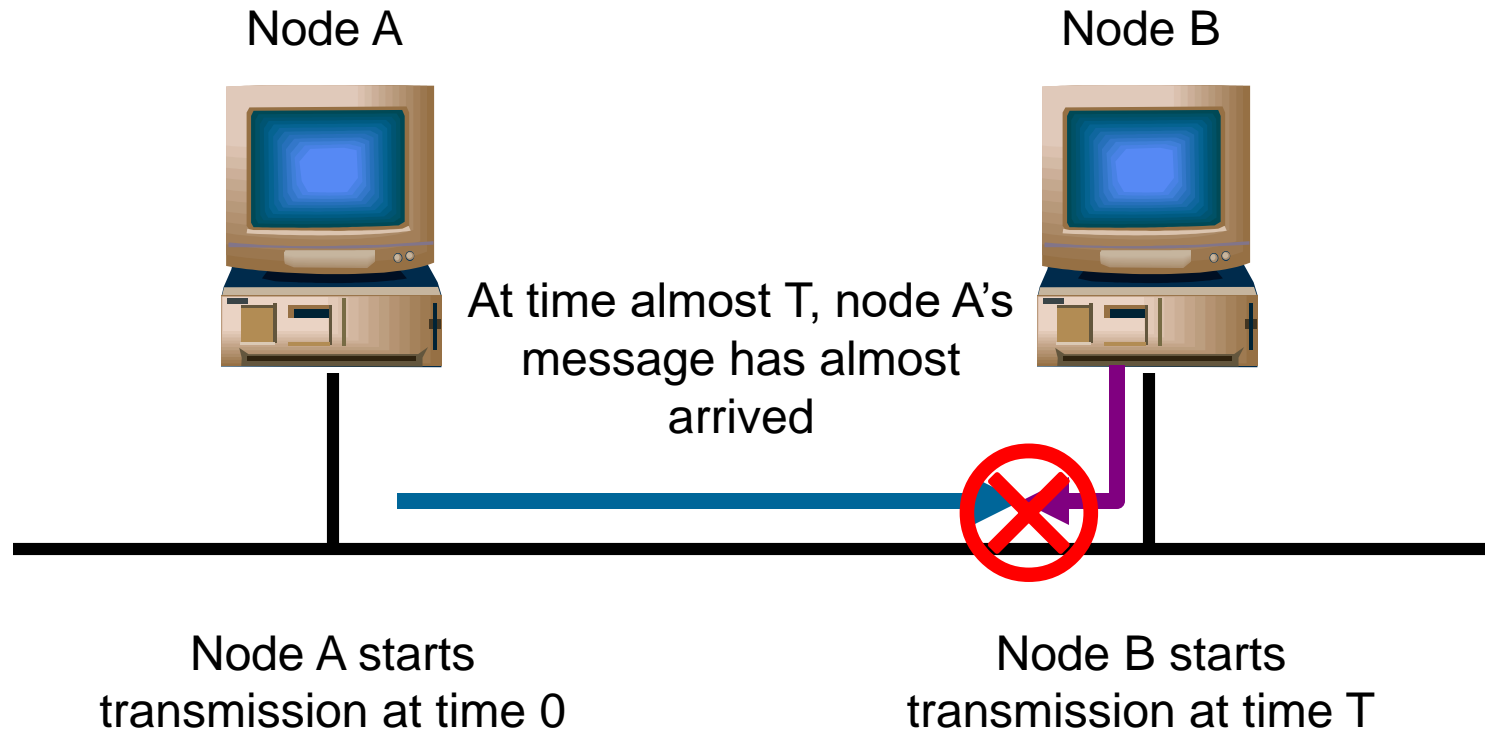


From Aloha comes Ethernet

- ▶ **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



How can we ensure that A knows about the collision?

Collision Detection

▶ Problem

- ▶ How can A detect a collision?

▶ Solution

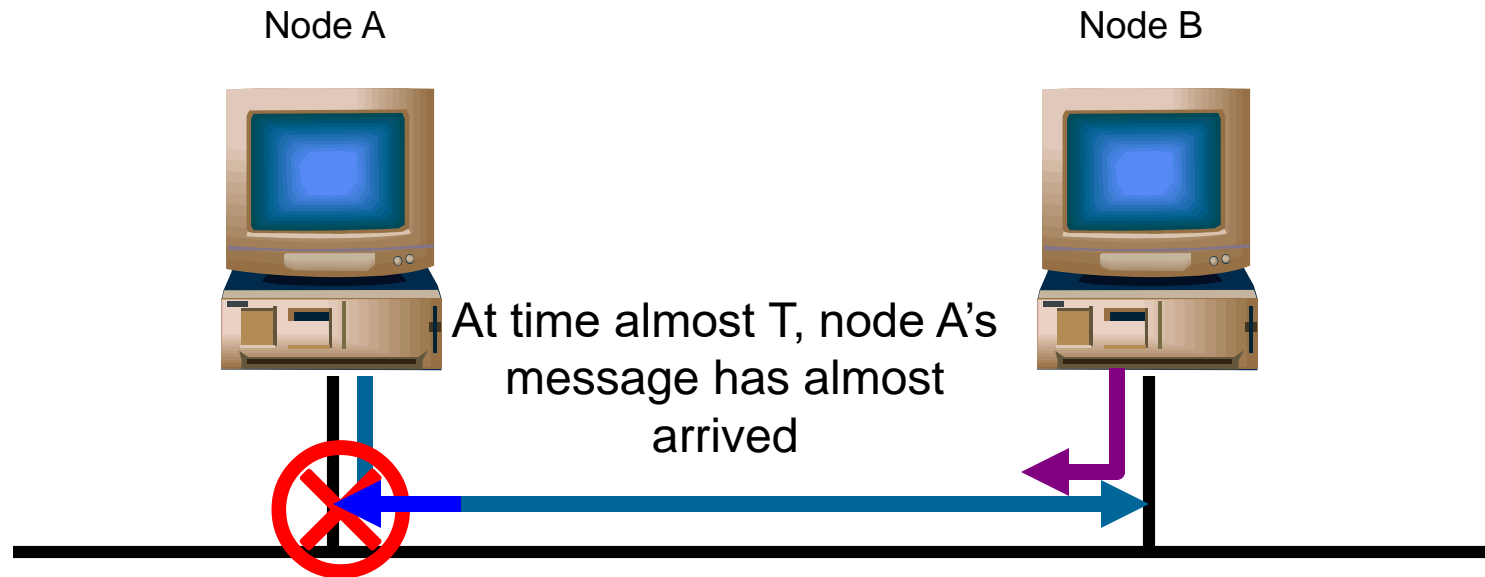
- ▶ A must still be transmitting when it receives B's transmission!

▶ 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 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 $51.2\mu\text{s}$
- ▶ At 10Mbps $51.2\mu\text{s} = 512\text{b}$ or $64 = 512\text{b}$ or 64B
- ▶ Packet length $\geq 64\text{B}$

- ▶ **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 μ s 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 μ s?

Too long: wastes time
Too short: doesn't allow other nodes to transmit (fairness)

Incoming signal \neq outgoing signal!

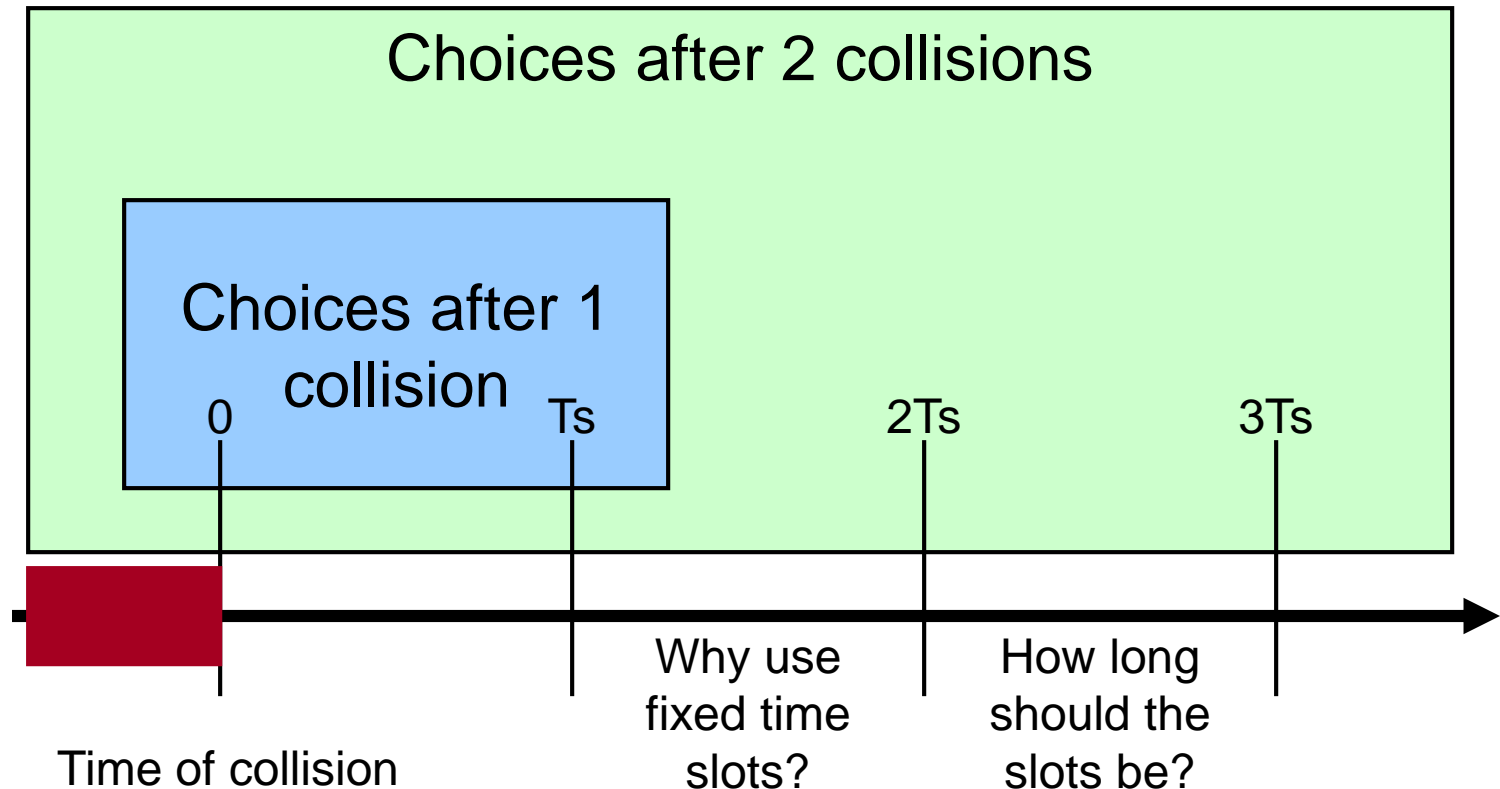


Retransmission

- ▶ 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



Binary Exponential Backoff

- ▶ For IEEE 802.3, $T = 51.2 \mu\text{s}$
- ▶ 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 $< 51.2 \mu\text{s}$
 - ▶ 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

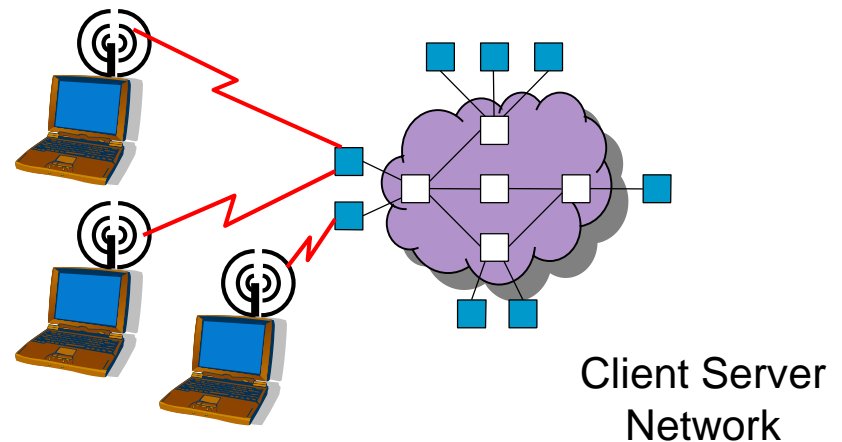
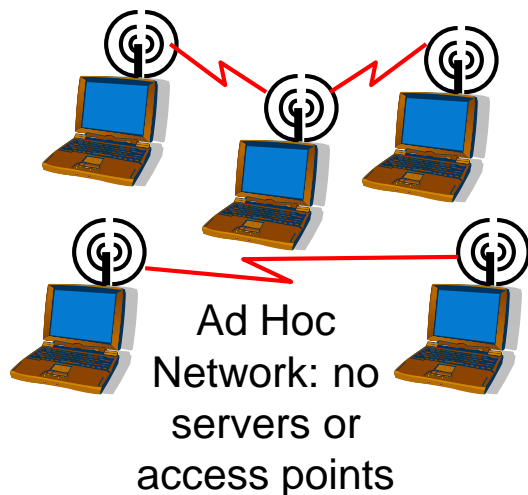
- ▶ When collision first occurs
 - ▶ Send a jamming signal to prevent further data being sent
- ▶ Resend a frame
 - ▶ After either 0 or T seconds, chosen at random
- ▶ If resend fails, resend the frame again
 - ▶ After either 0 , T , $2T$, or $3T$ seconds.
 - ▶ In other words, send after kT seconds, 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 n^{th} 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)

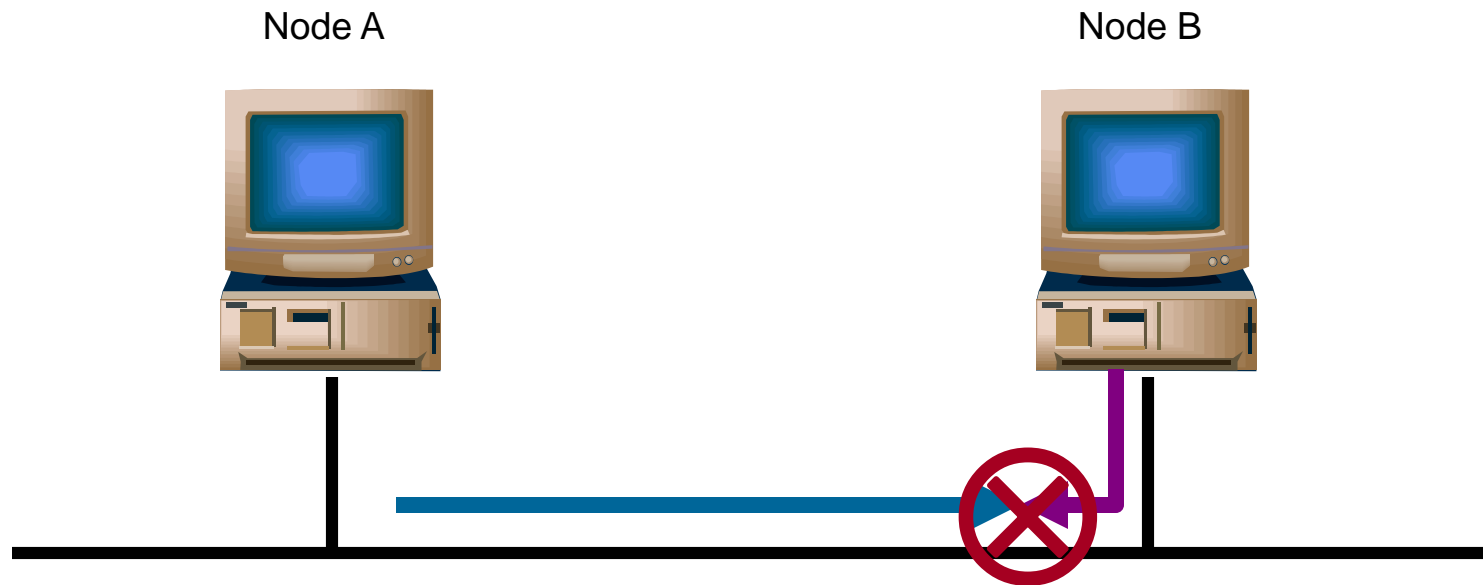


Medium Access Control

- ▶ Wireless channel is a shared medium
- ▶ Need access control mechanism to avoid interference
- ▶ Why not CSMA/CD?



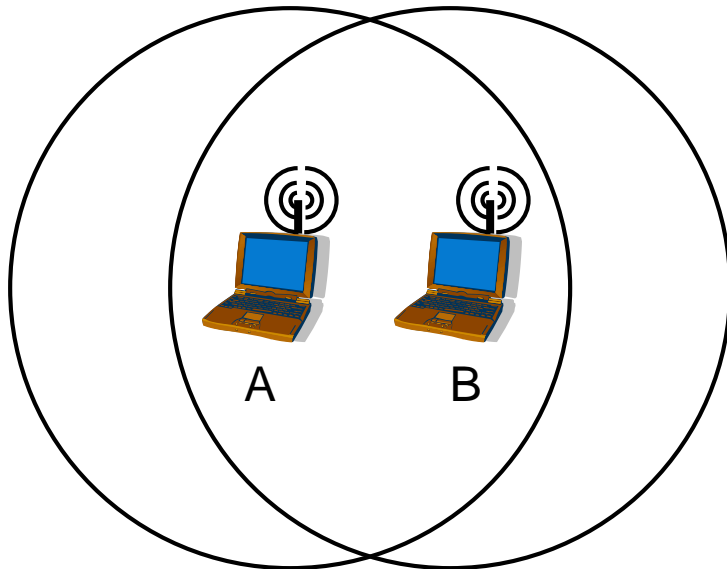
Ethernet MAC Algorithm



- 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!



- ▶ **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

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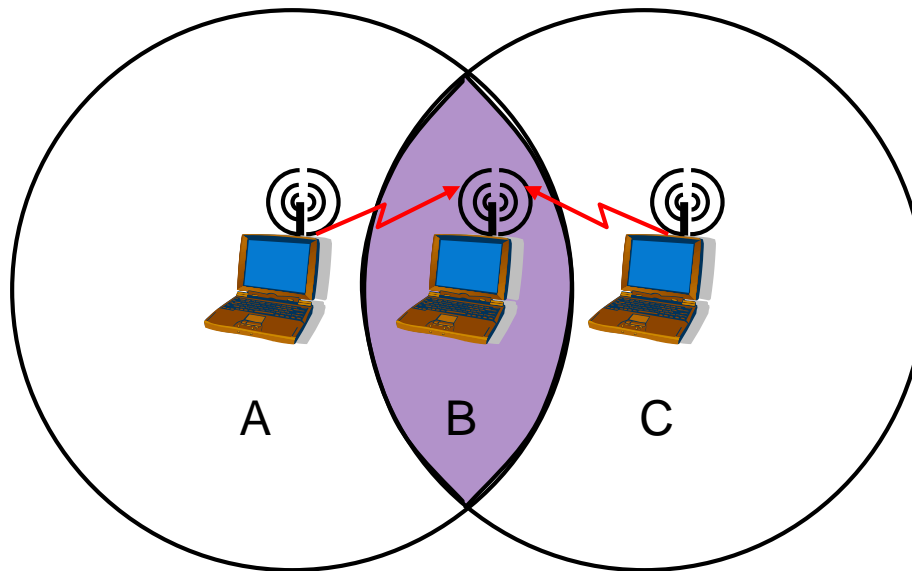
- ▶ **CA – Collision Avoidance**

- ▶ Nodes use protocol to prevent collisions from occurring



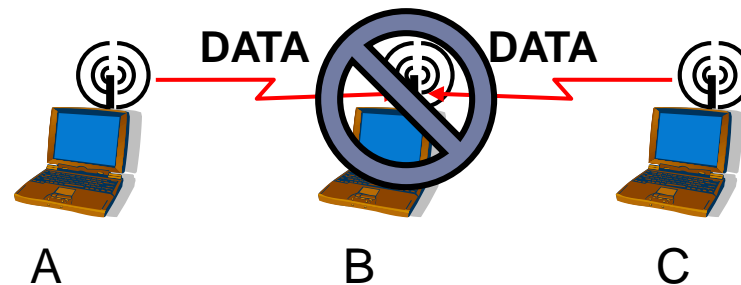
IEEE 802.11 MAC Layer Standard

- ▶ Similar to Ethernet
- ▶ But consider the following:



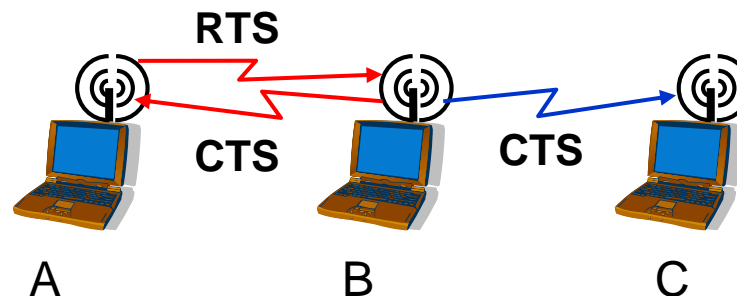
Hidden Terminal Problem

- ▶ 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



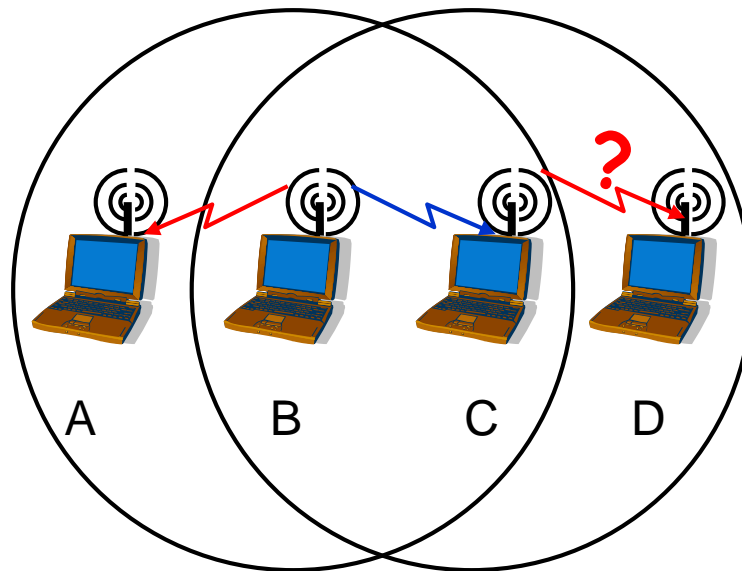
MACA Solution for Hidden Terminal Problem

- ▶ When node A wants to send a packet to node B
 - ▶ Node A first sends a Request-to-Send (RTS) to B
- ▶ On receiving RTS
 - ▶ Node B responds by sending Clear-to-Send (CTS) to A
 - ▶ provided node B is able to receive the packet
- ▶ When a node C overhears a CTS, it keeps quiet for the duration of the transfer



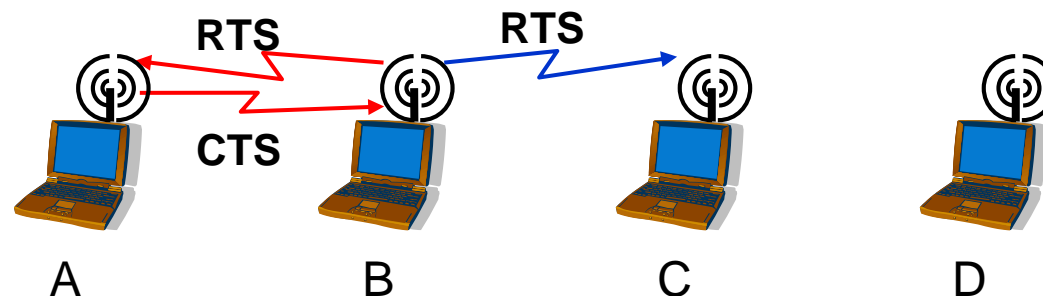
IEEE 802.11 MAC Layer Standard

- ▶ But we still have a problem



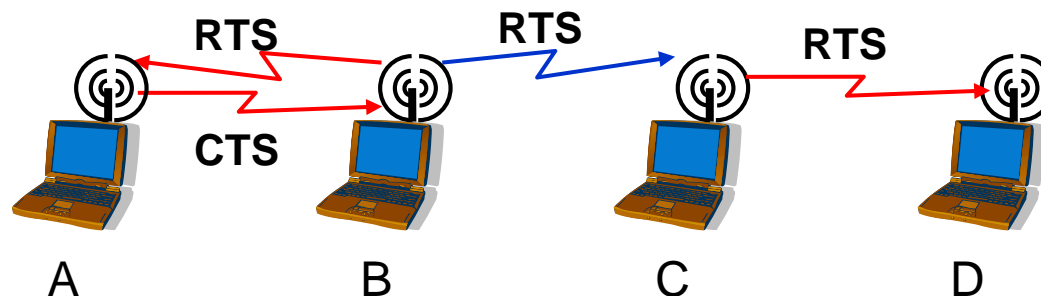
Exposed Terminal Problem

- ▶ 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)



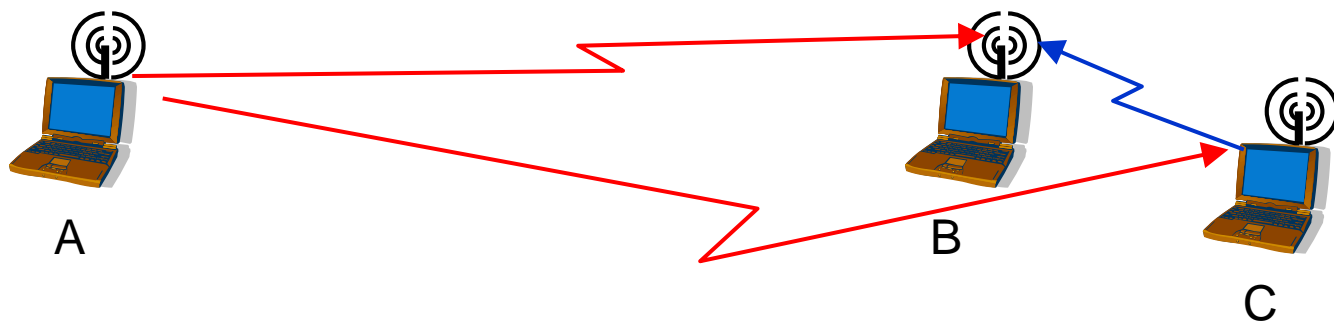
MACA Solution for Exposed Terminal Problem

- ▶ 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!



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



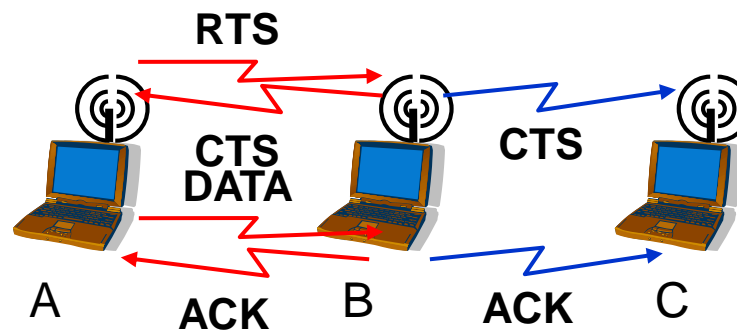
Reliability

- ▶ **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**



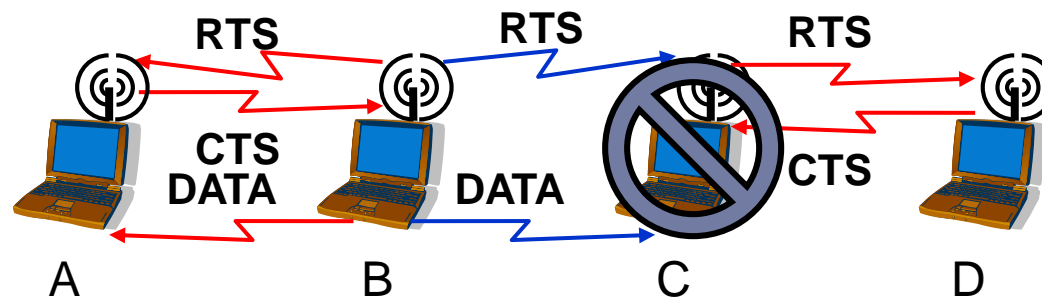
A Simple Solution to Improve Reliability - MACAW

- ▶ 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



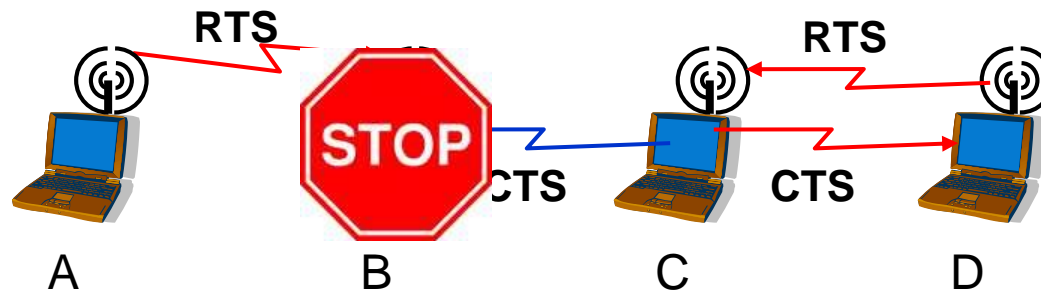
Backoff Algorithm

- ▶ **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

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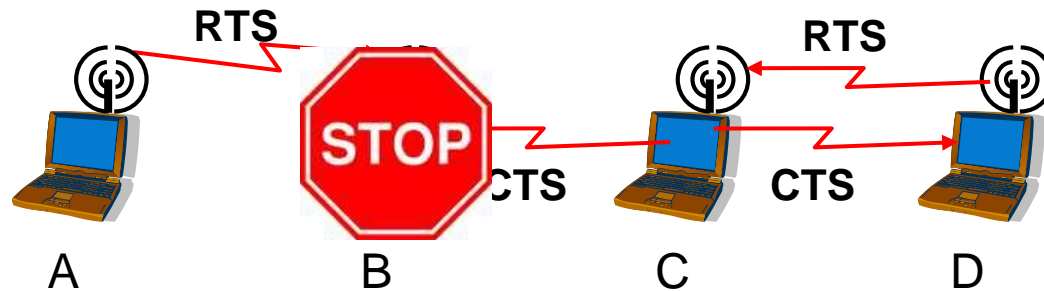
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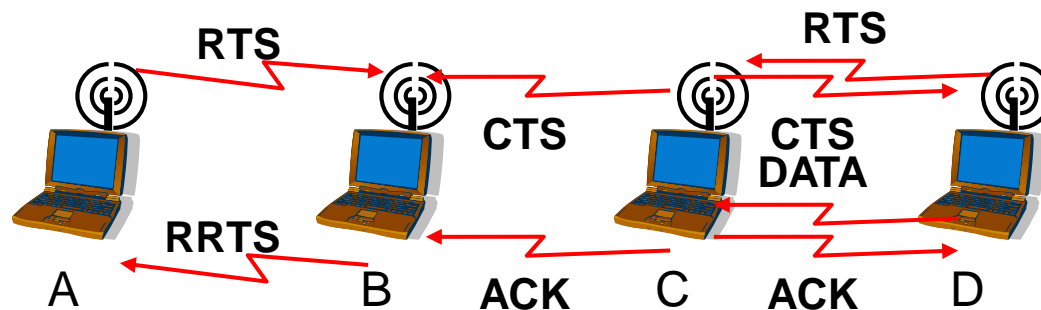
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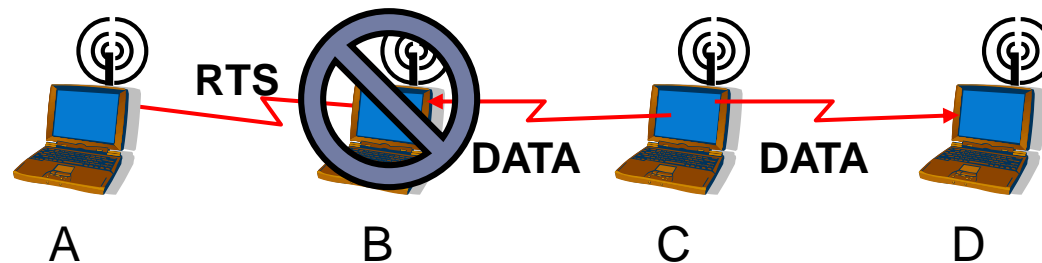
Request for RTS - MACAW

- ▶ 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)



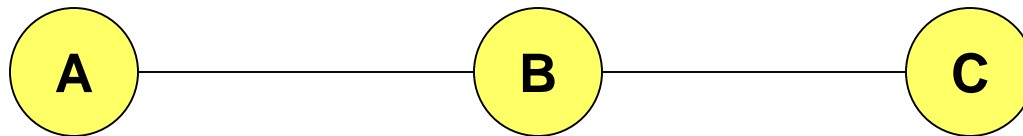
IEEE 802.11 Wireless MAC

- ▶ 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

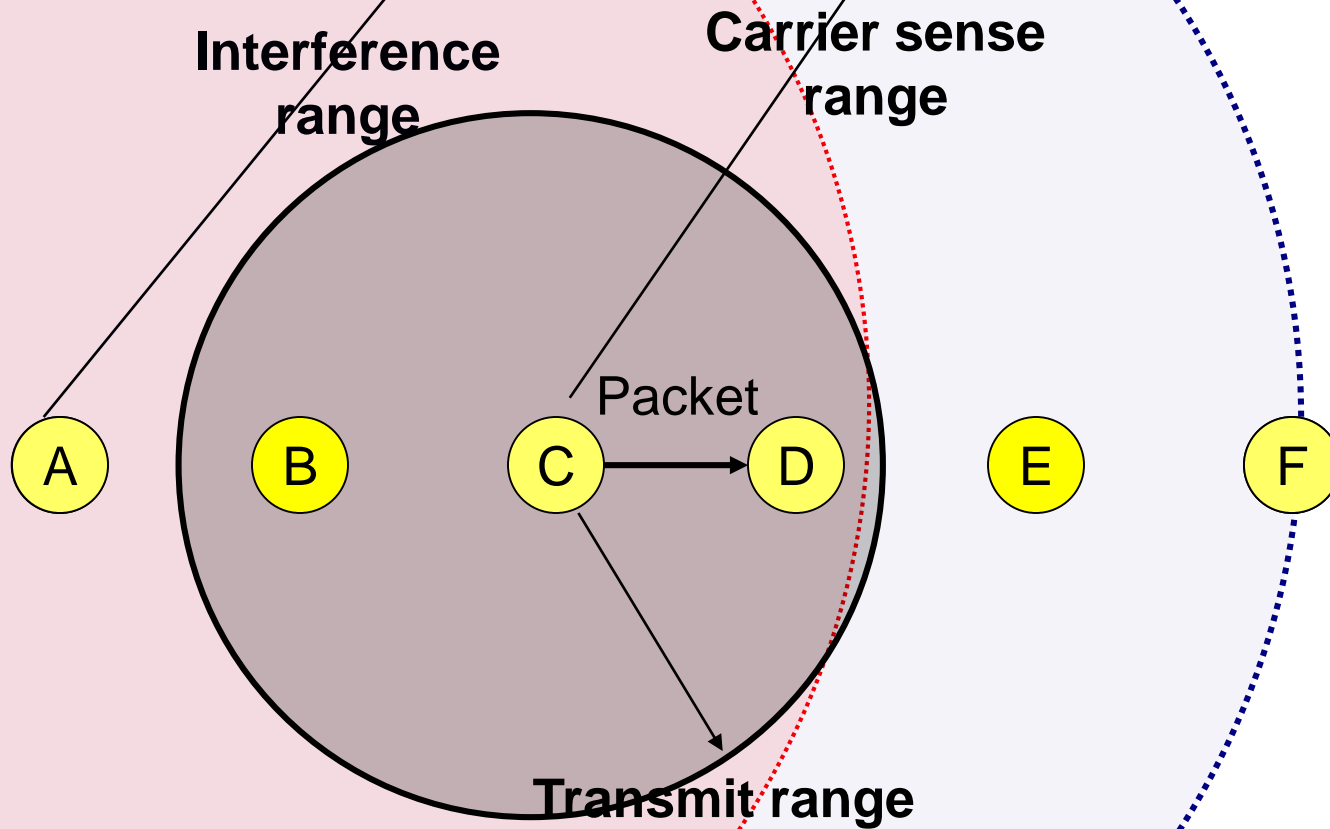


IEEE 802.11 CSMA/CA

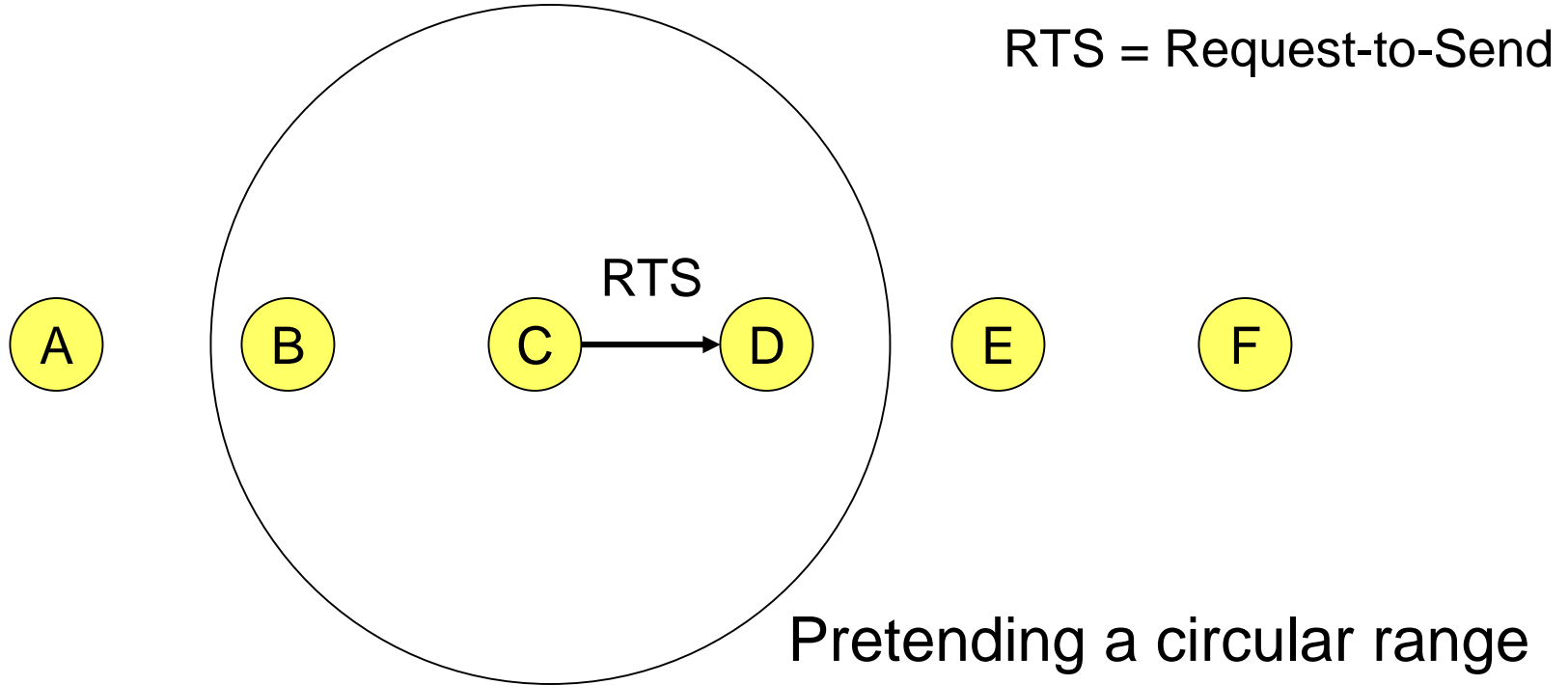
- ▶ **Nodes stay silent when carrier sensed**
 - ▶ Physical carrier sense
 - ▶ Virtual carrier sense
 - ▶ Network Allocation Vector (NAV)
 - ▶ NAV is updated based on overheard RTS/CTS/DATA/ACK packets, each of which specified duration of a pending transmission
- ▶ **Backoff intervals used to reduce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



IEEE 802.11 Physical Carrier Sense



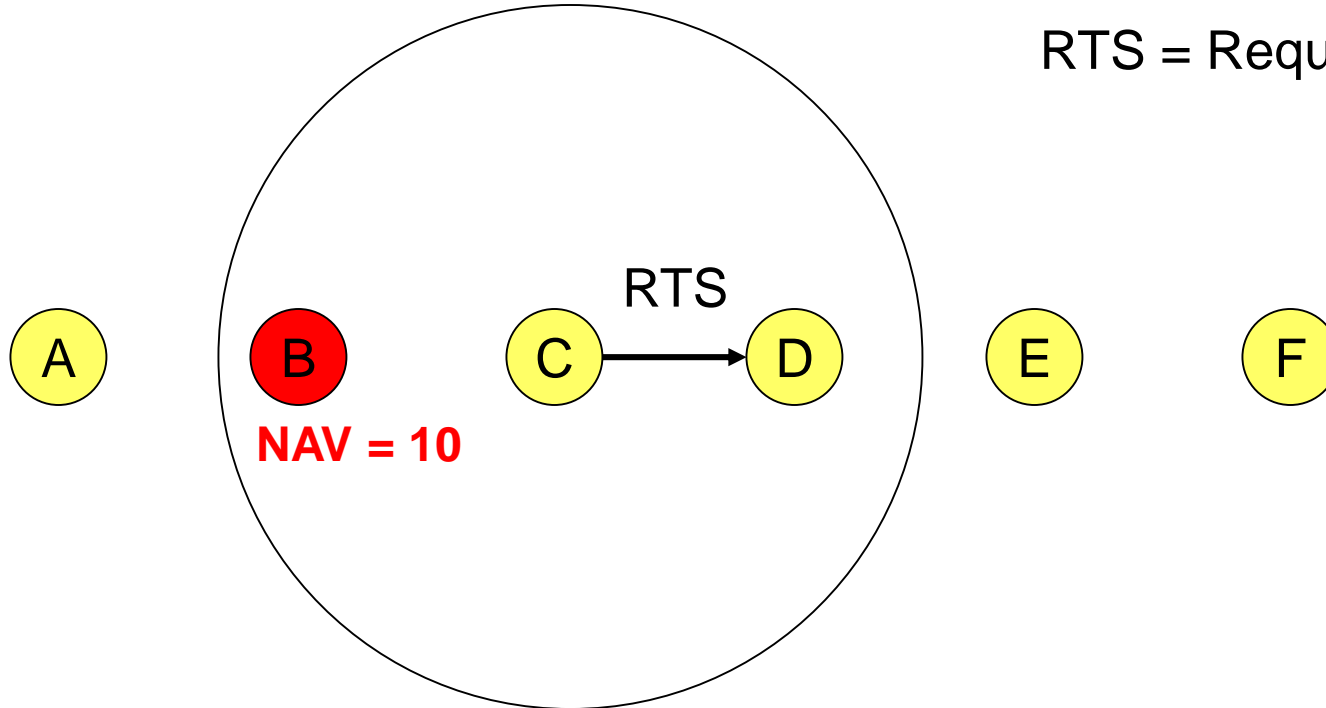
IEEE 802.11 Virtual Carrier Sense



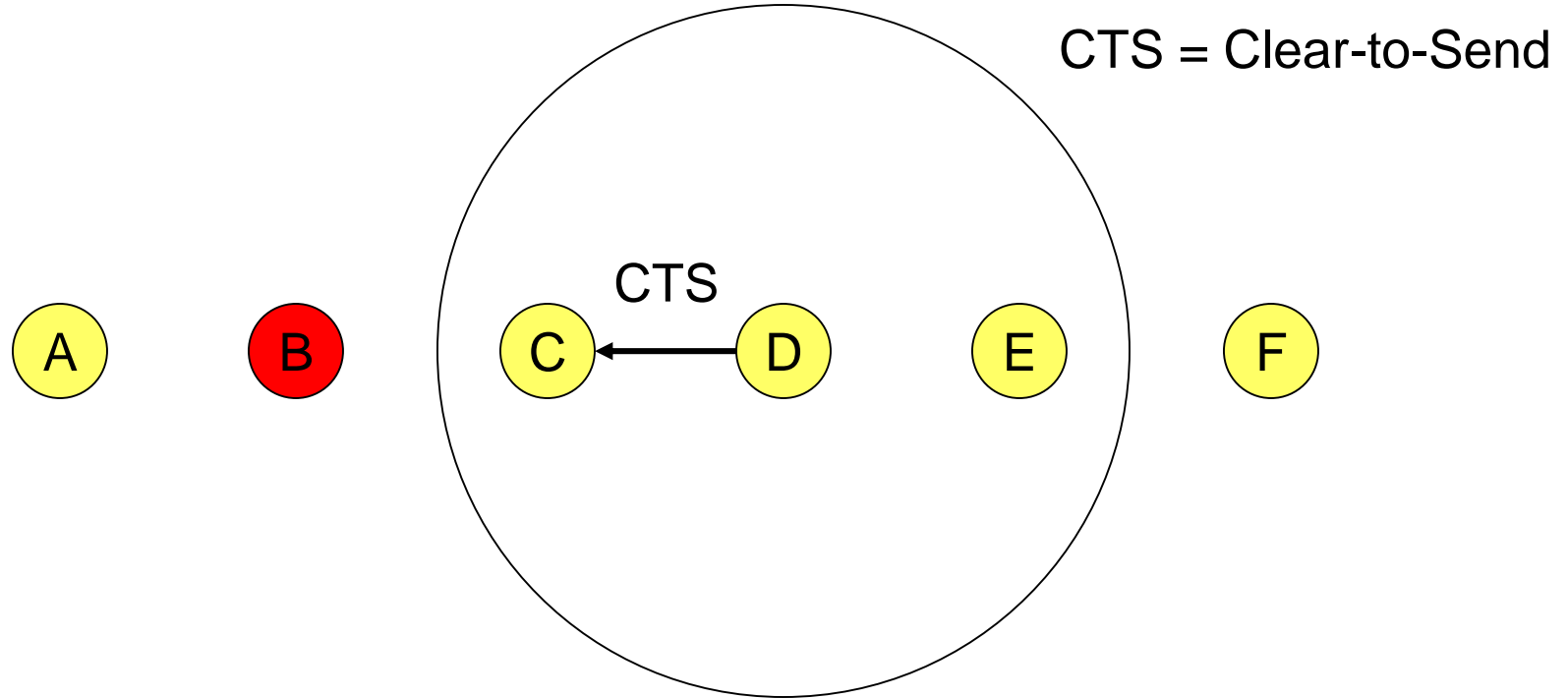
IEEE 802.11 Virtual Carrier Sense

NAV = remaining duration to keep quiet

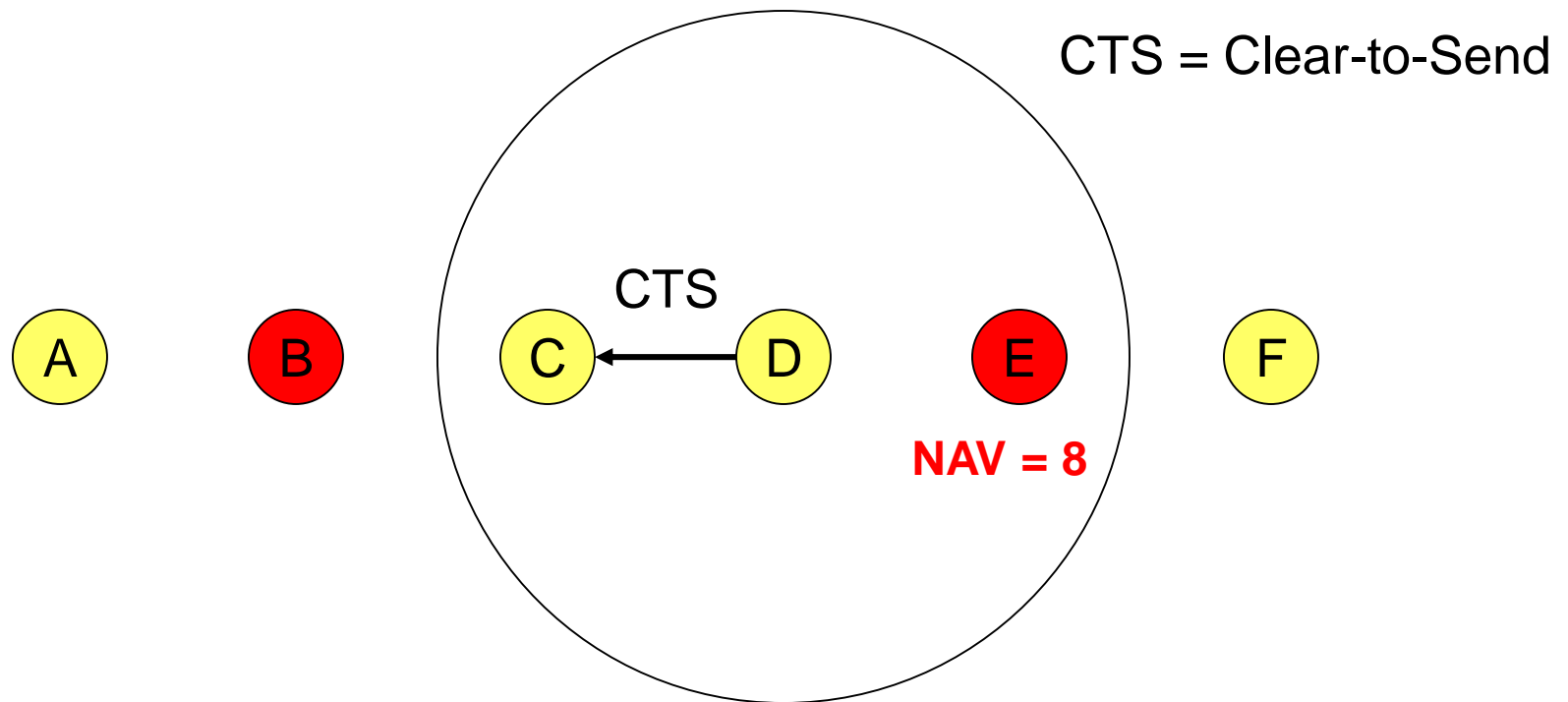
RTS = Request-to-Send



IEEE 802.11 Virtual Carrier Sense

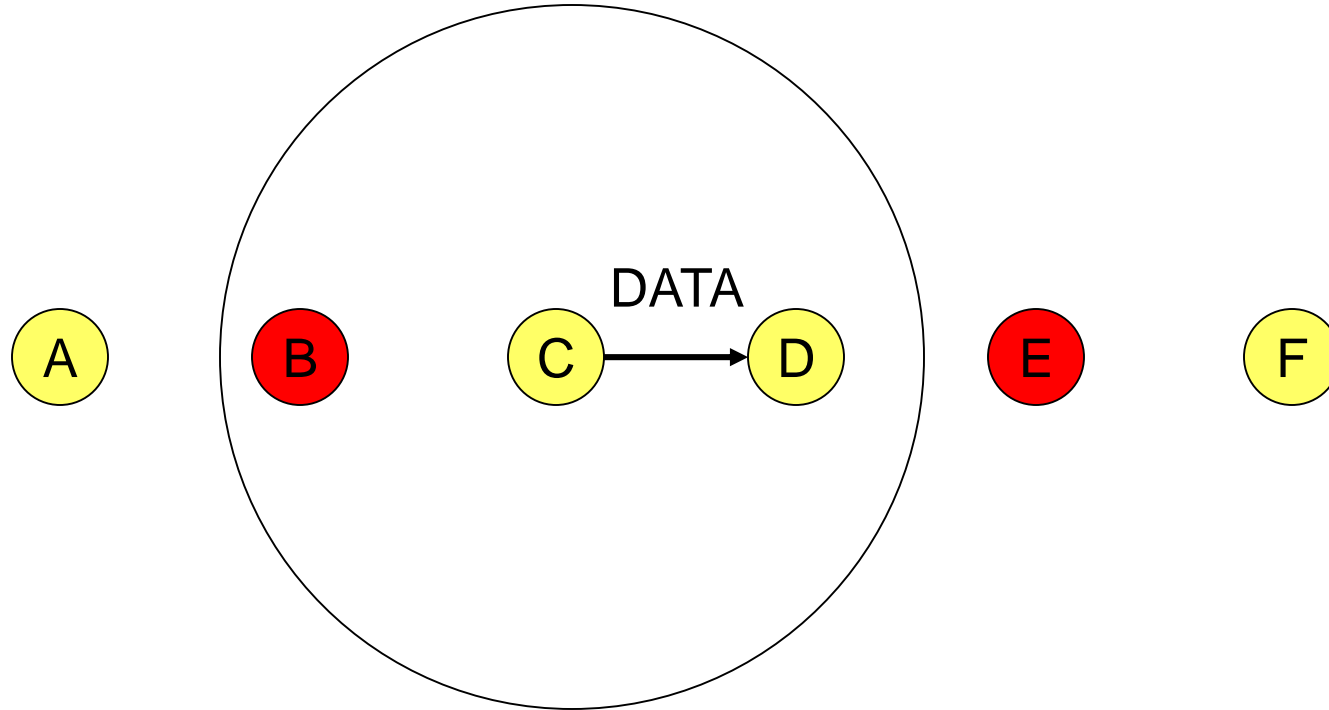


IEEE 802.11 Virtual Carrier Sense



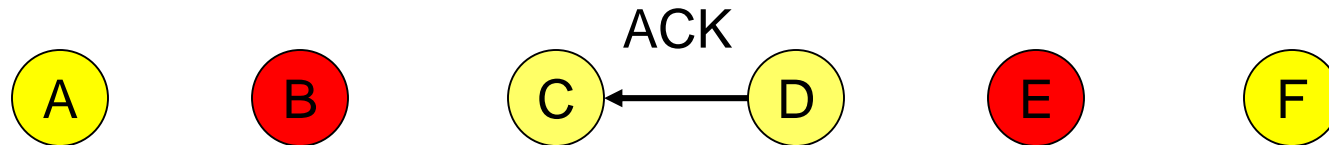
IEEE 802.11 Virtual Carrier Sense

- ▶ DATA packet follows CTS

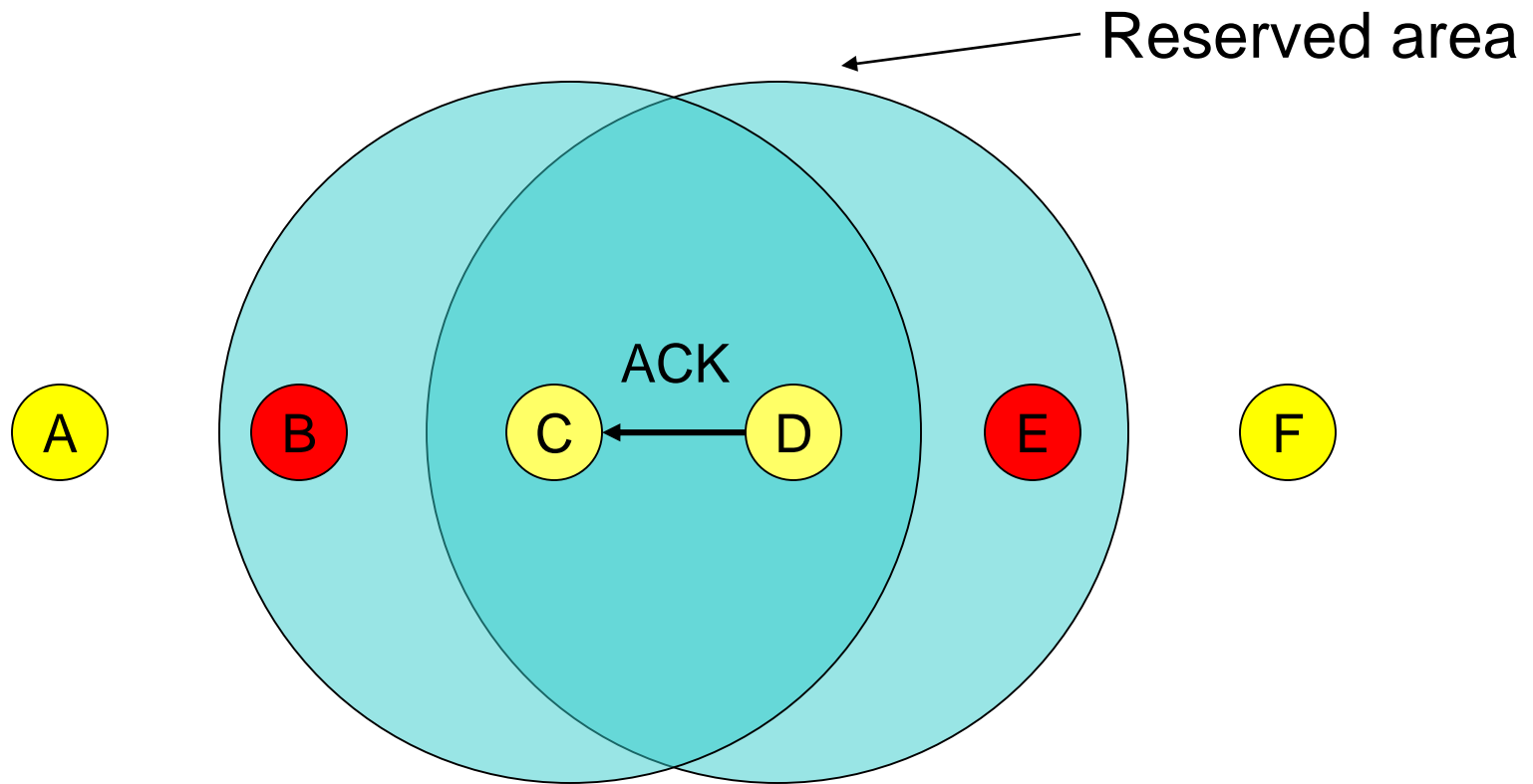


IEEE 802.11 Virtual Carrier Sense

- ▶ Successful data reception acknowledged using ACK



IEEE 802.11



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 μ s before sending again

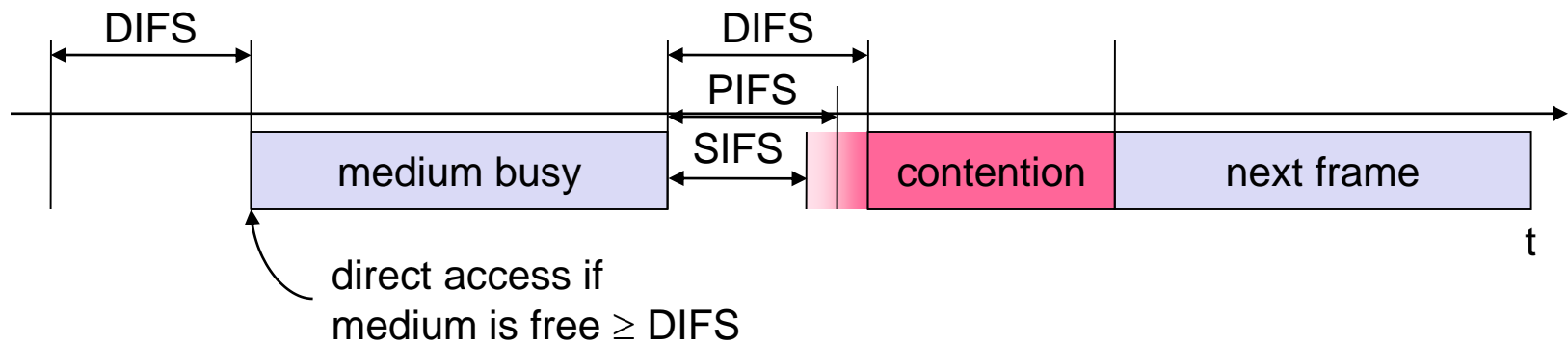
▶ If carrier is sensed

- ▶ When should a node transmit?



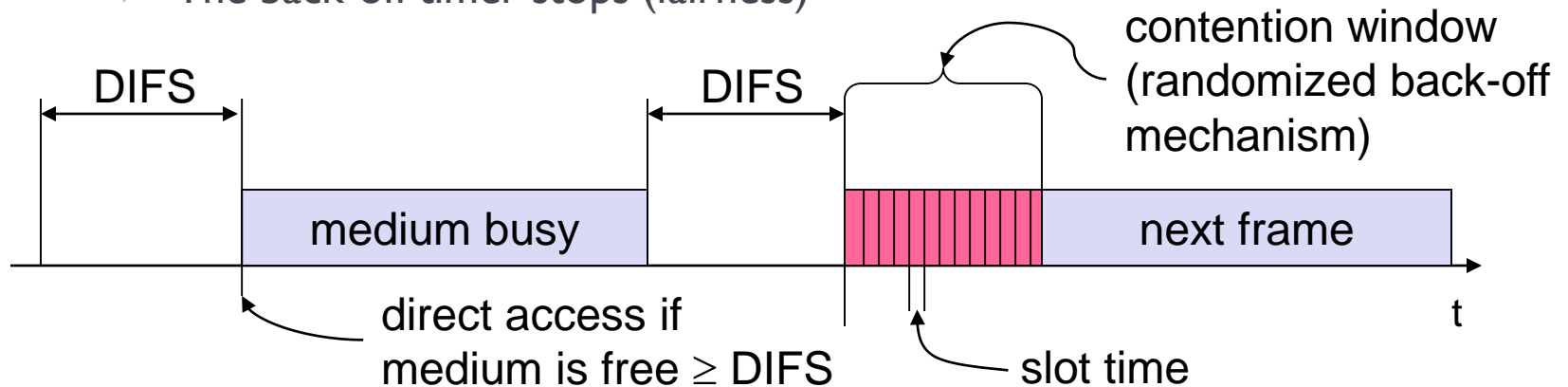
Interframe Spacing

- ▶ 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



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)



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**

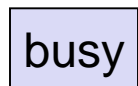
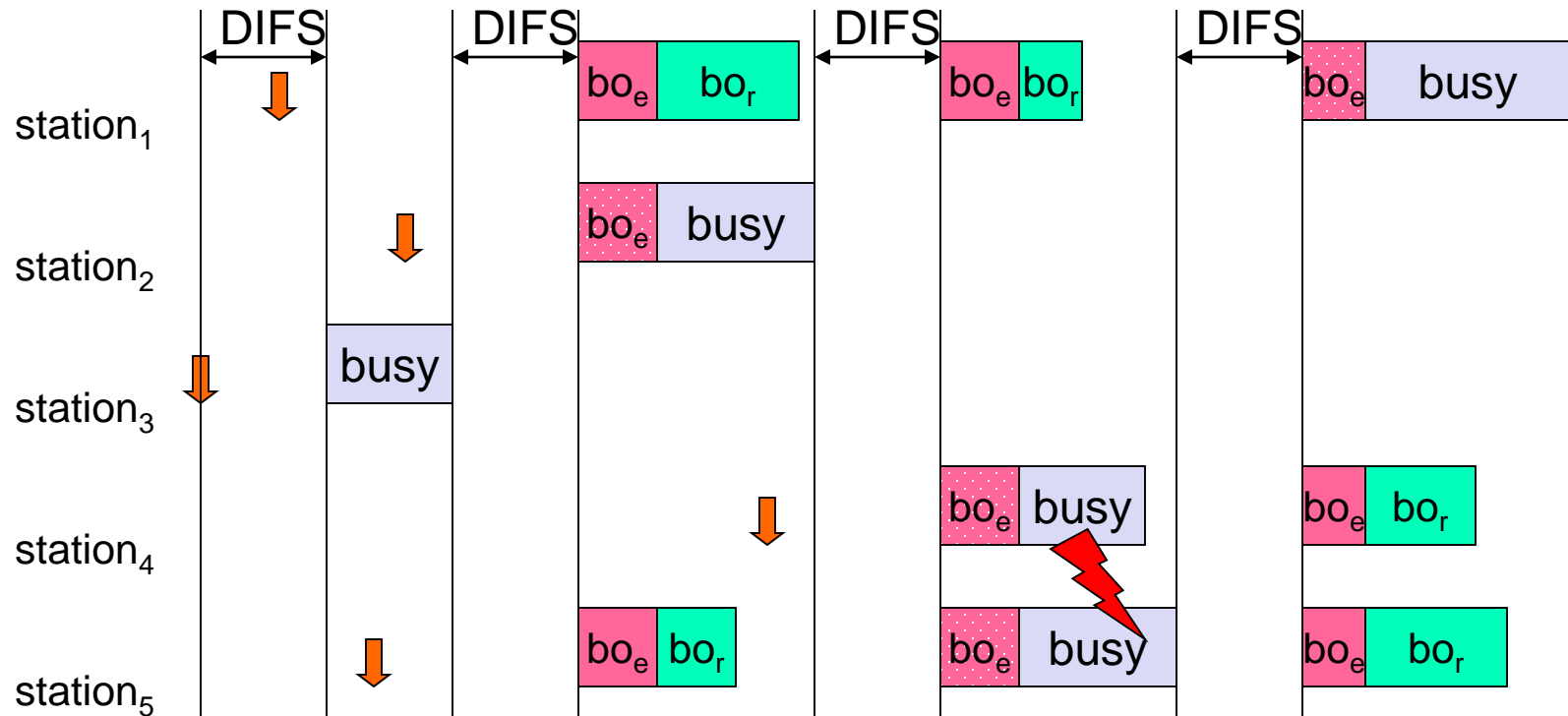
- ▶ PCF interframe space
- ▶ Minimum idle time for contention-free service ($>SIFS$, $<DIFS$)

- ▶ **EIFS**

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



IEEE 802.11 - Competing Stations



medium not idle (frame, ack etc.)



elapsed backoff time



packet arrival at MAC



residual backoff time

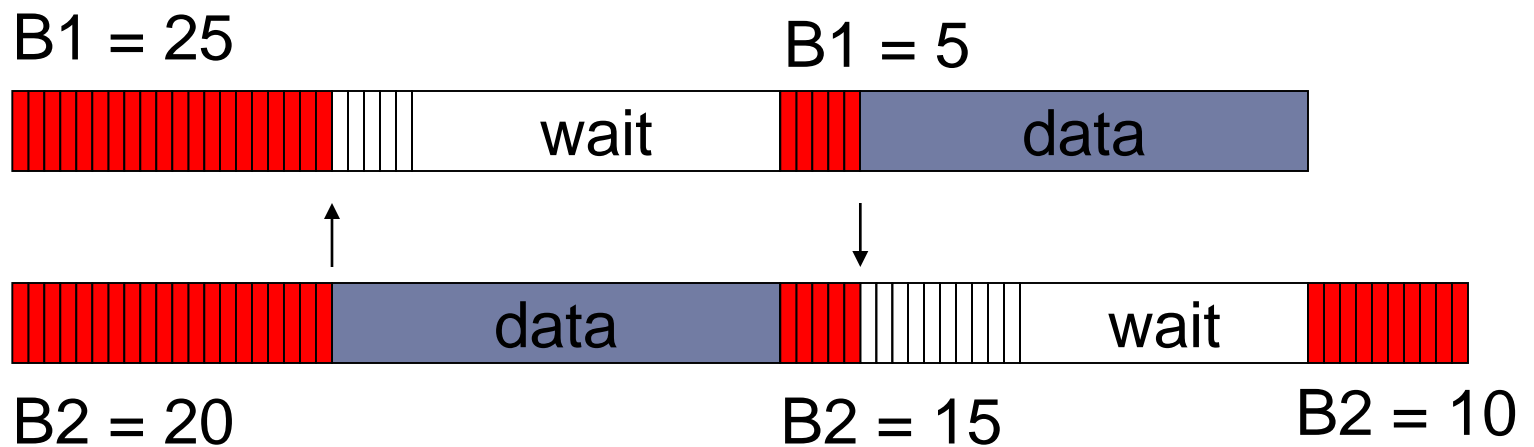


Backoff Interval

- ▶ 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



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

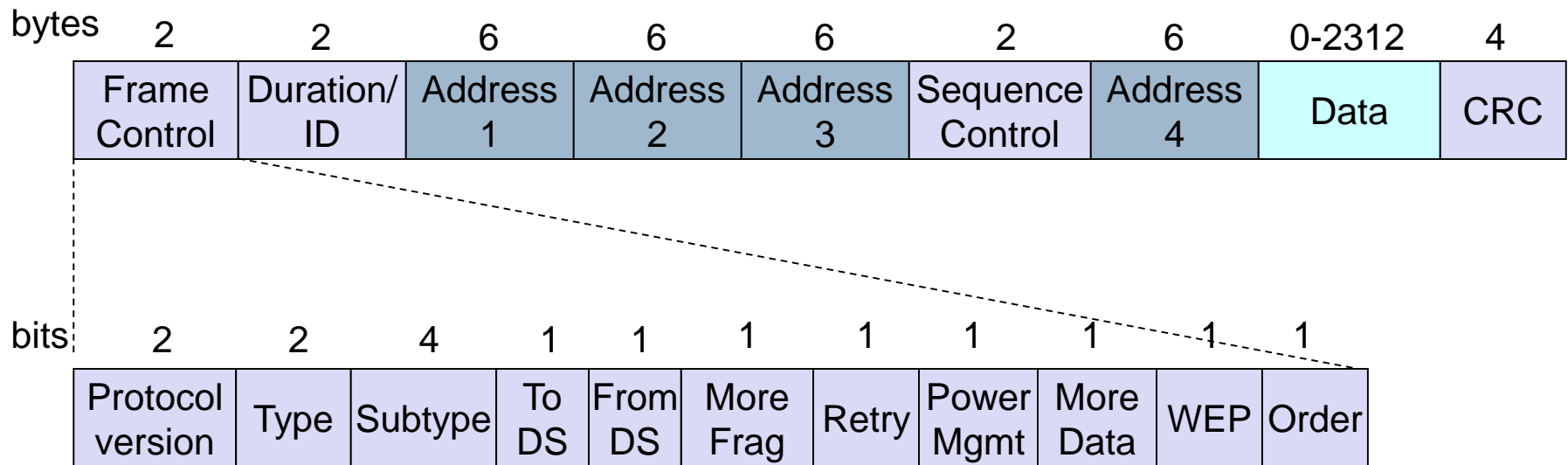
- ▶ receiver, transmitter (physical), BSS identifier, sender (logical)

▶ Miscellaneous

- ▶ sending time, checksum, frame control, data



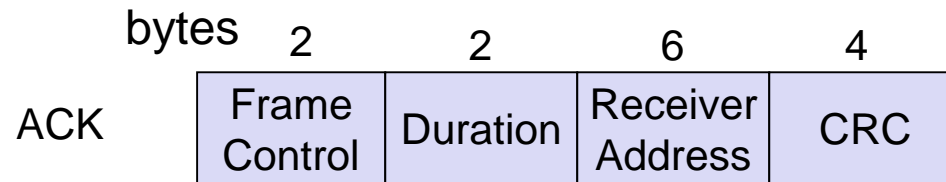
IEEE 802.11 Data Frame Format



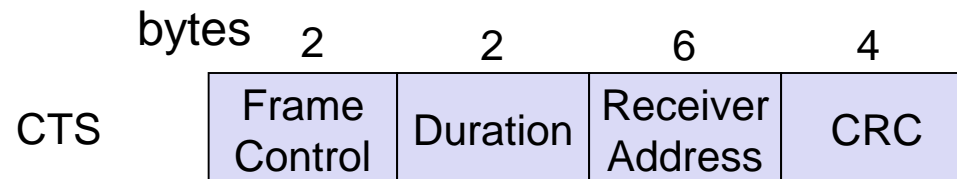
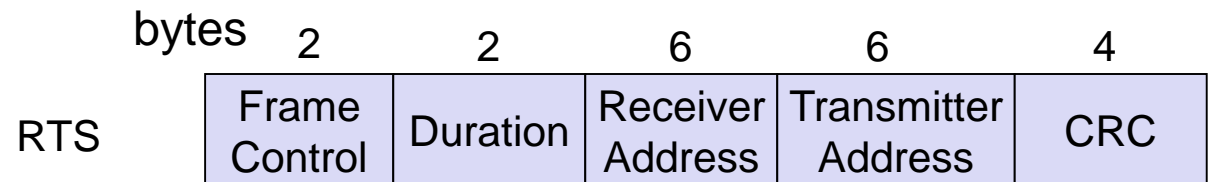
IEEE 802.11 Control Frame Format

- ▶ Acknowledgement

- ▶ Request To Send

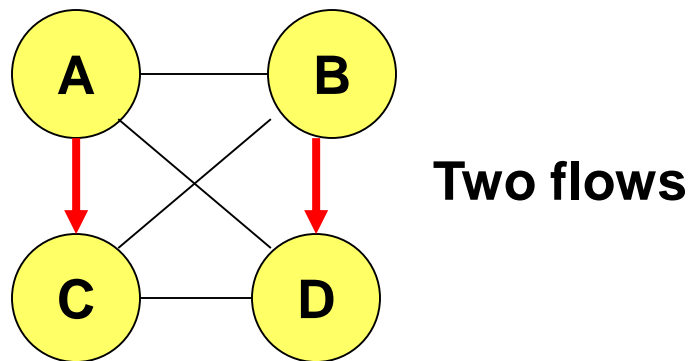


- ▶ Clear To Send



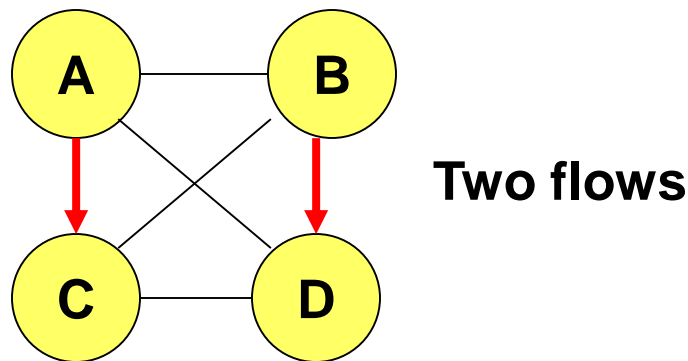
Fairness Issue

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



Fairness Issue

- ▶ Assume that initially, A and B both choose a backoff interval in range $[0,31]$ but their RTSs collide
- ▶ Nodes A and B then choose from range $[0,63]$
 - ▶ Node A chooses 4 slots and B choose 60 slots
 - ▶ After A transmits a packet, it next chooses from range $[0,31]$
 - ▶ It is possible that A may transmit several packets before B transmits its first packet



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 802.11ad:**
 - ▶ Very High Throughput 60 GHz (~ February 2014)
- ▶ **IEEE 802.11ae:**
 - ▶ Prioritization of Management Frames (2012)
- ▶ **IEEE 802.11af:**
 - ▶ TV Whitespace (February 2014)



In process amendments

- ▶ **IEEE 802.11ah:**
 - ▶ Sub 1 GHz sensor network, smart metering. (~March 2016)
- ▶ **IEEE 802.11ai:**
 - ▶ Fast Initial Link Setup (~November 2015)
- ▶ **IEEE 802.11aj:**
 - ▶ China MM Wave (~June 2016)
- ▶ **IEEE 802.11aq:**
 - ▶ Pre-association Discovery (~July 2016)
- ▶ **IEEE 802.11ak:**
 - ▶ General Links (~ May 2016)
- ▶ **IEEE 802.11mc:**
 - ▶ Maintenance of the standard (~ March 2016)
- ▶ **IEEE 802.11ax:**
 - ▶ High Efficiency WLAN (~ May 2018)
- ▶ **IEEE 802.11ay:**
 - ▶ Enhancements for Ultra High Throughput in and around the 60 GHz Band (~ TBD)
- ▶ **IEEE 802.11az:**
 - ▶ Next Generation Positioning (~ TBD)
- ▶ **IEEE 802.11ba**
 - ▶ Wake Up Radio (~ July 2020)
- ▶ **IEEE 802.11bb:**
 - ▶ Light Communications



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)

