CS/ECE 439: Wireless Networking

MAC Layer – Road to Wireless

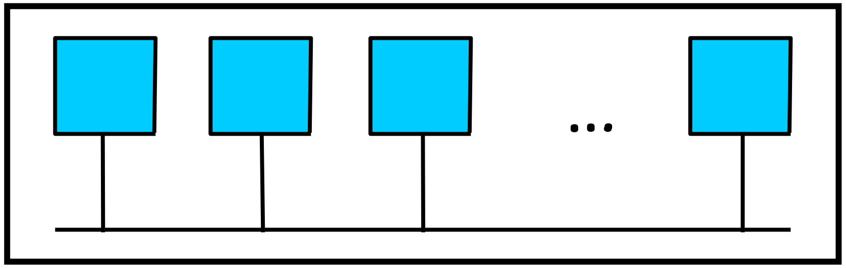
GRAINGER ENGINEERING

 Fall 2023

COMPUTER SCIENCE

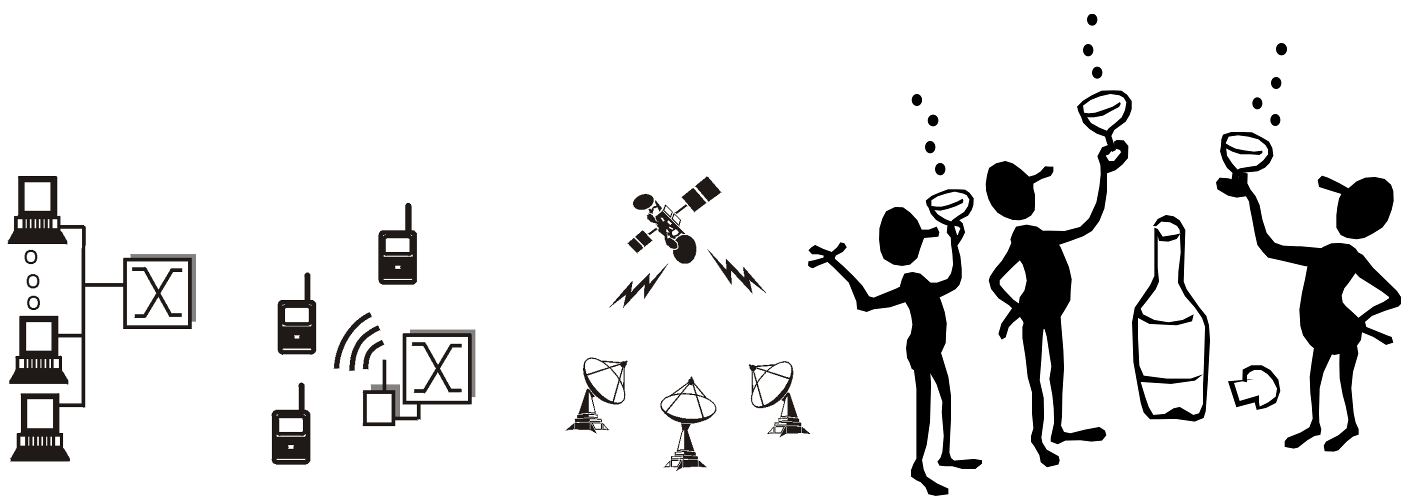
Multiple Access Media

- 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

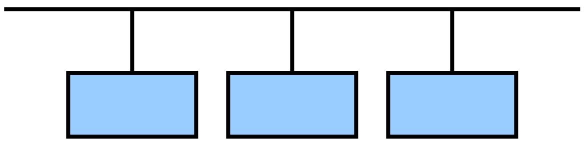


Point-to-Point vs. Broadcast Media

- 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

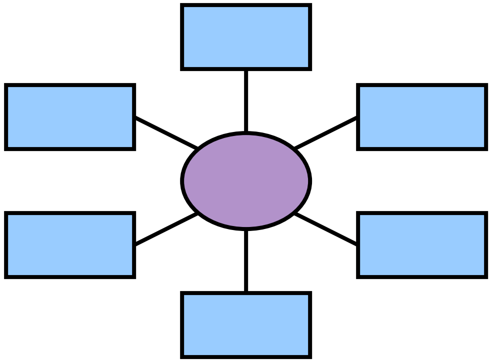


Types of Shared Link Networks

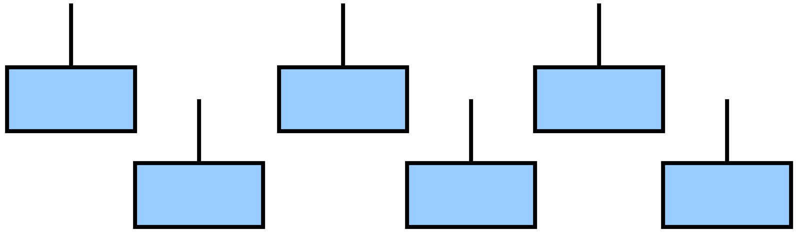


Bus Topology: Shared

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)

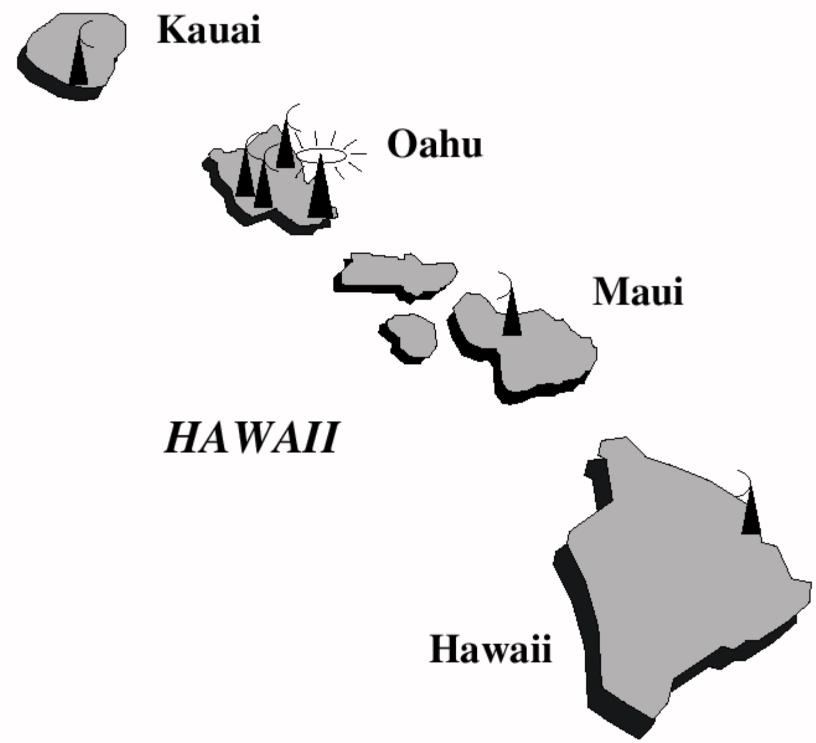
- These techniques are useful
  - But they have a number of limitations
  - They do not support bursty traffic efficiently
    - Lots of unused capacity, …
    - … while active users squeeze their bit stream through a very thin pipe
  - Work best in a provisioned service
    - Management of frequencies,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



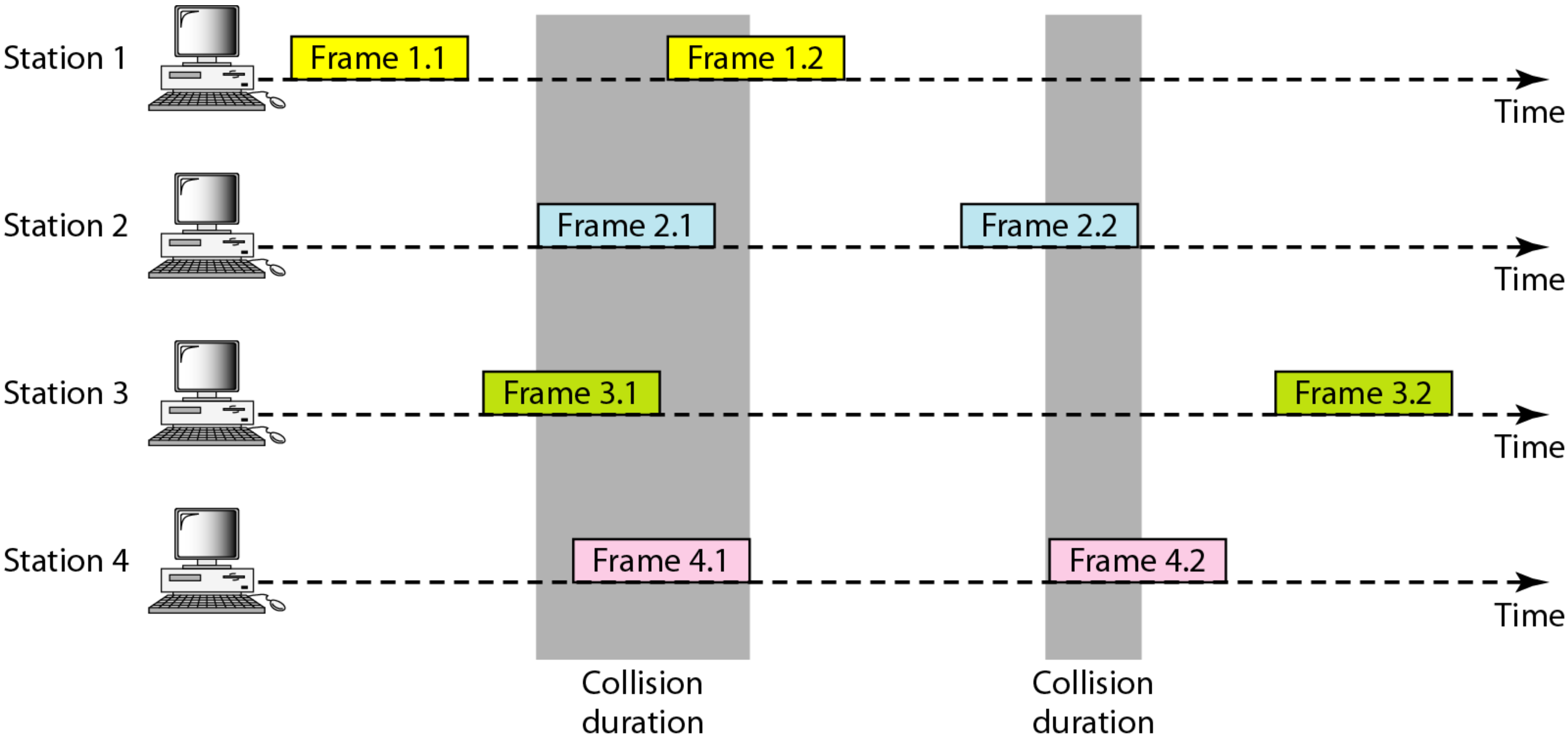
Pure ALOHA

- 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

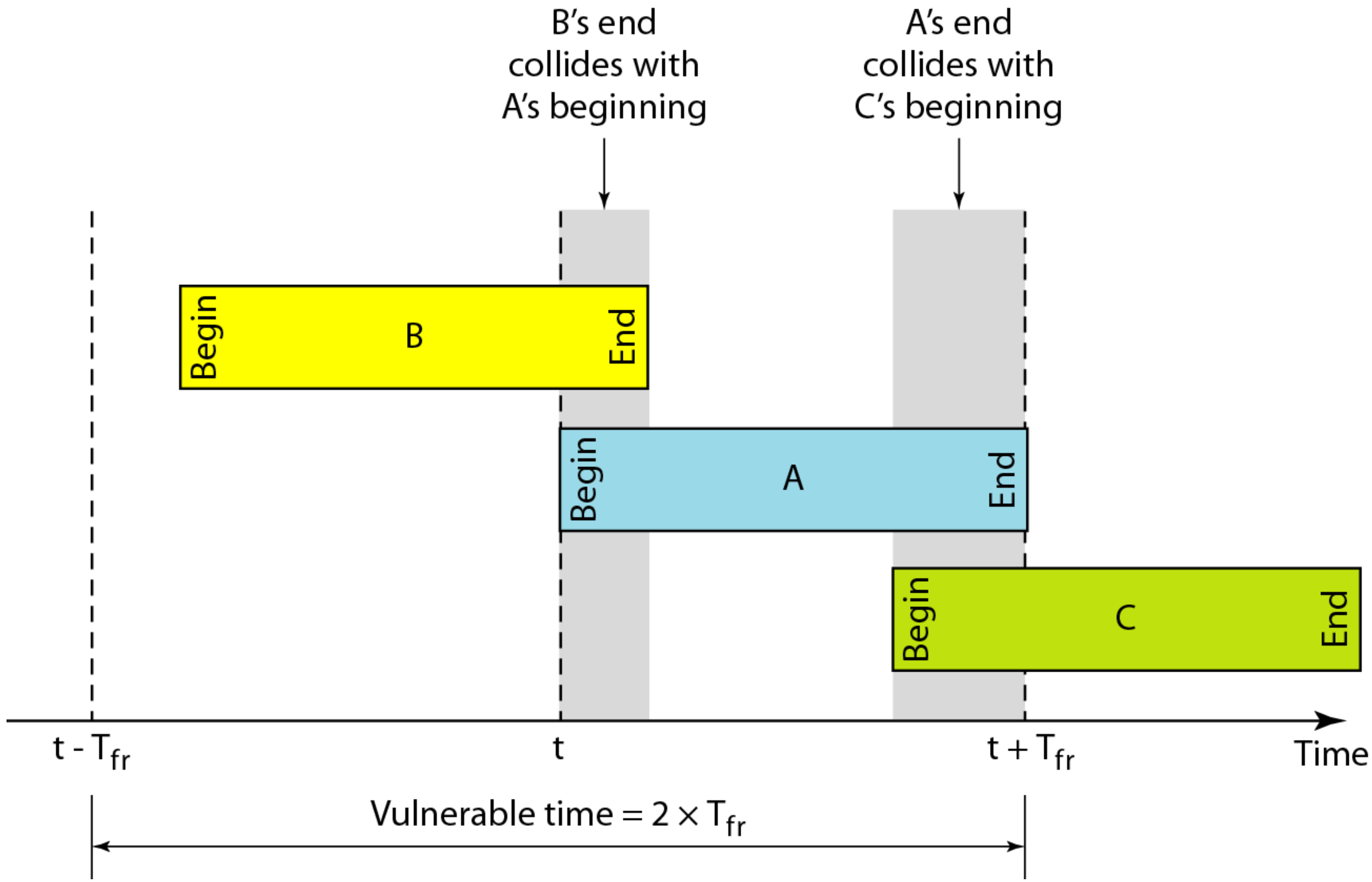


Station 1
Frame 1.1
Frame 1.2
Time
Station 2
Frame 2.1
Frame 2.2
Time
Station 3
Frame 3.1
Frame 3.2
Time
Station 4
Frame 4.1
Frame 4.2
Time
Collision duration
Collision duration

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



B's end collides with A's beginning
A's end collides with C's beginning
Begin
B
End
Begin
A
End
Begin
C
End
t - T_{fr}
t
t + T_{fr}
Time
Vulnerable time = $2 \times T_{fr}$

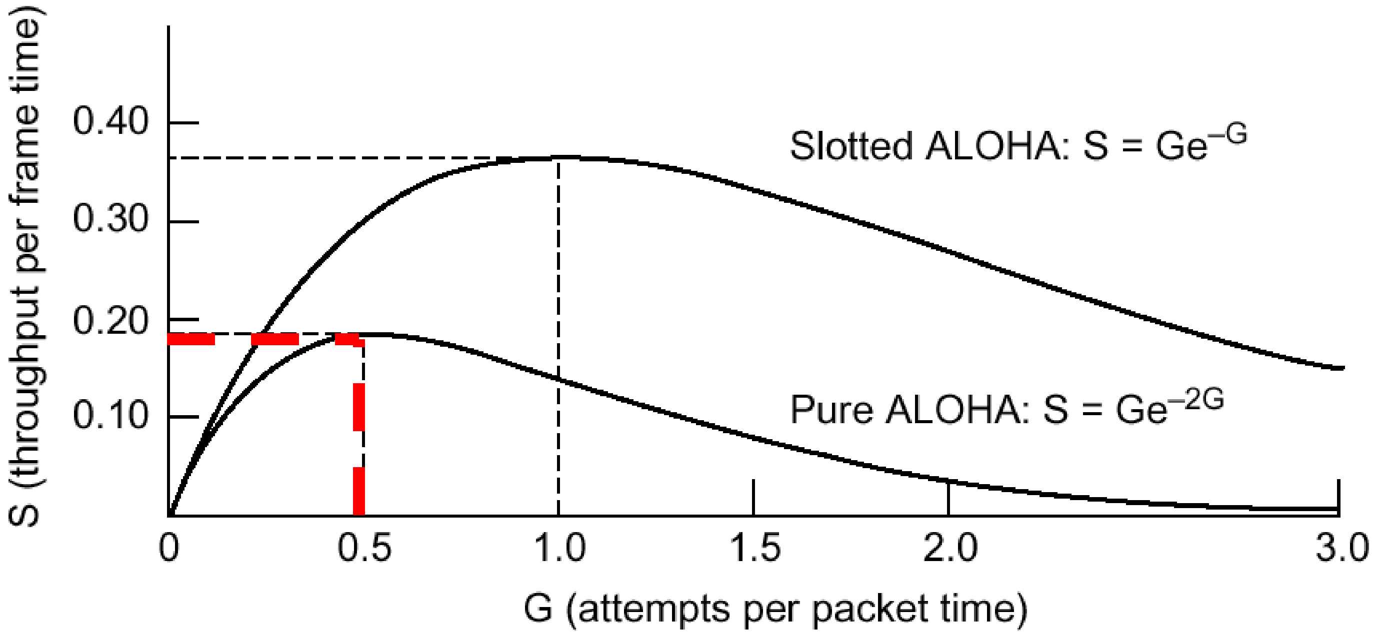
Pure ALOHA

- 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

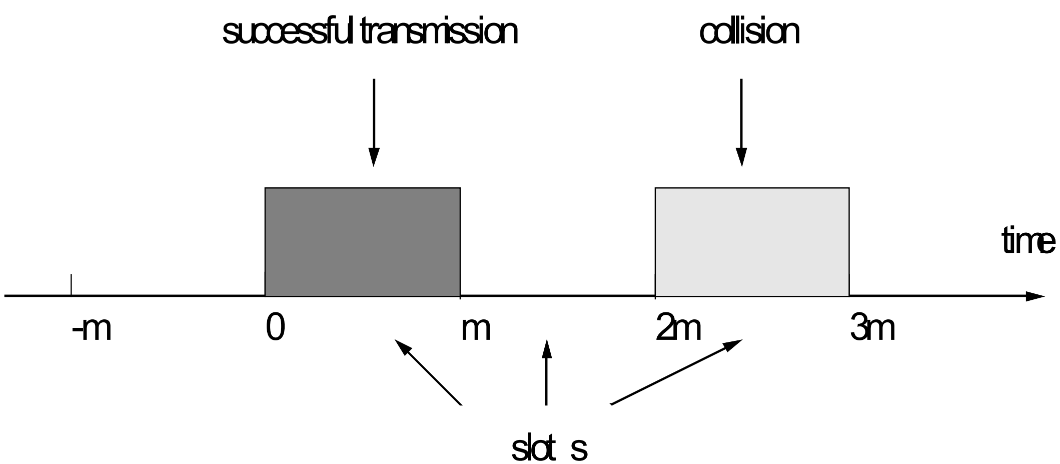
- Maximum throughput
  - *G = 0.5*
  - *S = 1/2e*

- Utilization
  - Maximum of 0.184!

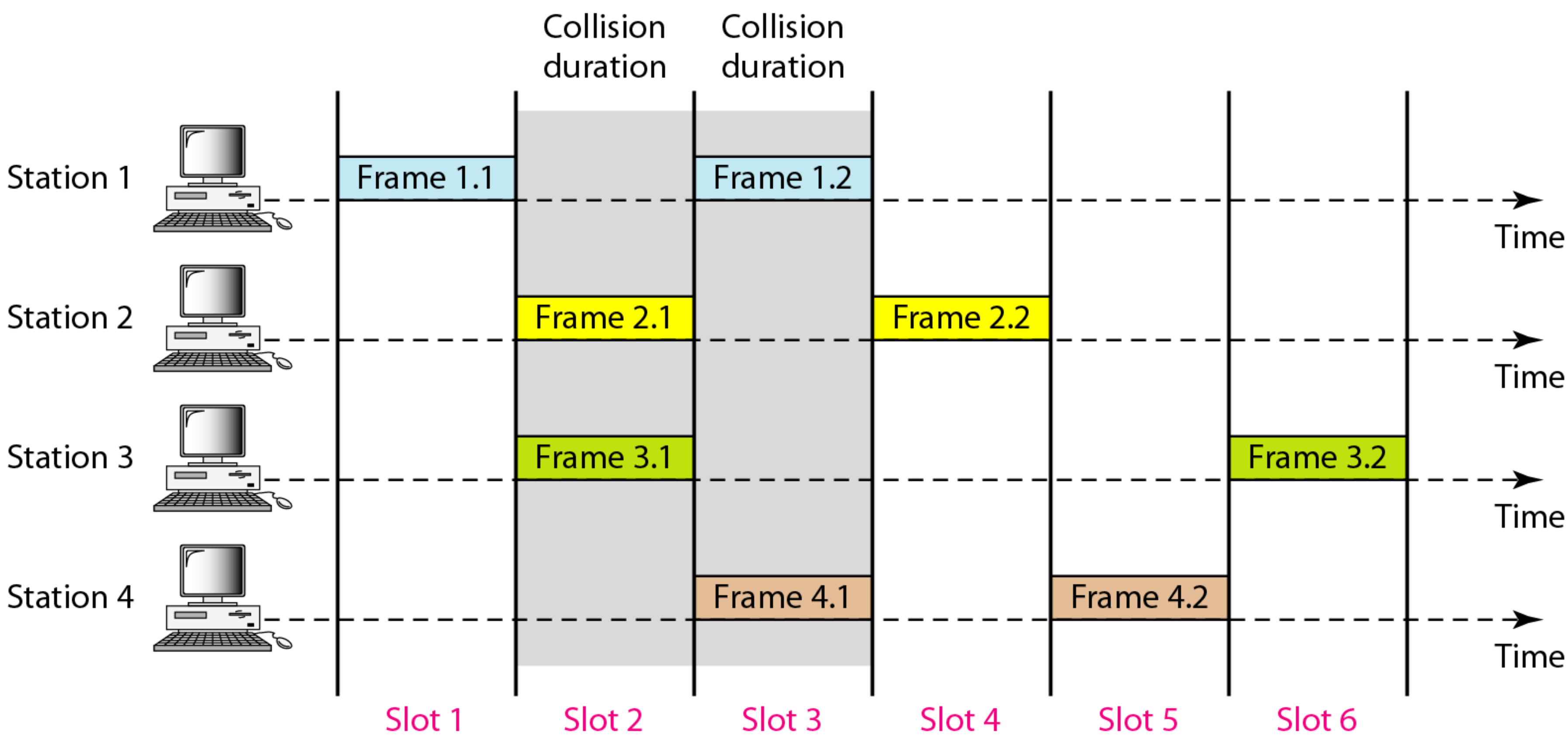


Slotted ALOHA

- 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

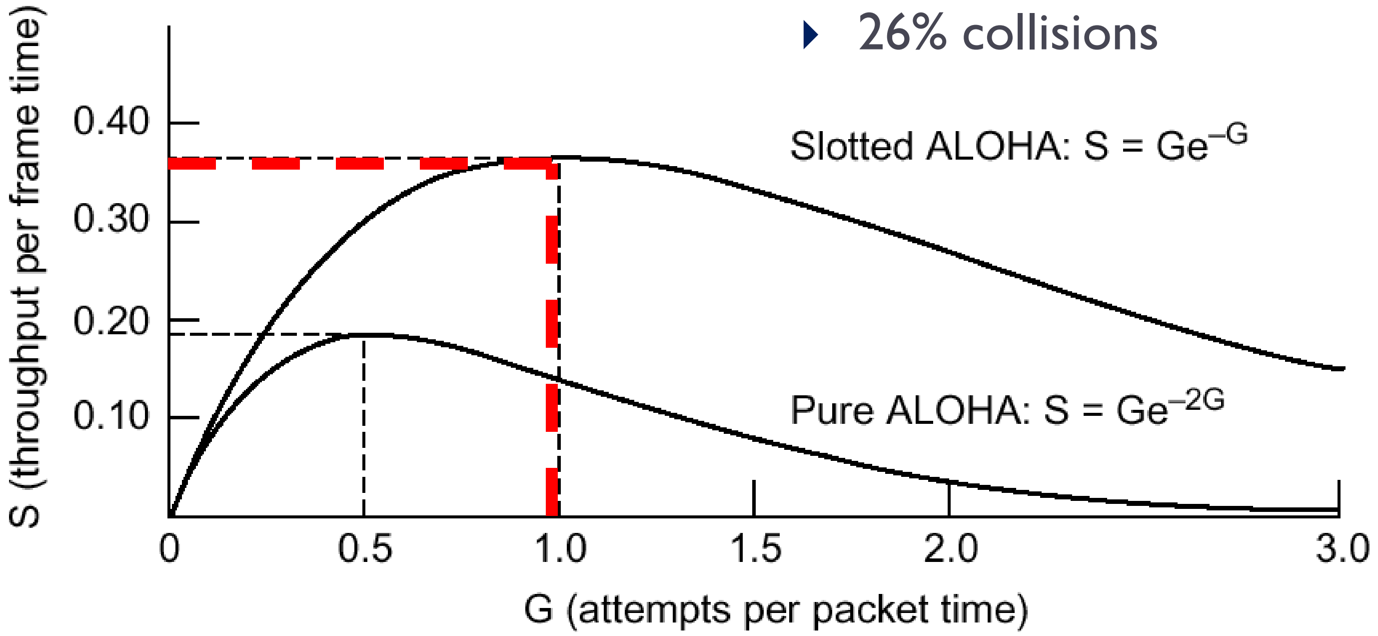
- In each interval *m*
  - Mean number of frames generated is G
  - The probability of no other traffic being generated during the entire vulnerable period is
    - $P_0 = e^{-G}$
    - $S = Ge^{-G}$

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?

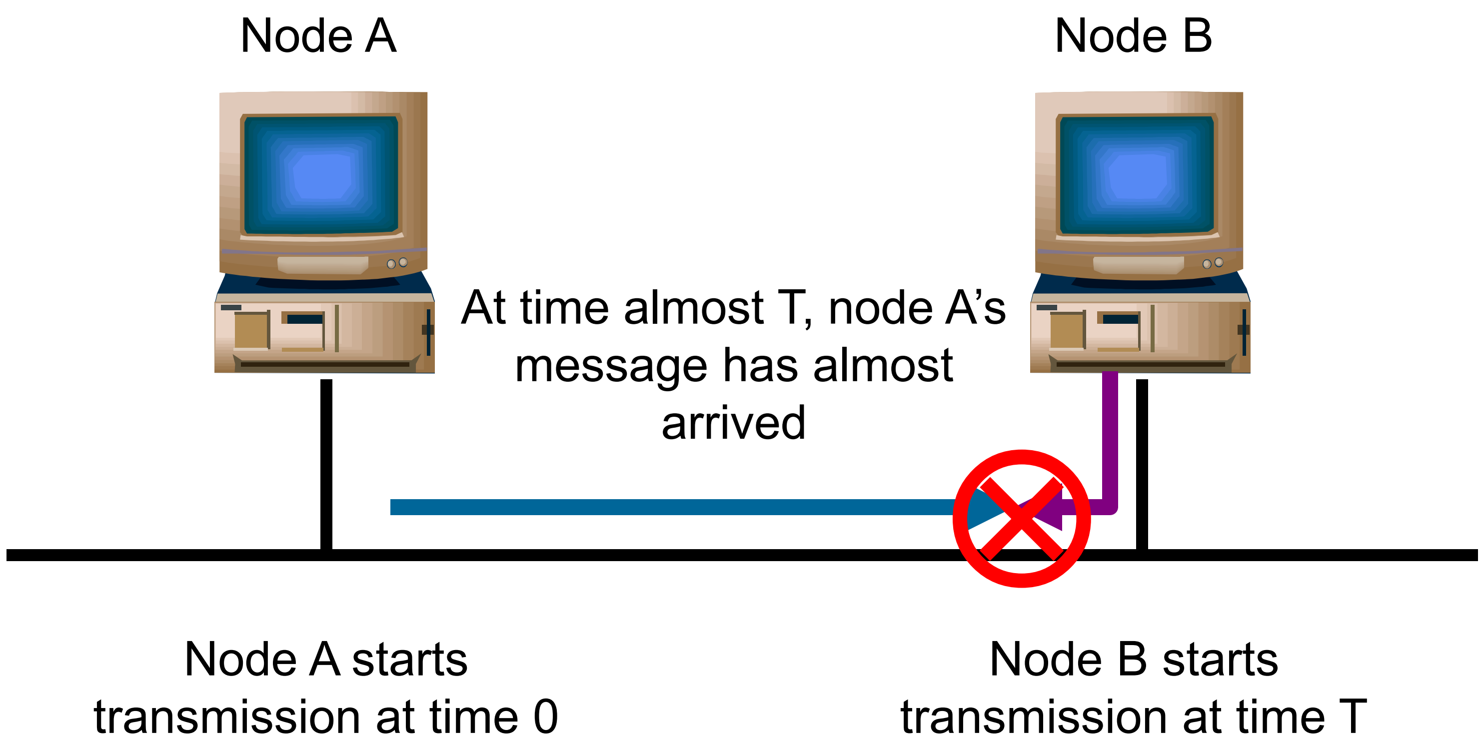
ALOHA Analysis

- 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

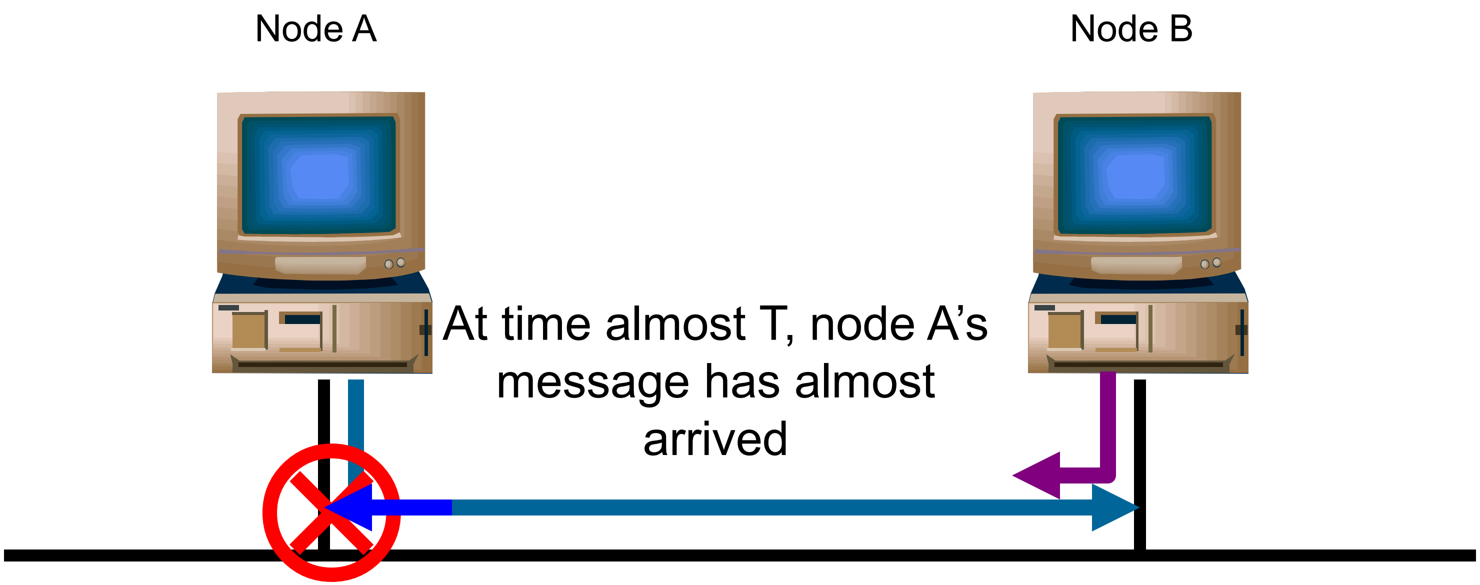


How can we ensure that A knows about the collision?

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 51.2μs
  - At 10Mbps 51.2μs = 512b or 64 = 512b or 64B
  - Packet length ≥ 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?

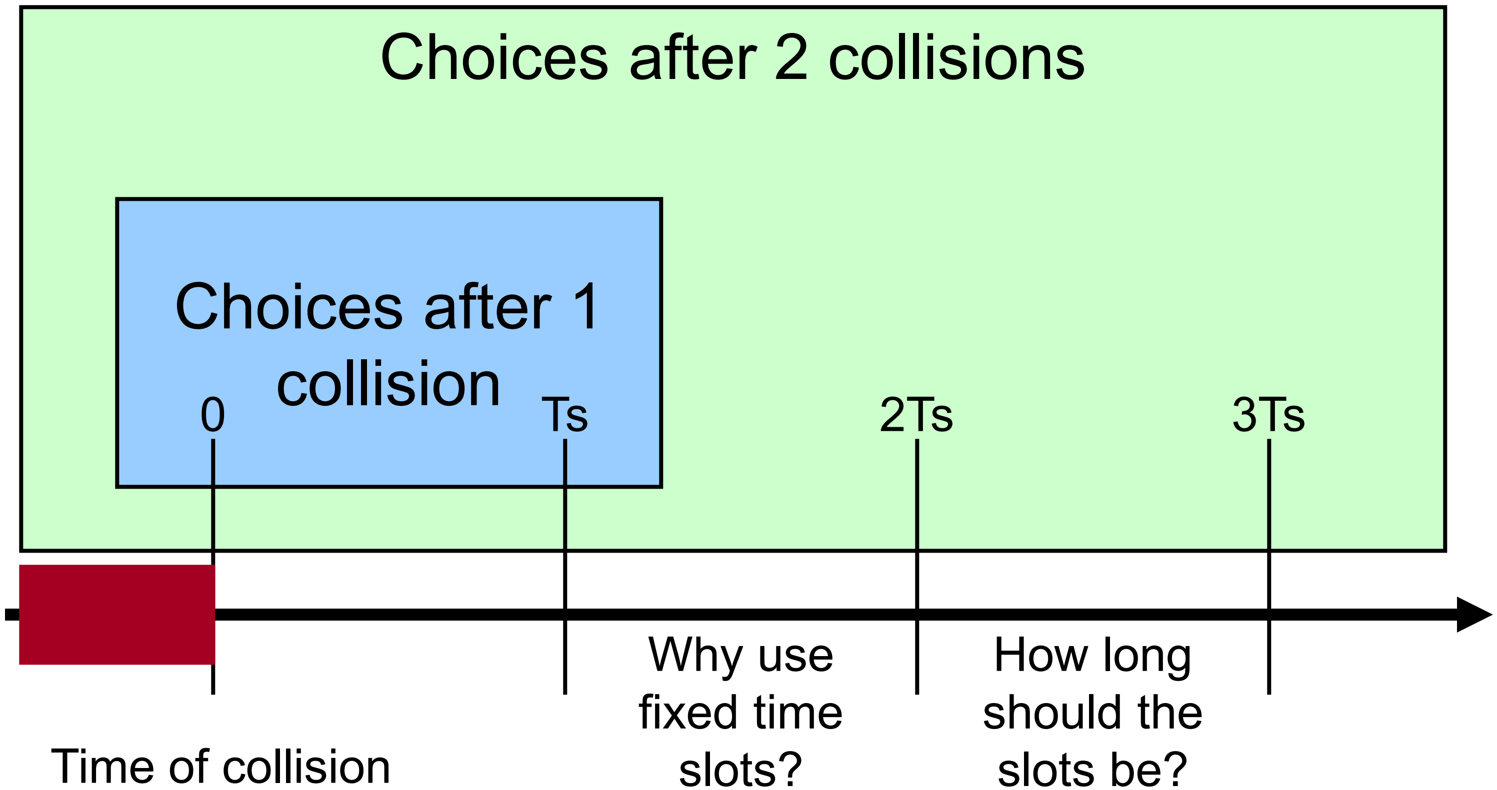
Too long: wastes time
Too short: doesn't allow other nodes to transmit (fairness)

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



Binary Exponential Backoff

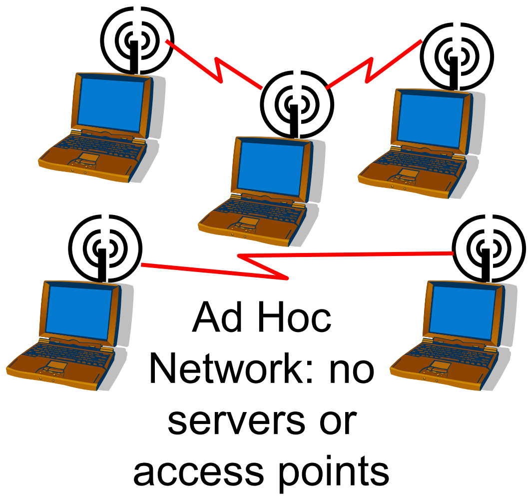
- For IEEE 802.3, T = 51.2 μs
- Consider the following
  - *k* hosts collide
  - Each picks a random number from *0* to $2^{(N-1)}$
  - If the minimum value is unique
    - All other hosts see a busy line
    - Note: Ethernet RTT < 51.2 μs
  - If the minimum value is not unique
    - Hosts with minimum value slot collide again!
    - Next slot is idle
    - Consider the next smallest backoff value

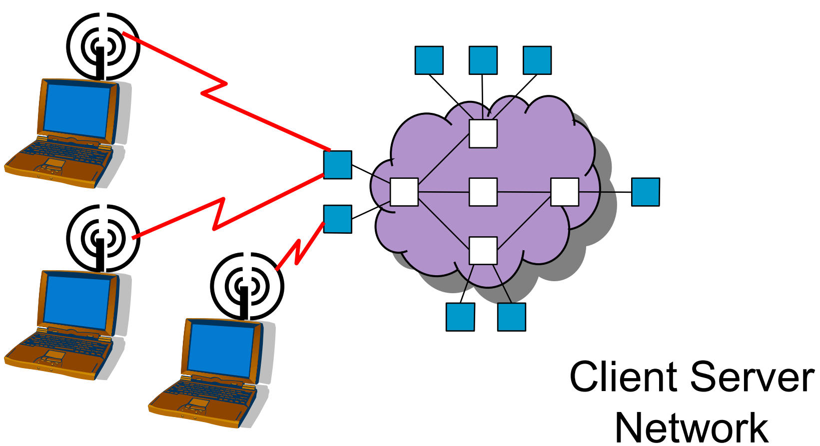
Binary Exponential backoff algorithm

- 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 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)

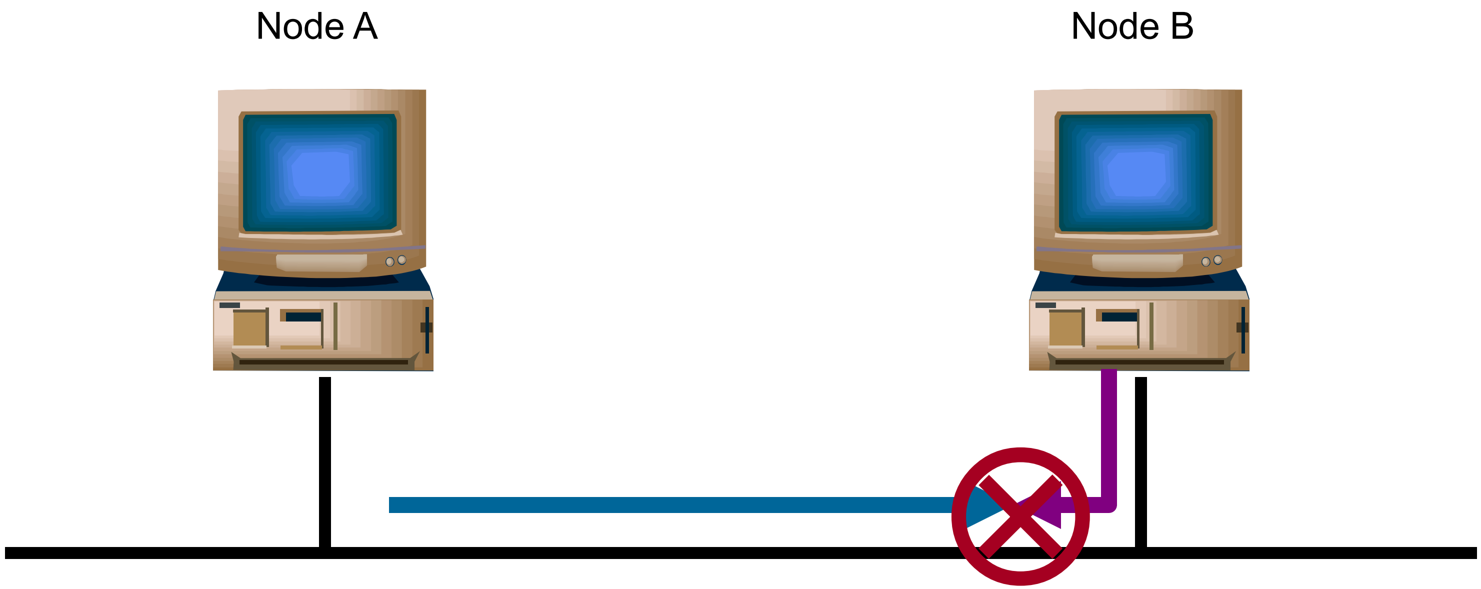




Medium Access Control

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

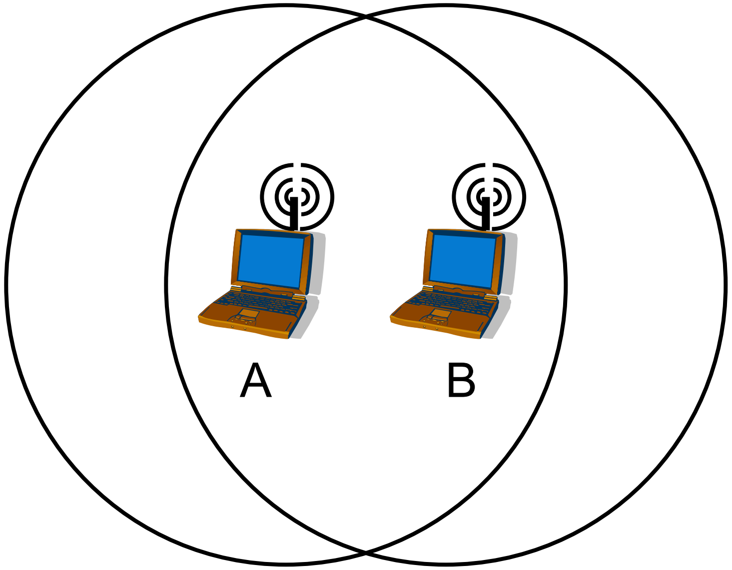
Ethernet MAC Algorithm



- 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

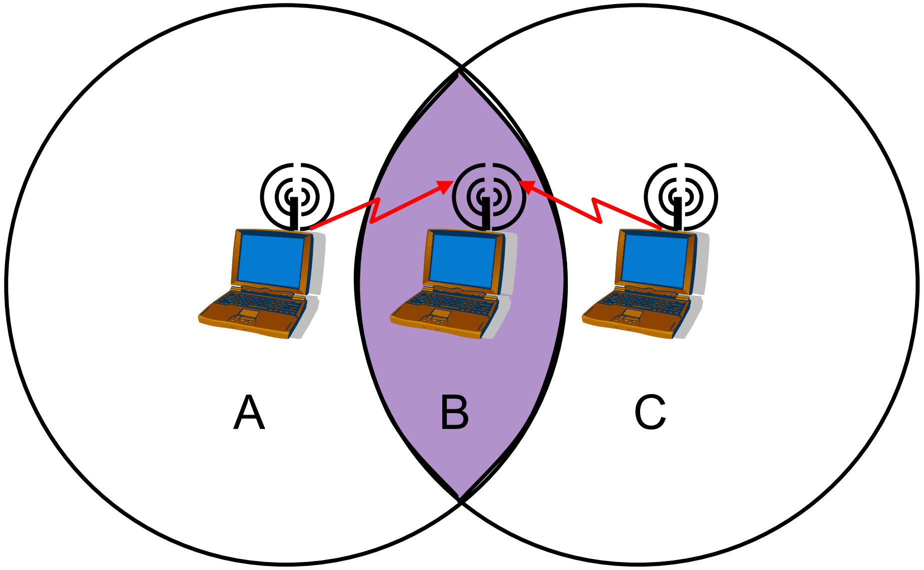
- CS – Carrier Sense
  - Nodes can distinguish between an idle and a busy link
- MA - Multiple Access
  - A set of nodes send and receive frames over a shared link
- CD – Collision Detection
  - Nodes listen during transmission to determine if there has been interference

Wireless Ethernet - CSMA/CA

- 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

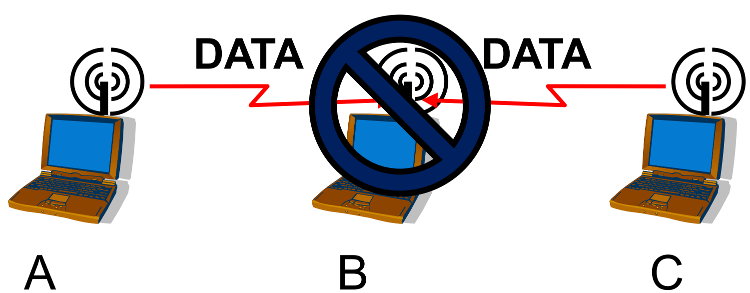
IEEE 802.11 MAC Layer Standard

- Similar to Ethernet
- But consider the following:



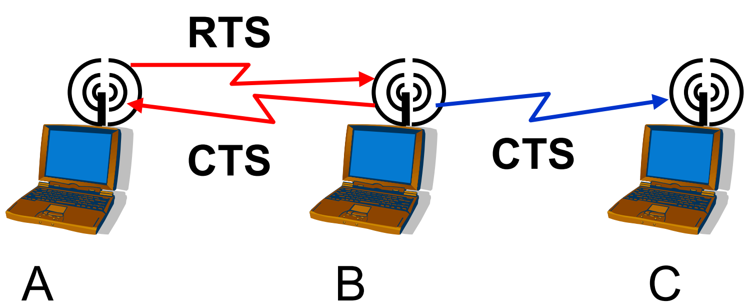
Hidden Terminal Problem

- 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



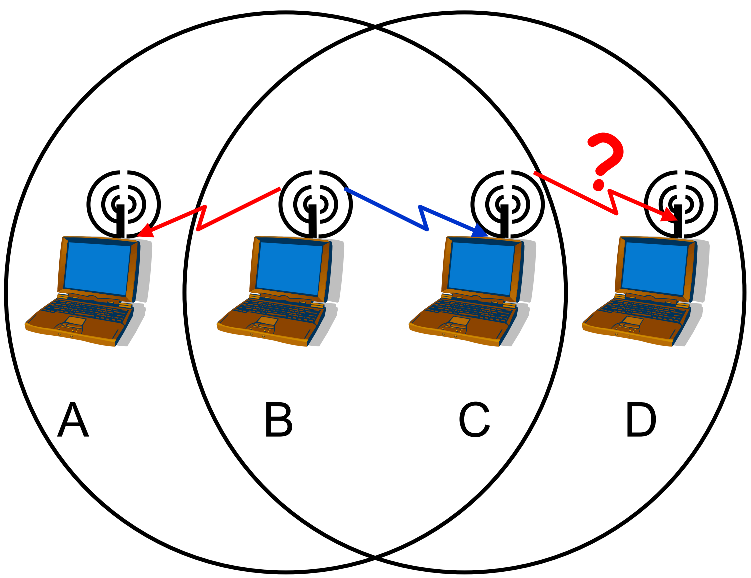
MACA Solution for Hidden Terminal Problem

- 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



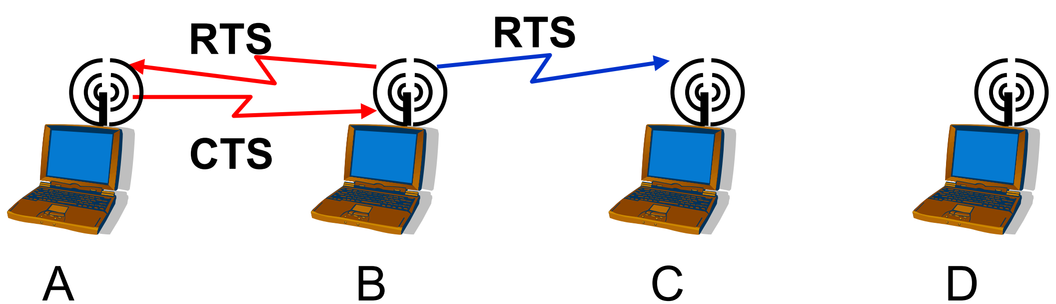
IEEE 802.11 MAC Layer Standard

- But we still have a problem



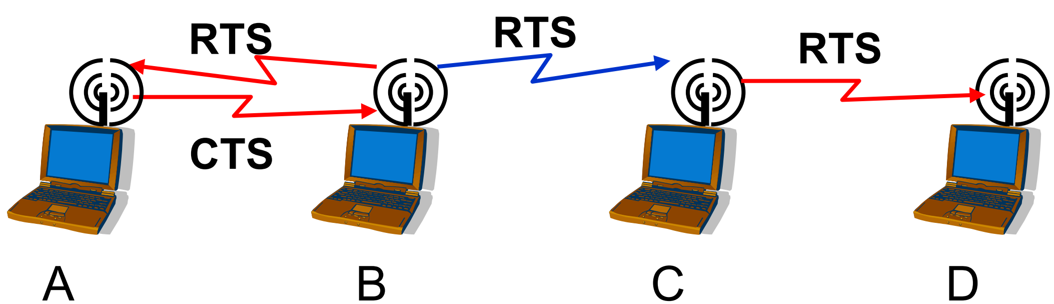
Exposed Terminal Problem

- 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)



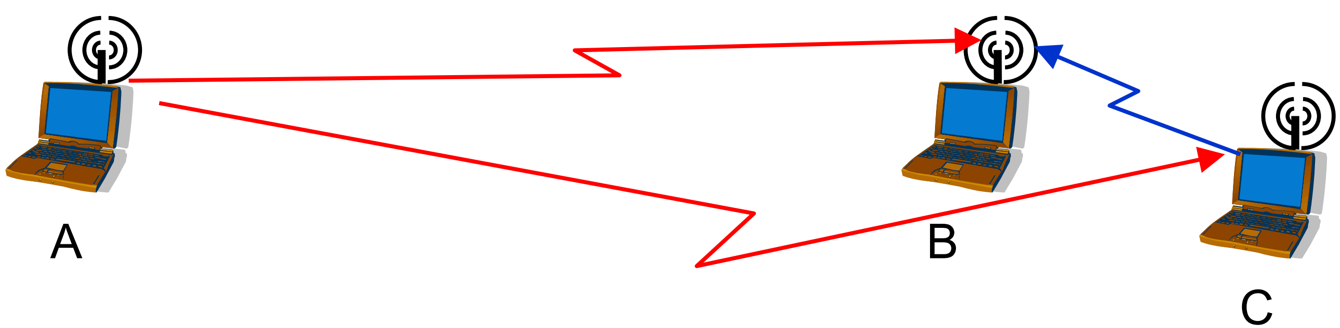
MACA Solution for Exposed Terminal Problem

- 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

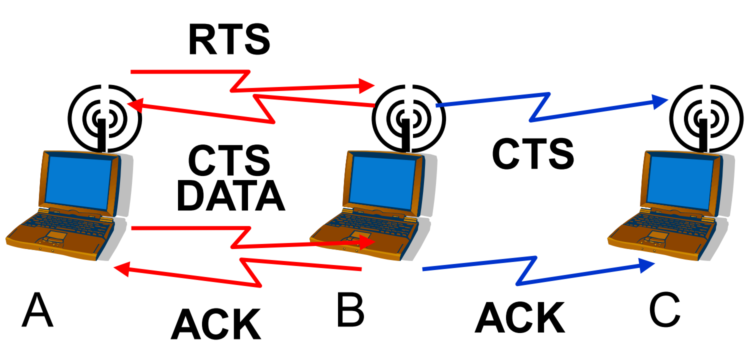
- Still possible
  - RTS packets can collide!
- Binary exponential backoff
  - Backoff counter doubles after every collision and reset to minimum value after successful transmission
  - Performed by stations that experience RTS collisions
- RTS collisions not as bad as data collisions in CSMA
  - Since 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

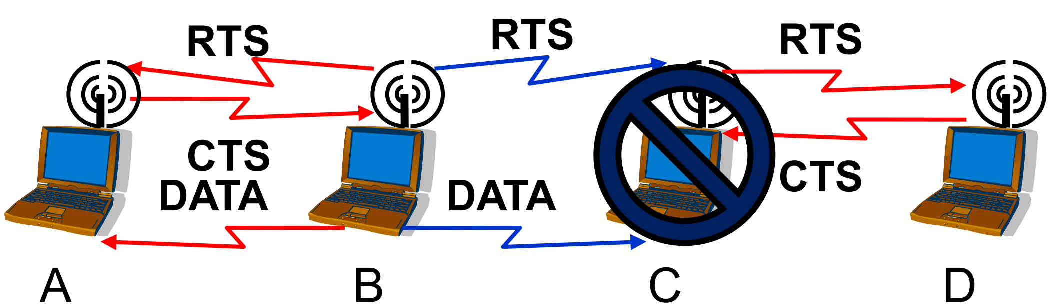
A Simple Solution to Improve Reliability - MACAW

- 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

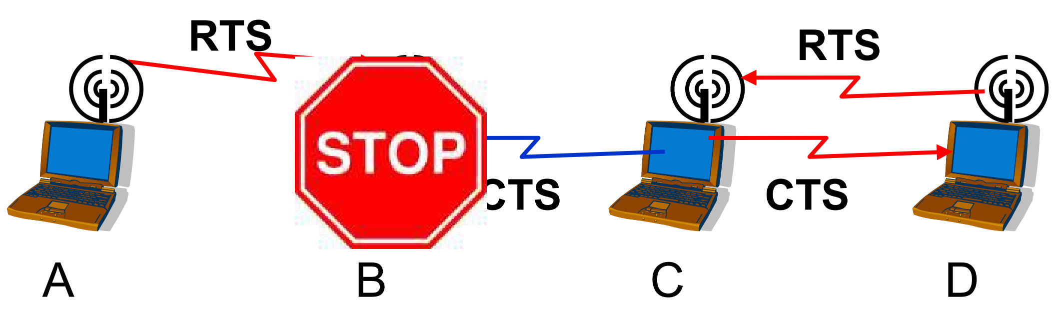
- One solution
  - Have C use carrier sense before RTS
- Alternative
  - B sends DS (data sending) packet before DATA
    - Short packet lets C know that B received A's CTS
    - Includes length of B's DATA so C knows how long to wait

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



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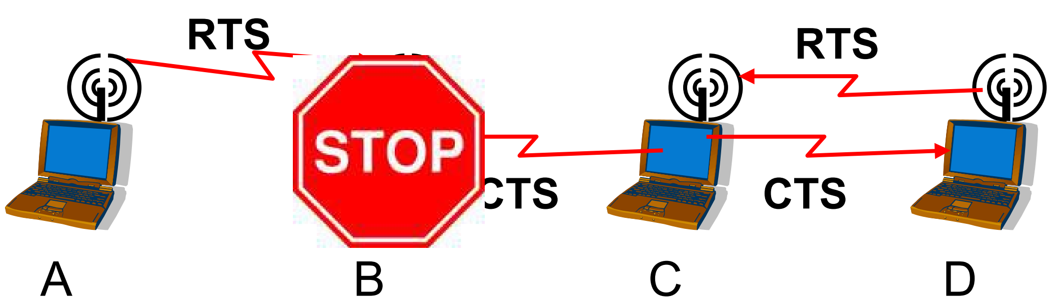
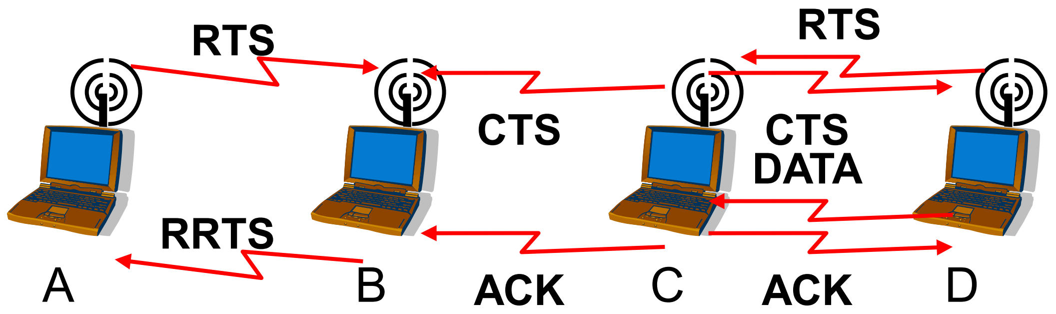


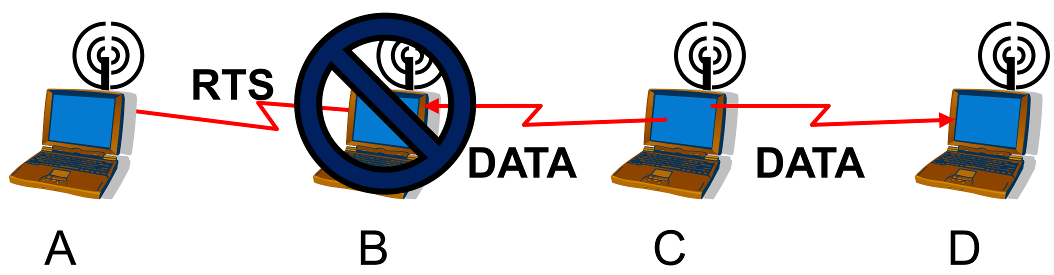
Request for RTS - MACAW

- 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

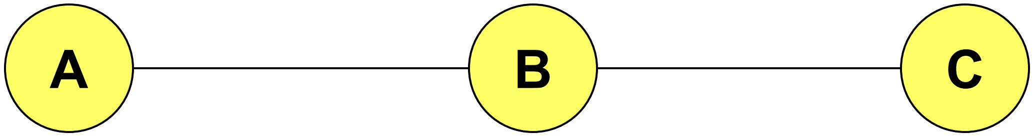
- MAC functionality
  - Addressing
  - CSMA/CA
- Error detection (FCS)
- Error correction (ACK frame)
- Flow control: stop-and-wait
- Fragmentation (More Frag)
- Collision Avoidance (RTS-CTS)

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

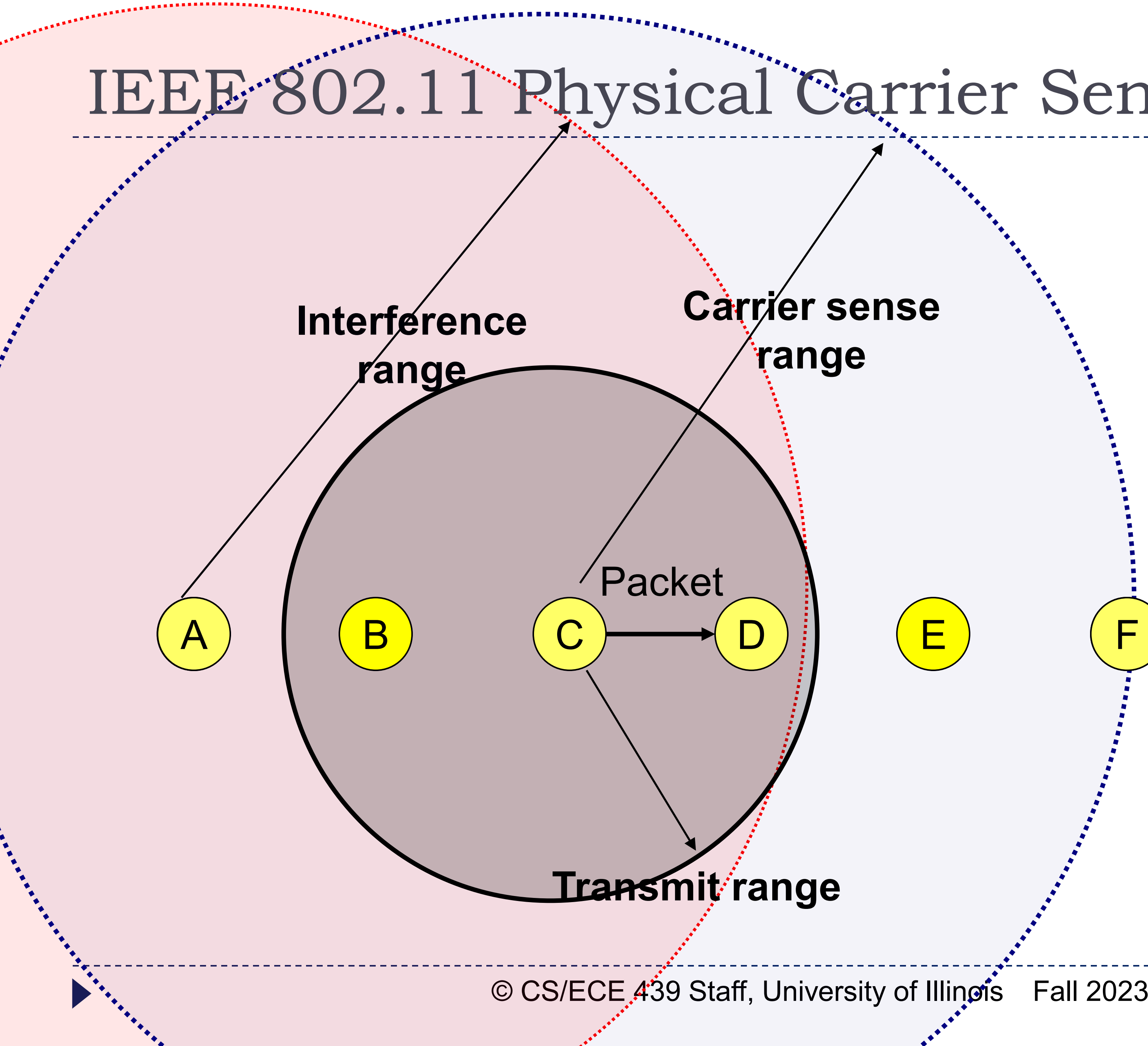
- Uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer
- Uses ACK to achieve reliability
- Any node receiving the RTS cannot transmit for the duration of the transfer
  - To prevent collision with ACK when it arrives at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



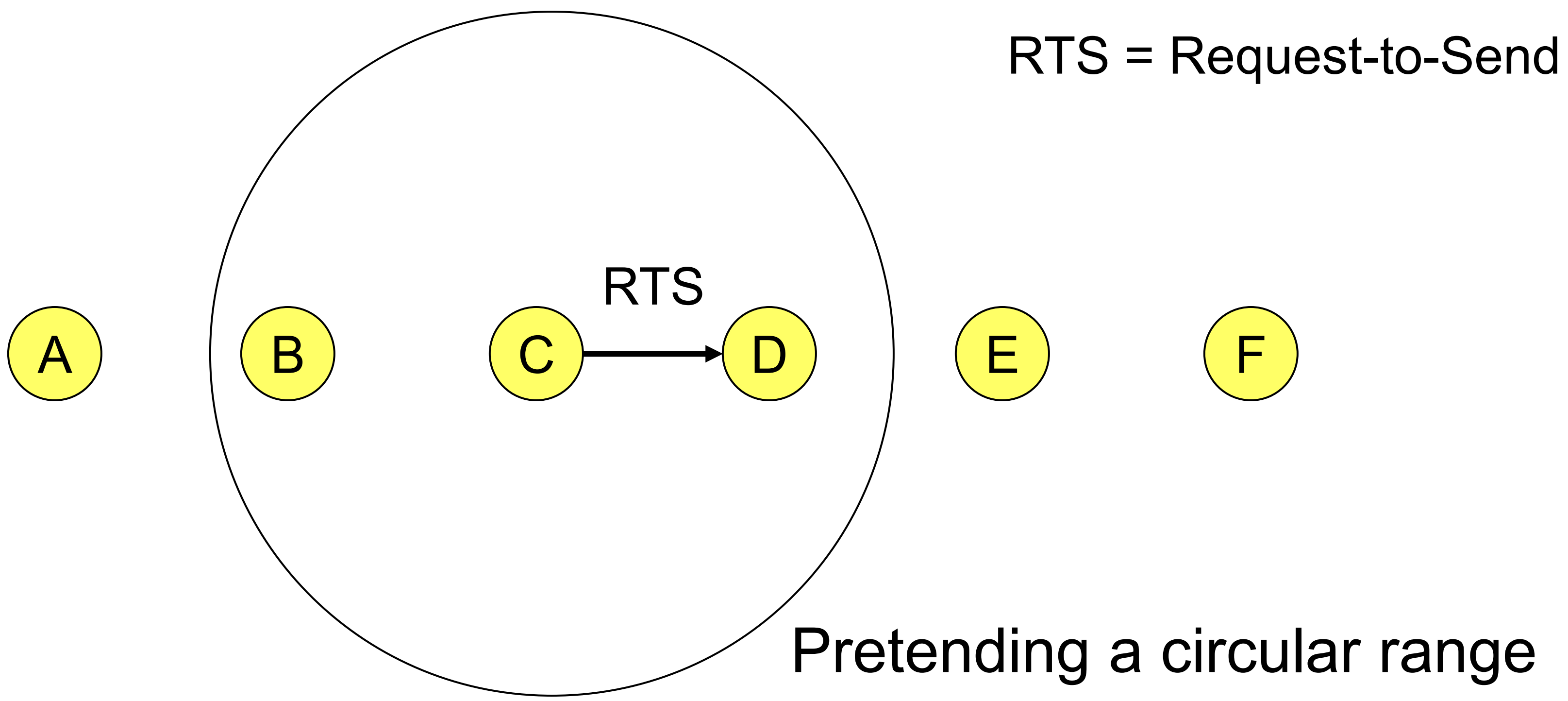
IEEE 802.11 CSMA/CA

- 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



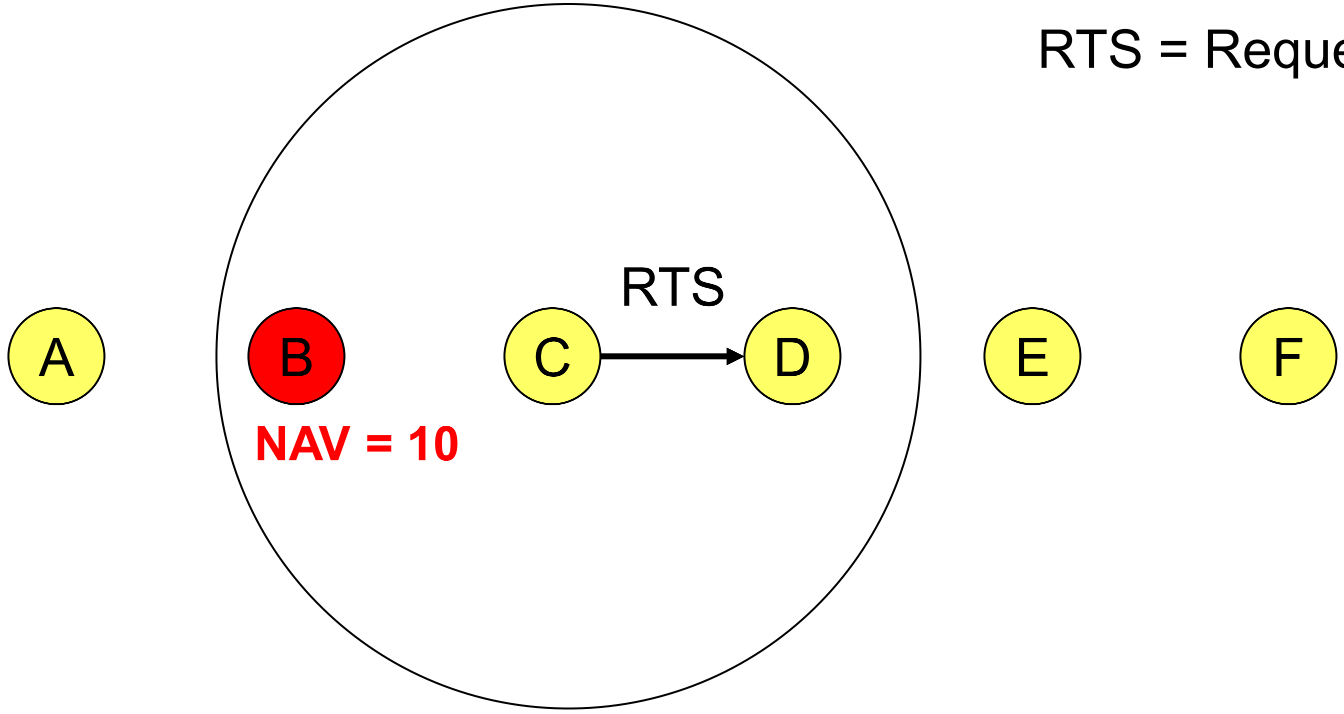
IEEE 802.11 Virtual Carrier Sense



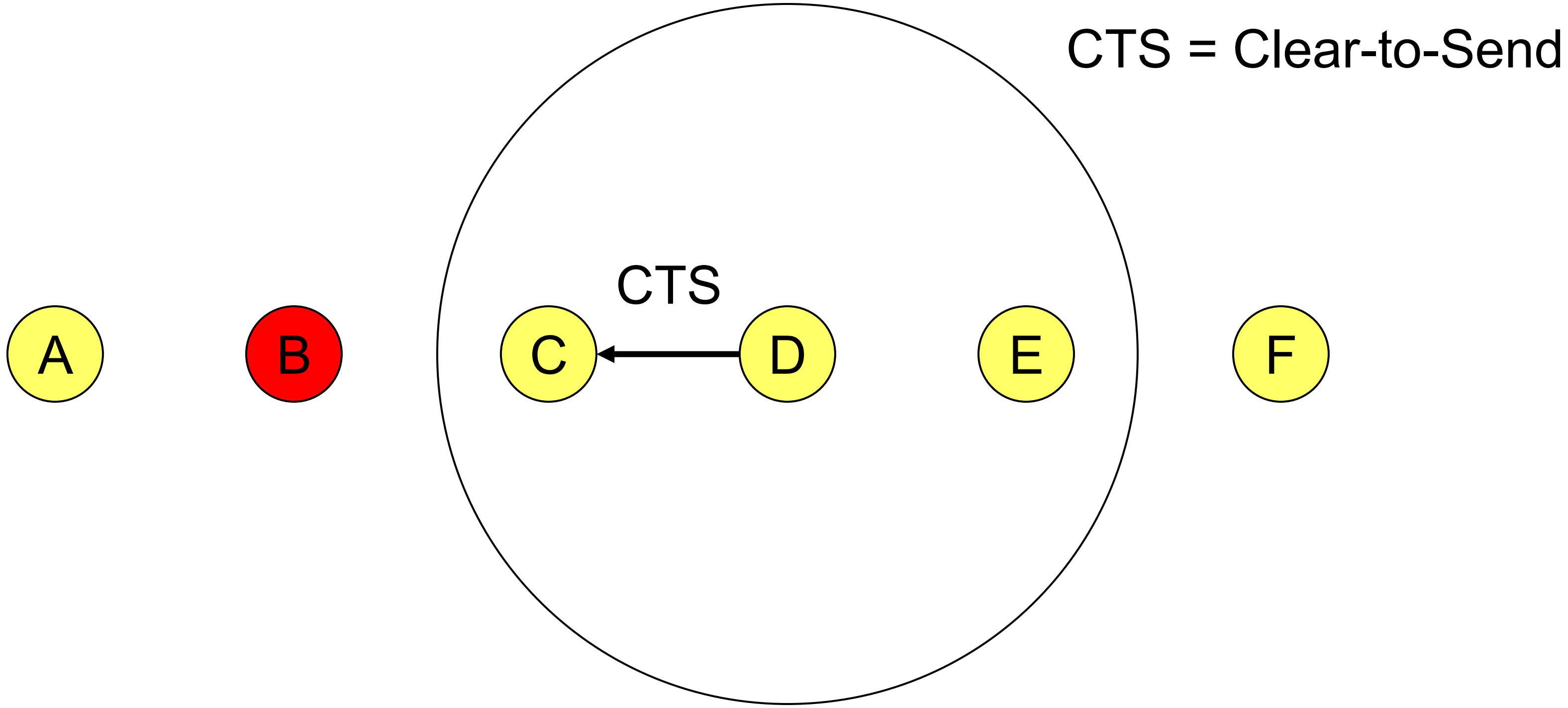
IEEE 802.11 Virtual Carrier Sense

NAV = remaining duration to keep quiet

RTS = Request-to-Send

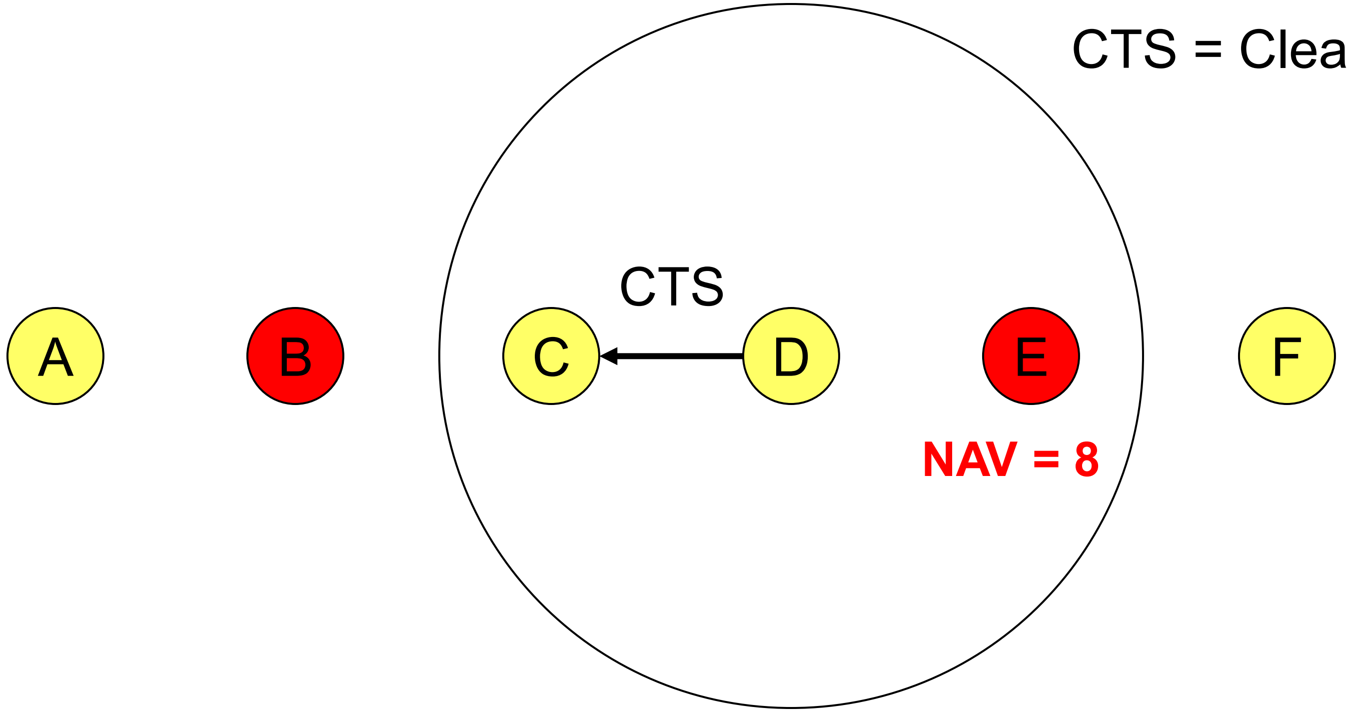


IEEE 802.11 Virtual Carrier Sense



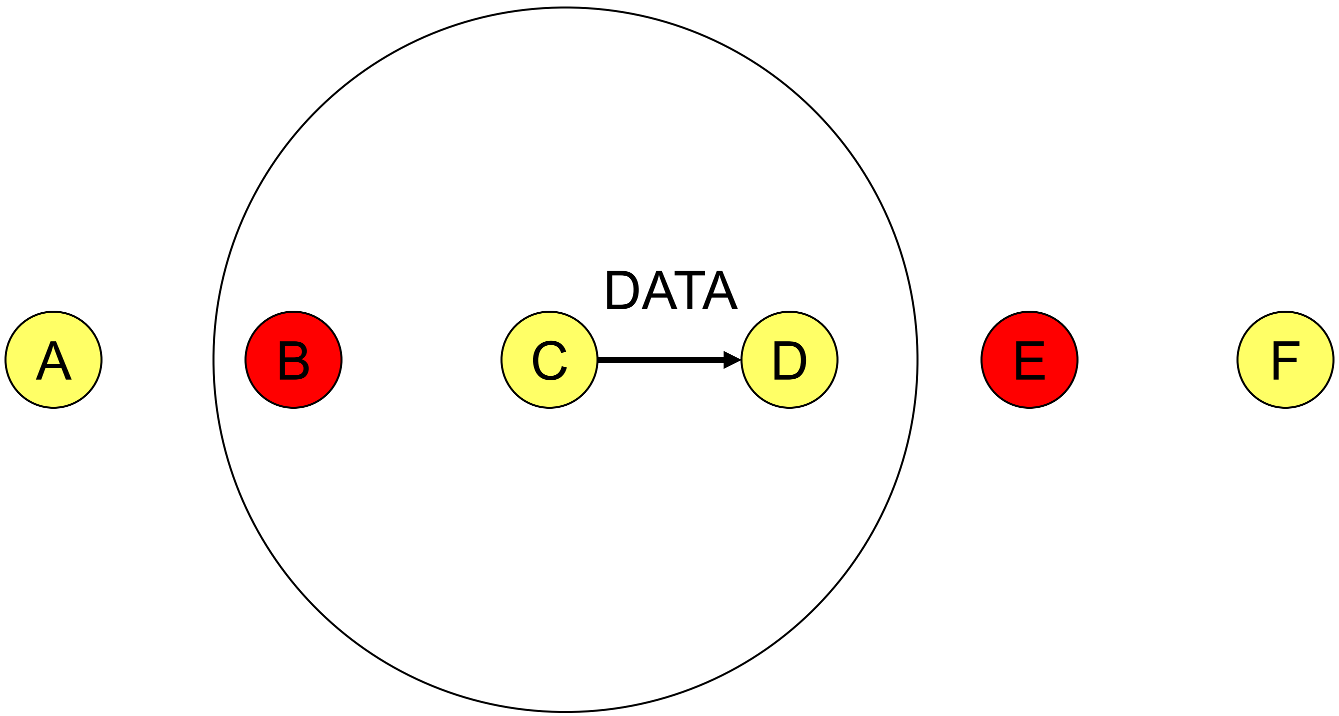
IEEE 802.11 Virtual Carrier Sense

CTS = Clear-to-Send



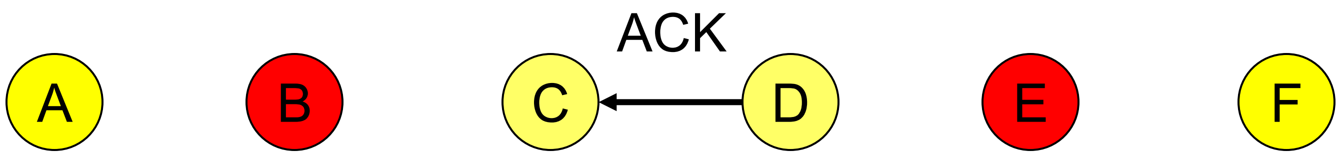
IEEE 802.11 Virtual Carrier Sense

- DATA packet follows CTS

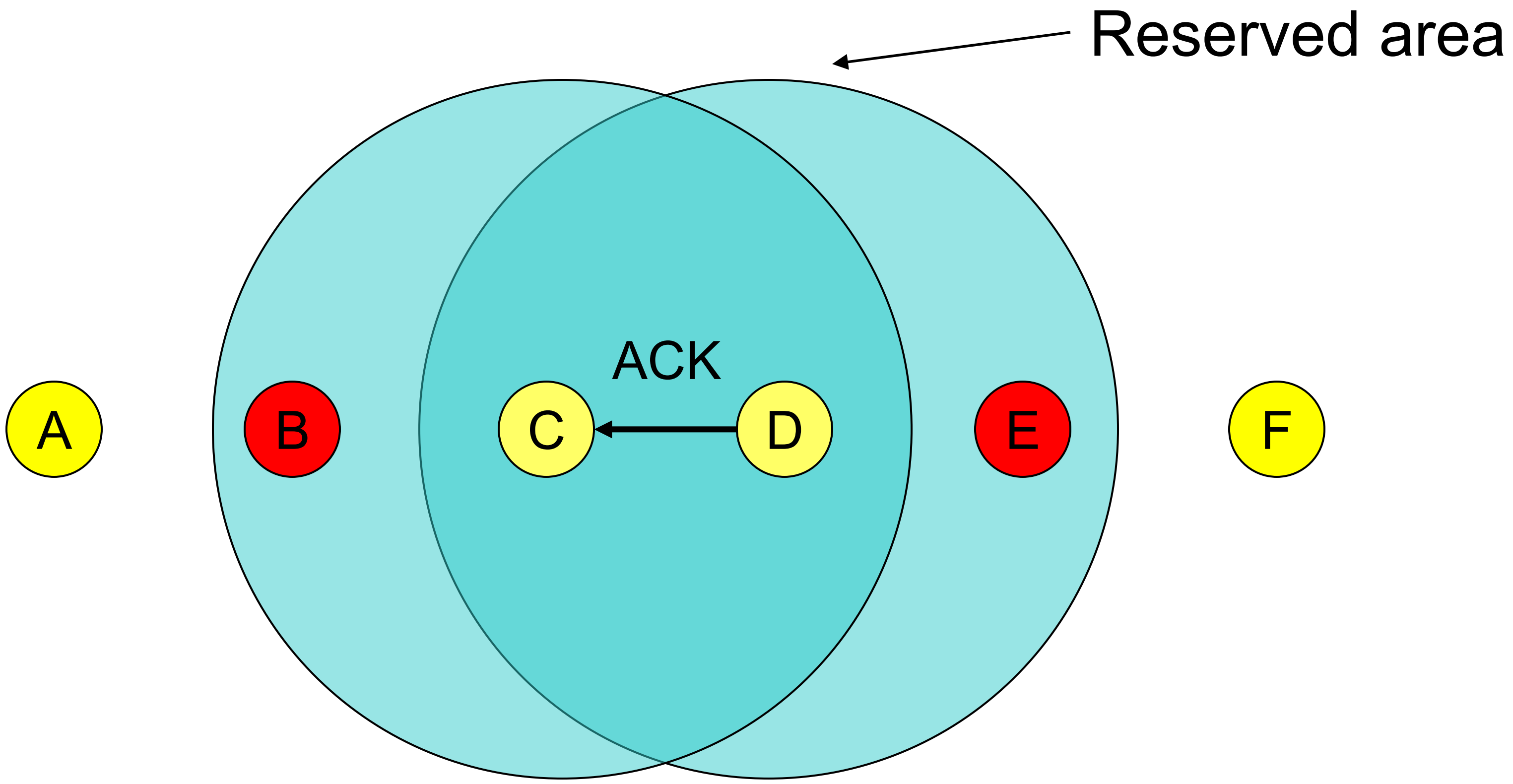


IEEE 802.11 Virtual Carrier Sense

- 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

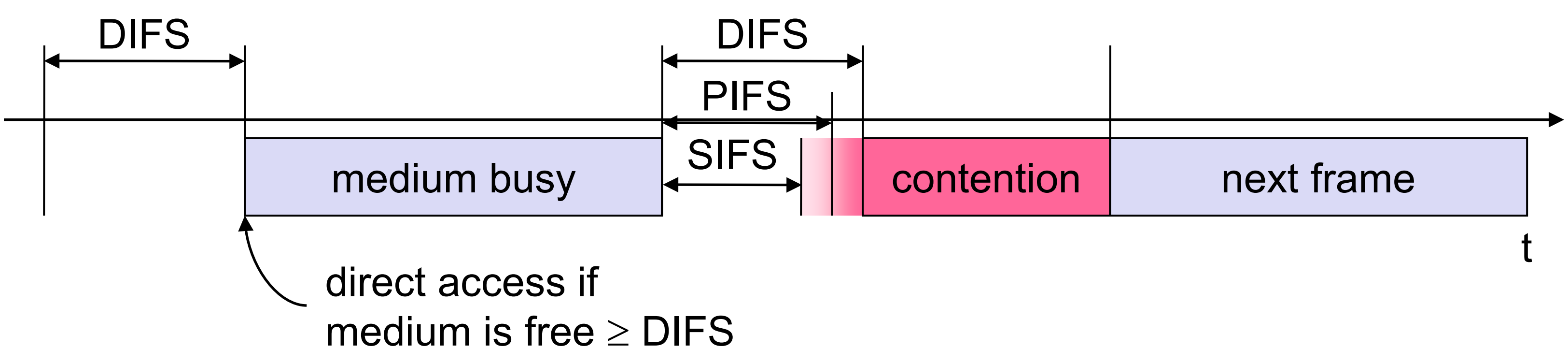
Ethernet vs. IEEE 802.11

- If carrier is sensed
  - Send immediately
  - Send maximum of 1500B data (1527B total)
  - Wait 9.6 μs before sending again

- If carrier is sensed
  - When should a node transmit?

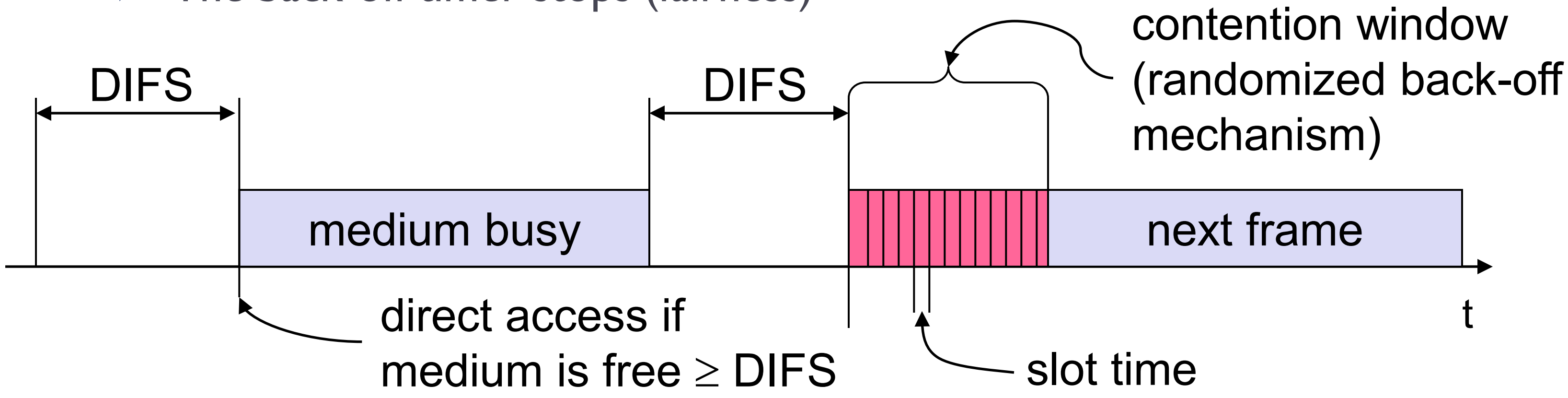
Interframe Spacing

- 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



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)



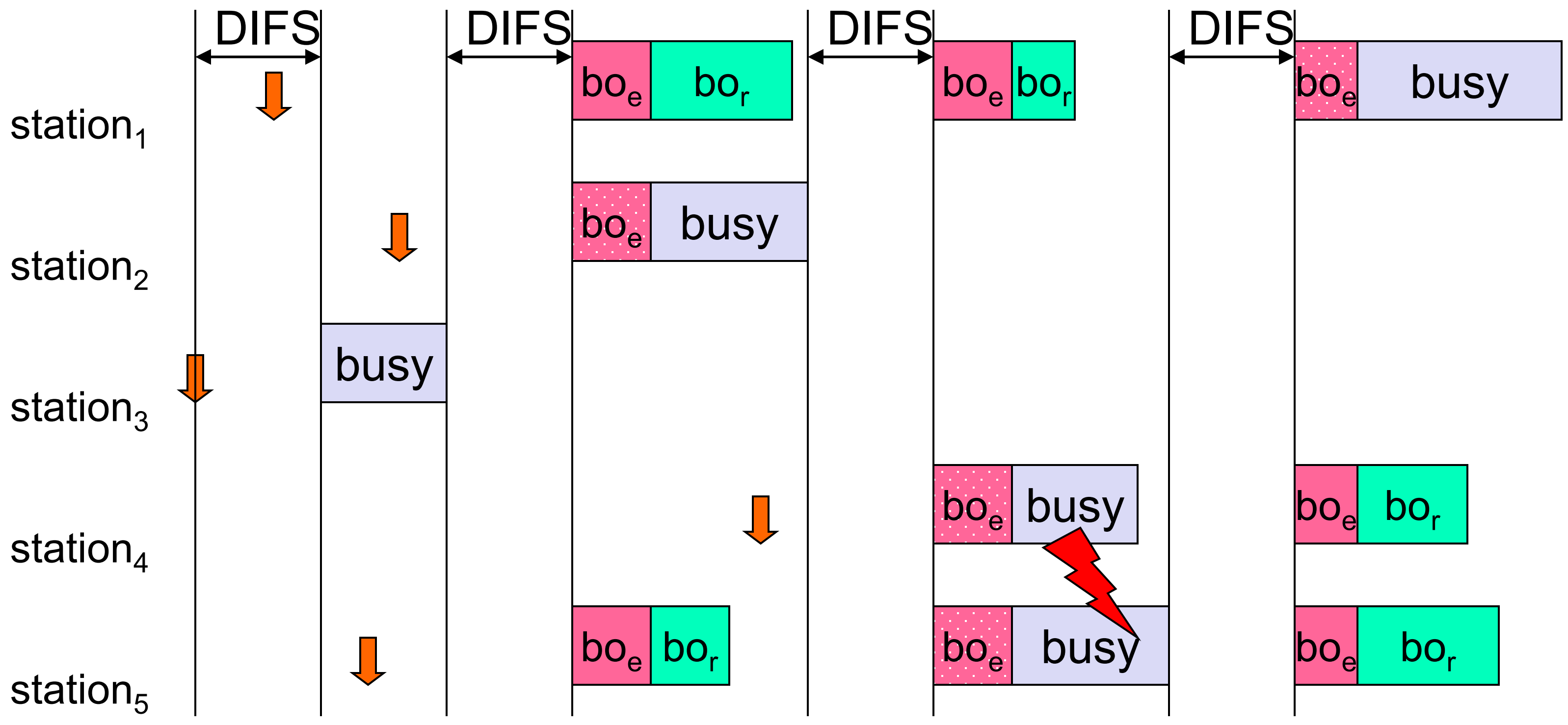
Types of IFS

- 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

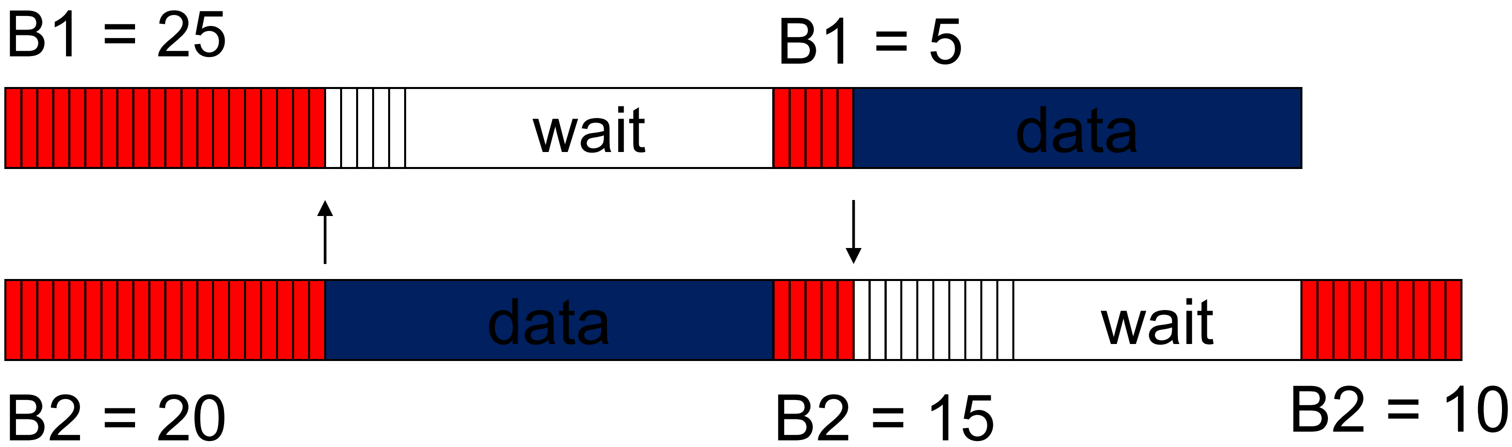


busy	medium not idle (frame, ack etc.)	bo$_e$	elapsed backoff time
⇩	packet arrival at MAC	bo$_r$	residual backoff time

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



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
- Clear To Send

ACK

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

RTS

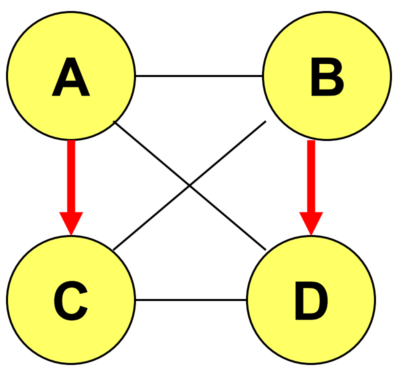
bytes	2	2	6	6	4
	Frame Control	Duration	Receiver Address	Transmitter Address	CRC

CTS

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

Fairness Issue

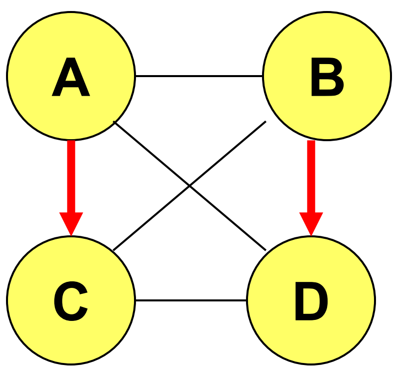
- Many definitions of fairness plausible
- Simplest definition
  - All nodes should receive equal bandwidth



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 802.11ad:
  - 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)