Wireless Media Access Protocols

Wired Communication

- Pros
  - Very reliable
    - For Ethernet, medium HAS TO PROVIDE a Bit Error Rate (BER) of 10^{-12} (one error for every trillion bits!)
      - Insulated wires; wires placed underground and in walls
      - Error Correction Techniques
  - Very high transfer rates - currently up to 100 Gbit/s
  - Long distance - Up to 40km in 10-Gbit/s Ethernet
- Cons
  - Expensive to set up infrastructure
  - Infrastructure is fixed once set up
  - No physical mobility

Wireless Communication

- Pros
  - Allows mobility
  - Much cheaper and easier to deploy, change, and upgrade!
- Cons
  - Exposed (unshielded) medium
    - Susceptible to physical phenomena (interference)
    - Variable BER – Error correction may not suffice in all cases
  - Slower data rates for wider distances
  - Link layer, and higher-layers, designed for wired medium
    - E.g. TCP assumes loss = congestion
    - Difficult to “hide” underlying behavior
  - Security: anyone in range hears transmission

Wireless

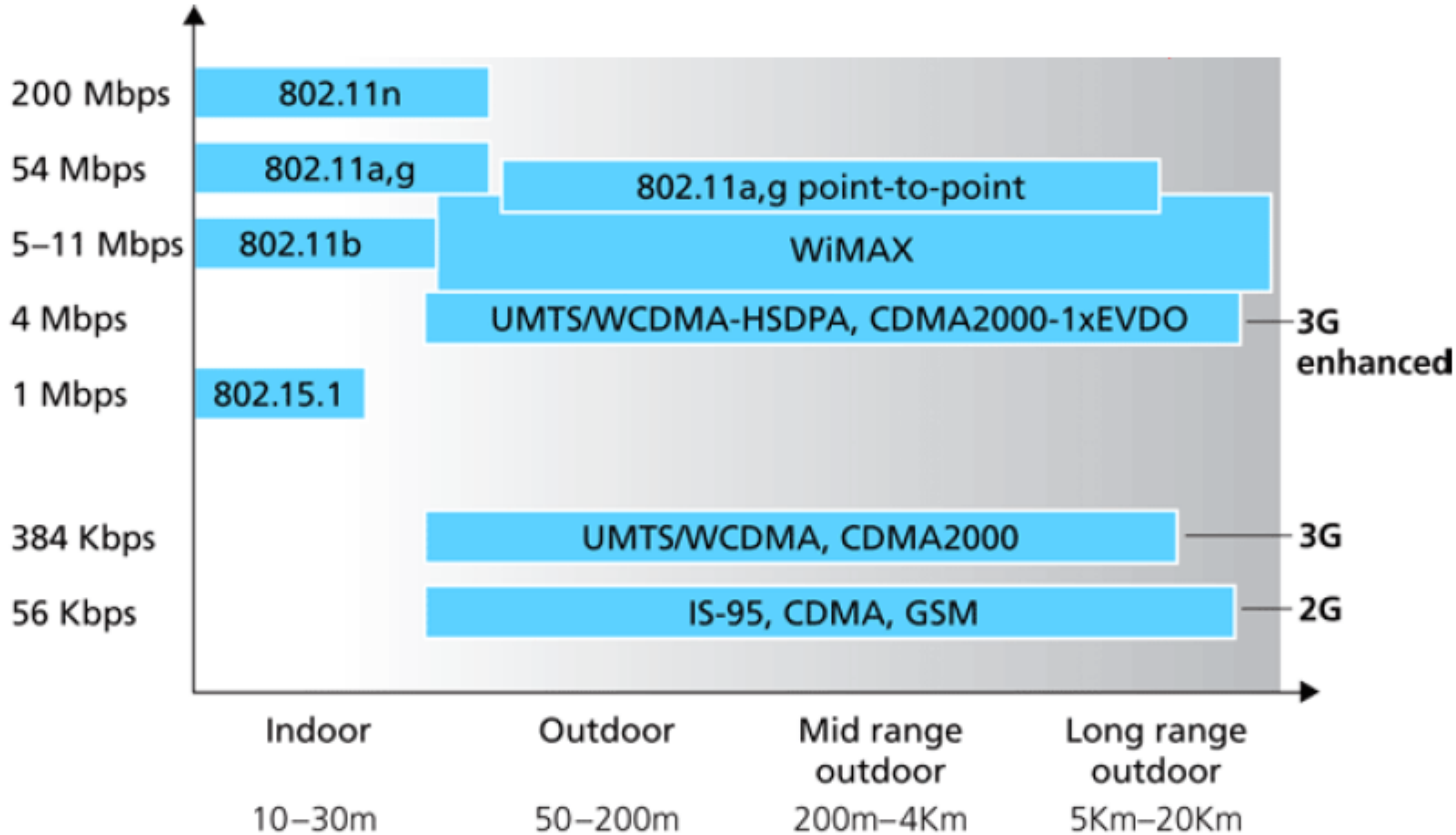
- FCC oversees all wireless communication
- Licensed Bands
  - Cellular phones, 3G,4G, AM/FM radio, broadcast television, satellites, WiMax
  - Use of resources left to "owner" of band
- Unlicensed Bands
  - 802.11, Bluetooth, ZigBee, IR, WiMax
  - No license needed – free for all!
  - Restrictions to limit interference
    - Limit on transmission power
    - Spread spectrum communication

Unlicensed Bands
900 MHz
    Industrial, Scientific and Medical (ISM)
2.4 GHz
5.4 GHz
10 – 66 GHz

Wireless Communication Standards (Alphabet Soup)

- Cellular (2G): GSM, CDMA, GPRS
- 3G: CDMA2000, W-CDMA, EDGE
- 4G: WiMAX, LTE
- IEEE 802.11
  - A: 5.0Ghz band, max 54Mbps
  - B: 2.4Ghz band, max 11Mbps
  - G: 2.4Ghz, max 54Mbps
  - N: 2.4/5Ghz, max 600Mbps
  - Many other versions
- IEEE 802.15 – lower power wireless
  - 802.15.1: 2.4Ghz, max 2.1 Mbps (Bluetooth)
  - 802.15.4: 2.4Ghz, max 250 Kbps (Sensor Networks)

Wireless Link Characteristics



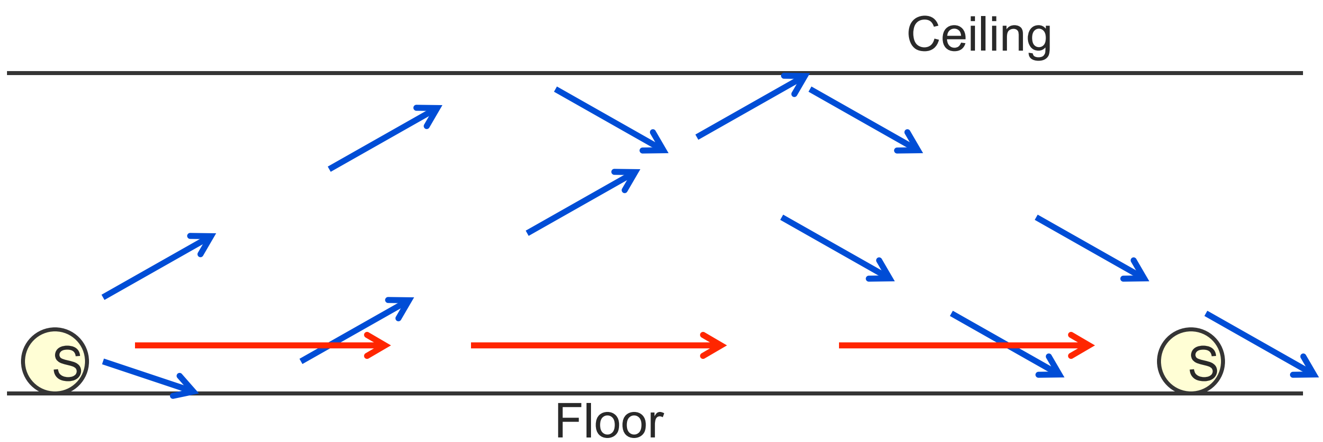
Challenges of wireless

- Path loss
  - Signal attenuation as a function of distance
  - Signal-to-noise ratio (SNR—Signal Power/Noise Power) decreases, make signal unrecoverable
- Multipath propagation
  - Signal reflects off surfaces, effectively causing self-interference
- Internal interference (from other users)
  - Hosts within range of each other collide with one another’ s transmission
- External interference
  - Microwave is turned on and blocks your signal

Path Loss

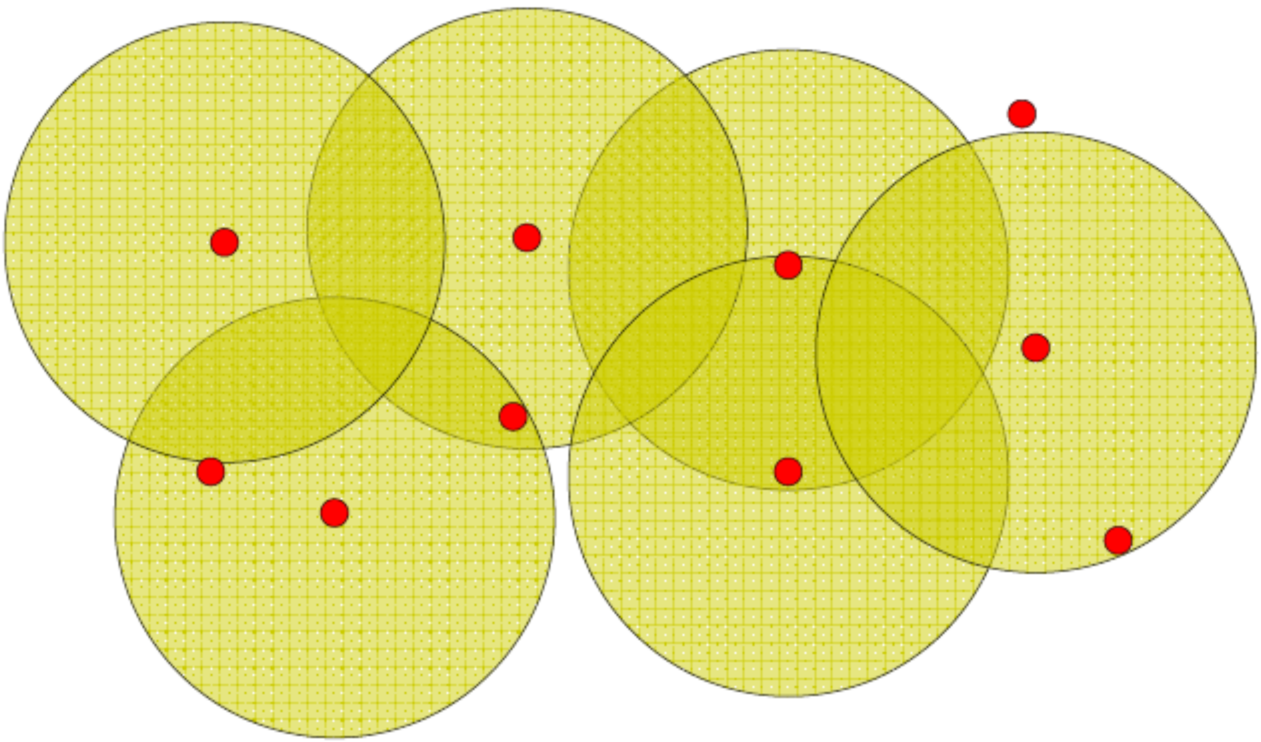
- Signal power attenuates by about ~r^2 factor for omni-directional antennas in free space
  - r is the distance between the sender and the receiver
- The exponent in the factor is different depending on placement of antennas
  - Less than 2 for directional antennas
  - Faster attenuation
    - Exponent > 2 when antennas are placed on the ground
    - Signal bounces off the ground and reduces the power of the signal

Multipath Effects

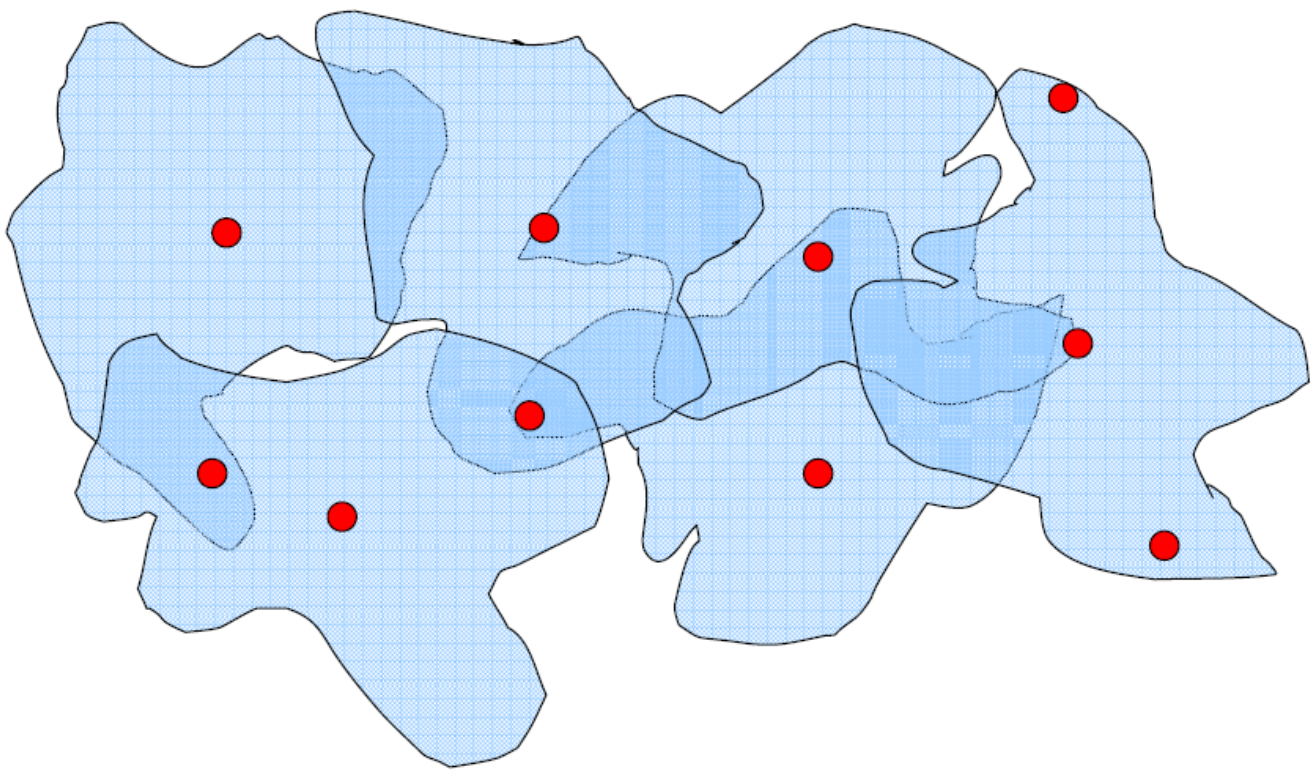


- Signals bounce off surfaces and interfere with one another
- What if signals are out of phase?
  - Orthogonal signals cancel each other and nothing is received!

What is a Wireless “Link”?



What is a Wireless "Link"?



Wireless Bit Errors

- The lower the SNR (Signal/Noise) the higher the Bit Error Rate (BER)
- How can we deal with this?
  - Make the signal stronger
- Why is this not always a good idea?
  - Increased signal strength requires more power
  - Increases the interference range of the sender, so you interfere with more nodes around you
- Error correction can correct some problems

Spread Spectrum

- Direct Sequence Spread Spectrum
  - Spread the signal over a wider frequency band than required
  - Originally designed to thwart jamming
  - Original 802.11 uses 83 MHz in 2.4 GHz band
- Frequency-Hopped Spread Spectrum
  - Uses 80 1MHz sub-bands in 2.4 GHz band
  - Transmit over a random sequence of frequencies

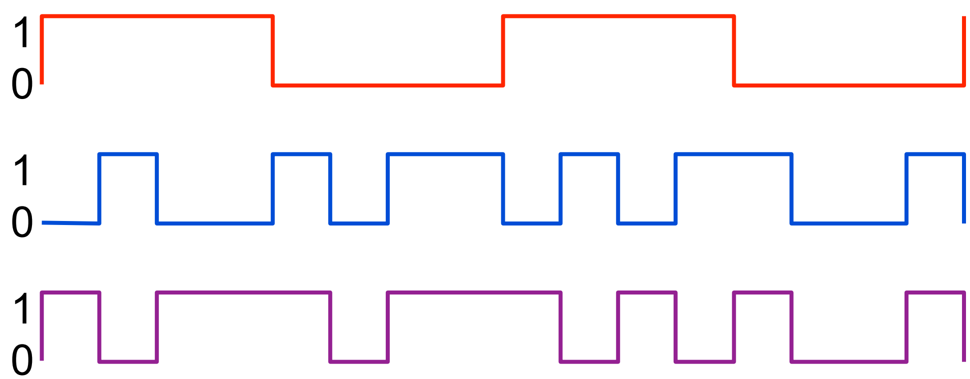
Spread Spectrum

- Direc
  - Sp
    tha
  - Or
  - Or
- Freq
  - Us
  - Tr
    fre

- Frequency hopping had many inventors
  - 1942: actress Hedy Lamarr and composer George Antheil patented Secret Communications System
  - Piano-roll to change between 88 frequencies, and was intended to make radio-guided torpedoes harder for enemies to detect or to jam
  - The patent was rediscovered in the 1950s during patent searches when private companies independently developed Code Division Multiple Access, a civilian form of spread-spectrum

Direct Sequence Spread Spectrum

- Spread Spectrum
  - For each bit, send XOR of that bit and n random bits
  - Random sequence is known to both sender and receiver
  - Called n-bit chipping code (802.11 uses 11bit code)



Data stream:
1010

Random sequence:
0100101101011001

XOR of the two:
1011101110101001

Communication Characteristics

- Rate
  - Defines the communication speeds
- Frequency
  - Defines the behavior in the physical environment
- Range
  - Defines the physical communication area
- Power
  - Defines the cost in terms of energy

Communication Characteristics

- Rate
  - Defines the communication speeds
  - Channel Bandwidth
    - Defined by the specifications of the technology
  - Available Bandwidth
    - Defined by the current use of the communication channel
      - Channel competition – MAC layer
      - Bandwidth competition – Transport layer

Communication Characteristics

- Frequency/signal characteristics
  - Defines the behavior in the physical environment
    - Does the signal go through walls?
    - Is the signal susceptible to multipath fading?
  - Challenge
    - Many technologies use the same frequency

Communication Characteristics

- Range
  - Defines the physical communication area
  - May be affected by buildings, walls, people
  - May be affected by distance

Communication Characteristics

- Power
  - Defines the cost in terms of energy
  - Power can be adapted to save energy
    - Inversely affects range

Communication Characteristics

- Rate
  - Defines the communication spee
- Frequency
  - Defines the behavior in th sical environment
- Range
  - Defines the physi nmunication area
- Power
  - Defines the t in terms of energy

Everything is inter-related!

Current Wireless Technologies

- IEEE 802.11
  - Wireless LAN (WLAN)
  - MAC layer based on Ethernet
    - Originally called “wireless Ethernet”

	Max Rate	Frequency	Range	Energy
Pre-802.11	2 Mbps	900 Mhz	100 m	100 mW
IEEE 802.11b	11 Mbps	2.4 GHz	35/150 m	100 mW
IEEE 802.11g	54 Mbps	2.4 GHz	35/150 m	100 mW
IEEE 802.11a	54 Mbps	5 GHz	10 /120 m	100 mW
IEEE 802.11n	600 Mbps	2.4/5 GHz	70 /250 m	100 mW

IEEE 802.11 - Physical Layer

- IEEE 802.11 b
  - Direct Sequence Spread Spectrum
    - Uses 83 MHz in 2.4 GHz band
    - Spread the signal over a wider frequency band than required
    - Originally designed to prevent jamming
  - 3 orthogonal channels
- IEEE 802.11 g
  - Frequency-Hopped Spread Spectrum
    - Uses 80 1MHz sub-bands in 2.4 GHz band
    - Transmit over a random sequence of frequencies
      - Hop 10 times a second
    - Originally designed to avoid snooping
  - 3 orthogonal channels

IEEE 802.11 - Physical Layer

- IEEE 802.11 a
  - Orthogonal Frequency Division Multiplexing (OFDM)
  - 13 orthogonal channels
- IEEE 802.11 n
  - Works on both 802.11a and 802.11g spectrum
  - MIMO – Multi-input, Multi-output antenna
    - Up to 4 antenna

IEEE 802.11 - Physical Layer

- Channel Rate vs. Signal strength
  - All versions of IEEE 802.11 can reduce the rate to increase the signal strength
    - IEEE 802.11 b: 1, 2, 5.5, 11 Mbps
    - IEEE 802.11 a, g: 6, 9, 12, 18, 24, 36, 48, or 54 Mbps
  - Increased range → lower signal → lower rate

IEEE 802.11 Extensions

- IEEE 802.11e
  - Enhancements: QoS, including packet bursting
- IEEE 802.11i
  - Enhanced security
- IEEE 802.11p
  - WAVE - Wireless Access for the Vehicular Environment
- IEEE 802.11s
  - ESS Mesh Networking
- IEEE 802.11u
  - Interworking with non-802 networks (for example, cellular)
- IEEE 802.11 ac
  - Provides high throughput in the 5 GHz band
  - Wider RF bandwidth, more streams (up to 8), and high-density modulation (up to 256 QAM)

Current Wireless Technologies

- BlueTooth – IEEE 802.15.1
  - Originally designed as a cable replacement technology
  - Master/Slave configuration
  - Bluetooth Low Energy (BLE) for low power discovery

	Max Rate	Frequency	Range	Energy
BlueTooth	3 Mbps	2.4 GHz	100 m	100 mW
			10 m	2.5 mW
			1 m	1 mW

BlueTooth

- Physical Layer
  - Frequency-Hopped Spread Spectrum
    - Uses 79 1MHz sub-bands in 2.4 GHz band
    - Transmit over a random sequence of frequencies
      - Hop 1600 times a second
    - 5 orthogonal sub-hopping sets
- MAC Layer
  - Slotted
    - Managed by the master
    - Single slot packet
      - Max data rate of 172Kbps
    - Multislot frames
      - Support higher rates of 721Kbps

Current Wireless Technologies

- ZigBee – IEEE 802.15.4
  - Low power, short range
    - Sensor networks
    - Personal area networks

	Max Rate	Frequency	Range	Energy
ZigBee (IEEE 802.15.4)	250 kbps	2.4 GHz	10 - 100 m	1 mW
	40 Kbps	915 MHz	10 - 100 m	1 mW
	20 Kbps	868 MHz	10 - 100 m	1 mW

ZigBee

- Physical Layer
  - Direct Sequence Spread Spectrum
    - 2.4 GHz – 16 orthogonal channels
    - 915 MHz – 10 orthogonal channels
    - 868 MHz – 1 channel
- MAC Layer
  - CSMA/CA
  - Battery Life Extension (BLE) mode
    - Limit the back-off exponent to max 2

Current Wireless Technologies

- InfraRed
  - Directional

	Max Rate	Frequency	Range	Energy
InfraRed – IrDA	9600 bps – 16 Mbps		< 1 m	Low

Current Wireless Technologies

- RFID
  - Passive technology
  - Used for inventory control

	Max Rate	Frequency	Range	Energy
RFID – Near Field			< 10 cm	Self-powered
RFID – Far Field			< 3 m	Self-powered

RFID

- RFID Basics
  - Reader powers the "tag"
  - Antenna "captures" the energy for a response
  - Simple MAC
    - All tags respond
  - Contention-based MAC
    - Use ALOHA or Tree-splitting algorithm to avoid collisions
- Near field
  - Magnetic induction
    - Range < 10 cm
- Far field
  - Electromagnetic wave capture
    - Range < 3 m

Current Wireless Technologies

- WiMAX – IEEE 802.16
  - Wireless Metropolitan Area Networks (WMAN)
  - May require line-of sight (LOS)

	Max Rate	**Frequency**	**Range**	**Energy**
WiMAX –LOS	70 Mbps	10-66 GHz	50 km	Very high
WiMAX Non-LOS	~14 Mbps	2-11 GHz	~10 km	Very high

Current Wireless Technologies

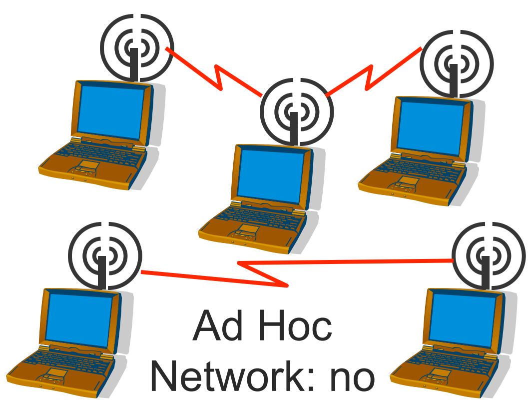
- WiMAX – IEEE 802.16
  - Transmissions to/from base station by hosts with omnidirectional antenna
  - Base station-to-base station backhaul with point-to-point antenna

	Max Rate	Frequency	Range	Energy
WiMAX –LOS	70 Mbps	10-66 GHz	50 km	Very high
WiMAX Non-LOS	~14 Mbps	2-11 GHz	~10 km	Very high

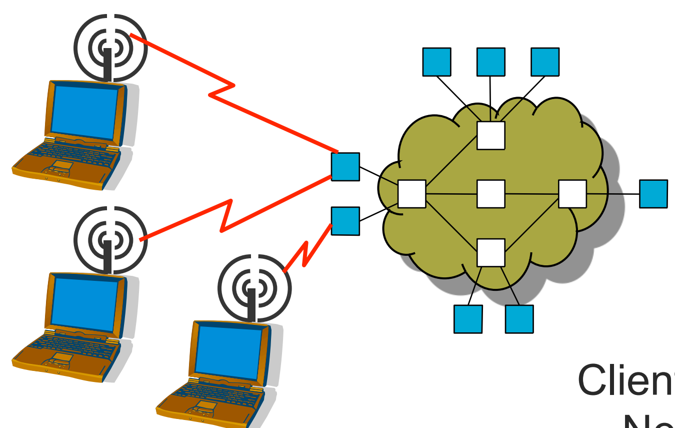
Media Access Control Protocols

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

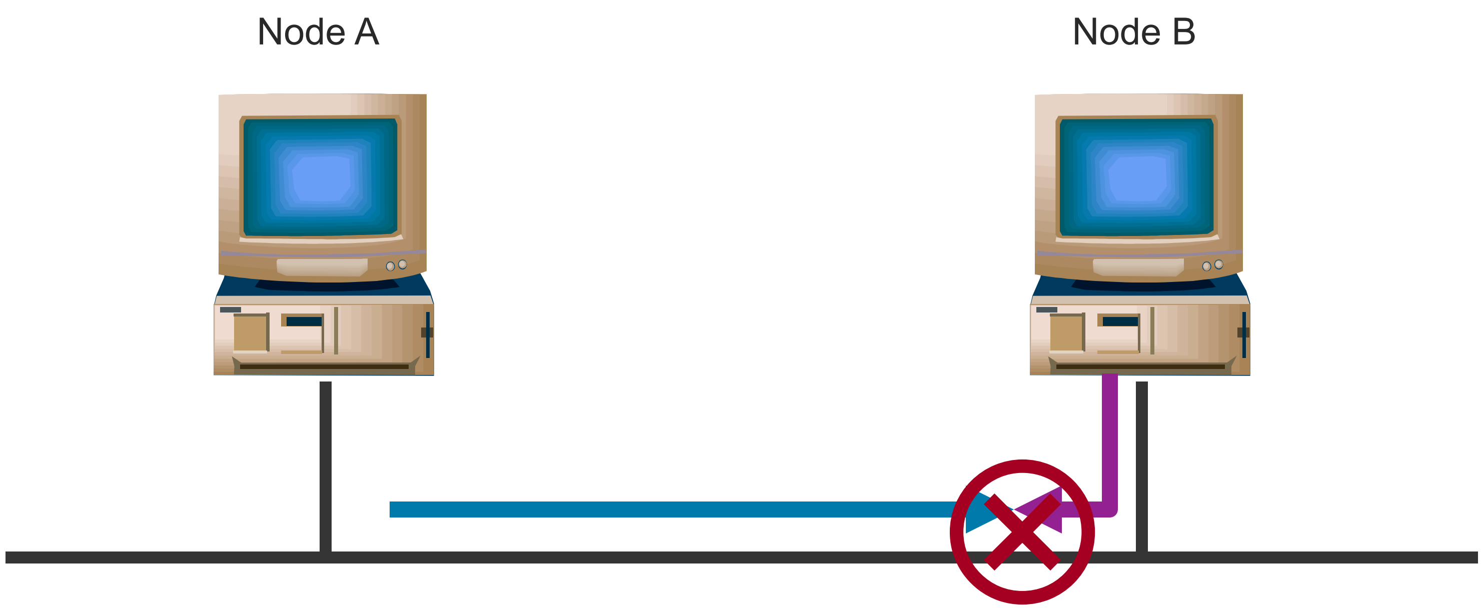


Client Server Network

Medium Access Control

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

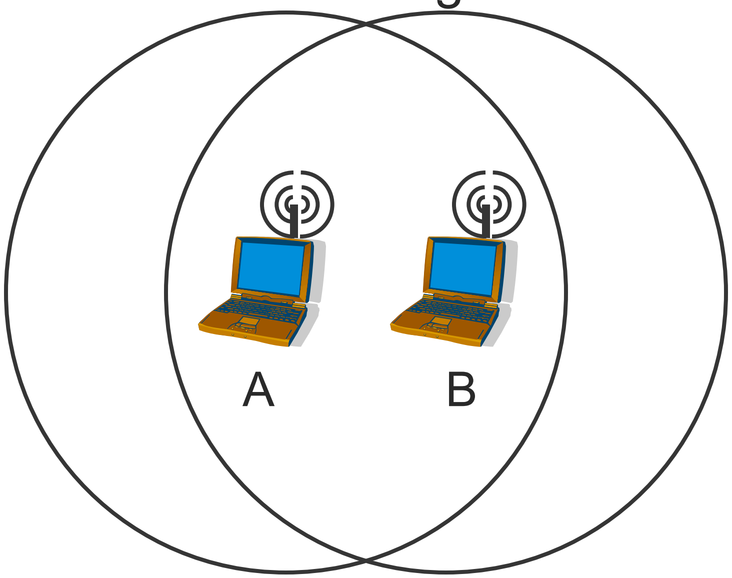
Ethernet MAC Algorithm



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

CSMA/CD in WLANs?

- Most (if not all) radios are half-duplex
  - Listening while transmitting is not possible
- Collision might not occur at sender
  - Collision at receiver might not be detected by sender!

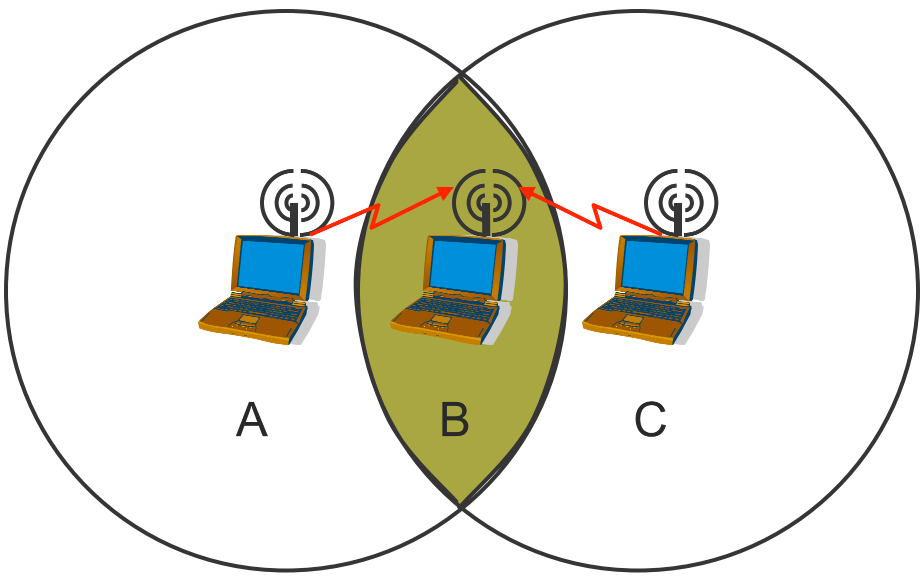


Wireless Ethernet - CSMA/CA

- 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

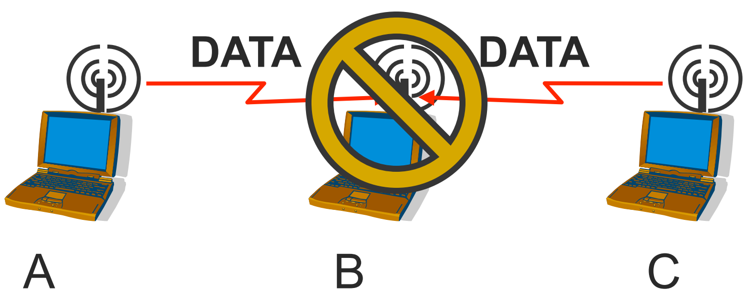
IEEE 802.11 MAC Layer Standard

- Similar to Ethernet
- But consider the following:



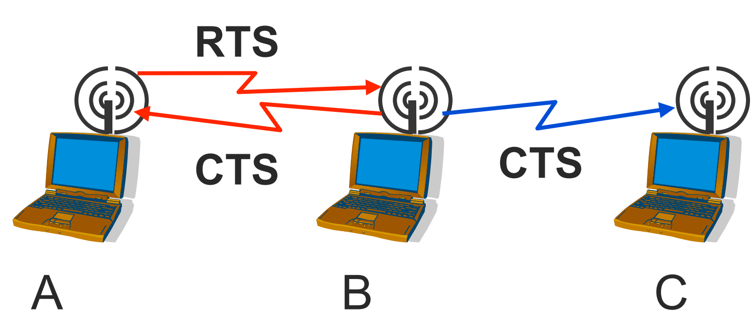
Hidden Terminal Problem

- 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



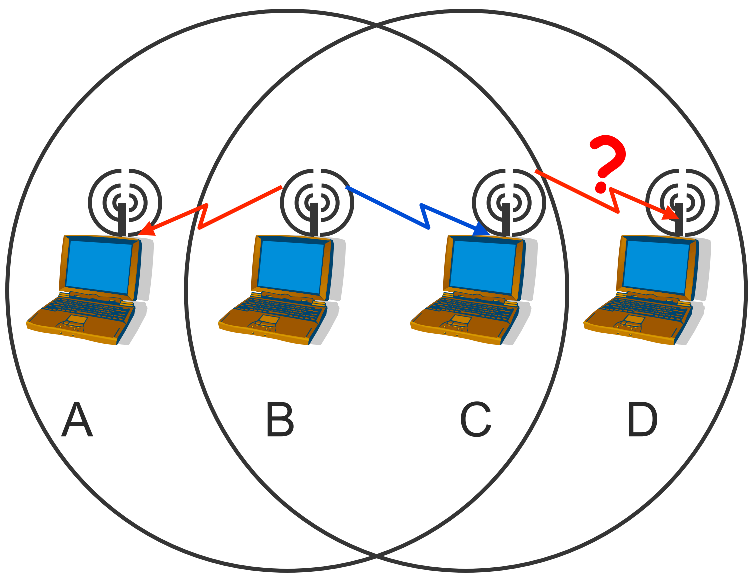
MACA Solution for Hidden Terminal Problem

- 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



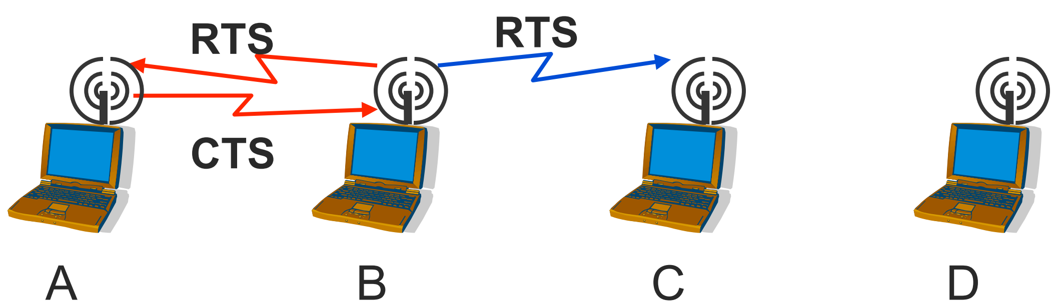
IEEE 802.11 MAC Layer Standard

- But we still have a problem



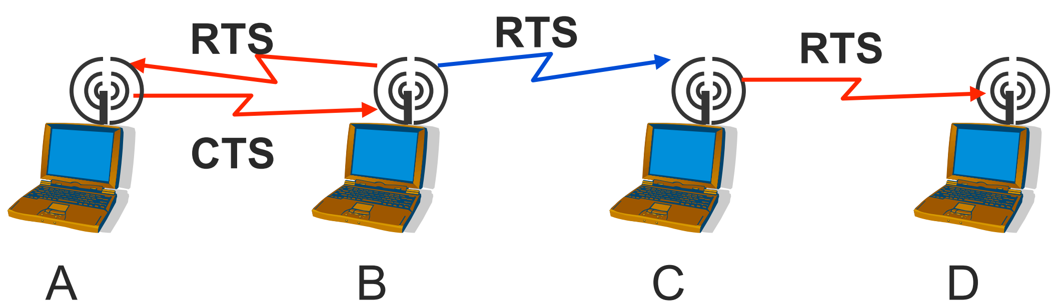
Exposed Terminal Problem

- 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



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

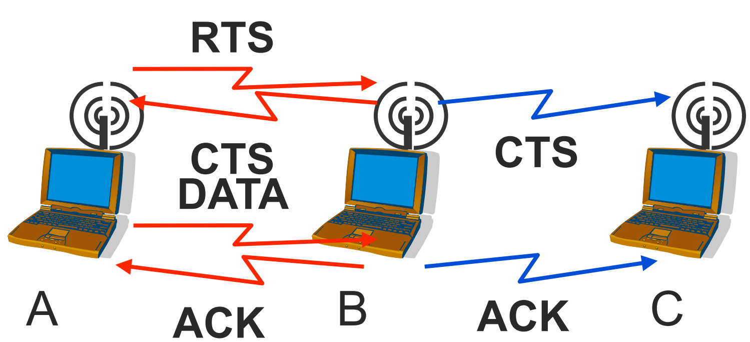
- Still possible
  - RTS packets can collide!
- Binary exponential backoff
  - Backoff counter doubles after every collision and reset to minimum value after successful transmission
  - Performed by stations that experience RTS collisions
- RTS collisions not as bad as data collisions in CSMA
  - Since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

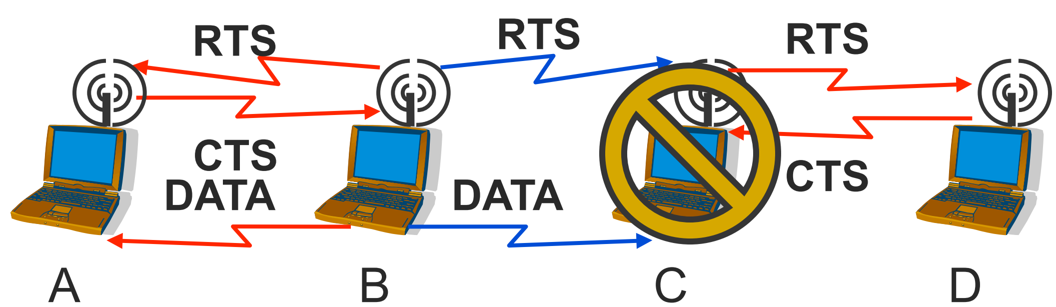
A Simple Solution to Improve Reliability - MACAW

- 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



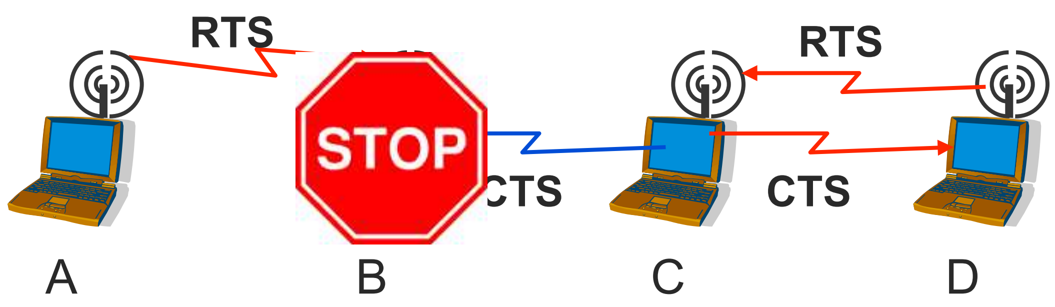
Revisiting the Exposed Terminal Problem

- 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



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



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

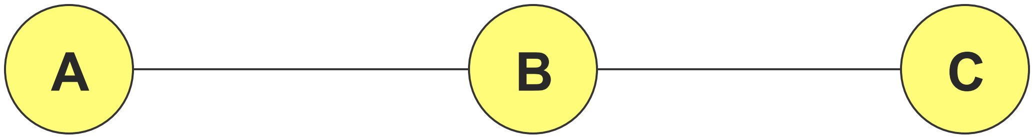
- Sort-of solution
  - Don't use CTS for multicast data
- Receivers recognize multicast destination in RTS
  - Don't return CTS
  - Sender follows RTS immediately by DATA
  - After RTS, all receivers defer for long enough for DATA
- Helps, but doesn't fully solve problem
  - Like normal CSMA, only those in range of sender will defer
  - Others in range of receiver will not defer

IEEE 802.11 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

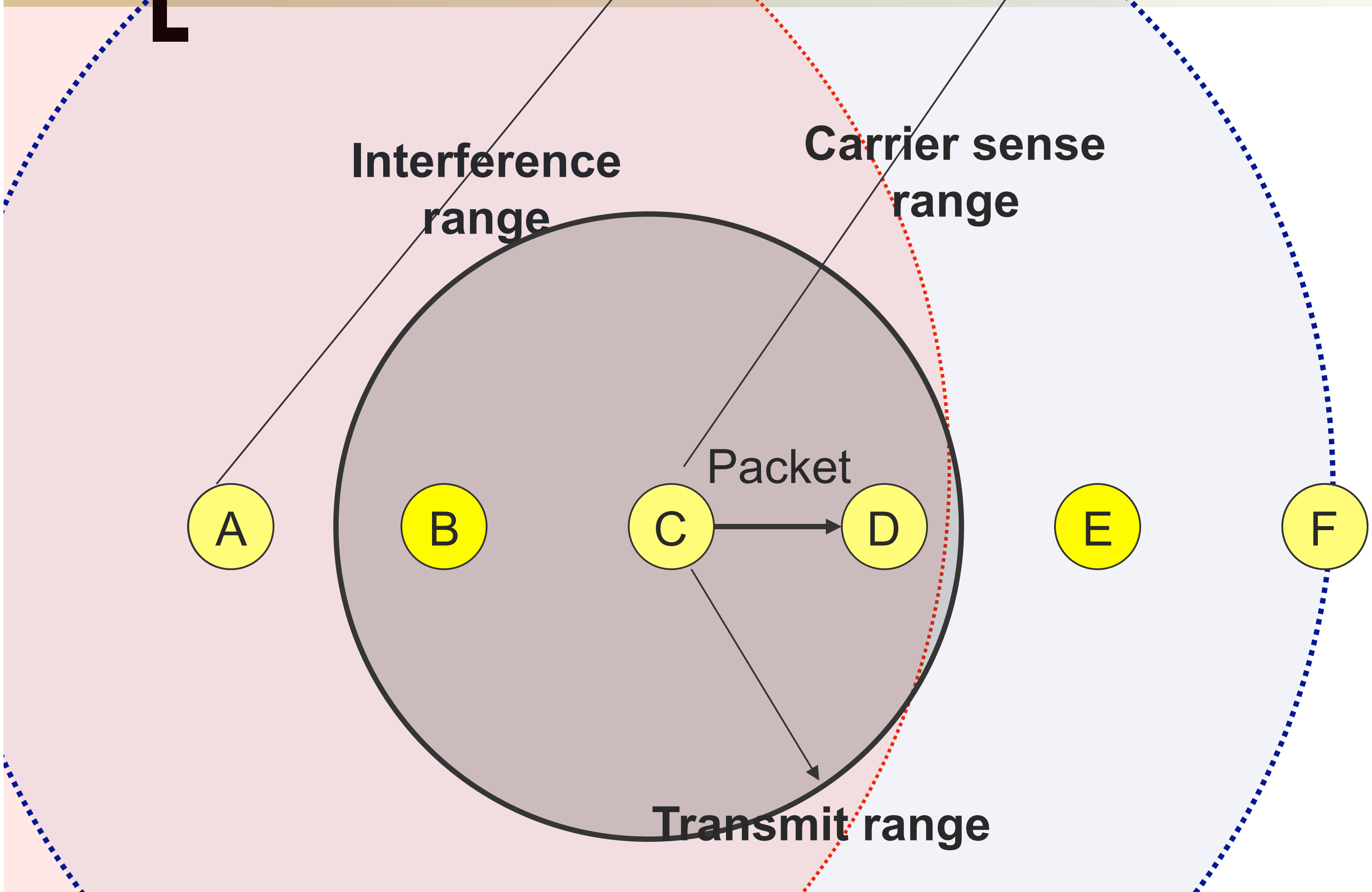
- Uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer
- Uses ACK to achieve reliability
- Any node receiving the RTS cannot transmit for the duration of the transfer
  - To prevent collision with ACK when it arrives at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



IEEE 802.11 CSMA/CA

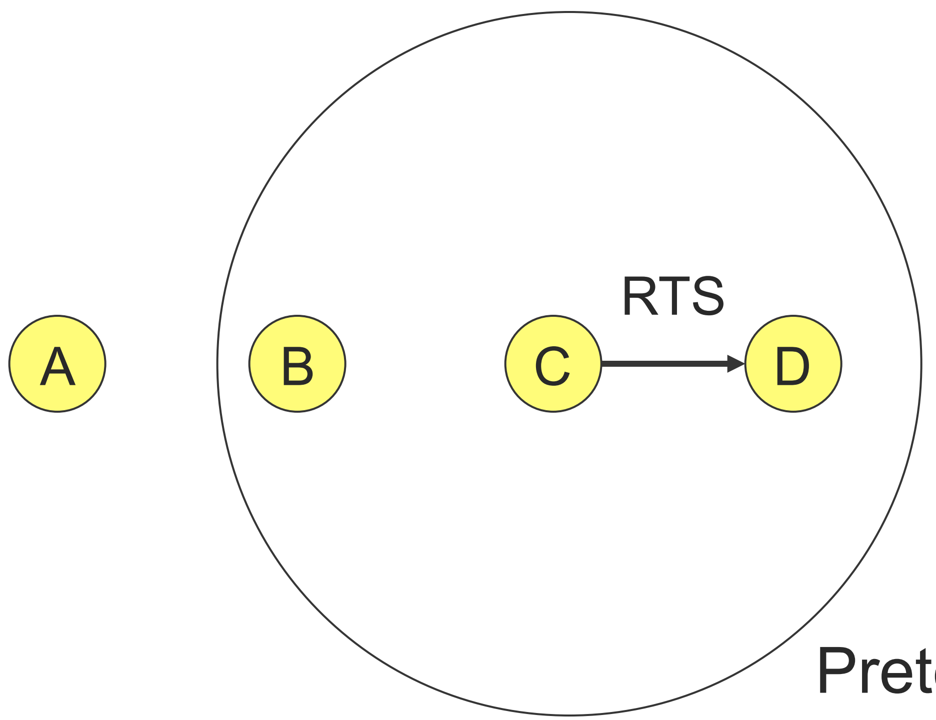
- Nodes stay silent when carrier sensed
  - Physical carrier sense
  - Virtual carrier sense
    - Network Allocation Vector (NAV)
    - NAV is updated based on overheard RTS/CTS/DATA/ ACK packets, each of which specified duration of a pending transmission
- Backoff intervals used to reduce collision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

IEEE 802.11 Physical Carrier Sense



IEEE 802.11 Virtual Carrier Sense

RTS = Request-to-Send

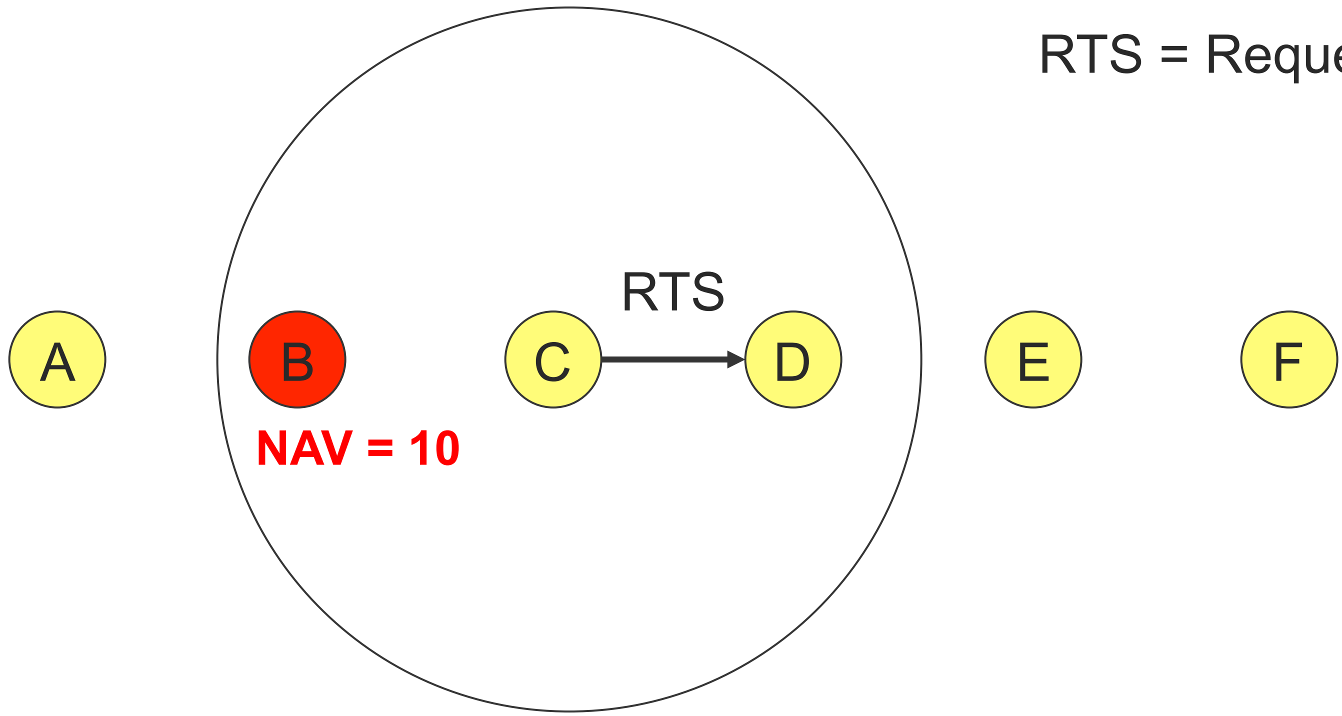


Pretending a circular range

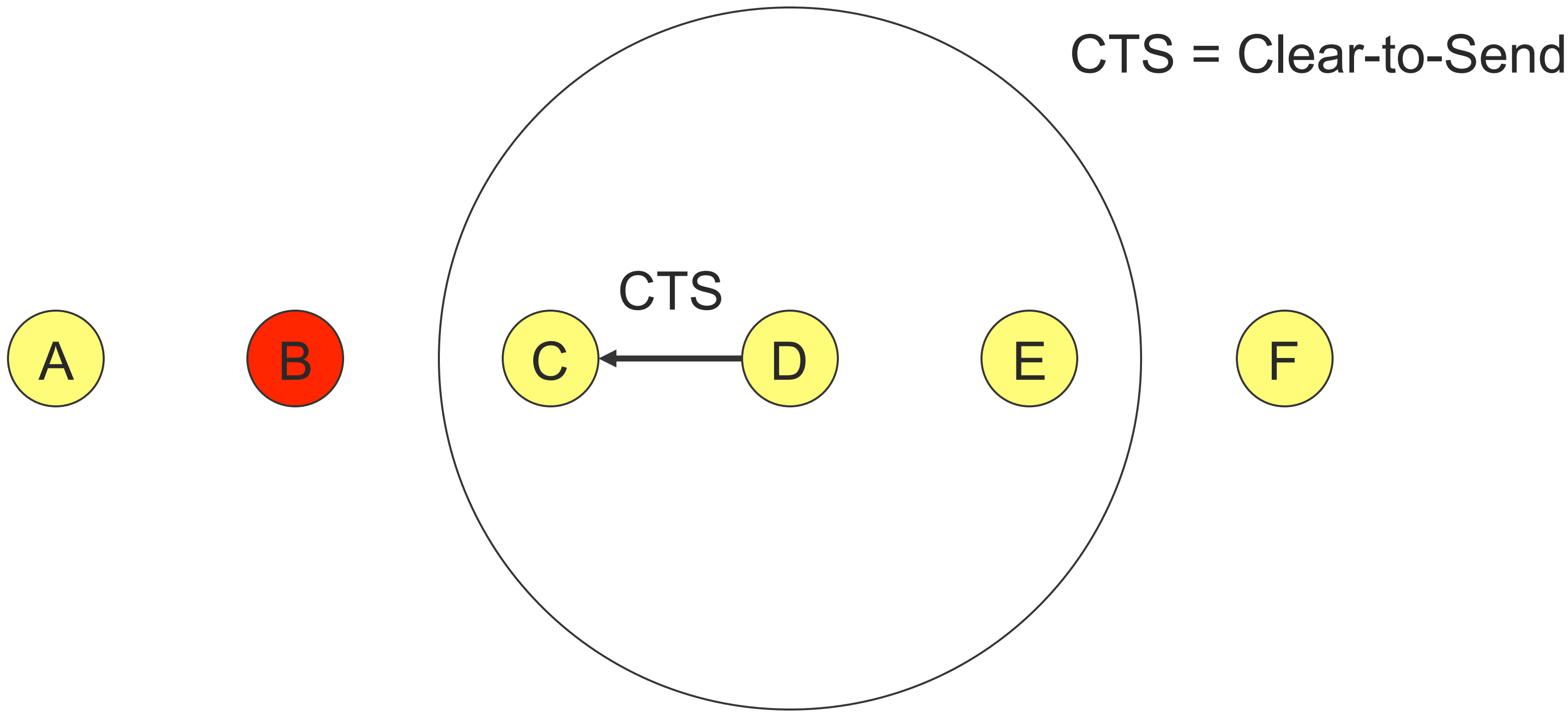
IEEE 802.11 Virtual Carrier Sense

NAV = remaining duration to keep quiet

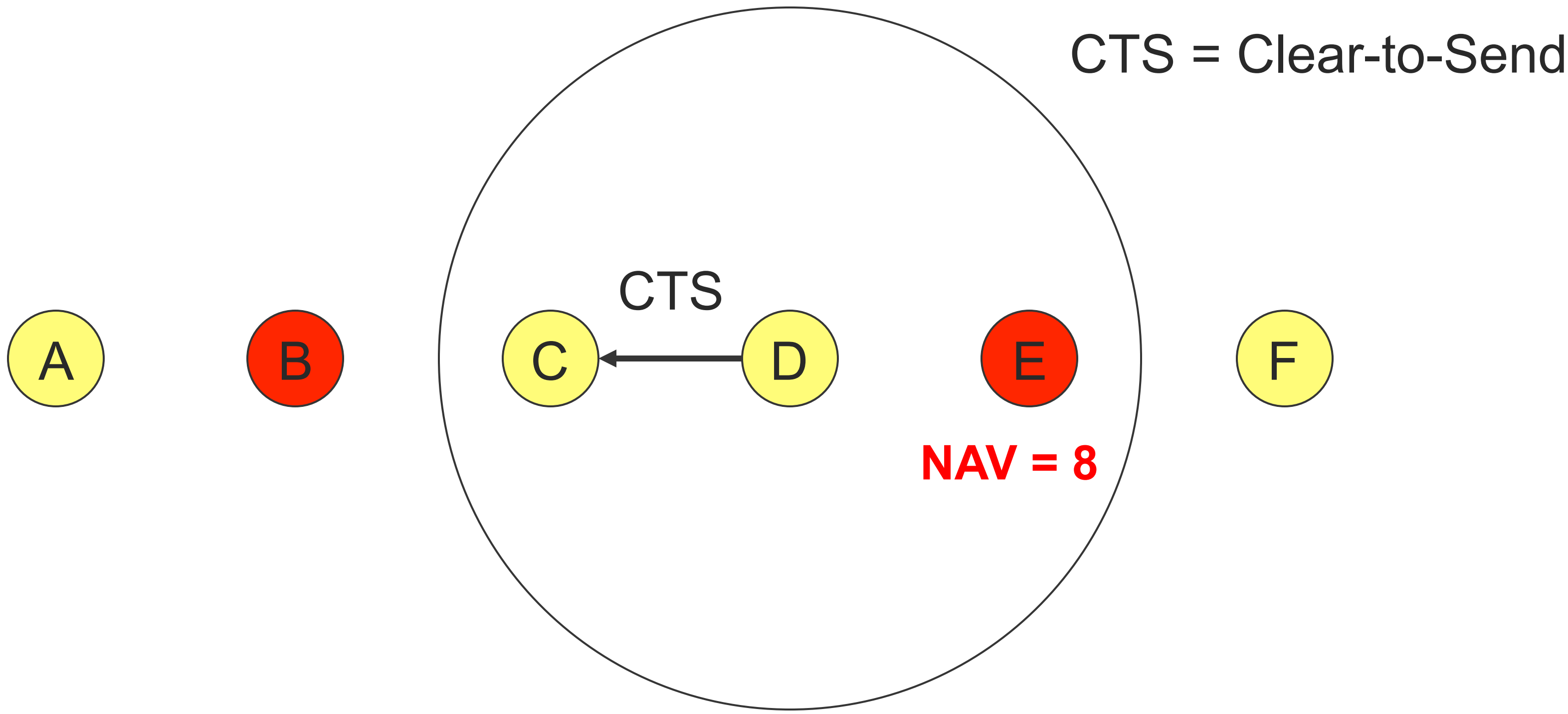
RTS = Request-to-Send



IEEE 802.11 Virtual Carrier Sense

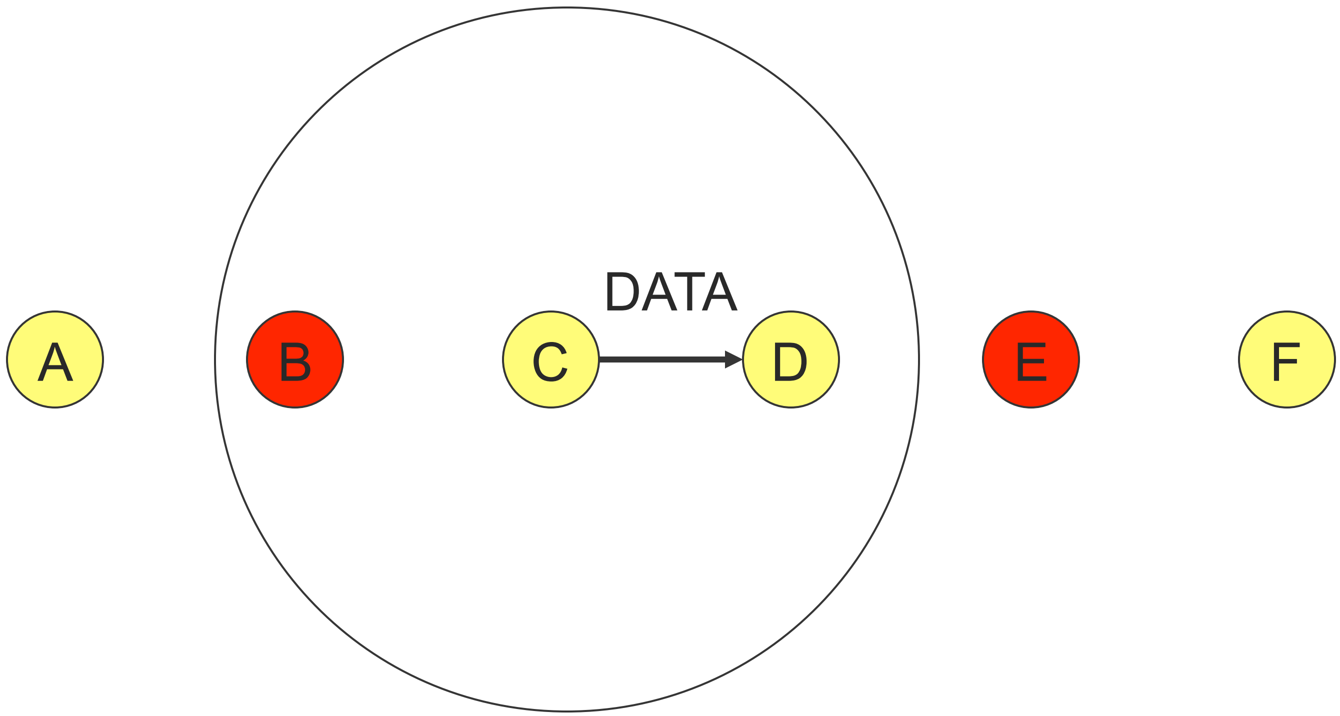


IEEE 802.11 Virtual Carrier Sense



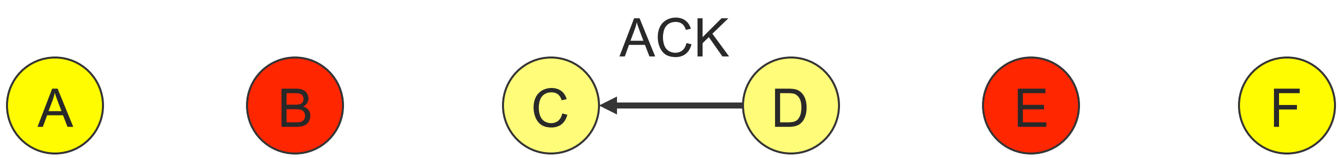
IEEE 802.11 Virtual Carrier Sense

- DATA packet follows CTS

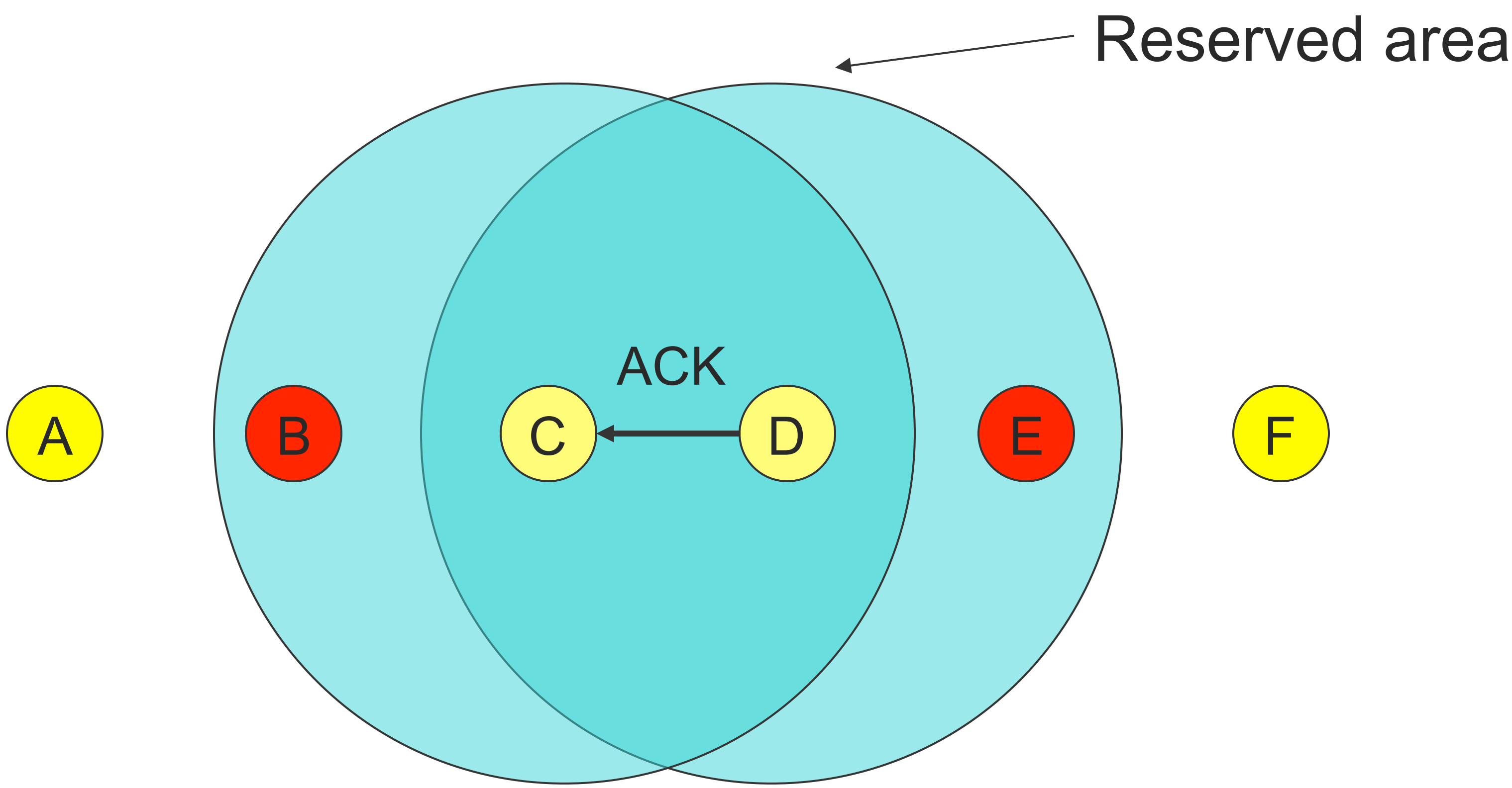


IEEE 802.11 Virtual Carrier Sense

- Successful data reception acknowledged using ACK



IEEE 802.11



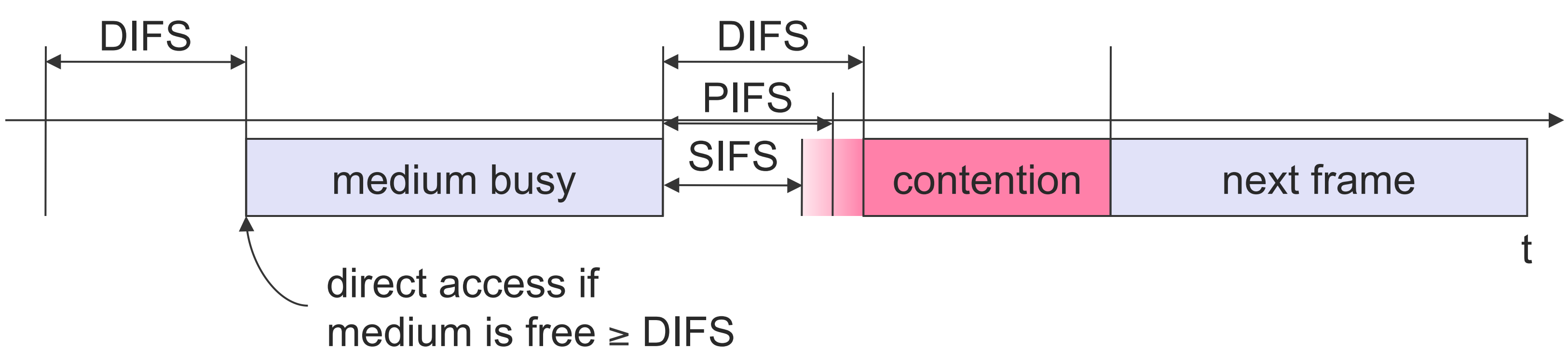
Ethernet vs. IEEE 802.11

- 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?

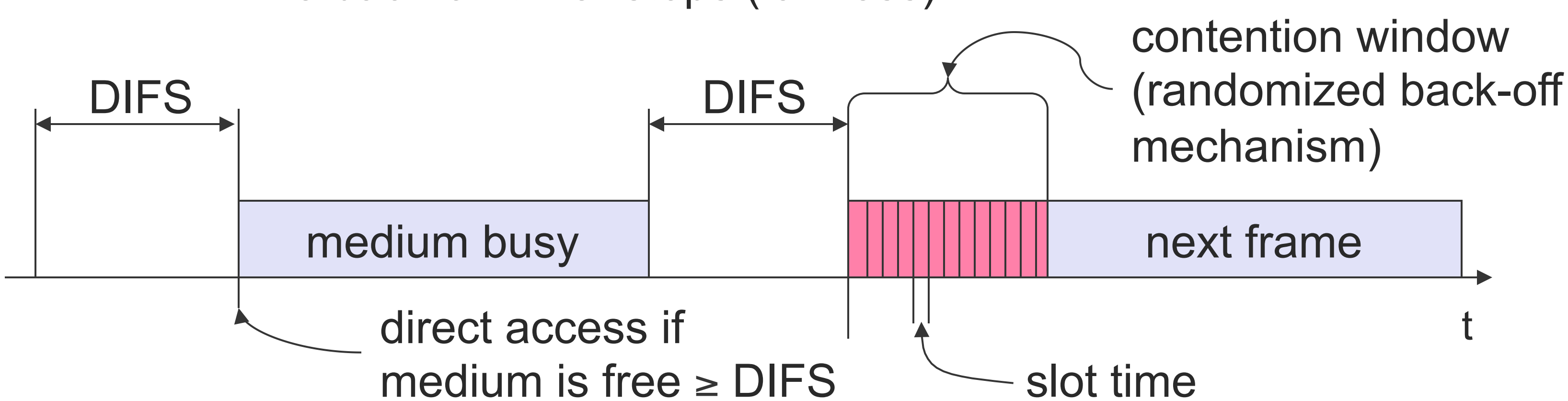
Interframe Spacing

- 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)



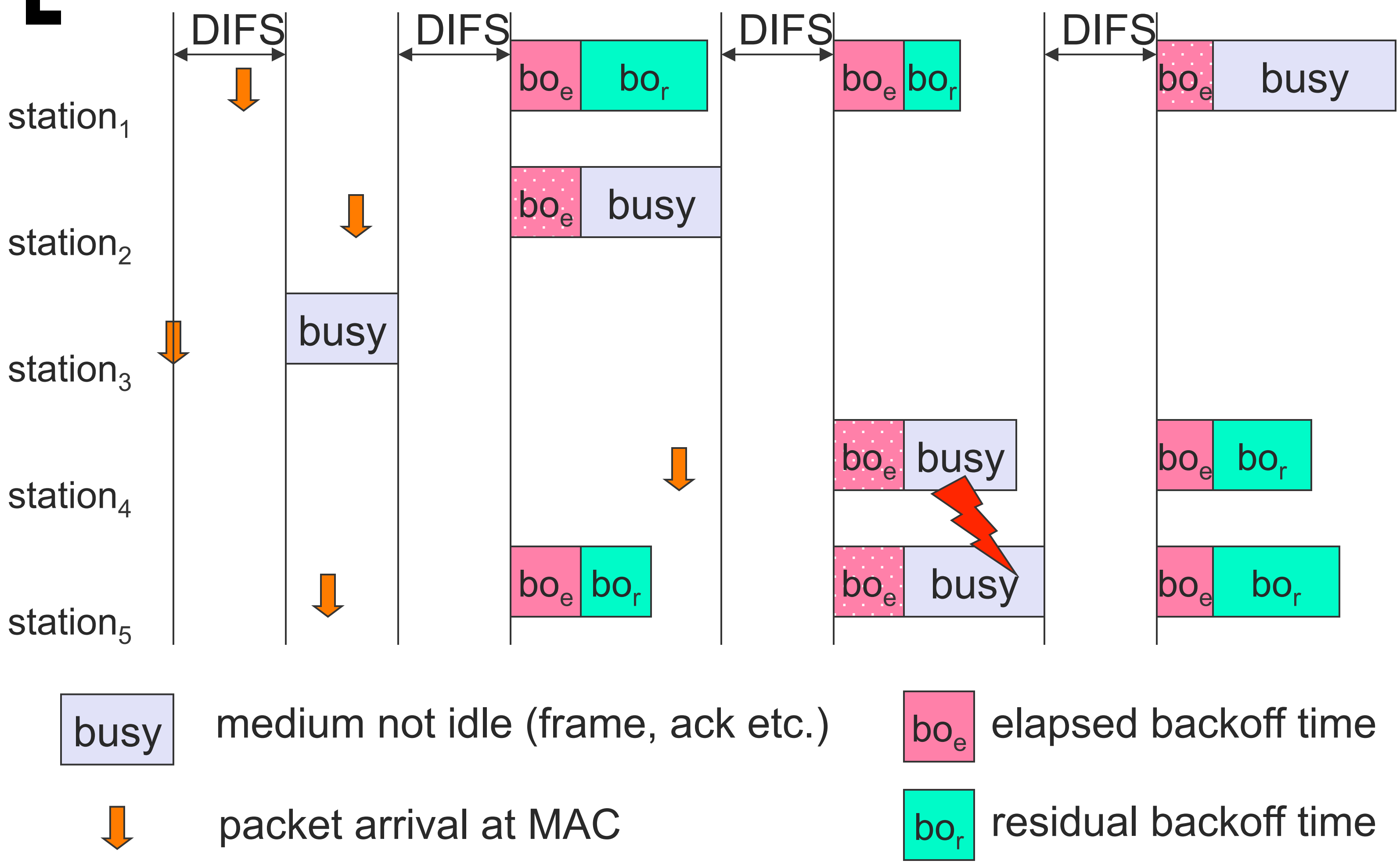
Types of IFS

- 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

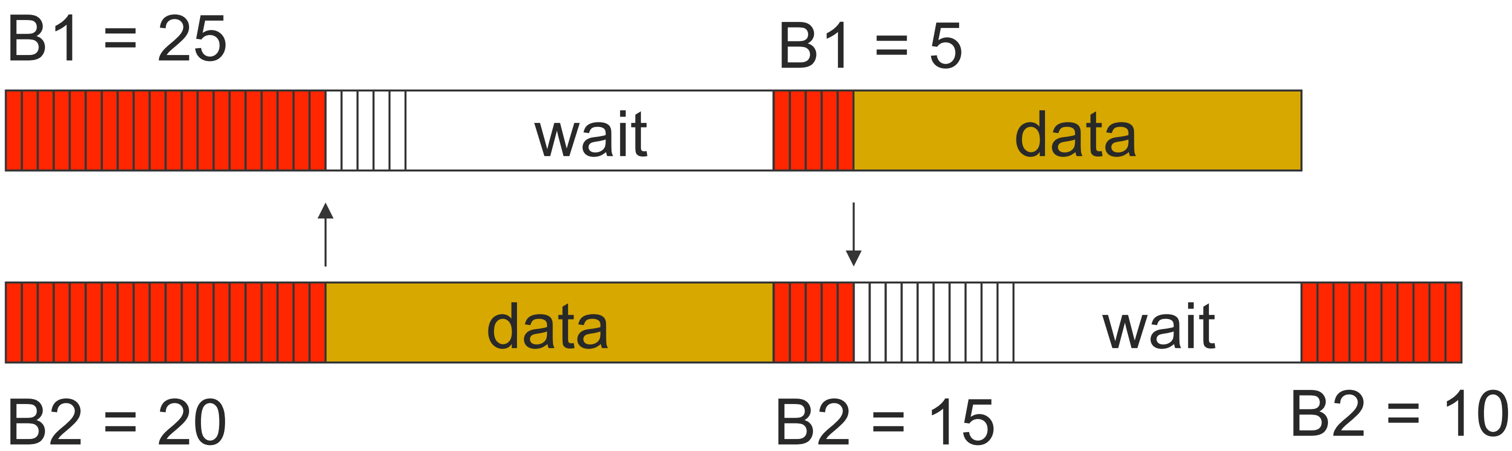
IEEE 802.11 - Competing Stations



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

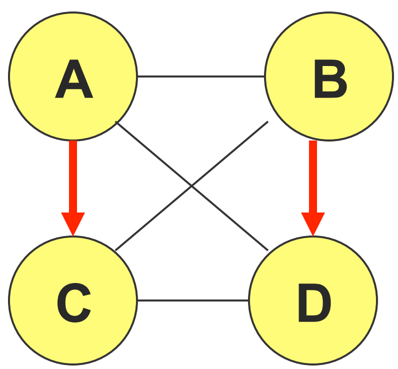
- The number of nodes attempting to transmit simultaneously may change with time
  - Some mechanism to manage contention is needed
- IEEE 802.11 DCF
  - Contention window CW is chosen dynamically depending on collision occurrence

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

Fairness Issue

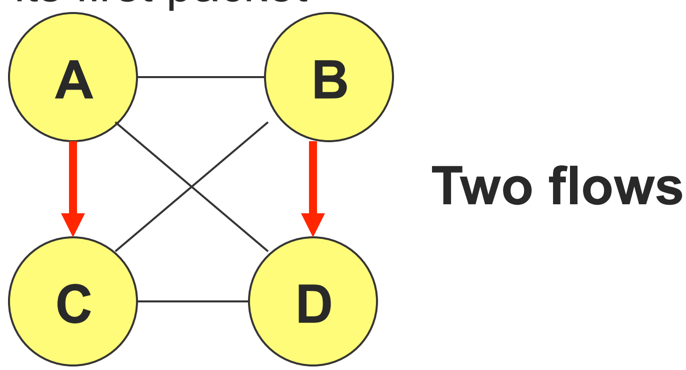
- Many definitions of fairness plausible
- Simplest definition
  - All nodes should receive equal bandwidth



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

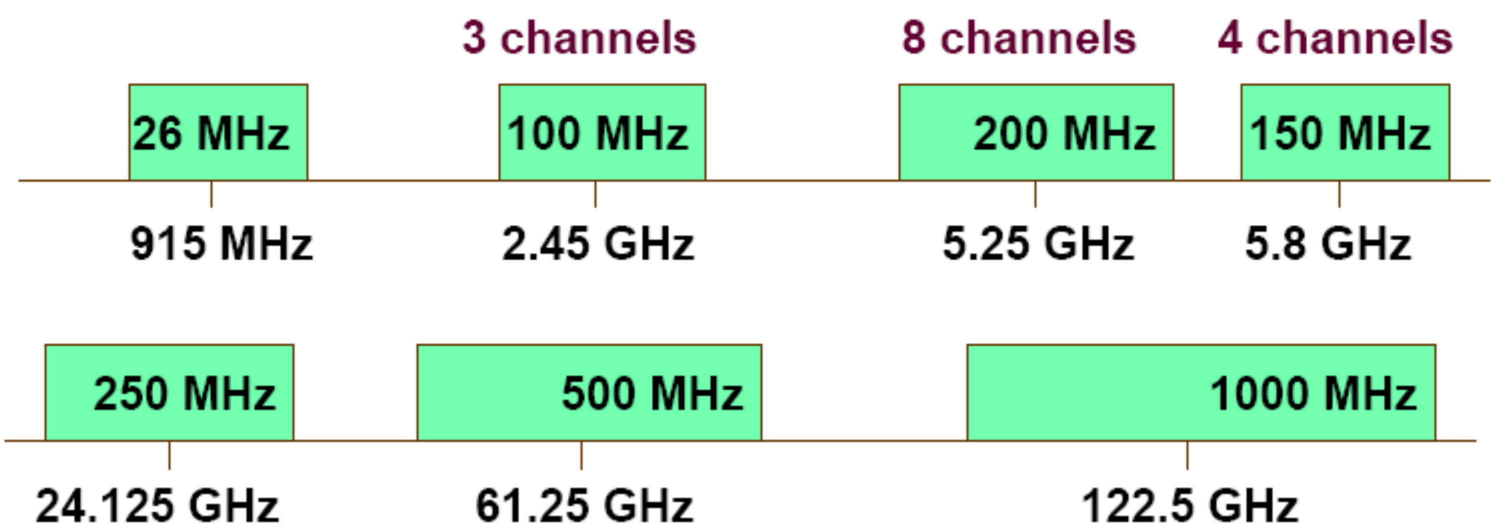


Fairness Issue

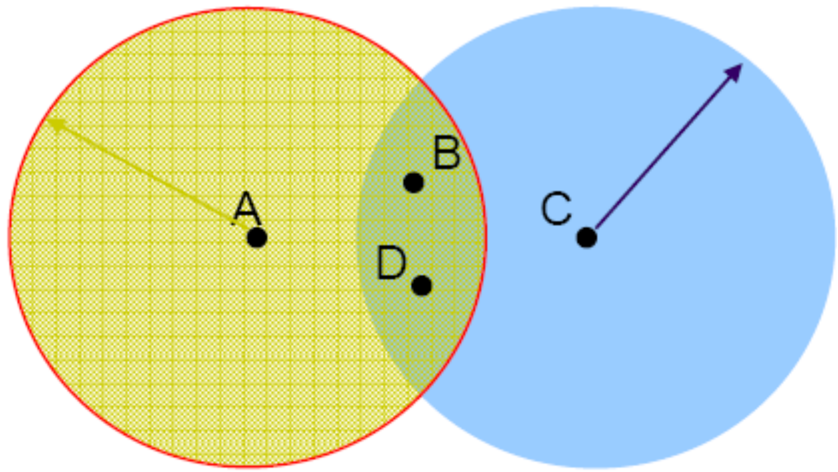
- Unfairness occurs when one node has backed off much more than some other node
- MACAW Solution
  - When a node transmits a packet
    - Append the cw value to the packet
    - all nodes hearing that CW value use it for their future transmission attempts

Channelization of spectrum

- Typically, available frequency spectrum is split into multiple channels
- Some channels may overlap



Preventing Collisions Altogether



- Frequency Spectrum partitioned into several channels
  - Nodes within interference range can use separate channels
  - Now A can send to B while C sends to D without any interference!
  - Aggregate Network throughput doubles

Using Multiple Channels

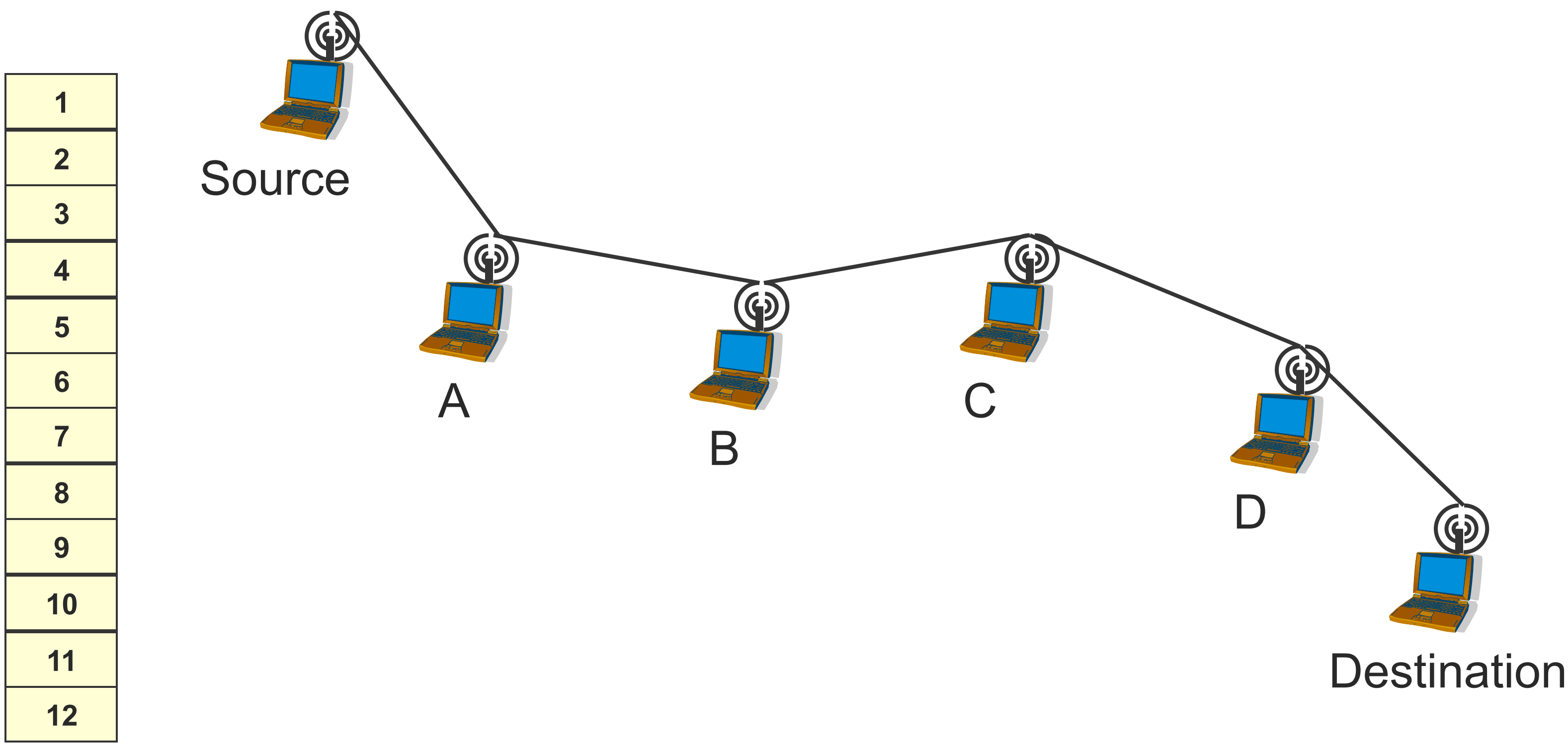
- 802.11: AP’s on different channels
  - Usually manually configured by administrator
  - Automatic Configuration may cause problems
- Most cards have only 1 transceiver
  - Not Full Duplex: Cannot send and receive at the same time
- Multichannel MAC Protocols
  - Automatically have nodes negotiate channels
    - Channel coordination amongst nodes is necessary
    - Introduces negotiation and channel-switching latency that reduce throughput

Wireless Multihop Networks

- Vehicular Networks
  - Delay Tolerant (batch) sending over several hops carry data to a base station
- Common in Sensor Network for periodically transmitting data
  - Infrastructure Monitoring
    - E.g., structural health monitoring of the Golden Gate Bridge
- Multihop networking for Internet connection sharing
  - Routing traffic over several hops to base station connected to Internet

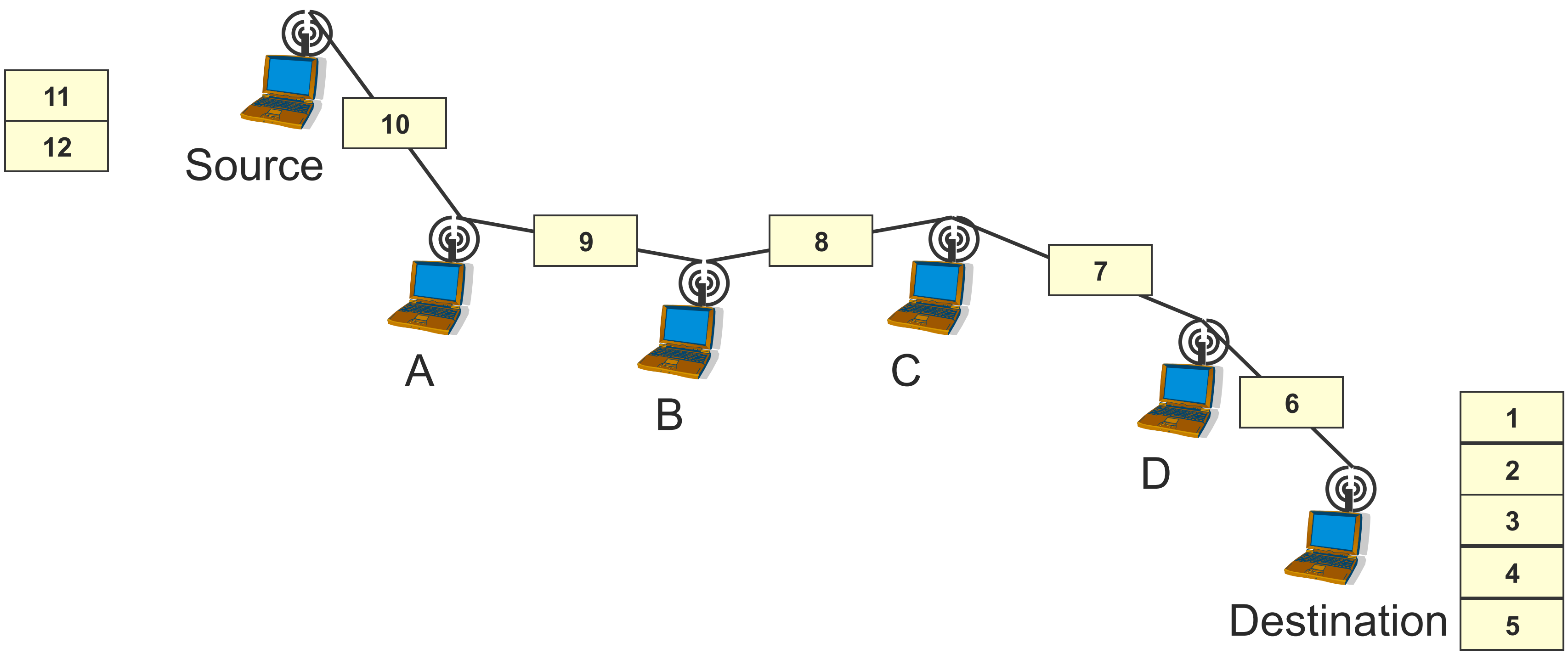
Multi-Hop Wireless Networks

- In an ideal world …



Multi-Hop Wireless Networks

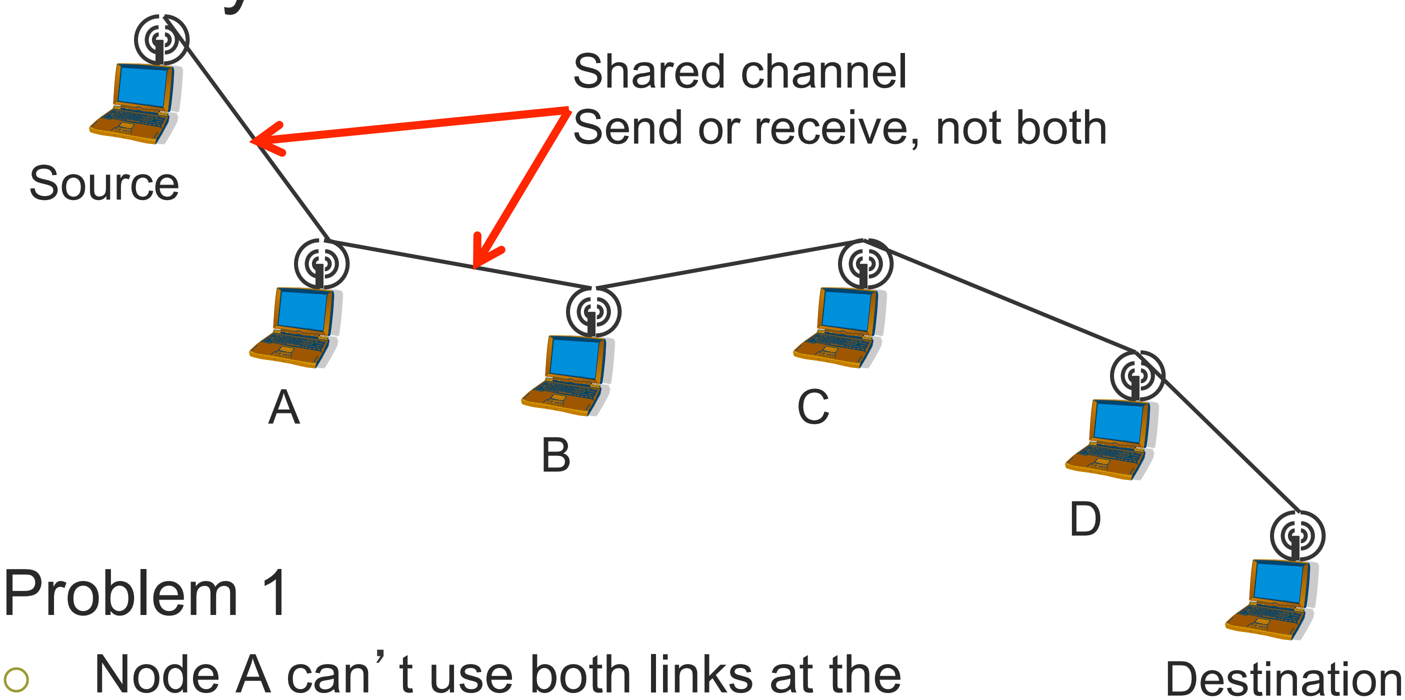
- In an ideal world …



Multi-Hop Wireless Networks

- Reality check …

1
2
3
4
5
6
7
8
9
10
11
12

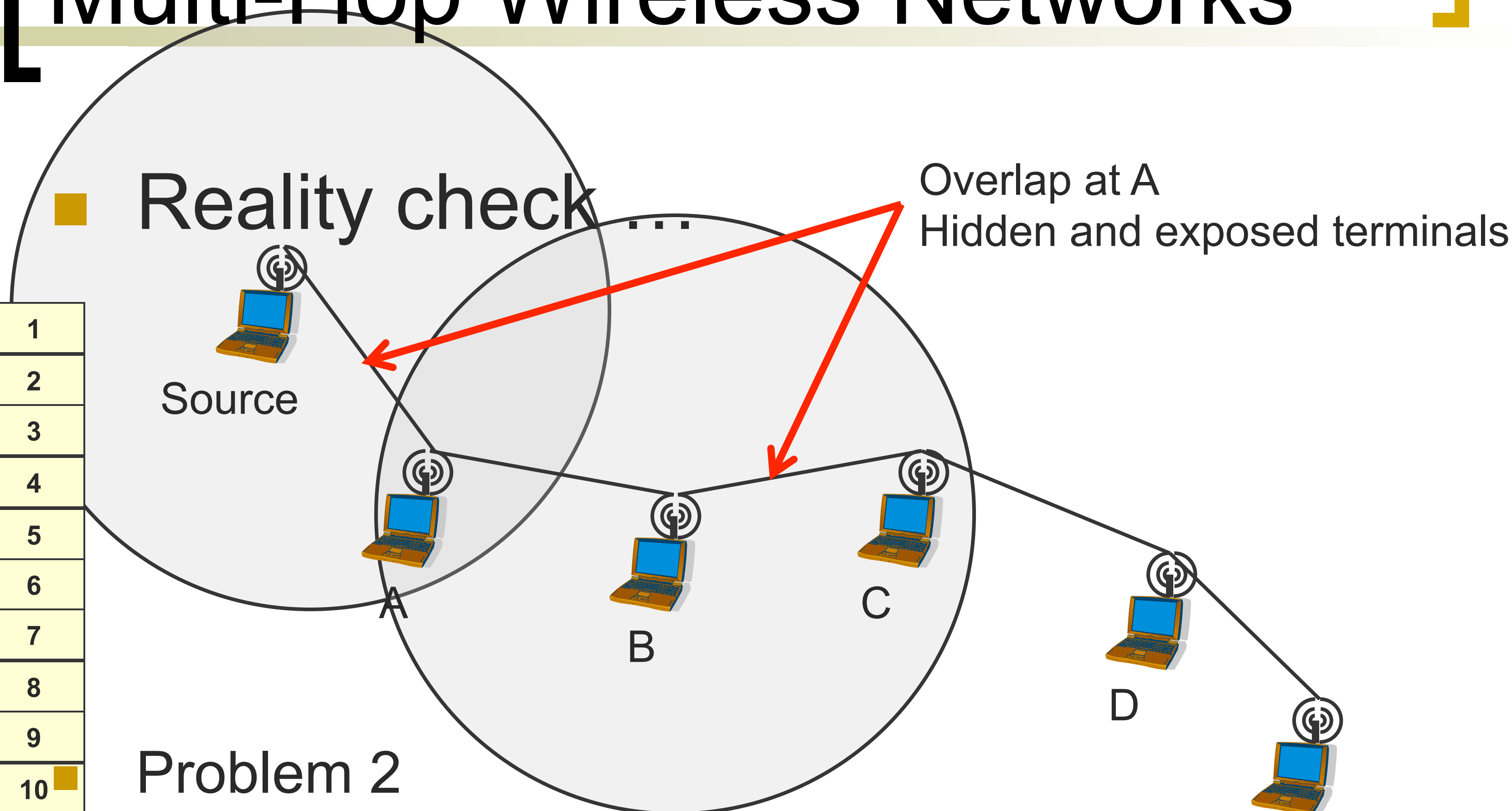


Problem 1

- Node A can't use both links at the same time

Multi-Hop Wireless Networks

- Reality check …



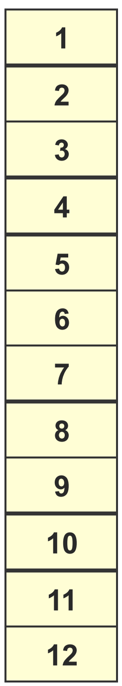
Problem 2

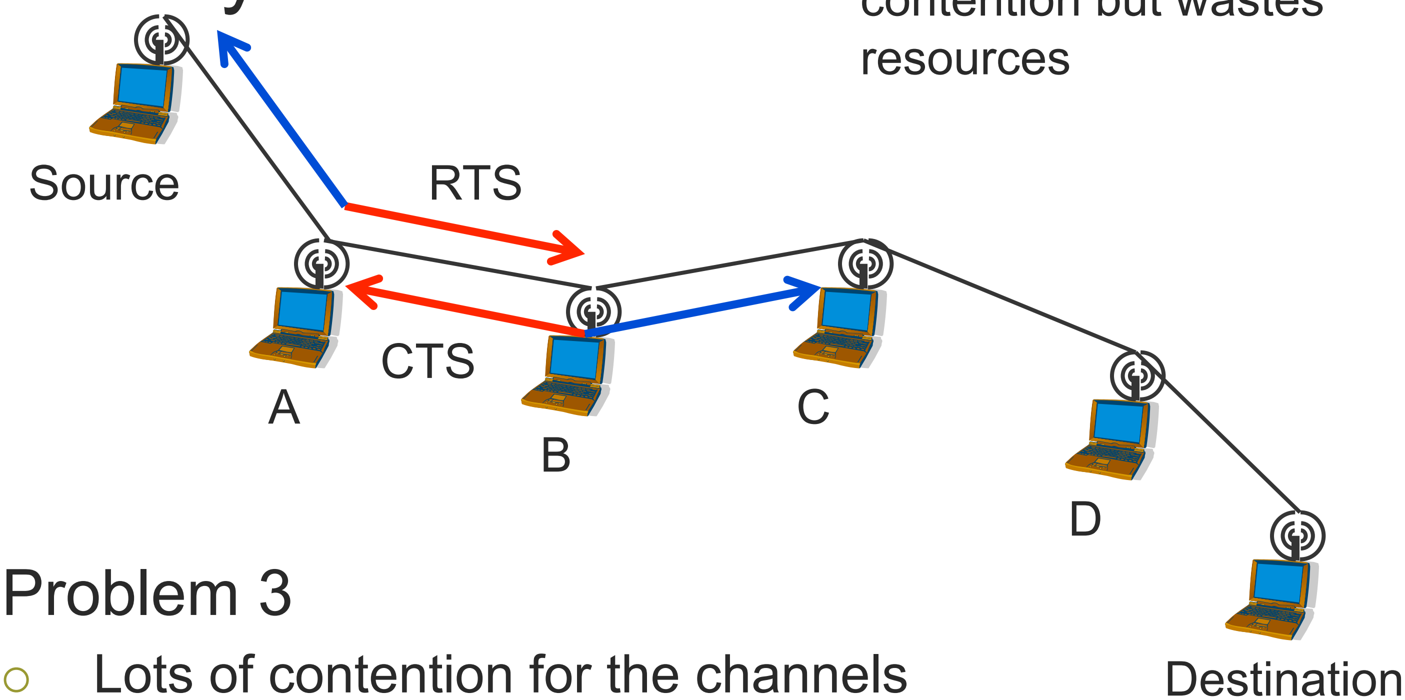
- Can't use both links at the same time

Multi-Hop Wireless Networks

- Reality check …

RTS/CTS helps with contention but wastes resources





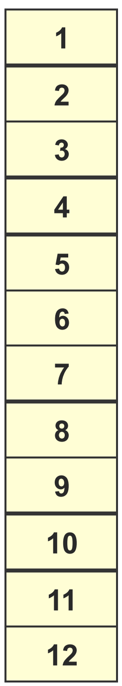
Problem 3

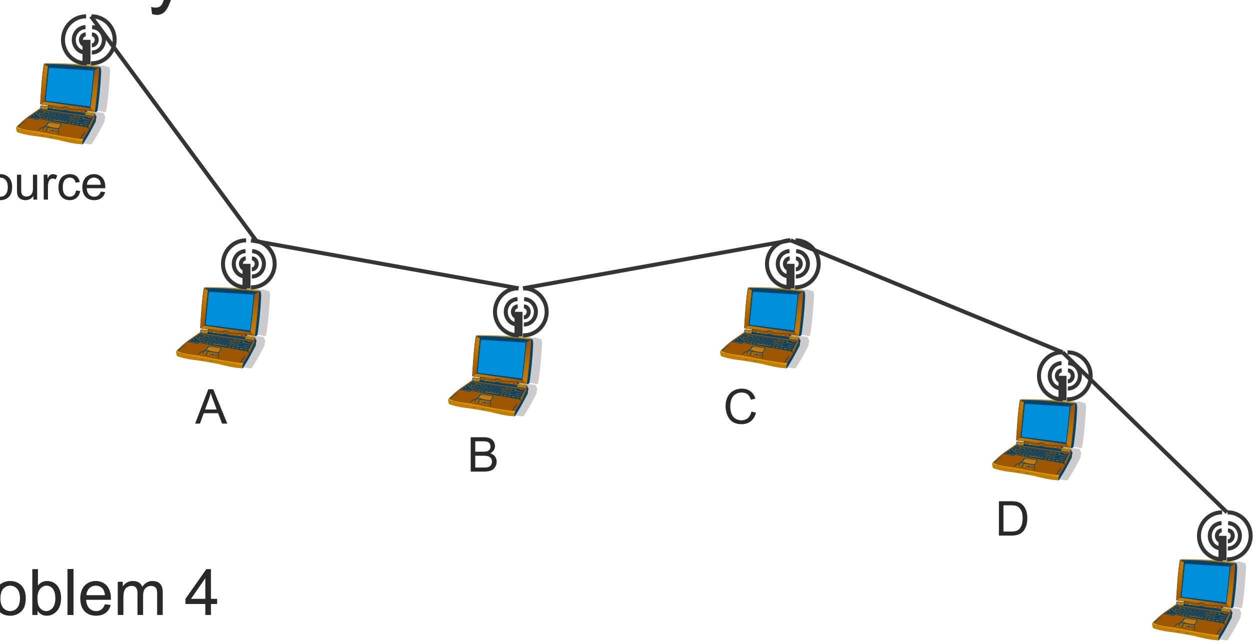
- Lots of contention for the channels
- Everyone wants to send

Multi-Hop Wireless Networks

- Reality check …

Higher layer protocols



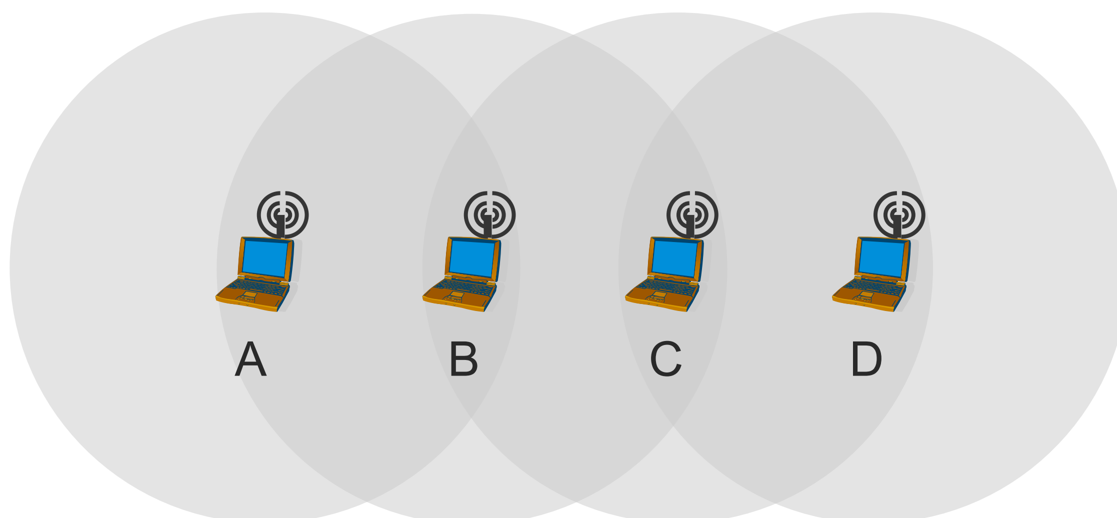


Problem 4

- TCP uses ACKS and bidirectional channels
- Even more contention!

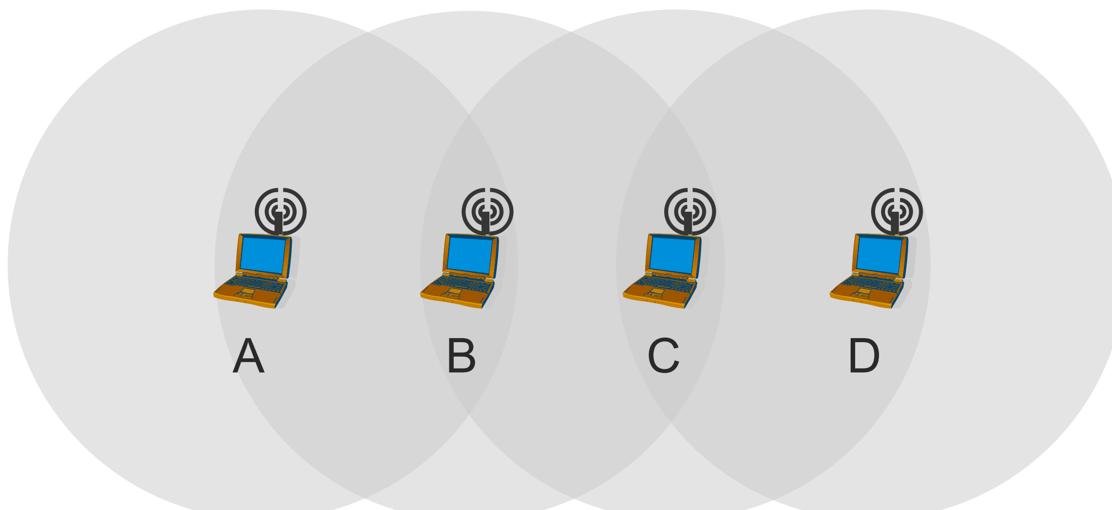
Bandwidth use in Ideal Scenarios

- A can only transmits to B; B to A and C; C to B and D; D to C
- Node A has an infinite supply of messages to send to D and there are no other messages in the network



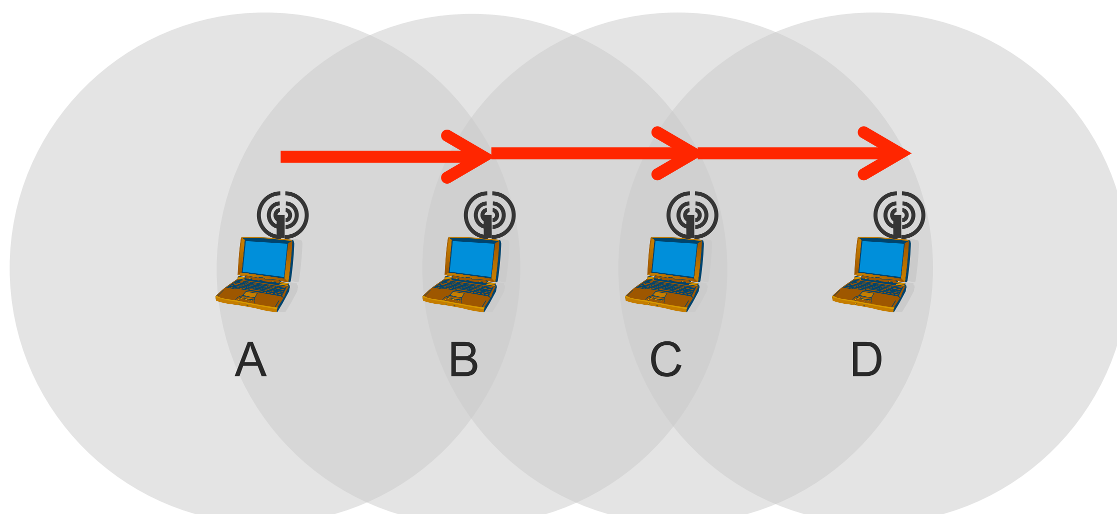
Bandwidth use in Ideal Scenarios

- Time is slotted, message transmission takes exactly one slot
- During a slot, a node can
  - send a message, receive a message, remain silent
- If a node hears two or more simultaneous transmissions, a collision occurs



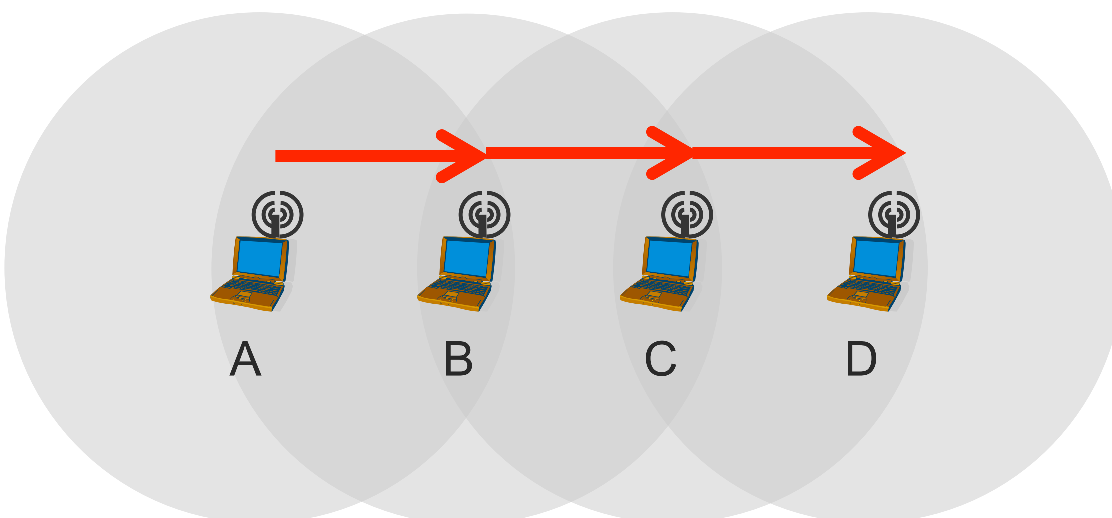
Bandwidth use in Ideal Scenarios

- Suppose a controller can command each node
- What is the maximum rate (message/slot) at which messages can be transferred from A to D?



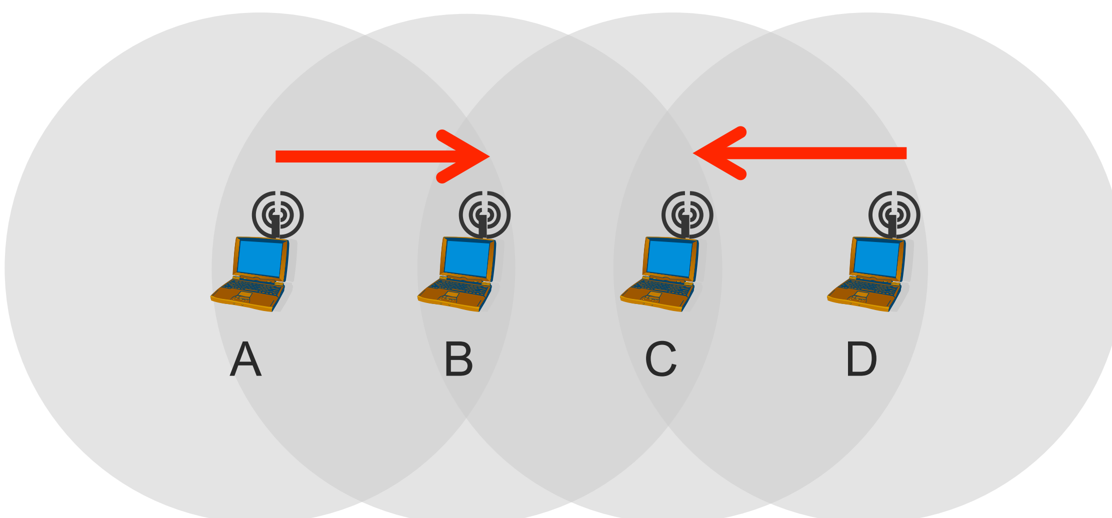
Bandwidth use in Ideal Scenarios

- Suppose a controller can command each node
- What is the maximum rate (message/slot) at which messages can be transferred from A to D?
- Who can transmit when A is transmitting?
  - C
- When B?
  - None
- When C?
  - A
- Answer
  - 1 msg/2 slots



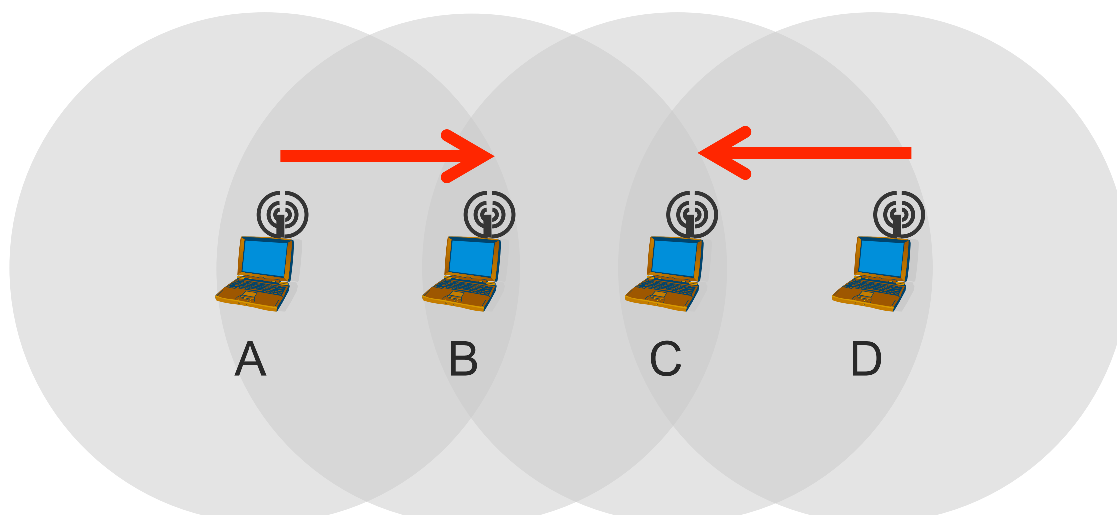
Bandwidth use in Ideal Scenarios

- Suppose now that A sends messages to B, and D sends messages to C
- What is the combined maximum rate at which data messages can flow from A to B and from D to C?



Bandwidth use in Ideal Scenarios

- Suppose now that A sends messages to B, and D sends messages to C
- What is the combined maximum rate at which data messages can flow from A to B and from D to C?
- Answer
  - A and D can transmit at the same time
  - 2 msgs/slot



Bandwidth use in Ideal Scenarios

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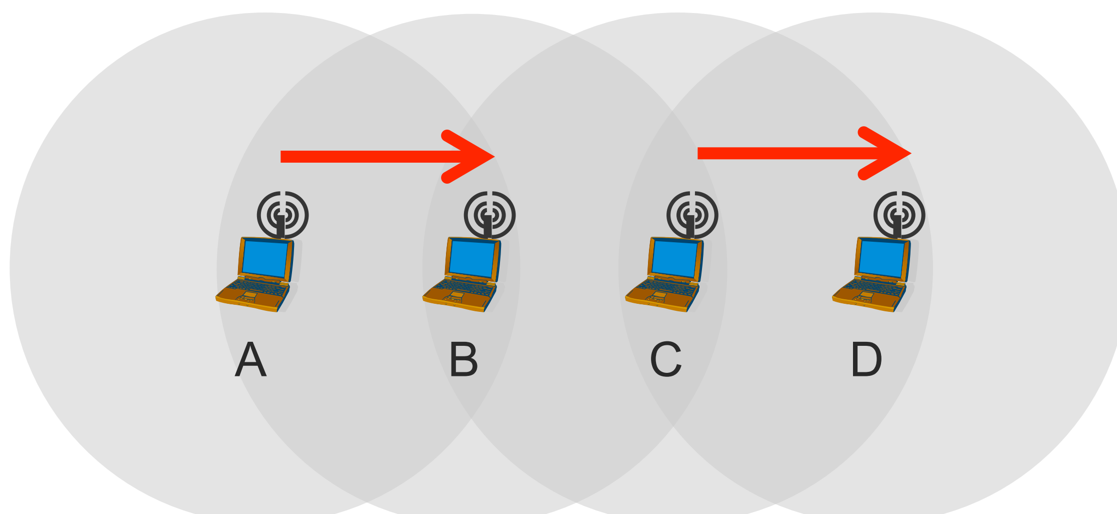
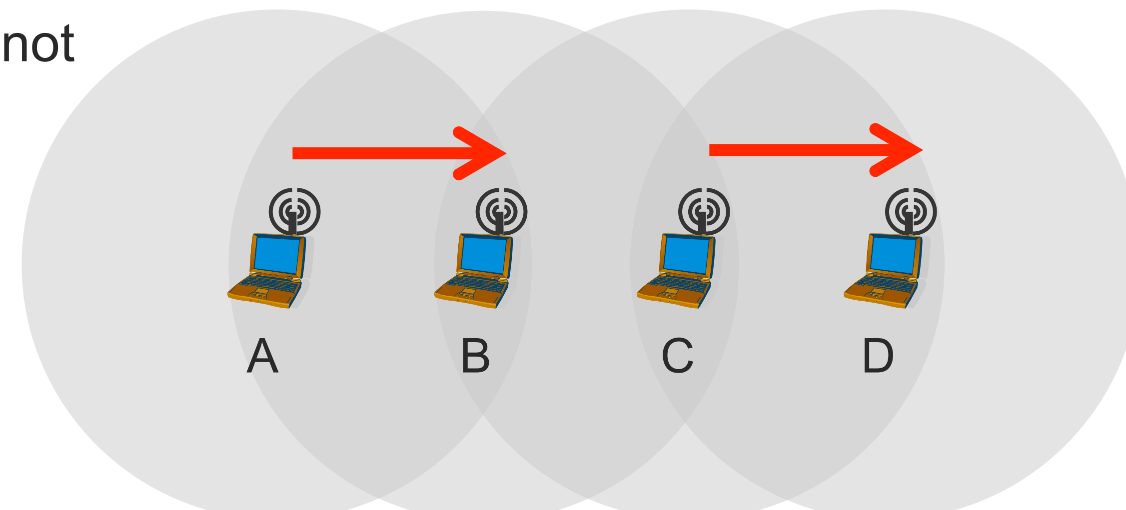


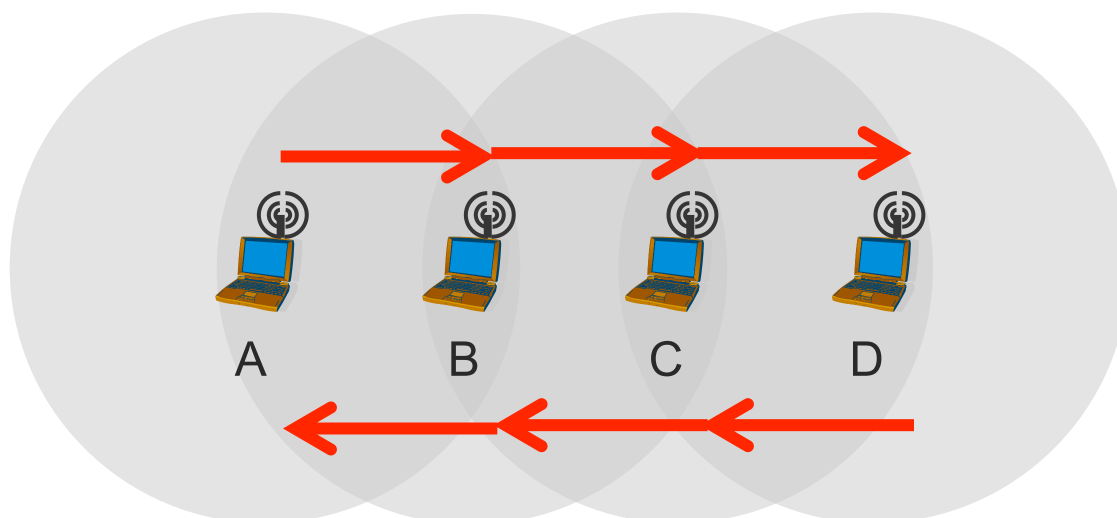
Bandwidth use in Ideal Scenarios

- Suppose now that A sends messages to B, and C sends messages to D
- What is the combined maximum rate at which data messages can flow from A to B and from C to D?
- Answer
  - A and C cannot transmit at the same time
  - 1 msg/slot



Bandwidth use in Ideal Scenarios

- Now suppose for every data message sent from source to destination, the destination will send an ACK message back to the source
- What is the maximum rate (message/slot) at which messages can be transferred from A to D?



Bandwidth use in Ideal Scenarios

- Now suppose for every data message sent from source to destination, the destination will send an ACK message back to the source
- What is the maximum rate (message/slot) at which messages can be transferred from A to D?
- Answer
  - Each message requires two transmissions
  - 1 msg/4 slots