



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

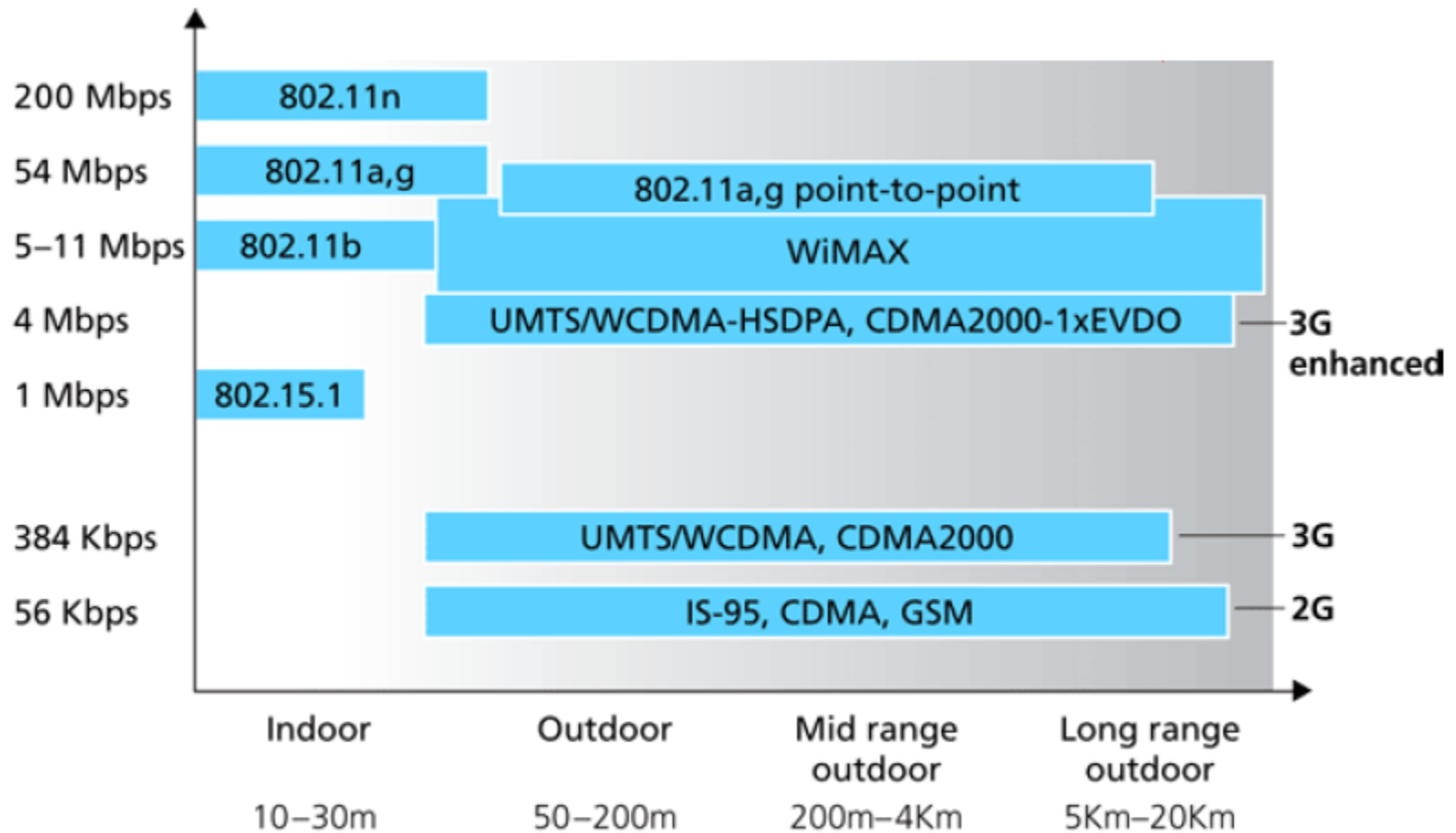


Wireless Communication Standards (Alphabet Soup)

- 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



[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

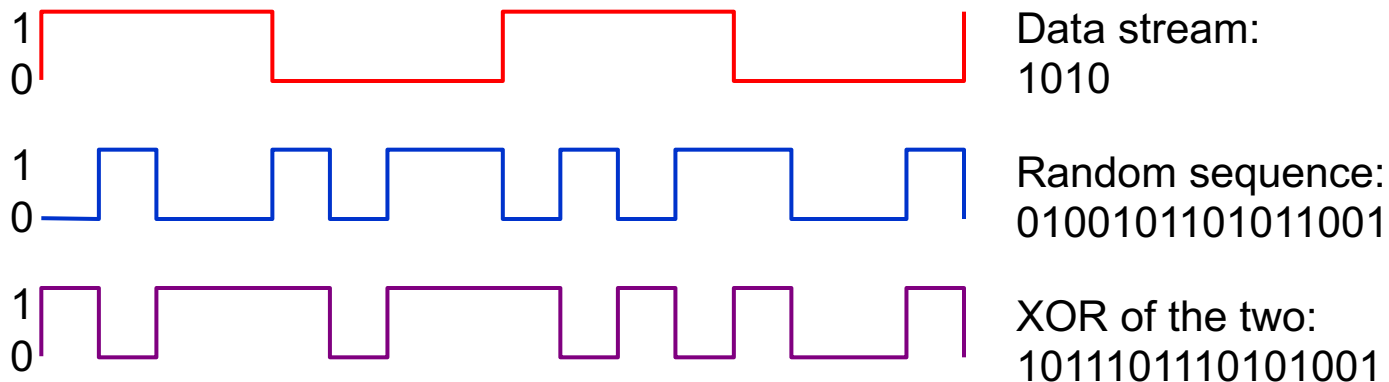
- Direct Sequence Spread Spectrum
 - Orthogonal Frequency
 - Orthogonal Code
- Frequency Hopping
 - Used in Bluetooth
 - Transmits over multiple frequencies
- Frequency hopping had many inventors
 - 1942: actress Hedy Lamarr and composer George Antheil patented Secret Communications System
 - Piano-roll 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)



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 speed

- Frequency

- Defines the behavior in the physical environment

- Range

- Defines the physical communication area

- Power

- Defines the ... 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

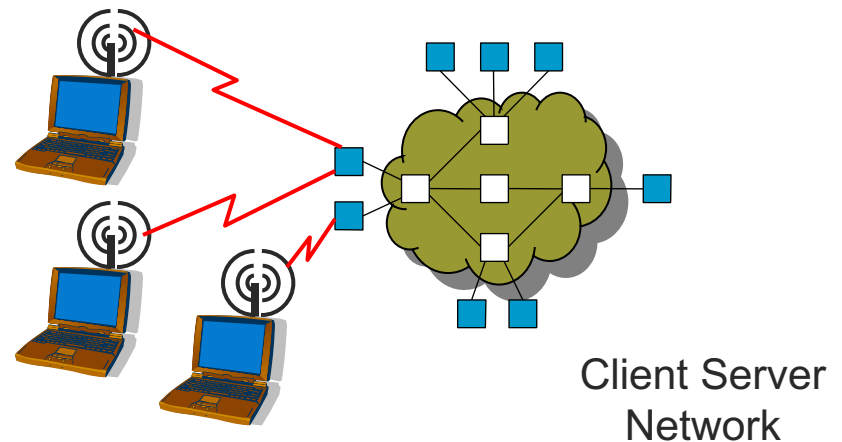
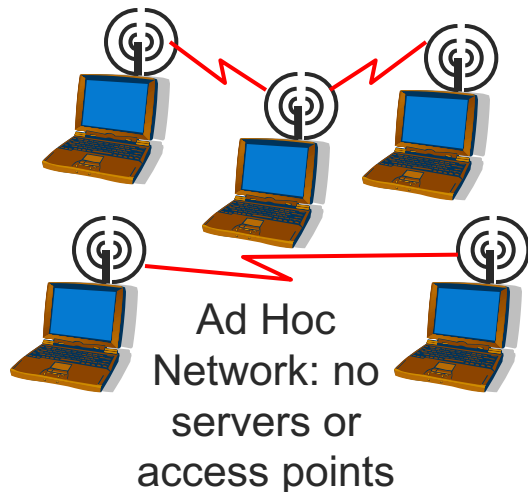




Media Access Control Protocols

Medium Access Control

- IEEE 802.11
 - A physical and multiple access layer standard for wireless local area networks (WLAN)



[Medium Access Control]

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



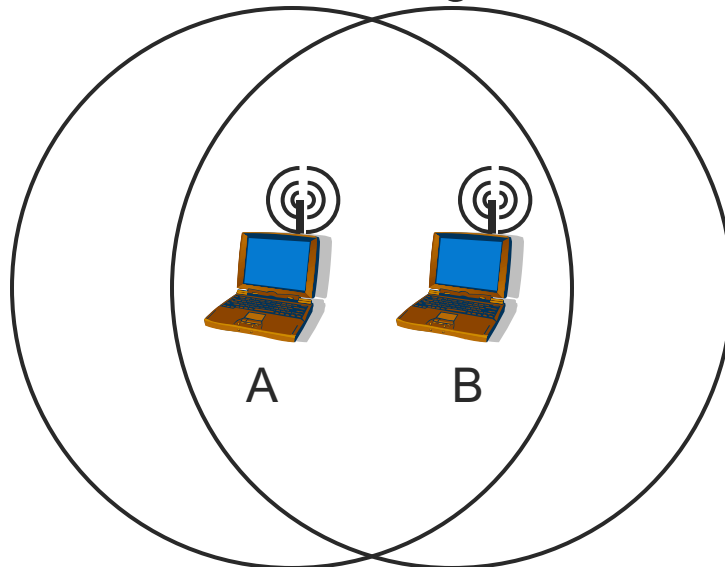
Ethernet MAC Algorithm



- 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!



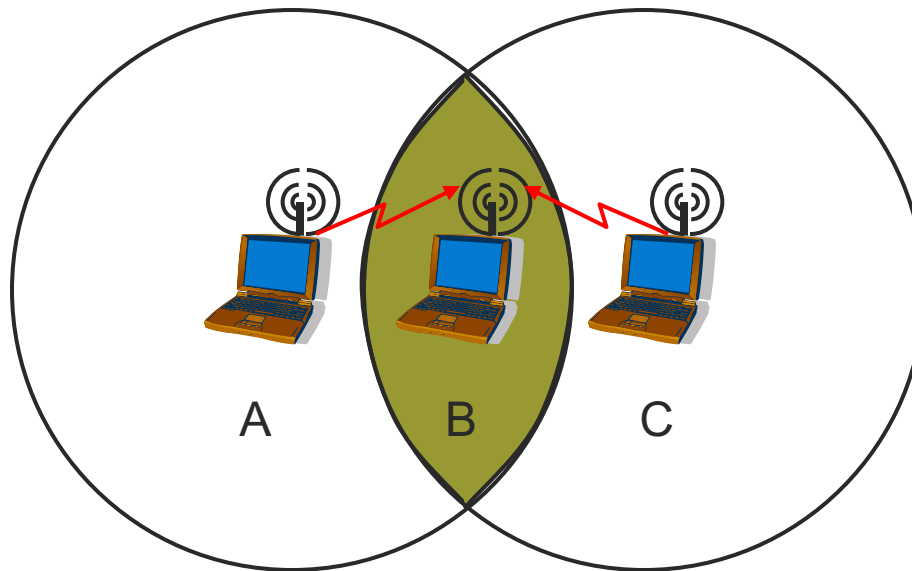
Wireless Ethernet - CSMA/CA

- 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 **A**voidance
 - Nodes use protocol to prevent collisions from occurring



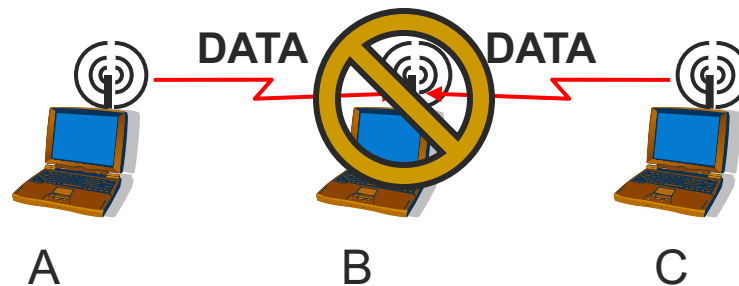
IEEE 802.11 MAC Layer Standard

- Similar to Ethernet
- But consider the following:



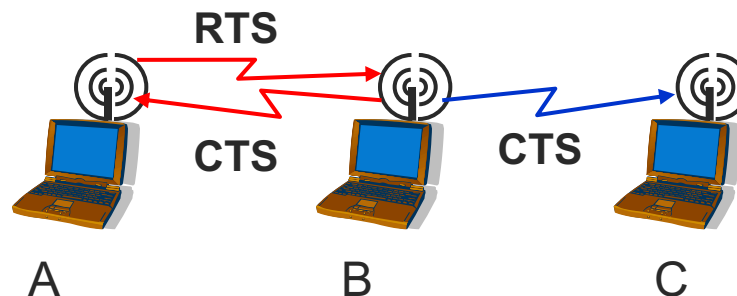
Hidden Terminal Problem

- 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



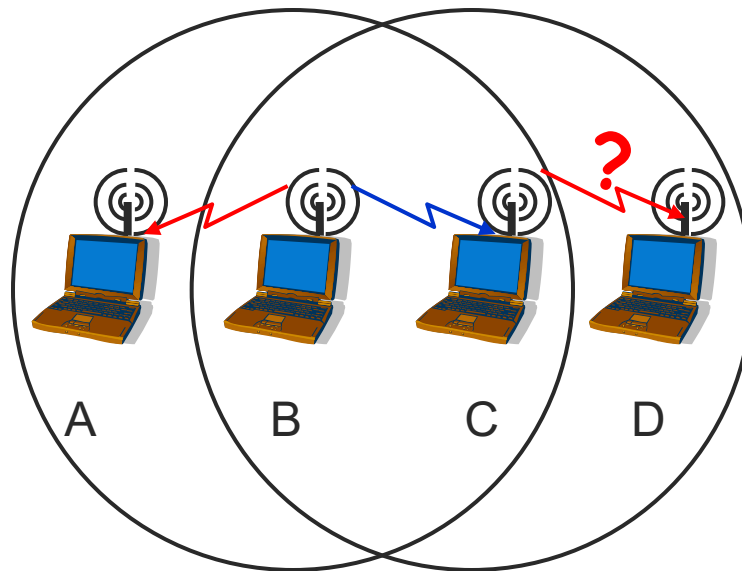
MACA Solution for Hidden Terminal Problem

- 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



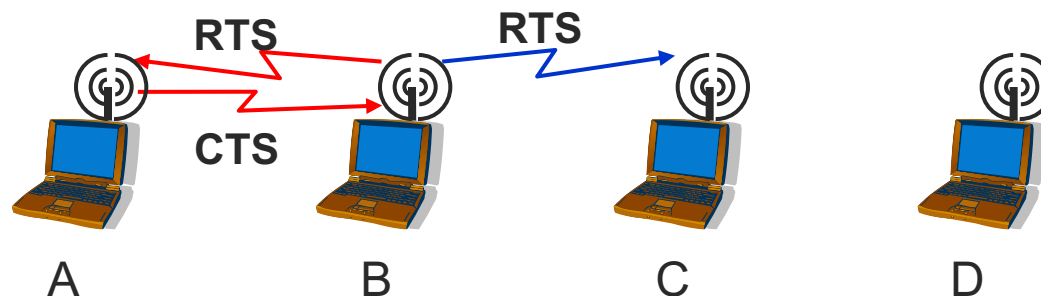
IEEE 802.11 MAC Layer Standard

- But we still have a problem



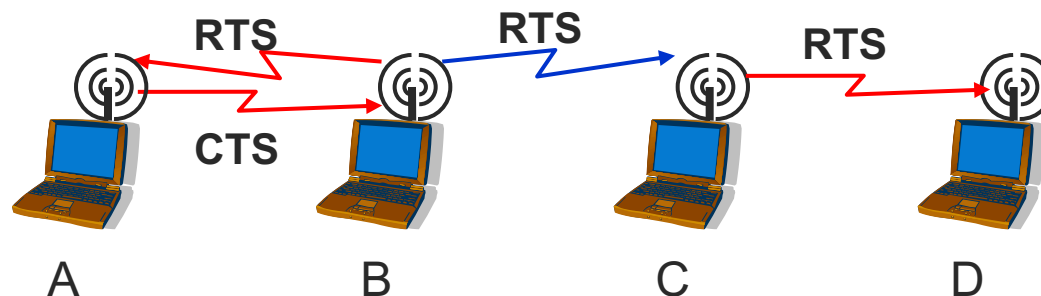
Exposed Terminal Problem

- 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



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



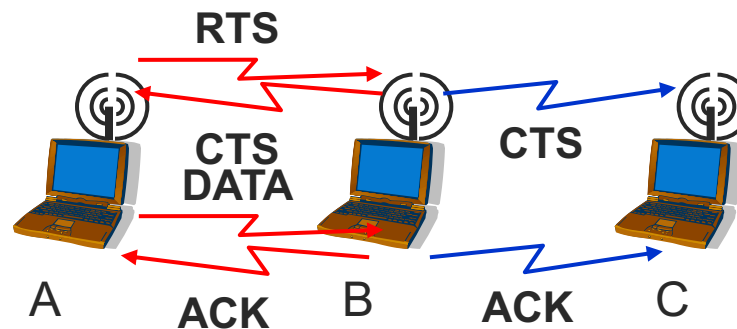
[Reliability]

- 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



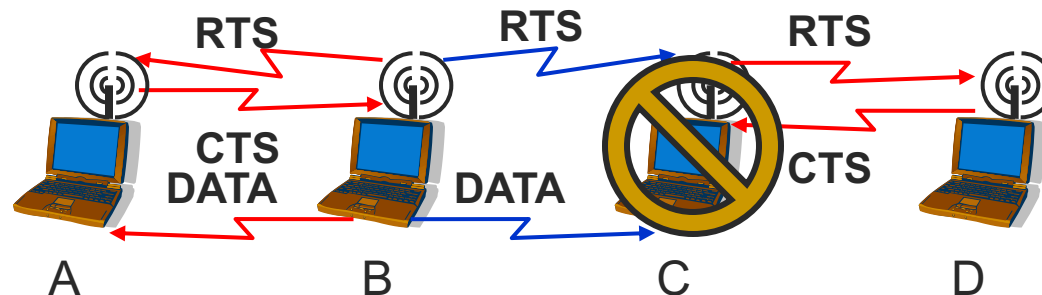
A Simple Solution to Improve Reliability - MACAW

- 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



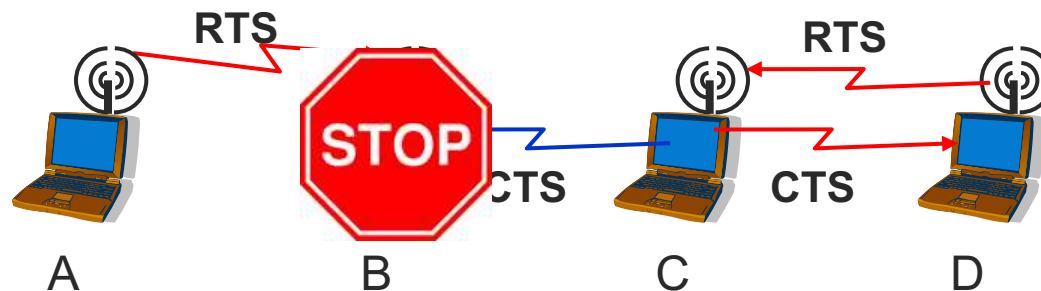
Revisiting the Exposed Terminal Problem

- 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



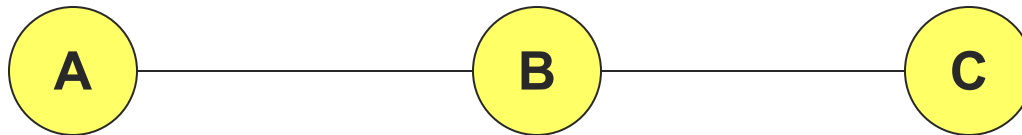
IEEE 802.11 Wireless MAC

- 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



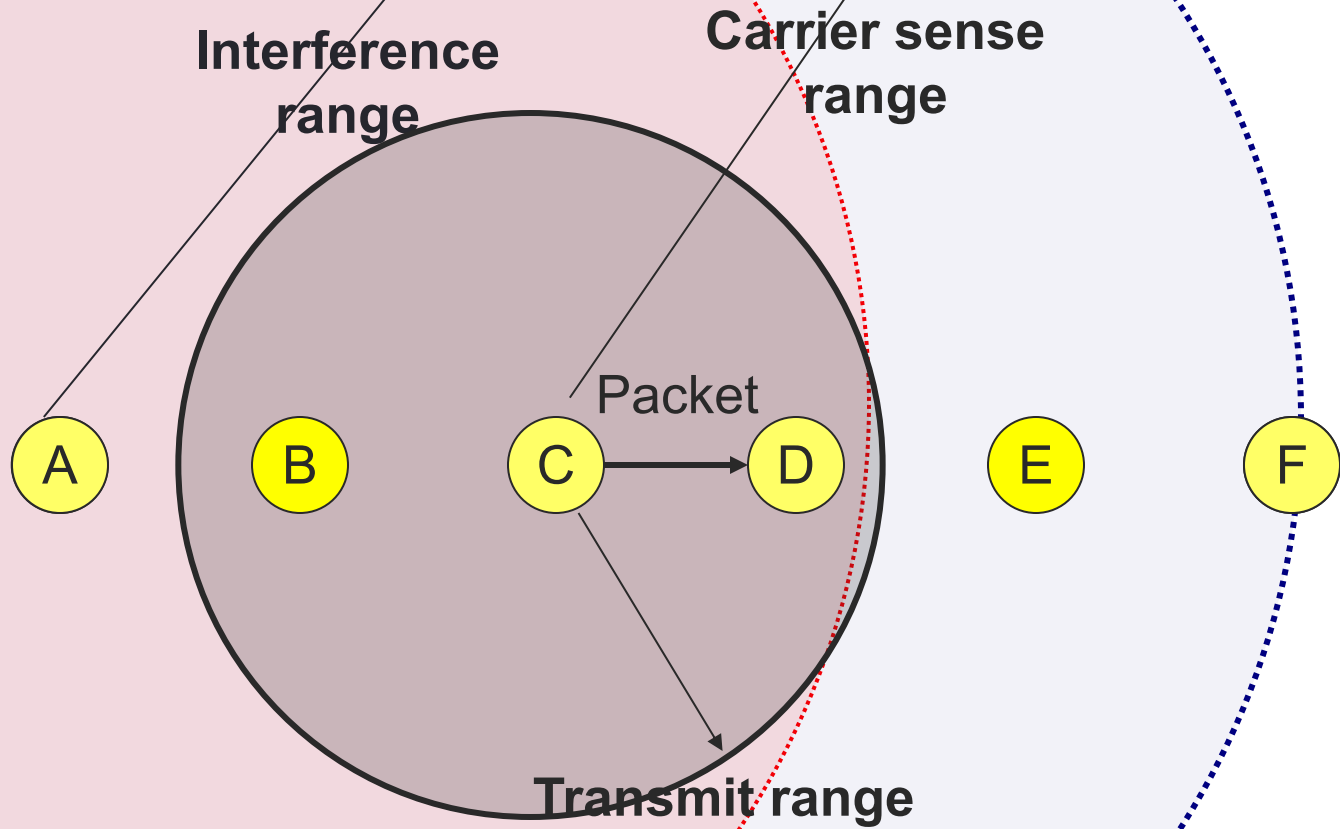
IEEE 802.11 CSMA/CA

- 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

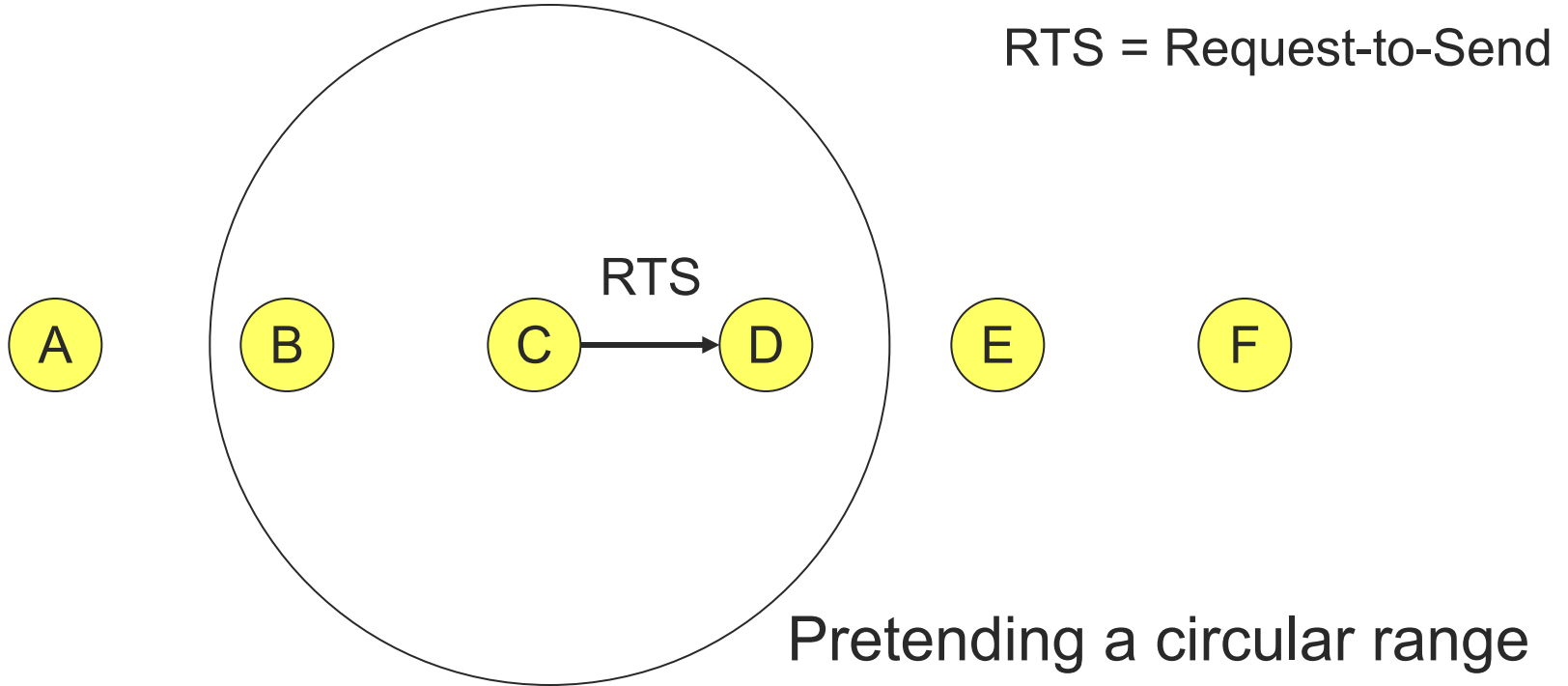


IEEE 802.11 Physical Carrier Sense

Sense



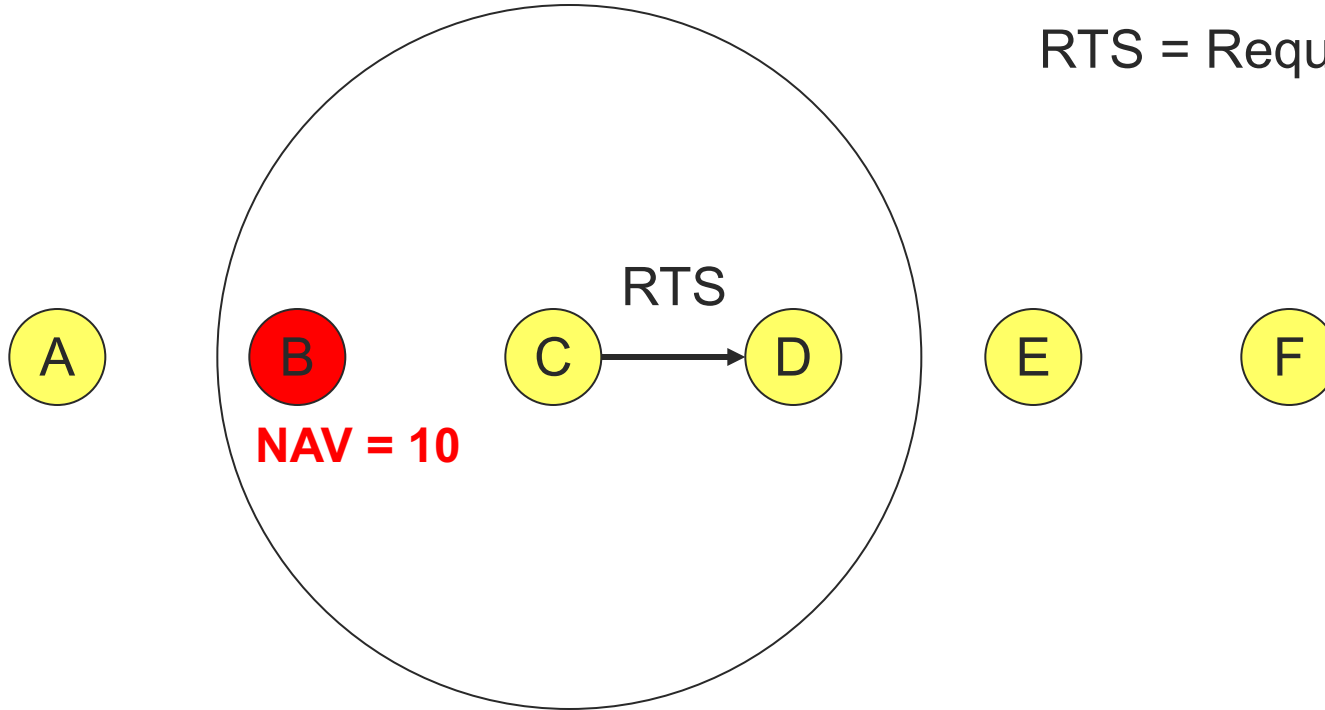
IEEE 802.11 Virtual Carrier Sense



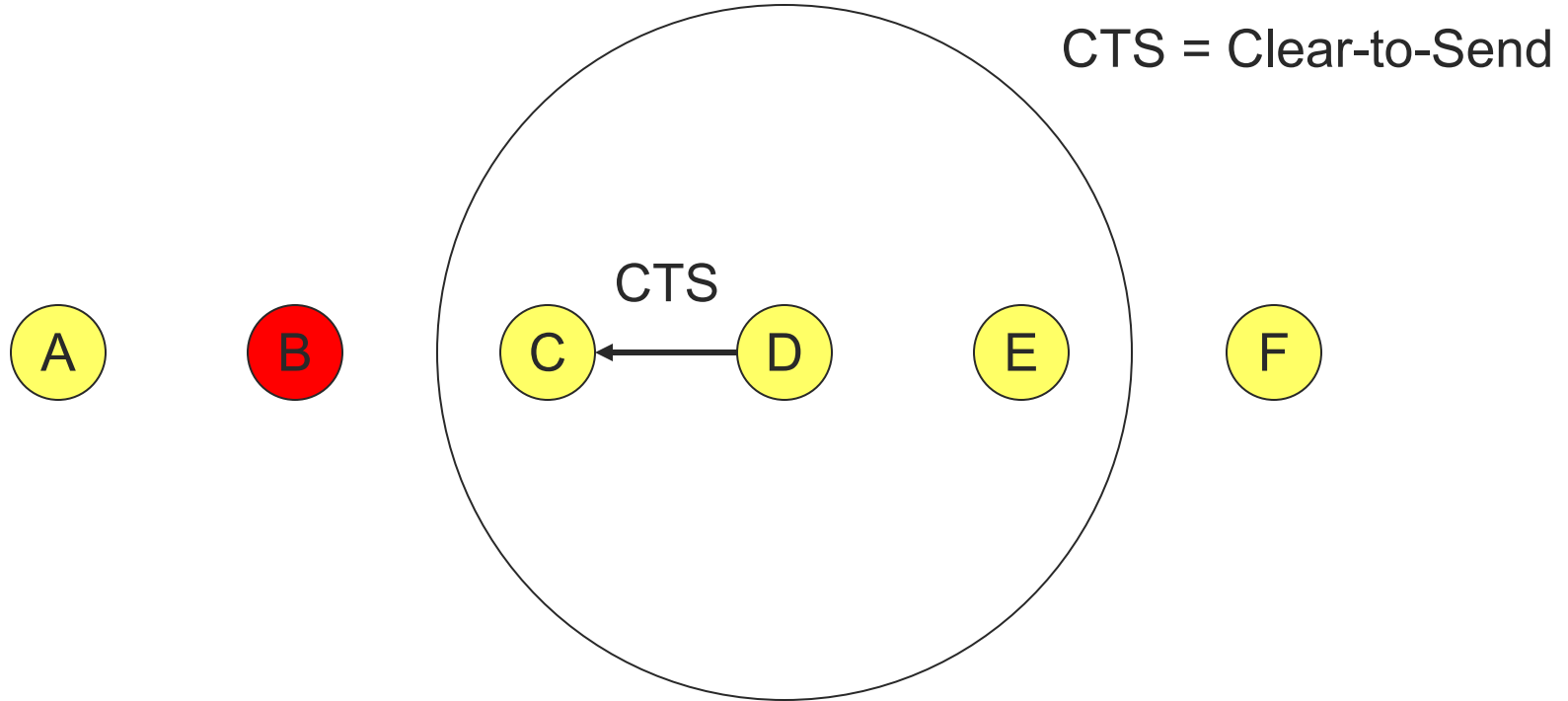
IEEE 802.11 Virtual Carrier Sense

NAV = remaining duration to keep quiet

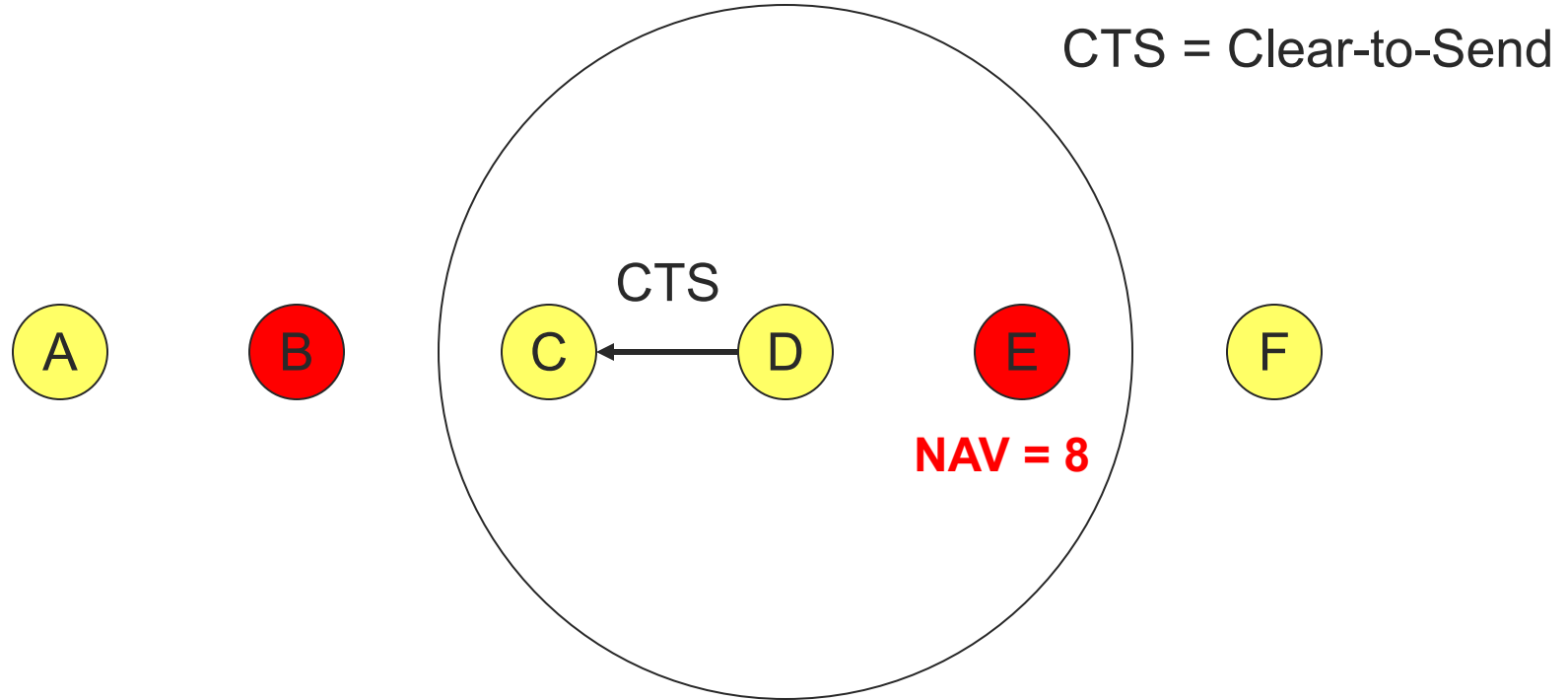
RTS = Request-to-Send



IEEE 802.11 Virtual Carrier Sense

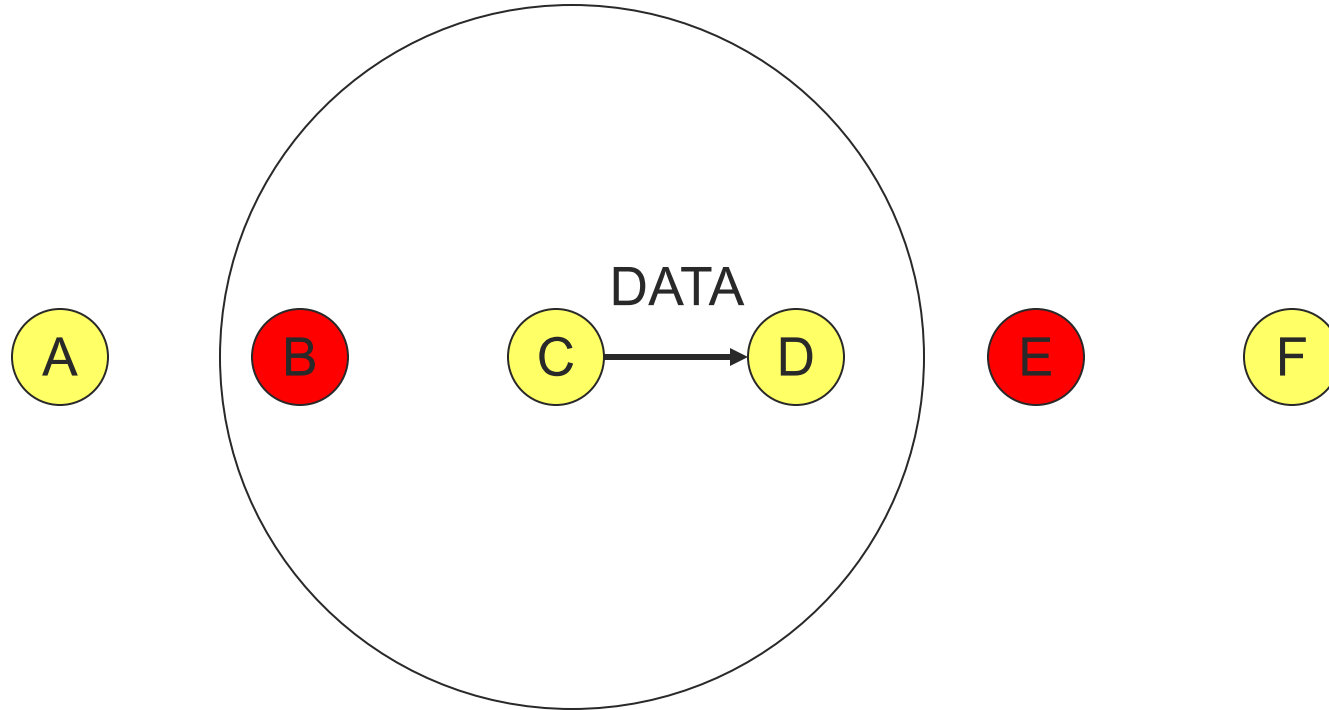


IEEE 802.11 Virtual Carrier Sense



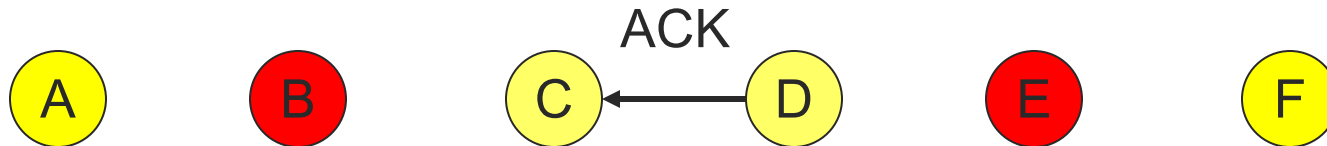
IEEE 802.11 Virtual Carrier Sense

- DATA packet follows CTS

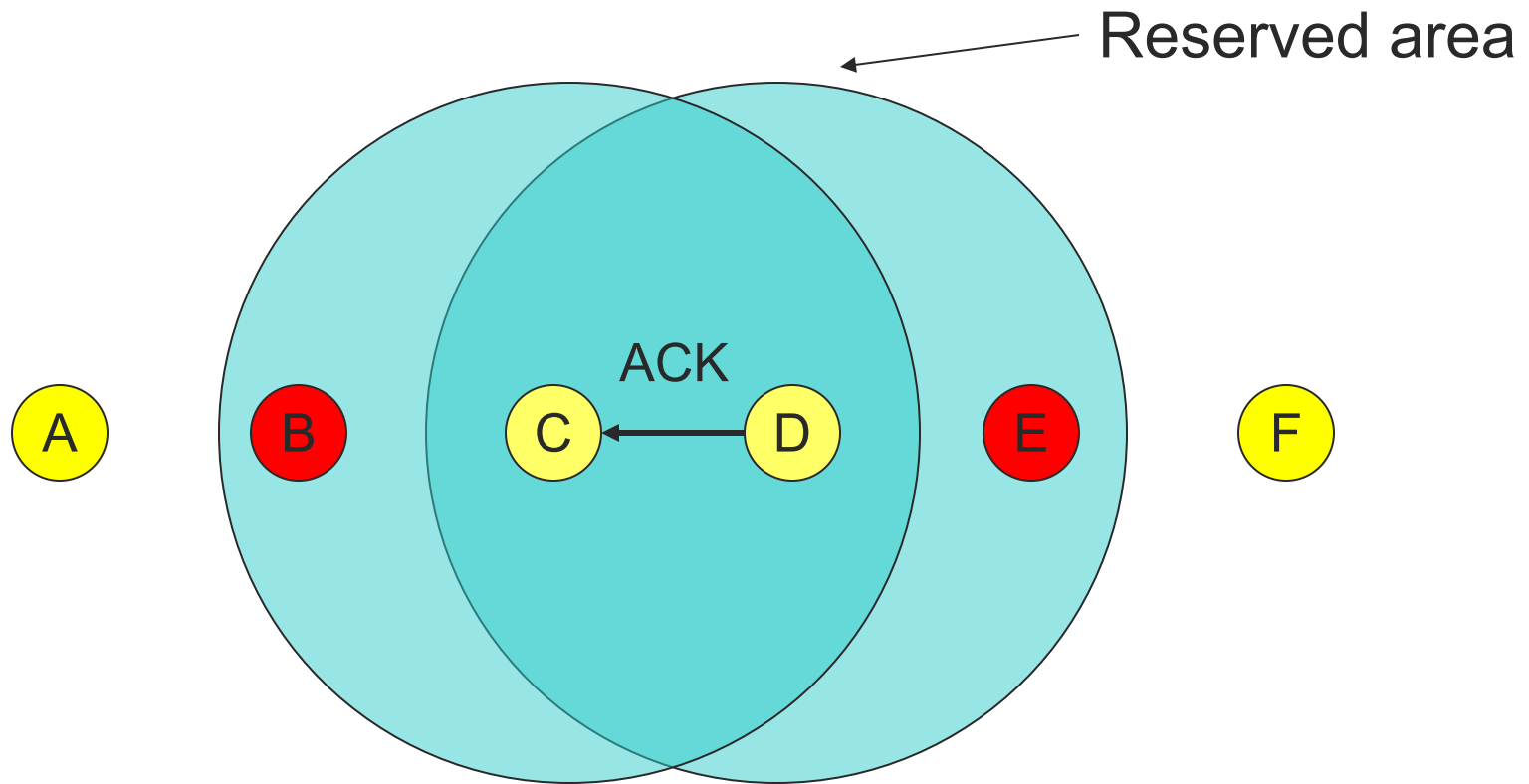


IEEE 802.11 Virtual Carrier Sense

- Successful data reception acknowledged using ACK



[IEEE 802.11]



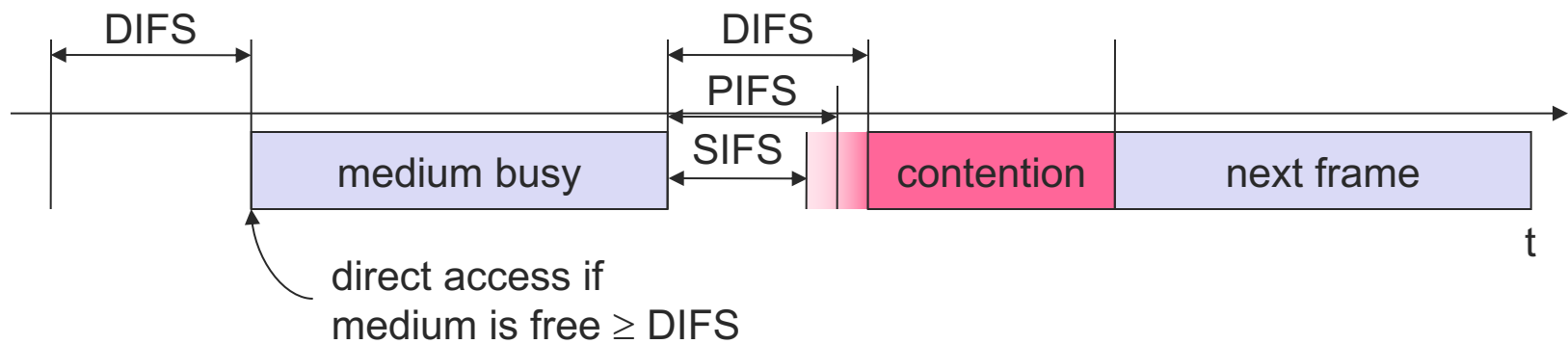
Ethernet vs. IEEE 802.11

- 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?



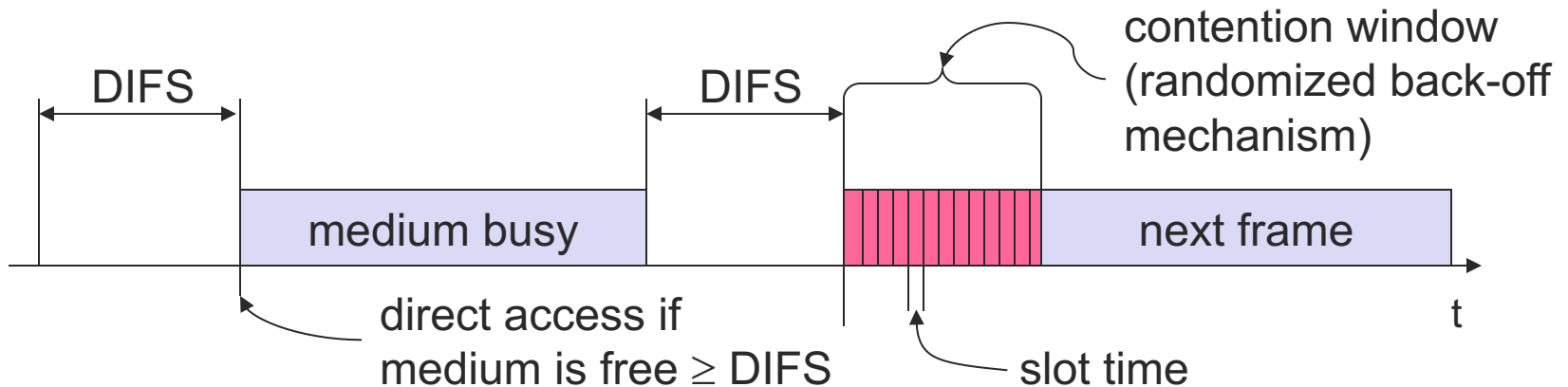
[Interframe Spacing]

- 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)

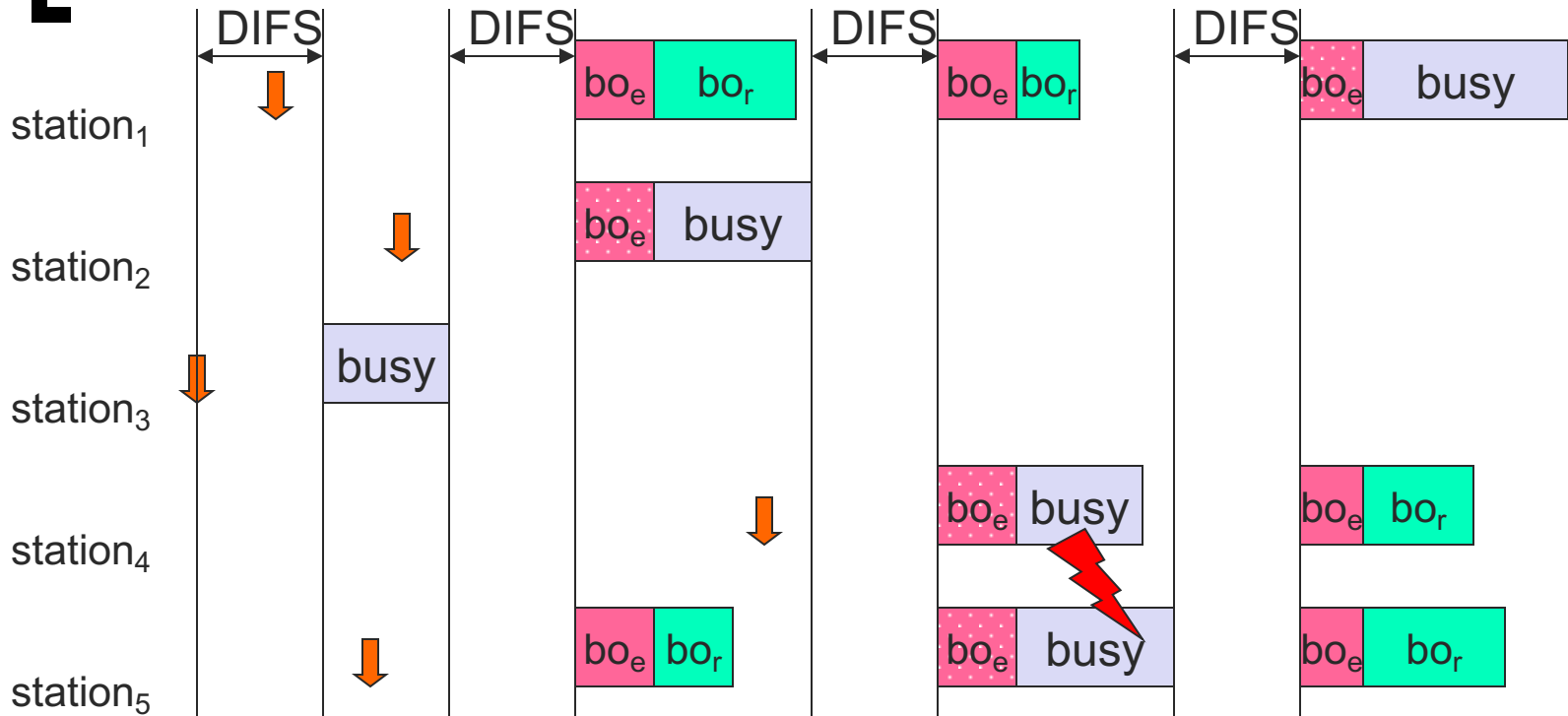


[Types of IFS]

- 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



busy

medium not idle (frame, ack etc.)

bo_e

elapsed backoff time



packet arrival at MAC

bo_r

residual backoff time

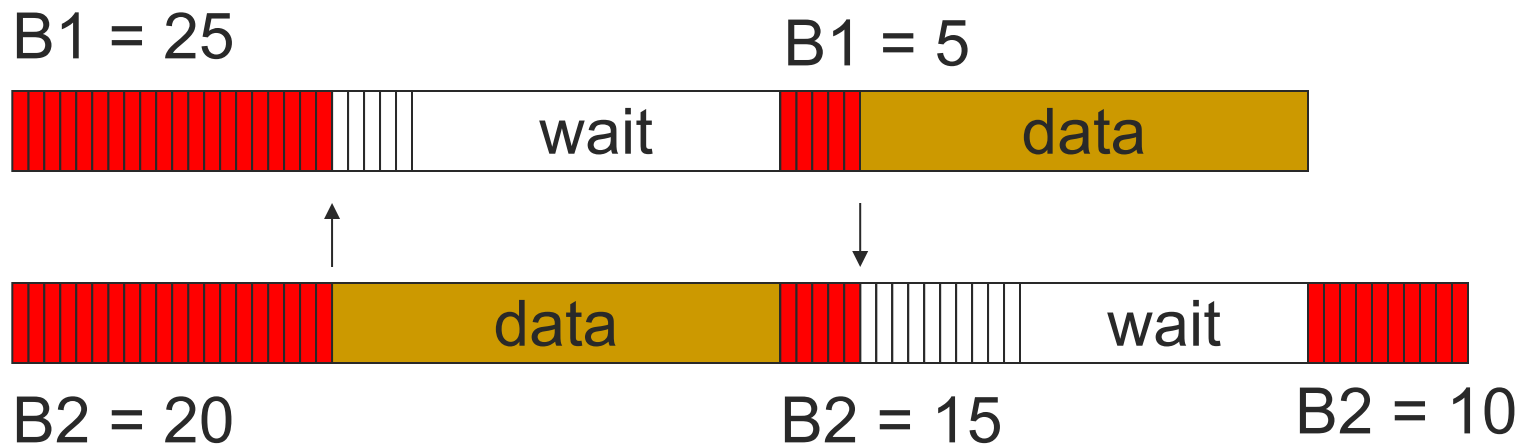


[Backoff Interval]

- 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



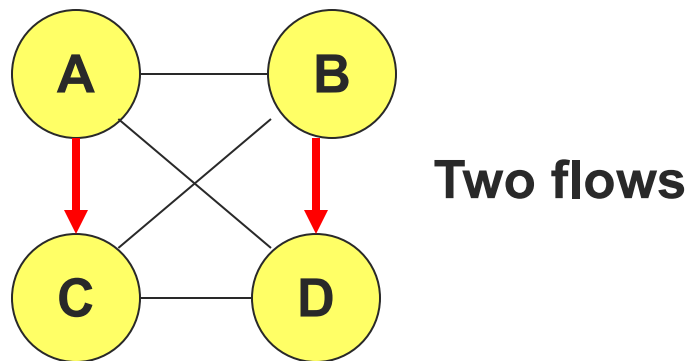
Binary Exponential Backoff in DCF

- 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



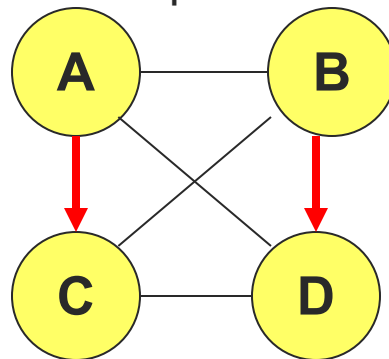
Fairness Issue

- 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



Two flows

[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



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 Millimeter 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)



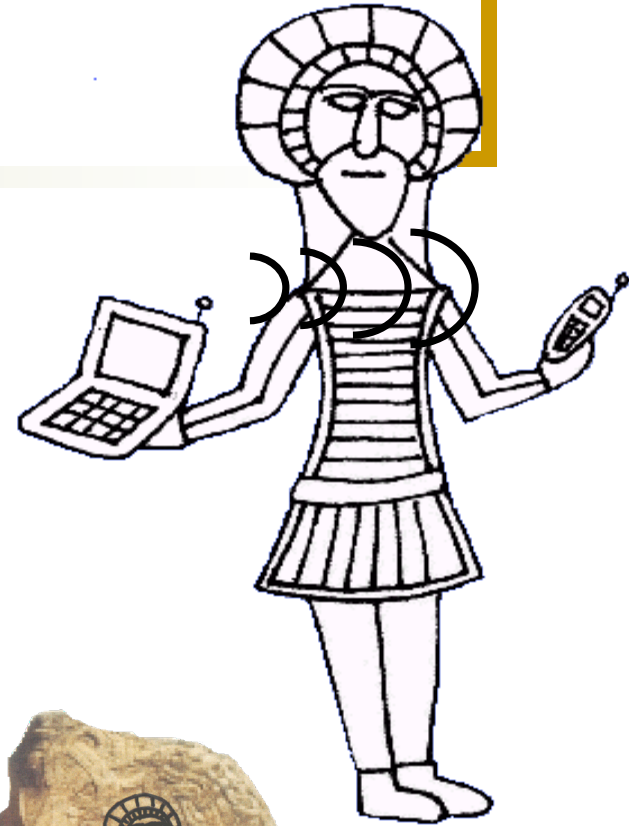
Other Technologies

- 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)



Bluetooth

- Harald Blaatand “Bluetooth” II
 - King of Denmark 940-981 AC
- Runic stones in his capital city of Jelling
 - The stone’s inscription (“runes”) says:
 - Harald Christianized the Danes
 - Harald controlled the Danes
 - Harald believes that devices shall seamlessly communicate [wirelessly]

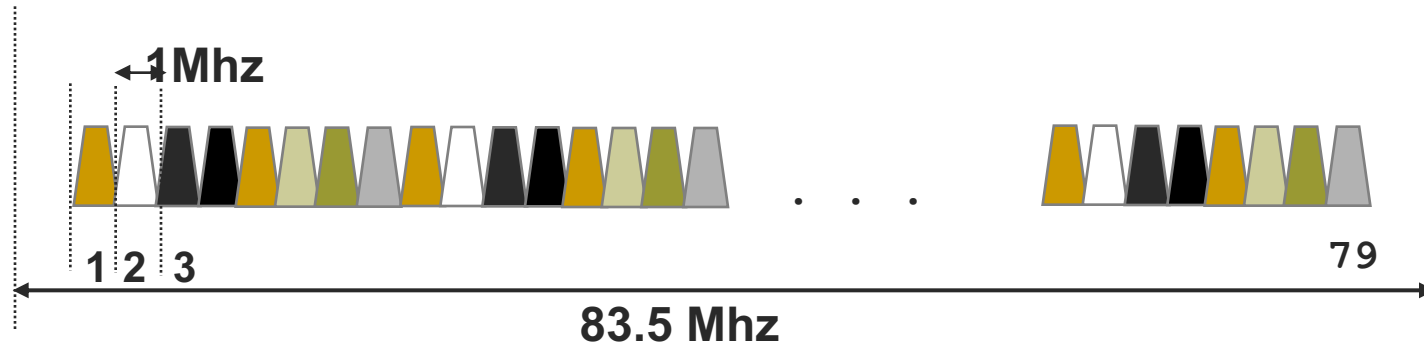


Classic Bluetooth

- Cable replacement
 - 2.4 GHz
 - FHSS over 79 channels (of 1MHz each), 1600hops/s
 - 1Mbps
 - Coexistence of multiple piconets
 - 10 meters (extendible to 100 meters)



Bluetooth Radio

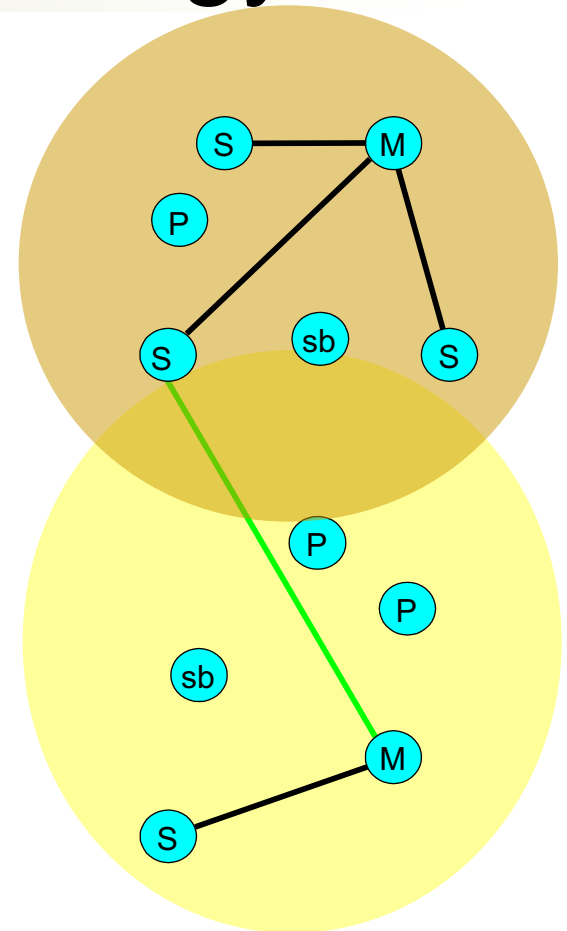


- MA scheme: Frequency hopping spread spectrum.
 - $2.402 \text{ GHz} + k \text{ MHz}$, $k=0, \dots, 78$
 - 1,600 hops per second.
 - 1 Mb/s data rate.



Bluetooth Network Topology

- Radio designation
 - Connected radios can be master or slave
 - Radios are symmetric (same radio can be master or slave)
- Piconet
 - Master can connect to 7 simultaneous or 200+ inactive (parked) slaves per piconet
 - Each piconet has maximum capacity (1 Mbps)
 - Unique hopping pattern/ID
- Scatternet
 - High capacity system
 - Minimal impact with up to 10 piconets within range
 - Radios can share piconets!



Bluetooth – Contention-free MAC

- Master performs medium access control
 - Schedules traffic through polling.
- Time slots alternate between master and slave transmission
 - Master-slave
 - Master includes slave address.
 - Slave-master
 - Only slave chosen by master in previous master-slave slot allowed to transmit.
 - If master has data to send to a slave, slave polled implicitly; otherwise, explicit poll.

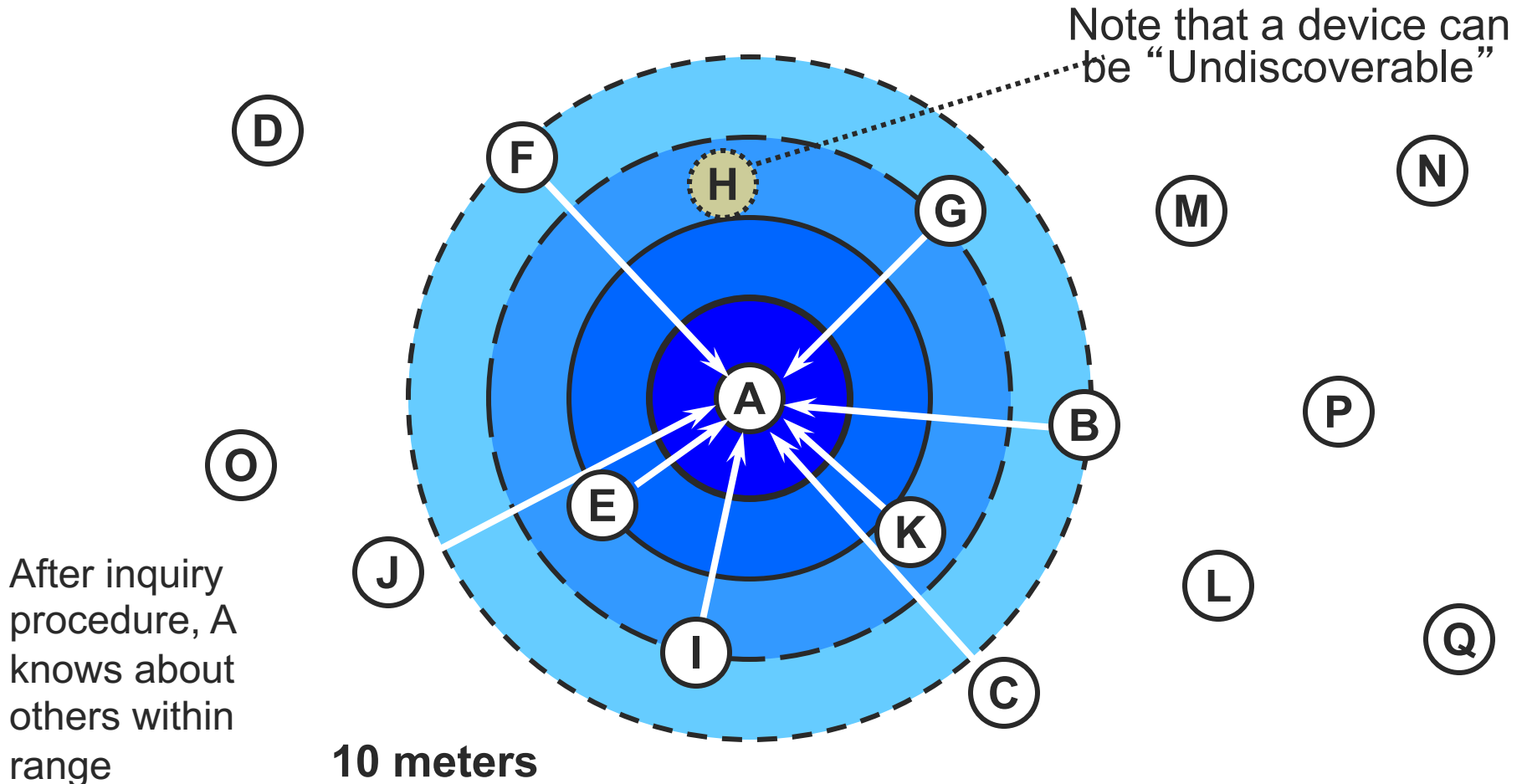


Bluetooth Device Discovery - Inquiry

- Device discovery
 - Sends out an inquire, which is a request for nearby devices (within 10 meters)
 - Devices that allow themselves to be discoverable issue an inquiry response
 - Listeners respond with their address
 - Can take up to 10.24 seconds, after which the inquiring device should know everyone within 10 meters of itself



Bluetooth Device Discovery - Inquiry



[Bluetooth Inquiry]

■ Sender

- Inquiry sent on 16 different frequencies
- 16 channel train
 - about 1.28 seconds per channel
 - One full 16 channel train takes 10ms

■ Receiver (device in standby mode)

- Scans long enough for an inquiring device to send the inquiry on 16 frequencies
- Scan must be frequent enough to guaranteed wake up during a 16 channel train
 - Enters inquiry scan state at least once every 1.28 seconds, and stays in that state for 10ms



Bluetooth Inquiry - Reliability

- Challenge

- Noisy channels

- Lost packets

- Train scan is repeated up to 4 times for each train (10.24 seconds)

- Designed to successfully communicate at least once with all devices within range



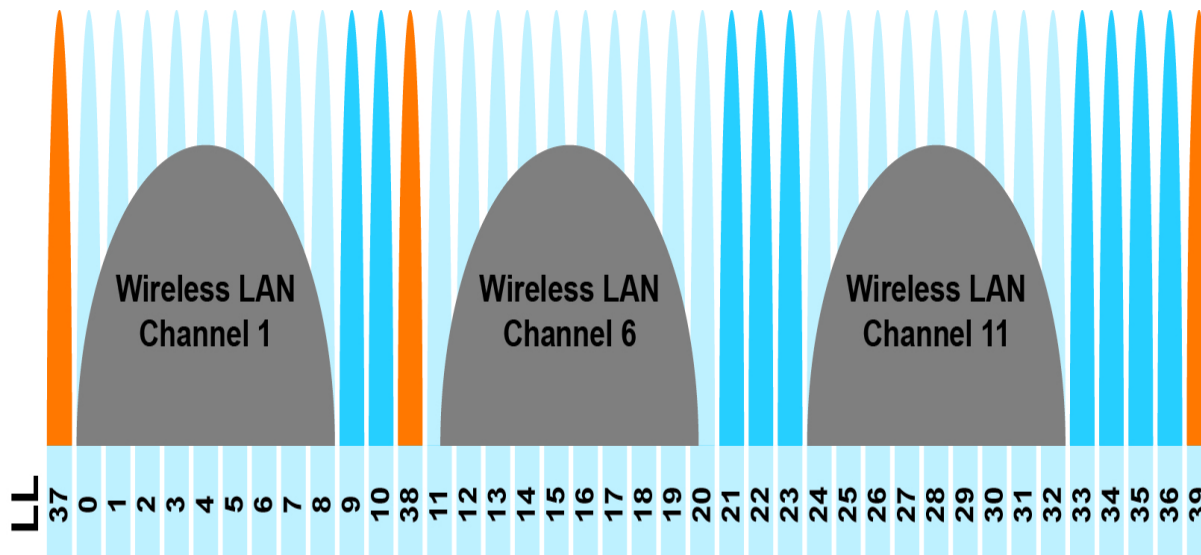
[BLE Highlights]

- Shared wireless channel
 - BLE operates in the 2.4 GHz ISM band with Wi-Fi and other technologies (phones, microwave ovens ...)
- BLE = Bluetooth Low Energy
 - Improved discovery
 - Key component: Beacons
 - Tags send out advertising beacons (typ. dist 30ft)
 - Phones scan for beacons



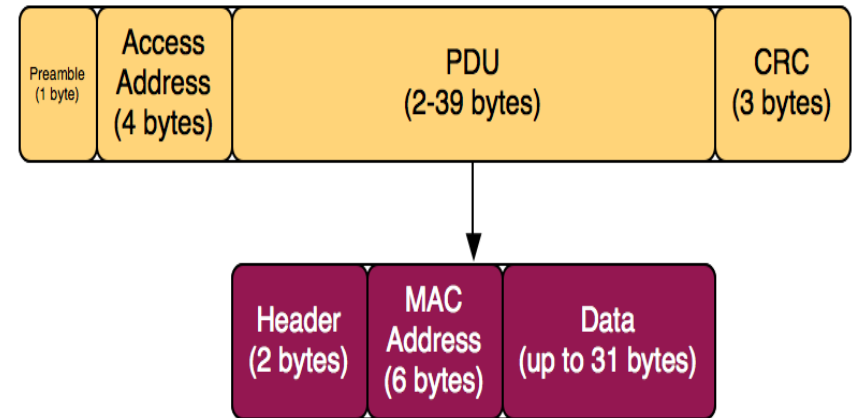
BLE Highlights: Channel Use and Coexistence with Wi-Fi

- Separate advertising and connected channels
 - Key: Three disjoint advertising channels (37, 38, 39)
 - Positioned between Wi-Fi channels (1, 6, 11)



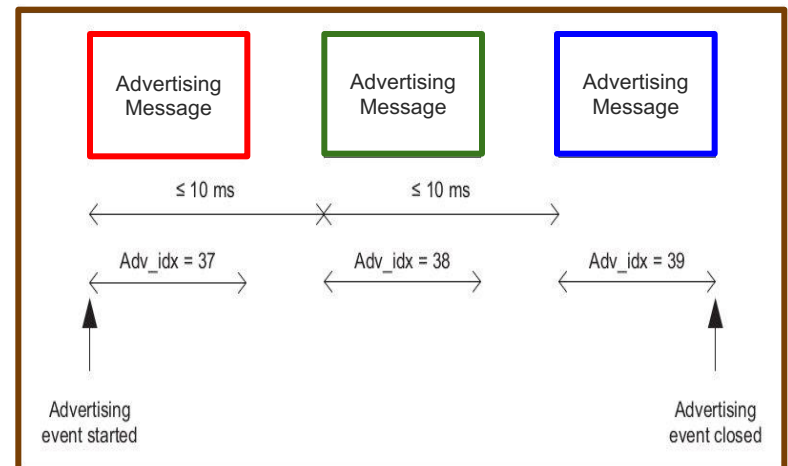
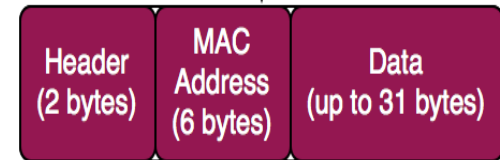
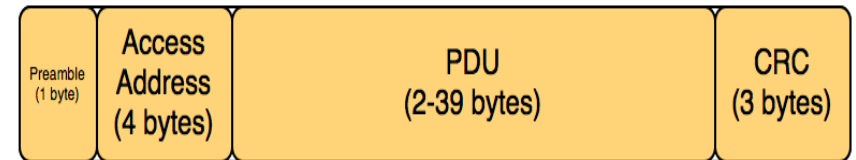
BLE Highlights: Advertising

- Advertising Tags
- Advertising Messages
 - Header + MAC Address + up to 31 Bytes of data
 - ~200 - 400 usec per packet
 - Two types: Non-scannable, Scannable



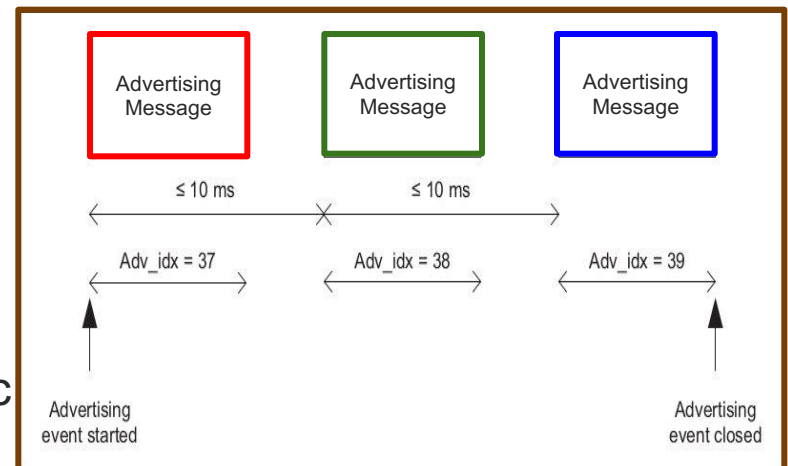
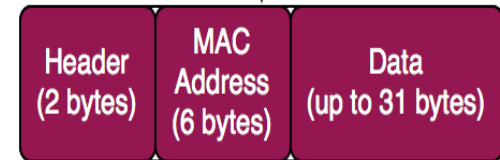
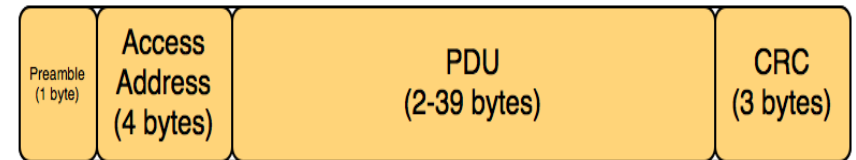
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- Advertising Event
 - One advertising message sent out on each advertising channel (37, 38, 39)



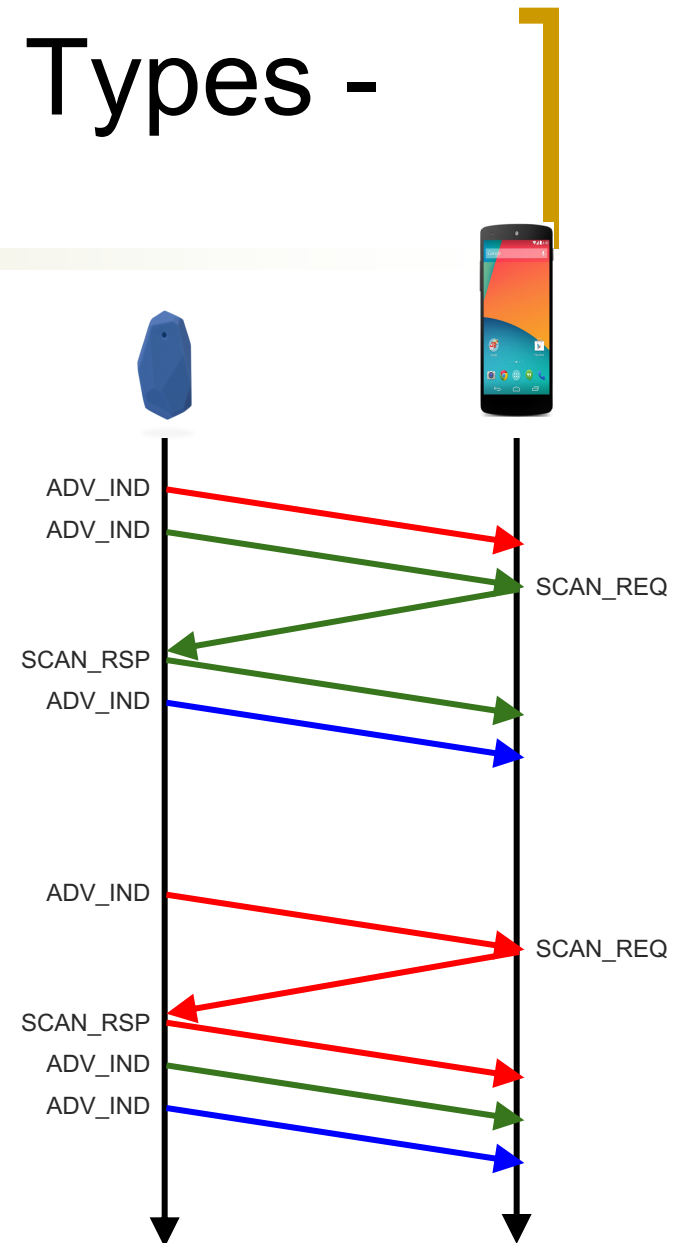
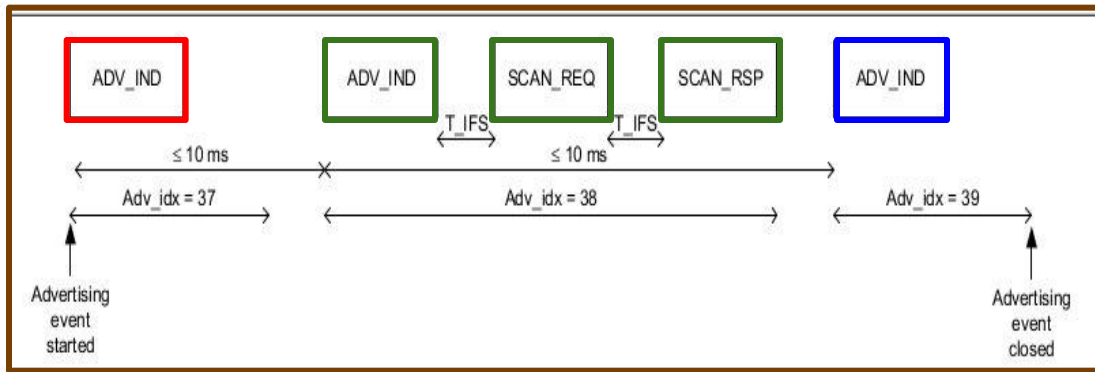
BLE Highlights: Advertising

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- Advertising Messages
 - Header + MAC Address + up to 31 Bytes of data
 - ~200 - 400 usec per packet
 - Two types: Non-scannable, Scannable
- Advertising Event
 - One advertising message sent out on each advertising channel (37, 38, 39)
- Advertising Interval
 - One advertising event per advertising interval, e.g., every 1 sec or 100 msec

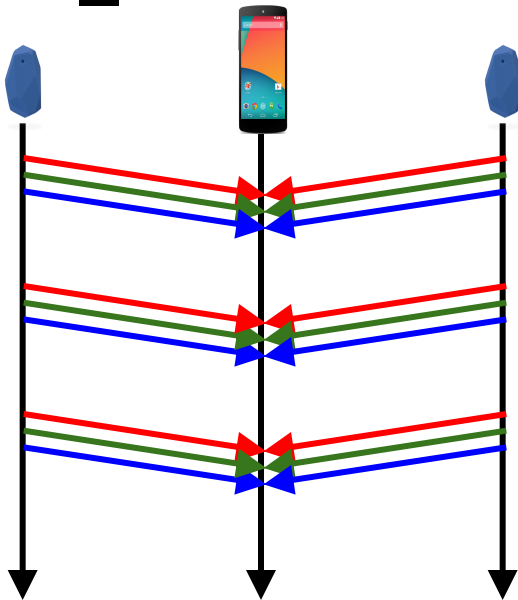


BLE Highlights: Tags Types - Scannable

- Scannable Tags
 - Tags send ADV_IND messages
 - Scanners respond with SCAN_REQ message
 - Tags respond with SCAN_RSP message
 - Up to 31 Bytes of extra data
 - Tags wait ~150 usec for a request after beacon



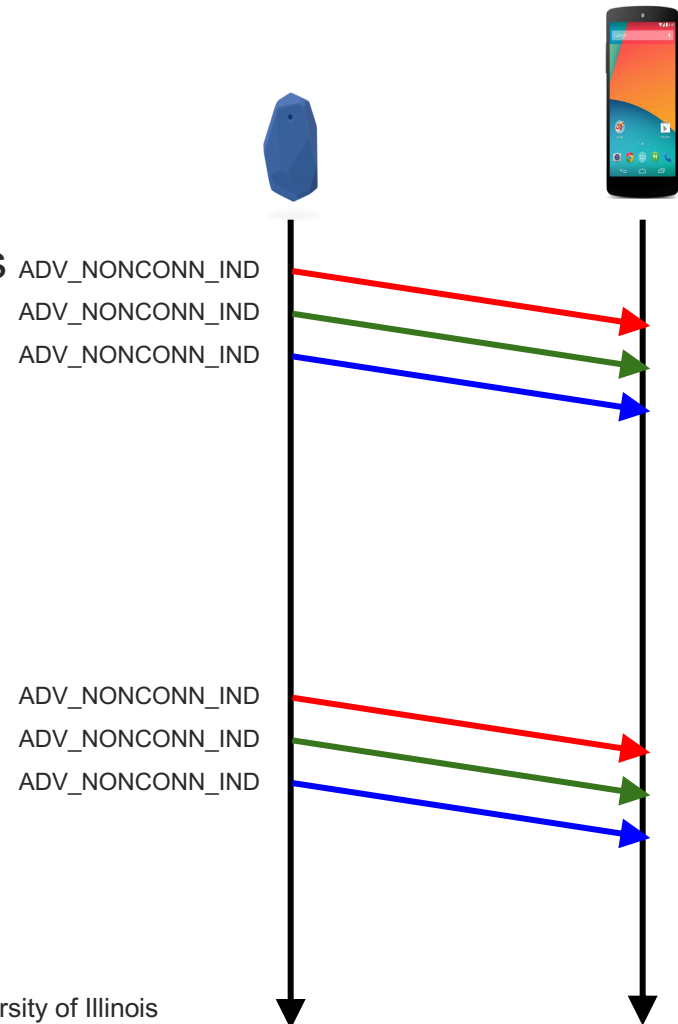
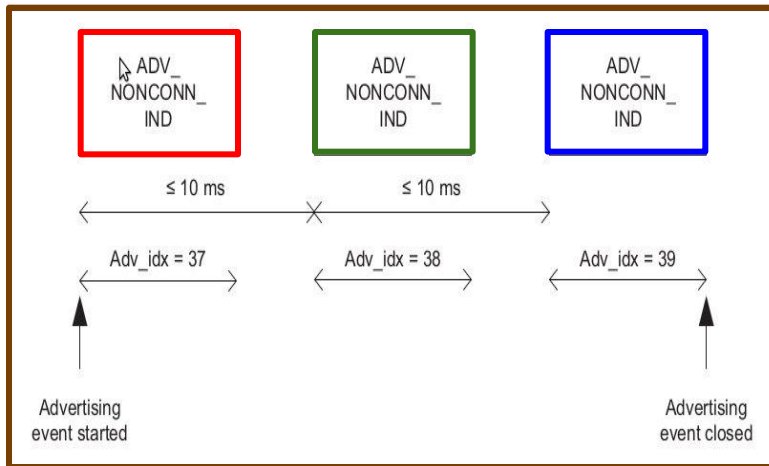
BLE Highlights: Advertising and Collisions



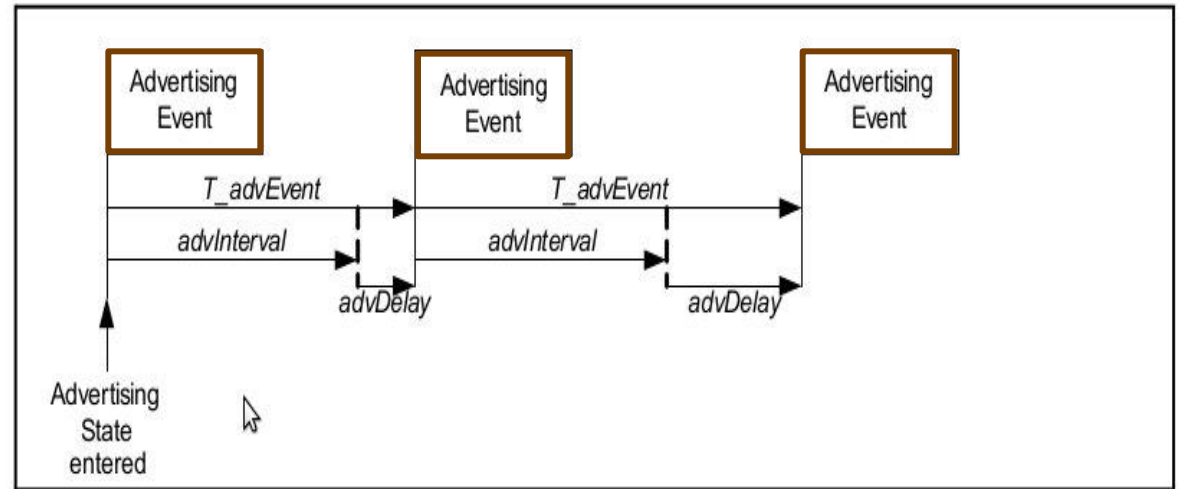
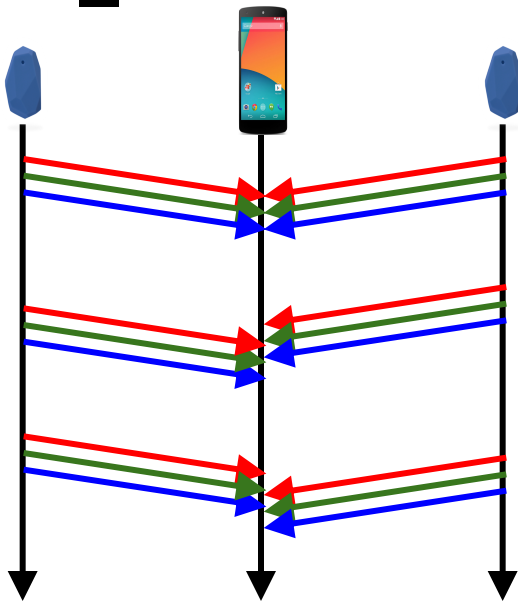
- If tags get synchronized, all advertising messages will collide

BLE Highlights: Tags Types - Non-Scannable

- Non-Scannable Tags
- Ex. gBeacon v3, iBeacon (?)
- Tags send ADV_NONCONN_IND messages
- Typically sent back-to-back
- Scanners listen, but do not respond



BLE Highlights: Advertising and Collisions

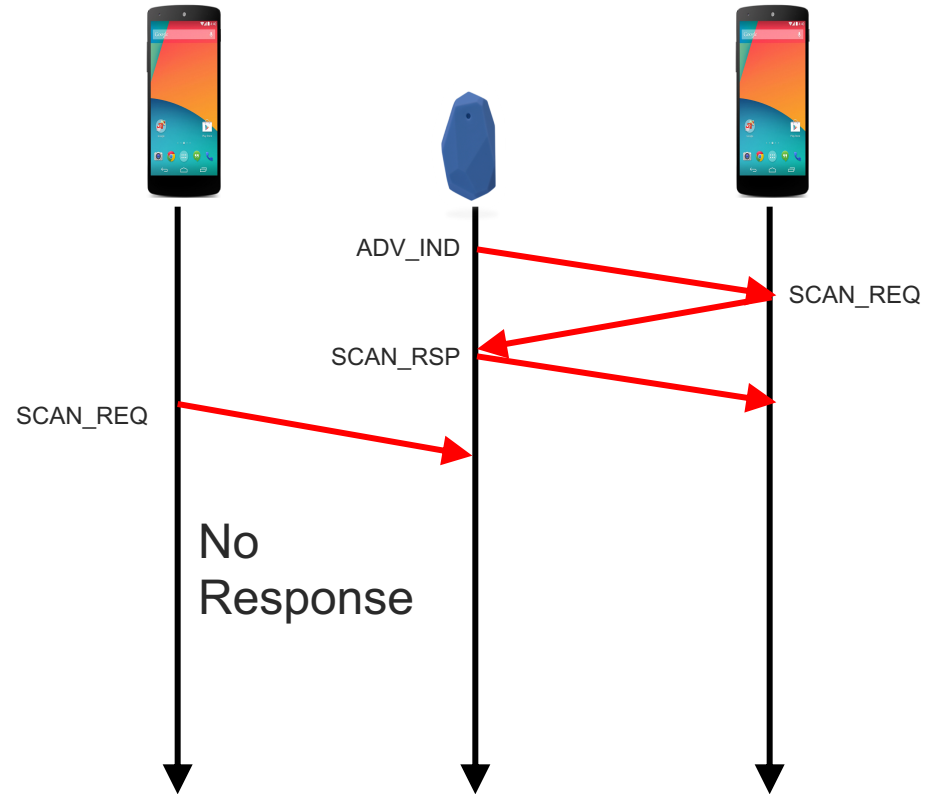


- Collision avoidance

- Jitter advertising times
- $advDelay$ is added on to the end of each advertising event
- $advDelay = \text{rand}[0, 10\text{ms}]$

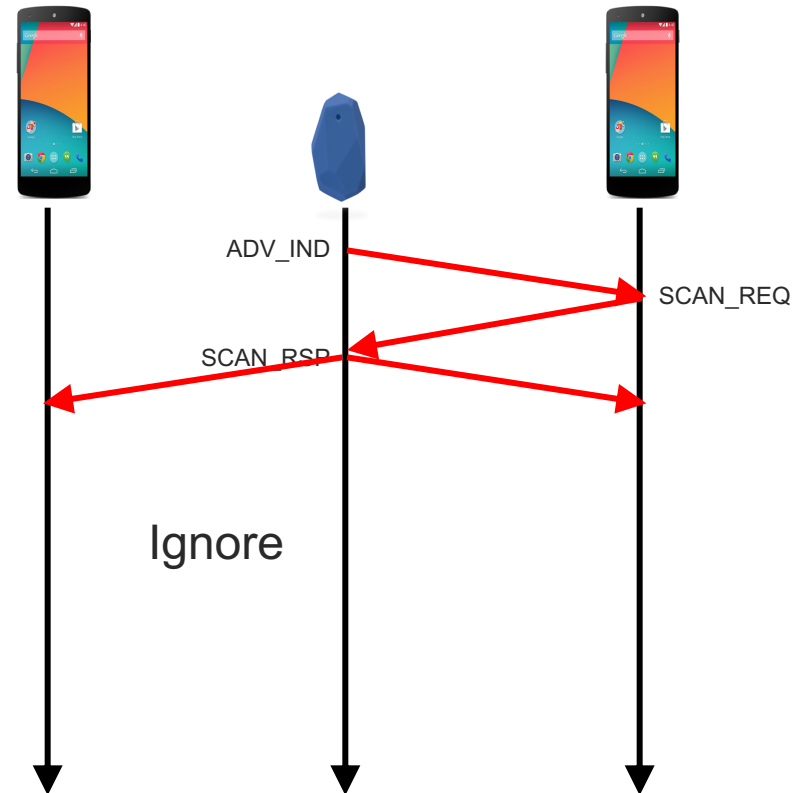
BLE Highlights: Scannable Tags

- One SCAN_RSP per channel per advertising event



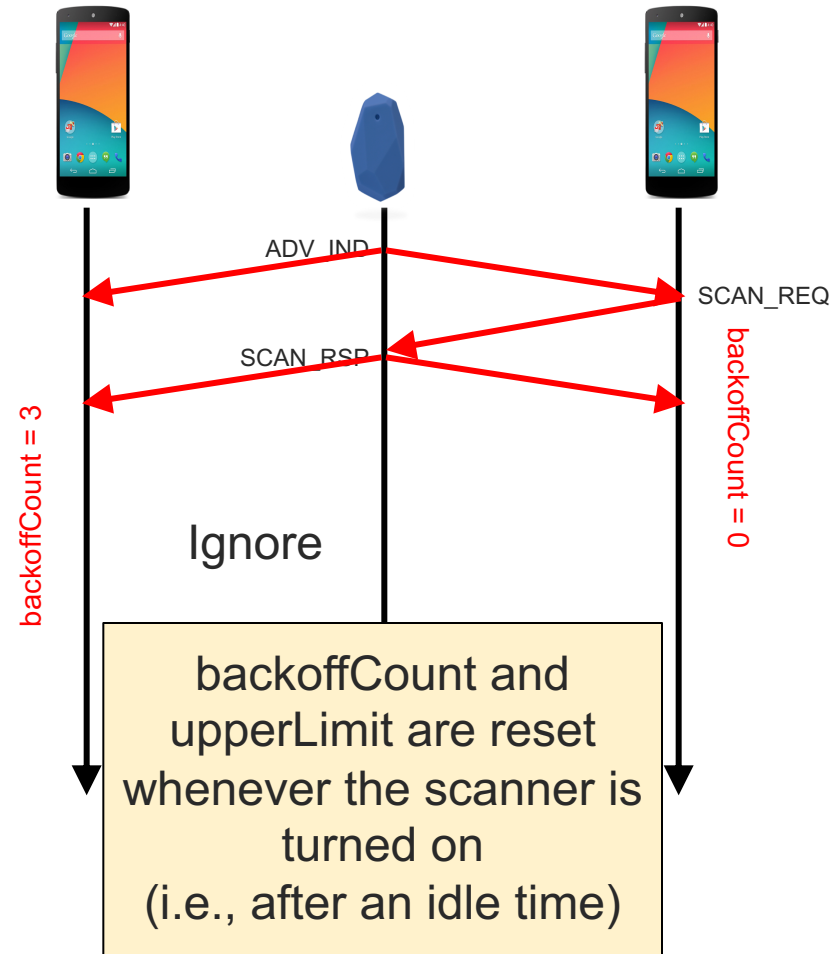
BLE Highlights: Scannable Tags

- ONLY accept SCAN_RSP if SCAN_REQ was sent to that tag on that channel during that advertising event
- Some collision tolerance
 - Any requesting scanner can receive a SCAN_RSP as long as one SCAN_REQ is received and the tag responds
 - BUT, No SCAN_RSP if all SCAN_REQs collide



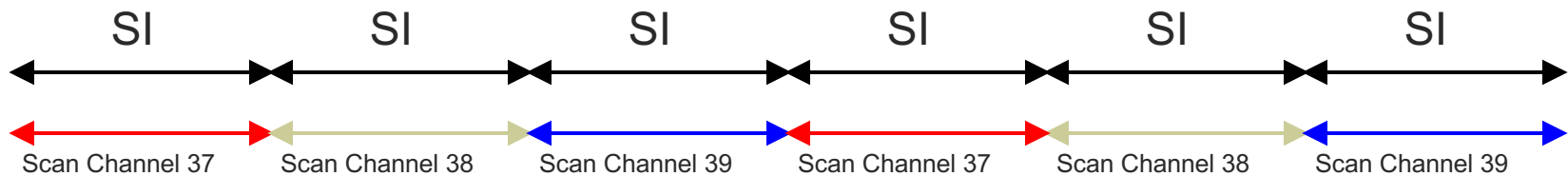
BLE Highlights: SCAN_REQ Collision Avoidance

- Scanner backoff procedure
 - Two parameters
 - backoffCount, upperLimit
 - On starting scan
 - upperLimit = 1, backoffCount = 1
 - Decrement backoffCount on receipt of ADV message
 - Only send SCAN_REQ if backoffCount == 0
 - Adapt upperLimit based on success or failure of receipt of SCAN_RSP
 - Reset backoffCount
 - backoffCount = rand (1, upperLimit)



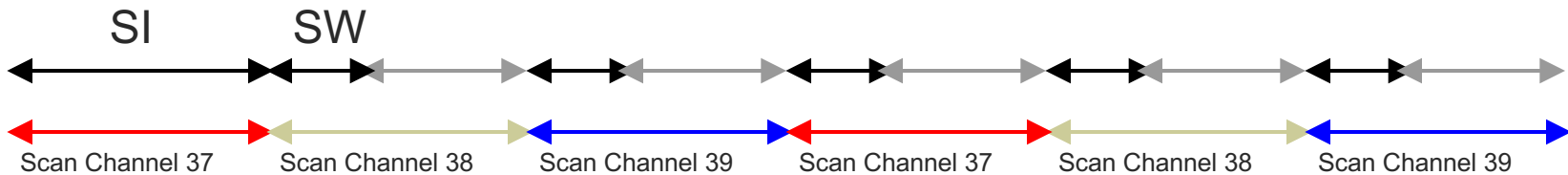
BLE Highlights: Low-level Scanning

- Scanners
- Scan for tags on sequential channels (37, 38, 39)
- Scan Interval (SI)
 - Time spent on a channel



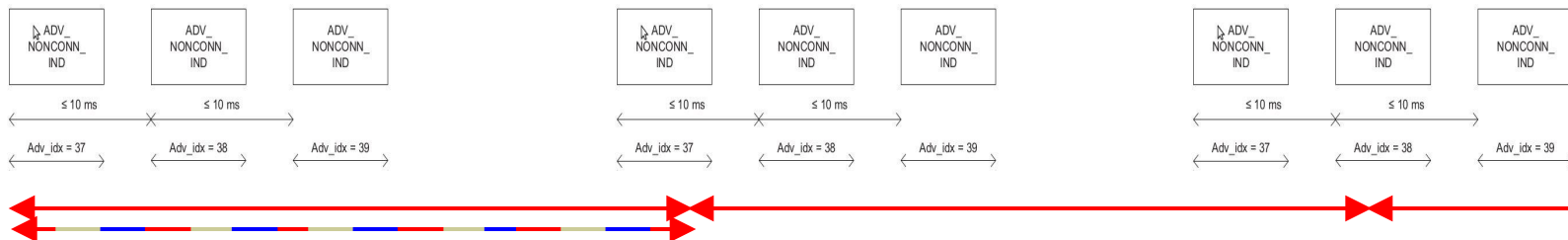
BLE Highlights: Low-level Scanning

- Scan Time
 - Scan Int == Scan Window
⇒ Always on
- Scanners
 - Scan for tags on sequential channels (37, 38, 39)
 - Scan Interval (SI)
 - Time spent on a channel
 - Scan Window (SW)
 - Time spent scanning at beginning of Scan Interval



BLE Highlights: Application-level Scanning

- Scanners
- Application Scan Time
 - > Tag Advertising Interval

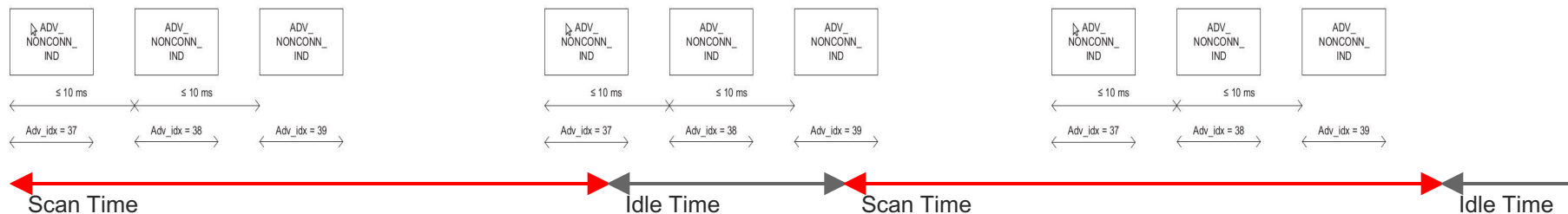


Application Scan Time



BLE Highlights: Application-level Scanning

- Scan Time
 - 100% on Idle Time = 0
- (Continuous scanning)
 - 10% on Idle Time = 10 * Scan Time
- Scanners
- Application Scan Time
 - > Tag Advertising Interval
- Application Idle Time



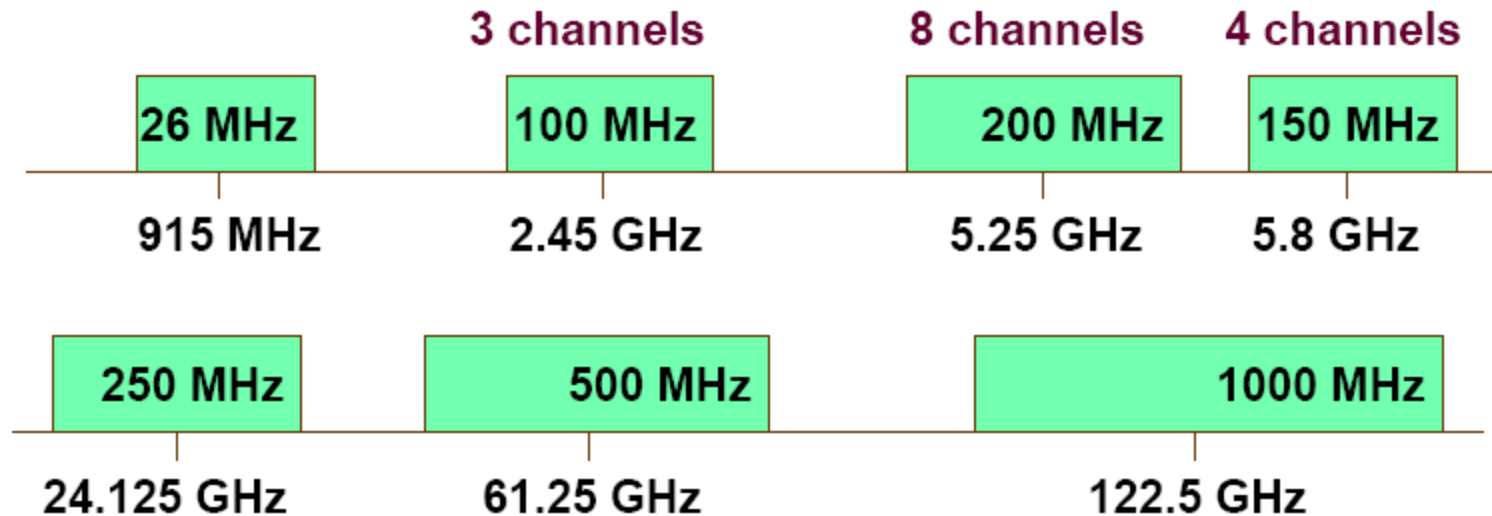
BLE Highlights: MAC Behavior

- No Carrier Sense
 - Tag does not listen for a clear channel before sending any message
- Minimal Contention Avoidance
 - Jitter length of advertising interval + rand [0, 10 ms]
 - Backoff for sending SCAN_REQ
- Other parameters
 - Inter-frame spacing 150us (from spec)
 - Channel switching delay 274us (from Nordic)
 - Scan Interval 11.25ms (from spec/Nexus 5)
 - Scan Window 11.25ms (continuous scanning)

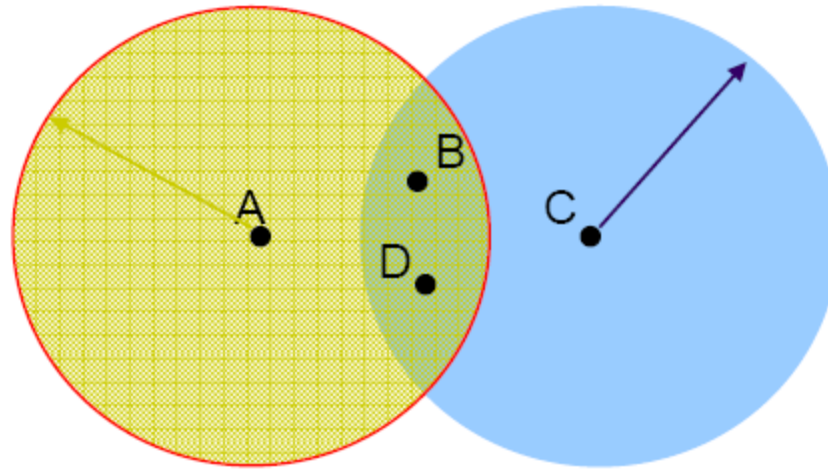


Channelization of spectrum

- 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

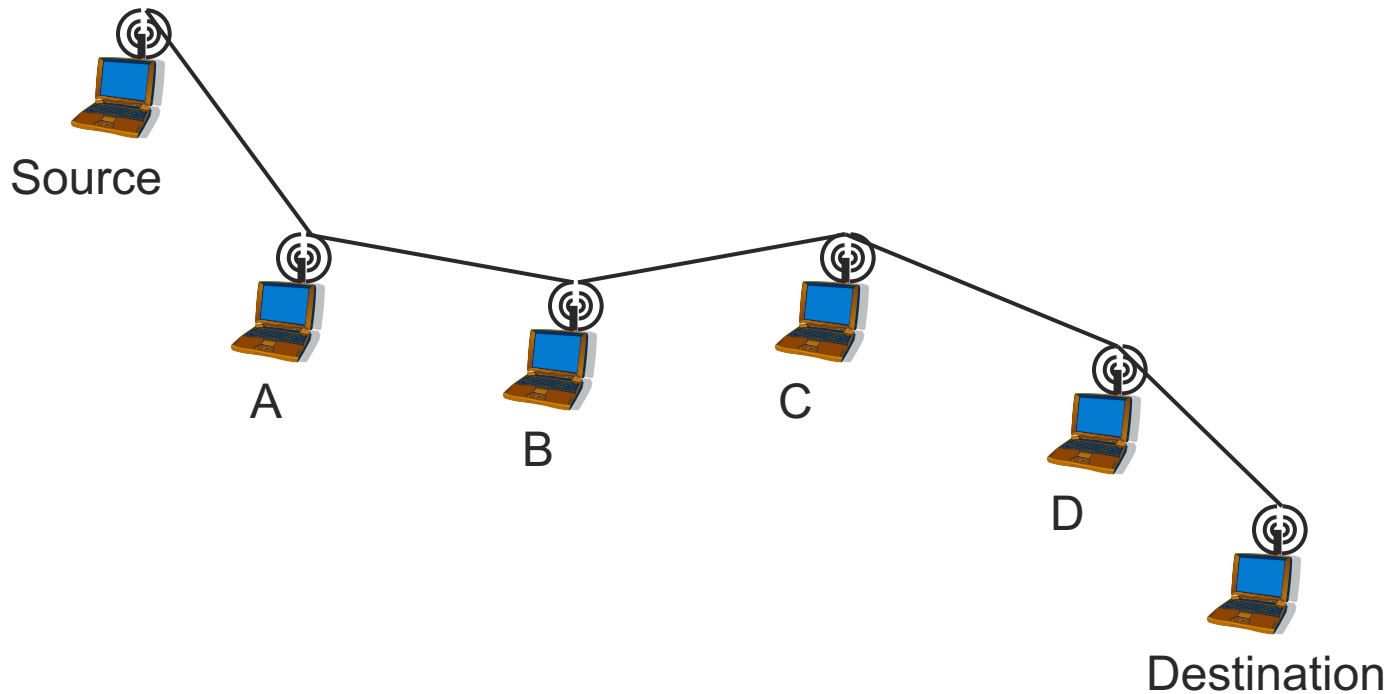
- Vehicular Networks
 - Delay Tolerant (batch) sending over several hops carry data to a base station
- Common in Sensor Network for periodically transmitting data
 - Infrastructure Monitoring
 - E.g., structural health monitoring of the Golden Gate Bridge
- Multihop networking for Internet connection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



Multi-Hop Wireless Networks

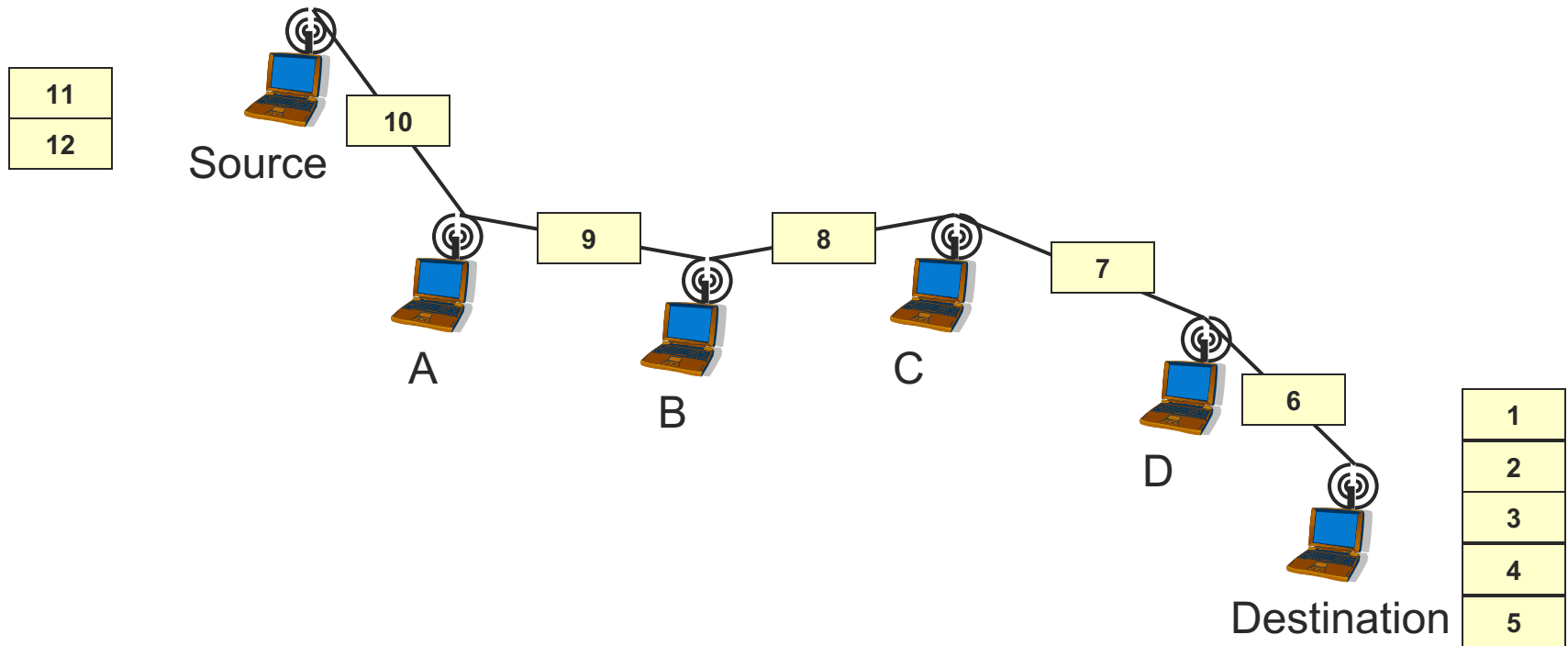
- In an ideal world ...

1
2
3
4
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6
7
8
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10
11
12



Multi-Hop Wireless Networks

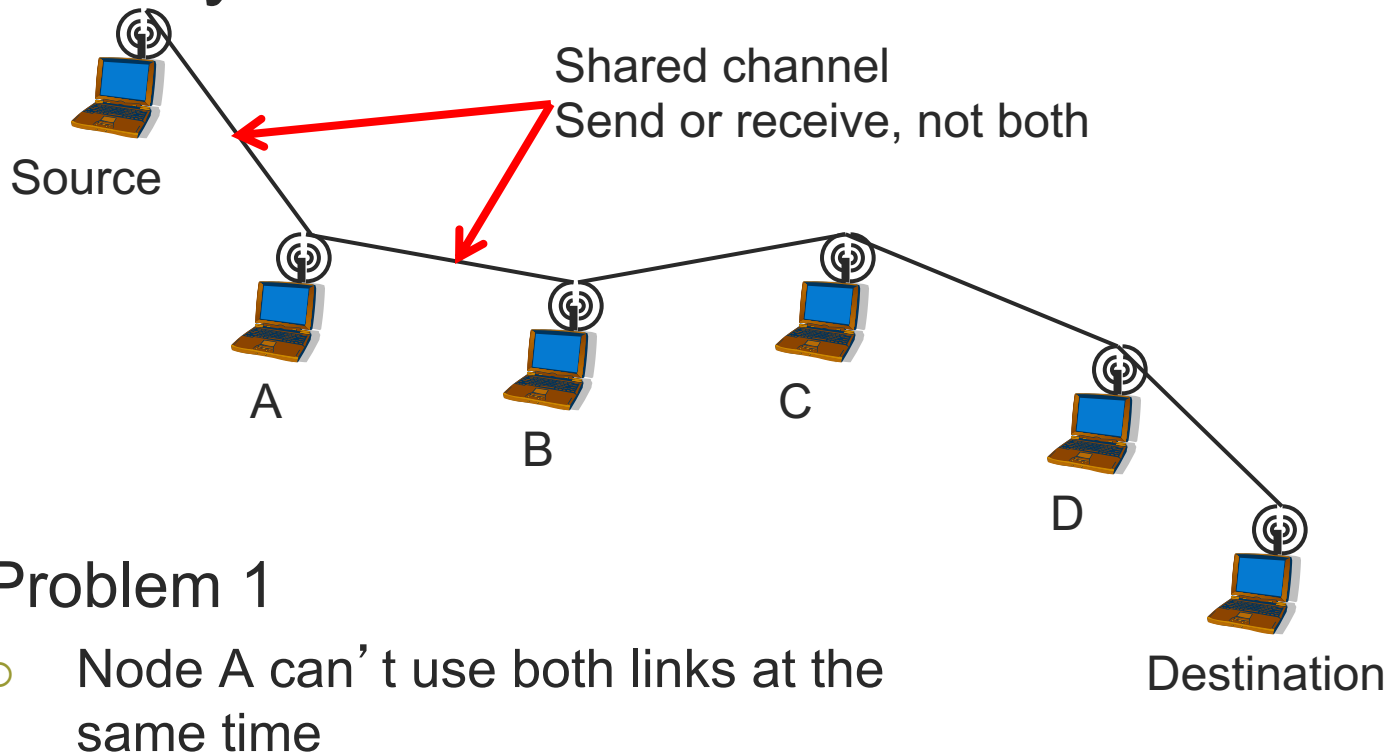
- In an ideal world ...



Multi-Hop Wireless Networks

Reality check ...

1
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12



Multi-Hop Wireless Networks

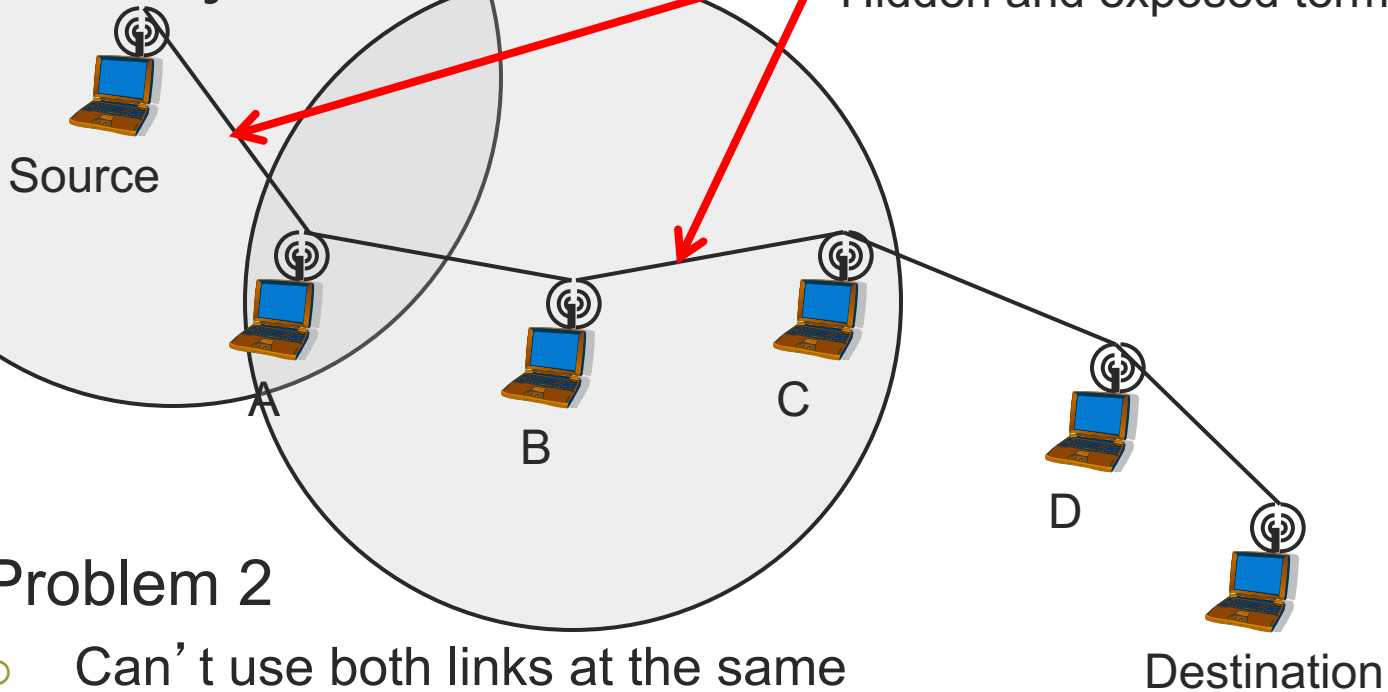
Reality check

Overlap at A
Hidden and exposed terminals

1
2
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11
12

Problem 2

- Can't use both links at the same time

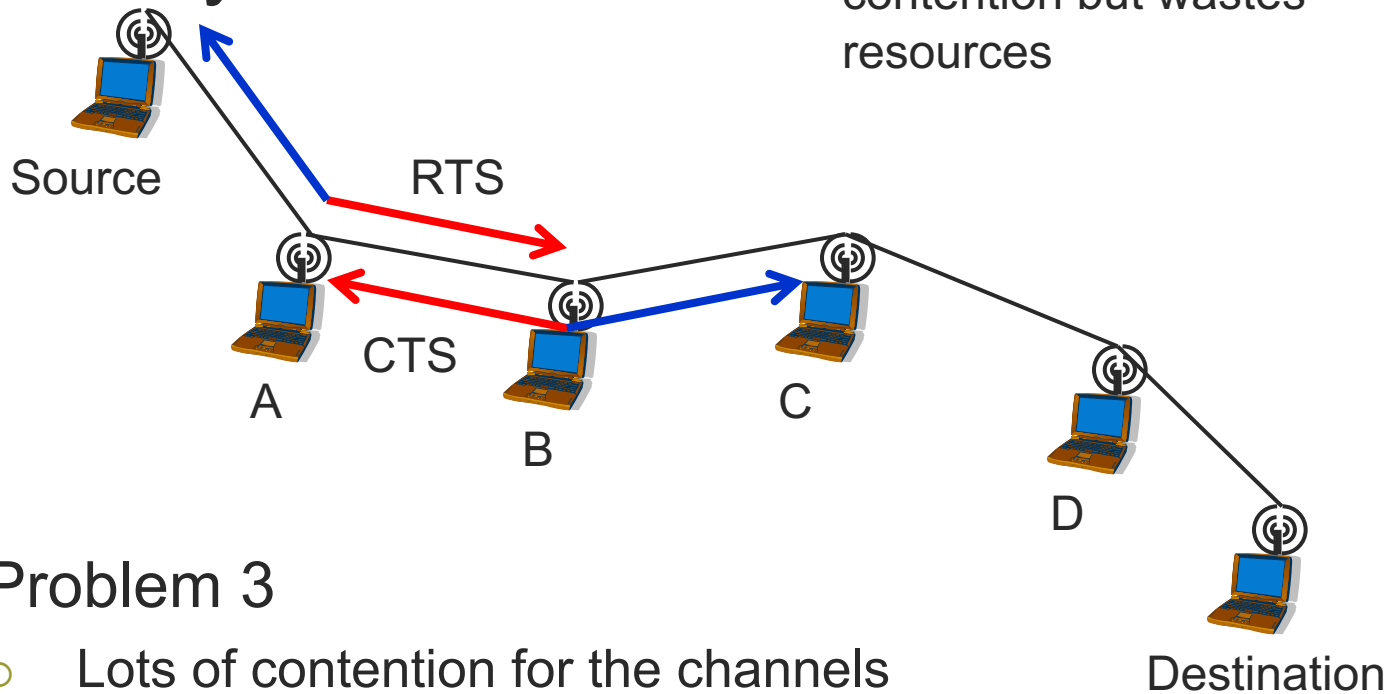


Multi-Hop Wireless Networks

Reality check ...

RTS/CTS helps with contention but wastes resources

1
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12



Problem 3

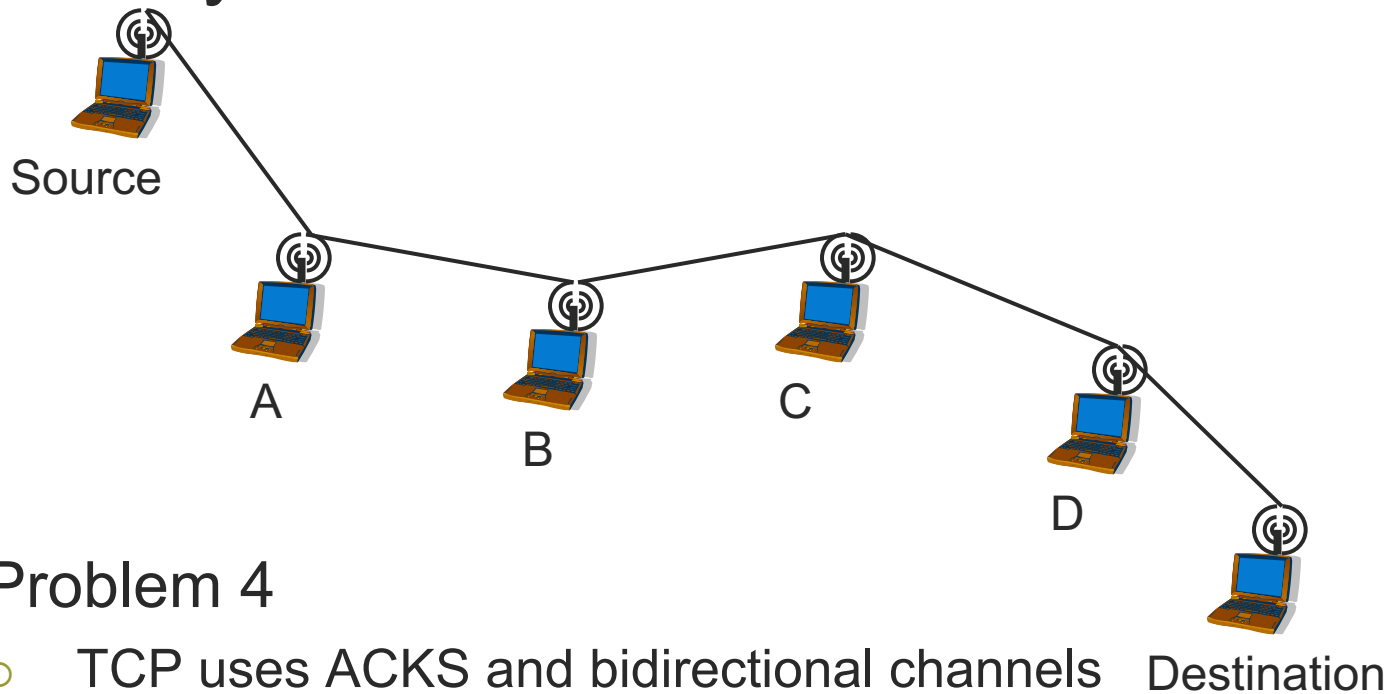
- Lots of contention for the channels
- Everyone wants to send

Multi-Hop Wireless Networks

Reality check ...

Higher layer protocols

1
2
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8
9
10
11
12



Problem 4

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