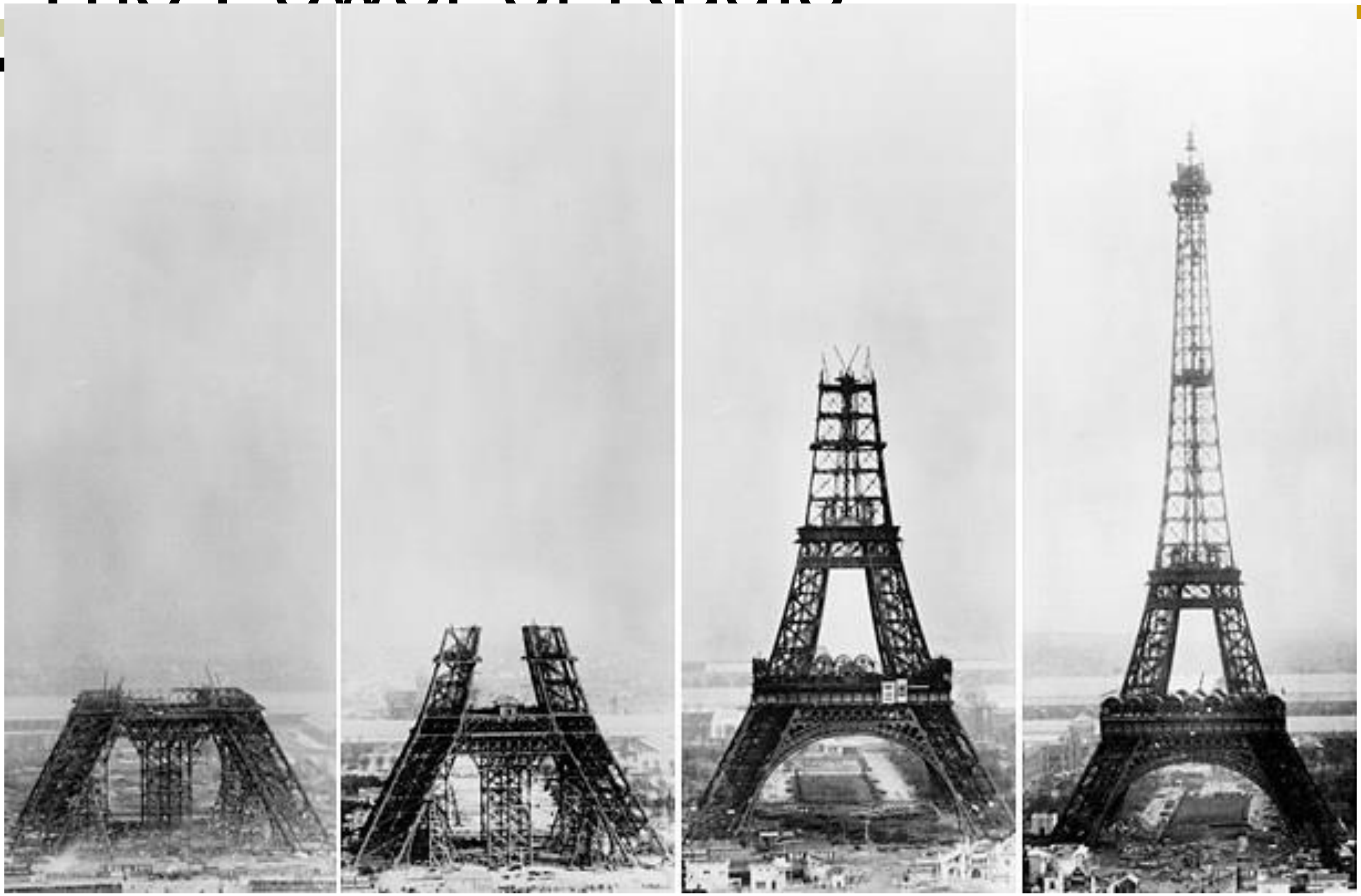
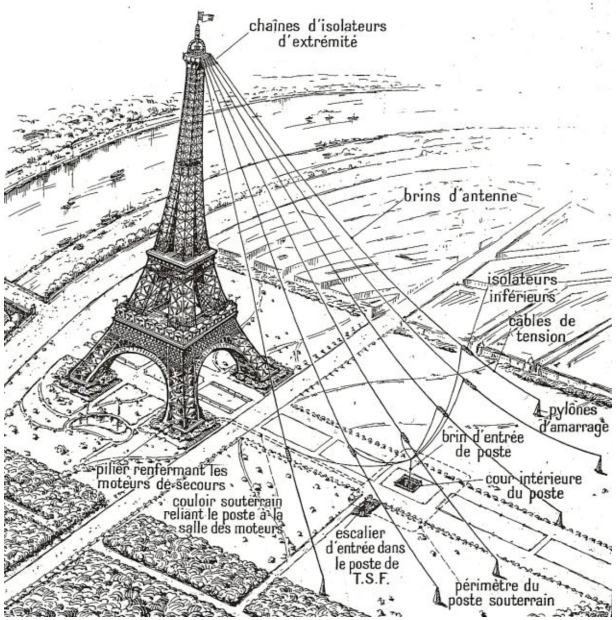
Wireless Media Access Protocols

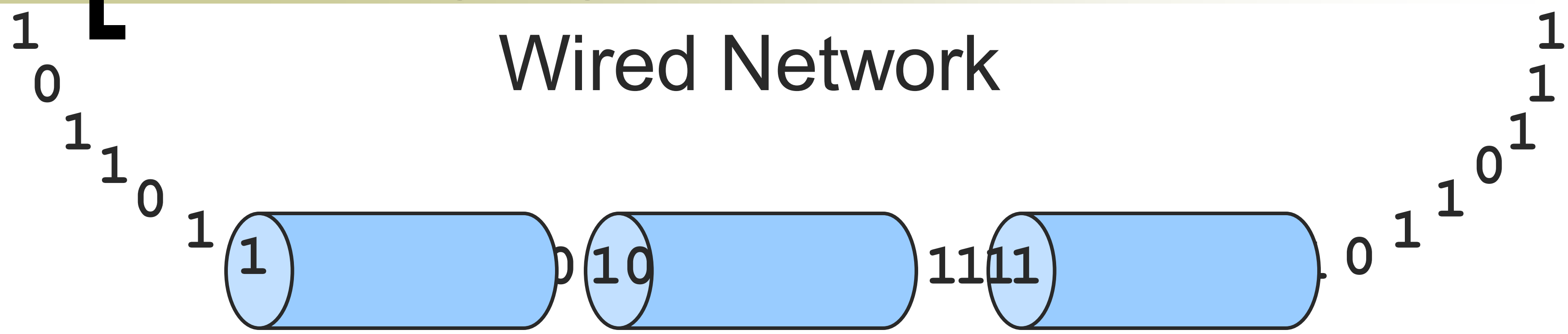
The Power of Radio



The Power of Radio



Why is wired networking challenging?



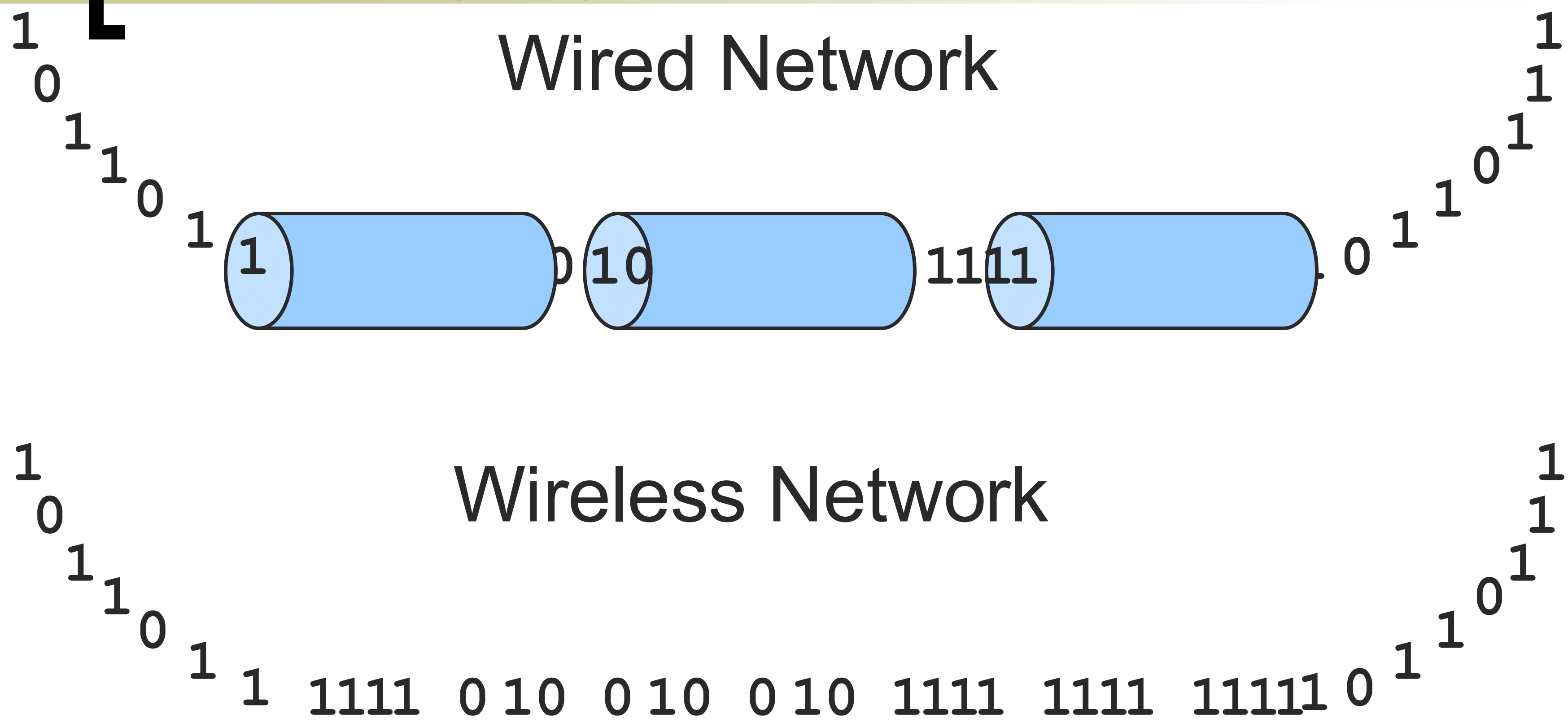
- Speed of light
- Shared infrastructure
- Things break
- Dynamic range
- Security

Getting the data through the pipes

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

Why is wireless networking challenging?



Same problems, but the pipes are gone!

Why use wireless?

There are no wires!

Several significant advantages

- No need to install and maintain wires
  - Reduces cost – important in offices, hotels, …
  - Simplifies deployment – important in homes, hotspots, …
- Supports mobile users
  - Move around office, campus, city, … - users get hooked
  - Remote control devices (TV, garage door, ..)
  - Cordless phones, cell phones, ..
  - WiFi, Bluetooth, UWB, …

What's so hard about wireless?

There are no wires!

- Wired networks
  - Links are constant, reliable and physically isolated
- Wireless networks
  - Links are variable, error-prone and share the ether with each other and other external, uncontrolled sources

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 GHz
6 GHz
60 GHz

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 … in terms of energy

Everything is inter-related!

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 Se
  - Spread

  - Uses 80
  - Transm frequen

- 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

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

Current Wireless Technologies

- IEEE 802.11
  - Wi-Fi 5 used OFDM (Orthogonal Frequency Division Multiplexing)
  - The switch Wi-Fi 6 introduced OFDMA Orthogonal Frequency Division Multiple Access)

	Max Rate	Frequency	Range	Energy
IEEE 802.11ac Wi-Fi 5	6.9 Gbps	2.4 GHz, 5 GHz	100 m	< 1 W
IEEE 802.11ax Wi-Fi 6	9.6 Gbps	2.4 GHz, 5 GHz, 6 GHz (6e)	35/100 m	< 1 W
IEEE 802.11be Wi-Fi 7	46 Gbps	2.4 GHz, 5 GHz, 6 GHz	35/100 m	< 1 W

IEEE 802.11 - Physical Layer

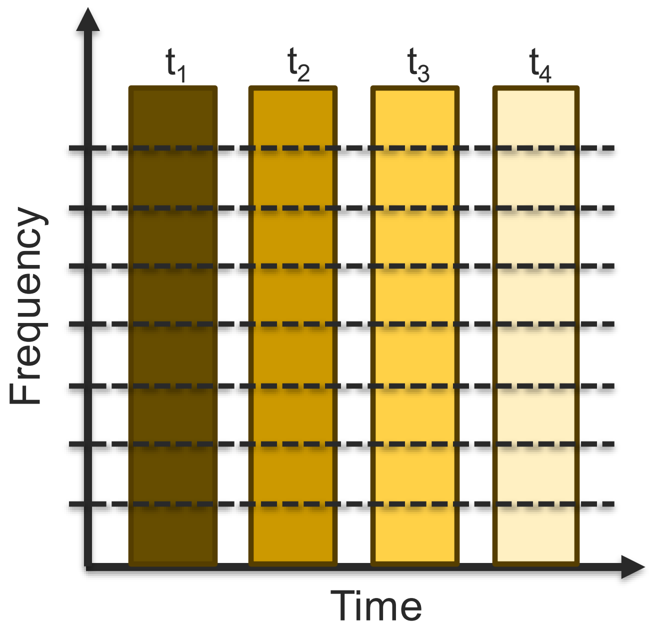
- IEEE 802.11 b
  - Direct Sequence Spread Spectrum
    - Uses 83 MHz in 2.4 GHz band
    - Spread the signal over a wider frequency band than required
    - Originally designed to prevent jamming
  - 3 orthogonal channels
- IEEE 802.11 g
  - Frequency-Hopped Spread Spectrum
    - Uses 80 1MHz sub-bands 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
- Wi-Fi 6/6e/7
  - Orthogonal Frequency Division Multiple Access (OFDMA)

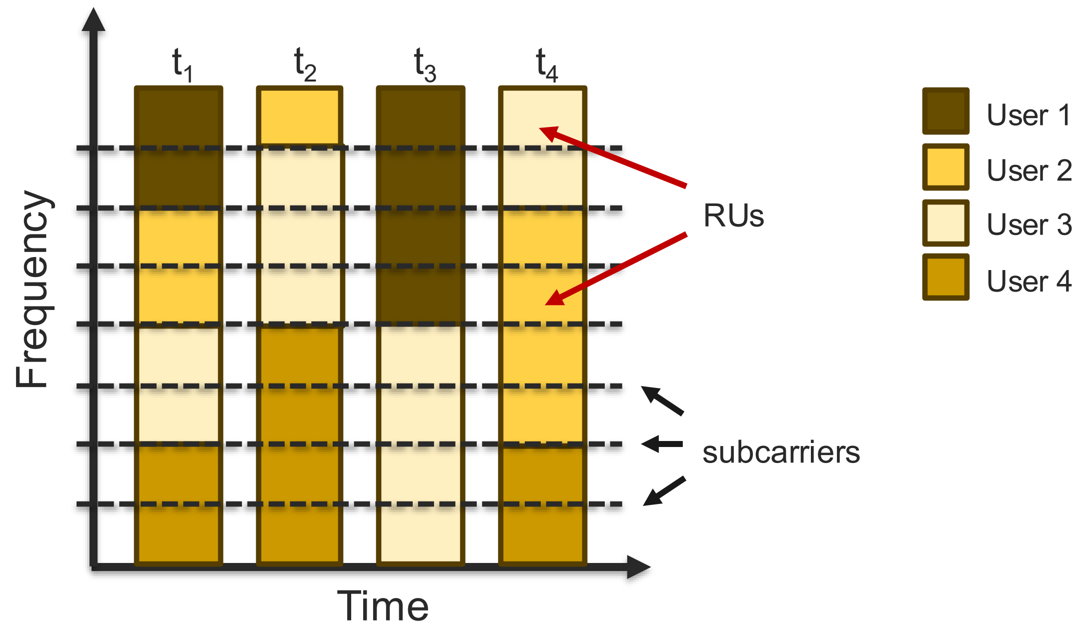
IEEE 802.11 - Physical Layer

OFDM (up to Wi-Fi 5)



Previous standards have clients use the **entire channel** to transmit data

OFDMA (Wi-Fi 6 and later)



OFDMA configures traffic for **multiple user packets per time segment**, increasing spectrum efficiency

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
    - Wi-Fi 5 802.11ac 2013 6.5–6,933 Mbps
    - Wi-Fi 6 802.11ax 2021 0.4–9,608 Mbps
    - Wi-Fi 7 802.11be 2024 0.4–23,059 Mbps
  - Increased range → lower signal → lower rate

Current Wireless Technologies

- Bluetooth – IEEE 802.15.1
  - Originally designed as a cable replacement technology
  - Controller/client 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 controller
    - Single slot packet
      - Max data rate of 172Kbps
    - Multislot frames
      - Support higher rates of 721Kbps
    - Secondary channels
      - Up to 3Mbps

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 and Li-Fi
  - Directional

	Max Rate	Frequency	Range	Energy
InfraRed – IrDA	9600 bps – 16 Mbps		< 1 m	Low
Li-Fi	Up to 10Gbps			

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

- UWB
  - Currently used for ranging

	Max Rate	Frequency	Range	Energy
UWB Ranging			< 100 m	3-4 mW

Current Wireless Technologies

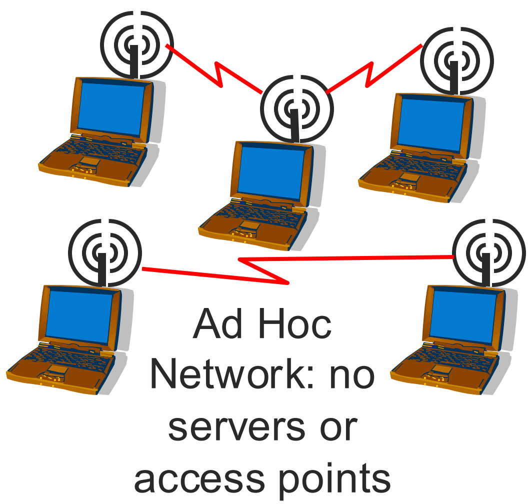
- LoRa
  - Long range
  - Infrequent use

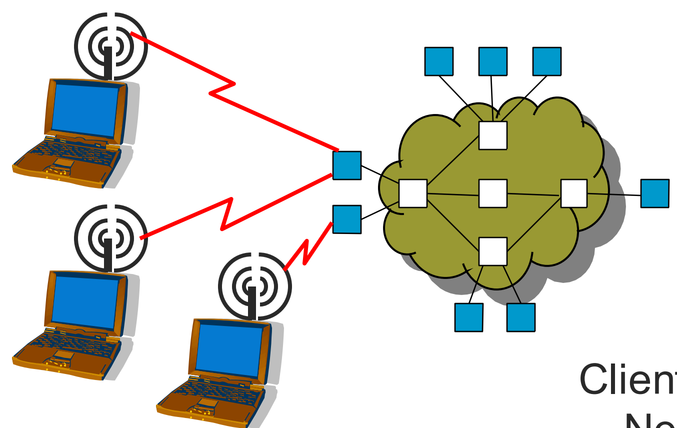
	Max Rate	Frequency	Range	Energy
LoRa			1-5km	50-120 mA

Media Access Control Protocols

Medium Access Control

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



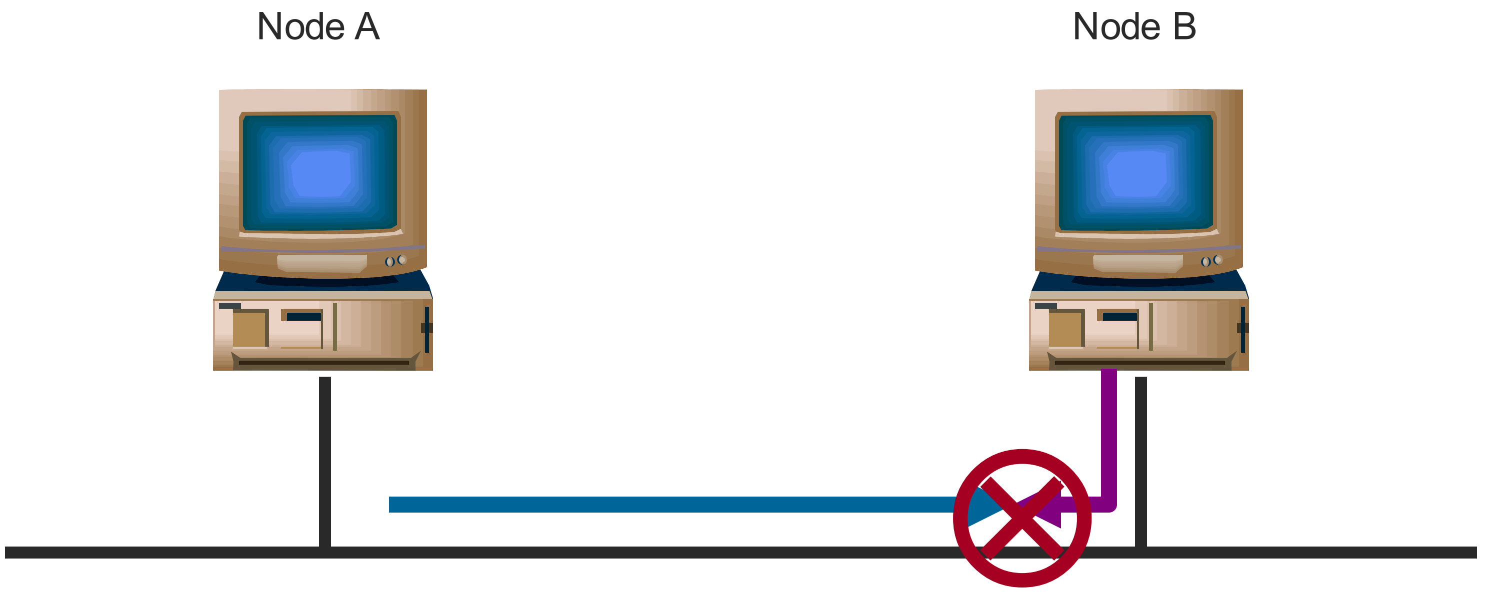


Client Server
Network

Medium Access Control

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

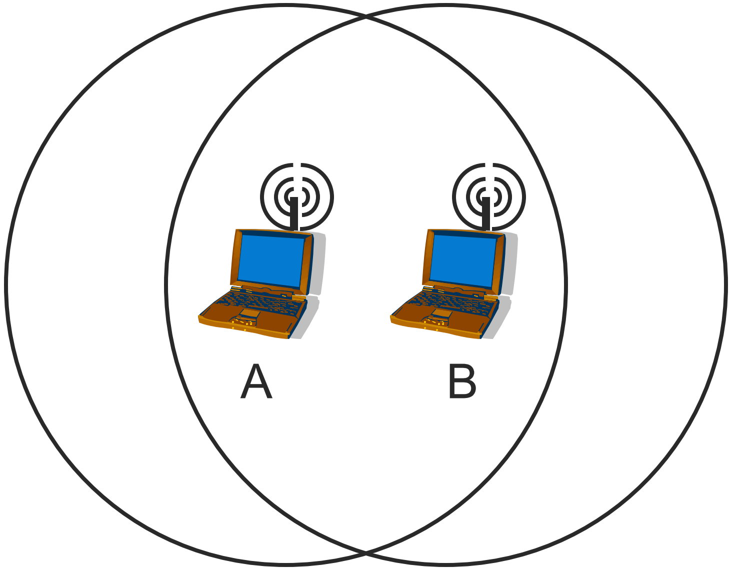
Ethernet MAC Algorithm



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

CSMA/CD in WLANs?

- Most 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!



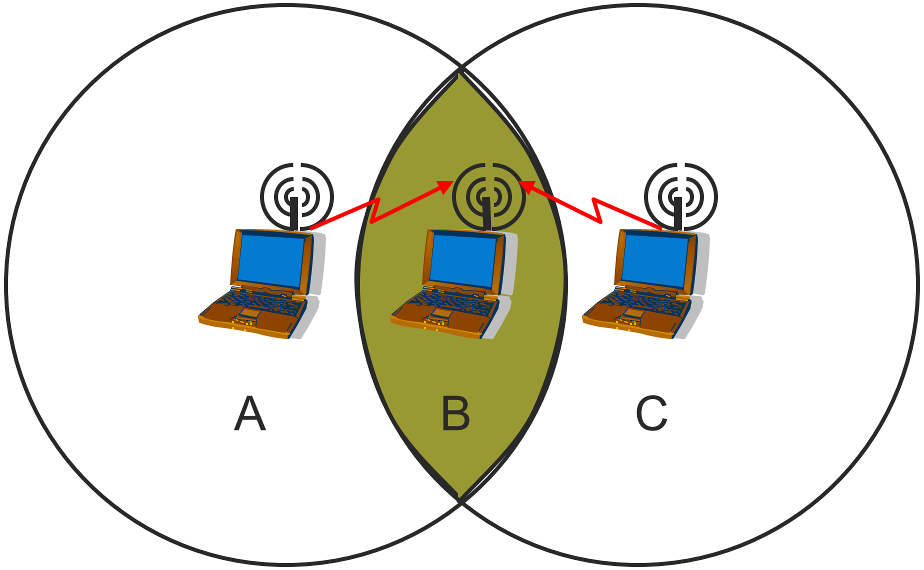
- Why do collisions happen?
  - Near simultaneous transmissions
    - Period of vulnerability: propagation delay

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
- CA – Collision Avoidance
  - Nodes use protocol to prevent collisions from occurring

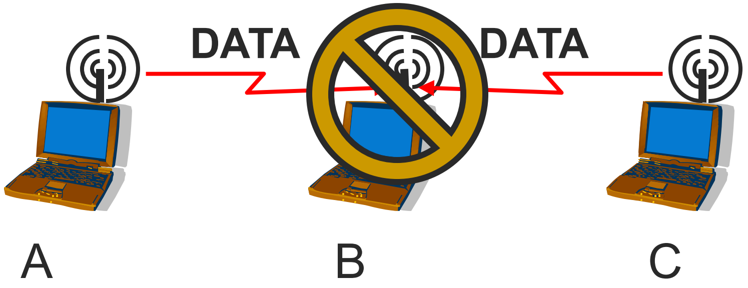
IEEE 802.11 MAC Layer Standard

- Similar to Ethernet
- But consider the following:



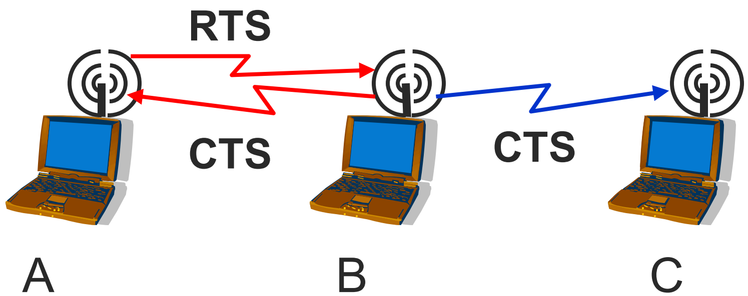
Hidden Terminal Problem

- Node B can communicate with both A and C
- A and C cannot hear each other
- When A transmits to B, C cannot detect the transmission using the carrier sense mechanism
- If C transmits, collision will occur at node B



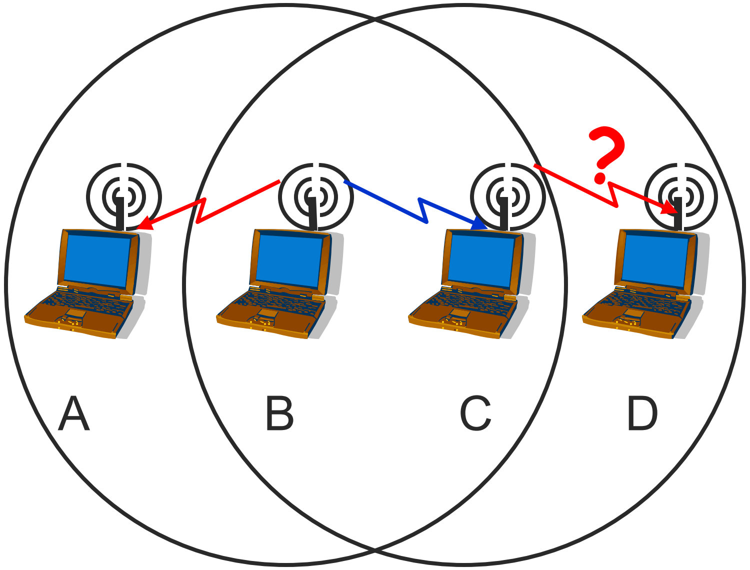
MACA Solution for Hidden Terminal Problem

- When node A wants to send a packet to node B
  - Node A first sends a Request-to-Send (RTS) to B
- On receiving RTS
  - Node B responds by sending Clear-to-Send (CTS)
  - 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



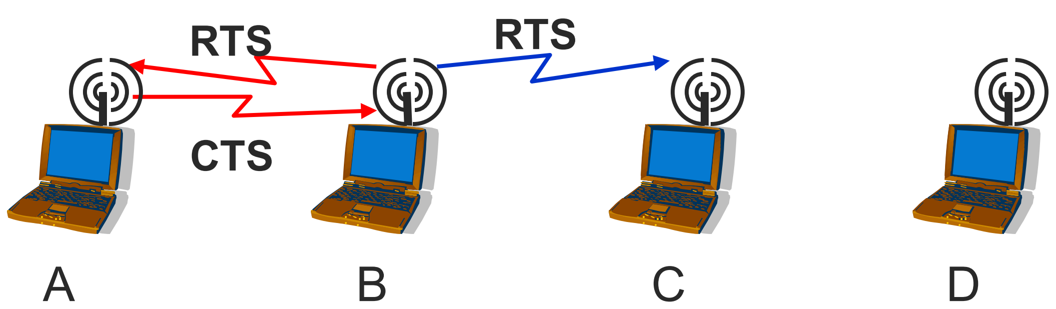
IEEE 802.11 MAC Layer Standard

- But we still have a problem



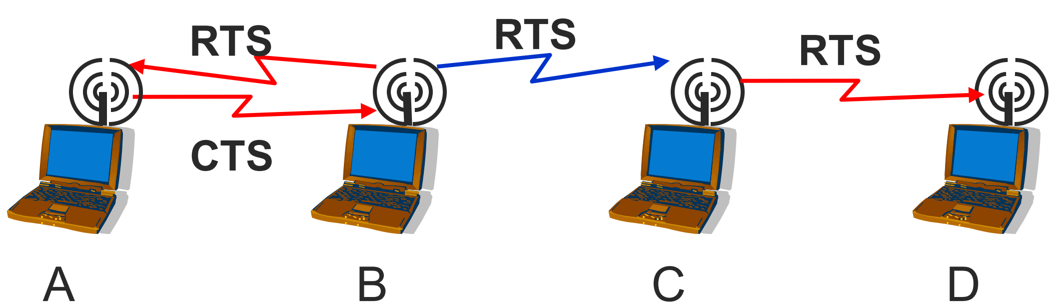
Exposed Terminal Problem

- 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

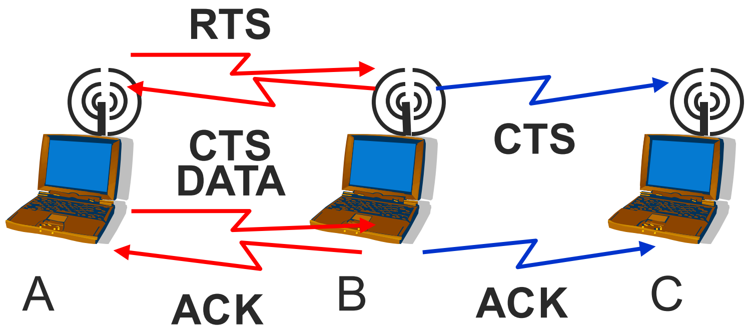
- Still possible
  - RTS packets can collide!
- Binary exponential backoff
  - Backoff counter doubles after every collision and reset to minimum value after successful transmission
  - Performed by stations that experience RTS collisions
- RTS collisions not as bad as data collisions in CSMA
  - Since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

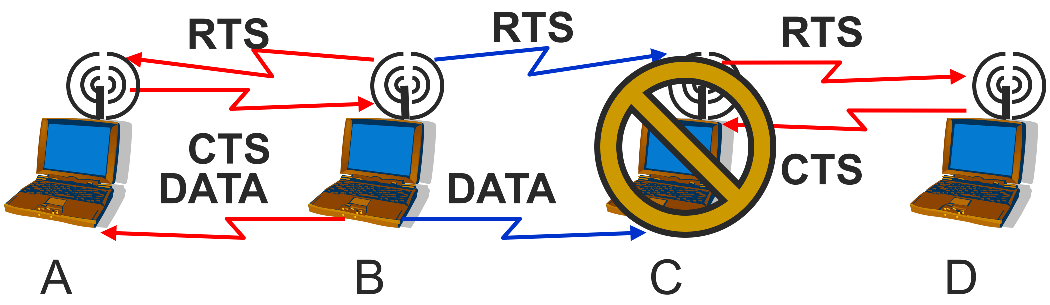
A Simple Solution to Improve Reliability - MACAW

- 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



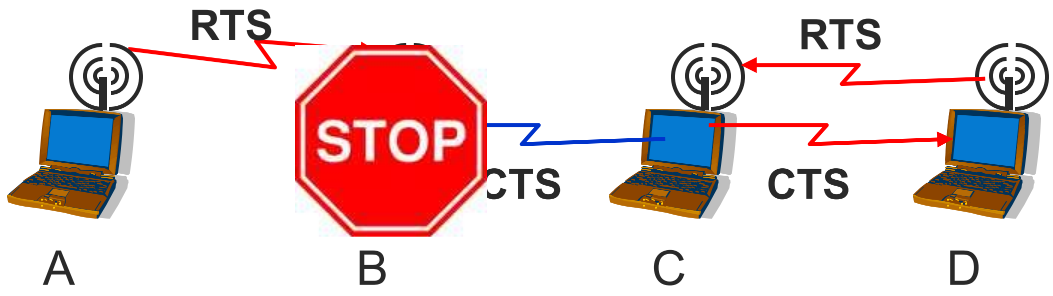
Revisiting the Exposed Terminal Problem

- 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

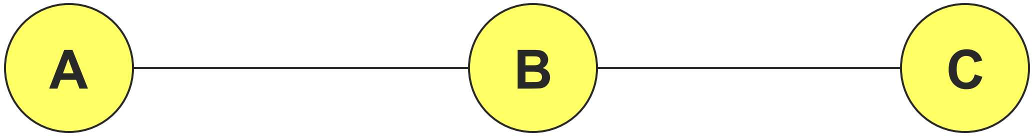
- Sort-of solution
  - Don’t use CTS for multicast data
- Receivers recognize multicast destination in RTS
  - Don’t return CTS
  - Sender follows RTS immediately by DATA
  - After RTS, all receivers defer for long enough for DATA
- Helps, but doesn’t fully solve problem
  - Like normal CSMA, only those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

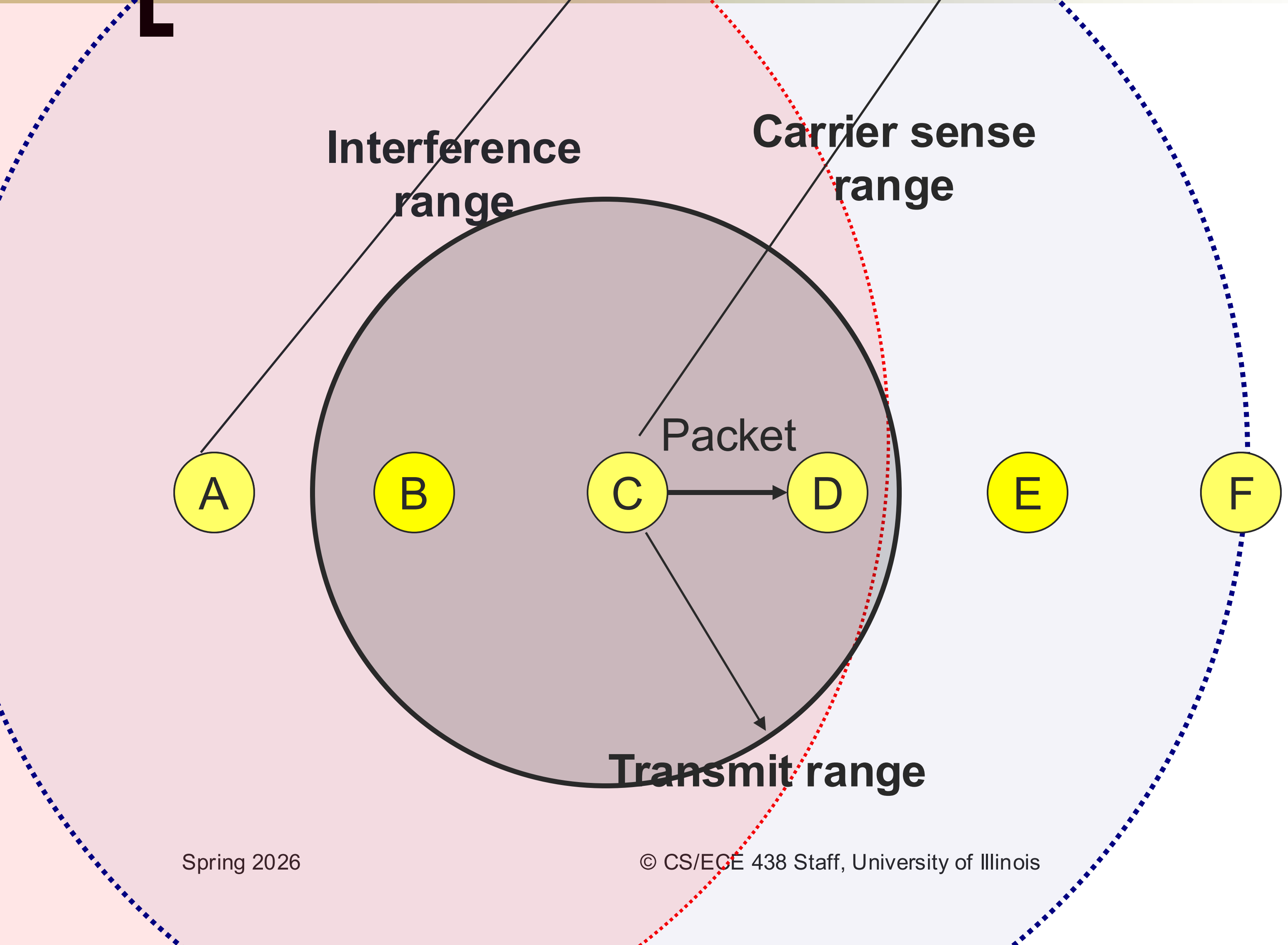
- Uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer
- Uses ACK to achieve reliability
- Any node receiving the RTS cannot transmit for the duration of the transfer
  - To prevent collision with ACK when it arrives at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



IEEE 802.11 CSMA/CA

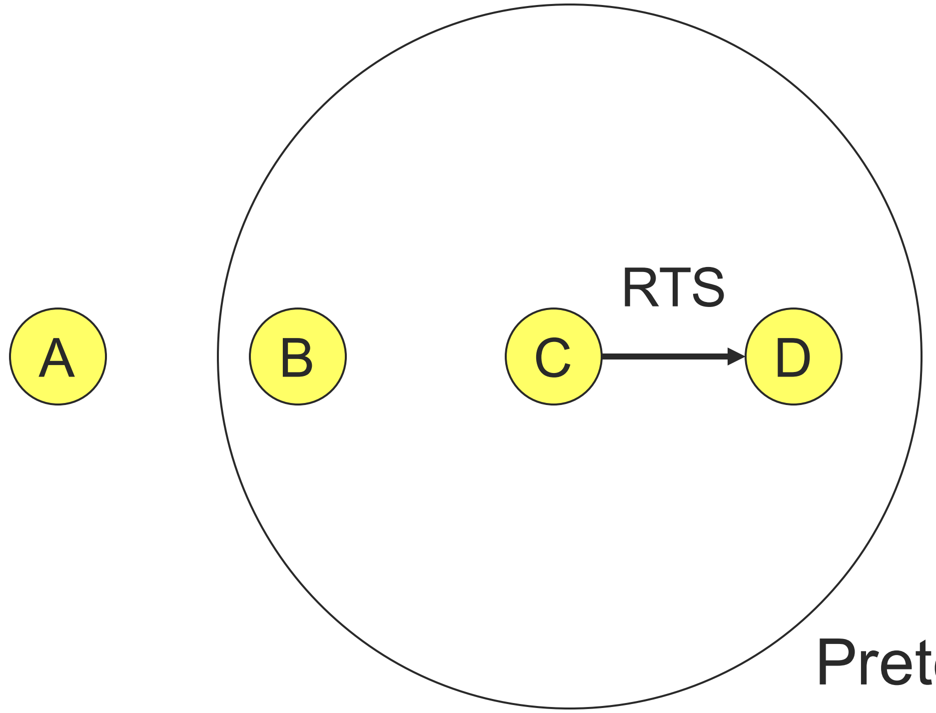
- Nodes stay silent when carrier sensed
  - Physical carrier sense
  - Virtual carrier sense
    - Network Allocation Vector (NAV)
    - NAV is updated based on overheard RTS/CTS/DATA/ACK packets, each of which specified duration of a pending transmission
- Backoff intervals used to reduce collision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

IEEE 802.11 Physical Carrier Sense



IEEE 802.11 Virtual Carrier Sense

RTS = Request-to-Send

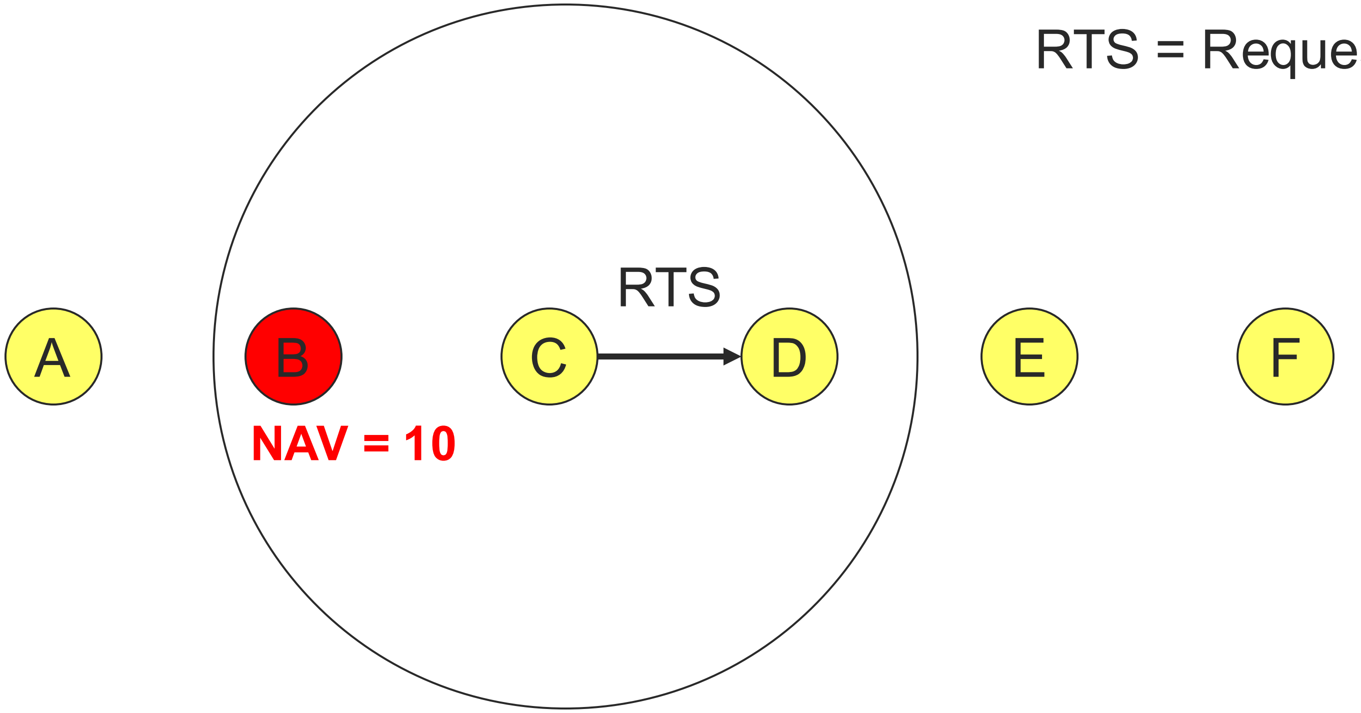


Pretending a circular range

IEEE 802.11 Virtual Carrier Sense

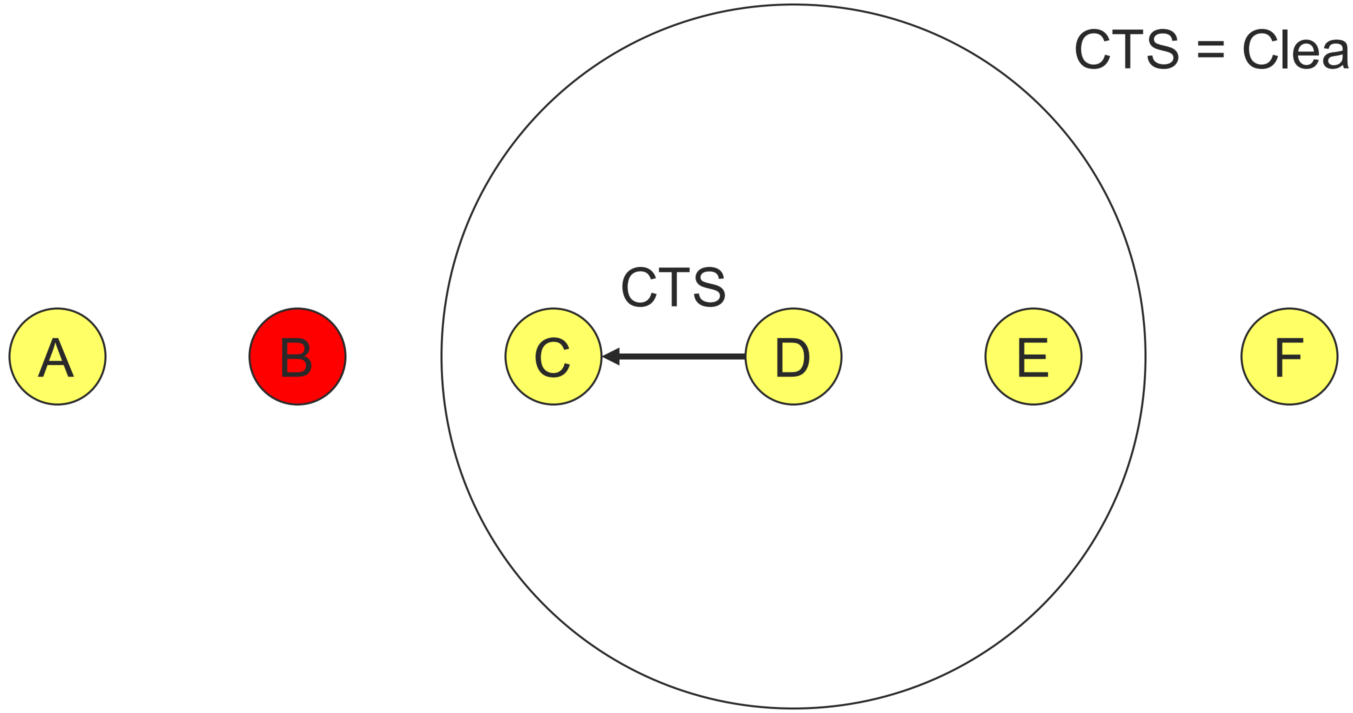
NAV = remaining duration to keep quiet

RTS = Request-to-Send

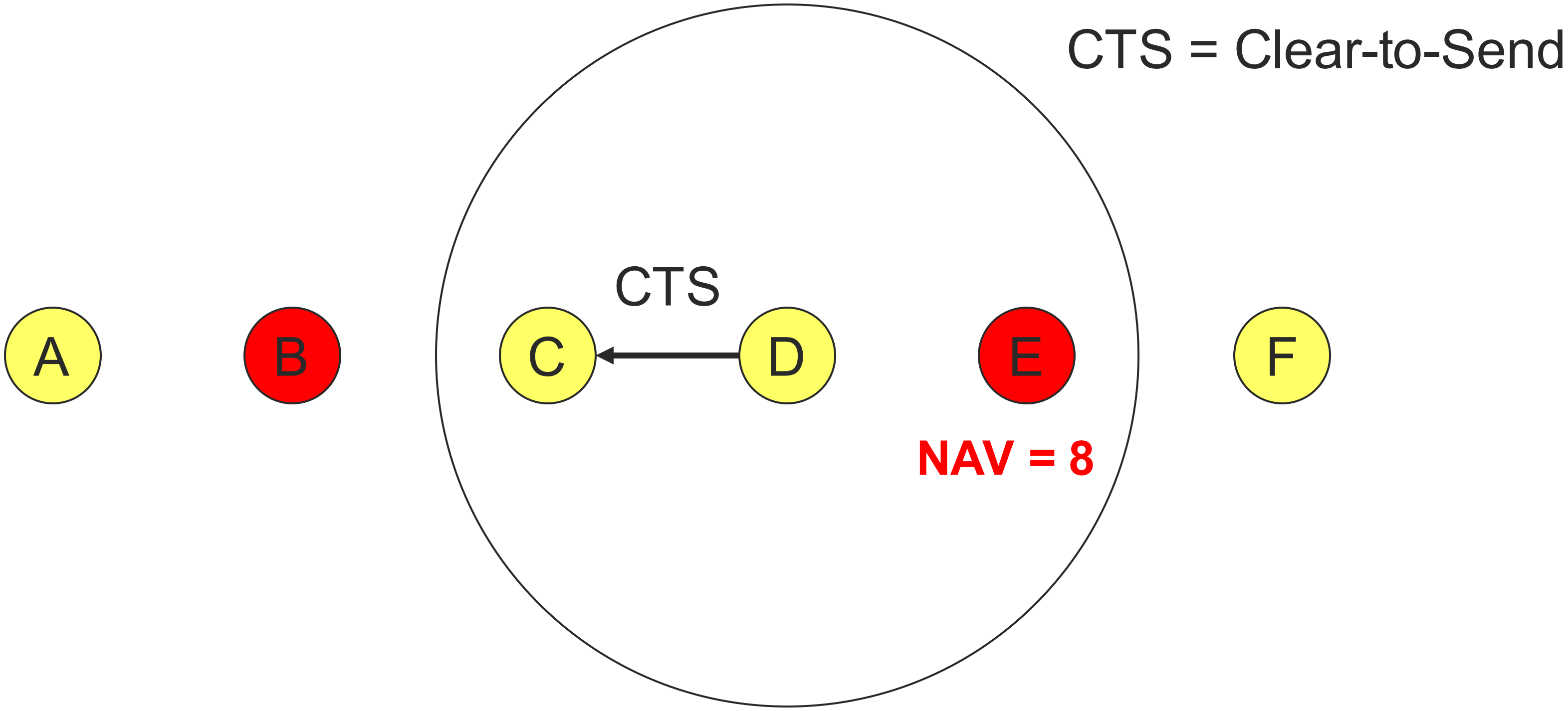


IEEE 802.11 Virtual Carrier Sense

CTS = Clear-to-Send

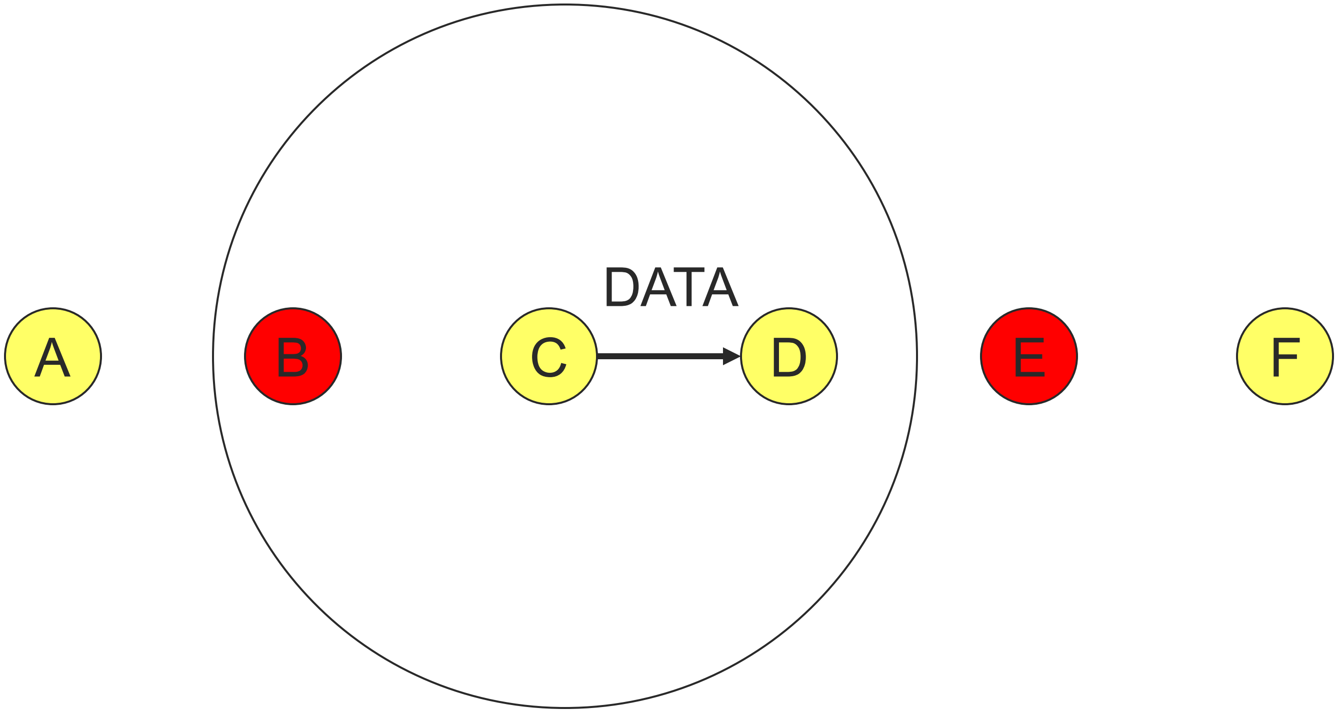


IEEE 802.11 Virtual Carrier Sense



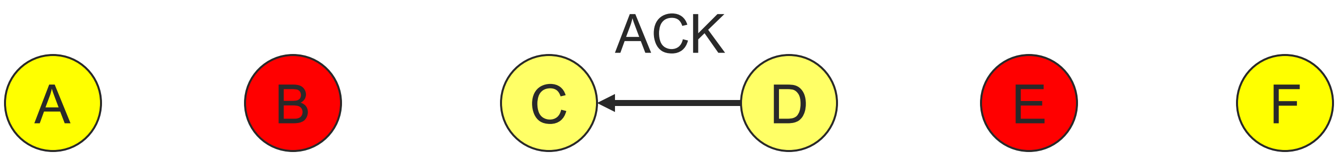
IEEE 802.11 Virtual Carrier Sense

- DATA packet follows CTS

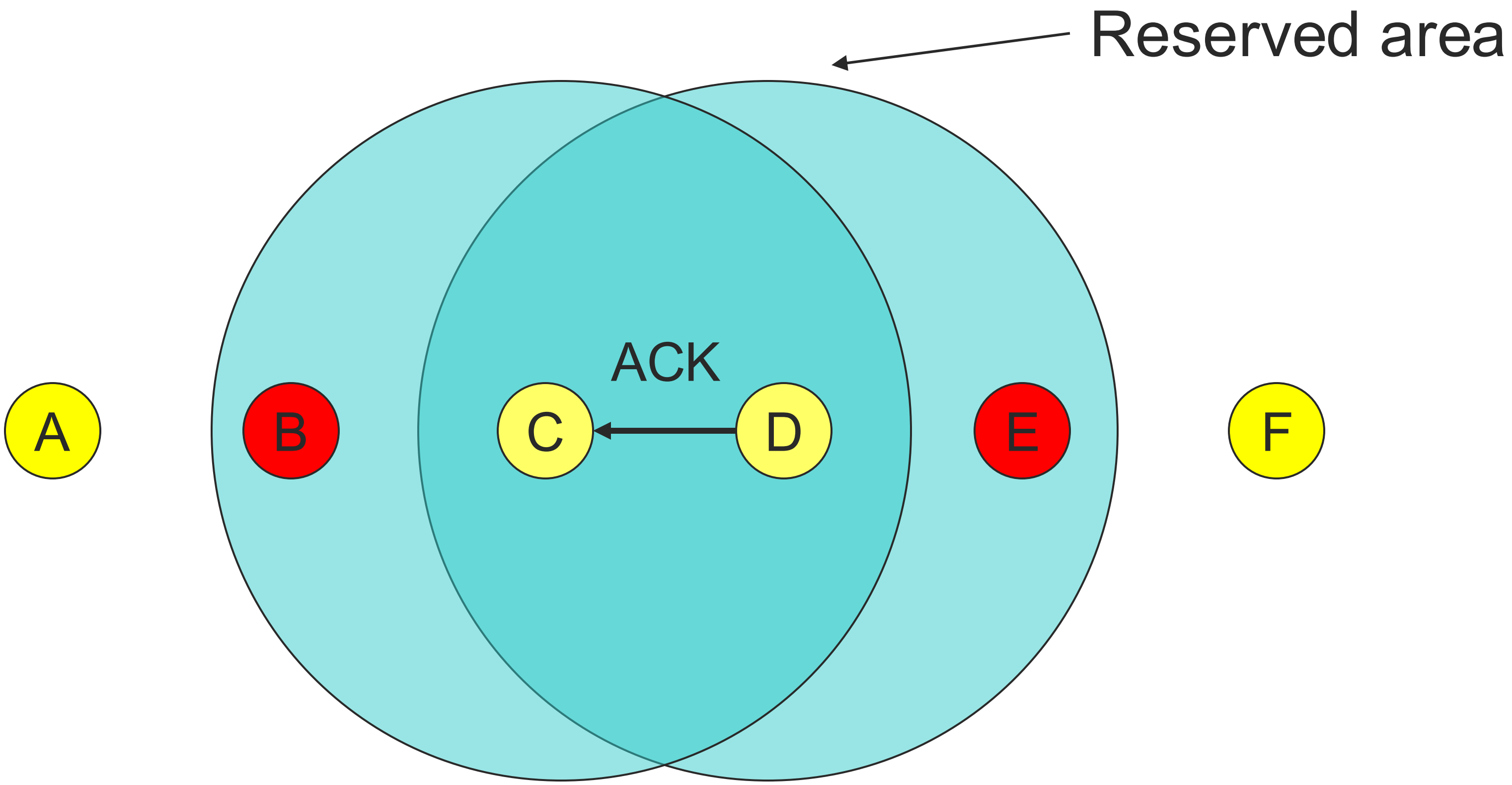


IEEE 802.11 Virtual Carrier Sense

- Successful data reception acknowledged using ACK



IEEE 802.11



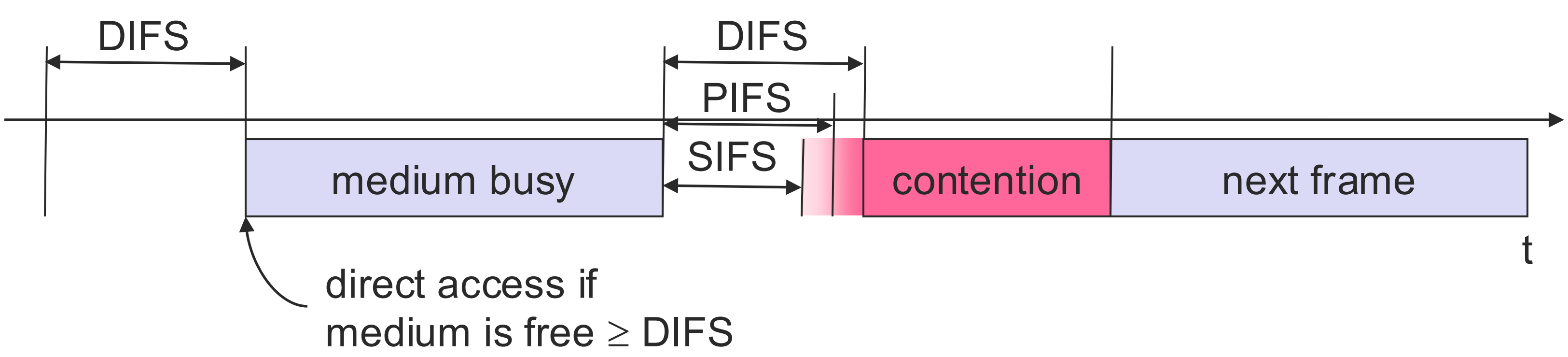
Ethernet vs. IEEE 802.11

- 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?

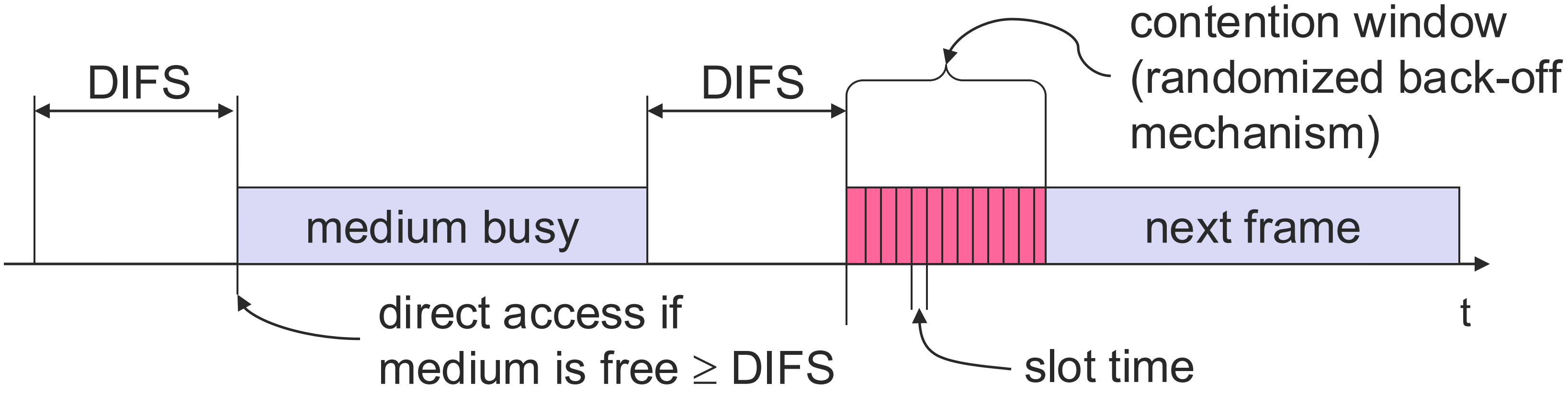
Interframe Spacing

- 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)



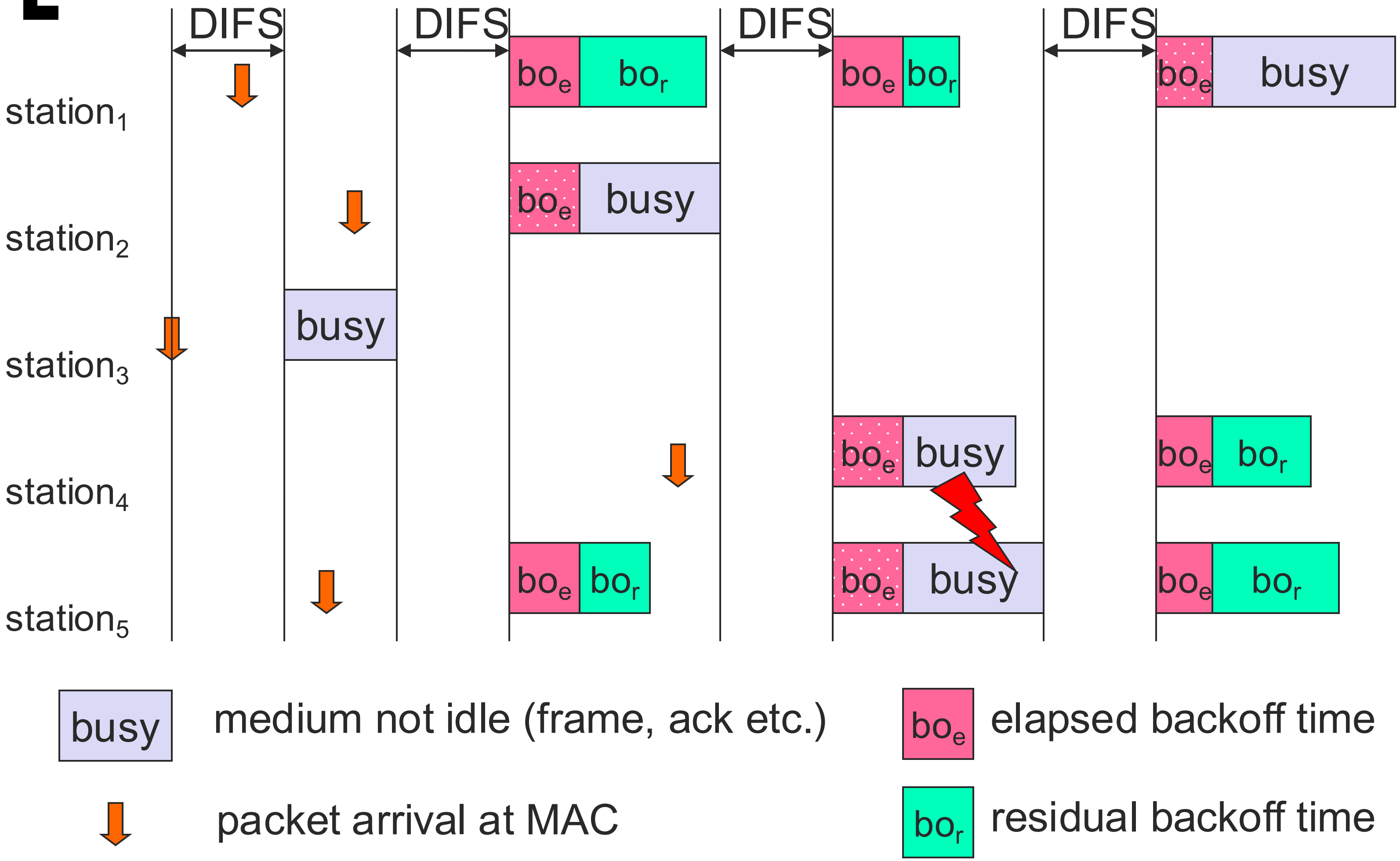
Types of IFS

- 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

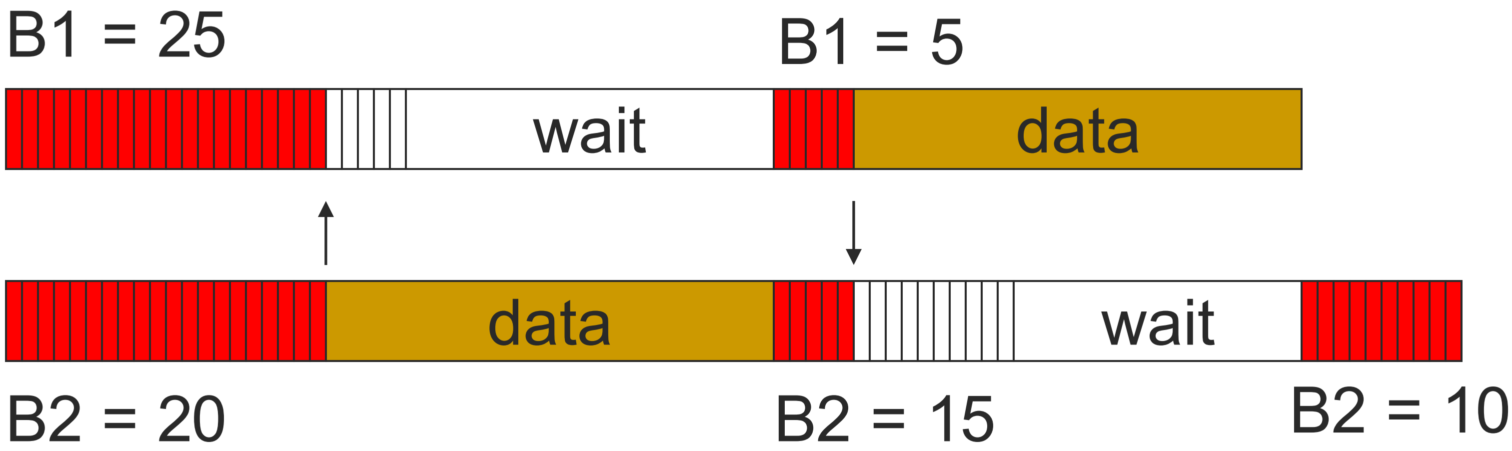
IEEE 802.11 - Competing Stations



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

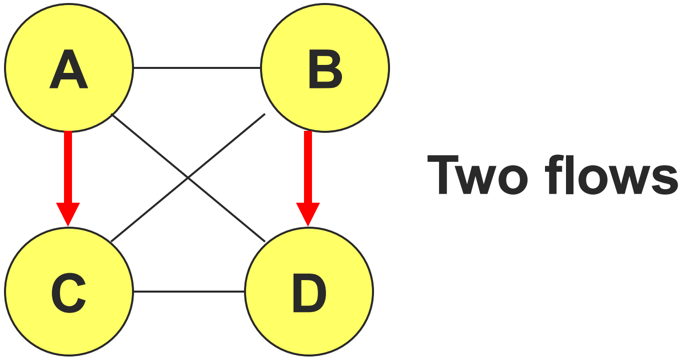
- The number of nodes attempting to transmit simultaneously may change with time
  - Some mechanism to manage contention is needed
- IEEE 802.11 DCF
  - Contention window CW is chosen dynamically depending on collision occurrence

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

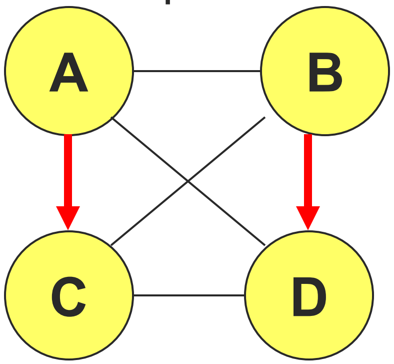
Fairness Issue

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



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

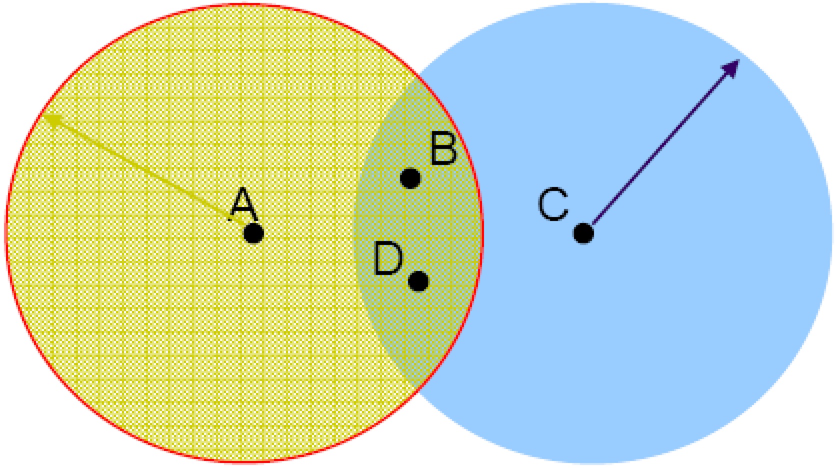


Two flows

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

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

802.11ax: High Efficiency WLANs

- OFDM
  - Orthogonal Frequency Division Multiplexing
- OFDMA
  - Orthogonal Frequency Division Multiple Access
  - Divides subcarriers into Resource Units (RUs)
  - Shares the channel among multiple devices simultaneously

Resource Units

- RUs are the allocation blocks of bandwidth in OFDMA
- Vary in size depending on channel width
- Adjacent subcarriers (tones) are grouped together into a resource unit (RU)

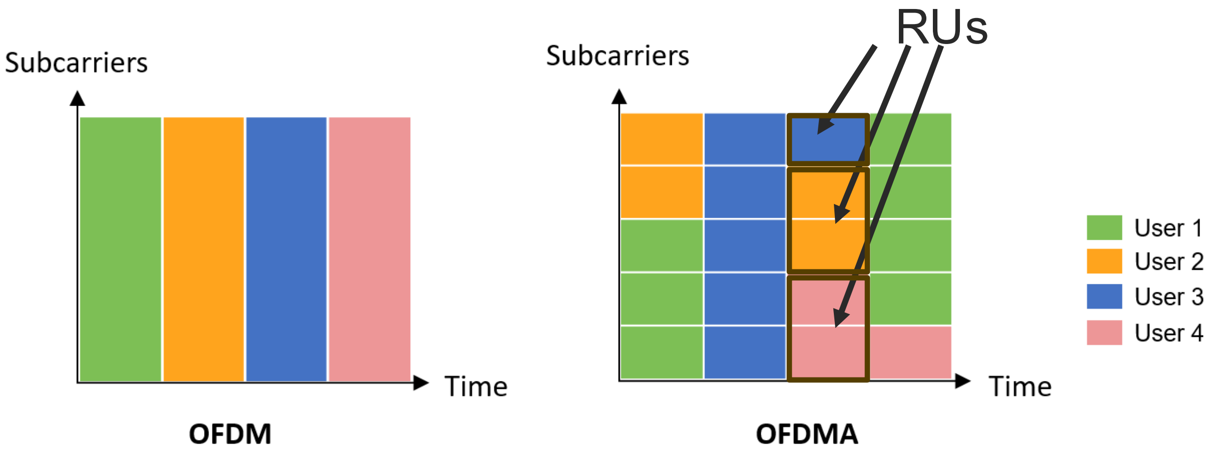
OFDM v OFDMA

OFDM

Single user on channel
at a time

https://oringnet.com/en/knowledge-base/how-does-wifi6-ofdma-work

OFDM v OFDMA

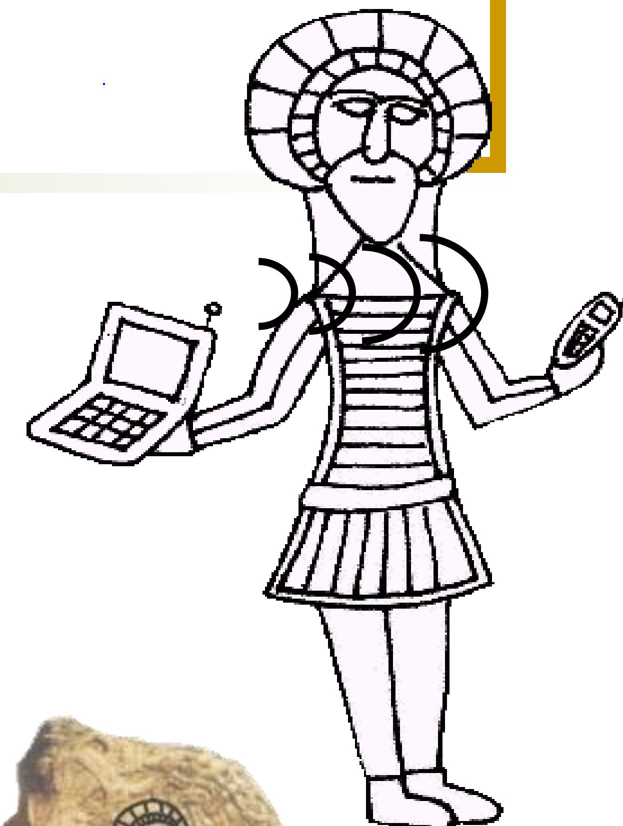


Single user on channel at a time

Multiple users, Various bandwidths

https://oringnet.com/en/knowledge-base/how-does-wifi6-ofdma-work

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]

Bluetooth Progression

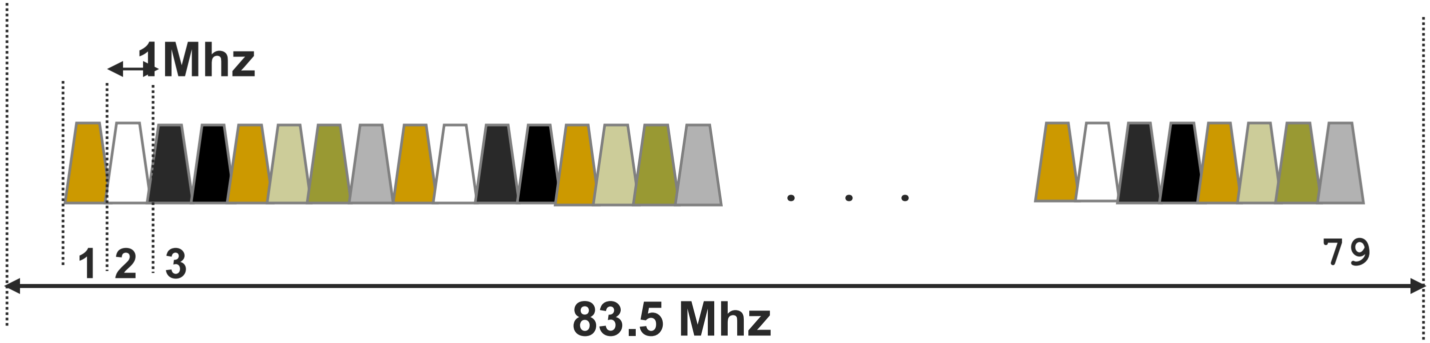
Bluetooth 1.0

Initial version

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)

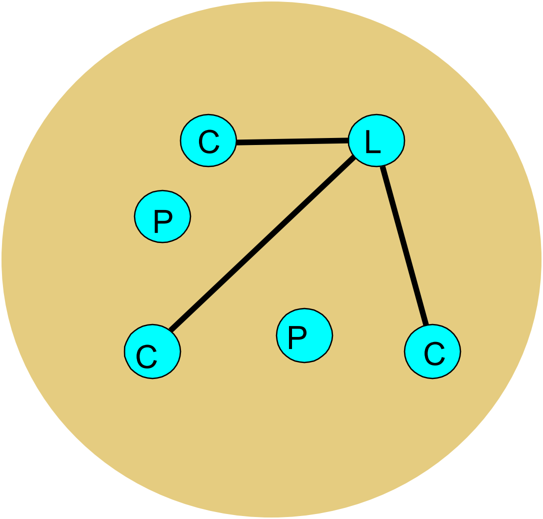
Bluetooth Radio



- MA scheme: Frequency hopping spread spectrum.
  - 2.402 GHz + k MHz, k=0, …, 78
  - 1,600 hops per second.
  - 1 Mb/s data rate
- Upgraded to 2 Mbps in BT 5.0

Bluetooth Network Topology

- Radio designation
  - Connected radios can be leaders or clients
  - Radios are symmetric (same radio can be leader or client)
- Piconet
  - Main can connect to 7 simultaneous or 200+ inactive (parked) clients per piconet
  - Each piconet has maximum capacity (1 Mbps)
  - Unique hopping pattern/ID



Bluetooth – Contention-free MAC

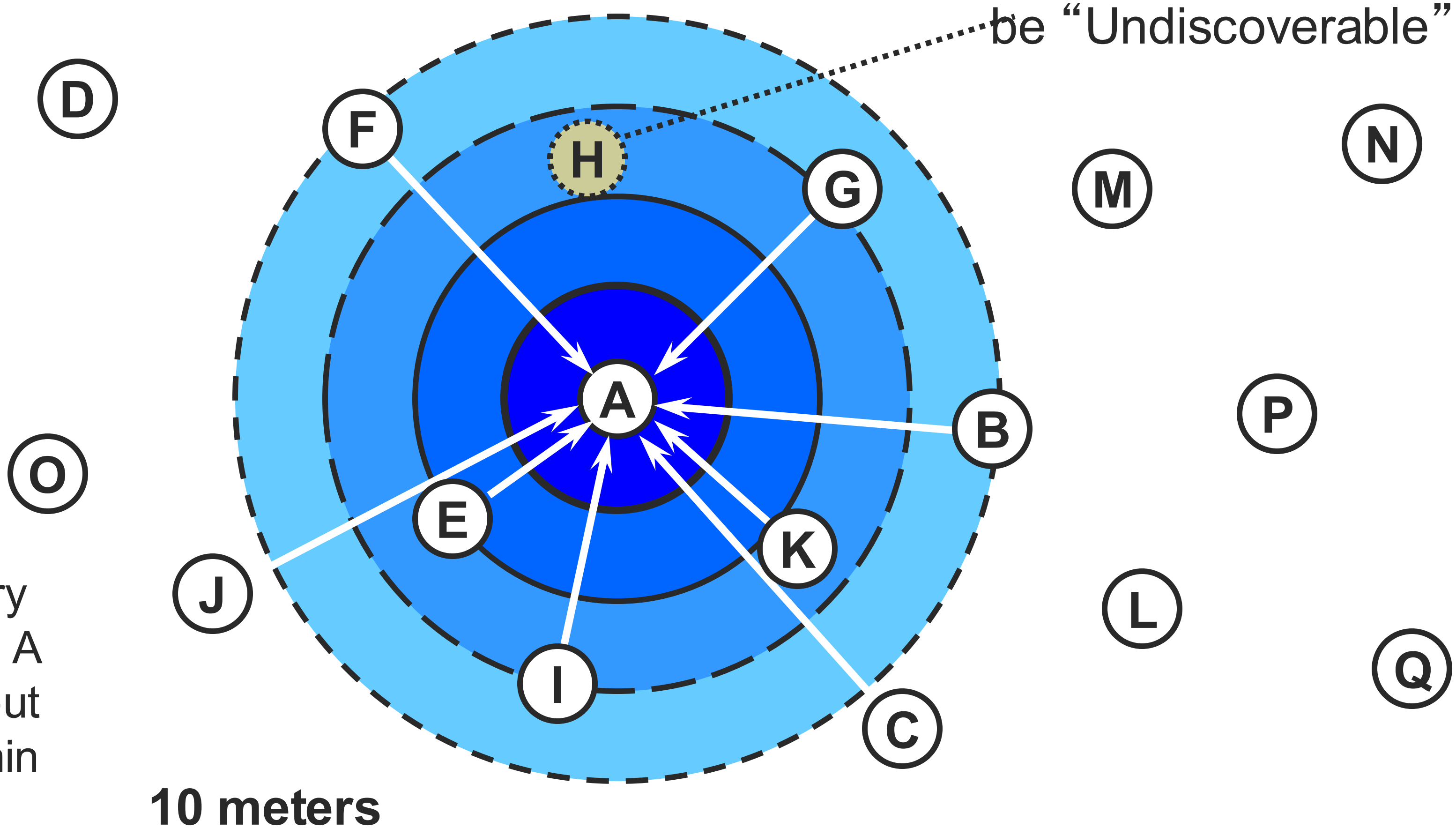
- Leader performs medium access control
  - Schedules traffic through polling
- Time slots alternate between leaders and clients transmission
  - Leader-client
    - Leader includes client address
  - Client-leader
    - Only clients chosen by leader in previous leader-client slot allowed to transmit.
  - If leader has data to send to a client, client polled implicitly; otherwise, explicit poll.

Bluetooth Device Discovery - Inquiry

- Device discovery
  - Sends out an inquiry, 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

Note that a device can be “Undiscoverable”



After inquiry procedure, A knows about others within range

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 Progression

Bluetooth 1.0	Bluetooth 2.0
Initial version	Significantly Increased Speed

Data Rate (3Mbps)
Improved power consumption
Expand to audio devices

Bluetooth Progression

Bluetooth 1.0	Bluetooth 2.0	Bluetooth 3.0
Initial version	Significantly Increased Speed	High-Speed Bluetooth

Bluetooth + Wifi Data Speed (24Mbps)
Efficiency/ Connection Stability/ Power Control …

Bluetooth Progression

Bluetooth 1.0	Bluetooth 2.0	Bluetooth 3.0	Bluetooth 4.0
Initial version	Significantly Increased Speed	High-Speed Bluetooth	Bluetooth Low Energy

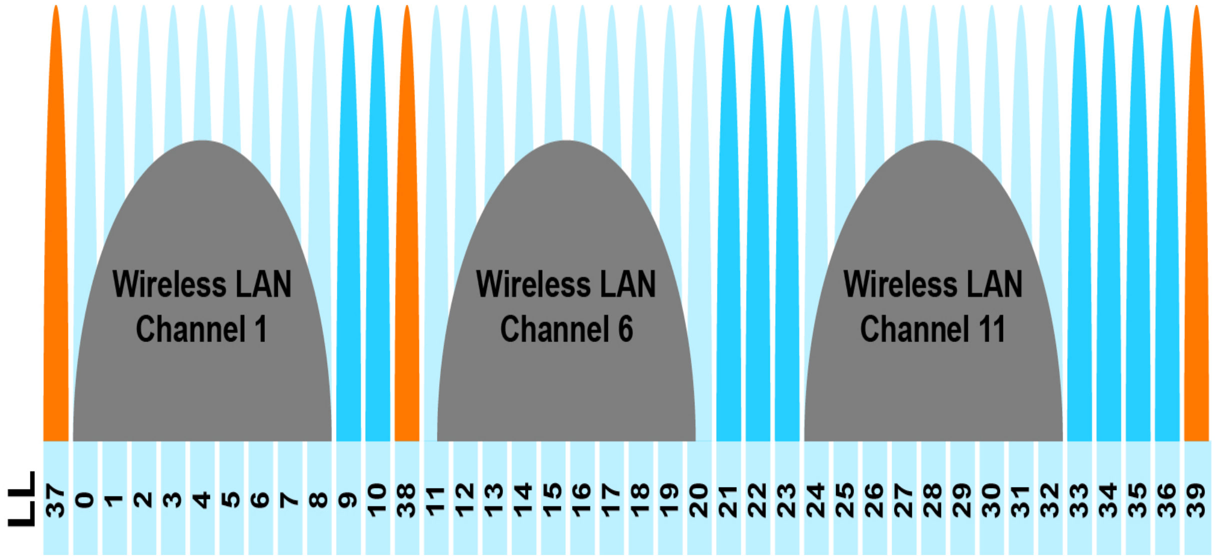
Market demands:
Low Power (0.01 - 0.5mW)
Longer Range
Decent speed
Faster discovery

BLE Highlights

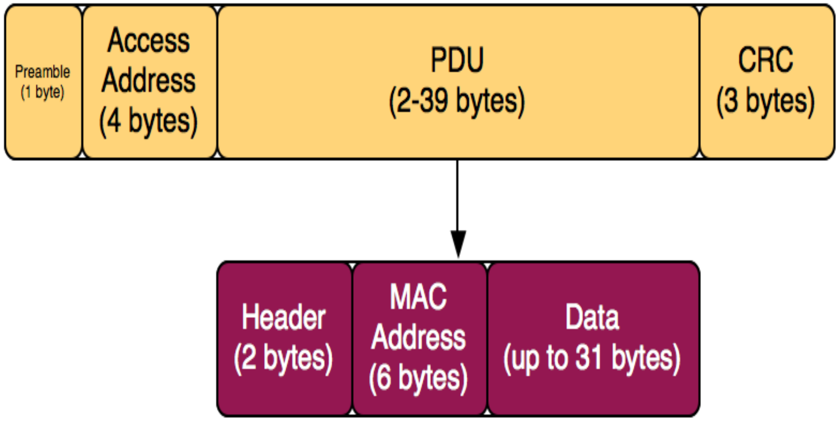
- Shared wireless channel
  - BLE operates in the 2.4 GHz ISM band with Wi-Fi and other technologies (phones, microwave ovens …)
- BLE = Bluetooth Low Energy
  - Improved discovery
  - Key component: Beacons
    - Tags send out advertising beacons (typ. dist 30ft)
    - Phones scan for beacons

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)



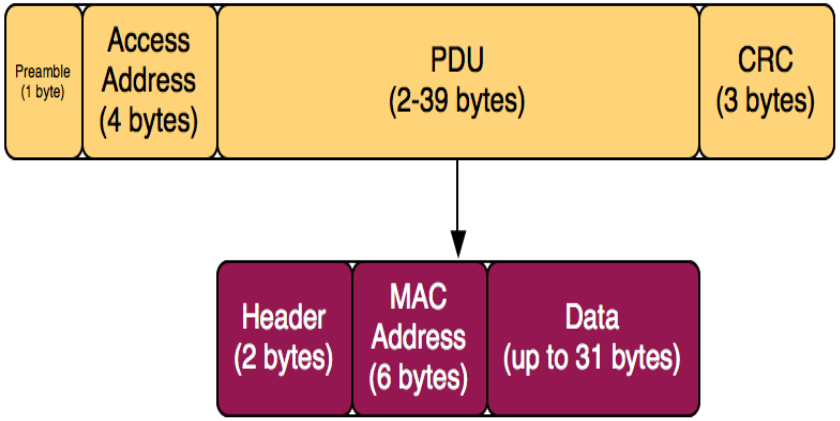
BLE Highlights: Advertising

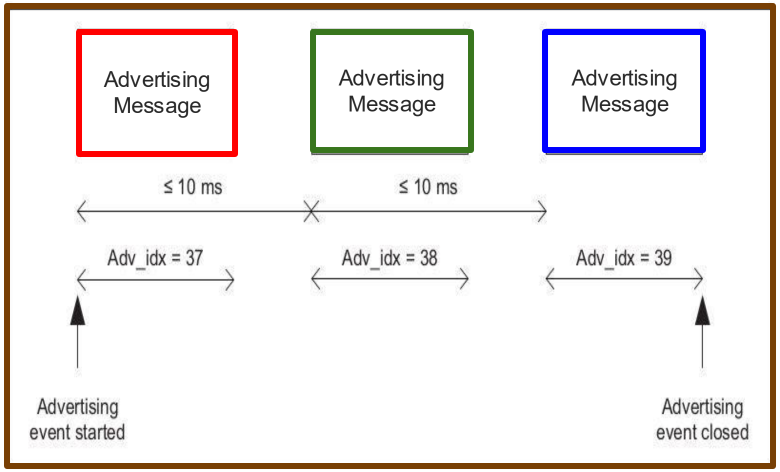


- Advertising Tags
- Advertising Messages
  - Header + MAC Address + up to 31 Bytes of data
    - ~200 - 400 usec per packet
  - Two types: Non-scannable, Scannable

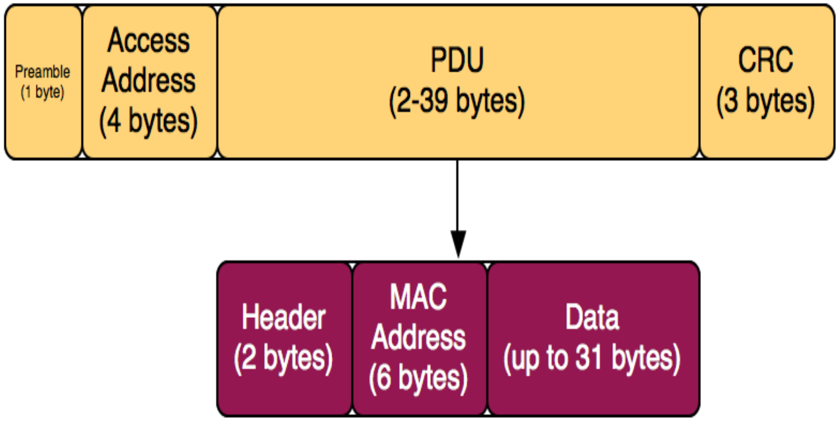
BLE Highlights: Advertising

- Advertising Tags
- Advertising Messages
  - Header + MAC Address + up to 31 Bytes of data
    - ~200 - 400 usec per packet
  - Two types: Non-scannable, Scannable
- Advertising Event
  - One advertising message sent out on each advertising channel (37, 38, 39)

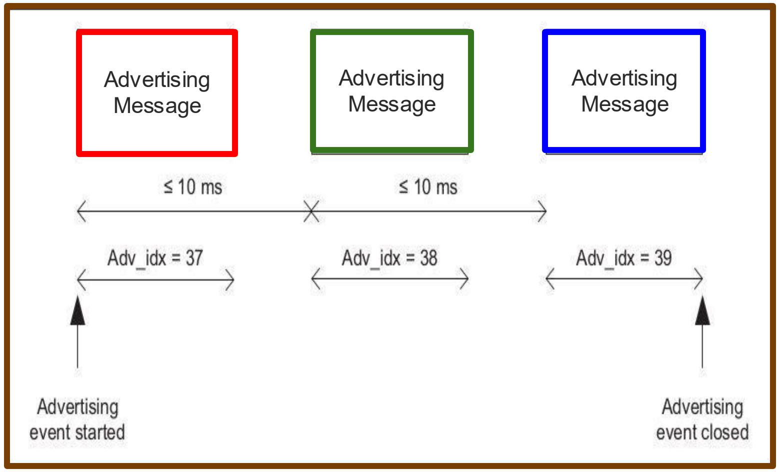




BLE Highlights: Advertising

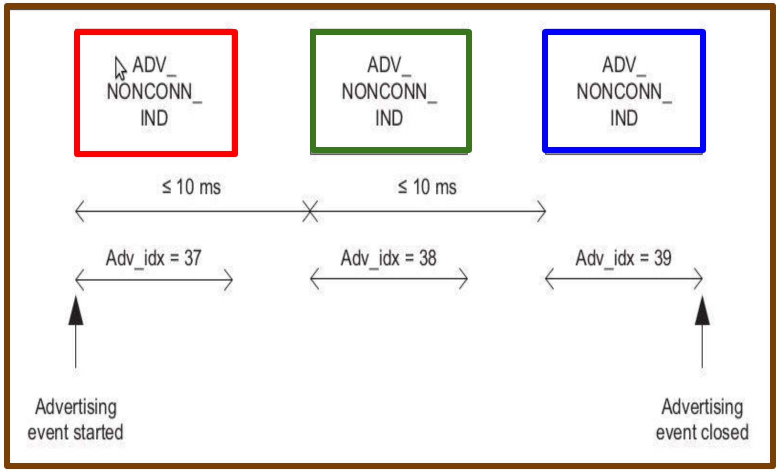


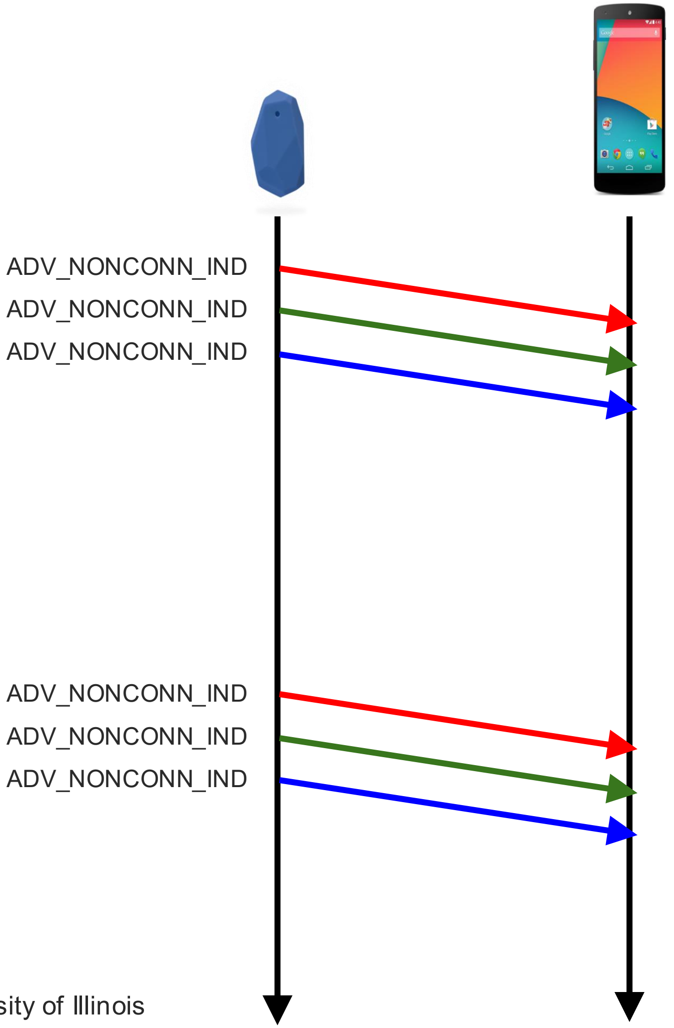
- Advertising Tags
- Advertising Messages
  - Header + MAC Address + up to 31 Bytes of data
    - ~200 - 400 usec per packet
  - Two types: Non-scannable, Scannable
- Advertising Event
  - One advertising message sent out on each advertising channel (37, 38, 39)
- Advertising Interval
  - One advertising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



BLE Highlights: Tags Types - Non-Scannable

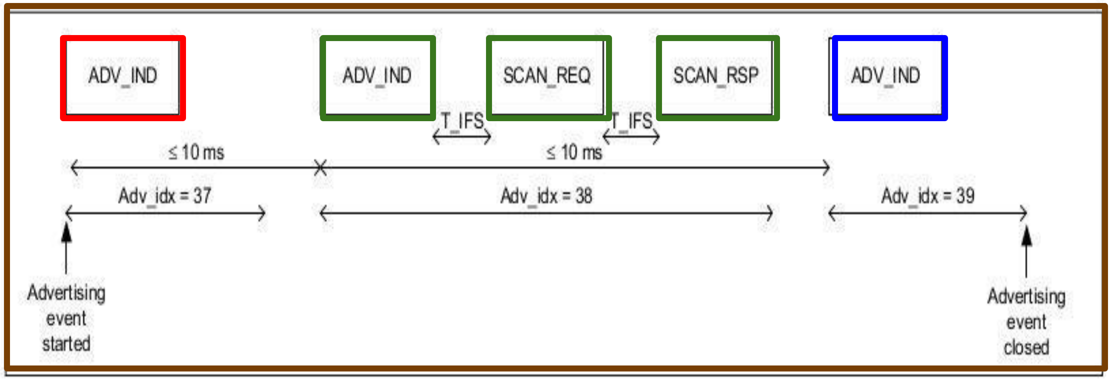
- Non-Scannable Tags
- Tags send ADV_NONCONN_IND messages
- Typically sent back-to-back
- Scanners listen, but do not respond

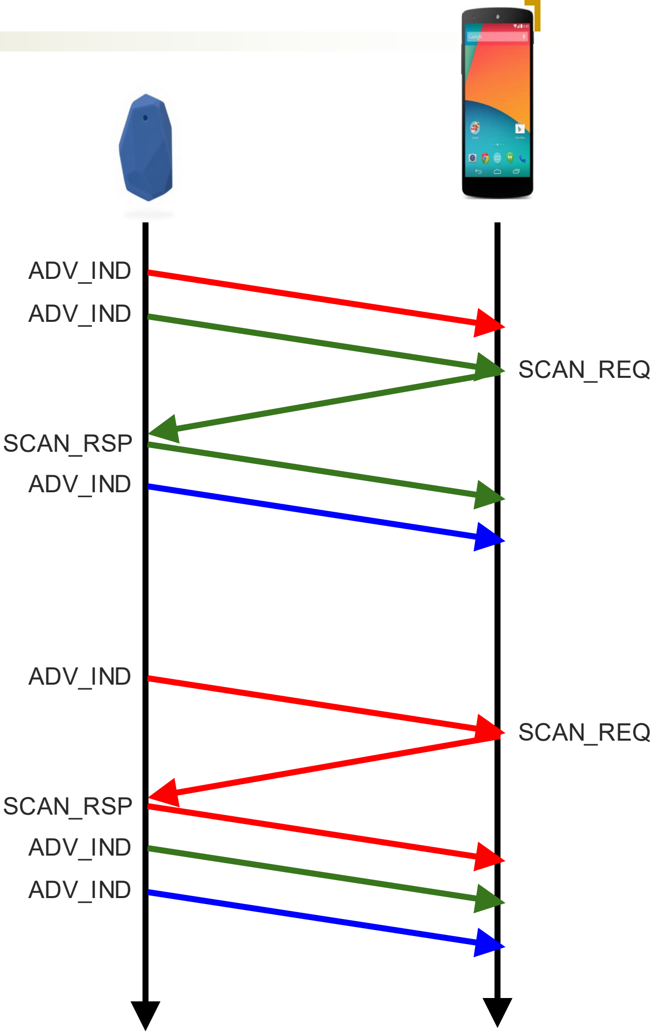




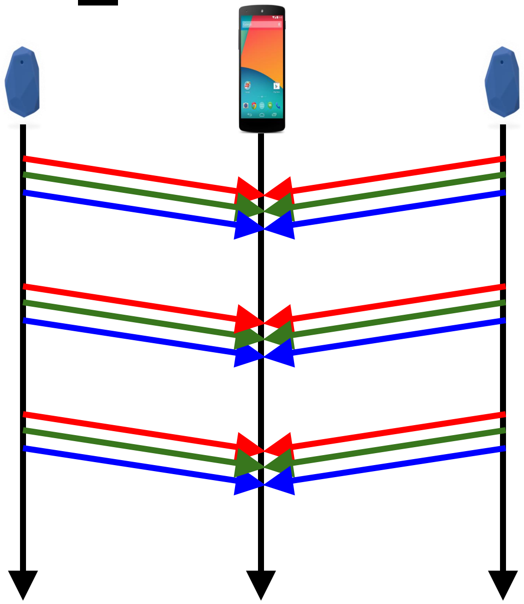
BLE Highlights: Tags Types - Scannable

- 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



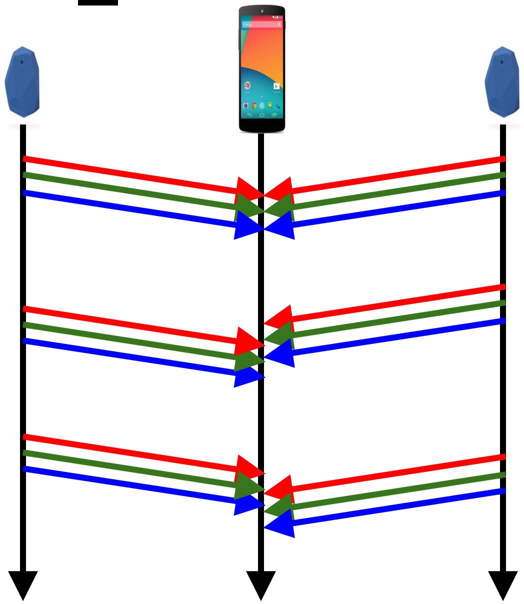


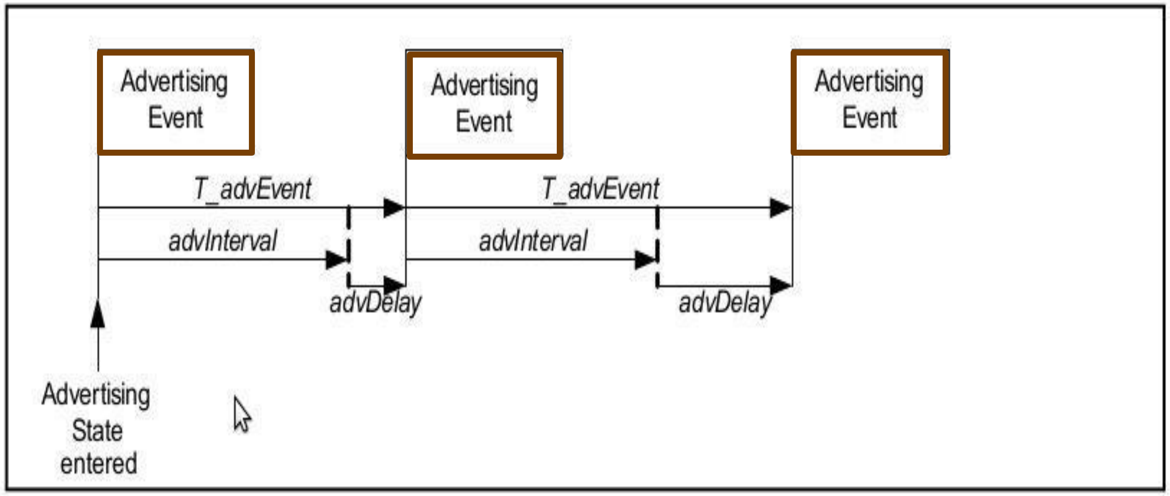
BLE Highlights: Advertising and Collisions



- If tags get synchronized, all advertising messages will collide

BLE Highlights: Advertising and Collisions





- Collision avoidance
  - Jitter advertising times
  - advDelay is added on to the end of each advertising event
  - advDelay = rand [0,10ms]

Bluetooth Progression

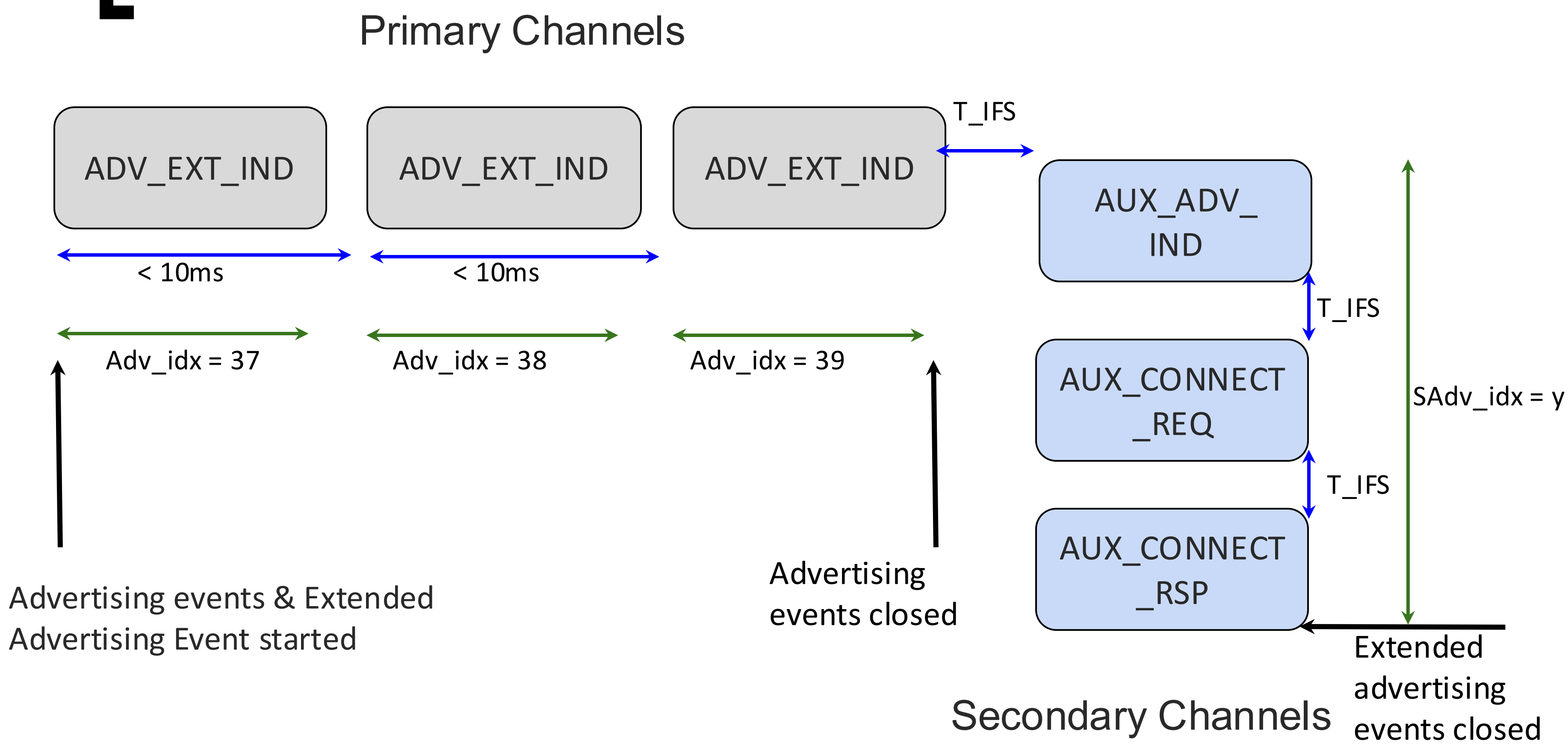
Bluetooth 1.0	Bluetooth 2.0	Bluetooth 3.0	Bluetooth 4.0	Bluetooth 5.0
Initial version	Significantly Increased Speed	High-Speed Bluetooth	Bluetooth Low Energy	IoT Bluetooth

4.0 is too slow
Low range (especially indoors)
Power issues
Issues relating to multiple radios on the same device

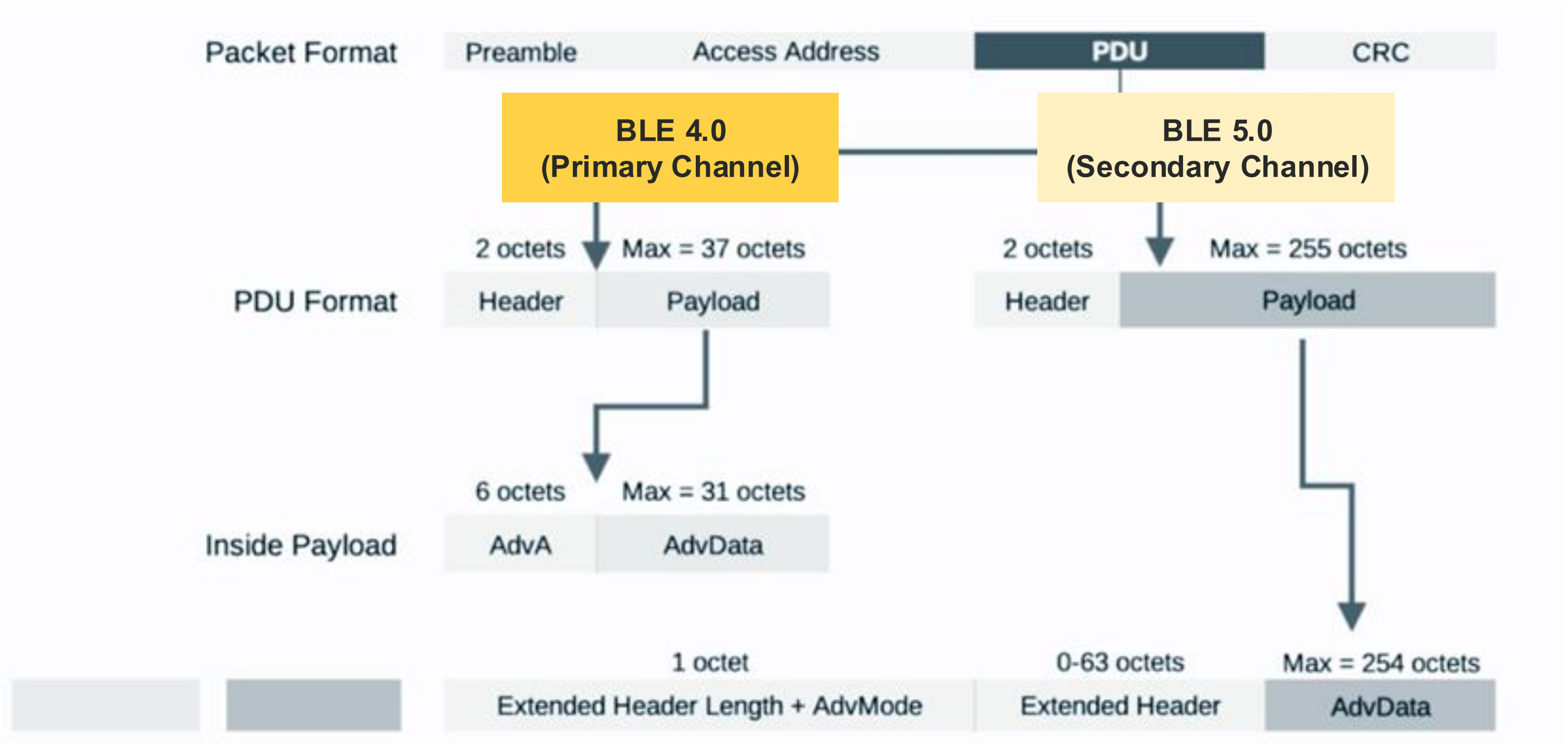
Bluetooth 5.0 Improvements

BLE 4.0	BLE 5.0
Advertising Congestion/Interference	Use of Secondary channels Increase payload size -> less transmission

Bluetooth 5.0: Extended Advertising



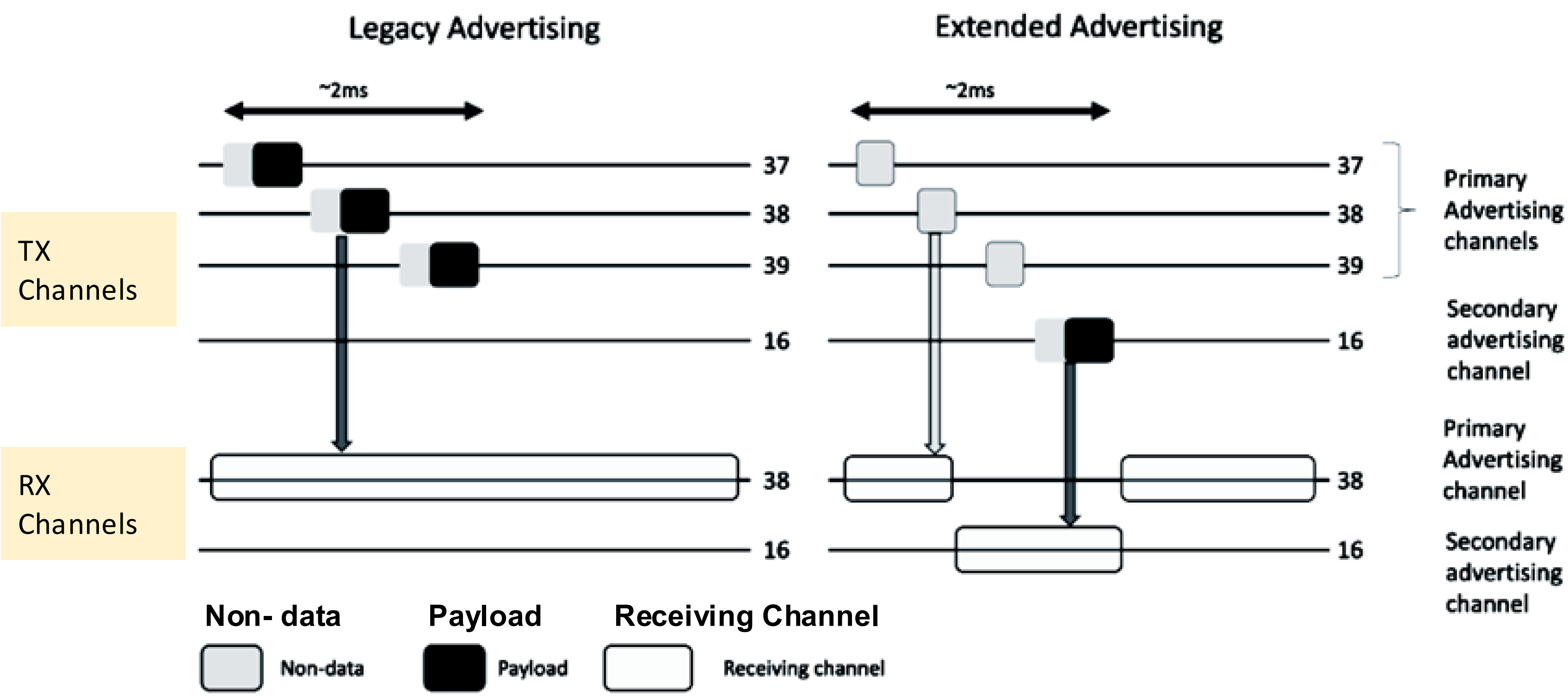
Bluetooth 5.0: Payload Increase



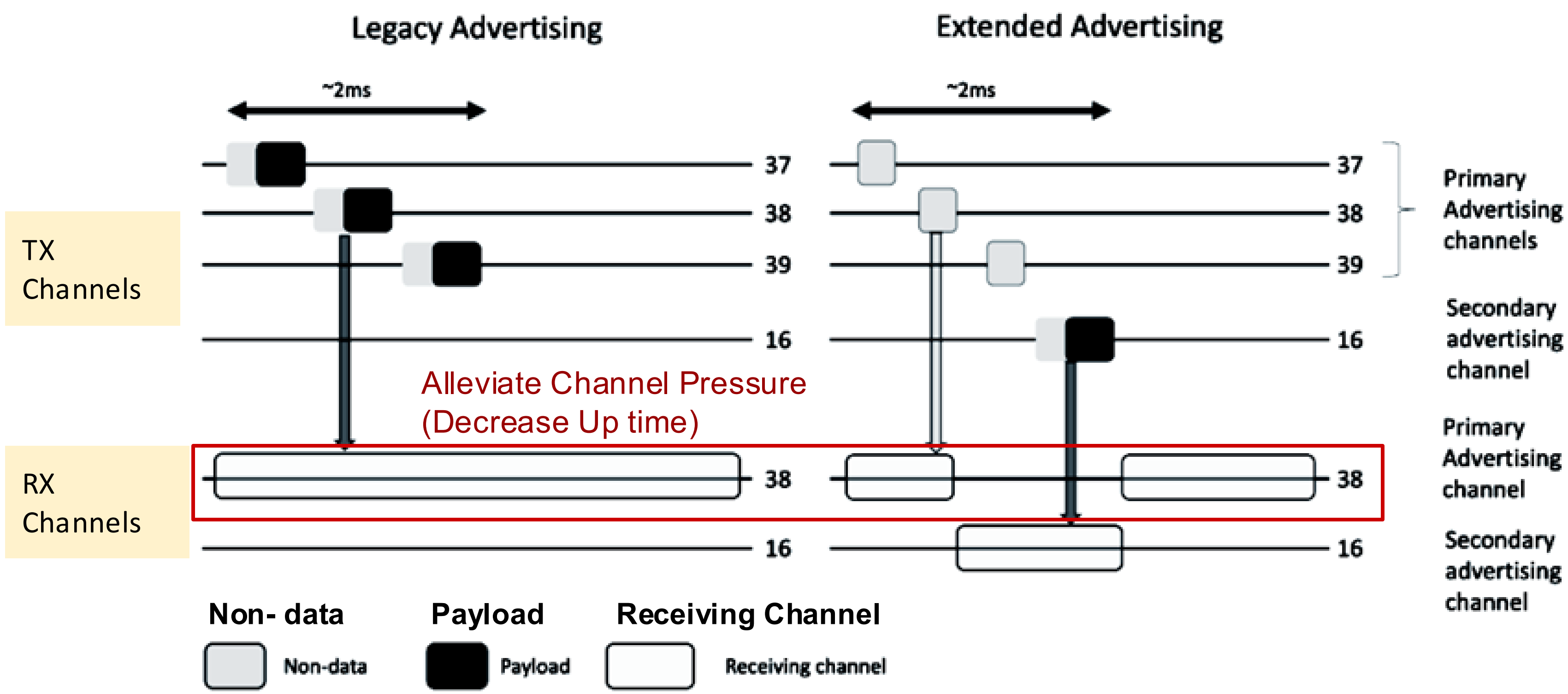
Bluetooth 5.0 Improvements

BLE 4.0	BLE 5.0
Advertising Congestion/Interference	Use of Secondary channels Increase payload size -> less transmission
Insufficient for High Data Rate Applications	Increased max transfer speed (1Mbps -> 2Mbps)

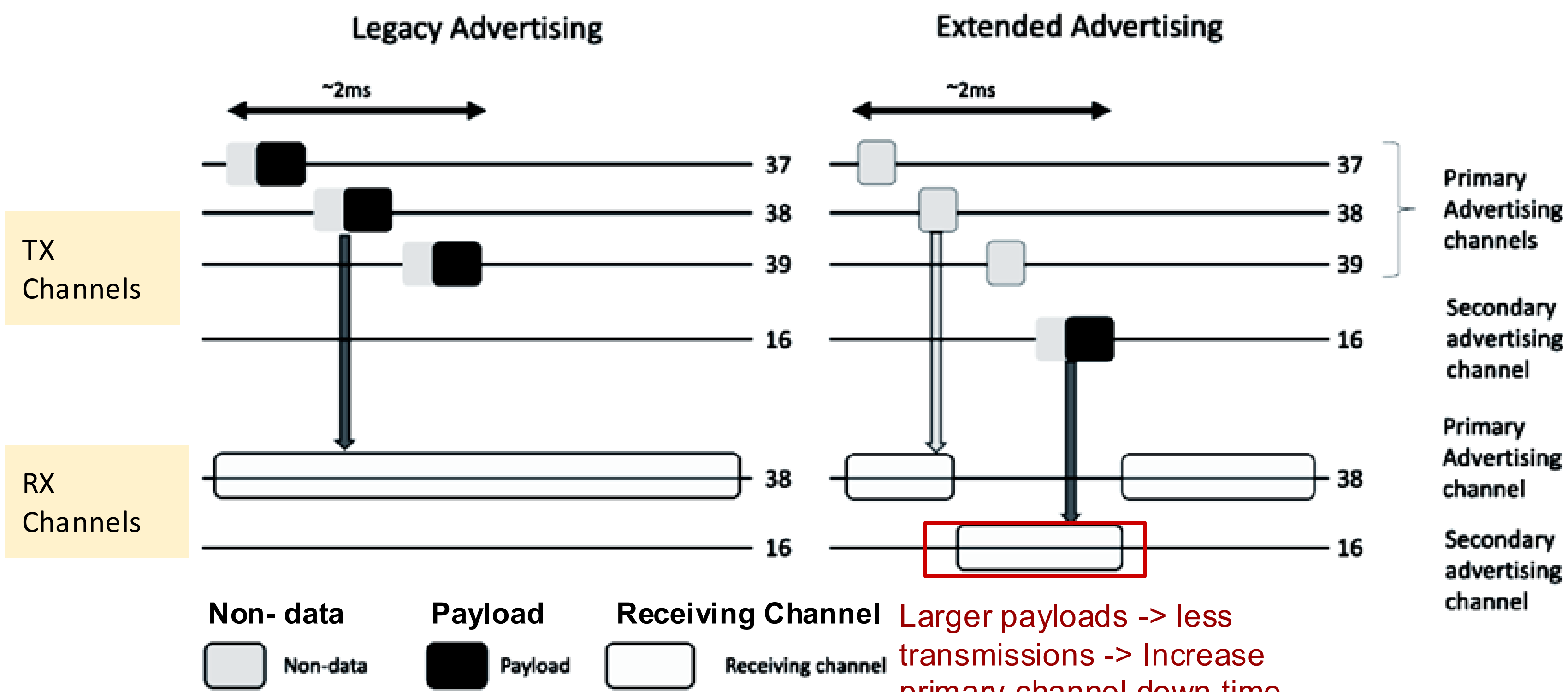
Bluetooth 5.0: Congestion Management



Bluetooth 5.0: Congestion Management



Bluetooth 5.0: Congestion Management



Larger payloads -> less transmissions -> Increase primary channel down time

Bluetooth 5.0 Improvements

BLE 4.0	BLE 5.0
Advertising Congestion/Interference	Use of Secondary channels Increase payload size -> less transmission
Insufficient for High Data Rate Applications	Increased max transfer speed (1Mbps -> 2Mbps)
Inadequate for Long Range Applications	Coded physical layer (up to 400m – 1km) Robust algorithm to strengthen signal

Bluetooth 5.0: Coded PHY

Parameter	LE 1M	LE Coded S2	LE Coded S8	LE 2M
Symbol Rate	1 Msps	1 Msps	1 Msps	2 Msps
Data Rate	1 Mbps	500 kbps	125 kbps	2 Mbps
Error Correction	None	FEC	FEC	None
Range Multiplier	1	~ 2	~ 4	~ 0.8

- Symbols per sec
  - S2: 2 symbols = 1 bit
  - S8: 8 symbols = 1 bit

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Baseline for BLE 4.0

- Symbols per sec
  - S2: 2 symbols = 1 bit
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Bluetooth 5.0: Coded PHY

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- Symbols per sec
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2Mbps max data rate for BLE 5.0 (High data rate application, reduced range)

Bluetooth 5.0: Coded PHY

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Data Rate	1 Mbps	500 kbps	125 kbps	2 Mbps
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- Symbols per sec
  - S2: 2 symbols = 1 bit
  - S8: 8 symbols = 1 bit

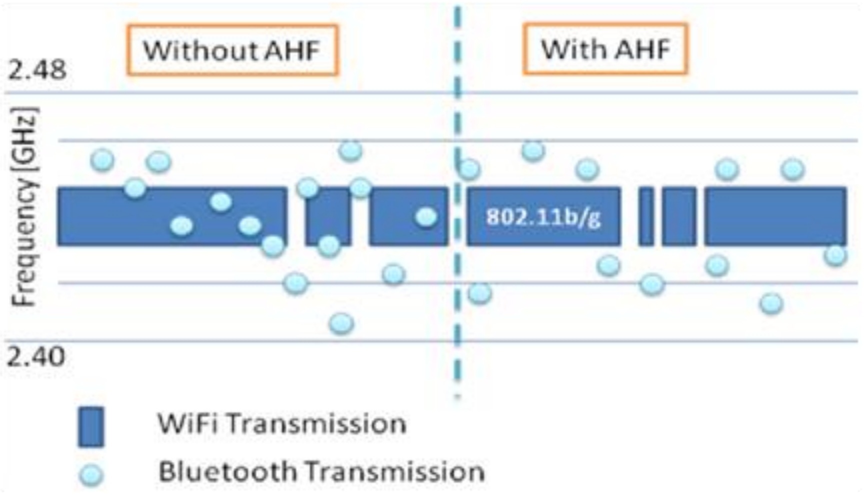
Quadruple distance for coded PHY (Long range application, reduced data rate)

Bluetooth 5.0 Improvements

BLE 4.0	BLE 5.0
Advertising Congestion/Interference	Use of Secondary channels Increase payload size -> less transmission
Insufficient for High Data Rate Applications	Increased max transfer speed (1Mbps -> 2Mbps)
Inadequate for Long Range Applications	Coded physical layer (up to 400m – 1km) Robust algorithm to strengthen signal
Limited Advertising Capabilities / Power efficiency	Dynamic advertising sets Improved Channel Selection Algorithm Precise Timing Controls

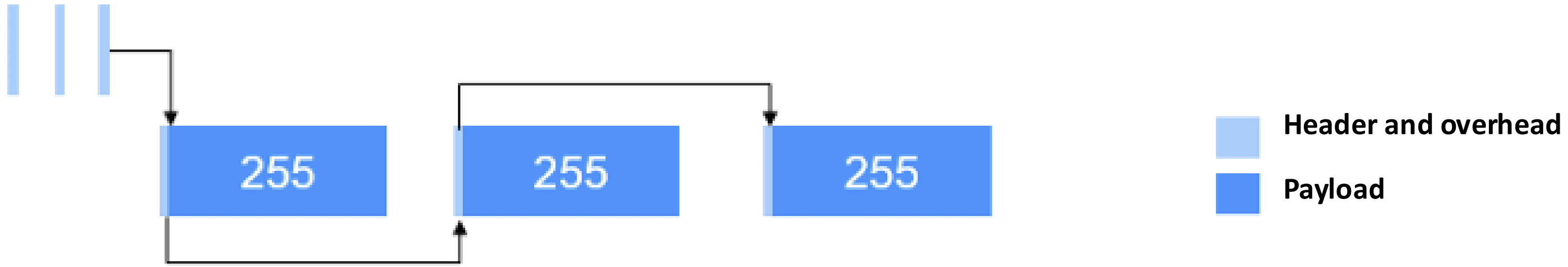
Bluetooth 5.0: Adaptive Frequency Hopping

- Adaptive Frequency Hopping
  - Channels (0-36) set to used or unused, algorithmically determine sequence
  - Channel Selection Algorithm (CSA) #1: 12 distinct sets
  - CSA #2 allows for many distinct sequences, reduces collisions



Bluetooth 5.0: Packet Chaining

- Controller can chain packets together, using AuxPtr header fields (references to Auxiliary Packets containing payload)
- AuxPtr includes the channel number 0-36, receiver can find it
- Up to 1,650 bytes
- Improves efficiency, data transfer rate, power, etc.

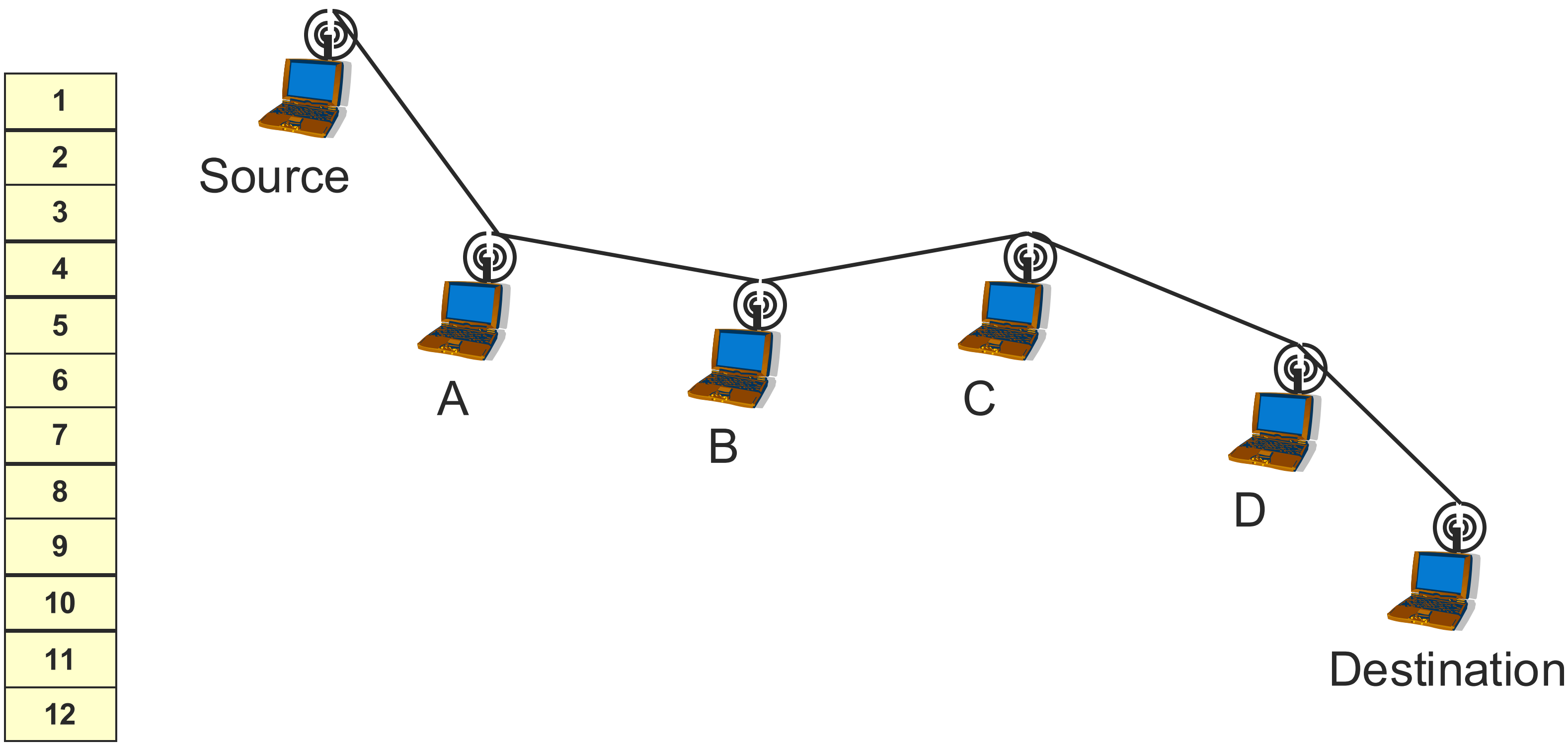


Wireless Multihop Networks

- 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

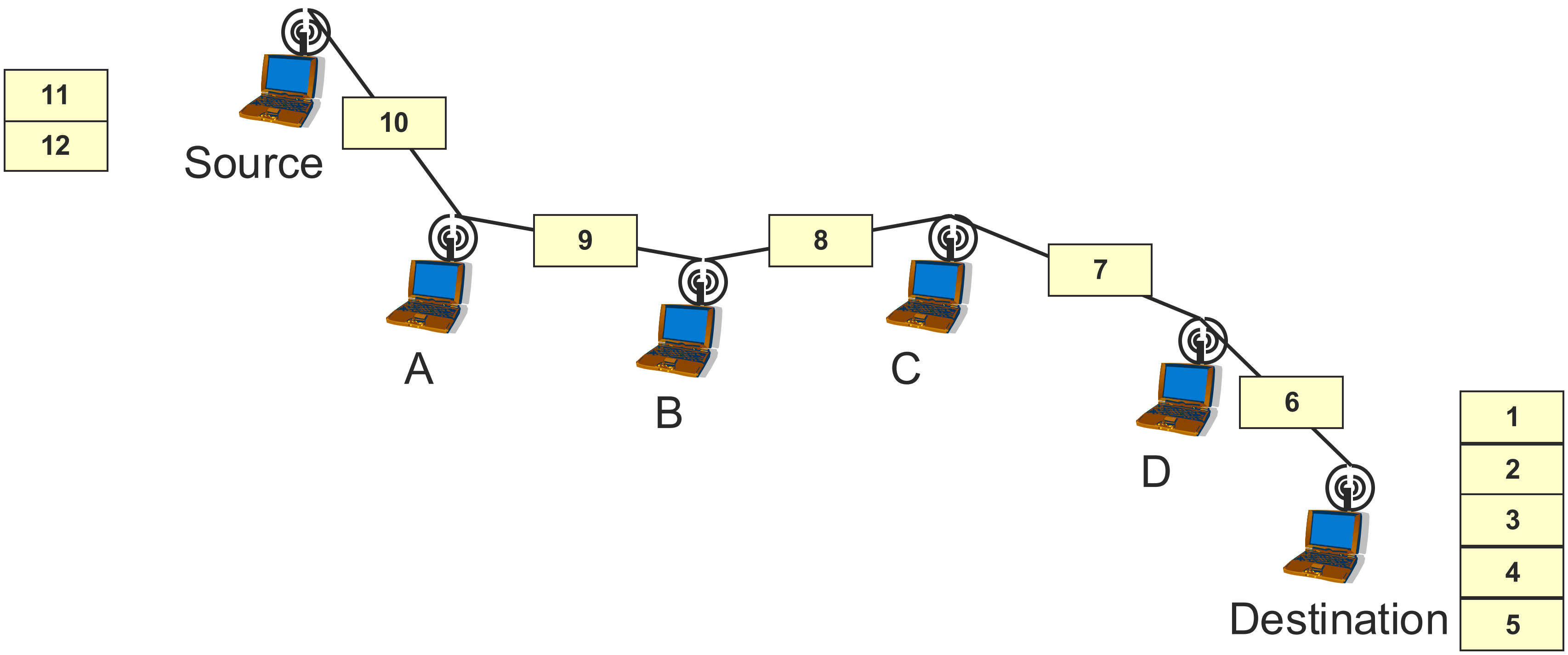
Multi-Hop Wireless Networks

- In an ideal world …



Multi-Hop Wireless Networks

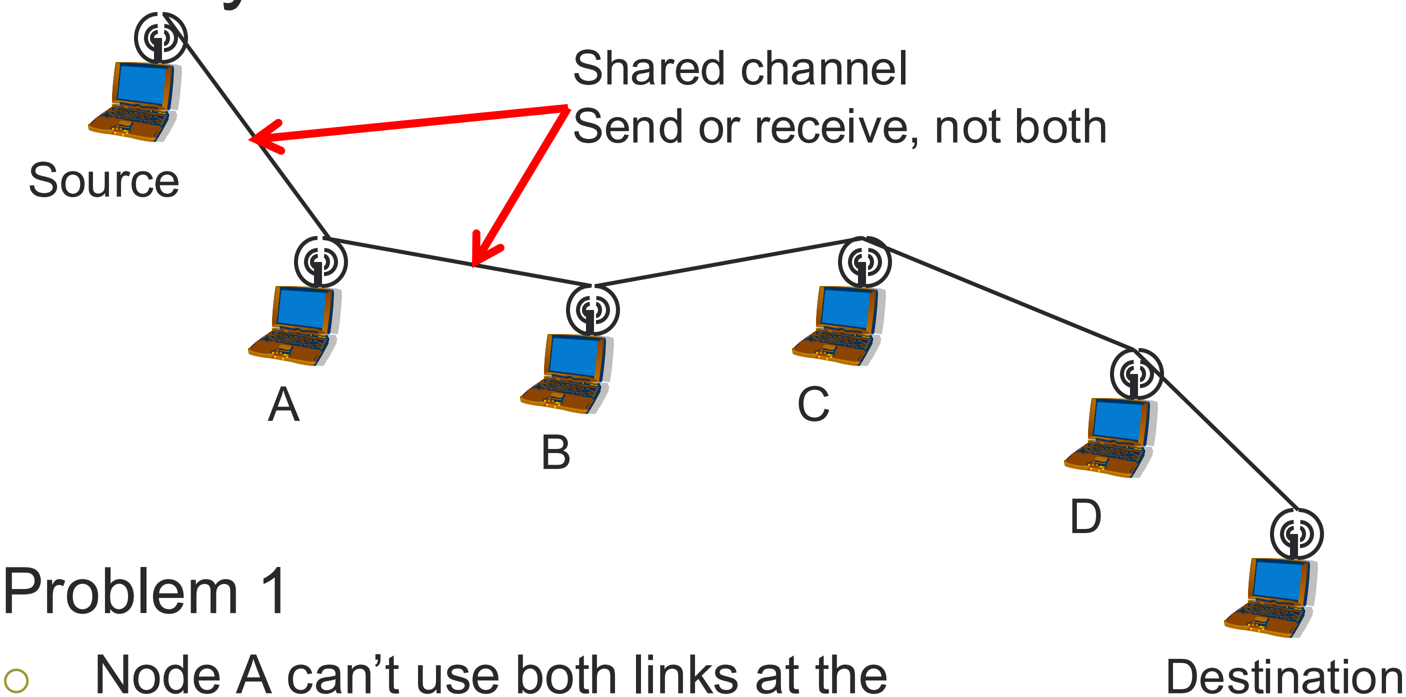
- In an ideal world …



Multi-Hop Wireless Networks

- Reality check …

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

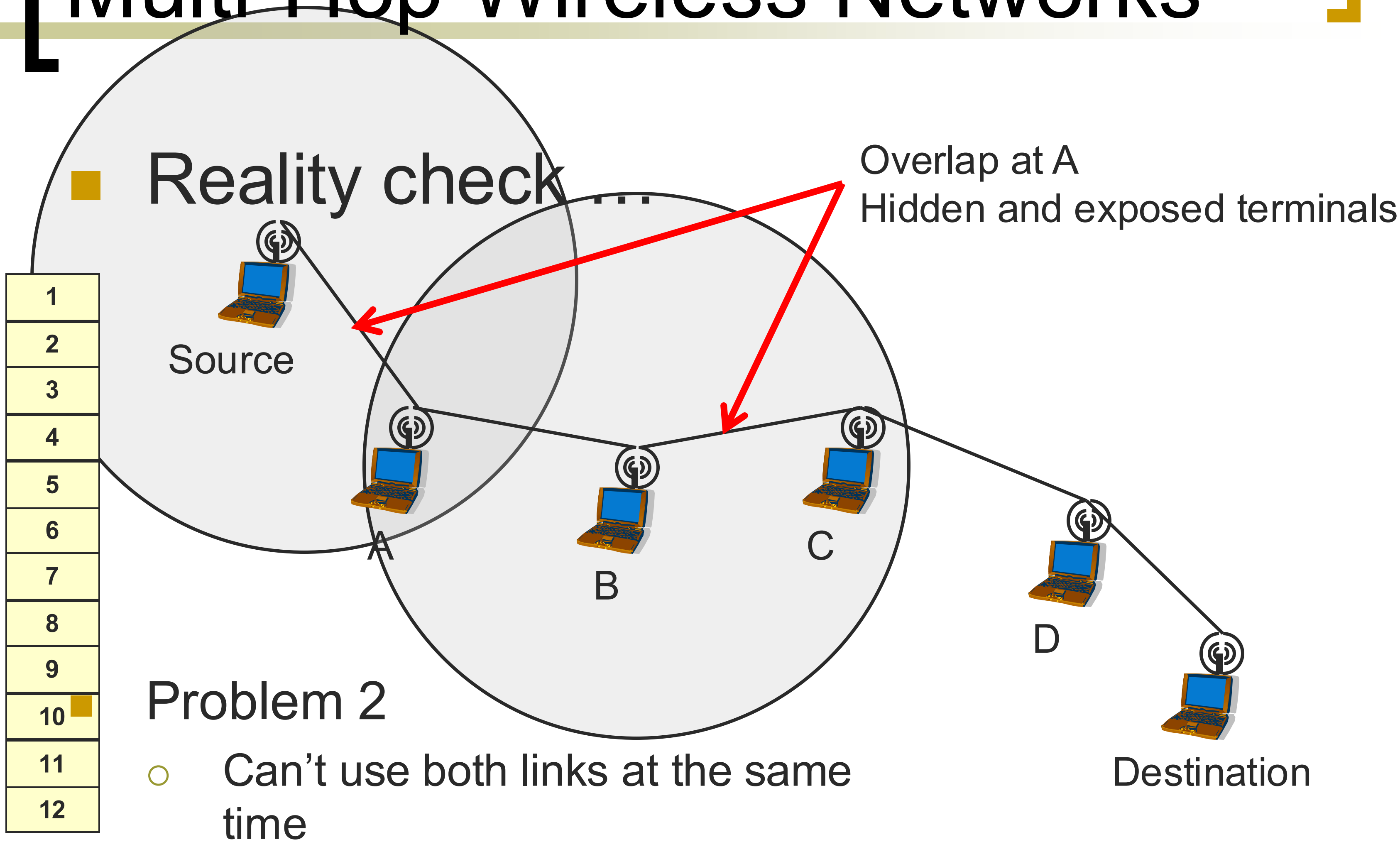


Problem 1

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

Multi-Hop Wireless Networks

- Reality check …

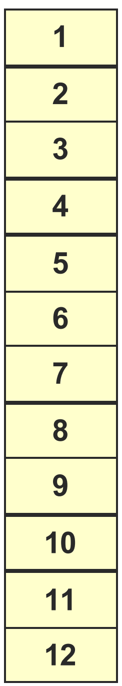


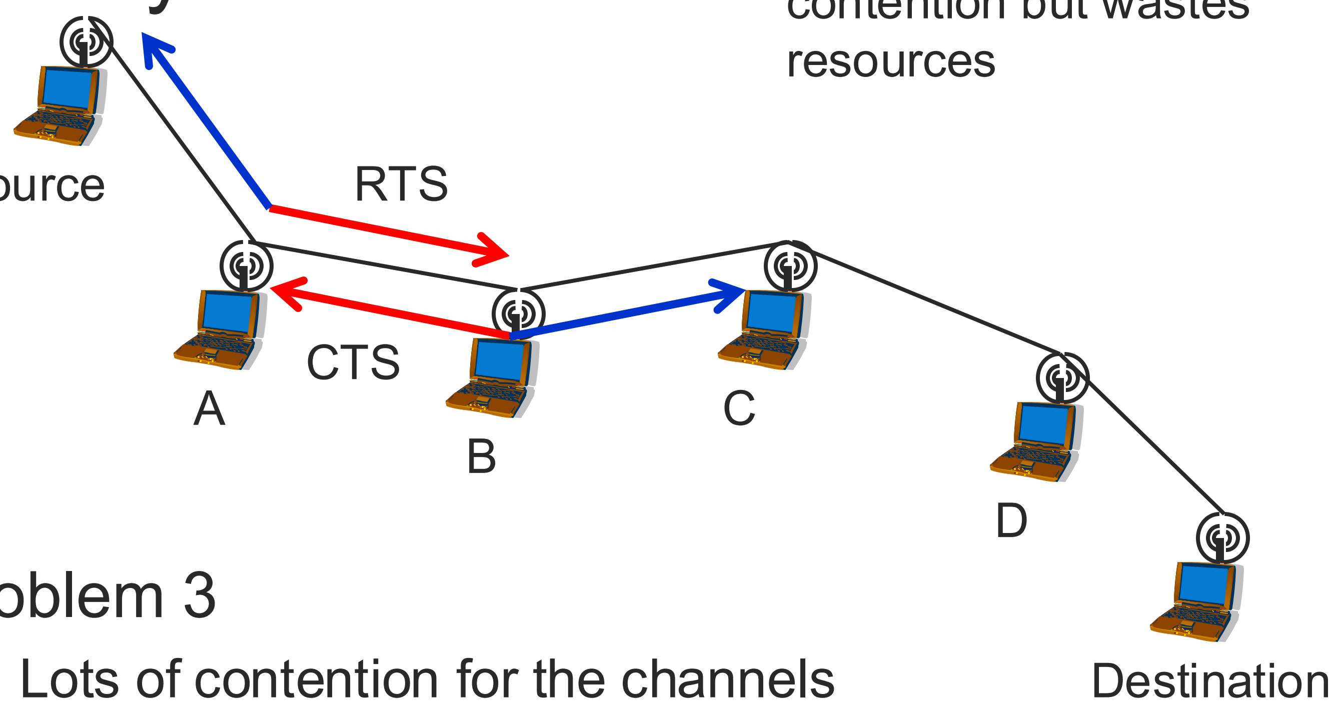
- Problem 2
  - Can't use both links at the same time

Multi-Hop Wireless Networks

- Reality check …

RTS/CTS helps with contention but wastes resources





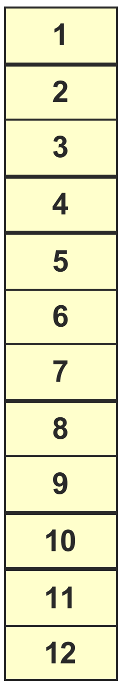
Problem 3

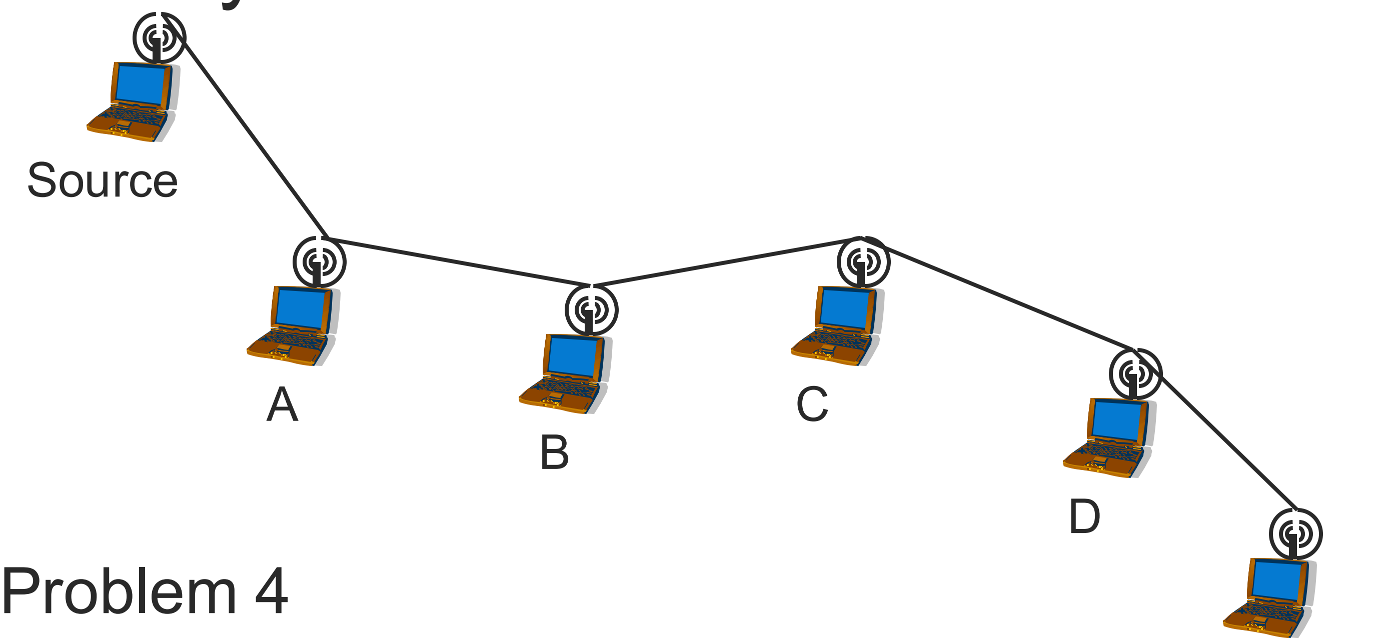
- Lots of contention for the channels
- Everyone wants to send

Multi-Hop Wireless Networks

- Reality check …

Higher layer protocols





Problem 4

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