# 04832250 – Computer Networks (Honor Track)

## A Data Communication and Device Networking Perspective

### Module 3: (W)LAN Concepts and Link Technologies

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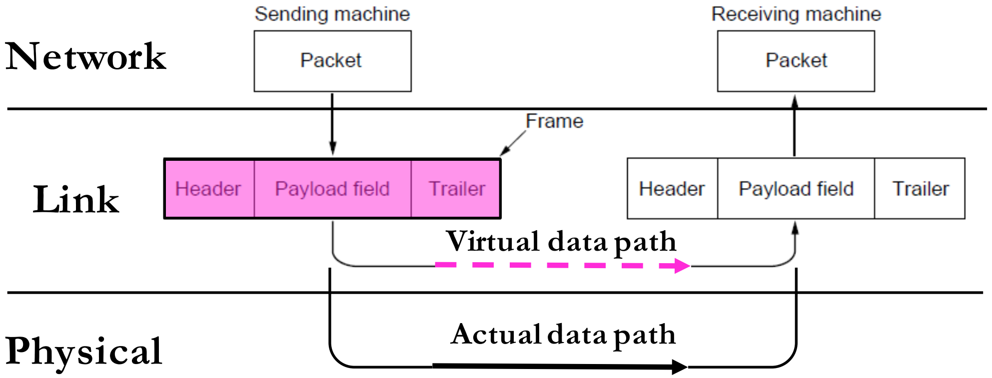
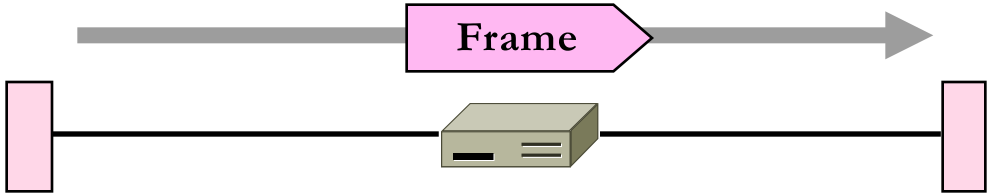
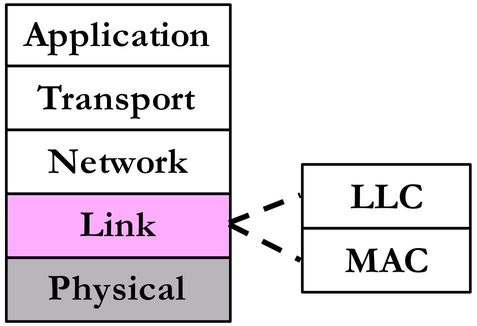
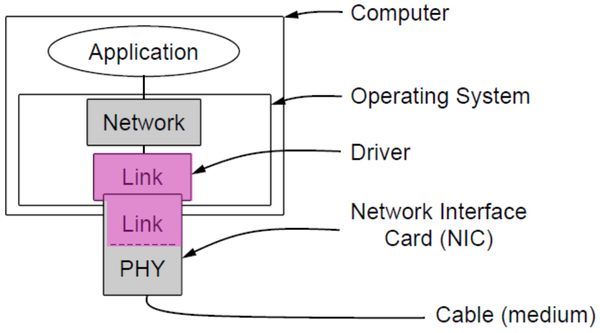
# Link Layer Overview

- Scope of the Link Layer
  - Concerns how to transfer messages over one or more connected links
    - Messages are <u>frames</u>, of limited size
    - Builds on the physical layer



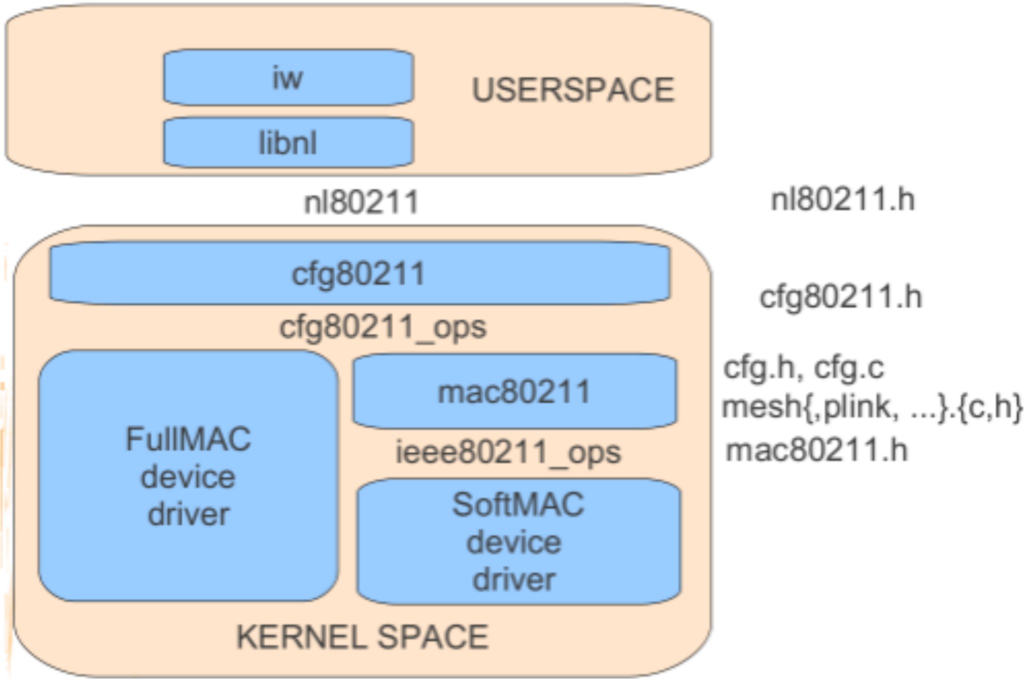




- Logic Link Control (LLC)
  - Provide interfaces for higher layers
  - Error control and flow control
- Media Access Control (MAC)
  - Encapsulate data into frames when transmitting
  - Acquire data from frames received
  - Control the access on media
- Protocol Standards on Layer 2
  - 802.3 (Ethernet), 802.11 (e.g. WLAN), …

# Implementation

- Every host, access point, switch and router
- Implemented in “adaptor” or network interface card (NIC) or on a chip
  - Ethernet card, 802.11 card; Ethernet chipset
  - implements link and physical layers
- Attaches to host system buses
- Combination of hardware, software, firmware
- Adaptors communicating
  - Sending side:
    - Encapsulates datagram in link layer frame
    - Adds error checking bits, reliable data transfer, flow control, etc.
  - Receiving side:
    - Looks for errors, reliable data transfer, flow control, etc
    - Extracts datagram, passes to upper layer



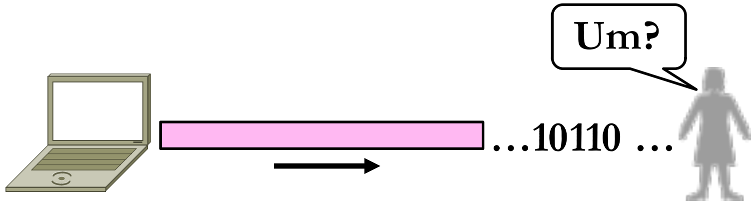

Architecture of Linux 802.11

# Topics

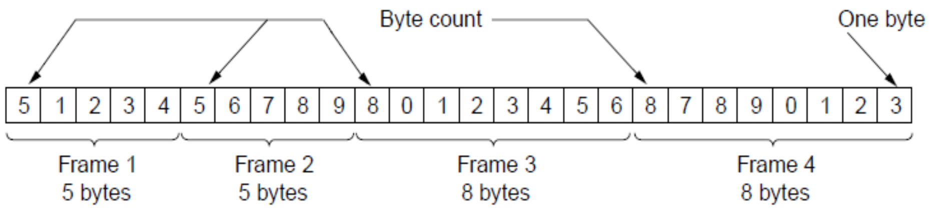
- Framing – How to turn raw bits into information units?
  - Delimiting start/end of frames
- Error Control
  - Error control and correction, retransmission
- Multiple Access
  - MAC and CSMA
- (W)LAN
  - 802.11, modern Ethernet and switching

# Framing Methods

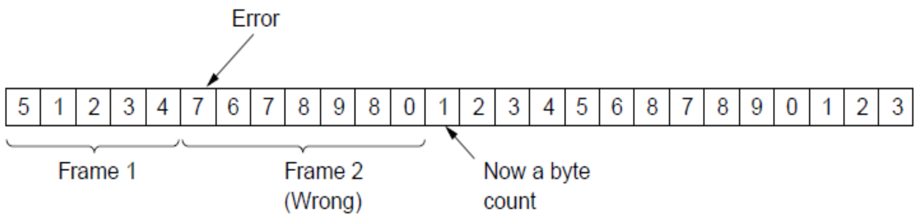
- The physical/PHY layer gives us a stream of bits.
- How do we interpret it as a sequence of frames?
- In practice, the physical layer often helps to identify frame boundaries
  - E.g., Ethernet, 802.11



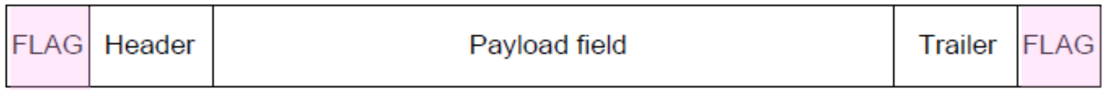

- Byte Count
  - Start each frame with a length field



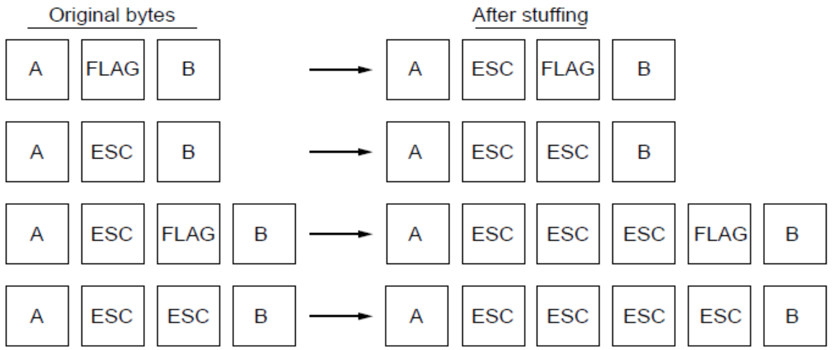

  - Difficult to re-synchronize after framing error




- Byte Stuffing
  - Have a special flag byte value that means start/end of frame



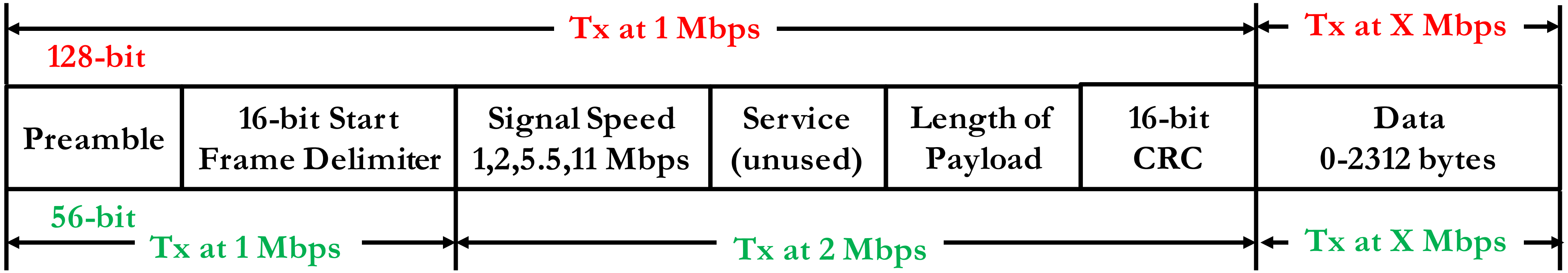

  - Replace ("stuff") the flag inside the frame with an escape code
  - Now any unescaped FLAG is the start/end of a frame



# Practical Framing

| Preamble | Dest. Address | Source Address | Type | Length | Data | CRC |
|---|---|---|---|---|---|---|

- Typical structure of a "wired" packet:
  - Preamble: synchronize clocks between sender and receiver
  - Header: addresses, type field, length, etc.
  - The data to be send, e.g., an IP packet
  - Trailer: padding, CRC, ..
- How does wireless differ?
  - Different rates for different parts of packet
  - Explicit multi-hop support
  - Control information for physical layer
  - Ensure robustness of the header
- 802.11 Long Preamble: 144 bits
  - Interoperable with and only needed for some older 802.11 devices and in networks with high interference or low SNR
  - Entire Preamble and 48 bit PLCP Header sent at 1 Mbps
- 802.11 Short Preamble: 72 Bits
  - Preamble transmitted at 1 Mbps
  - PLCP header transmitted at 2 Mbps
  - More efficient than long preamble



# Topics

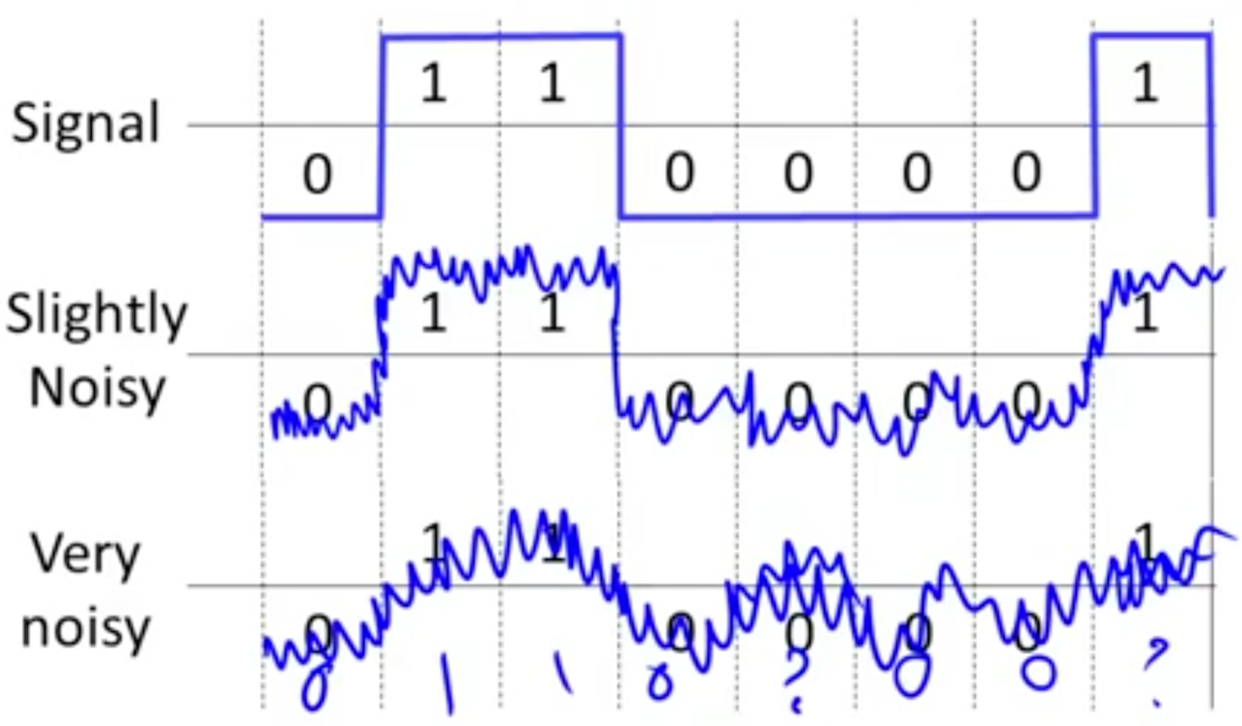
- Framing
  - Delimiting start/end of frames
- Error Control – what can network do if link error and loss?
  - Error control and correction, retransmission
- Multiple Access
  - MAC and CSMA
- (W)LAN
  - 802.11, modern Ethernet and switching

# Error Handing

- Some bits will be received in error due to noise. What can we do?
  - Detect errors with codes
  - Correct errors with codes
  - Retransmit lost frames
- Reliability is a concern that cuts across the layers
  - Link layer?
  - Network layer?
  - Transport layer?
  - Application layer?

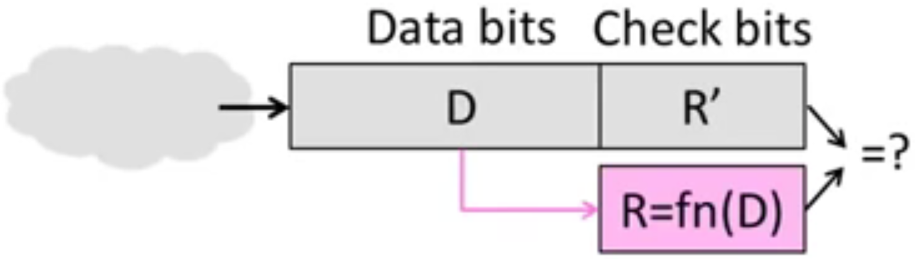
# Motivating Example

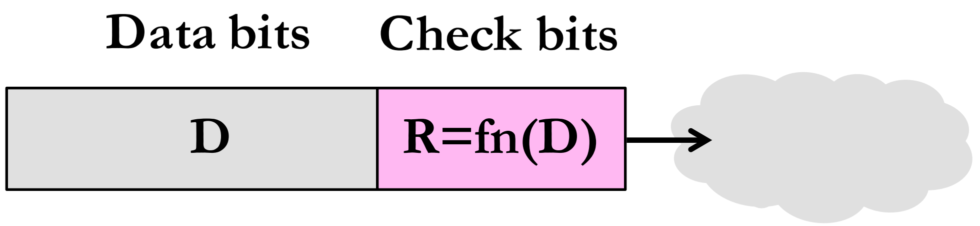
- Problem – Noise may flip received bits
- Approach – Add Redundancy
  - Error detection codes
    - Add check bits to the message bits to let some errors be detected
  - Error correction codes
    - Add more check bits to let some errors be corrected
  - Key issue is now to structure the code to detect many errors with few check bits and modest computation



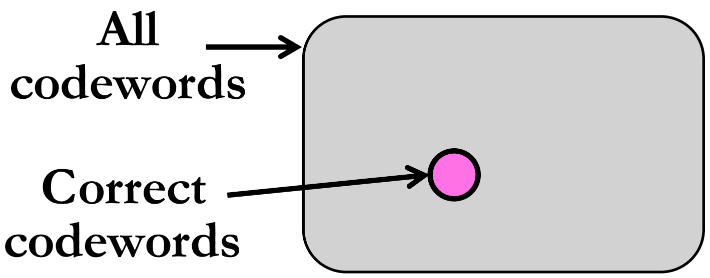
# Using Error Codes

- Codeword consists of D data plus R check bits
- Sender:
  - Compute R check bits based on the D data bits; send the codeword of D+R bits
- Receiver:
  - Receive D+R bits with unknown errors
  - Recompute R check bits based on the D data bits; error if R doesn't match R'



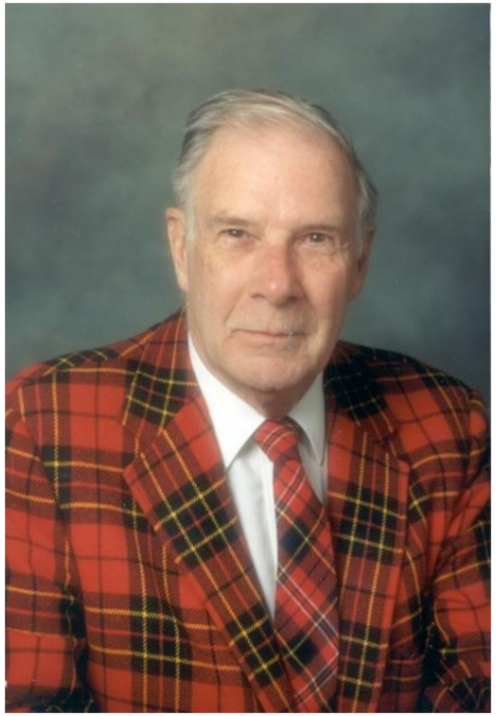

- Intuition for Error Codes
  - For D data bits, R check bits:




  - Randomly chosen codeword is unlikely to be correct ($1/2^R$); overhead is low

# R.W. Hamming (1915-1998)

- Much early work on codes:
  - "Error Detecting and Error Correcting Codes", BSTJ, 1950
- See also:
  - "You and Your Research", 1986
- Distance in the context of coding
  - Distance is the number of bit flips needed to change $(D+R)_1$ to $(D+R)_2$
  - Hamming distance of a code
    - The minimum distance between any pair of codewords
  - Error detection:
    - For a code of distance d+1, up to d errors will always be detected
  - Error correction:
    - For a code of distance 2d+1, up to d errors can always be corrected by mapping to the closest codeword



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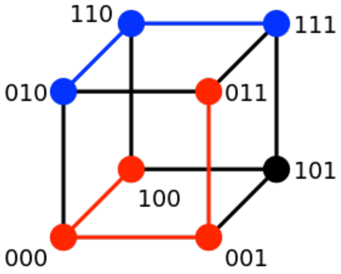
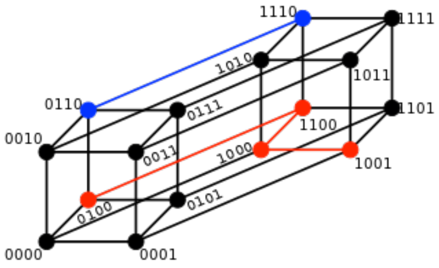


# Error Detection

- Some bits may be received in error due to noise. How do we detect this?
  - Parity
    - Is little used
  - Checksums
    - Used in Internet: IP, TCP, UDP, … but it is weak
  - CRCs
    - Widely used on links: Ethernet, 802.11, ADSL, Cable, …
- Detection will let us fix the error, for example, by retransmission (later).

# Error Detection – Parity Bit

- Take D data bits, add 1 check bit that is the sum of the D bits
  - Sum is modulo 2 or XOR
  - Example: 1001100 → 1
- How well does parity work?
  - What is the distance of the code? 2
  - How many errors will it detect/correct? 1/0
- What about larger errors?
  - Odd # of errors

# Error Detection – Checksums

| 1500 bytes | 16 bits |
| --- | --- |

*"The checksum field is the 16 bit one's complement of the one's complement sum of all 16 bit words …"* – RFC 791

- Idea: sum up data in N-bit words
  - Widely used in, e.g., TCP/IP/UDP
  - Stronger protection than parity
- Internet Checksum
  - Sum is defined in 1s complement arithmetic (must add back carries) – And it's the negative sum
  - Sending
    1. Arrange data in 16-bit words
    2. Put zero in checksum position, add
    3. Add any carryover back to get 16 bits
    4. Negate (complement) to get sum

```
   0001
   f203
   f4f5
   f6f7
+(0000)
------
  2ddf0
    ↓
   ddf0
+     2
------
   ddf2
    ↓
   220d
```

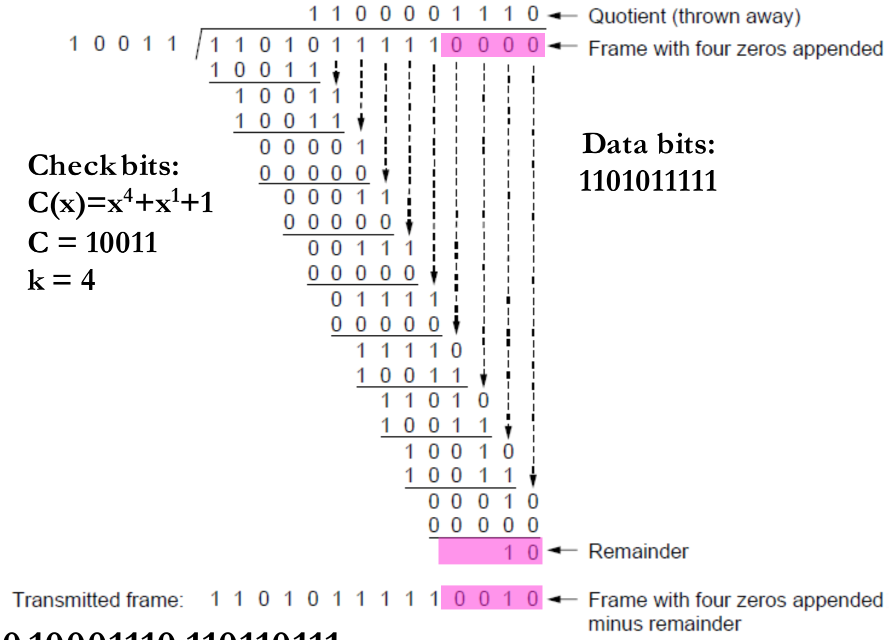
  - How well does the checksum work?
    - What is the distance of the code? 2
    - How many errors will it detect/correct? 1/0
    - What about larger errors? All burst error up to 16
  - Receiving
    1. Arrange data in 16-bit words
    2. Checksum will be non-zero, add
    3. Add any carryover back to get 16 bits
    4. Negate the result and check it is 0

```
   0001
   f203
   f4f5
   f6f7
+  220d
------
  2fffd
    ↓
   fffd
+     2
------
   ffff
    ↓
   0000
```

# Error Detection – Cyclic Redundancy Check (CRC)

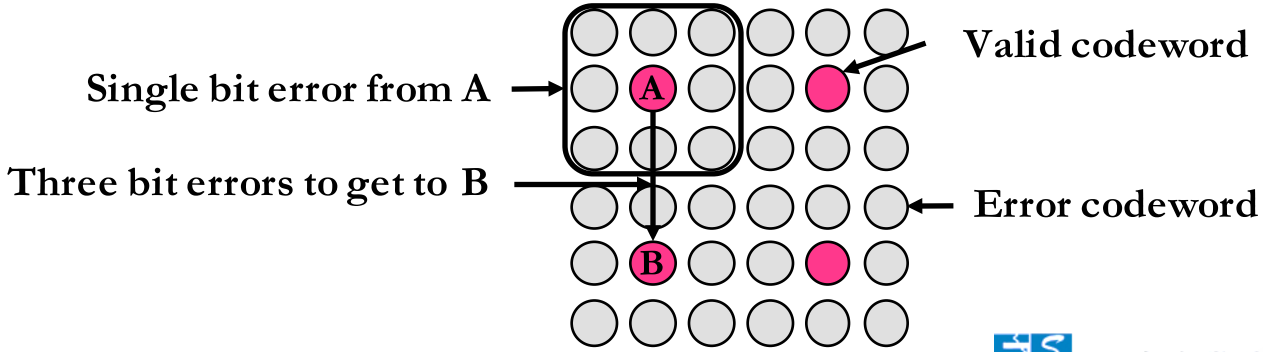
- Even stronger protection
  - Given n data bits, generate k check bits such that the n+k bits are evenly divisible by a generator C
- The catch:
  - It's based on mathematics of finite fields, in which "numbers" represent polynomials
  - E.g, 10011010 is $x^7 + x^4 + x^3 + x^1$
- What this means:
  - We work with binary values and operate using modulo 2 arithmetic

- Send Procedure:
  - Extend the n data bits with k zeros
  - Divide by the generator value C
  - Keep remainder, ignore quotient
  - Adjust k check bits by remainder
- Receive Procedure:
  - Divide and check for zero remainder
- Protection depend on generator
  - Standard CRC-32 is 10000010 01100000 10001110 110110111
- Properties:
  - Hamming distance=4, detects up to triple bit errors
  - Also odd number of errors
  - And bursts of up to k bits in error
  - Not vulnerable to systematic errors like checksums



# Why Error Correction is Hard

- If we had reliable check bits we could use them to narrow down the position of the error
  - Then correction would be easy
- But error could be in the check bits as well as the data bits!
  - Data might even be correct
- Intuitions for error correction code
  - Suppose we construct a code with a Hamming distance of at least 3
    - Need ≥3 bit errors to change one valid codeword into another
    - Single bit errors will be closest to a unique valid codeword
  - If we assume errors are only 1 bit, we can correct them by mapping an error to the closest valid codeword
    - Works for d errors if HD ≥ 2d + 1
  - Visualization of code



# Hamming Code

- Gives a method for constructing a code with a distance of 3
  - Uses $n = 2^k - k - 1$, e.g., n=4, k=3
  - Put check bits in positions p that are powers of 2, starting with position 1
  - Check bit in position p is parity of positions with a p term in their values
- Example: data = 0101, 3 check bits →
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

- To decode:
  - Recompute check bits
    - With parity sum including the check bit
  - Arrange as a binary number
  - Value (syndrome) tells error position
    - Value of zero means no error
    - Otherwise, flip bit to correct

| Code construction | No Error | Error Correction |
|---|---|---|
| 0 1 0 0 1 0 1 | 0 1 0 0 1 0 1 | 0 1 0 0 1 1 1 |
| $p_1$= 0+1+1 = 0, | $p_1$= 0+0+1+1 = 0 | $p_1$= 0+0+1+1 = 0 |
| $p_2$= 0+0+1 = 1, | $p_2$= 1+0+0+1 = 0 | $p_2$= 1+0+1+1 = 1, |
| $p_4$= 1+0+1 = 0 | $p_4$= 0+1+0+1 = 0 | $p_4$= 0+1+1+1 = 1 |
| | Syndrome = 000, | Syndrome = 110, |
| | no error | flip position 6 |
| | Data = 0 1 0 1 | Data = 0 1 0 1 |

# Detection vs. Correction

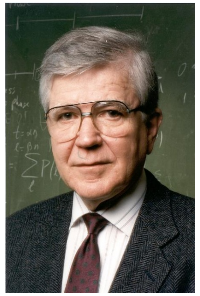
- Which is better will depend on the pattern of errors. For example:
  - 1000 bit messages with a bit error rate (BER) of 1 in 10000, i.e., 10% has one error in message
- Which has less overhead?
  - It still depends! We need to know more about the errors

| | Error correction | Error detection |
|---|---|---|
| Bit errors are random – messages have 0 or maybe 1 error | Need ~10 check bits per message<br>Overhead: 10 | Need ~1 check bits per message plus 1000 bit retransmission 1/10 of the time<br>Overhead: 1 + 1000*0.1 = 101 |
| Errors come in bursts of 100 – only 1 or 2 messages in 1000 have errors | Need >>100 check bits per message<br>Overhead: >>100 | Need 32? check bits per message plus 1000 bit resend 2/1000 of the time<br>32+1000*0.002 = 34 bits |
| In general | Needed when errors are expected, or when no time for retransmission | More efficient when errors are not expected, and when errors are large when they do occur |

# Coding in the State of Art

## Other (in practice) Error Correction Codes

- Convolutional codes
  - Take a stream of data and output a mix of the recent input bits
  - Makes each output bit less fragile
  - Decode using Viterbi algorithm (which can use bit confidence values)
- Low Density Parity Check
  - Invented by Robert Gallager in 1963 in his PhD thesis
    - Promptly forgotten until 1996 because it is very "practical" with today's technology
  - Based on sparse matrices, decoded iteratively using a belief propagation algorithm
  - Performance is similar to turbo codes but it has some implementation advantages



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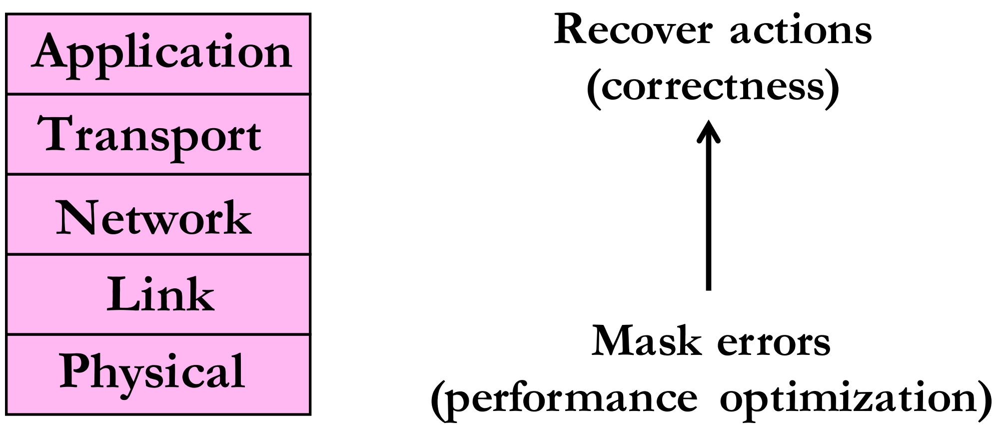
## Error Correction in Practice

- Heavily used in physical layer
  - LDPC is the future, used for demanding links like 802.11, DVB, WiMAX, LTE, power-line, …
  - Convolutional codes widely used in practice
- Error detection (w/retransmission) is used in the link layer and above for residual errors
- Correction also used in the application layer
  - Called Forward Error Correction (FEC)
    - Normally with an erasure error model
    - E.g., Reed-Solomon (CDs, DVDs, etc.)

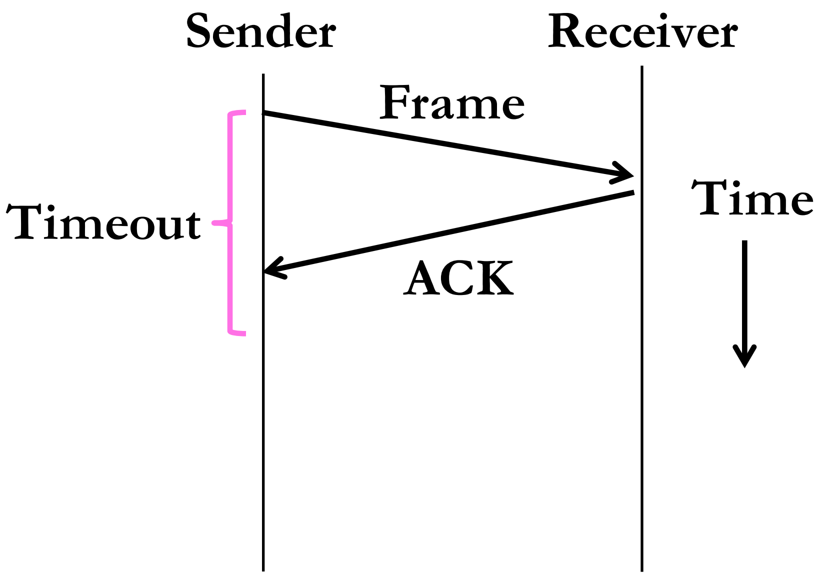
# Context on Reliability

- Where in the stack should we place reliability functions?
- Everywhere! It is a key issue
  - Different layers contribute differently

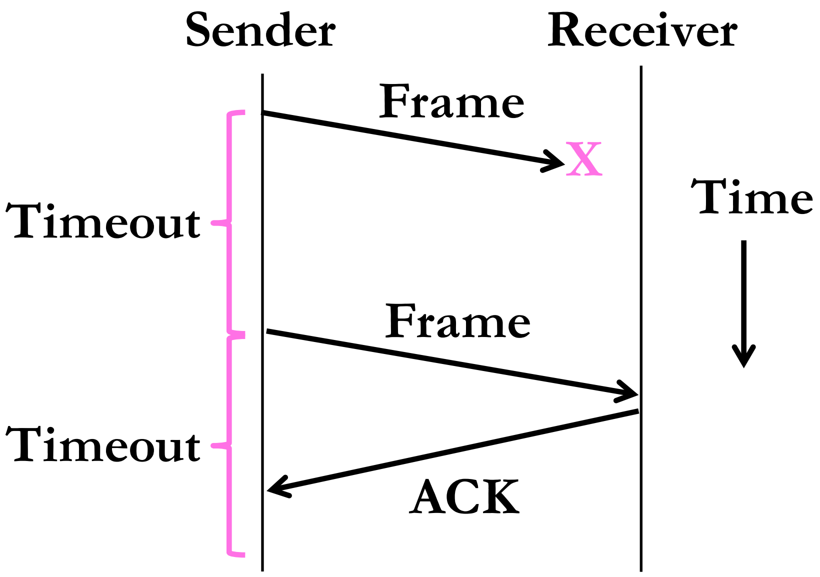


# Automatic Repeat rQuest (ARQ)

- ARQ often used when errors are common or must be corrected
  - E.g., WiFi, and TCP (later)
- Rules at sender and receiver:
  - Receiver automatically acknowledges correct frames with an ACK
  - Sender automatically resends after a timeout, until an ACK is received
- Normal operation (no loss)

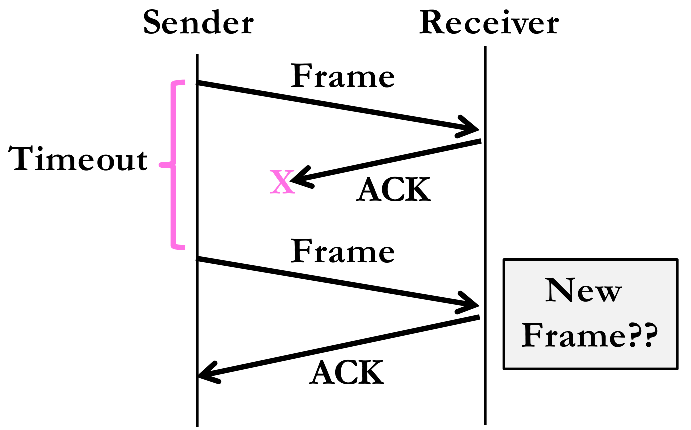



- Loss and retransmission

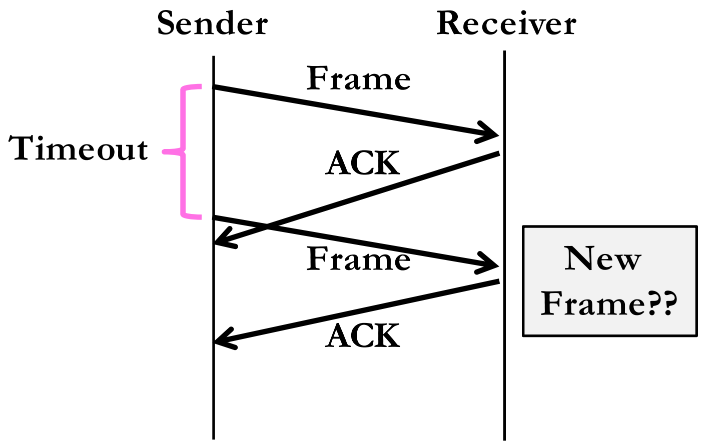


# So What's Tricky About ARQ?

- Two non-trivial issues:
  - How long to set the timeout?
  - How to avoid accepting duplicate frames as new frames
- Want performance in the common case and correctness always
- Timeout
  - Timeout should be:
    - Not too big (link goes idle)
    - Not too small (spurious resend)
  - Fairly easy on a LAN
    - Clear worst case, little variation
  - Fairly difficult over the Internet
    - Much variation, no obvious bound
    - We'll revisit this with TCP (later)
- Duplication
  - What happens if an ACK is lost?

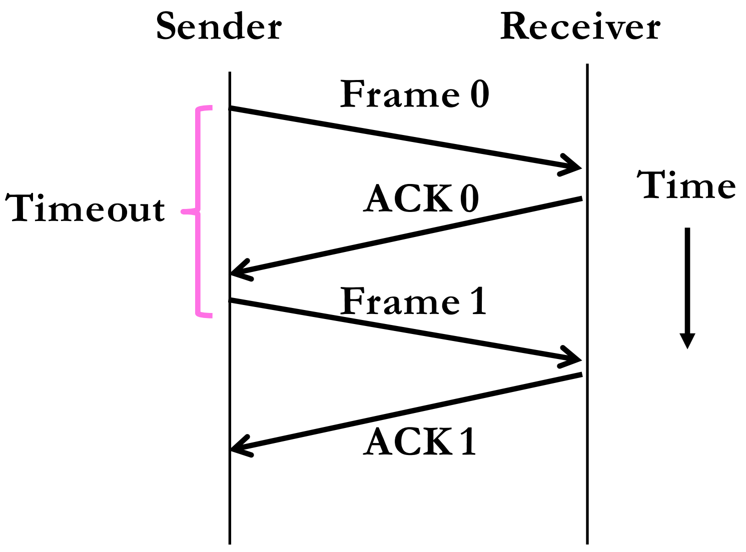



  - Or the timeout is early?

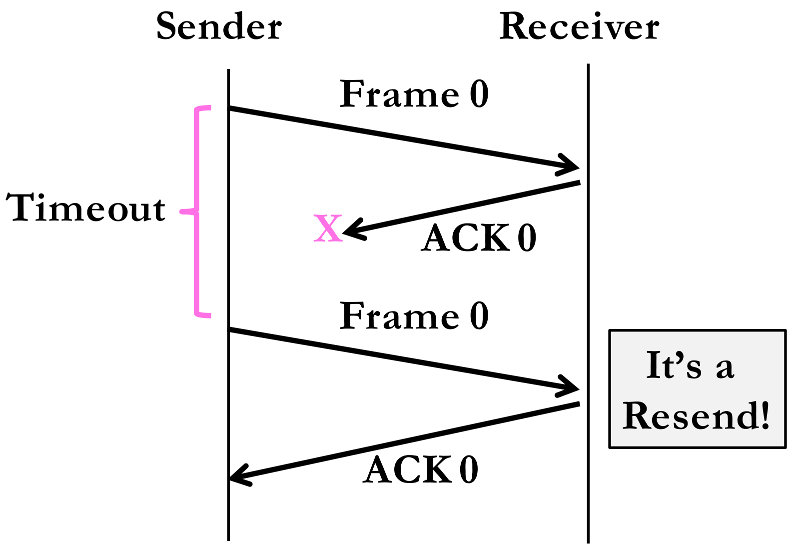


# Sequence Numbers

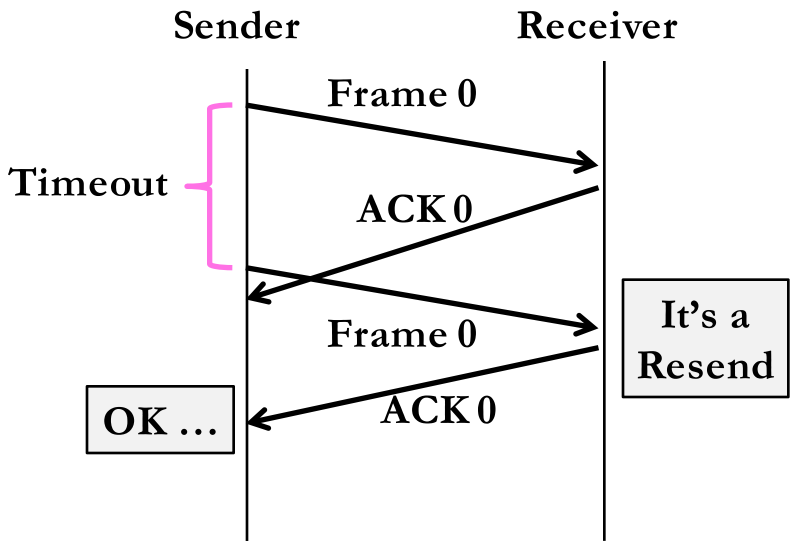
- Frames and ACKs must both carry sequence numbers for correctness
- To distinguish the current frame from the next one, a single bit (two numbers) is sufficient – called Stop-and-Wait




In the normal case



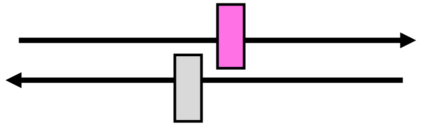

With ACK Loss



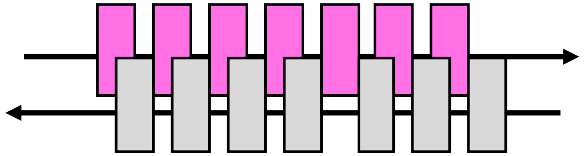

With early timeout

# Limitation of Stop-and-Wait

- It allows only a single frame to be outstanding from the sender – one packet at a time:
  - Good for LAN, not efficient for high BD



- Ex: R=1 Mbps, D = 50 ms
  - How many frames/sec? If R=10 Mbps?
- Sliding Window – Generalization of stop-and-wait
  - Allows W frames to be outstanding
  - Can send W frames per RTT (=2D)
  - Various options for numbering frames/ACKs and handling loss
    - Will look at along with TCP (later)



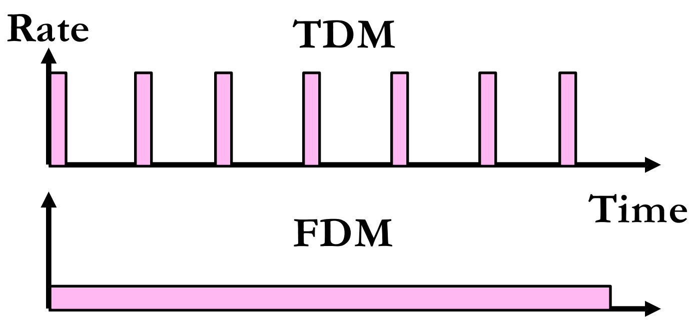
- In the end, why do we need reliable transmission on both link and e2e level?

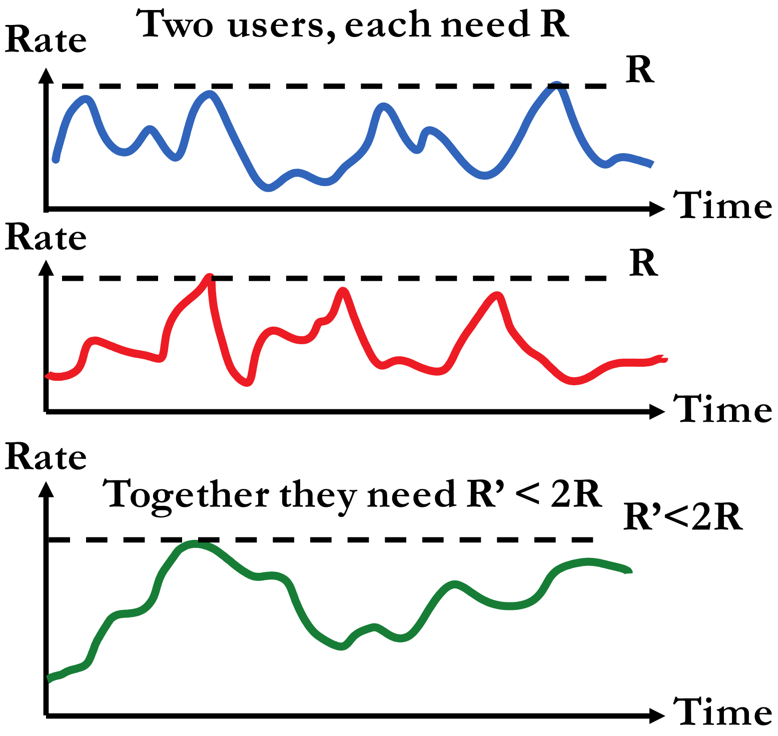
# Topics

- Framing
  - Delimiting start/end of frames
- Error Control
  - Error control and correction, retransmission
- Multiple Access – How to coordinate network access over a broadcast medium?
  - MAC and CSMA
- (W)LAN
  - 802.11, modern Ethernet and switching

# Multiplexing Network Traffic Allows Multiple Access

- Review: TDM and FDM
  - In TDM a user sends at a high rate a fraction of the time; in FDM, a user sends at a low rate all the time
  - Statically divide a resource
    - Suited for continuous traffic, fixed number of users
  - Widely used in telecommunications
    - TV/radio stations use FDM; Earlier cellular allocates calls us TDM within FDM
- Network traffic is <u>bursty</u>
  - Load varies greatly over time
  - Inefficient to always allocate user their ON needs with TDM/FDM
- <u>Multiple access</u> schemes
  - Multiplex users based on demands – for gains of statistical multiplexing
  - But communication about channel sharing must use channel itself!



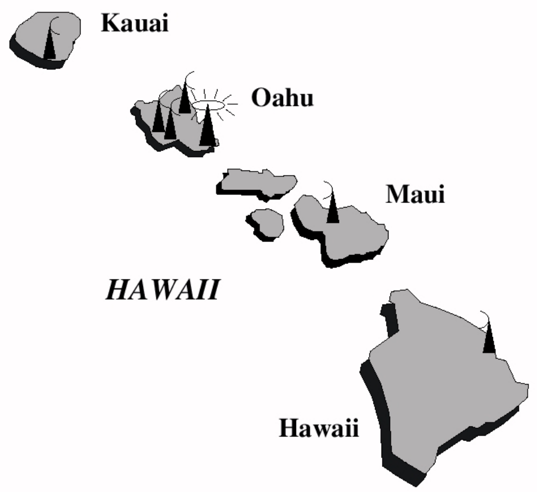



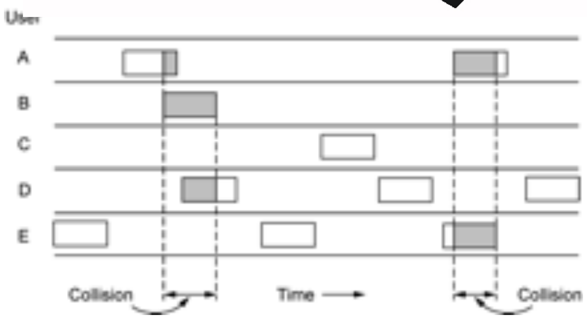
# Centralized versus Decentralized Multiple Access

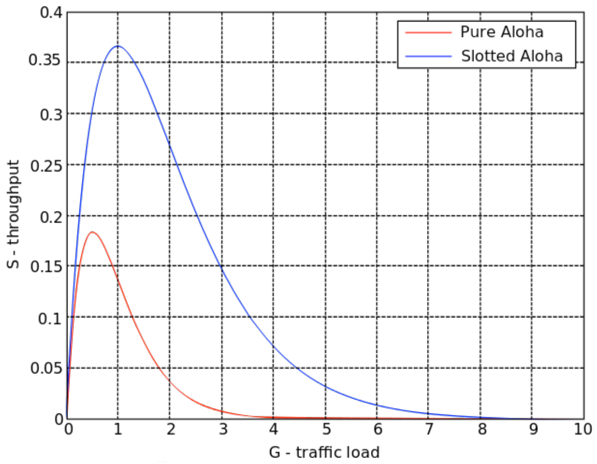

- Who gets to send a packet next?
- Scheduled multiple access
  - Explicit coordination ensures that only one node transmits
  - Looks cleaner, more organized, but …
  - Coordination introduces overhead – require communication
  - Not efficient for real traffic – burty and opportunistic
- Assume no-one is in charge
  - How do nodes share a single link? Who sends when, collision and its detection
- We will look at two kinds of multiple/media/medium access (MAC) protocols
  - Randomized: nodes randomize their resource access attempts, e.g., (slotted) ALOHA, CSMA/(CD/CA)
    - Good for low load situations
  - Contention-free: nodes order their resource access attempts
    - Good for high load or guaranteed quality of service situations

# ALOHA Network and ALOHA Protocol

- Seminal computer network connecting the Hawaiian islands in the late 1960s
  - When should nodes send? A new protocol was devised by Norm Abramson …
- Simple idea:
  - Assume:
    - All frames have the same length and the frame time is T
    - Node just sends when it has traffic.
    - Population of stations attempt to transmit within period T follows Poisson distribution
    - G be the average # of stations that begin transmission within period T
    - If there was a collision (no ACK received) then wait a random time and resend
  - Probability that exactly $x$ stations begin transmission during T: $P[X = x] = \frac{G^x e^{-G}}{x!}$
  - P(success) = P(exactly 1 node tx in [$t_0$, $t_0$+T]) P(no nodes tx in [$t_0$-T,$t_0$]) = $Ge^{-G}e^{-G}$
- Simple, decentralized protocol that works well under low load!
  - Not efficient under high load – analysis shows at most 18% efficiency
- Slotted ALOHA: divides time into slots and efficiency goes up to 36%
  - Transmission can only start at the beginning of each slot of period T

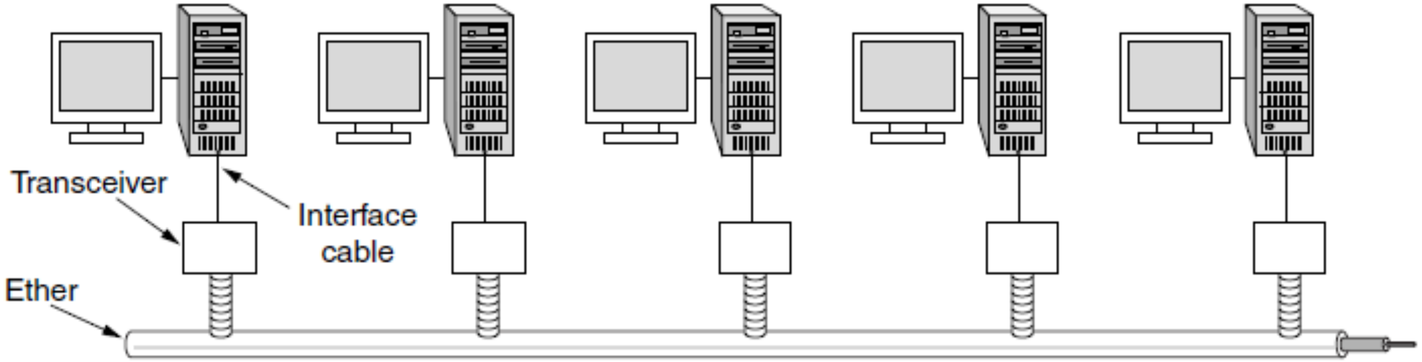


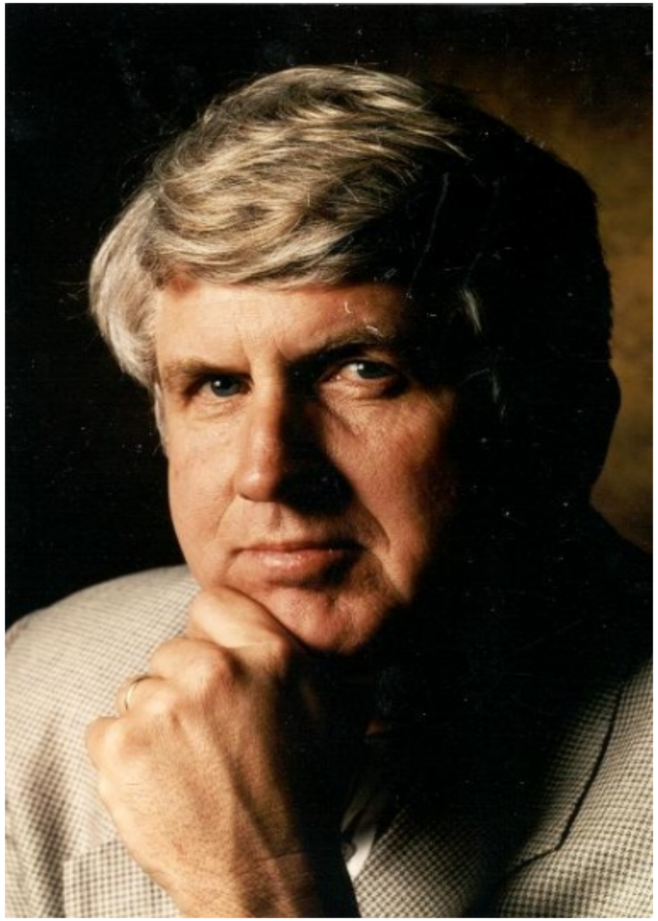



# Classic Ethernet

- **ALOHA inspired Bob Metcalfe to invent Ethernet for LANs in 1973**
  - Nodes share 10 Mbps coaxial cable
  - Hugely popular in 1980s, 1990s

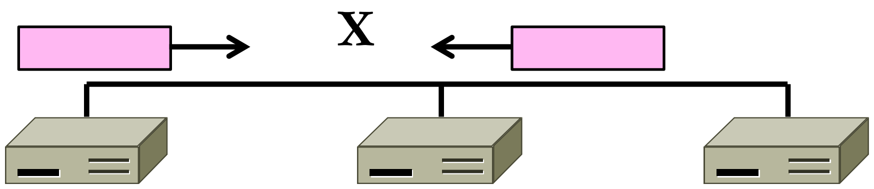


: © 2009 IEEE

# Carrier Sense Multiple Access (CSMA)

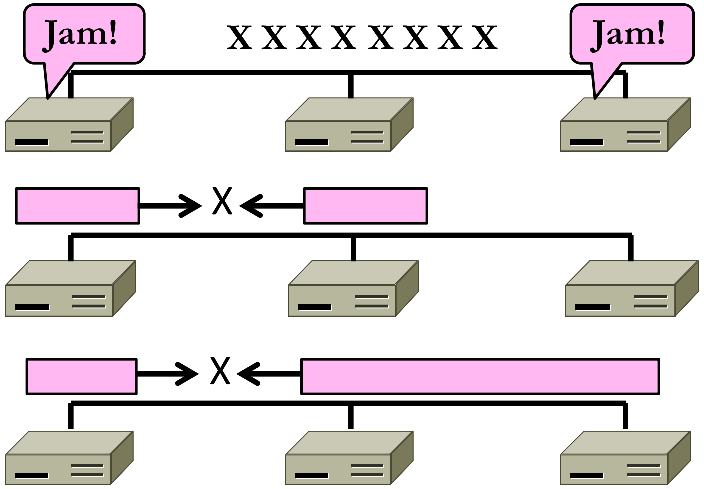
- Improve ALOHA by carrier sensing: make sure the channel is idle before we send
  - If channel sensed idle: transmit entire frame
  - If channel sensed busy, defer transmission
  - Can do easily with wires, not wireless

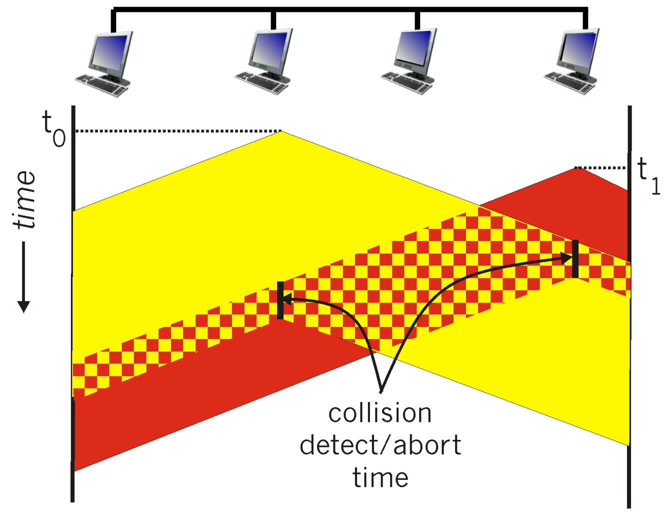



- Collision can still occur
  - Still possible to listen and hear nothing when another node is sending because of delay
  - Entire packet transmission time wasted
    - Distance and propagation delay play role in determining collision probability
- CSMA is a good defense against collisions only when BD is small, i.e., << packet

# CSMA/CD (with Collision Detection)

- Collisions are detected by listening on the medium and comparing the received and transmitted signals
  - Only one transmitter can transmit at a time
- Can reduce the cost of collisions by detecting them and aborting by sending jam signal the rest of the frame time
  - Want everyone who collides to know that it happened ASAP!
  - If the frame is too short, sender may realize collision happens too late!
  - Time window in which a node may hear of a collision is 2D seconds
    - D: propagation delay
- Impose a minimum frame size that lasts for 2D seconds
  - So transmission can't finish before collision
    - The first bit in another transmission arrives
  - Ethernet minimum frame is 64 bytes
- How do we avoid that two nodes retransmit at the same time collision?

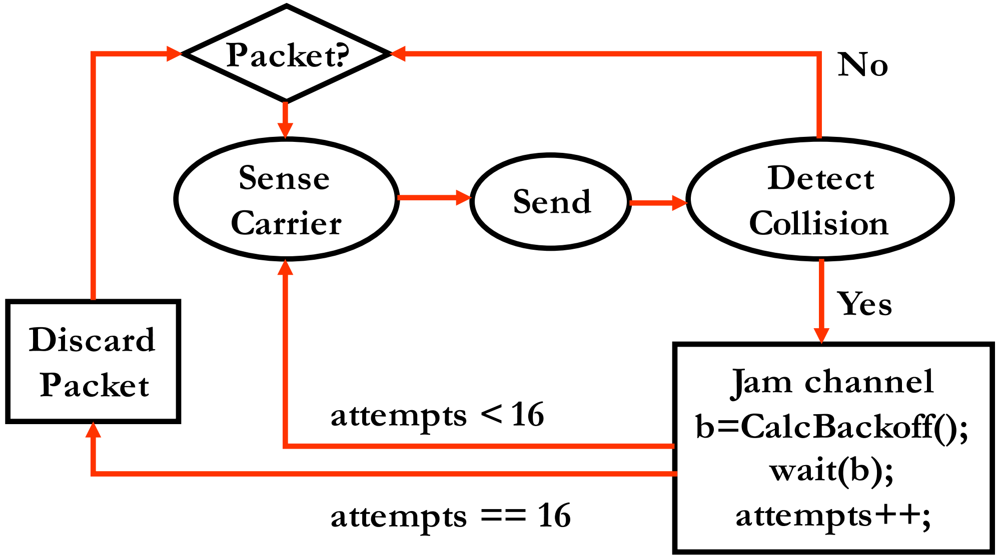


# Binary Exponential Backoff (BEB)

**Procedure**

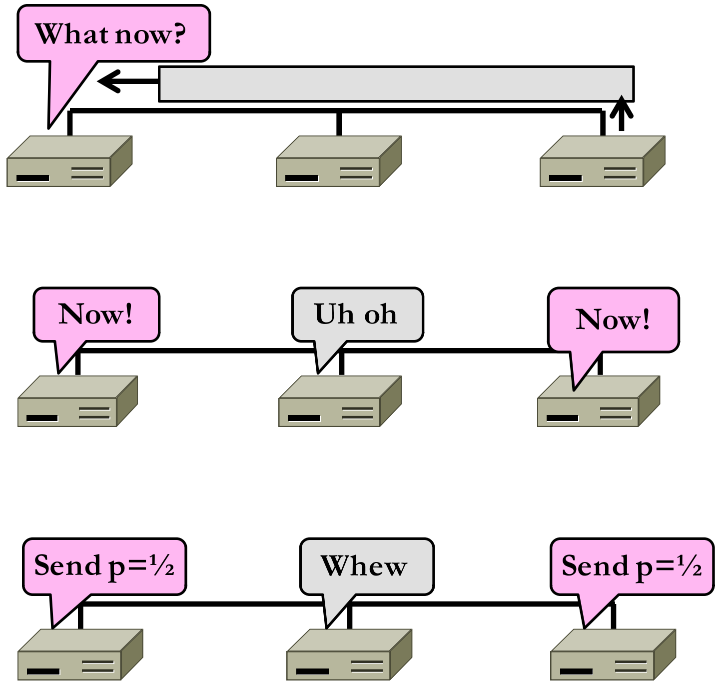
- NIC receives datagram from network layer, creates frame
  - If NIC senses channel idle, starts frame transmission.
  - Else if NIC senses channel busy, waits until channel idle, then transmits.
- If NIC transmits entire frame without detecting another transmission, NIC is done with frame!
- If NIC detects another transmission while transmitting, aborts and sends jam signal
- After aborting, NIC enters BEB:
  - After mth collision, NIC chooses K at random from {0,1,2, …, $2^m$-1}. NIC waits K x 512 bit times, returns to Step 2
    - After ten or more collision, choose K from {0,1,2,3,4, …, 1023}
  - Longer backoff interval with more collisions




- Exponentially increasing random delay
  - Infer # of senders from # of collisions
  - More senders → increase wait time
- BEB doubles interval for each successive collision
  - Quickly gets large enough to work
  - Very efficient in practice

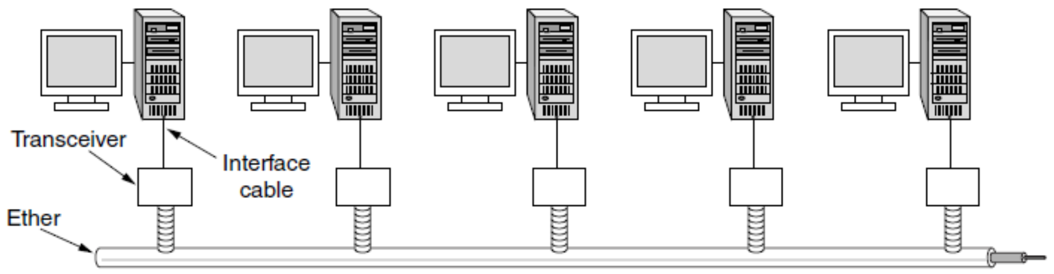
# CSMA "Persistence" – scalability issue

- What should a node do if the line is busy?
- Idea: wait until it is done, and send
- Problem is that multiple waiting nodes will queue up then collide
  - More load, more of a problem
- Intuition for a better solution
  - If there are N queued senders, we want each to send next with probability 1/N, but what's N?
- p-persistent scheme
  - Transmit with probability p once the channel goes idle
  - Delay the transmission by $t_{prop}$ with 1-p
- Non-persistent scheme
  - Reschedule transmission for a later time based on a delay distribution
  - Sense the channel at that time, and repeat

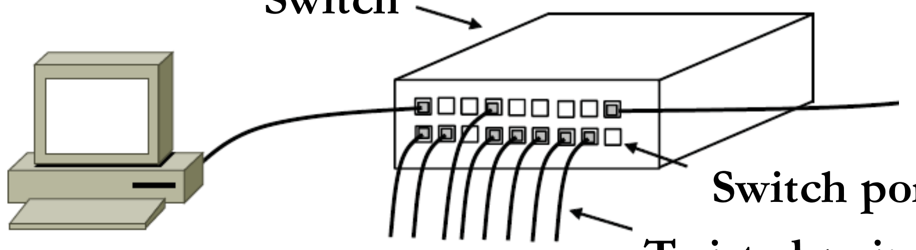


# Ethernet, or IEEE 802.3

- Classic Ethernet, or IEEE 802.3
  - Most popular LAN of the 1980s, 1990s
    - 10 Mbps over shared coaxial cable, with baseband signals
    - Multiple access with “1-persistent CSMA/CD with BEB”




- Modern Ethernet
  - Use point-to-point “links” with switches
    - Store-and-forward, not multiple access, but still called Ethernet
    - Very common in wired networks, at multiple layers



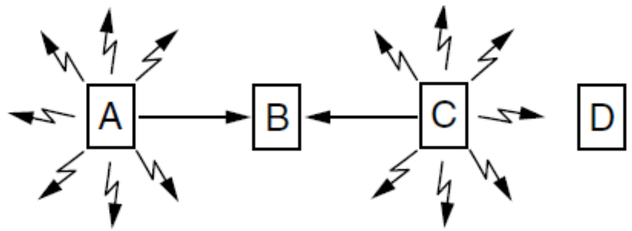

- Frame Format
  - Has addresses to identify the sender and receiver
  - CRC-32 for error detection; no ACKs or retransmission
  - Start of frame identified with physical layer preamble

Packet from Network layer (IP)

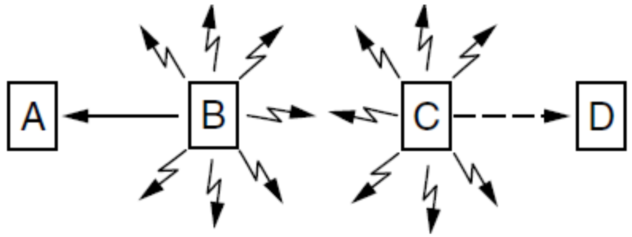
| | Preamble | Destination address | Source address | Type | Data | Pad | Check-sum |
|---|---|---|---|---|---|---|---|
| Bytes | 8 | 6 | 6 | 2 | 0-1500 | 0-46 | 4 |

# Wireless Complications – Different Coverage Areas

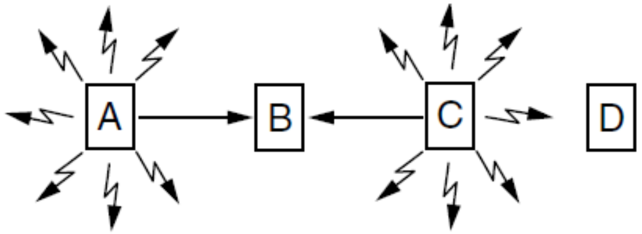
- Nodes A and C are <u>hidden terminals</u> when sending to B
  - Can't hear each other (to coordinate) yet collide at B
  - We want to avoid the inefficiency of collisions




- Nodes B and C are <u>exposed terminals</u> when sending to A and D
  - Can hear each other yet don't collide at receivers A and D
  - We want to send concurrently to increase performance




- Node C will almost always "win" if there is a collision at receiver D
  - This "capture effect" can lead to extreme unfairness and even starvation
  - Power control is the solution, but very difficult to manage in a non-provisioned environment

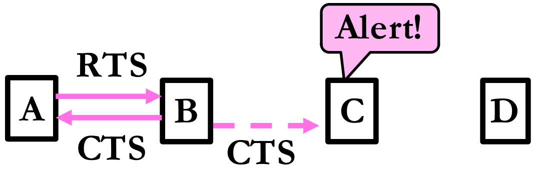



- Collision detection is not practical in radio environment
  - While transmitting, a station cannot distinguish incoming weak signals from noise – its own signal is too strong
  - Transmitter cannot detect competing transmitters

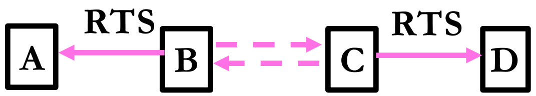
# Possible Solution: Multiple Access Collision Avoidance (MACA)

- MACA uses a short handshake instead of CSMA (Karn, 1990)
  - 802.11 uses a refinement of MACA
- Protocol rules:
  1. A sender node transmits a RTS (Request-To-Send, with frame length)
  2. The receiver replies with a CTS (Clear-To-Send, with frame length)
  3. Sender transmits the frame while nodes hearing the CTS stay silent
     - Collisions on the RTS/CTS are still possible, but less likely
- A → B with hidden terminal C
  - A sends RTS, to B

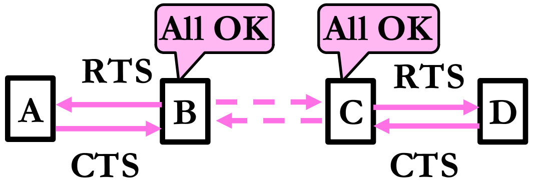

  - B sends CTS, to A, and C too




- B → A, C → D as exposed terminals
  - A and D send CTS to B and C




  - A and D send CTS to B and C

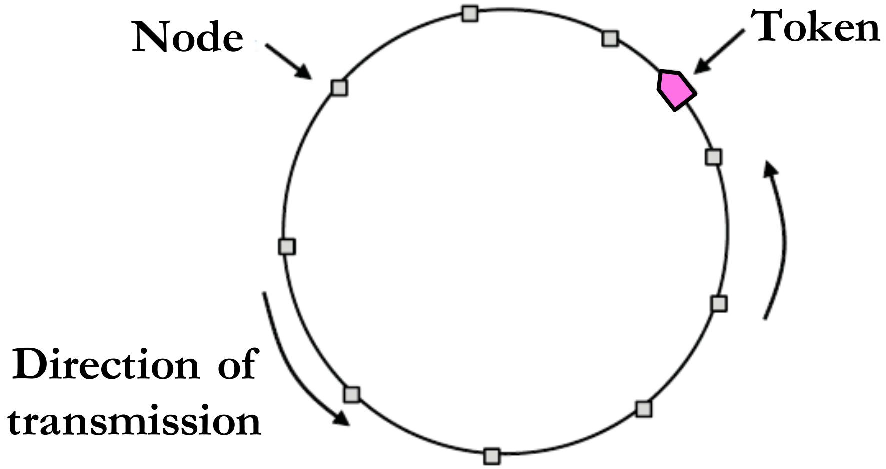


# Issues with Random Multiple Access

- CSMA is good under low load:
  - Grants immediate access
  - Little overhead (collisions)
- But not so good under high load:
  - High overhead (expect collisions)
  - Access time varies (lucky/unlucky)
- We want to do better under load!

# Turn-Taking Multiple Access Protocols – Token Ring as an Example

- Define an order in which nodes get a chance to send
  - Or pass, if no traffic at present
- Arrange nodes in a ring; token rotates "permission to send" to each node in turn
- Advantage
  - Fixed overhead with no collisions
    - More efficient under load
  - Regular chance to send with no unlucky nodes
  - Predictable service, easily extended to guaranteed quality of service
- Disadvantage
  - More things that can go wrong than random access protocols!
    - E.g., what if the token is lost?
  - Higher overhead at low load
  - Latency



# Topics

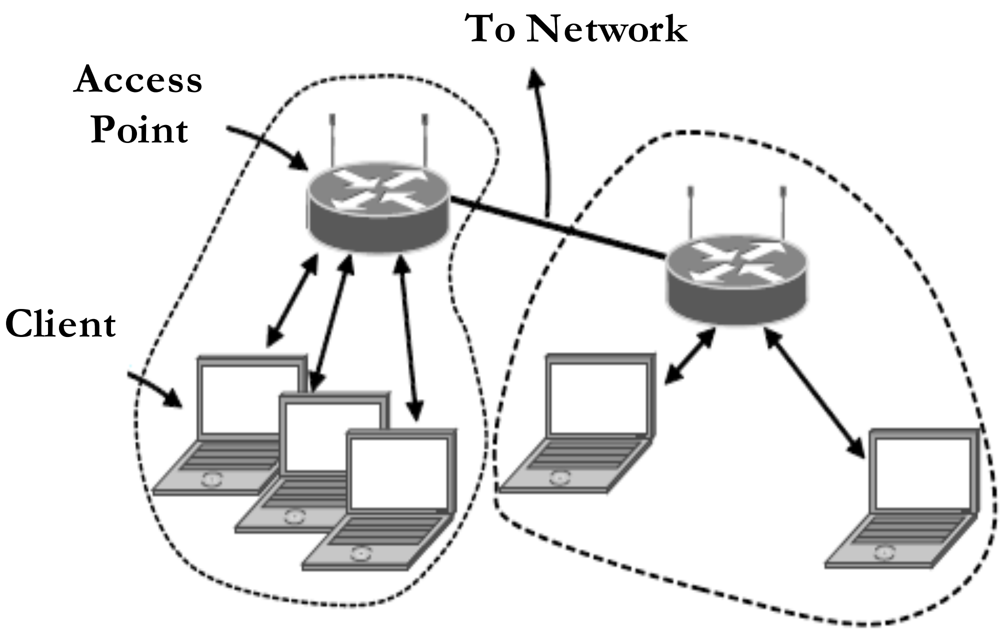
- Framing
  - Delimiting start/end of frames
- Error Control
  - Error control and correction, retransmission
- Multiple Access
  - MAC and CSMA
- (W)LAN – How does your packet go into the network?
  - 802.11, modern Ethernet and switching

# WLAN Design Space and Requirements

- Throughput
  - MAC protocol should maximize capacity of the wireless medium
- Number of nodes
  - Hundred of nodes
- Connection to backbone LAN
  - Accommodation for mobile users and ad hoc wireless networks
- Service area
  - Coverage area has a diameter of 100 – 300 m
- Battery power consumption
  - Sleep mode is a critical design
- Transmission robustness and security
  - Vulnerable to interference and network eavesdropping
- Collocated network operation
  - Interference of coexisted wireless networks
- License-free operation
  - No need to secure a license for the frequency band
- Handoff/roaming
  - Layer 2 client mobility
- Dynamic configuration
  - Automated addition, deletion and relocation of end systems without disruption to other users

# 802.11, or WiFi Overview

- A WLAN standard adopted in 1997 with goal of providing
  - Last mile multi-access to (Internet) services in wired networks
  - High throughput and highly reliable data delivery
  - Continuous network connection, e.g., client mobility
- The protocol defines
  - MAC sublayer and MAC management protocols and services
  - Several PHY layers: IR, FHSS, DSSS, OFDM
- Various features have been developed over time




- Physical Layer
  - Uses 20/40 MHz channels on ISM bands
    - 802.11b/g/n on 2.4 GHz; 802.11 a/n/ac on 5 GHz
  - OFDM modulation (except 802.11b)
    - Rates adaption for varying SNRs plus error correction
    - Since 802.11n uses multiple antennas
- Link Layer
  - Multiple access uses CSMA/CA; RTS/CTS optional
  - Frames are ACKed and retransmitted with ARQ
  - Funky addressing (four addresses!) due to AP
  - Errors are detected with a 32-bit CRC
  - Many, many features (e.g., encryption, power save)

# Wi-Fi vs. IEEE 802.11?

- IEEE 802.11 is a standard
- Wi-Fi = "Wireless Fidelity" is a trademark
- Fidelity = Compatibility between wireless equipment from different manufactures
- Wi-Fi Alliance is a non-profit organization that does the compatibility testing
  - WiFi.org
- 802.11 has many options and it is possible for two equipment based on 802.11 to be incompatible.
- All equipment with "Wi-Fi" logo have selected options such that they will interoperate.

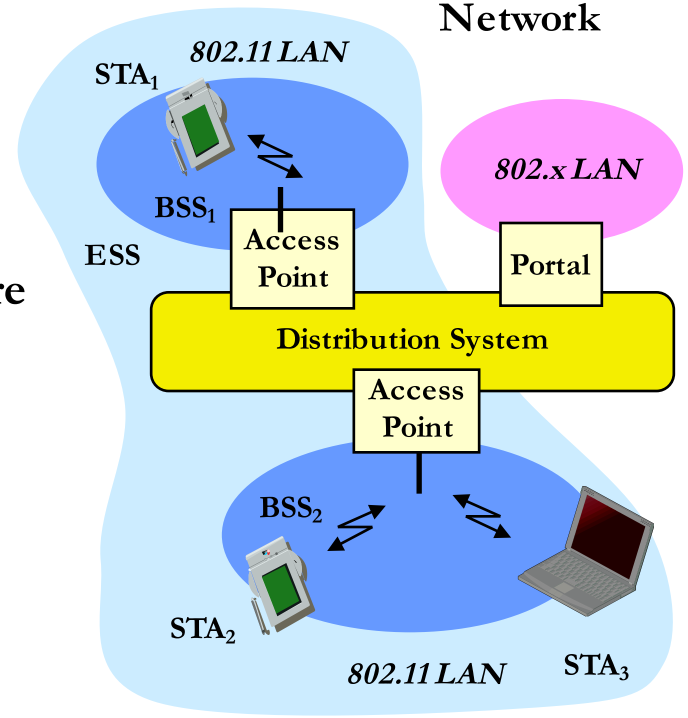
# Infrastructure and Ad Hoc Mode

- Infrastructure mode: stations communicate with one or more access points which are connected to the wired infrastructure, with two modes of operation:
  - Distributed Control Functions – DCF
    - What is deployed in practice
  - Point Control Functions – PCF
    - PCF is rarely used – inefficient, not discussed in this course
- Alternative is "ad hoc" mode: multi-hop, assumes no infrastructure
  - Rarely used, e.g. military
  - Hot research topic!
    - Sensor, Vehicular, Drone, Millimeterwave

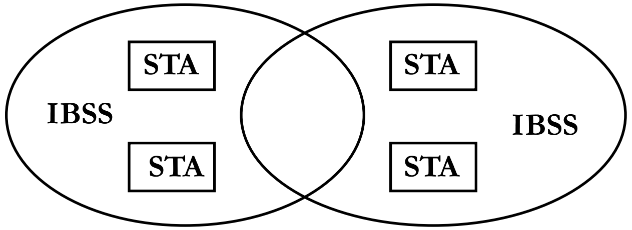
# 802.11 Architecture

- Station (STA)
  - Terminal with access mechanisms to the wireless medium and radio contact to the access point
- Access Point (AP)
  - Station integrated into the wireless LAN and the distribution system
- Basic Service Set (BSS)
  - Set of stations associated with one AP that provides access to wired infrastructure
- Extended Service Set (ESS)
  - A set of infrastructure BSSs that work together – aggregation of APs from BSSs
- Distribution System (DS)
  - Interconnection network to form one logical network (ESS) based on BSSs
- Portal
  - Bridge to other (wired) networks
- Independent BSS (IBSS)
  - Set of computers in ad-hoc mode

Infrastructure Network

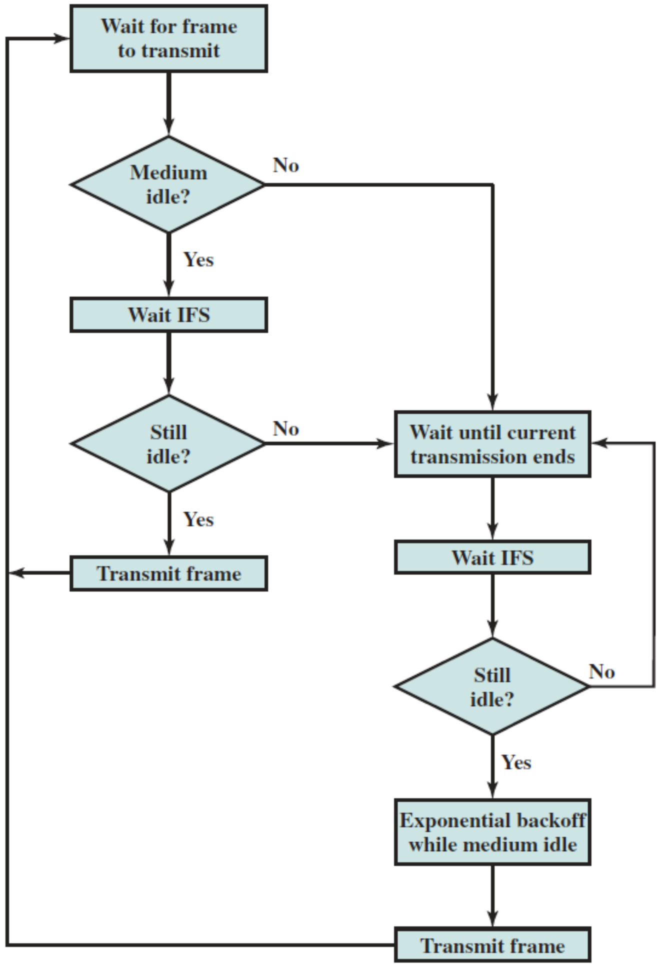


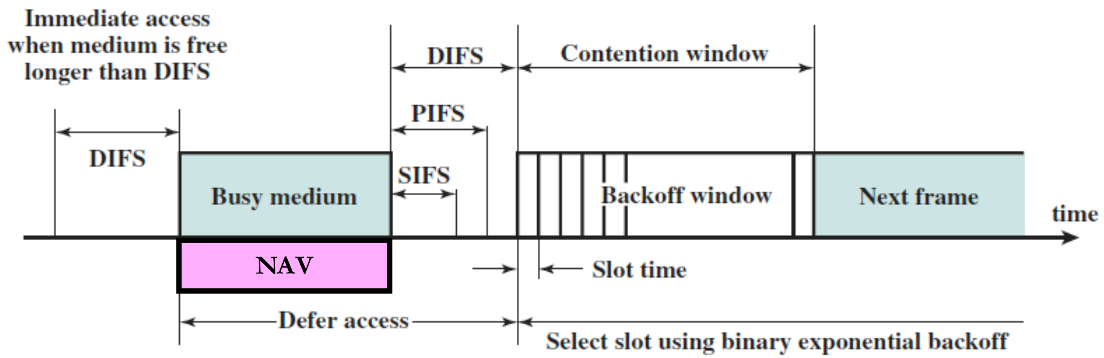

Ad Hoc Network



# 802.11 MAC Overview

- Carrier Sense Multiple Access (with Collision Avoidance)
  - Frame is transmitted only when medium is sensed idle for now and after an Distributed Coordination Function interframe space (DIFS)
  - The the channel is sensed busy, the station defers transmission until the current transmission is over
    - Busy time can be sensed by physical/virtual carrier sensing
  - Once current transmission is over, the station delays another DIFS, sends the frame if the channel is idle not only for now but also after a random backoff (contention window).
    - The backoff timer is halted if the medium becomes busy and resume once it becomes idle
    - If the frame is sent and an ACK is not received after a SIFS, then retransmit after the random backoff procedure
  - RTS/CTS can be turned off to reduce overhead



# 802.11 Carrier Sense Fundamentals

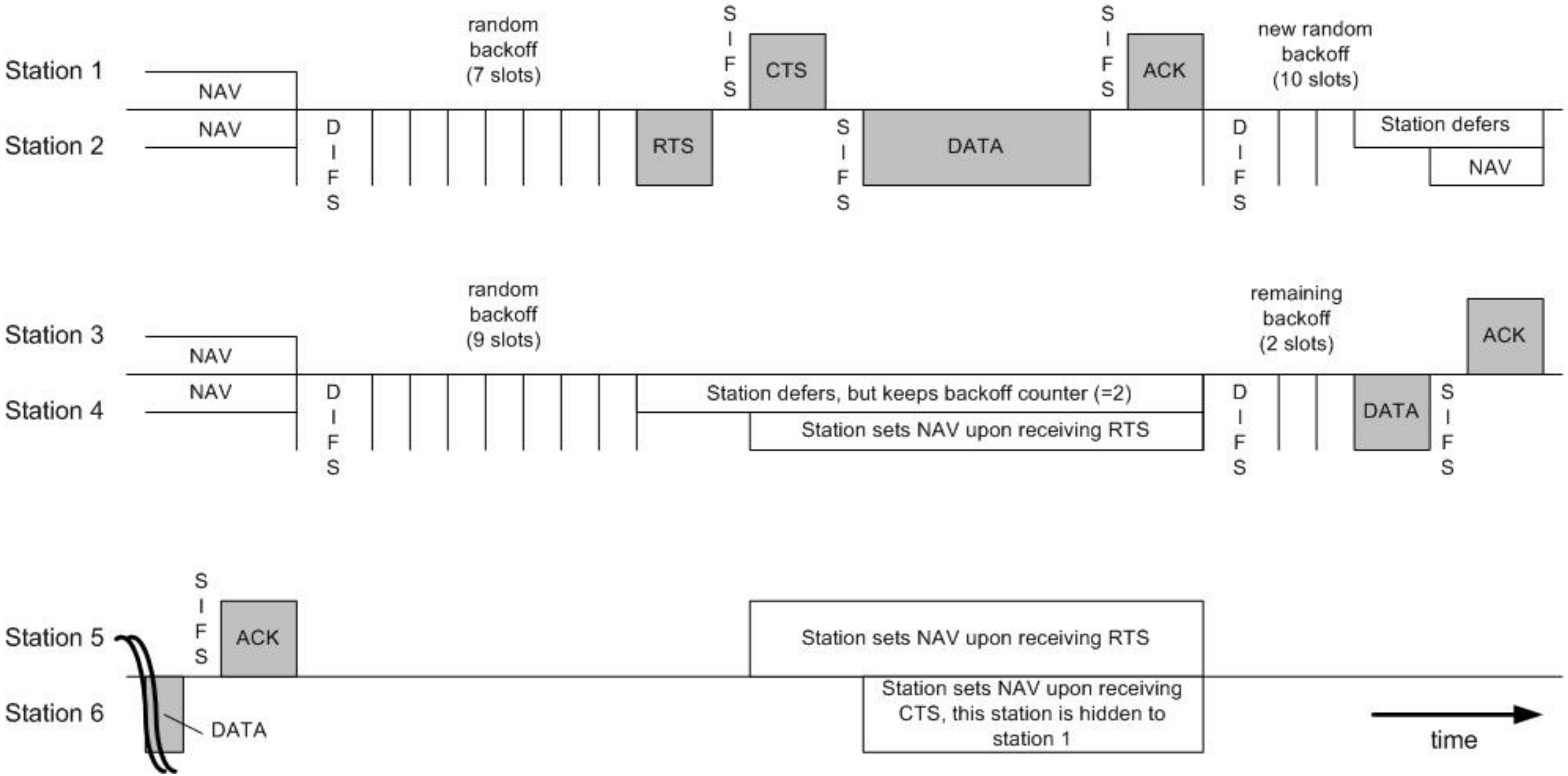
## Physical Carrier Sense

- Clear Channel Assessment (CCA): listens the received energy on the radio interface
- Carrier Sense: the ability of the receiver to detect (and decode) an incoming WiFi signal preamble
  - "BUSY" will be held for the length of the received frame as indicated in the frame's PLCP Length field (in us for full frame MPDU payload)
  - Indicates the medium is busy for the current frame
- Energy Detection: the ability of the receiver to detect the non-WiFi energy level present on the current channel
  - Based on noise floor, ambient energy, interference sources and unidentifiable/corrupted WiFi transmissions
  - Sample rate and sensitivity level needs to be engineered

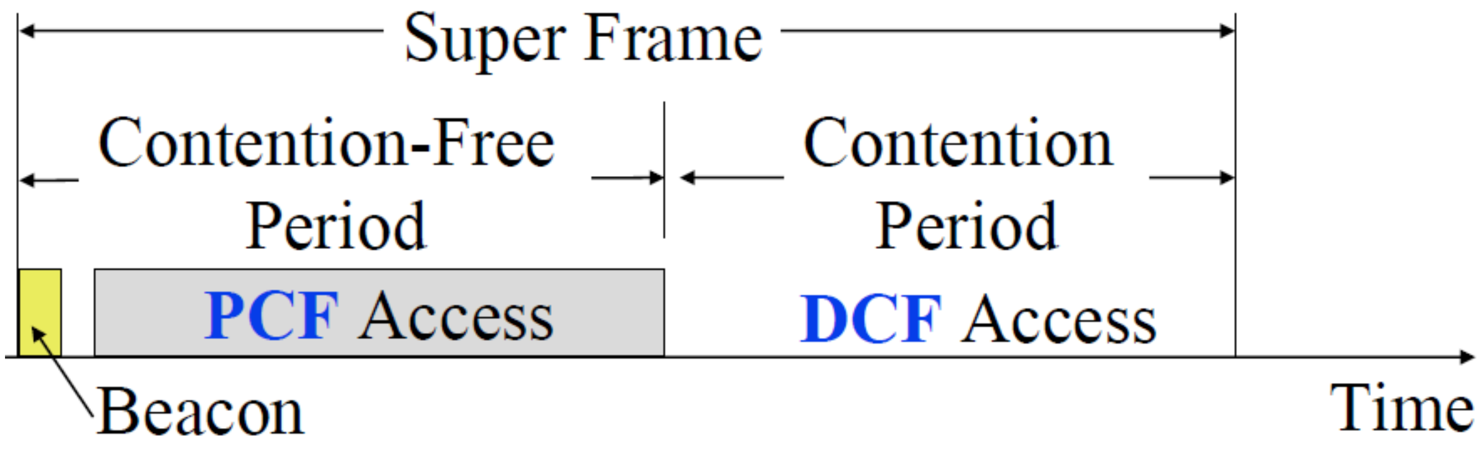
## Virtual Carrier Sense

- Network Allocation Vector (NAV)
  - Every frame has a "Duration ID" which indicates how long the medium will be busy.
    - RTS has duration of RTS + SIF + CTS + SIF + Data + SIF + ACK
    - CTS has duration of CTS + SIF + Frame + SIF + ACK
    - Data has duration of Data + SIF + ACK
    - ACK has a duration of ACK
  - All stations keep a "NAV" timer in which they record the duration of the each frame they hear.
  - Stations do not need to sense the channel for idle status until NAV becomes zero.

# Use of RTS/CTS



# Time Critical Services




- Time critical services use Point Coordination Function
- The point coordinator allows only one station to access
- Coordinator sends a beacon frame to all stations. Then uses a polling frame to allow a particular station to have contention-free access
- Contention Free Period varies with the load.

# 802.11 Frame Format

| Frame Control | Duration /ID | Address 1 | Address 2 | Address 3 | Sequence Control | Address 4 | Data | FCS | |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 6 | 6 | 6 | 2 | 6 | 0-2312 | 4 | bytes |

**Duration /ID:**
NAV information in DCF mode
Or
Short Id for PS-Poll

**Data:**
Upper layer data
2048 byte max
256 upper layer header

**Frame Control:**
Protocol Version (2-bit)
Frame Type and Sub Type (2-bit)
- Management: Beacon/Assoc/Auth…
- Control: ACK/RTS/CTS/…
- Data

To DS and From DS (2-bit)
- See next slide

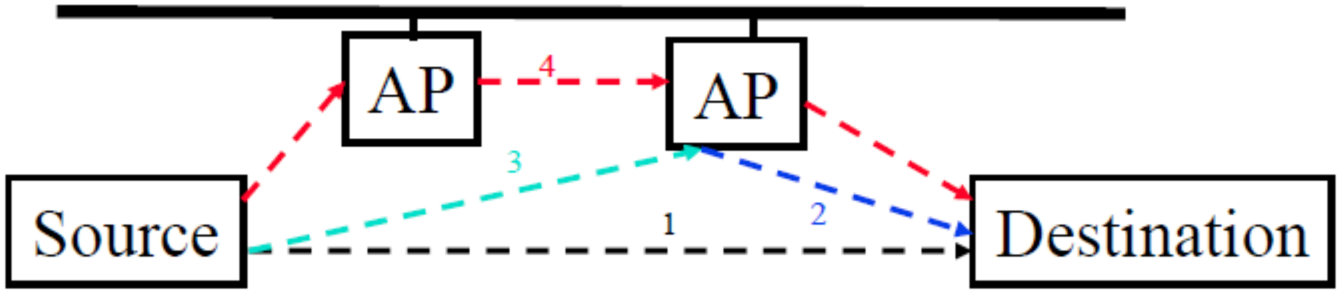
More Fragments (1-bit)
Retry (1-bit)
Power Management (1-bit)
More Data (1-bit)
WEP (1-bit)
Order (1-bit): strictly order service

**Address 1–4:**
IEEE 48 bit
MAC address –
See next slide

**Sequence Control:**
Sequence # (12-bit)
Fragment # (4-bit)

**FCS:**
CCIT CRC-32
Polynomial

# 802.11 Frame Address Fields




RA: Receiver Address

TA: Transmitter Address

DA: Destination Address

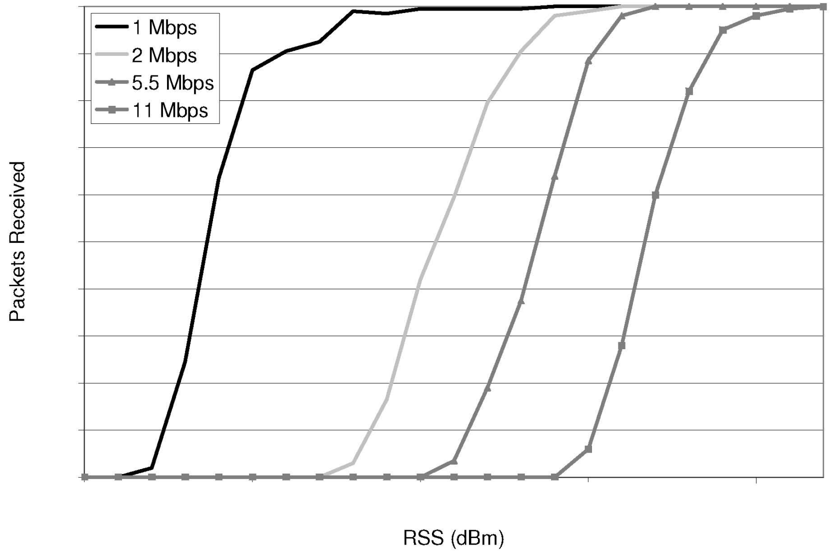
SA: Source Address

BSSID: MAC address of AP in an infrastructure BSS

| | To DS | From DS | Message | Address 1 | Address 2 | Address 3 | Address 4 |
|---|---|---|---|---|---|---|---|
| Ad hoc | 0 | 0 | station-to-station frames in an IBSS; all mgmt/control frames | DA | SA | BSSID | -- |
| from AP | 0 | 1 | From AP to station | DA | BSSID | SA | -- |
| to AP | 1 | 0 | From station to AP | BSS ID | SA | -- | DA |
| in DS | 1 | 1 | From one AP to another in same DS | RAP | TAP | SA | DA |
| | | | | Physical Receiver | Physical Transmitter | Logical Transmitter | Logical Receiver |

# Multi-bit Rate

- All modern WiFi standards allow for multiple bit rates
  - 802.11b has 4 rates, more recent standards have 10s
  - Allows for adaptation to channel conditions
  - Specific rates dependent on the version and vendor
  - Packets have multi-rate format
    - Different parts of the packet are sent at different rates
- Algorithm for selecting the rate is not defined by the standard – left to vendors
- Many factors influence packet delivery:
  - Fast and slow fading: nature depends strongly on the environment
  - Interference versus WiFi contention: response to collisions is different
  - Random packet losses: can confuse “smart” algorithms
  - Hidden terminals: decreasing the rate increases the chance of collisions
- Transmit rate adaptation: how does the sender pick?



# High Level Designs of Rate Adaptation

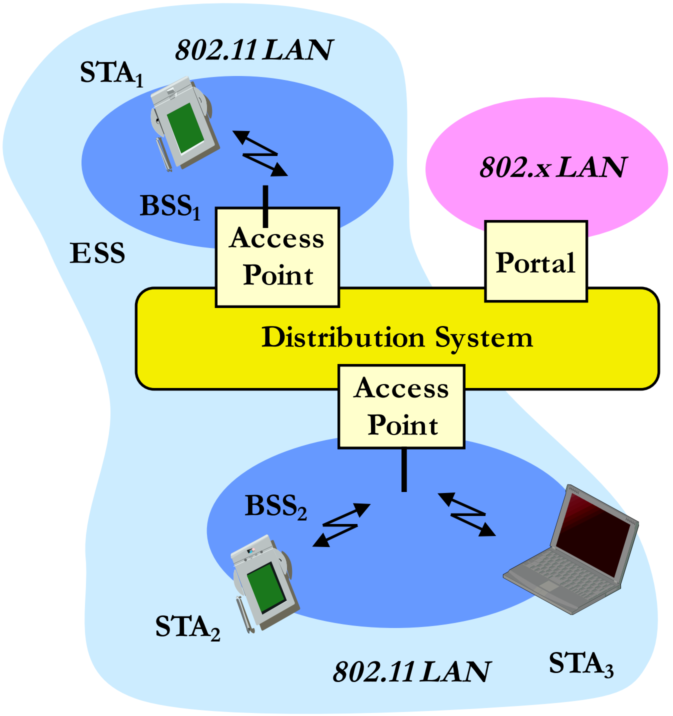
- Goal: pick rate that provides best throughput
- "Trial and Error": senders use past packet success or failures to adjust transmit rate
  - Sequence of x successes: increase rate
  - Sequence of y failures: reduce rate
  - Hard to get x and y right
  - Random losses can confuse the algorithm
  - Many variants – RRAA
- Signal strength: stations use channel state information to pick transmit rate
  - Use path loss information to calculate "best" rate
  - Assumes a relationship between PDR and SNR
    - Need to recover if this fails, e.g., hidden terminals
  - Tends to be a bit harder to manage – Charm

# 802.11 Management and Control Services

- Association management
- Handoff/Roam
- Security: authentication and privacy
- Power management
- QoS

# WLAN Identification

- Service Set Identifier (SSID) – identifier for a WLAN
  - Human readable. E.g., “Wifeless EECS”, “Password is not 123456”
  - Mechanism used to segment wireless networks
    - Effectively the name of the wireless network – a set of multiple interconnected wireless BSSs that share the same SSID
    - Multiple independent wireless networks can coexist in the same location – Extended Service Set (ESS)
  - Each AP is programmed with a SSID that corresponds to its network
  - Client computer presents correct SSID to access AP
  - Security Compromises
    - AP can be configured to “broadcast” its SSID
    - Broadcasting can be disabled to improve security
    - SSID may be shared among users of the wireless segment
- Basic Service Set Identifier (BSSID)
  - The MAC address of the AP
  - A subset of SSID



# Association Management Overview

- Stations must associate with an AP before they can use the wireless network
  - AP must know about them so it can forward packets
  - Often also must authenticate
- Association is initiated by the wireless host – involves multiple steps:
  - Scanning: finding out what access points are available
    - Active/Passive scanning
  - Selection: deciding what AP (or ESS) to use
  - Authentication: needed to gain access to secure APs – many options possible
  - Association: protocol to "sign up" with AP – involves exchange of parameters
- Disassociation: station or AP can terminate association
  - Client send disassociation request or timeout
- Remember: this is layer 2 connectivity
  - Don't guarantee a higher layer connectivity, e.g., Internet access

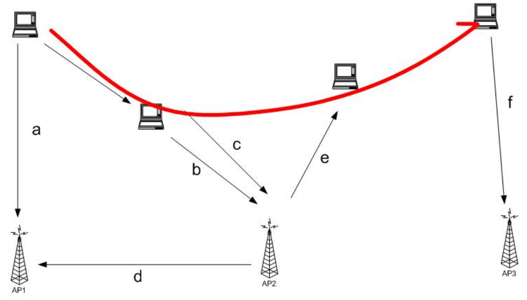
# Association Management: Scan, Select and Join

- Stations can detect AP based by scanning
  - Passive Scanning: station simply listens for Beacon and gets info of the BSS
    - Beacons are sent roughly 10 times per second
    - Power is saved
  - Active Scanning: station transmits Probe Request; elicits Probe Response from AP
    - Saves time + is more thorough
    - Wait for 10-20 msec for response
  - Scanning all available channels can become very time consuming!
    - Especially with passive scanning
    - Cannot transmit and receive frames during most of that time – not a big problem during initial association

- Selecting a BSS or ESS typically must involve the user
  - What networks do you trust? Are you willing to pay?
  - Can be done automatically based on stated user preferences
- The wireless host selects the AP it will use in an ESS based on vendor-specific algorithm
  - Uses the information from the scan
  - Typically simply joins the AP with the strongest signal
- Associating with an AP
  - Synchronization in Timestamp Field and frequency
  - Adopt PHY parameters
  - Other parameters: BSSID, WEP, Beacon Period, etc.

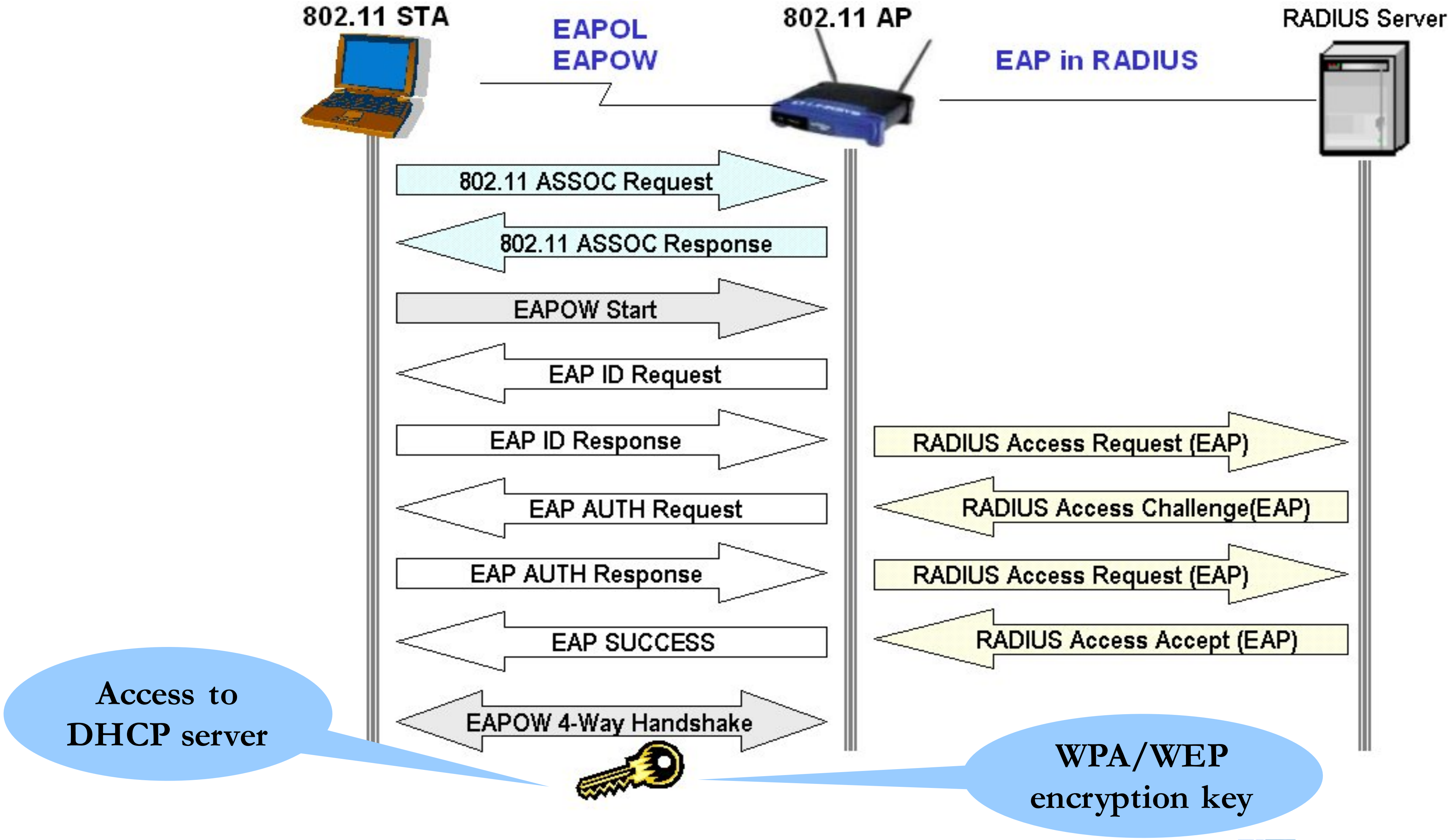
# Association Management: Roaming

- Reassociation: association is transferred from active AP to a new target AP
  - Supports mobility in the same ESS – layer 2 roaming
- Client driven
  - Failure driven: only try to reassociate after connection to current AP is lost
    - Typically efficient for stationary/nomadic clients since it not common that the best AP changes during a session
    - Can be very disruptive for mobile devices and latency sensitive applications
  - Proactive reassociation: periodically try to find an AP with a stronger signal
    - Tricky part: cannot communicate while scanning other channels, but can do this using power save mode
    - Throughput during scanning is still affected though
- Distribution System assisted
  - Coordination between APs is defined in 802.11f
  - Inter-AP authentication and discovery typically coordinated using a RADIUS server
  - "Fast roaming" support (802.11r) also streamlines authentication and QoS, e.g. for VoIP




(a) ---- The station finds AP1, it will authenticate and associate.
(b) ---- As the station moves, it may pre-authenticate with AP2.
(c) ---- When the association with AP1 is no longer desirable, it may reassociate with AP2.
(d) ---- AP2 notify AP1 of the new location of the station, terminates the previous association with AP1.
(e) ---- At some point, AP2 may be taken out of service. AP2 would disassociate the associated stations.
(f) ---- The station find another access point and authenticate and associate.

# 802.1x and EAP Protocol Execution



# WLAN Security Discussion

- Requirements
  - Authentication: only allow authorized stations to associate with and use the AP
  - Confidentiality: hide the contents of traffic from unauthorized parties
  - Integrity: make sure traffic contents is not modified while in transit
- Examples
  - Insertion attacks: unauthorized Clients or AP
    - Client: reuse MAC or IP address – free service on "secured" APs
    - AP: impersonate an AP, e.g., use well known name
  - Interception and unauthorized monitoring
    - Packet Analysis by "sniffing" – listening to all traffic
  - Brute Force Attacks Against AP Passwords
    - Dictionary Attacks Against SSID
  - Encryption Attacks
    - Exploit known weaknesses of WEP
  - Misconfigurations, e.g., use default password
  - Jamming – denial of service
    - Cordless phones, baby monitors, leaky microwave oven, etc.

# Best Practices for WiFi Security

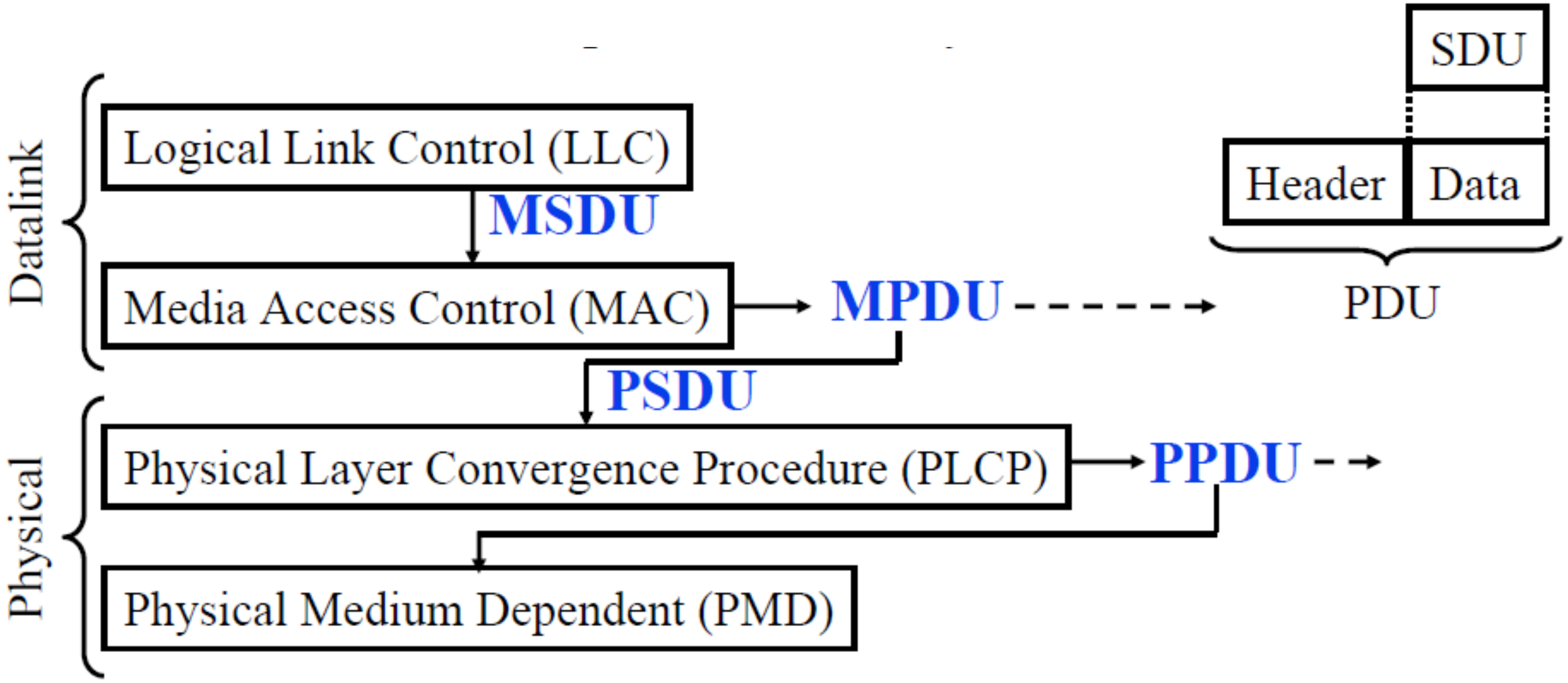
- Use WPA2
  - Widely supported today
  - If not available, use WEP or WPA
    - Better than no security plus some possible legal benefits
- Change the default configuration of your AP:
  - Change default passwords on APs
  - Don't name your AP by brand name
  - Don't name your AP by model #
  - Change default SSID
- Use MAC filtering if available
- Use a VPN or application layer encryption
  - Must assume that wireless segment is untrusted
  - Provides end-to-end encryption – is what you want!

# Power Management

- Goal: to enhance battery life of the (mobile) stations
- Observation: idle receive state dominates LAN adapter power consumption over time
- Simple idea: Allow idle stations to power off their NIC (go into sleep mode) while still maintaining an active session
  - AP keeps track of stations in Power Savings mode and buffers their packets
    - Traffic Indication Map (TIM) is included in beacons to inform which power-save stations have packets waiting at the AP
  - Power Saving stations wake up periodically and listen for beacons
    - If they have data waiting, they can send a PS-Poll to request that the AP sends their packets
- Timing Synchronization Function (TSF) assures AP and stations are synchronized
  - Synchronizes clocks of the nodes in the BSS via beacon frames
  - On a commercial level, industry vendors assume the synchronization to be within 25 microseconds
- Broadcast/multicast frames are also buffered at AP
  - Sent after beacons that includes Delivery Traffic Indication Map (DTIM)
  - AP controls DTIM interval

# Protocol Data Units (PDUs)

- Each layer has Service Data Units (SDUs) as input
- Each layer makes Protocol Data Units (PDUs) as output to communicate with the corresponding layer at the other end
- SDUs may be fragmented or aggregated to form a PDU; PDUs have a header specific to layer.



# Several Primary 802.11 Amendments

- 802.11a – 1999: PHY Standard: 8 channels: OFDM, up to 54 Mbps in the 5 GHz band
- 802.11b – 1999: PHY Standard: 3 channels: DSSS, up to 11 Mbps in the 2.4 GHz band.
- 802.11g – 2003: PHY Standard: 3 channels: OFDM and PBCC, extend 802.11b to 20+ Mbps
- 802.11n – 2009: PHY/MAC Standard: MIMO, Enhancements for higher throughput (+100 Mbps)
- 802.11ac – 2013: PHY/MAC Standard: Enhancements to support 0.5-1 Gbps in < 5 GHz band
- 802.11ad – 2012: PHY/MAC Standard: Enhancements to support 1+ Gbps in < 60 GHz band
- Others:
  - 802.11c: Bridge operation at 802.11 MAC layer
  - 802.11d: MAC Standard: support for multiple regulatory domains (countries)
  - 802.11e: MAC Standard : QoS and security support: supported by many vendors
  - 802.11f: Inter-Access Point Protocol: deployed
  - 802.11h: MAC Standard: spectrum managed 802.11a (TPC, DFS): standard
  - 802.11i: MAC Standard: Enhance security and authentication mechanisms

# 802.11 PHY Layer Standards

| Standard | 802.11a | 802.11b | 802.11g | 802.11n | 802.11ac | 802.11ad |
|---|---|---|---|---|---|---|
| Year introduced | 1999 | 1999 | 2003 | 2000 | 2012 | 2014 |
| Maximum data transfer speed | 54 Mbps | 11 Mbps | 54 Mbps | 65 to 600 Mbps | 78 Mbps to 3.2 Gbps | 6.76 Gbps |
| Frequency band | 5 GHz | 2.4 GHz | 2.4 GHz | 2.4 or 5 GHz | 5 GHz | 60 GHz |
| Channel bandwidth | 20 MHz | 20 MHz | 20 MHz | 20, 40 MHz | 40, 80, 160 MHz | 2160 MHz |
| Highest order modulation | 64 QAM | 11 CCK | 64 QAM | 64 QAM | 256 QAM | 64 QAM |
| Spectrum usage | DSSS | OFDM | DSSS, OFDM | OFDM | SC-OFDM | SC, OFDM |
| Antenna configuration | 1×1 SISO | 1×1 SISO | 1×1 SISO | Up to 4×4 MIMO | Up to 8×8 MIMO, MU-MIMO | 1×1 SISO |