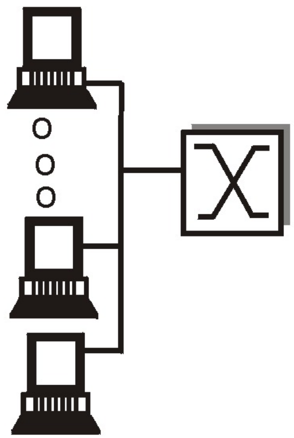
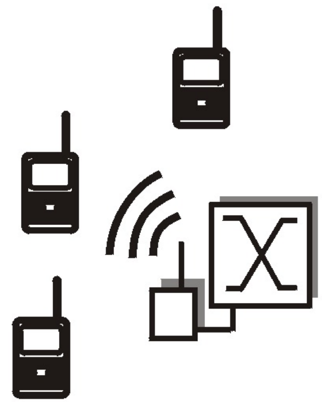
Data-Link Layers

Note: The slides are adapted from the materials from Prof. Richard Han at CU Boulder and Profs. Jennifer Rexford and Mike Freedman at Princeton University, and the networking book (Computer Networking: A Top Down Approach) from Kurose and Ross.

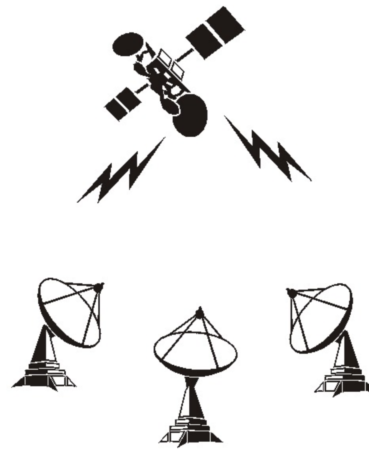
Broadcast Links: Shared Media



shared wire
(e.g. Ethernet)



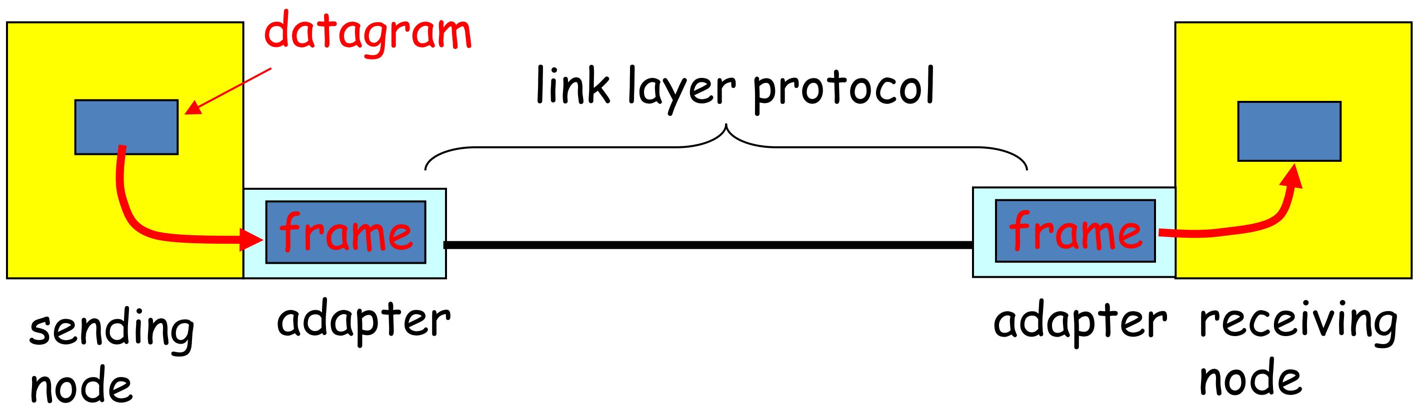
shared wireless
(e.g. Wavelan)



satellite

cocktail party

Digital adaptors Communicating



- Link layer implemented in adaptor (network interface card)
  - Ethernet card, PCMCIA card, 802.11 card
- Sending side:
  - Encapsulates datagram in a frame
  - Adds error checking bits, flow control, etc.
- Receiving side
  - Looks for errors, flow control, etc.
  - Extracts datagram and passes to receiving node

Link-Layer Services

- Encoding
  - Representing the 0s and 1s
- Framing
  - Encapsulating packet into frame, adding header, trailer
  - Using MAC addresses, rather than IP addresses
- Error detection
  - Errors caused by signal attenuation, noise.
  - Receiver detecting presence of errors
- Error correction
  - Receiver correcting errors without retransmission
- Flow control
  - Pacing between adjacent sending and receiving nodes

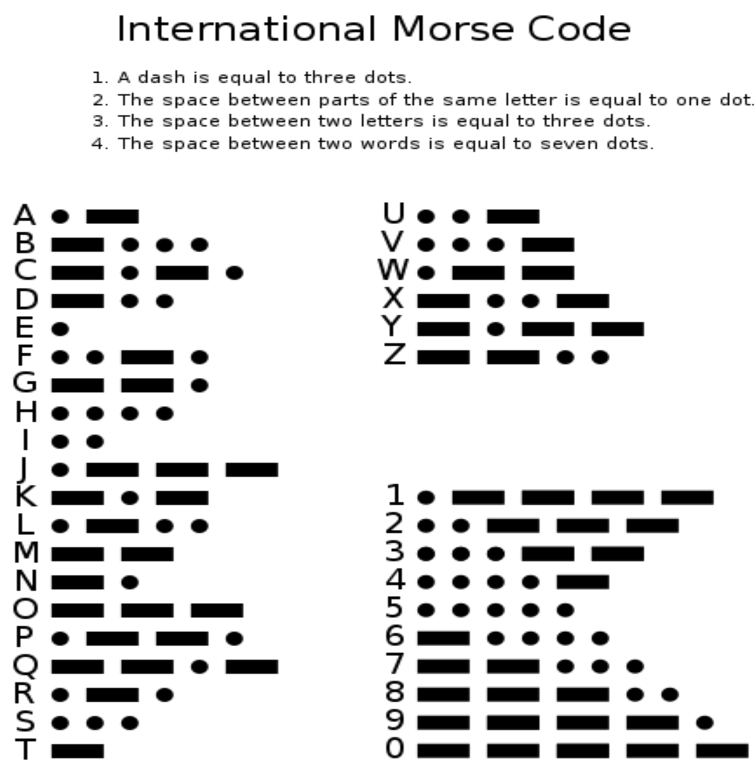
Link-Layer Protocols

Outline

- Link-layer protocols
  - Encoding, framing, error detection
- Multiple-access links: sharing is caring!
  - Strict isolation: division over time or frequency
  - Centralized management (e.g., token passing)
  - Decentralized management (e.g., CSMA/CD)

Digital -> Analog Encoding

- Signals sent over physical links
  - Source node: bits -> signal
  - Receiving node: signal -> bits
- Encoding in telegraph
  - Morse code: “long” and “short” signals



Digital -> Analog Encoding

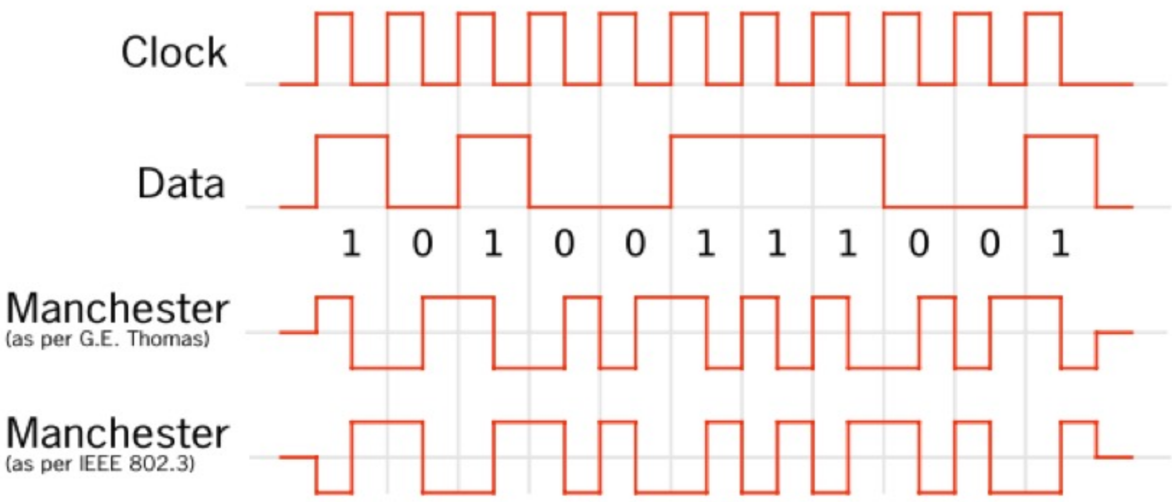
- Signals sent over physical links
  - Source node: bits -> signal
  - Receiving node: signal -> bits
- Simplify some electrical engineering details
  - Assume two discrete signals, high and low
  - E.g., could correspond to two different voltages
- Simple approach: Non-return to zero
  - High for a 1, low for a 0

Problem With NRZ

- Long strings of 0s or 1s introduce problems
  - No transitions from low-to-high, or high-to-low
- Receiver keeps average of signal it has received
  - Uses the average to distinguish between high and low
  - Long flat strings make receiver sensitive to small change
- Transitions also necessary for clock recovery
  - Receiver uses transitions to derive its own clock
  - Long flat strings do not produce any transitions
  - Can lead to clock drift at the receiver
- Alternatives (see Section 2.2)
  - Non-return to zero inverted, and Manchester encoding

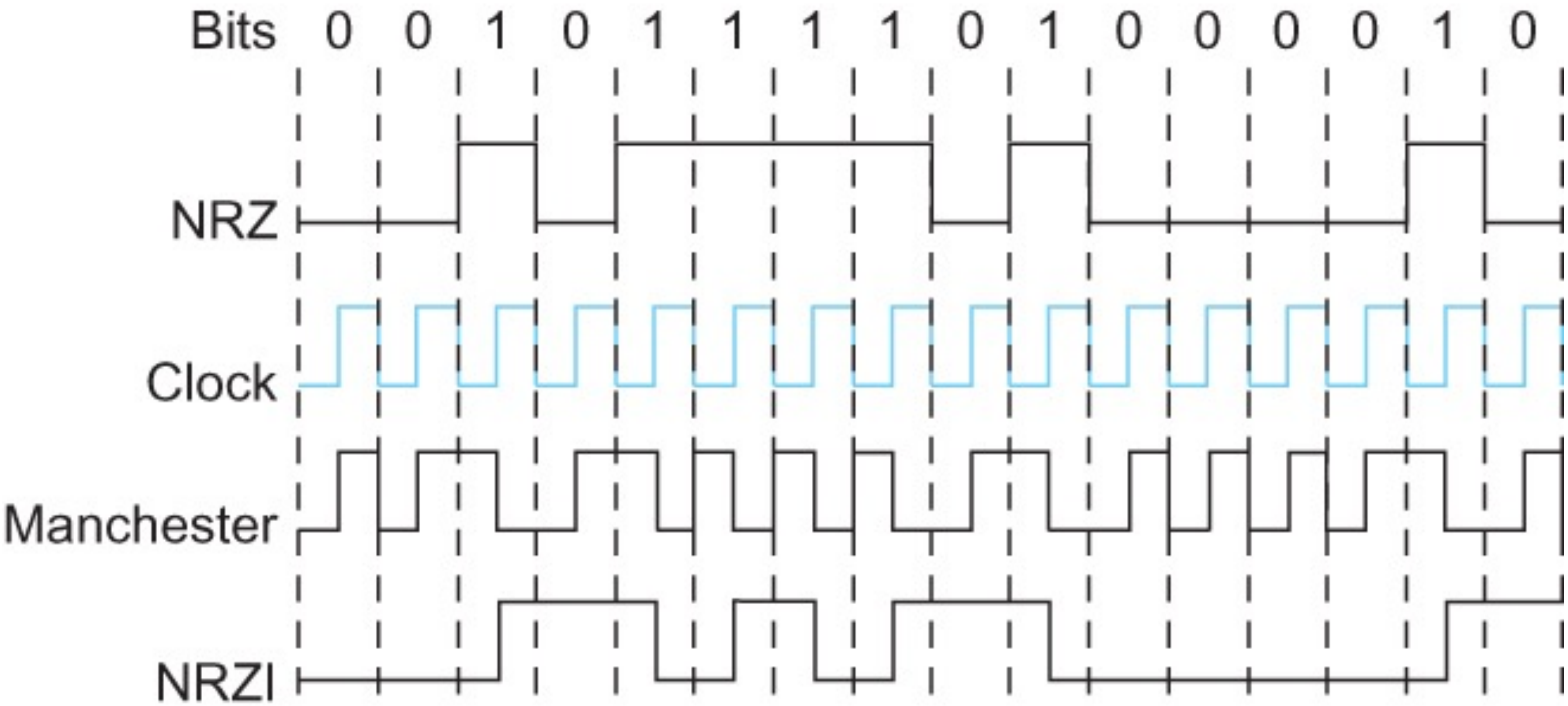
Protocols with clock-recovery

- Manchester encoding (basic Ethernet)
  - clock XOR NRZ: 802.3: H→L (0), L→H (1) : self-clocking



- Efficiency? (read 4B/5B encoding in Sec 2.2)
  - Manchester: 2 clock transitions per bit: 50% efficient
  - 1 GbE: 8b/10b: 80% efficient
  - 10 GbE: 64b/66b: 96.9% efficient

Different Encoding Strategies



Framing

- Break sequence of bits into a frame
  - Typically implemented by the network adaptor
- Sentinel-based
  - Delineate frame with special pattern (e.g., 01111110)

01111110	Frame contents	01111110

  - Problem: what if special patterns occurs within frame?
  - Solution: escaping the special characters (stuffing)
    - E.g., sender always inserts a 0 after five 1s
    - … and receiver always removes a 0 appearing after five 1s
    - Byte stuffing (BiSync, PPP) and bit stuffing (HDLC)
  - Similar to escaping special characters in C programs

Framing (Continued)

- Counter-based
  - Include the payload length in the header
  - … instead of putting a sentinel at the end
  - Problem: what if the count field gets corrupted?
    - Causes receiver to think the frame ends at a different place
  - Solution: catch later when doing error detection
    - And wait for the next sentinel for the start of a new frame
- Clock-based
  - Make each frame a fixed size
  - No ambiguity about start and end of frame
  - But, may be wasteful

Character/Byte Stuffing Example

- Sentinel X, at both start and end of packet
- Stuff X in data, replace X with escape character "E" (DLE in textbook) and X, i.e., X -> (E,X)

Data: AKLWXIKKEZLXKDKLEXYBE

Send: XAKLWEXIKKEEZLEXKDKLEEEXYBEEX

Receiver: AKLWXIKKEZLXKDKLEXYBE

Bit Stuffing Example

- Similar to byte stuffing, except bit stuffing is not confined to byte boundaries
- HDLC denotes beginning and end of a packet/frame with “01111110” flag
- Since “01111110” may occur anywhere (across byte boundaries) in data, then “stuff” it:
  - At sender, after 5 consecutives one, insert a “0”
  - At receiver, “0111110” -> stuffing, so destuff, “01111110” -> end of frame, “01111111” -> error

Data: `0110111111100111110111111111100000`

Send: `0111110011011111011001111100111110111110000000111110`

Receiver: `0110111111100111110111111111100000`

Error Detection

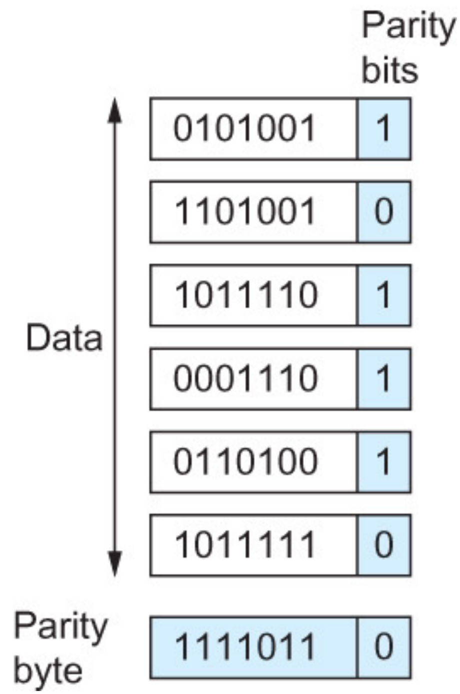
- Errors are unavoidable
  - Electrical interference, thermal noise, etc.
- Error detection
  - Transmit extra (redundant) information
  - Use redundant information to detect errors
  - Extreme case: send two copies of the data
  - Trade-off: accuracy vs. overhead

Probability of Packet Error

- Send N bits. Probability of bit error = P_b
- Assume independent bit errors. What is the probability of packet error?
  - Prob[packet error] = Prob[at least 1 bit is corrupt] = 1- Prob[every bit is clean] = $1-(1-P_b)^N$
  - If $P_b = 10^{-6}$, and N=10000 bits, then Prob[packet error] = $9.95 * 10^{-3}$ ~= 1%
- Optical links have much lower probabilities of bit error: 10^{-12}
- Wireless links have much higher probabilities of bit error: 10^{-3}
  - Bit errors correlated, not independent

Error Detection Techniques

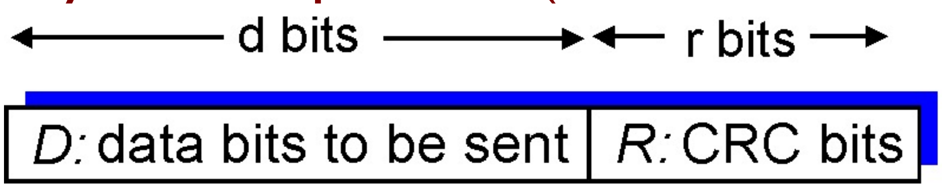
- Parity check
  - Add an extra bit to a 7-bit code
  - Odd parity: ensure an odd number of 1s
    - E.g., 0101011 becomes 01010111
  - Even parity: ensure an even number of 1s
    - E.g., 0101011 becomes 01010110
  - Two dimensional parity



- Checksum
  - Treat data as a sequence of 16-bit words
  - Compute a sum of all 16-bit words, with no carries
  - Transmit the sum along with the packet
- Cyclic Redundancy Check (CRC)
  - See Section 2.4.3

Cyclic redundancy check

- more powerful error-detection coding
- view data bits, D, as a binary number
- choose r+1 bit pattern (generator), G
- goal: choose r CRC bits, R, such that
  - <D,R> exactly divisible by G (modulo 2)
  - receiver knows G, divides <D,R> by G. If non-zero remainder: error detected!
  - can detect all burst errors less than r+1 bits
- widely used in practice (Ethernet, 802.11 WiFi, ATM)



bit pattern

$$D * 2^r \ \text{XOR} \ R$$

mathematical formula

CRC example

want:

$D \cdot 2^r$ XOR $R = nG$

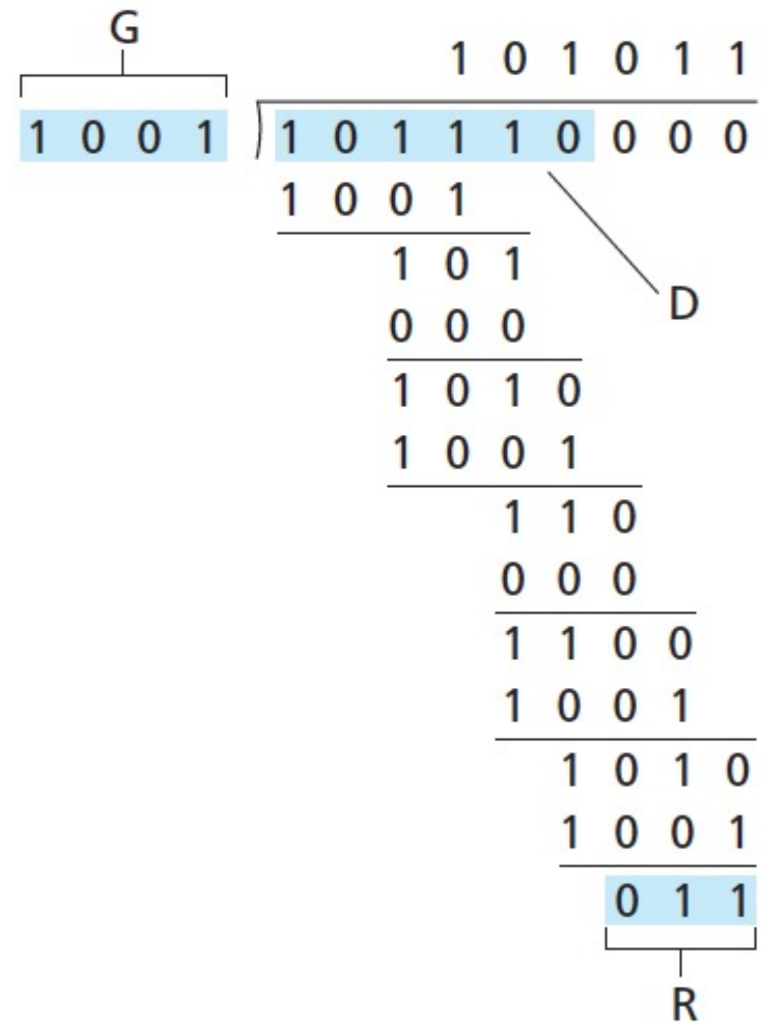
equivalently:

$D \cdot 2^r = nG$ XOR R

equivalently:

if we divide $D \cdot 2^r$ by G, want remainder R to satisfy:

$$\boxed{R = remainder\left[\frac{D \cdot 2^r}{G}\right]}$$



Error Correction

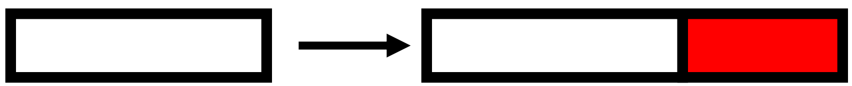
- Correct an error, rather than just detecting an error
- Simple technique: Send 2 copies of data with the data (repetition coding), and then do majority logic decoding at the receiver
  - Original data: 0100
  - Send: 0100 0100 0100
- Problems
  - In efficient
  - It cannot correct 2 errors in the same bit

Receiver: 0100
0110
0100
Decode: 0100

Corrupt Bit

Error Correction (Continued)

- Forward Error Correction (FEC)
  - Many types, e.g., Reed-Solomon coding
  - Add K bits of redundancy to N bits, to form a (N+K)-bit long packet, or vector



  - N dimensions -> N+K dimensions
  - 2N patterns or vectors mapped into 2N+K possibilities
  - Spread out these vectors as far away from neighbors as possible in (N+K)-dimensional space
  - N=2, K=3, N+K = 5

11	→	11111
10	→	01010
01	→	10101
00	→	00000

  - Receive 01111 – closet to 11111, so decode “11” and correct one bit error

Performance of Data Link Layer

Performance of a Data Link Layer Protocol

- Round-trip Time RTT =

  forward propagation delay of 1^{st} bit

  + forward transfer time (width of data packet)

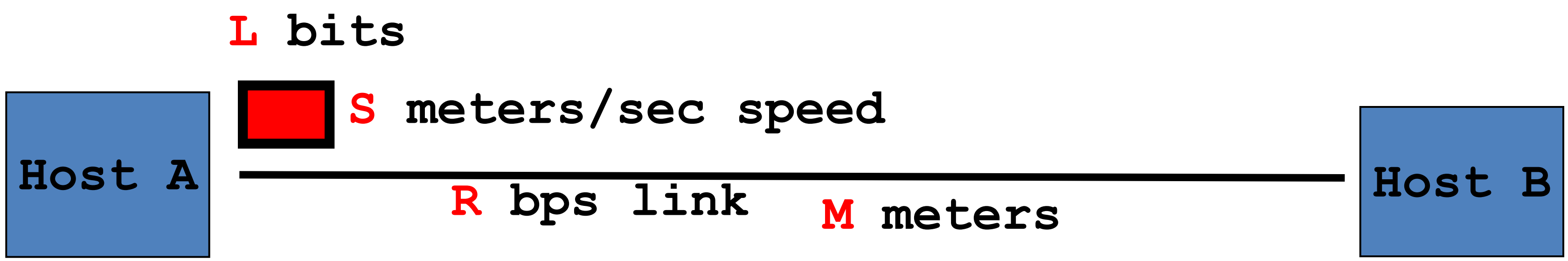
  + processing at the receiver

  + reverse propagation delay of 1^{st} bit

  + reverse transfer time of reply packet

- Transfer time = P/B
  - D = Propagation delay
  - P = Packet Size
  - B = Bit rate or bandwidth of the link

Performance of a Data Link Layer Protocol



Propagation delay = M/S
Transmission time = L/R
End-to-End delay = (M/S + L/R) if we ignore queueing delays

Bandwidth*delay product (BDP) of a Link

- Bandwidth*delay product indicates how many bits can be fit into a given link
  - D: Propagation delay
  - B: Bit rate or bandwidth of the link
  - BDP = B * D
- Assuming a roundtrip time of 2D
  - BDP = B * 2D
- Assuming only one way delay
  - BDP = B * D

Sample Bandwidth Delay Products

Link Type	Bandwidth (Typical)	Distance (Typical)	RTT	Delay x BW
Dial-up	56 Kbps	10 km	87 μs	5 bits
Wireless LAN	54 Mbps	50 m	33 μs	**1.8 kbits**
Satellite	45 Mbps	35000 km	230 ms	10 Mb
Cross-country fiber	10 Gbps	4000 km	40 ms	400 Mb

BDP Q/A

- What is the maximum number of packets in flight on the link with following characteristics:
  - Bandwidth: 8Mbps
  - RTT between two end hosts: 250ms
  - 1 packet size: 1024 bytes

```
(8*1024*1024*0.25)/(1024*8) = 256 pkts
```

Sharing the Medium

Collisions

- Single shared broadcast channel
  - Avoid having multiple nodes speaking at once
  - Otherwise, collisions lead to garbled data

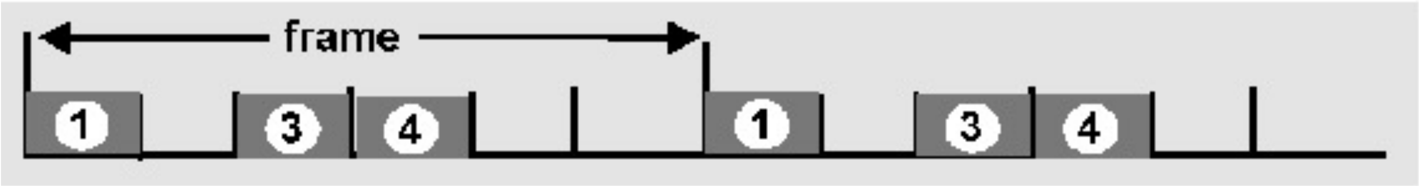
Multiple Access Protocol

- Single shared broadcast channel
  – Avoid having multiple nodes speaking at once
  – Otherwise, collisions lead to garbled data
- Multiple access protocol
  – Distributed algorithm for sharing the channel
  – Algorithm determines which node can transmit
- Classes of techniques
  – Channel partitioning: divide channel into pieces
  – Taking turns: passing a token for the right to transmit
  – Random access: allow collisions, and then recover

Channel Partitioning: TDMA

TDMA: time division multiple access

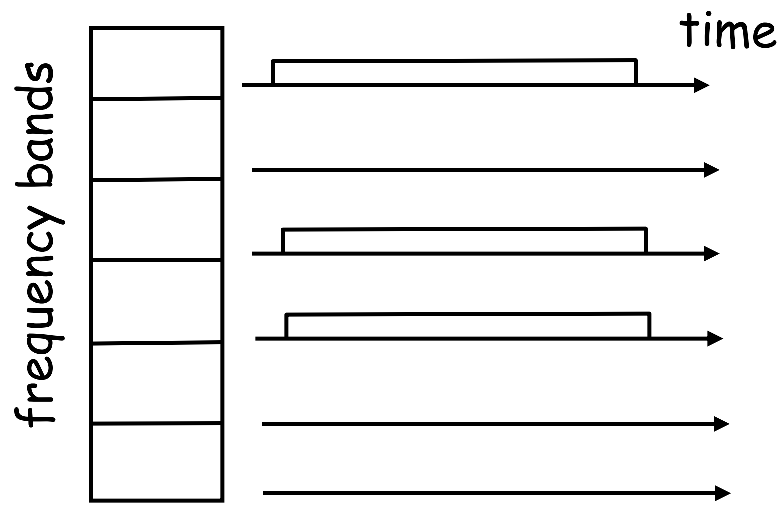
- Access to channel in "rounds"
  - Each station gets fixed length slot in each round
- Time-slot length is packet transmission time
  - Unused slots go idle
- Example: 6-station LAN with slots 1, 3, and 4



Channel Partitioning: FDMA

FDMA: frequency division multiple access

- Channel spectrum divided into frequency bands
  - Each station has fixed frequency band (Wifi channels 1-11)
- Unused transmission time in bands go idle
- Example: 6-station LAN with bands 1, 3, and 4



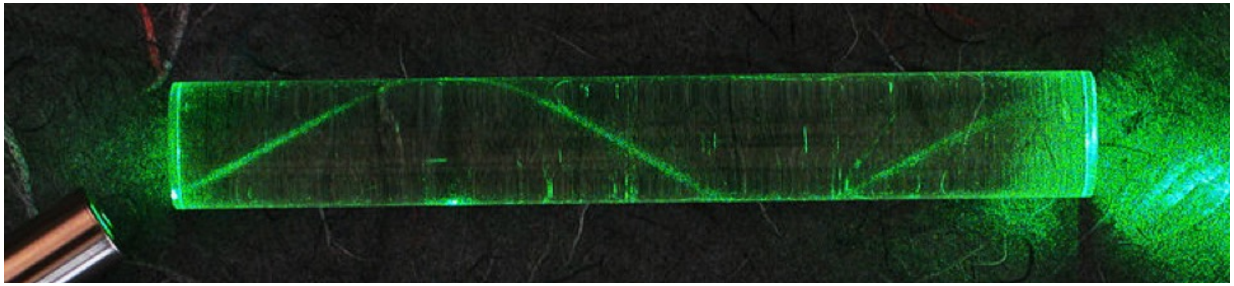
Channel Partitioning: FDMA

FDMA: frequency division multiple access

- Channel spectrum divided into frequency bands
  - Each station has fixed frequency band (Wifi channels 1-11)
- Unused transmission time in bands go idle
- Example: 6-station LAN with bands 1, 3, and 4

WDM: Wavelength division multiplexing

- Multiple wavelengths λ on same optical fiber



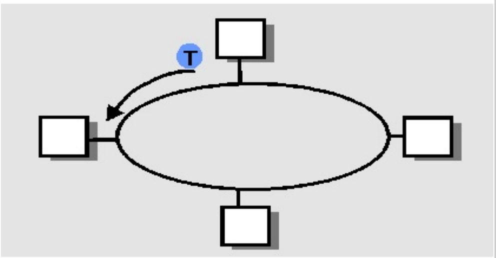
“Taking Turns” MAC protocols

Polling

- Primary node “invites” secondary nodes to transmit in turn
- Concerns:
  - Polling overhead
  - Latency
  - Single point of failure (primary)

Token passing

- Control token passed from one node to next sequentially
- Token message
- Concerns:
  - Token overhead
  - Latency
  - Single point of failure (token)



Random Access Protocols

- When node has packet to send
  - Transmit at full channel data rate R.
  - No *a priori* coordination among nodes
- Two or more transmitting nodes ➜ "collision"
- Random access MAC protocol specifies:
  - How to detect collisions
  - How to recover from collisions

Key Ideas of Random Access

- Carrier Sense (CS)
  - *Listen before speaking, and don't interrupt*
  - Checking if someone else is already sending data
  - … and waiting till the other node is done
- Collision Detection (CD)
  - *If someone else starts talking at the same time, stop*
  - Realizing when two nodes are transmitting at once
  - …by detecting that the data on the wire is garbled
- Randomness
  - *Don't start talking again right away*
  - Waiting for a random time before trying again

ALOHA Protocol

- “pure” ALOHA: hosts transmit whenever they have information to send – form of random access
  - Collision will occur when two hosts try to transmit packets at the same time
  - Hosts wait a timeout=1RTT for an ACK
  - If no ACK by timeout, then wait a randomly selected delay to avoid repeated collision, then retransmit
- Collision of packets can occur when packet overlaps another packet
  - Wasted time due to a collision = up to 2 packet intervals
  - Maximum throughput is around 18% (Poisson packet arrival)
- How to improve?
  - How about using a fixed time slot? Slotted ALOHA

Slotted ALOHA

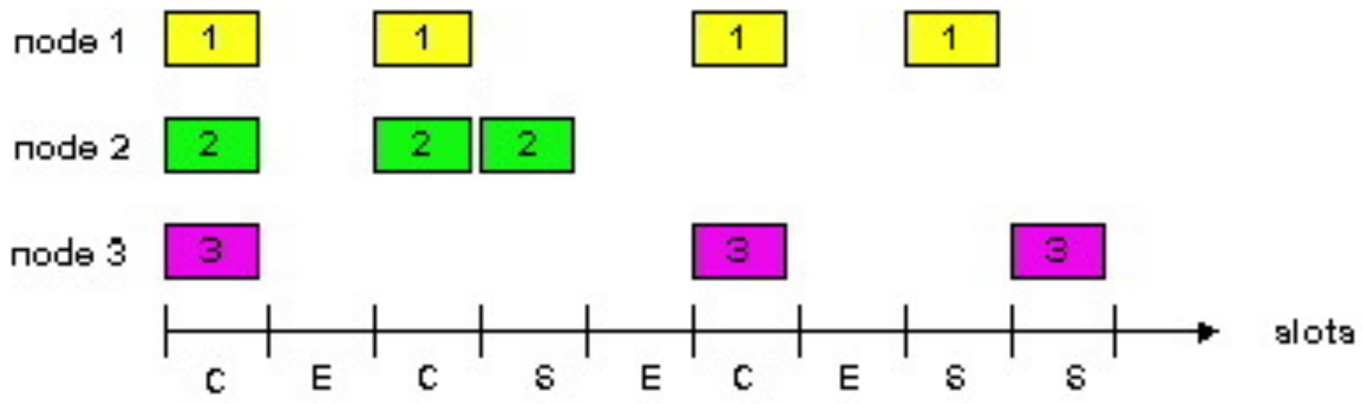
Assumptions

- All frames same size
- Time divided into equal slots (time to transmit a frame)
- Nodes start to transmit frames only at start of slots
- Nodes are synchronized
- If two or more nodes transmit, all nodes detect collision

Operation

- When node obtains fresh frame, transmits in next slot
- No collision: node can send new frame in next slot
- Collision: node retransmits frame in each subsequent slot with probability *p* until success

Slotted ALOHA



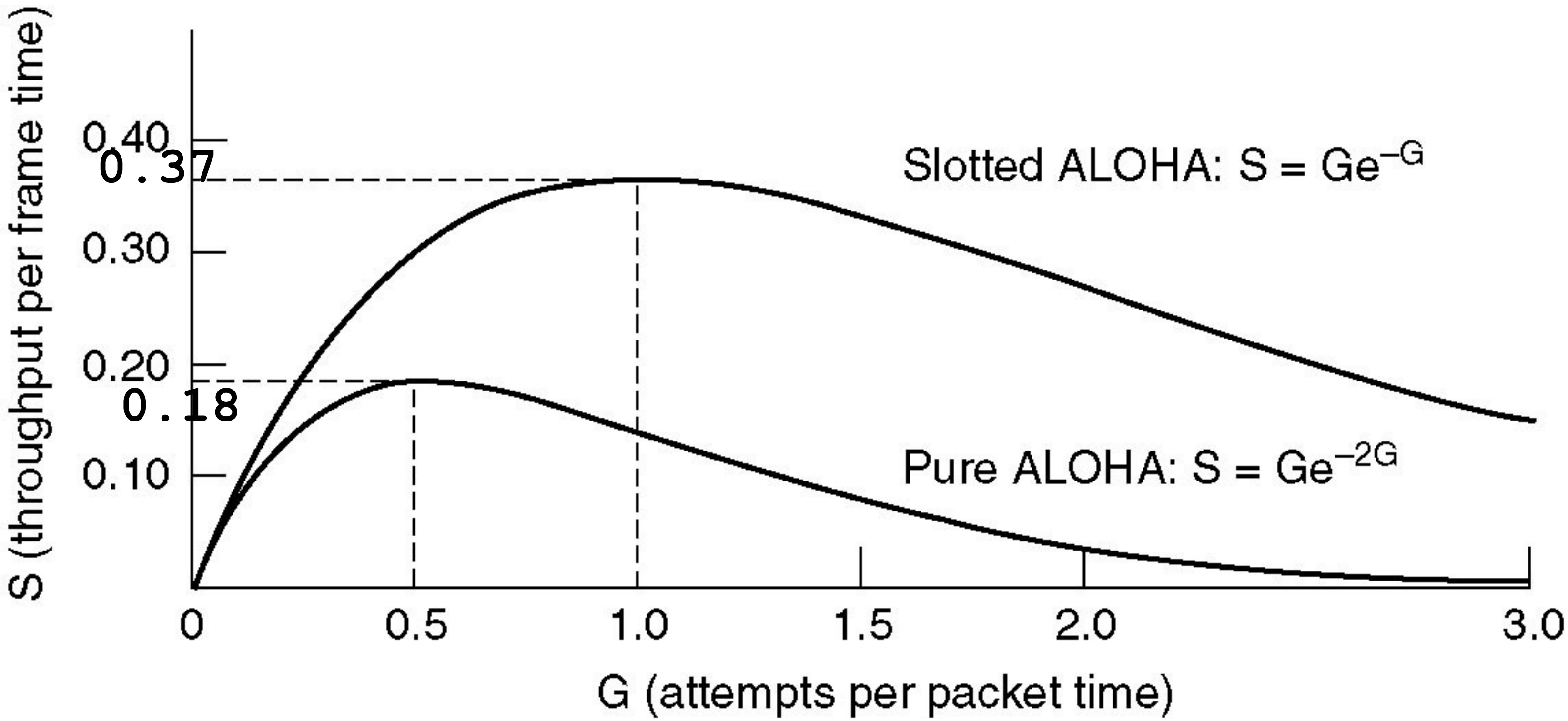
Pros

- Single active node can continuously transmit at full rate of channel
- Highly decentralized: only slots in nodes need to be in sync
- Simple

Cons

- Collisions, wasting slots
- Idle slots
- Nodes may be able to detect collision in less than time to transmit packet
- Clock synchronization

ALOHA vs. Slotted ALOHA



G is a measure of the aggregate offered load

CSMA (Carrier Sense Multiple Access)

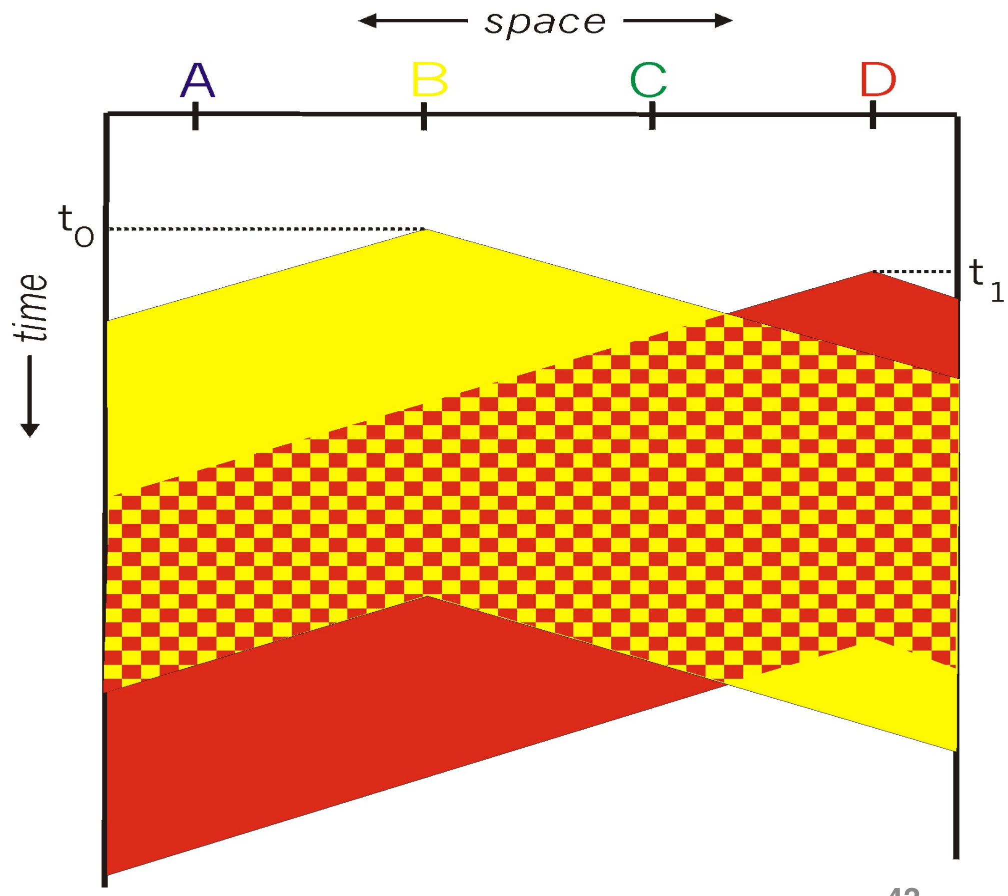
- Collisions hurt the efficiency of ALOHA protocol
  - At best, channel is useful 37% of the time
- ALOHA: transmit before listen
- CSMA: listen before transmit
  - If channel sensed idle: transmit entire frame
  - If channel sensed busy, defer transmission
- Human analogy: don't interrupt others!

CSMA (Carrier Sense Multiple Access)

CSMA: Listen before transmit

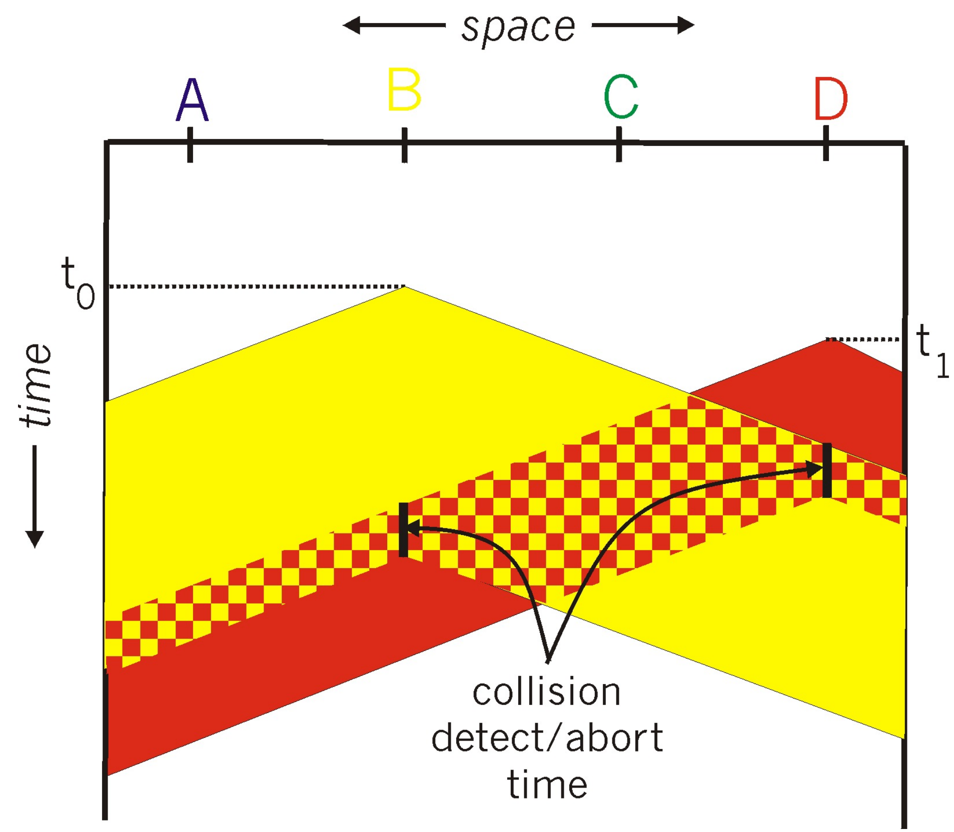
Collisions *can* still occur: propagation delay means two nodes may not hear each other's transmission

Collision: entire packet transmission time wasted



CSMA/CD Collision Detection

- Detect collision
  - Abort transmission
  - Jam the link
- Wait random time
  - Transmit again
- Hard in wireless
  - Must receive data while transmitting



Three Ways to Share the Media

- Channel partitioning MAC protocols:
  - Share channel efficiently and fairly at high load
  - Inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!

- "Taking turns" protocols
  - Eliminates empty slots without causing collisions
  - Vulnerable to failures (e.g., failed node or lost token)

- Random access MAC protocols
  - Efficient at low load: single node can fully utilize channel
  - High load: collision overhead

Comparing the Three Approaches

- Channel partitioning is
  (a) Efficient/fair at high load, inefficient at low load
  (b) Inefficient at high load, efficient/fair at low load
- "Taking turns"
  (a) Inefficient at high load
  (b) Efficient at all loads
  (c) Robust to failures
- Random access
  (a) Inefficient at low load
  (b) Efficient at all load
  (c) Robust to failures