CS 332
Computer Networks
Link Layer (1)

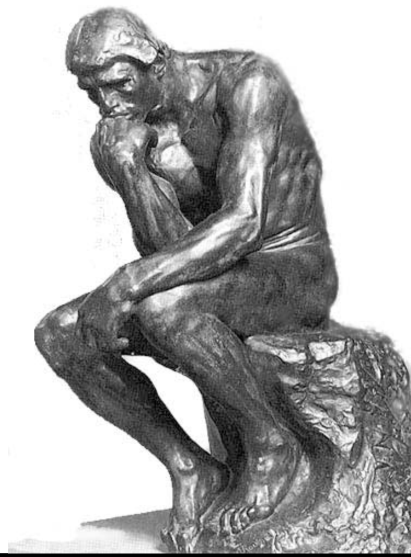
Professor Szajda

Last Time

- We talked about intra-AS routing protocols:
  - Which routing algorithm is used in RIP? OSPF?
  - What techniques allow OSPF to scale?
- We also talked about THE inter-AS routing protocol:
  - What two sub-protocols make up BGP?
  - How does BGP avoid routing loops?
  - Are there any security issues?

Aren't We Finished?

- This class is called "Computer Networks". What else is there below the network layer?
- Believe it or not, how you move packets on each hop is a non-trivial task.
  - Wireless is much different than Ethernet. What about the core?
- Looks like there is more to think about...



Chapter 5: The Data Link Layer

Our goals:

- understand principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
  - reliable data transfer, flow control: done!
- instantiation and implementation of various link layer technologies

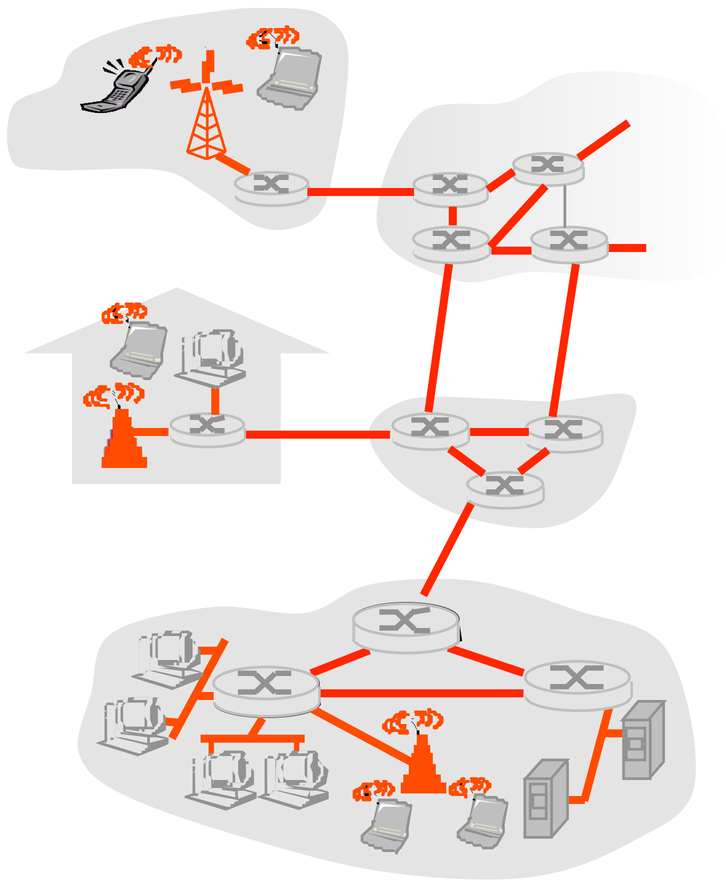
Link Layer

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3 Multiple access protocols
- 5.4 Link-Layer Addressing
- 5.5 Ethernet
- 5.6 Hubs and switches
- 5.7 PPP
- 5.8 Link Virtualization: ATM and MPLS

Link Layer: Introduction

Some terminology:

- hosts and routers are nodes
- communication channels that connect adjacent nodes along communication path are links
  - wired links
  - wireless links
  - LANs
- layer-2 packet is a frame, encapsulates datagram



data-link layer has responsibility of transferring datagram from one node to adjacent node over a link

Link layer: context

- Datagram transferred by different link protocols over different links:
  - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- Each link protocol provides different services
  - e.g., may or may not provide rdt over link

transportation analogy

- trip from Princeton to Lausanne
  - limo: Princeton to JFK
  - plane: JFK to Geneva
  - train: Geneva to Lausanne
- tourist = datagram
- transport segment = communication link
- transportation mode = link layer protocol
- travel agent = routing algorithm

Link Layer Services

- Framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - channel access if shared medium
  - "MAC" addresses used in frame headers to identify source, dest
    - different from IP address!
- Reliable delivery between adjacent nodes
  - we learned how to do this already (chapter 3)!
  - seldom used on low bit error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?

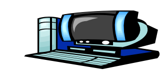
Link Layer Services (more)

- Flow Control:
  - pacing between adjacent sending and receiving nodes
- Error Detection:
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame

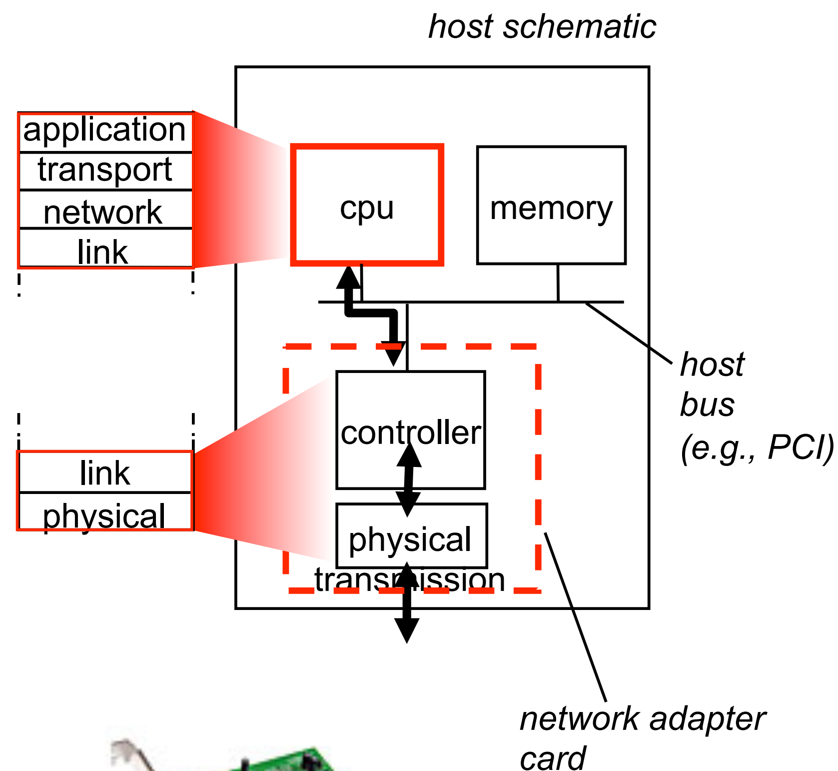
- Error Correction:
  - receiver identifies and corrects bit error(s) without resorting to retransmission
- Half-duplex and full-duplex
  - with half duplex, nodes at both ends of link can transmit, but not at same time

Where is the link layer implemented?

- in each and every host

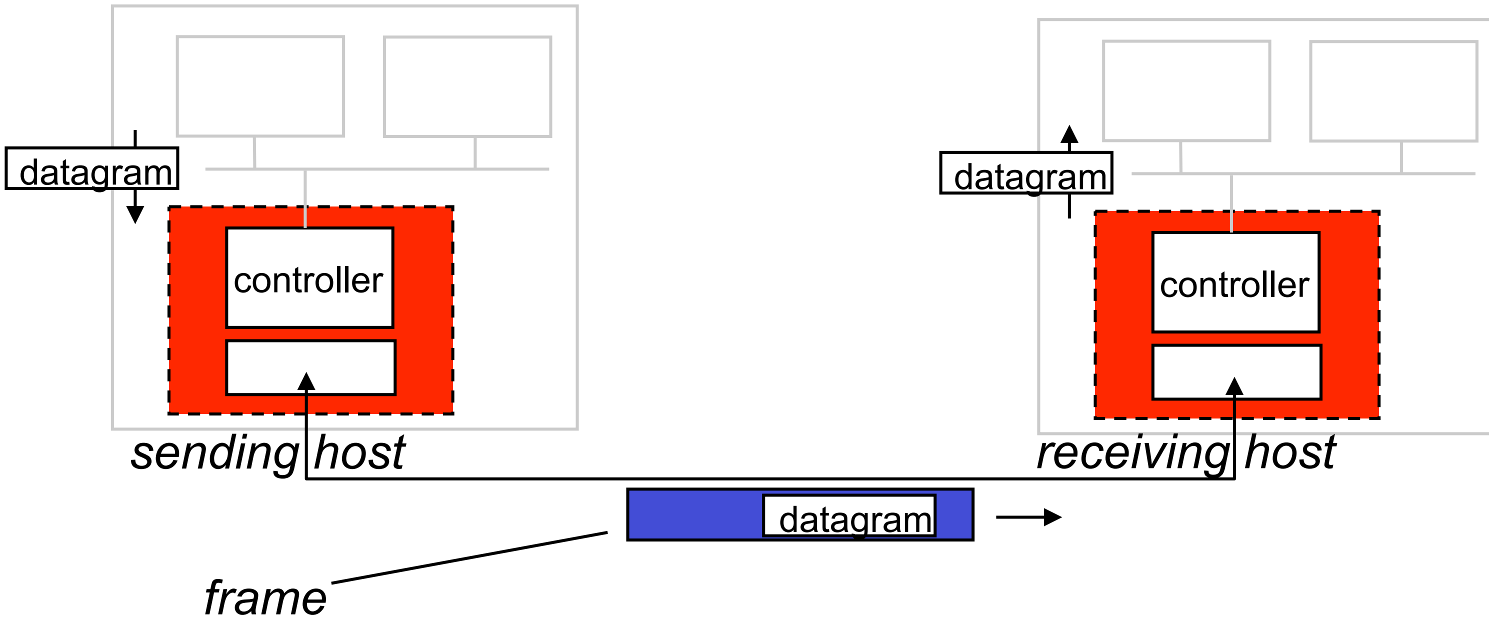


- link layer implemented in "adaptor" (aka *network interface card* NIC)
  - Ethernet card, PCMCI card, 802.11 card
  - implements link, physical layer



- attaches into host's system buses
- combination of hardware, software, firmware

Adaptors Communicating



- sending side:
  - encapsulates datagram in a frame
  - adds error checking bits, rdt, flow control, etc.
- receiving side
  - looks for errors, rdt, flow control, etc
  - extracts datagram, passes to rcving node

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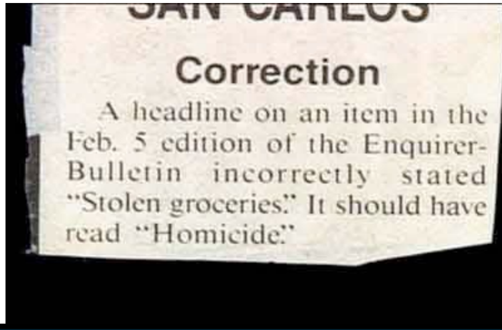


SAN CARLOS

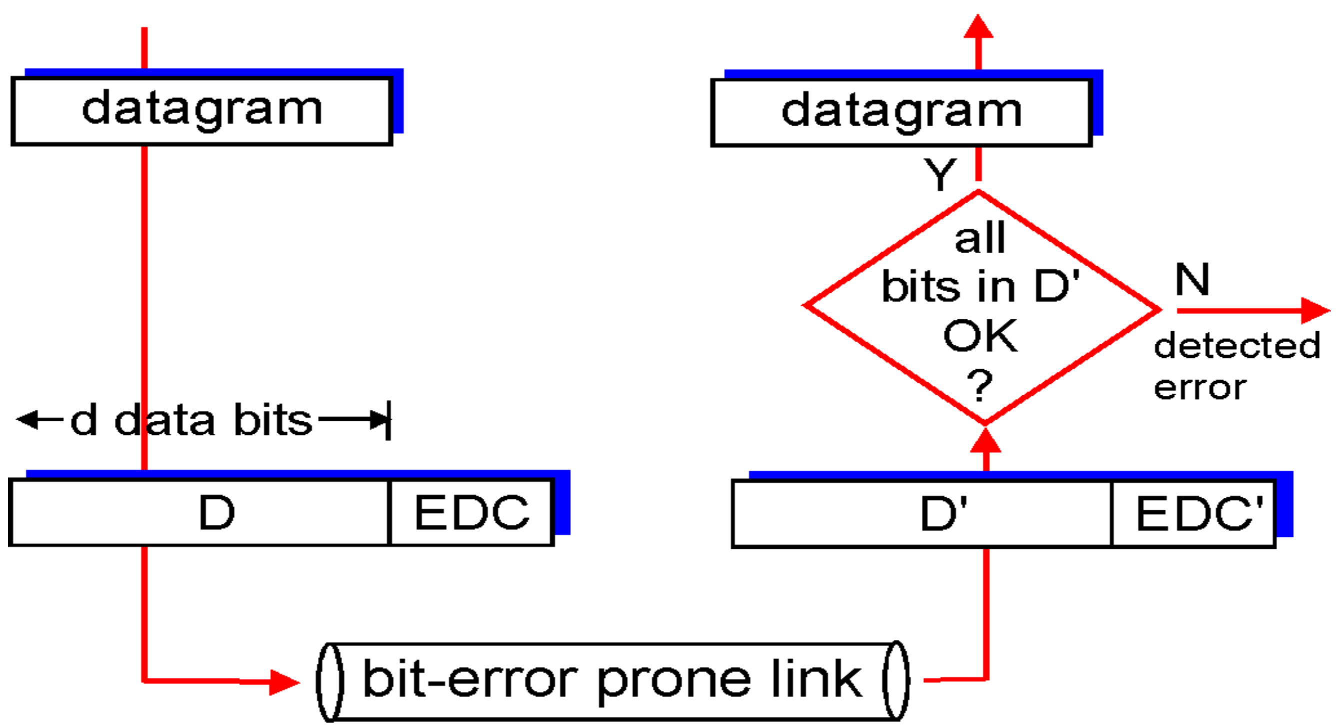
Correction

A headline on an item in the Feb. 5 edition of the Enquirer-Bulletin incorrectly stated "Stolen groceries." It should have read "Homicide."

Error Detection

EDC= Error Detection and Correction bits (redundancy)
D = Data protected by error checking, may include header fields

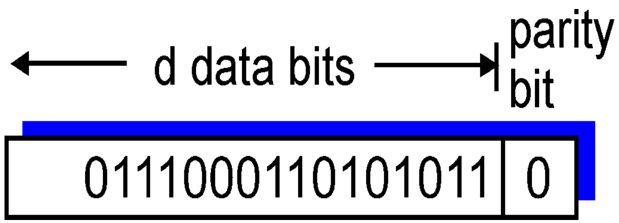
- Error detection not 100% reliable!
  - protocol may miss some errors, but rarely
  - larger EDC field yields better detection and correction



Parity Checking

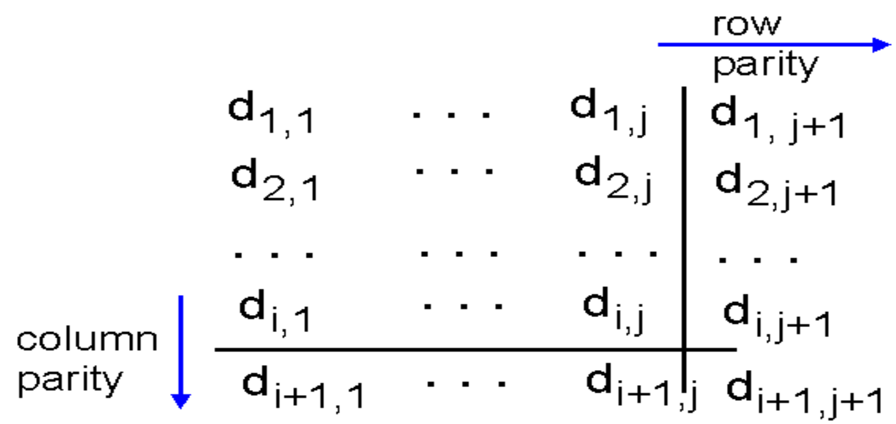
Single Bit Parity:

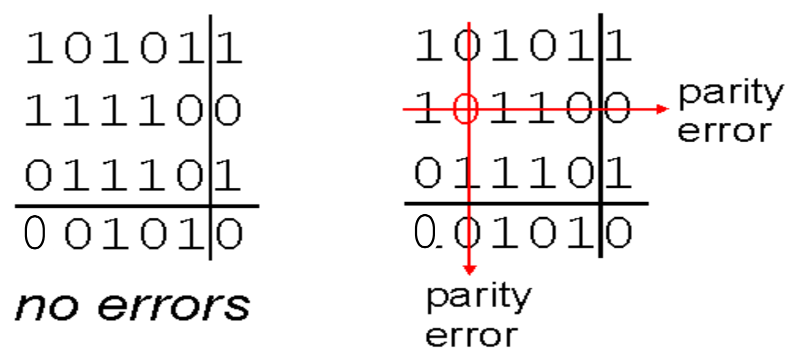
Detect single bit errors



Two Dimensional Bit Parity:

Detect and correct single bit errors





no errors

correctable single bit error

Internet checksum

Goal: detect "errors" (e.g., flipped bits) in transmitted segment (note: used at transport layer only)

Sender:

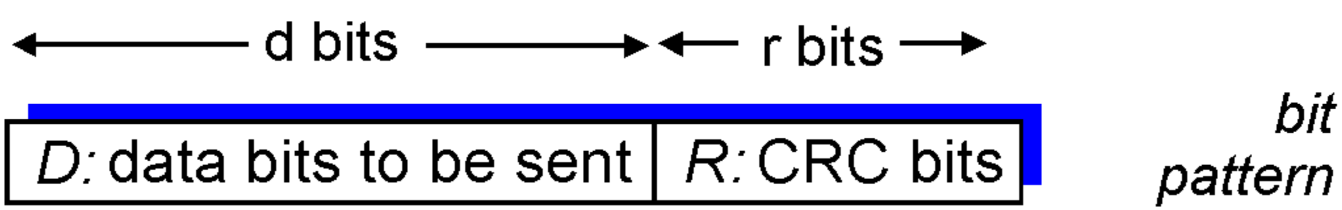
- treat segment contents as sequence of 16-bit integers
- checksum: addition (1's complement sum) of segment contents
- sender puts checksum value into UDP checksum field

Receiver:

- compute checksum of received segment
- check if computed checksum equals checksum field value:
  - NO - error detected
  - YES - no error detected. But maybe errors nonetheless? More later ….

Checksumming: Cyclic Redundancy Check

- 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 (ATM, HDLC)



$$D * 2^r \quad XOR \quad R$$

mathematical formula

CRC Example

Want:

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

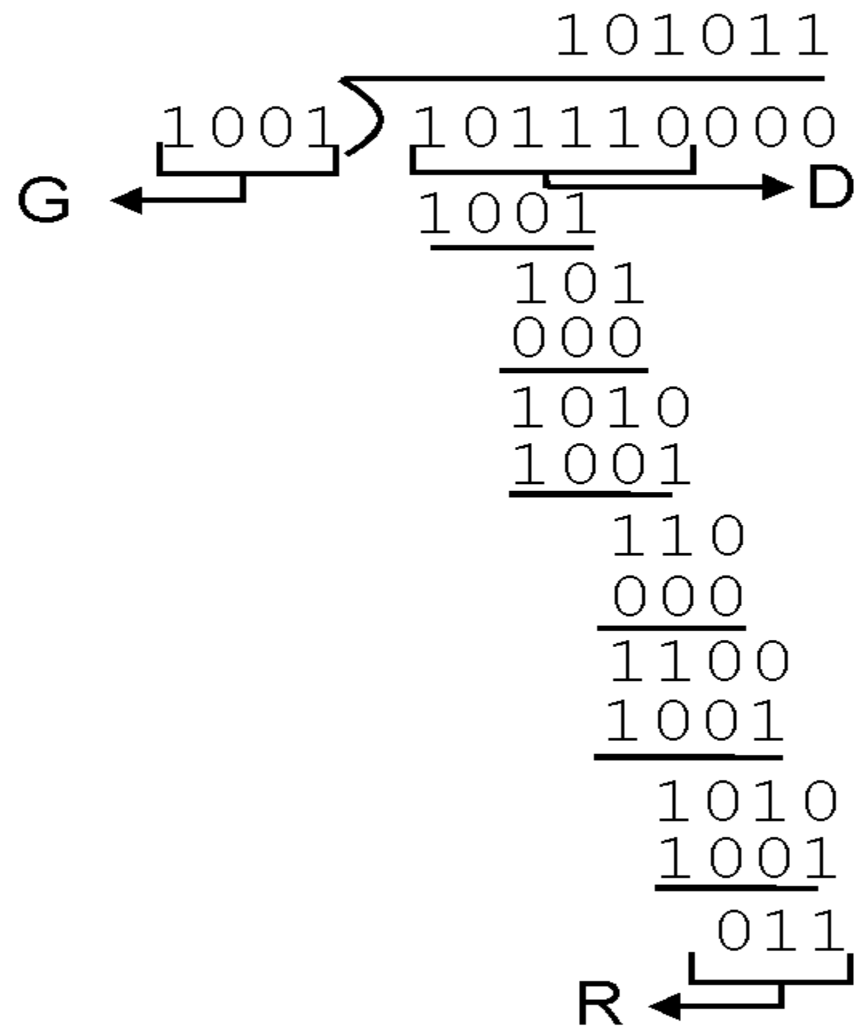
equivalently:

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

equivalently:

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

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



CRC Facts

- International Standards Defined for 8, 12, 16, and 32 bit generators G
  - $G_{CRC\text{-}32}$ = 1 00000100 11000001 00011101 10110111
- Detects burst errors of fewer than r + 1 bits
  - All consecutive bit errors of length <= r will be detected
  - Burst of length greater than r + 1 are detected with probability $1 - (0.5)^r$
  - Can detect any odd number of bit errors
- See Prof. Davis for details

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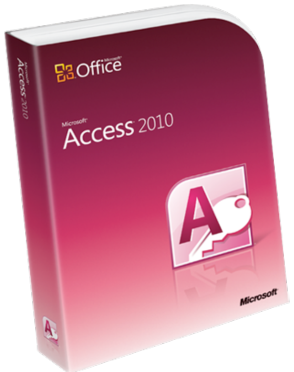
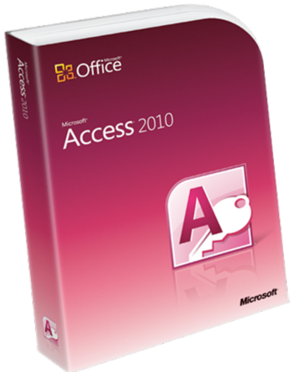
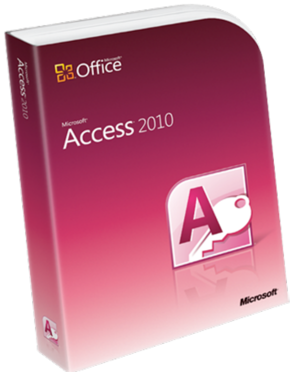
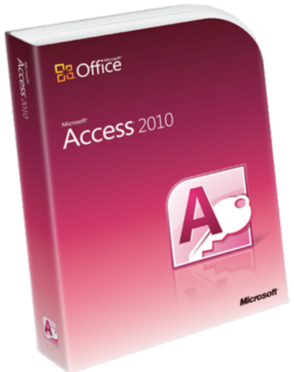




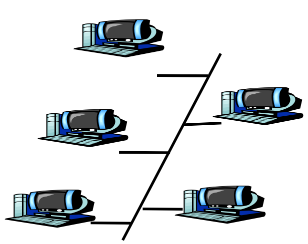




Multiple Access Links and Protocols

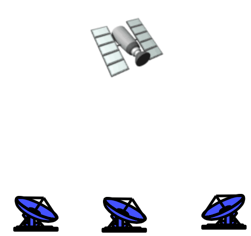
Two types of "links":

- point-to-point
  - PPP for dial-up access
  - point-to-point link between Ethernet switch and host
- broadcast (shared wire or medium)
  - Old-fashioned Ethernet
  - upstream HFC (Hybrid Fiber-Coaxial)
  - 802.11 wireless LAN



shared wire (e.g., cabled Ethernet)

shared RF (e.g., 802.11 WiFi)



shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

Multiple Access protocols

- single shared broadcast channel
- two or more simultaneous transmissions by nodes: interference
  - collision if node receives two or more signals at the same time

multiple access protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination

Ideal Multiple Access Protocol

Broadcast channel of rate R bps

1. When one node wants to transmit, it can send at rate R.
2. When M nodes want to transmit, each can send at average rate R/M
3. Fully decentralized:
    - no special node to coordinate transmissions
    - no synchronization of clocks, slots
4. Simple

MAC Protocols: a taxonomy

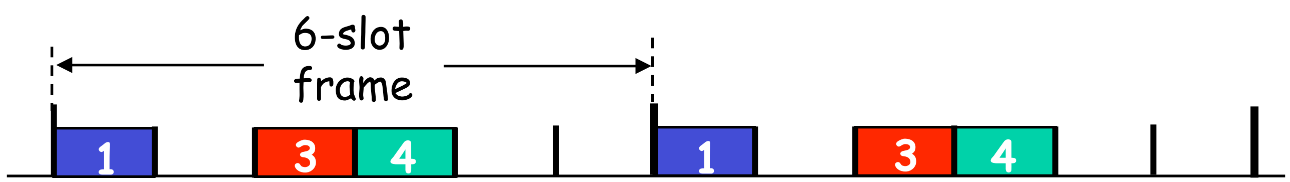
Three broad classes:

- Channel Partitioning
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - allocate piece to node for exclusive use
- Random Access
  - channel not divided, allow collisions
  - "recover" from collisions
- "Taking turns"
  - Nodes take turns, but nodes with more to send can take longer turns

Channel Partitioning MAC protocols: TDMA

TDMA: time division multiple access

- access to channel in "rounds"
- each station gets fixed length slot (length = pkt trans time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have pkt, slots 2,5,6 idle

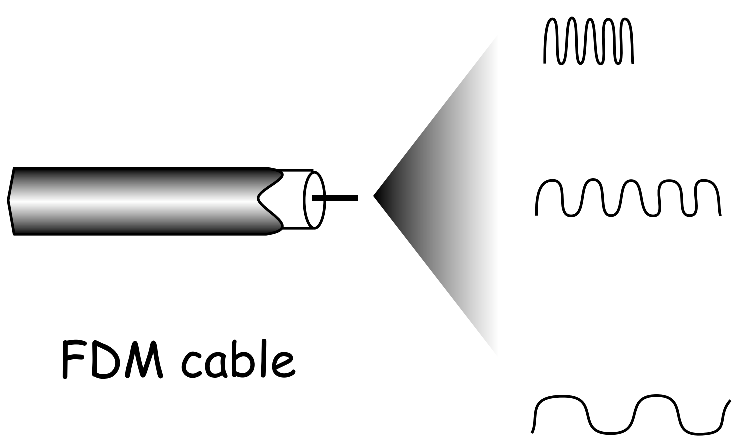


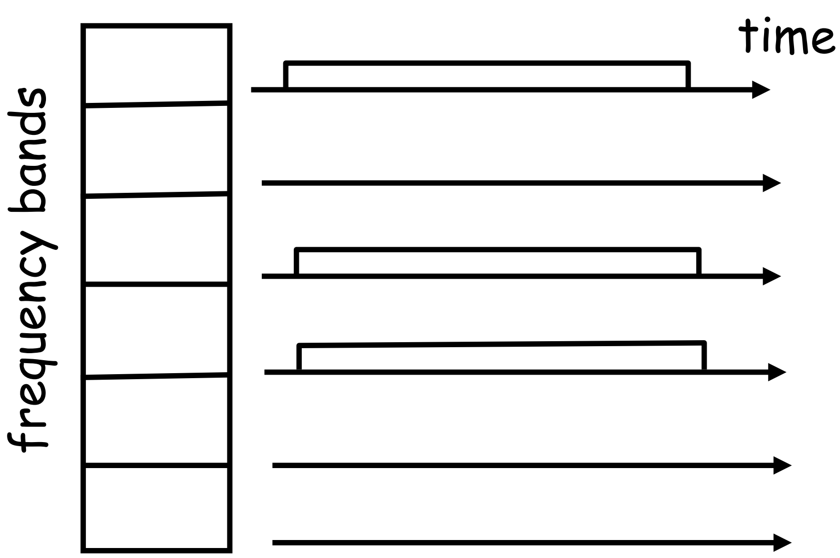
- GSM cellular uses an 8-slot TDM service model.

Channel Partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle
- example: 6-station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle





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 (e.g., via delayed retransmissions)
- Examples of random access MAC protocols:
  - slotted ALOHA
  - ALOHA
  - CSMA, CSMA/CD, CSMA/CA

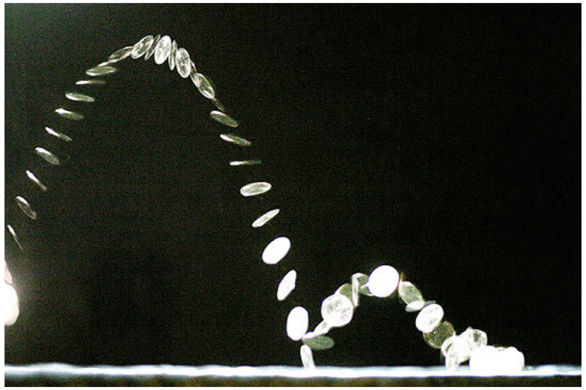
Slotted ALOHA

Assumptions

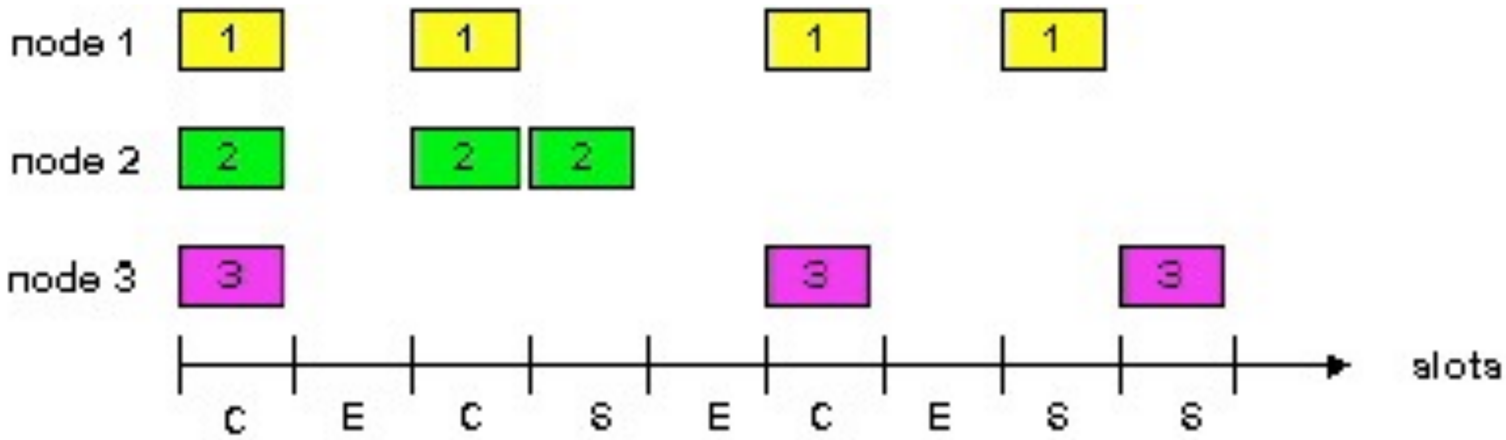
- all frames same size
- time is divided into equal size slots, time to transmit 1 frame
- nodes start to transmit frames only at beginning of slots
- clocks are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

Operation

- when node obtains fresh frame, it transmits in next slot
- no collision, node successfully transmitted the frame
- if collision, node retransmits frame in each subsequent slot with prob. 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

Slotted Aloha efficiency

Efficiency is the long-run fraction of successful slots when there are many nodes, each with many frames to send

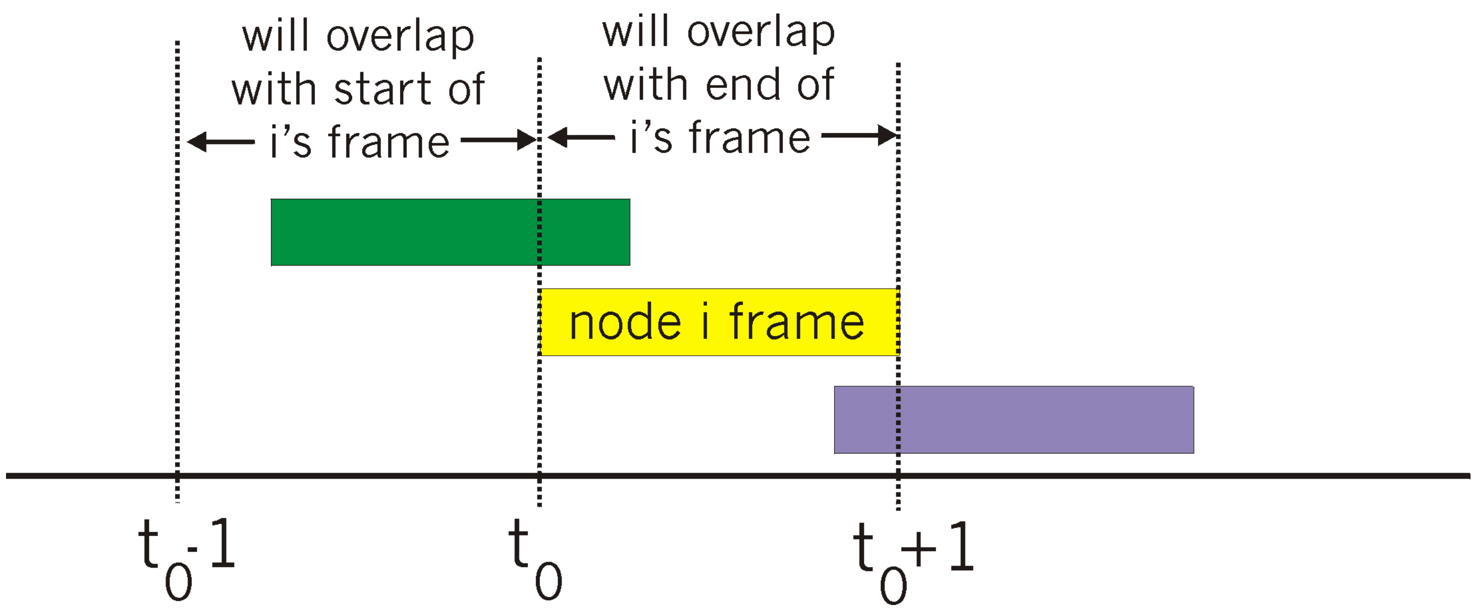
- Suppose N nodes with many frames to send, each transmits in slot with probability p
- prob that node 1 has success in a slot $= p(1-p)^{N-1}$
- prob that any node has a success $= Np(1-p)^{N-1}$

- For max efficiency with N nodes, find p* that maximizes $Np(1-p)^{N-1}$
- For many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives $1/e = .37$

At best: channel used for useful transmissions 37% of time!

Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization
- when frame first arrives
  - transmit immediately
- collision probability increases:
  - frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$



Pure Aloha efficiency

P(success by given node) = P(node transmits) $\cdot$

P(no other node transmits in $[p_0\text{-}1, p_0]$ $\cdot$

P(no other node transmits in $[p_0\text{-}1, p_0]$

$= p \cdot (1\text{-}p)^{N-1} \cdot (1\text{-}p)^{N-1}$

$= p \cdot (1\text{-}p)^{2(N-1)}$

… choosing optimum p and then letting n -> infty ...

$= 1/(2e) = .18$

Even worse than slotted Aloha!

A closer look at the math ...

- We can model both ALOHA and Slotted ALOHA by assuming a load G arriving as a Poisson distribution
  - Throughput = load x Prob[success] ($T = G \cdot P_0$), where

$$P(k) = \frac{G^k e^{-G}}{k!} \qquad P(0) = e^{-G}$$ (for one interval)

  - In ALOHA, one frame can collide with 2 other frames!
    - Therefore, we use: $P_0 = e^{-2G} \Rightarrow T = G \cdot e^{-2G}$
  - However, in Slotted ALOHA, only 1 collision
    - Therefore,

$$T = G \cdot e^{-G}$$

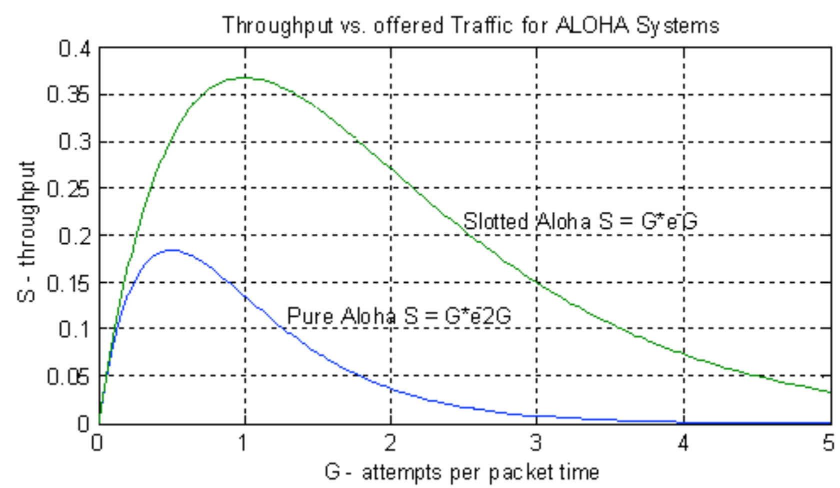


Image from: http://www.etcs.ipfw.edu/~lin/ECET581_CS590/lectures/Lin_Lect_11_WSN_MAC%20Protocols.html

So how many slots until I can transmit?

- The probability of success on the kth try is:

$$P_k = e^{-G}(1 - e^{-G})^{k-1}$$

- Hence, the expected number of slots is:

$$E = \sum_{k=1}^{\infty} kP_k = \sum_{k=1}^{\infty} ke^{-G}(1 - e^{-G})^{k-1} = e^G$$

- If each slot is 1 second, and it takes 3 tries, what is the average delay until the start of transmission?

CSMA (Carrier Sense Multiple Access)

CSMA: listen before transmit:

If channel sensed idle: transmit entire frame

- If channel sensed busy, defer transmission

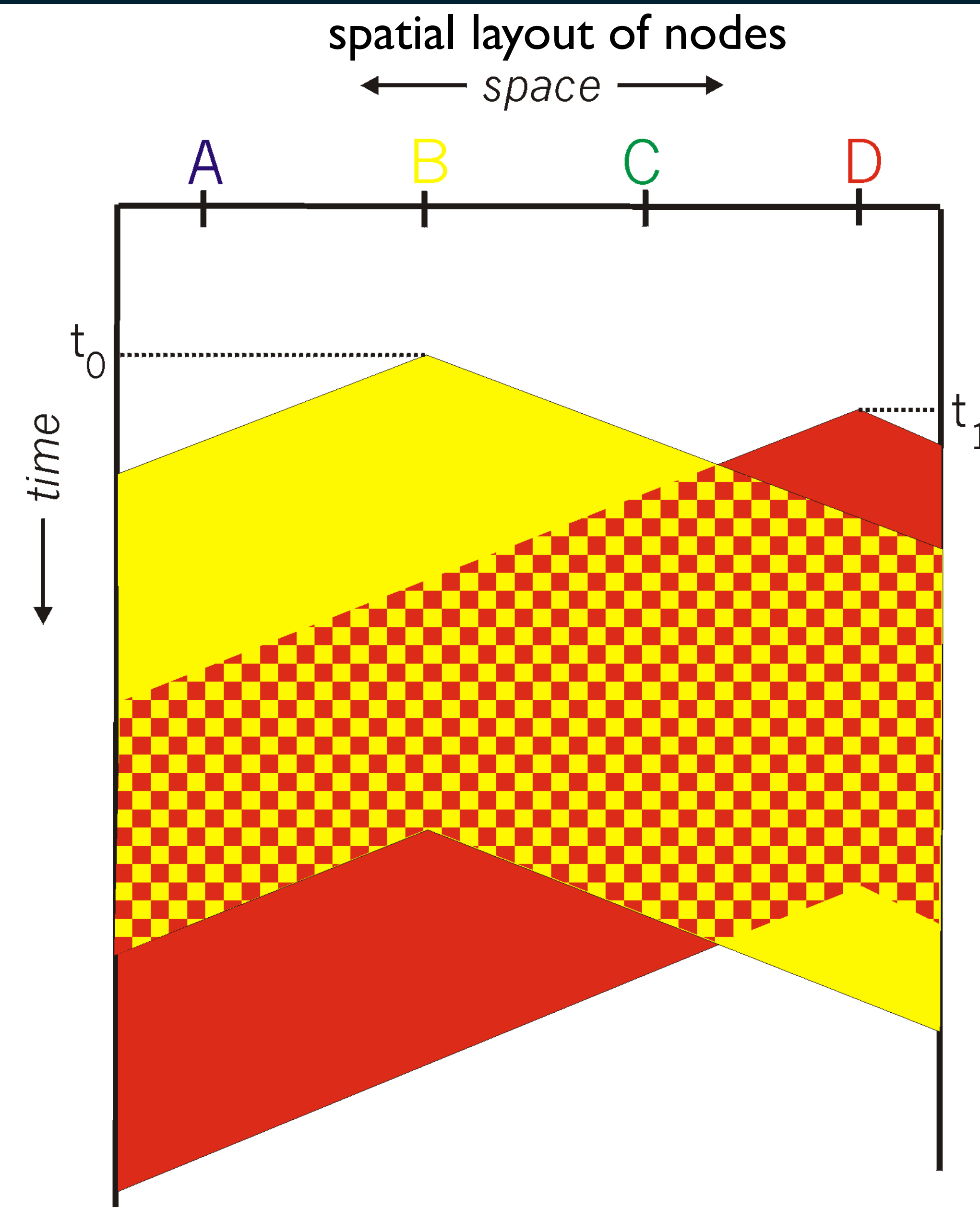
- Human analogy: don't interrupt others!

CSMA collisions

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

collision:
entire packet transmission time wasted

note:
role of distance & propagation delay in determining collision probability



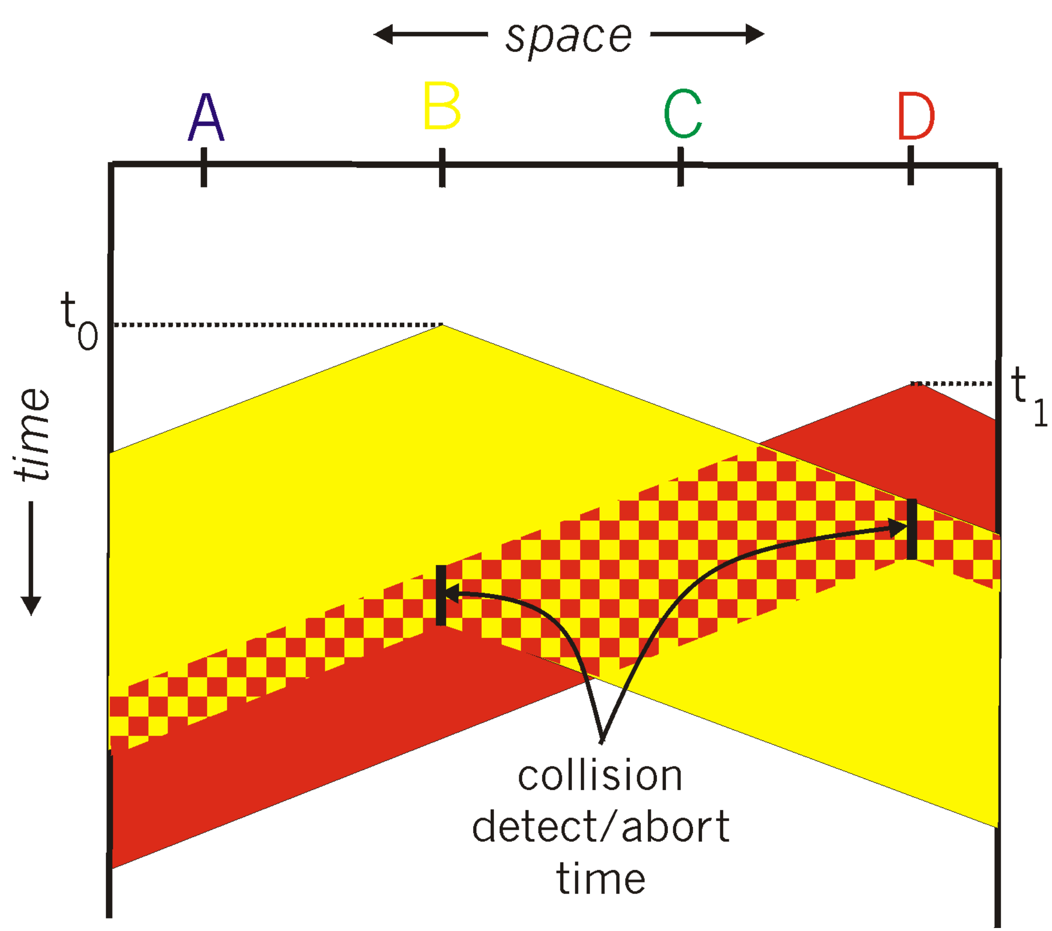
CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA

- collisions detected within short time
- colliding transmissions aborted, reducing channel wastage

- collision detection:
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: receiver shut off while transmitting
- human analogy: the polite conversationalist

CSMA/CD collision detection



“Taking Turns” MAC protocols

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!

Random access MAC protocols

- efficient at low load: single node can fully utilize channel
- high load: collision overhead

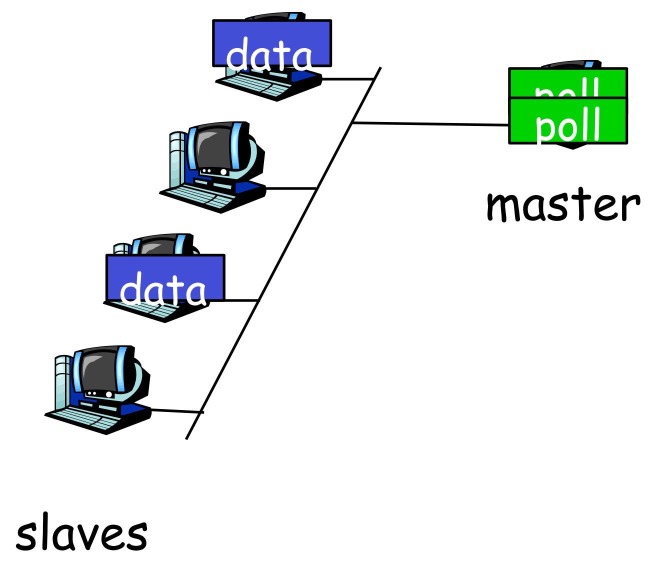
“taking turns” protocols

look for best of both worlds!

“Taking Turns” MAC protocols

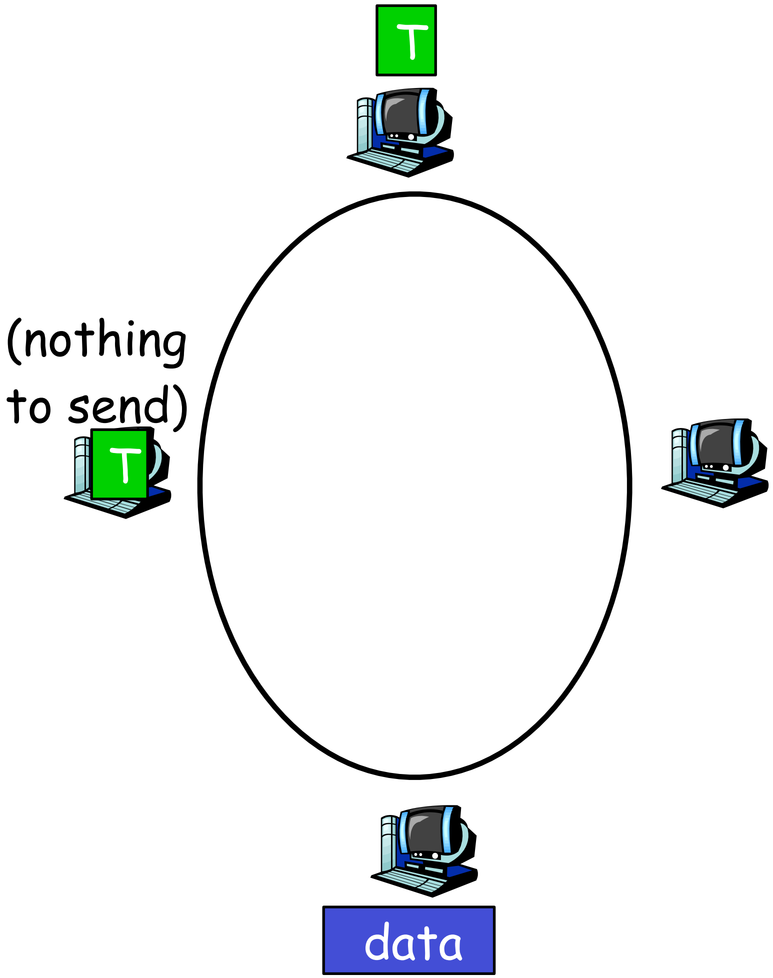
Polling:

- master node “invites” slave nodes to transmit in turn
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)



“Taking Turns” MAC protocols

- *Token passing:*
  - control token passed from one node to next sequentially.
  - token message
  - concerns:
    - token overhead
    - latency
    - single point of failure (token)



Summary of MAC protocols

- What do you do with a shared media?
  - Channel Partitioning, by time, frequency or code
    - Time Division, Frequency Division
  - Random partitioning (dynamic),
    - ALOHA, S-ALOHA, CSMA, CSMA/CD
    - carrier sensing: easy in some technologies (wire), hard in others (wireless)
    - CSMA/CD used in Ethernet
    - CSMA/CA used in 802.11
  - Taking Turns
    - polling from a central site, token passing

LAN technologies

Data link layer so far:

- services, error detection/correction, multiple access

Next: LAN technologies

- addressing
- Ethernet
- hubs, switches
- PPP

Next Time

- Read Sections 5.4-5.6
  - Link Layer Addressing
  - Ethernet
  - LAN topologies