COMP 3234B
Computer and Communication Networks

2nd semester 2023-2024

Link Layer (II)

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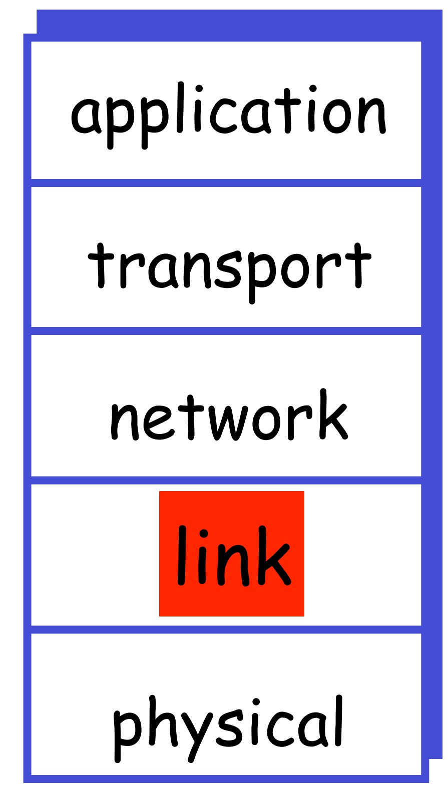
Roadmap

Link layer

- Principles behind link-layer services (ILO1,2,3)
  - error detection and correction
  - multiple access protocols
  - link-layer addressing
- Implementation of various link-layer technologies (ILO2,3)
  - Ethernet
  - switches
  - 802.11 wireless LAN (WiFi)
  - …



Multiple access

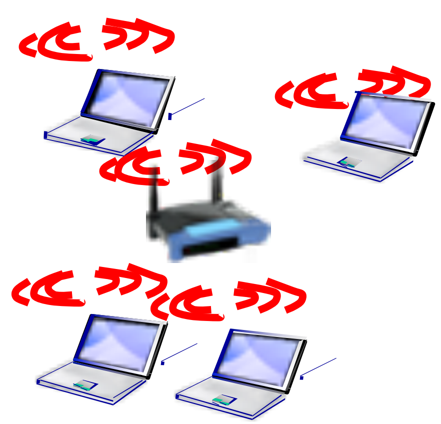
- Two types of “links”
  - point-to-point: a single sender at one end and a single receiver at the other end

    e.g., a dial-up telephone line that connects user home to ISP

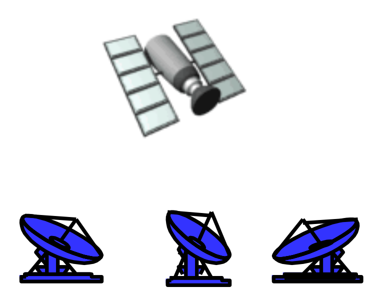
    point-to-point link between Ethernet switch and host
  - broadcast : multiple senders and receivers connected to the same communication channel (shared wire or medium)

    e.g., old-fashioned Ethernet, Wireless LAN (802.11 WiFi).

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 (cont'd)

- Multiple access problem
  - In a single shared broadcast channel, if two or more nodes transmit simultaneously, collision occurs at receivers which receive two or more signals at the same time. Then

    none of the received frames can be recovered

    =>all frames involved in the collision are lost

- Multiple access protocol (or Medium Access Control Protocol, or MAC protocol)
  - algorithm that determines how nodes share channel, i.e., determines when a node can transmit
  - communication about channel sharing uses channel itself

Multiple access protocols

Ideal multiple access protocol should achieve: in a broadcast channel of rate R bps

1. when only one node wants to transmit, it can send at rate R.
2. when N nodes want to transmit, each can send at average rate R/N
3. fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. simple, inexpensive to implement

Multiple access protocols

- 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 protocols: TDMA

- TDMA: time division multiple access
  - Same idea as Time Division Multiplexing (TDM) (page 30 in 2_Introduction_COMP3234B_s2024.pdf)

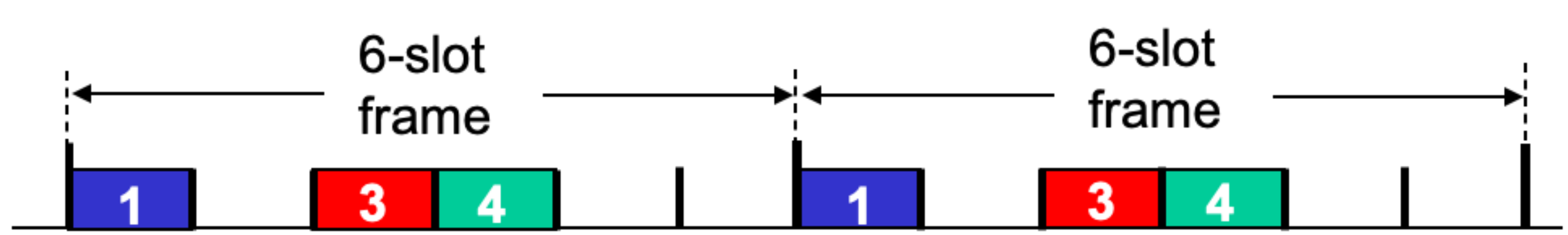
    divide time into frames and frame into time slots

    time slot length = one packet transmission time
  - senders access channel in "rounds"

    each sender gets a time slot in each frame

    unused slots go idle
  - disadvantage

    each node is limited to an average rate of R/N bps and must wait for its time slot



Example: 6-node LAN, 1,3,4 have packets, 2,5,6 idle

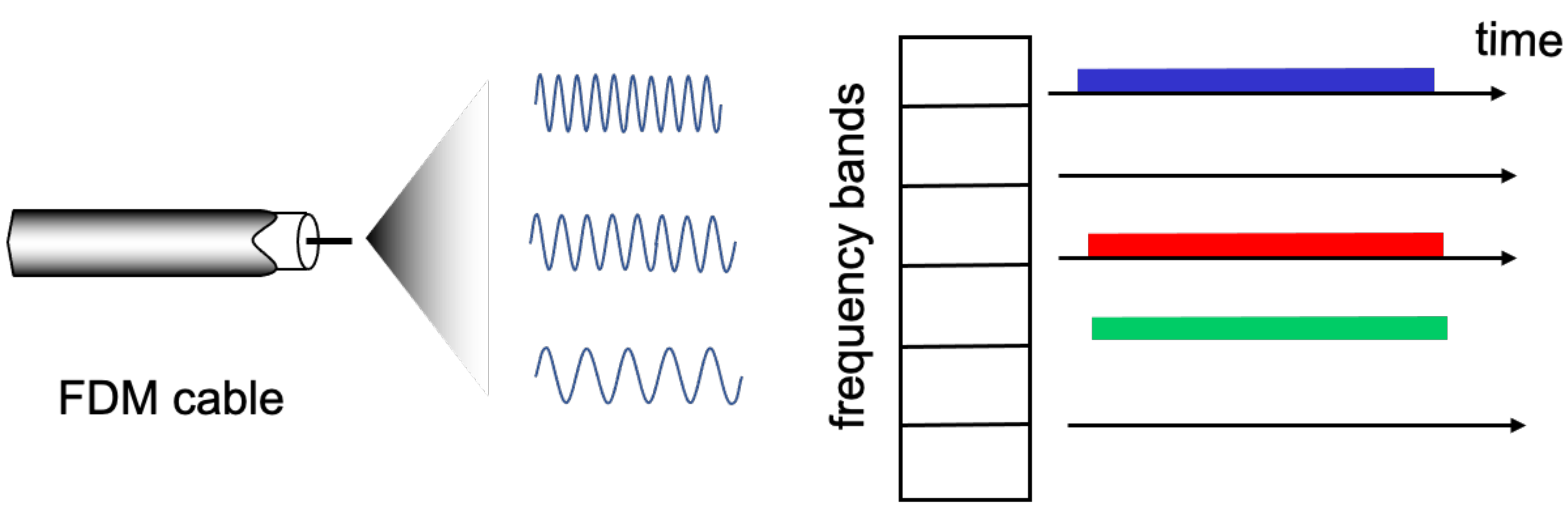
Channel partitioning protocols: FDMA

- FDMA: frequency division multiple access
  - Same idea as Frequency Division Multiplexing (FDM) (page 29 in 2_Introduction_COMP3234B_s2024.pdf)

    divide channel spectrum into frequency bands
  - each sender assigned one frequency band

    unused transmission time in an allocated frequency band goes idle
  - disadvantage

    each node is limited to an average rate of R/N bps



example: 6-node LAN, 1,3,4 have packets, 2,5,6 idle

Random access protocols

- Basic idea:
  - When a node has a frame to send, it transmits at full channel data rate R
    without *a priori* coordination among nodes
  - If two or more nodes are concurrently transmitting, collision occurs; each node repeatedly retransmits its frame, until the frame is correctly received
    not necessarily immediately retransmit, but may wait a random delay

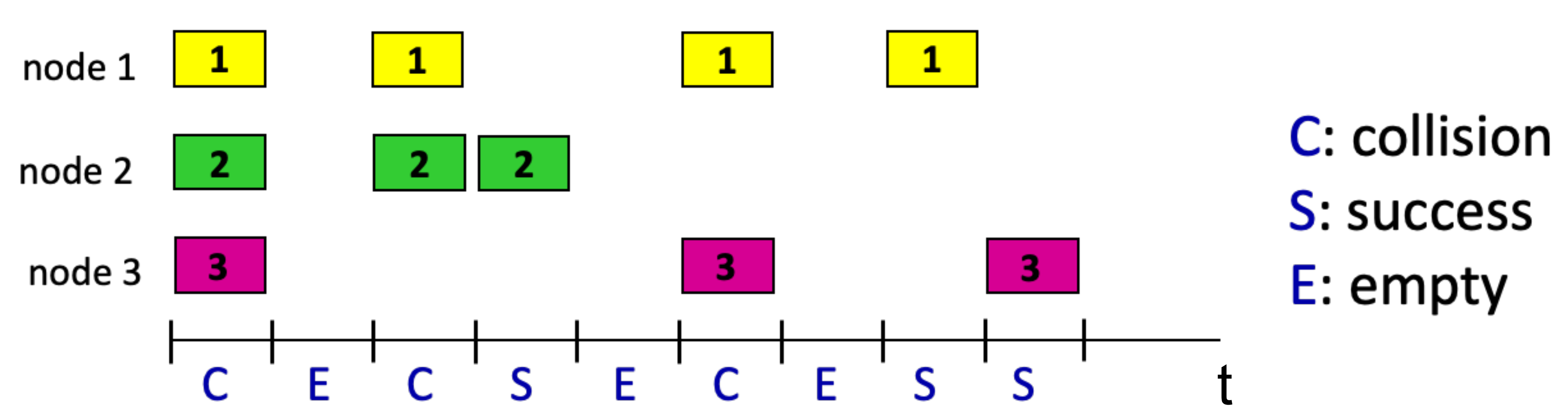
- Protocol needs to specify
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)

- Examples of random access protocols
  - Slotted Aloha › Aloha
  - CSMA, CSMA/CD, CSMA/CA (used in 802.11 WiFi)

Slotted Aloha

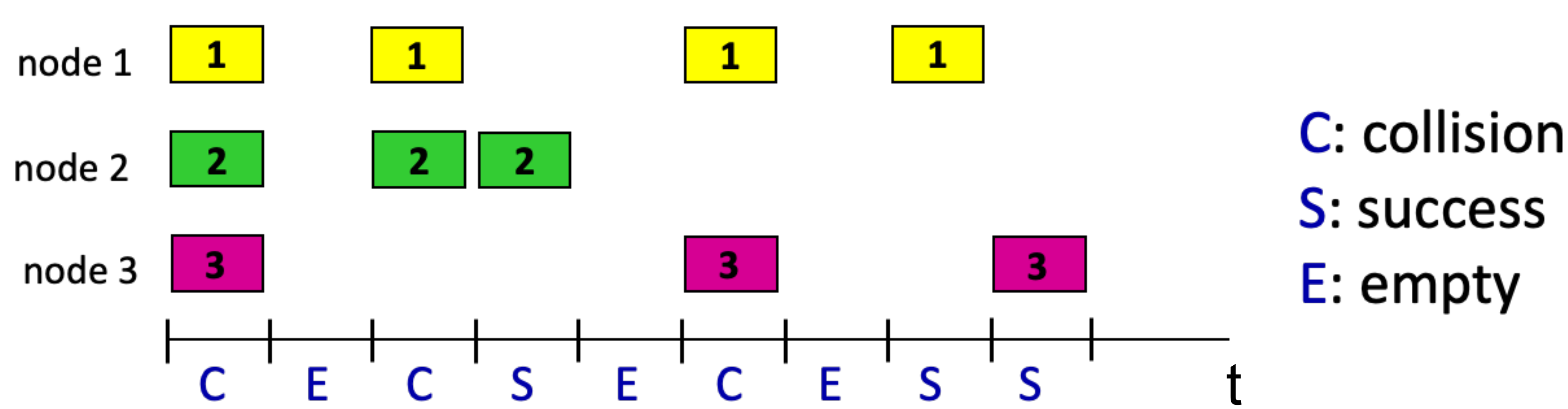
- Assumption
  - all frames have the same size
  - time divided into equal-size slots (equal to time to transmit 1 frame)
  - nodes start to transmit only at the beginning of a slot
  - nodes are synchronized
  - if 2 or more nodes transmit in a slot, all nodes detect collision

- Basic protocol
  - when a node obtains a frame, it transmits in the next slot
  - if no collision detected, node can send new frame in the next slot
  - if collision detected, node retransmits frame in each subsequent slot with probability p (or wait for a frame transmission time with probability 1-p), until success



Slotted Aloha: discussions

- Advantage
  - single active node can continuously transmit at full rate of channel R
  - highly decentralized: only slots in nodes need to be in sync
  - simple to implement
- Disadvantage
  - collisions, wasting slots
  - idle slots
  - clock synchronization
  - nodes may detect collision in less than a frame transmission time, but may only retransmit in the next time slot
    efficiency is not high



Slotted Aloha: efficiency

- Efficiency of a slotted multiple access protocol
  - fraction of successful slots over long run of the protocol, when there are a large number of active nodes, each having a large number of frames to send
- Calculating efficiency
  - suppose N nodes, each transmits in a slot with probability p

    P(node i has success in a slot) = $p(1-p)^{N-1}$

    P(any node has a success in a slot) = $Np(1-p)^{N-1}$ → channel efficiency
- Calculating max efficiency with a large number of active nodes
  - find p* that maximizes $Np(1-p)^{N-1}$ and take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity:

    Max efficiency = 1/e = 0.37

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

<=>

effective throughput of the channel is only 0.37R!

Derivation of maximum efficiency of slotted Aloha:

Let $E(p)$=P(any node has a success in a slot)=$Np(1-p)^{N-1}$

$$\begin{aligned} E'(p) &= N(1-p)^{N-1} - Np(N-1)(1-p)^{N-2} \\ &= N(1-p)^{N-2}((1-p) - p(N-1)) \end{aligned}$$

$$E'(p) = 0 \Rightarrow p^* = \frac{1}{N}$$

$$E(p^*) = N\frac{1}{N}(1-\frac{1}{N})^{N-1} = (1-\frac{1}{N})^{N-1} = \frac{(1-\frac{1}{N})^N}{1-\frac{1}{N}}$$

$$\lim_{N\to\infty}(1-\frac{1}{N}) = 1 \qquad \lim_{N\to\infty}(1-\frac{1}{N})^N = \frac{1}{e}$$

$$Thus, \lim_{N\to\infty} E(p^*) = \frac{1}{e}$$

CSMA

- Carrier Sense Multiple Access (CSMA)
  - decrease the time colliding with each other (as compared to Aloha)

    <=> increase the time the channel is used for successful transmission

    <=> increase the amount of data that can be successfully delivered

    <=>improve efficiency
  - carrier sensing: listen before transmitting

- Basic protocol
  - If channel is sensed idle, node transmits the frame
  - If channel is sensed busy (i.e., another node is transmitting), node waits until it senses no signal energy and then starts to transmit the frame

Human analogy: don't interrupt others!

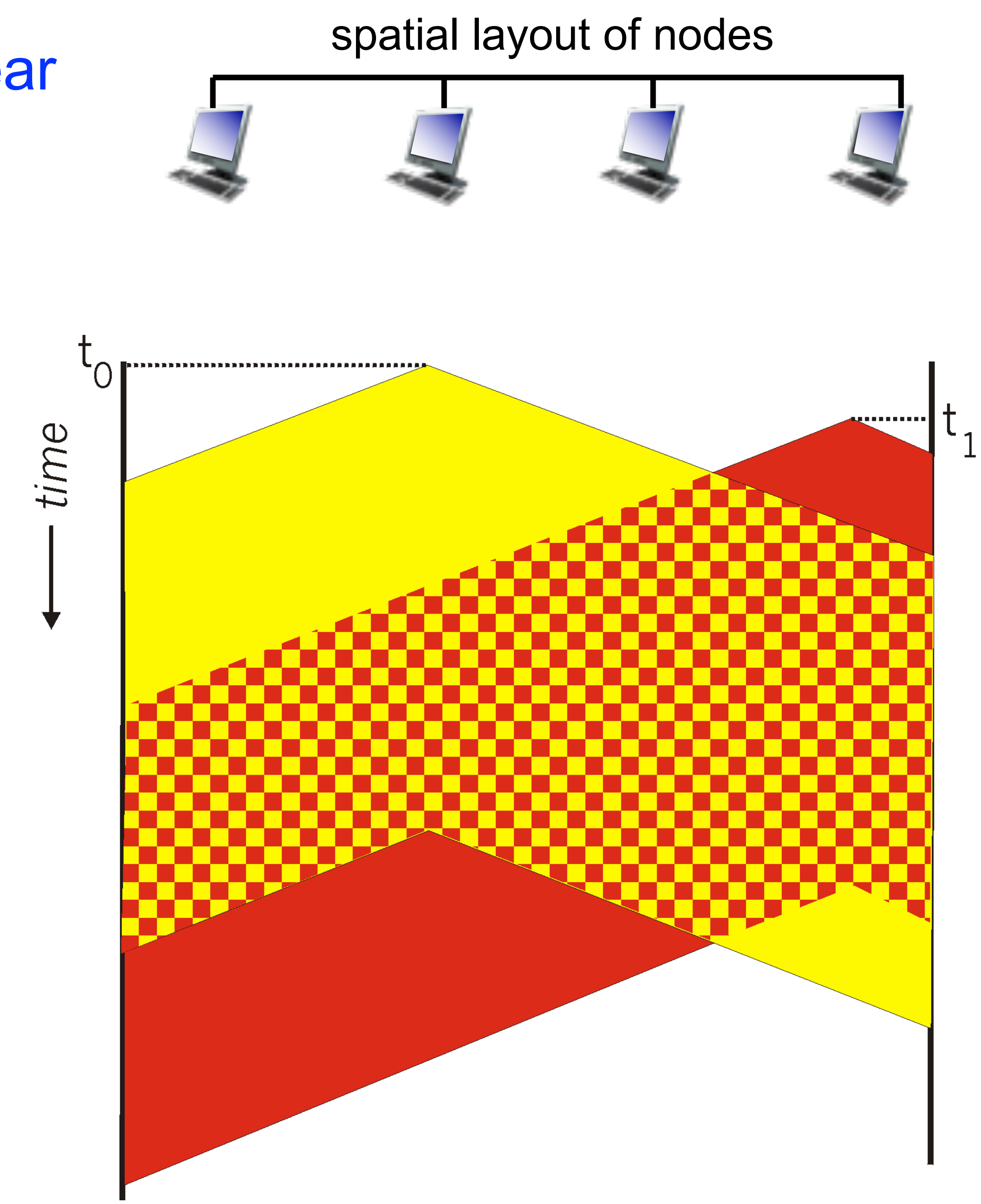
CSMA: collisions

- Collisions can still occur
  - due to propagation delay, two nodes may not hear each other's transmission

    the longer the propagation delay is, the larger the chance that a node is not able to sense an already started transmission

  - in case of collision, node continues transmitting the entire frame in CSMA

    the entire frame transmission time wasted



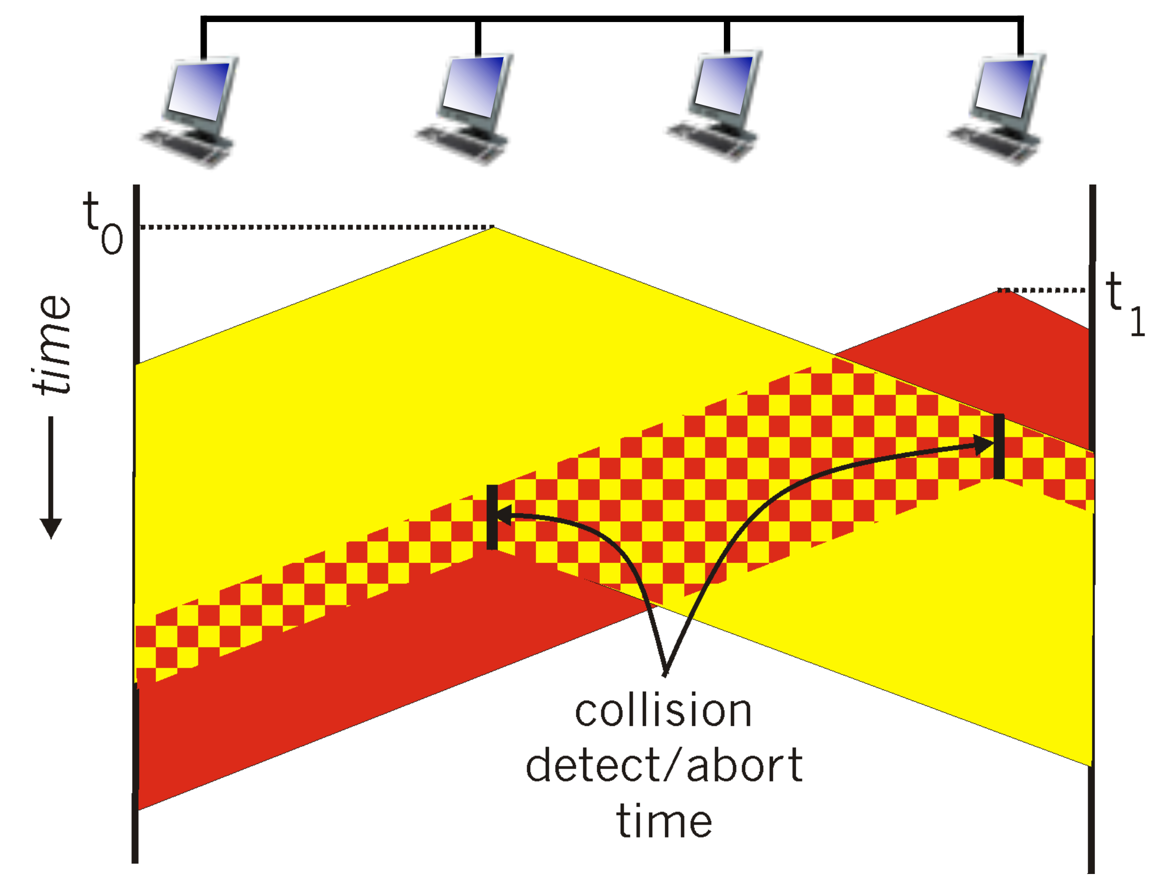
CSMA/CD

- Carrier Sense Multiple Access with Collision Detection (CSMA/CD)
  - collision detection: if other transmission detected, node aborts its current transmission

    further reduce channel wastage (time transmitting useless collided frames), to improve efficiency

    easy in wired LANs: measure signal strengths, compare transmitted and received signals

    difficult in wireless LANs: received signal strength overwhelmed by local transmission strength



Human analogy: the polite conversationalist

Ethernet's CSMA/CD

- Ethernet CSMA/CD

1. Adapter receives datagram from network layer, creates frame
2. If adapter senses channel idle, starts frame transmission; if adapter senses channel busy, waits until channel idle, then transmits
3. If adapter transmits entire frame without detecting another transmission, adapter is done with the frame
4. If adapter detects another transmission while transmitting, aborts and sends jam signal
5. After aborting, adapter enters exponential backoff:

   after nth collision, adapter chooses K at random from $\{0,1,2,\ldots,2^m-1\}$ where $m=\min(n, 10)$.

   adapter waits $K\cdot512$ bit times, returns to Step 2

Carrier sensing and collision detection are performed at Ethernet adapter by measuring signal strength before and during transmission

Ethernet's CSMA/CD (cont'd)

- Bit time
  - the time to transmit one bit, e.g., 0.1 microsec for 10 Mbps Ethernet

- Exponential backoff

after nth collision, adapter chooses K at random from $\{0,1,2,\ldots,2^m-1\}$ where $m=\min(n, 10)$, and waits $K \cdot 512$ bit times,

first collision: choose K from {0,1}; delay is $K \cdot$ 512 bit transmission time

after second collision: choose K from {0,1,2,3}

…

after ten collisions, choose K from {0,1,2,3,4,…,1023}

  - goal: adapt retransmission attempts to estimated current load
  - heavy load: random wait will be longer

- Jam signal: 48 bits
  - make sure all other transmitters are aware of the collision

Ethernet's CSMA/CD: efficiency

- Efficiency of Ethernet's CSMA/CD
  - the long-run fraction of time during which frames are being transmitted on the channel without collision, when there are a large number of active nodes and each node has a large number of frames to send

t_{prop} = maximum propagation delay between two nodes in Ethernet LAN

t_{trans} = time to transmit max-size frame

$$efficiency = \frac{1}{1 + 5t_{prop}/t_{trans}}$$

  - efficiency goes to 1
    as t_{prop} goes to 0
    as t_{trans} goes to infinity

=>better performance than ALOHA, and simple, cheap, decentralized!

Taking-turns protocols

- Motivation
  - Channel partitioning protocols

    share channel efficiently and fairly at high load (i.e., many nodes and each has frames to send)

    inefficient at low load: delay in channel access; R/N bandwidth allocated even if only 1 active node!

  - Random access protocols

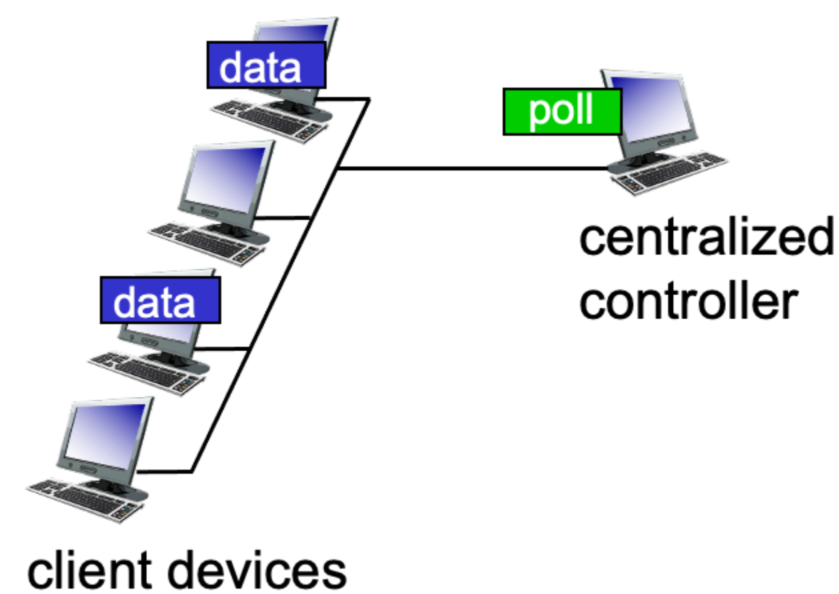
    efficient at low load: single node can fully utilize the channel (i.e., transmitting at full rate R)

    at high load: collision overhead; cannot guarantee that each node has an average throughput of R/N, when there are N nodes

- “Taking turns” protocols
  - look for best of both worlds

Polling

- Basic idea
  - master node "invites" slave nodes to transmit in turn (round-robin fashion)
- Advantage
  - eliminate collisions and empty slots
    =>higher efficiency
- Disadvantage
  - polling overhead, delay
  - centralized: single point of failure at master node
- Example usage
  - Bluetooth



- Required Reading:
  - *Computer Networking: A Top Down Approach* (8th Edition)
    Ch 6.3

- Acknowledgement:
  - Some materials are extracted from the slides created by Prof. Jim F. Kurose and Prof. Keith W. Ross for the textbook.