CS 352
Medium Access Control

CS 352, Lecture 23.1

http://www.cs.rutgers.edu/~sn624/352

Srinivas Narayana

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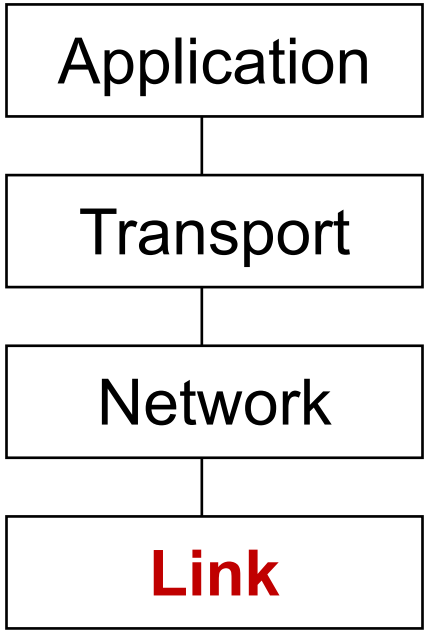
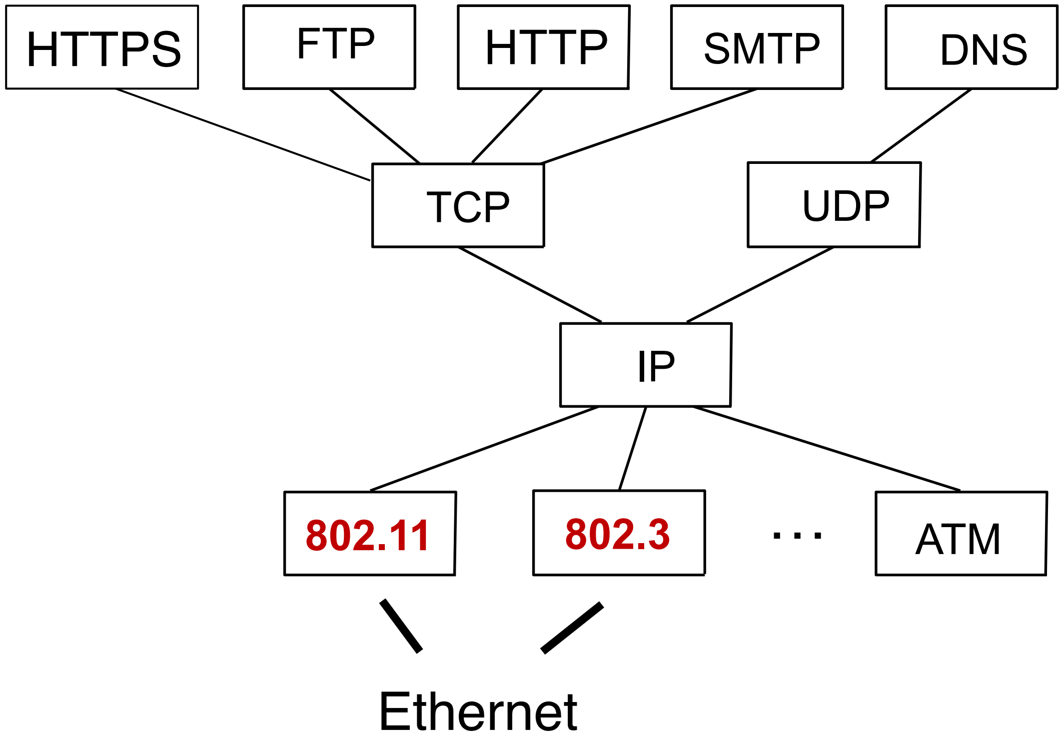
Link layer





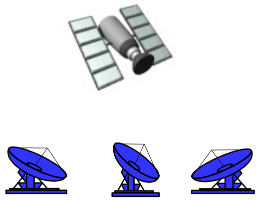
The main function of the link layer is link-local delivery: getting packets from one side of the link to the other.

Two kinds of link layers

- point-to-point
  - Switched Ethernet link between switch and host
  - PPP for dial-up Internet access
- broadcast (shared medium)
  - Shared Ethernet
  - 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

- When there is a single shared broadcast channel, two or more simultaneous transmissions by nodes causes interference
- We say there is a collision if a node receives two or more signals at the same time
- A multiple access protocol is a distributed algorithm that determines how nodes share channel
  - i.e., who can transmit?
- Communication about channel sharing must use channel
  - no separate (out-of-band) channel for coordination

Sharing resources: sound familiar?

Medium access control

- Q: how to share a link over ~packet transmission time (microseconds)?
- Link is attached to the endpoints
- Link (usually) cannot support simultaneous transmissions; collision results
- Collision can be usually detected within a packet transmission period

Congestion control

- Q: how to share a bottleneck link over ~RTT (10-100 milliseconds)?
- Link is (usually) remote from the endpoint
- Router buffer can hold simultaneous transmissions for a short period
- Detecting congestion is indirect (i.e., through loss, delay, etc.) and takes a round-trip time

An ideal multiple access protocol

Given a broadcast channel of rate R, goals:

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 or transmission slots
4. “simple”

MAC protocols: Taxonomy

Three broad classes:

- channel partitioning
  - divide channel into smaller pieces (time slots, frequency, code)
  - allocate piece to node for exclusive use
- turn taking
  - nodes with more to send can take more or longer turns
- random access
  - channel not divided, allow collisions
  - use methods to recover from collisions

MAC protocols: Taxonomy

Three broad classes:

- channel partitioning
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This module

- random access
  - channel not divided, allow collisions
  - use methods to recover from collisions

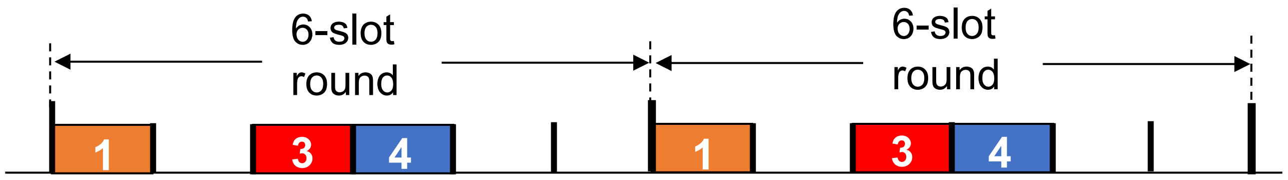
Next module

Channel Partitioning

Dividing time

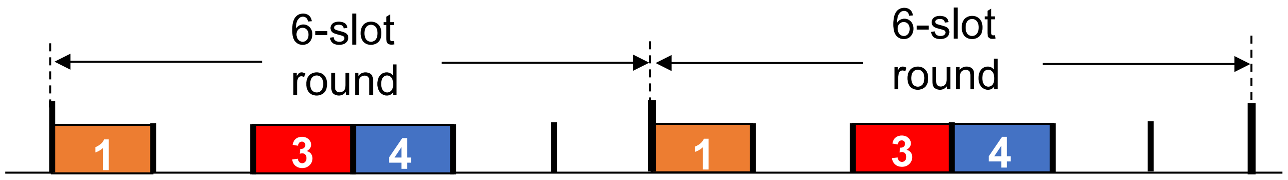
Time-division multiple access (TDMA)

- access the channel in rounds
- Simplest scheme: each node gets fixed length slot
  - length of the slot = packet transmission time
- unused slots go idle
- example: 6-node link, 1,3,4 have packets to send, slots 2,5,6 idle



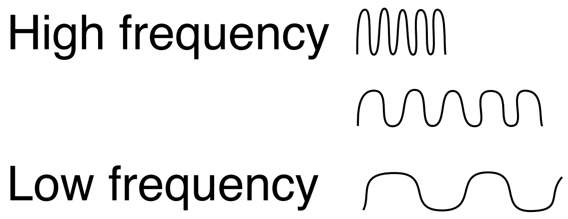
Dividing time

- If channel is partitioned statically, users with higher demand cannot use idle slots. Inefficient
- Example: Nodes 1, 3, or 4 may have more data to send, yet cannot use the slots of nodes 2, 5, or 6.

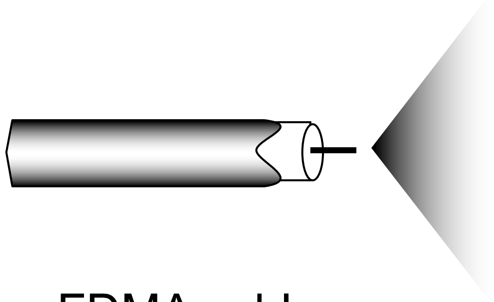


Dividing frequency

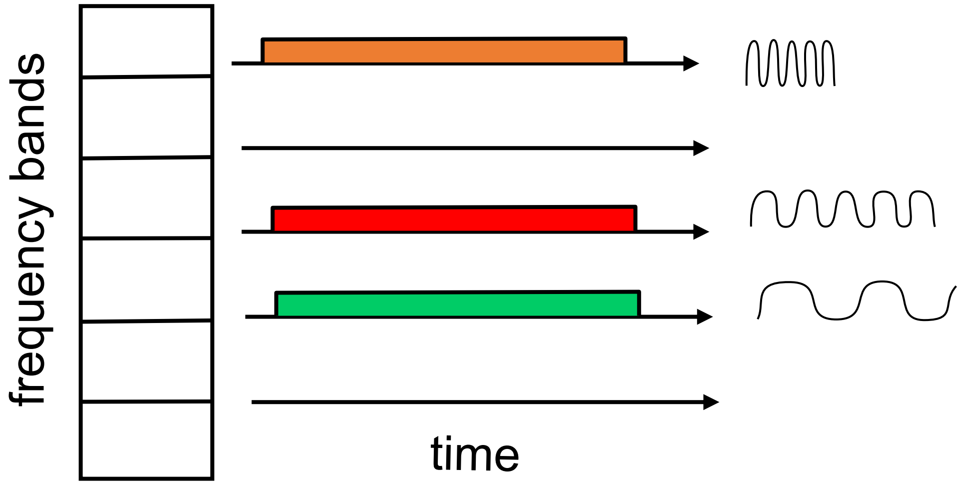
FDMA: frequency division multiple access



- Channel divided into frequency bands
- Simple scheme: each node assigned a fixed frequency band
- Unused transmission time in frequency bands go idle
- Example: 6-node link, 1,3,4 have packets to send, frequency bands 2,5,6 idle



FDMA cable

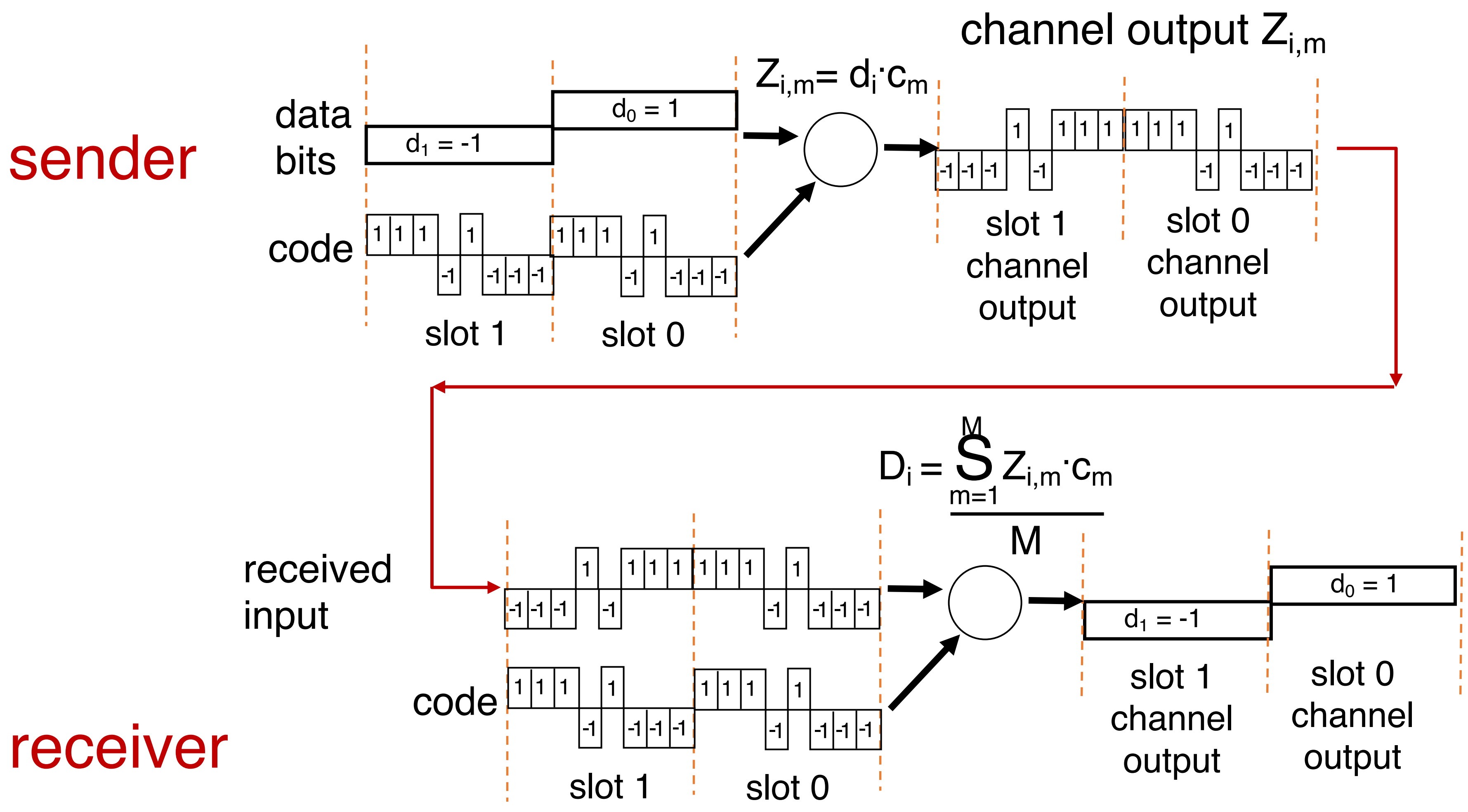


Dividing code

Code Division Multiple Access (CDMA)

- A unique code is assigned to each pair of nodes
  - Also called chipping sequence
- Users can share frequency bands and can transmit at the same time
- Encoded signal = data signal * chipping sequence
- Decoded signal = received signal X chipping sequence
  - Here "X" denotes the inner product of two vectors
  - Example: [1, 2, 3] X [4, 5, 6] = [1*4, 2*5, 3*6]/3 = [4/3, 10/3, 18/3]

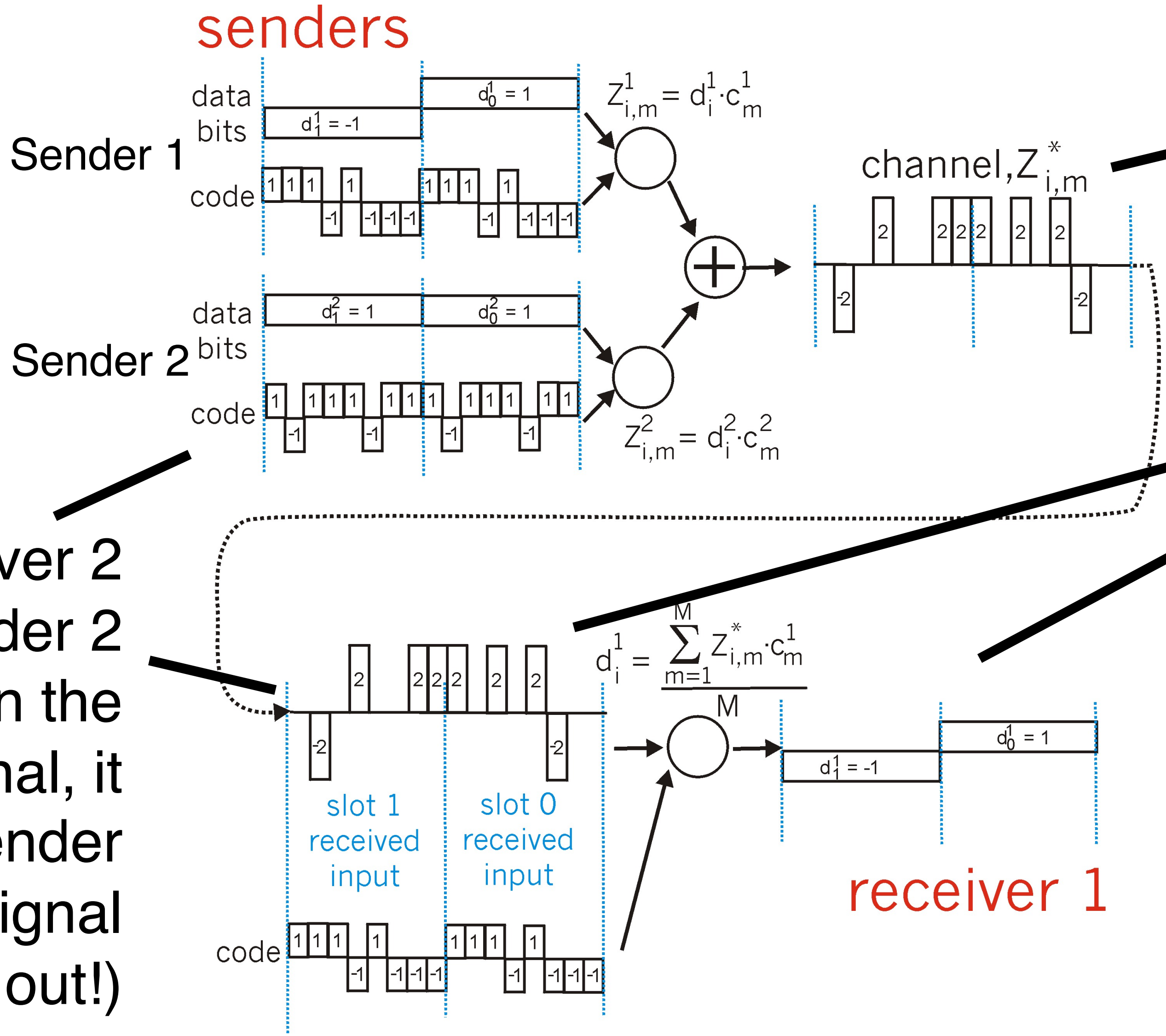
Example of CDMA encode/decode



CDMA trade-offs

- In the place of transmitting 2 (data) bits, we're sending 2 * 8 = 16 bits on the channel. Seems wasteful?
- Real benefit: when multiple users transmit
- Suppose resulting signal levels just add up in the channel and the sum is received by each receiver
- With CDMA, each receiver can independently decode its corresponding sender's transmission using the (respective) code!

CDMA with two senders



channel sums together transmissions by sender 1 and 2

using same code as sender 1, receiver recovers sender 1's transmission from summed channel data!

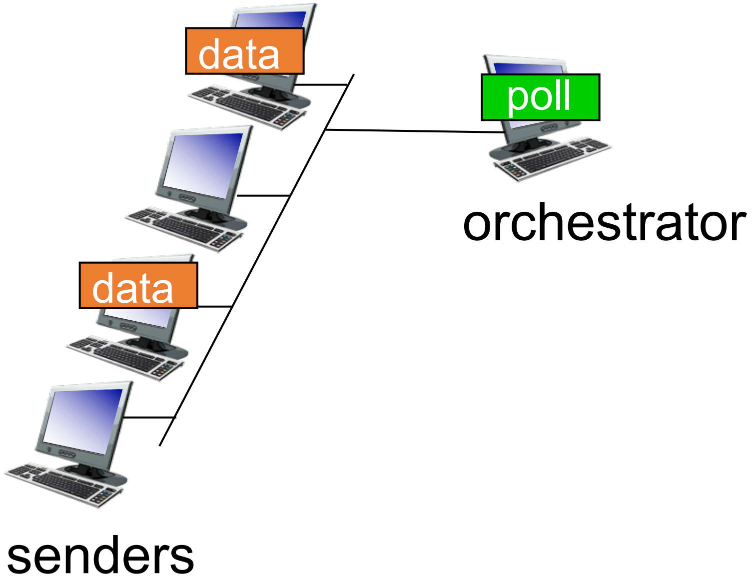
When receiver 2 uses sender 2 code on the same signal, it decodes sender 2's signal (try it out!)

Turn-taking protocols

Nodes taking turns

Polling

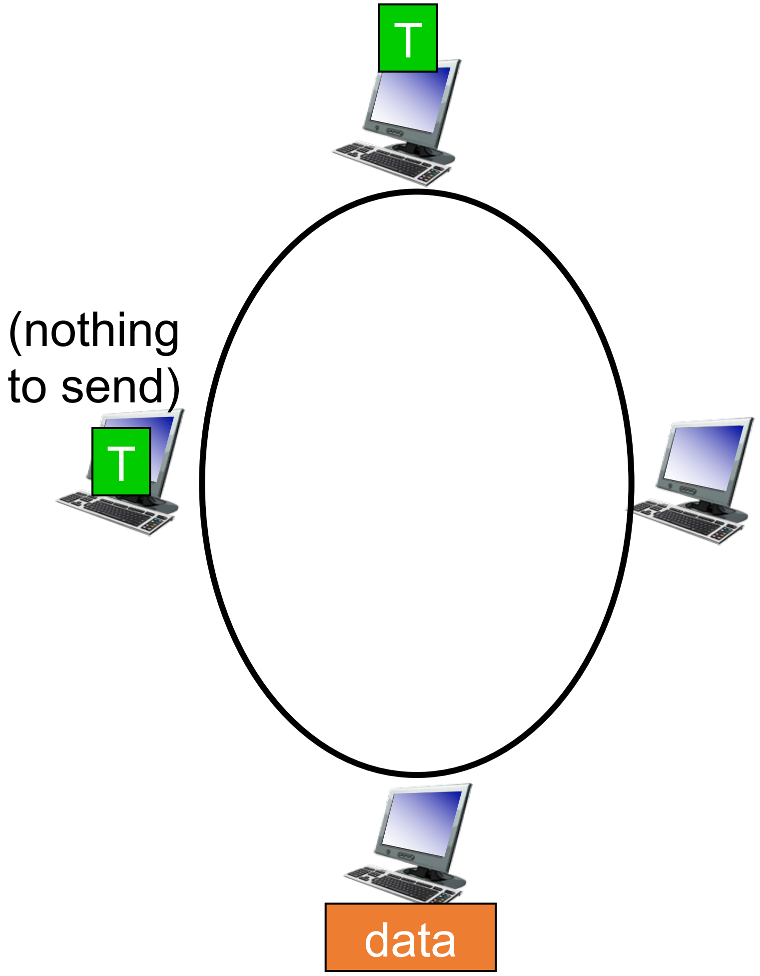
- Orchestrator node "invites" sender nodes to transmit in turn
- Concerns:
  - polling overhead
  - latency
  - single point of failure
    - The orchestrator



Nodes taking turns

Token passing

- control token passed from one node to next sequentially
- Node with token can transmit
- Else, pass it on to the next node in the "ring"
- Concerns:
  - latency
  - single point of failure (node holding the token)



Summary

- Medium access control: a distributed algorithm to transmit over a shared link
- Channel partitioning: TDMA, FDMA, CDMA
- Turn-taking: polling, token passing

- TDMA, FDMA, & CDMA are widely used in cellular communication
    - TDMA, FDMA: GSM
    - CDMA: Qualcomm/Verizon

CS 352
Random Access Protocols

CS 352, Lecture 23.2

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Review

Medium access control

A distributed algorithm running at nodes to determine
who should transmit over a shared link

Channel Partitioning

Turn taking

Random access

Random access protocols

- What if nodes decide to transmit randomly?

- When node has packet to send
  - Transmit at full channel data rate R
  - No *a priori* coordination among nodes

- Collision possible when two or more transmitting nodes choose to send simultaneously

Random access protocols

- A random-access MAC protocol specifies:
  - (1) How to detect collisions
  - (2) How to recover from collisions
  - … Usually by retransmitting after a while

- Examples of random-access MAC protocols:
  - Slotted ALOHA
  - ALOHA
  - CSMA
  - CSMA/CD
  - CSMA/CA

Rest of this lecture

Next lecture

Slotted ALOHA

Slotted ALOHA

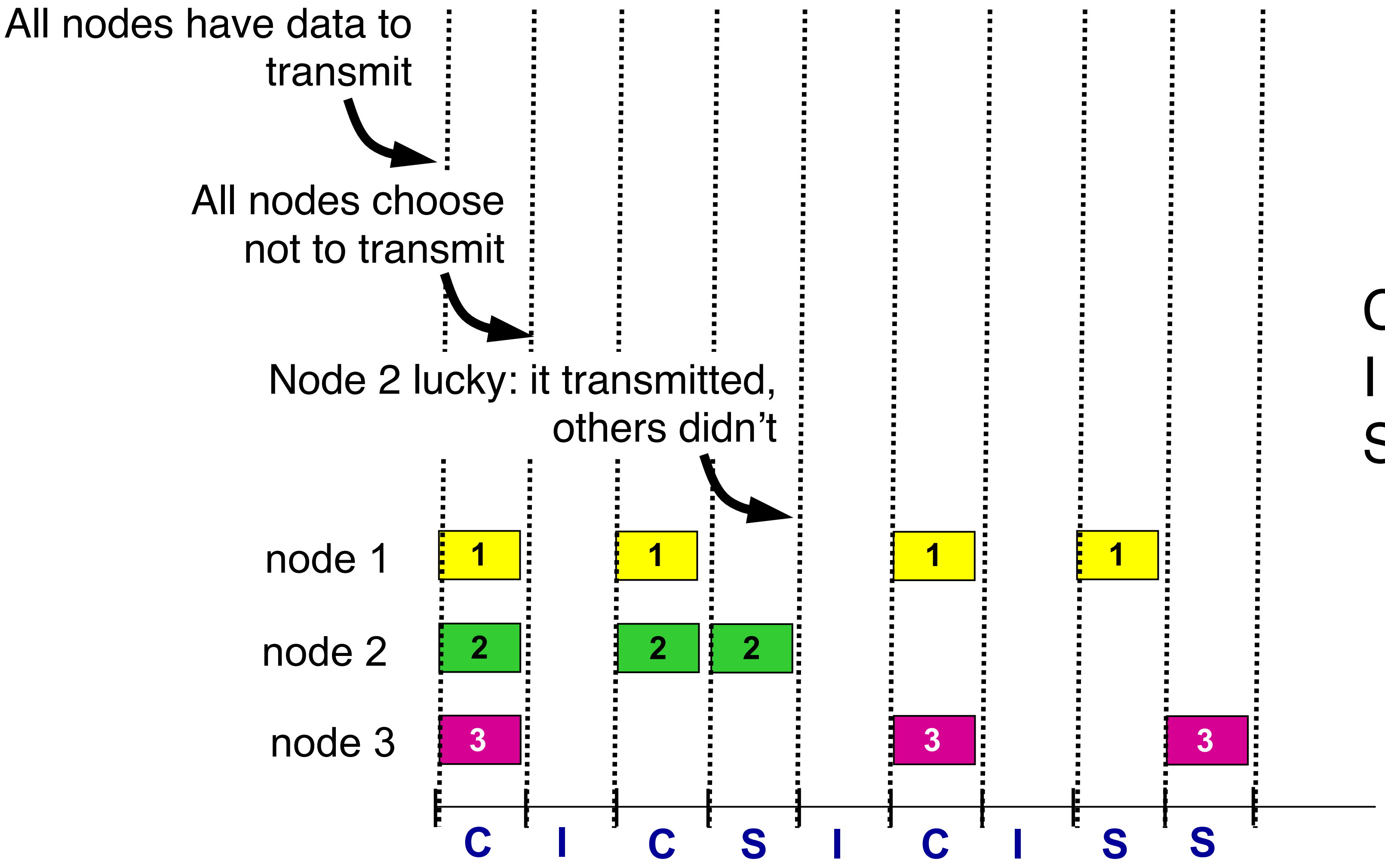
Assumptions:

- All frames same size
- Time divided into equal size slots (time to transmit 1 frame)
- Nodes start to transmit only slot beginning
- Node clocks are synchronized
- If 2 or more nodes transmit in slot, all nodes detect collision

Operation:

- when node obtains fresh frame, transmits in next slot
  - if no collision: node can send new frame in next slot
  - if collision: node retransmits frame in each subsequent slot with prob. p until success

Slotted ALOHA: example



C = collision
I = idle
S = successful xmit

Slotted ALOHA

Advantages

- Single active node can continuously transmit at full rate of channel
- Simple, decentralized protocol

Disadvantages

- Clock synchronization: nodes must sync on slot start times
- Collisions waste slots
- Idle slots possible even if demand exists
- Must ensure that collision is detected within a frame duration
- Even if detection is fast, whole frame time still wasted

Slotted ALOHA: efficiency

- Q: What fraction of slots are likely to be successful?
  - i.e., exactly one node transmits
- Assume N nodes, all have frames to send
- Steady state: all have detected collision the last time the frame was attempted to be transmitted
- Success: one node must choose to transmit (probability p), all other nodes choose not to transmit (probability 1-p)

Slotted ALOHA: efficiency

- Prob that given node has success in a slot $= p(1\text{-}p)^{N\text{-}1}$
- Prob that *any* node has a success $= Np(1\text{-}p)^{N\text{-}1}$
- max efficiency: find p^* that maximizes $Np(1\text{-}p)^{N\text{-}1}$
- for many nodes, take limit of $Np^*(1\text{-}p^*)^{N\text{-}1}$ as N goes to infinity, gives:

  Max efficiency = 1/e = .37
- at best: channel used for useful transmissions 37% of the time!

Pure ALOHA

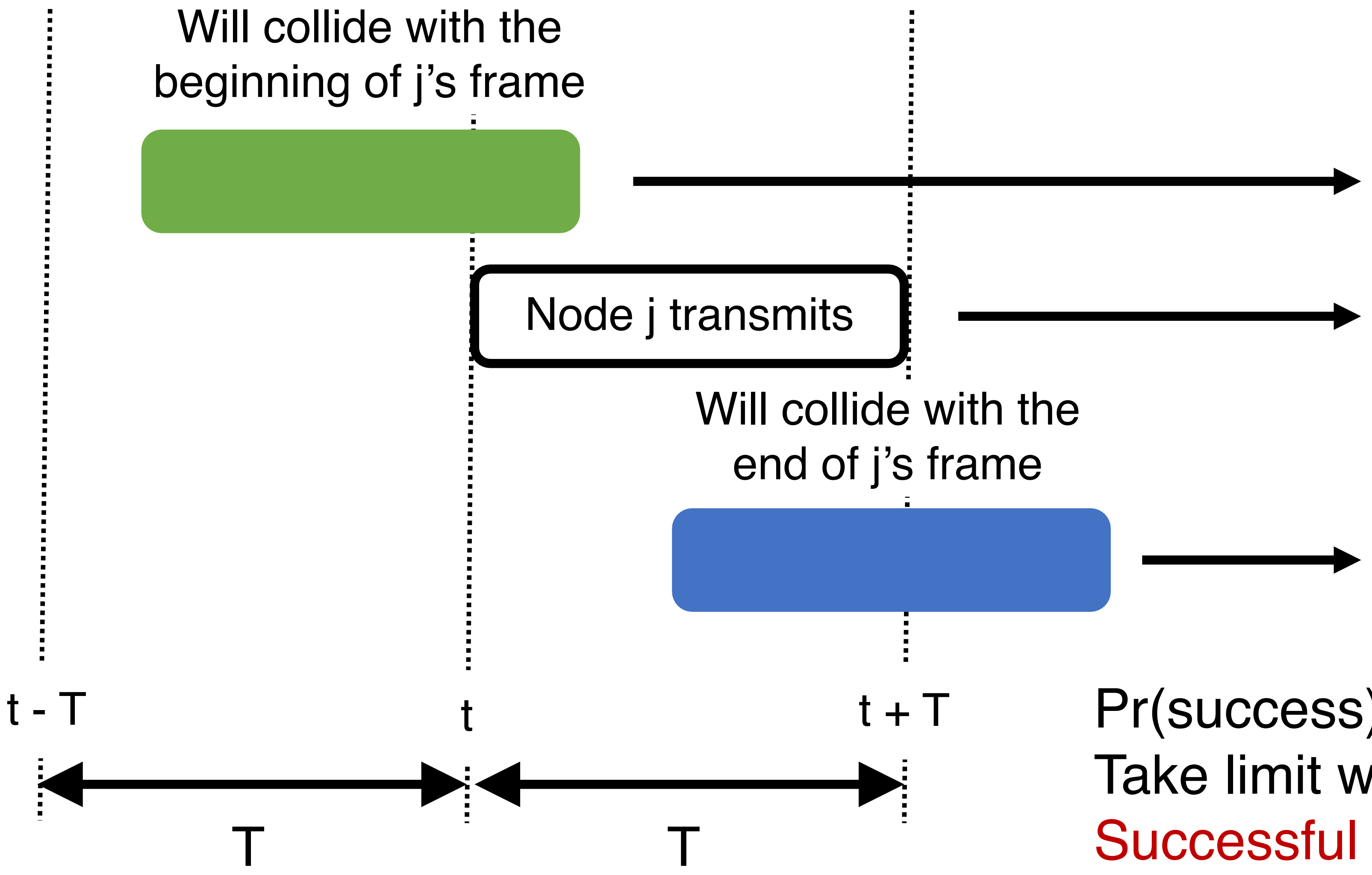
Pure (unslotted) ALOHA

- Even simpler algorithm than ALOHA: No synchronization

- When a frame first arrives, transmit immediately
  - No need to wait for the start of a transmission slot

- However, the collision probability increases:
  - Frame sent at t collides with other frames sent in [t-T,t+T]
  - Here T is the frame transmission time

Collisions in pure ALOHA



$Pr(success) = Np(1-p)^{2(N-1)}$

Take limit with optimal p as $N \rightarrow \infty$

Successful 18% of the time!

Worse than slotted ALOHA.

Are there better strategies to transmit rather than independently and randomly?

Carrier Sensing Multiple Access (CSMA)

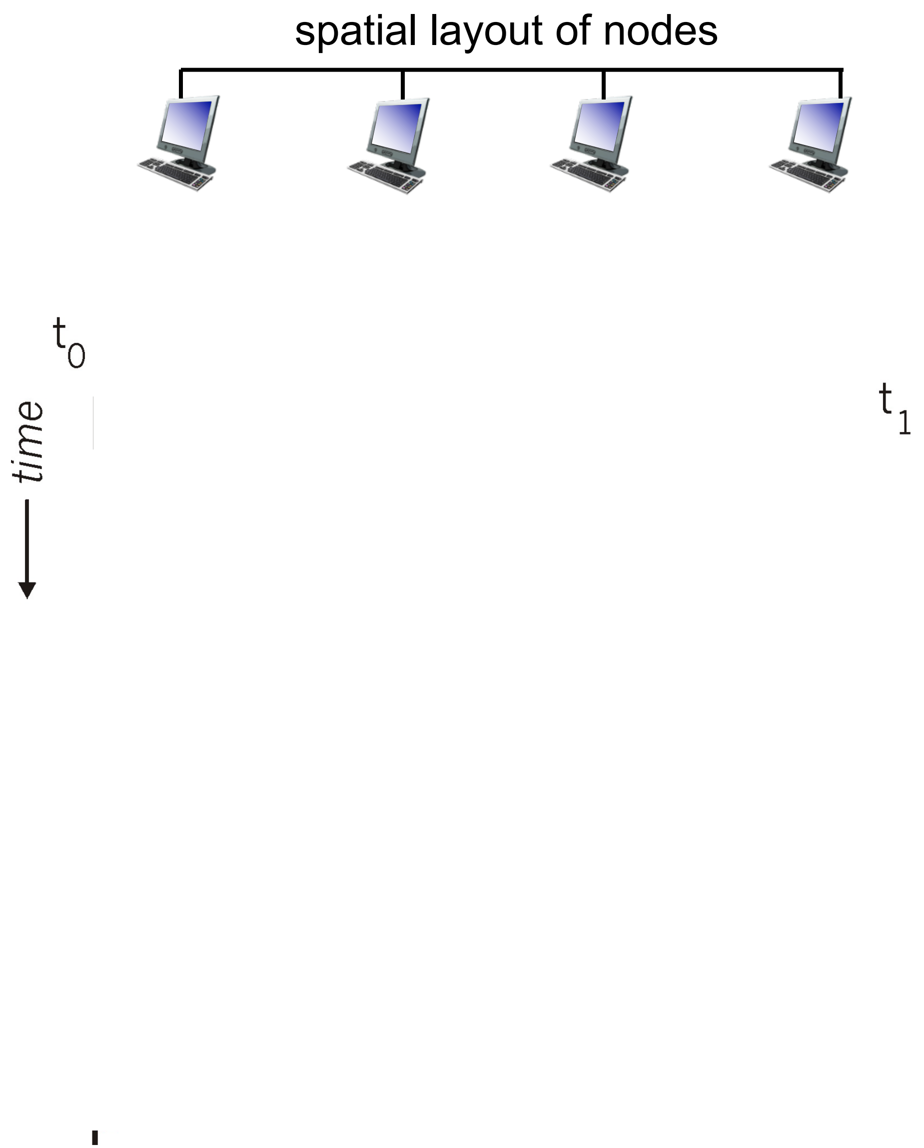
Carrier Sense Multiple Access (CSMA)

Key idea: listen to the channel before transmission

- If the channel sensed idle, then transmit entire frame
- If the channel sensed busy, then defer transmission
- Human analogy: don’t interrupt others!

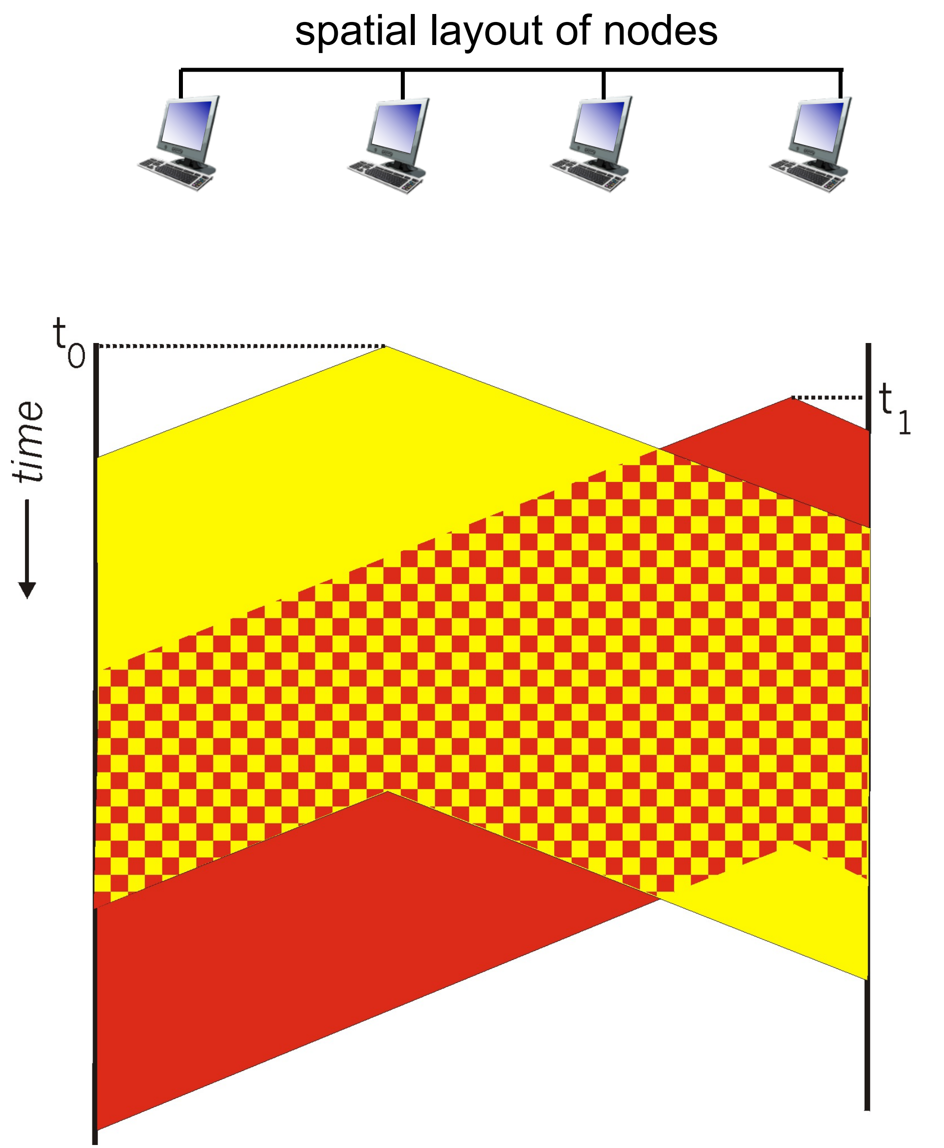
CSMA collisions

- Collisions can still occur. Due to propagation delay, two nodes may not hear each other's transmissions right away
- If there is a collision, the entire packet transmission time is wasted



CSMA collisions

- Collisions can still occur. Due to propagation delay, two nodes may not hear each other's transmissions right away
- If there is a collision, the entire packet transmission time is wasted
- Propagation delay between the nodes plays a key role in determining the collision probability



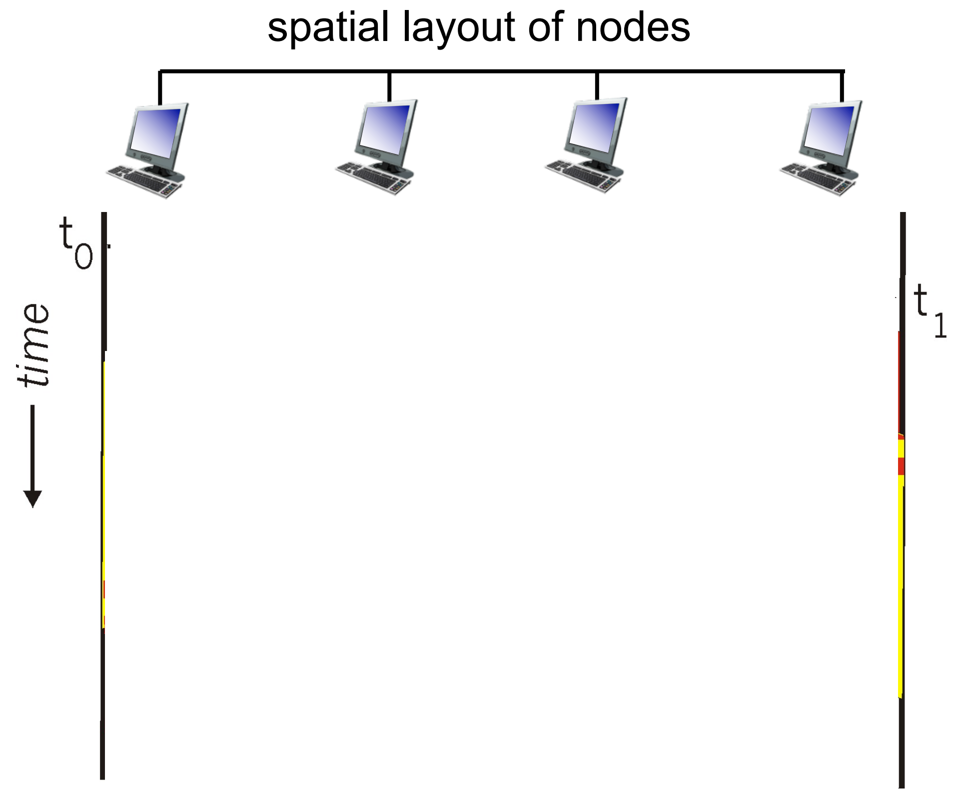
Carrier Sensing with Collision Detection (CSMA/CD)

Carrier sensing + collision detection

- On certain types of link technologies (e.g., wired Ethernet), continuous carrier sensing can enable detecting collisions very quickly
  - Not always possible, e.g., wireless LANs (next lecture)
- Suppose it is possible to detect collisions as soon as signal from one node reaches another (transmitting) node
  - Measure received signal, compare with transmitted signal
- CSMA/CD: Stop transmitting when a collision is detected
  - Reduce wastage of channel capacity
  - Improve the chances of retransmitting earlier
- Analogy: “polite speaker”: stop speaking when interrupted

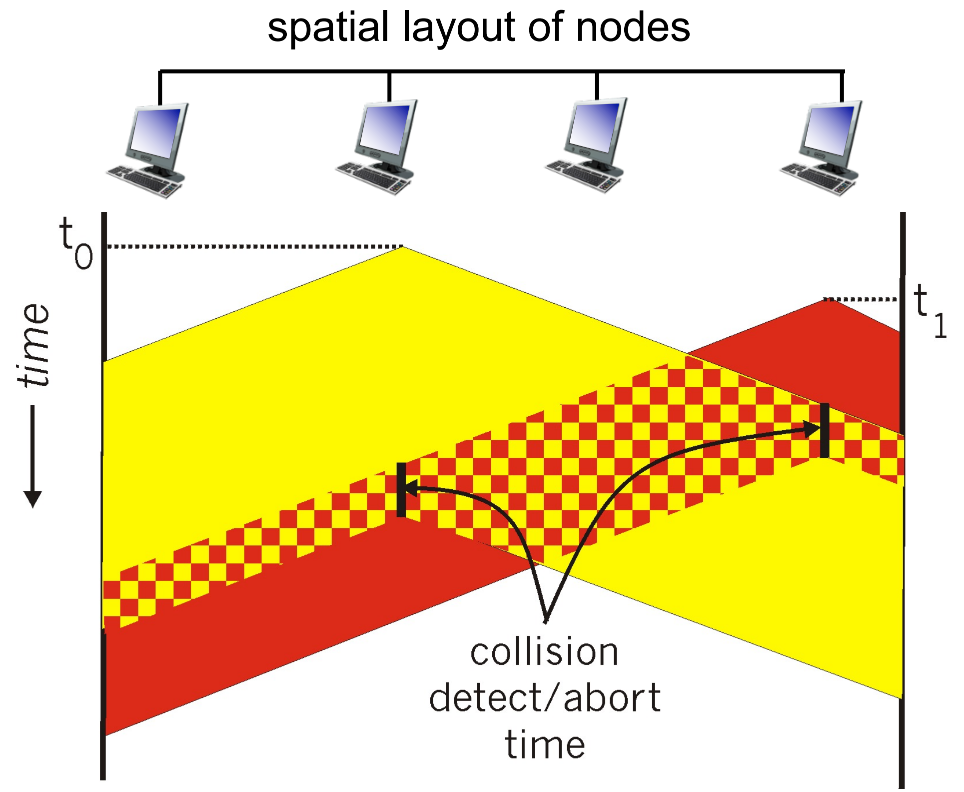
CSMA/CD

- Collisions can still occur. Due to propagation delay, two nodes may not hear each other's transmissions right away
- However, upon detecting a collision, node stops transmitting



CSMA/CD

- Collisions can still occur. Due to propagation delay, two nodes may not hear each other's transmissions right away
- However, upon detecting a collision, node stops transmitting
- CSMA/CD reduces time spent in collided frames relative to just CSMA



Impact of random access protocols

- The ALOHA protocols were part of ALOHANet, one of the first packet radio networks to be deployed. Connected the islands of Hawaii

- Simple protocols, simple node design, no requirement of centralized control or synchronization

- Highly influential ideas contributing to the mainstream today
  - Shared ethernet uses CSMA/CD
  - Wireless Ethernet (WiFi) MAC protocol on these ideas

CS 352
CSMA/CD in Shared Ethernet

CS 352, Lecture 23.3

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Review

Medium access control

A distributed algorithm running at nodes to determine
who should transmit over a shared link

Channel Partitioning

Turn taking

Random access

Slotted ALOHA
ALOHA
CSMA
CSMA/CD

Review of CSMA/CD

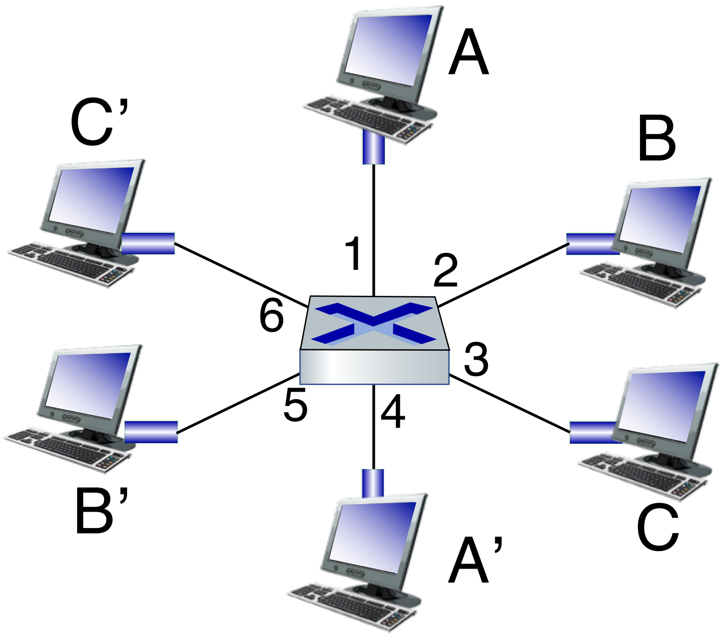
- Sense the medium for existing transmissions
- If the medium is idle, transmit
- If a collision is detected during transmission, abort the transmission
- Retry transmission “later”

- Retransmission in the ALOHA protocols:
    - Transmit with some probability during the next frame time

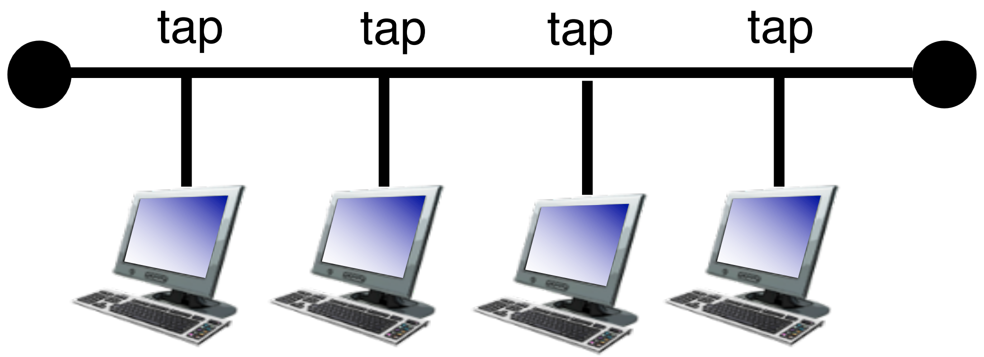
CSMA/CD in Shared Ethernet

Switched Ethernet vs. Shared Ethernet

- Nodes connected over dedicated link to a switch (previous lecture)



- Multiple nodes connected to the same Ethernet cable
- Classic method: limited geographic coverage, easy to add nodes by adding a tap
- Every node can hear every other node



MAC in shared Ethernet

- Since the cable is a broadcast medium, it is important to decide which node can transmit at any time.

- Shared Ethernet uses CSMA/CD MAC, with a twist

Shared Ethernet: CSMA/CD

1. NIC receives data to send (e.g., from network layer), creates a frame
2. If NIC senses channel idle, starts frame transmission. If NIC senses channel busy, waits until channel idle, then transmits (CSMA)
3. If NIC transmits entire frame without detecting another transmission, NIC is done with frame.
4. If NIC detects another transmission while transmitting, the NIC aborts the transmission and sends a “jam signal” (CD)
5. The NIC waits for some period and attempts to retransmit the frame.

(Note: in ALOHA, retransmission is probabilistic)

Q: how long should the NIC wait?

Ethernet binary exponential backoff

- After a frame has experienced a collision, the NIC enters a backoff phase
- after `m'`th collision, NIC chooses K at random from $\{0,1,2, \ldots, 2^m-1\}$.
- NIC waits K·512 “bit times” (time to transmit a single bit)
- NIC returns to Step 2 (carrier sensing) after the wait

Ethernet binary exponential backoff

- Waiting longer to transmit is a way of responding to higher load
  - More collisions on the same frame ←→ more transmitting nodes on link
- Increasing backoff period exponentially is a way to respond to the number of other transmitting nodes without knowing a priori how many!
- Still, each node chooses a random interval to wait (from range)
  - Only the upper bound of the interval increases exponentially
- Randomness avoids synchronization (and repeated collisions) between nodes

CSMA/CD efficiency

- T_{prop} = max prop delay between 2 nodes in 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 (closer the nodes, the more efficient)
  - as t_{trans} goes to infinity (longer the frames, the more likely that carrier sensing prevents collisions)
- All from a simple, cheap, decentralized protocol!

Impact of Ethernet CSMA/CD

- Basis for the design of wireless medium access control: widely implemented and deployed today in WiFi
  - We’ll do a deeper dive next lecture
- Birth of a powerful idea in Computer Science: exponential backoff
  - TCP multiplicative decrease was inspired by exponential backoff
  - A general method to react to load without a priori global information

Comparison of MAC protocols

Channel partitioning	Turn-taking	Random access
(typically) static allocation of channel	Adapts to node demands by design	Node with access transmits at full rate
Efficient and fair at high loads (1/N’th)	May increase delay to transmit (at low load)	Responsive to load (e.g., exp backoff)
Inefficient at low loads	Suffers from a single point of failure	Capacity may be wasted: collision, idle