Last Lecture: Data Link Layer

1. *Design goals and issues* ✔
2. *(More on) Error Control and Detection* ✔
3. *Multiple Access Control (MAC)*
4. *Ethernet, LAN Addresses and ARP*
5. *Hubs, Bridges, Switches*
6. *Wireless LANs*
7. WLAN Security
8. Mobile Networking

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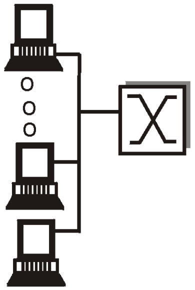
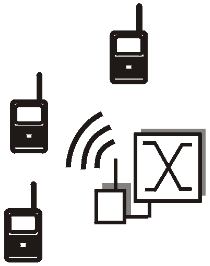
Multiple Access Links and Protocols

There are two types of “links”:

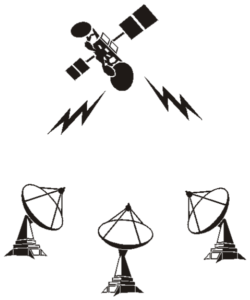
- *Point-to-point*
  - PPP for dial-up access
  - Point-to-point link between Ethernet switch and host
- *Broadcast* (e.g., shared wire or other medium)
  - Traditional Ethernet
  - Upstream HFC
  - 802.11 wireless LAN, radio networks



shared wire
(e.g. Ethernet)



shared wireless
(e.g. Wavelan)



satellite

cocktail party

Multiple Access Control (MAC)

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes leads to interference
    - only one node can send *successfully* at a time

Need *Multiple Access Control (MAC) protocol*

- Distributed algorithm that determines how nodes share channel
    - Typically, communication about channel sharing must use channel itself!

Ideal MAC Protocol

Given a broadcast channel of rate R bps

1. *Fully utilized*
   - When one node wants to transmit, it can send at rate *R*.
   - When *M* nodes want to transmit, each can send at average rate *R/M* (over the long run)
2. *Fully decentralized*:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
3. *Simple*
   - the network cards should be inexpensive
   - plug-and-play

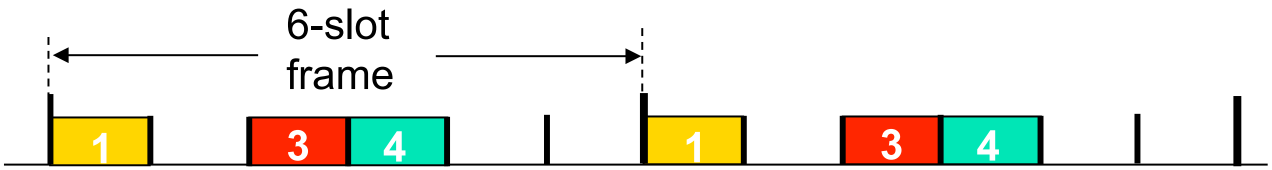
Three Broad Classes of MAC Protocols

1) *Channel Partitioning*
   - Divide channel into smaller "pieces" (*time slots* - TDMA, *frequency* - FDMA, *code* - CDMA)
   - Allocate piece to node for exclusive use
2) *Random Access*
   - Channel not divided, allow collisions (contention)
   - "Recover" from collisions
3) *"Taking turns" (or Round Robin)*
   - Tightly coordinate shared access to avoid collisions

Channel Partitioning with TDMA

TDMA: time division multiple access

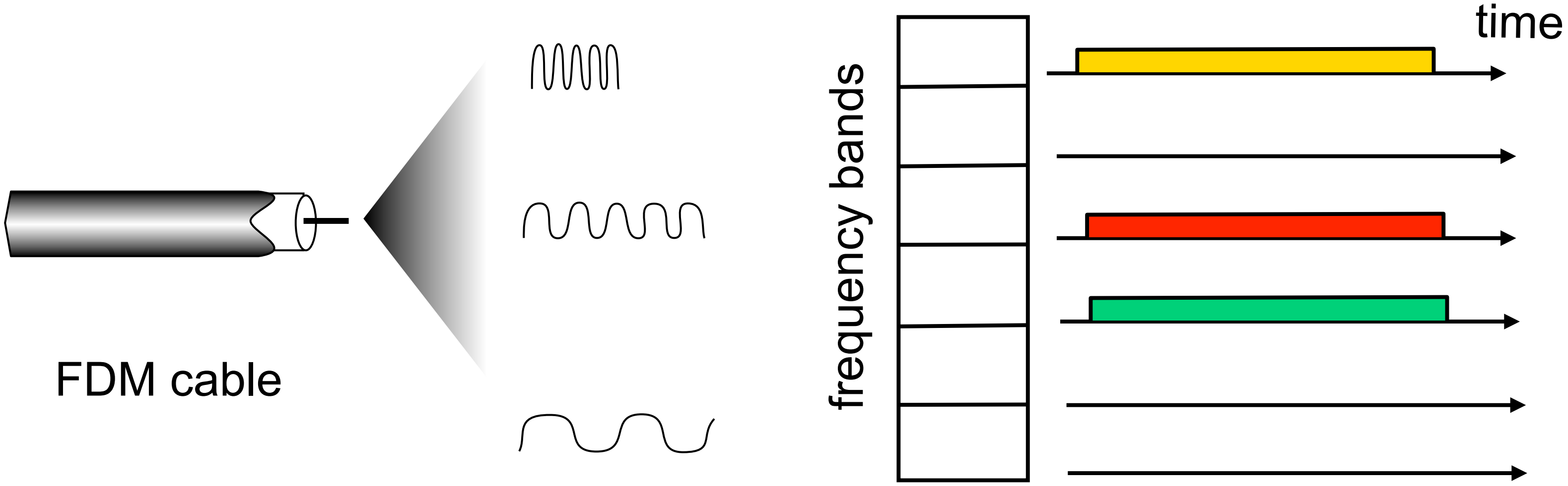
- Access to channel in "rounds"
- Each station gets fixed length slot (length = pkt trans time) in each round
- Unused slots go idle
- *Example*: 6-station LAN, 1,3,4 have pkt, slots 2,5,6 idle



Channel Partitioning with 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



Channel Partitioning with CDMA

CDMA (Code Division Multiple Access)

- Unique “code” assigned to each user
- Used mostly in wireless broadcast channels (cellular, satellite, etc)
- All users share same frequency, but each user has own “chipping sequence” (i.e., code) to encode data
- Allows multiple users to “coexist” and transmit simultaneously with minimal interference (if codes are “orthogonal”)

CDMA: Orthogonal Chip Sequences

4 stations A, B, C, D with chip sequences

A: (-1 –1 –1 +1 +1 –1 +1 +1)

B: (-1 –1 +1 –1 +1 +1 +1 –1)

C: (-1 +1 –1 +1 +1 +1 –1 –1)

D: (-1 +1 –1 –1 –1 –1 +1 –1)

Note that:

- M = 8 (in practice, M = 64, 128)
- The chip sequences are orthogonal!
- Orthogonal chip sequences can be obtained from *Walsh codes* (which comes from *Hadamard* matrices)

CDMA: Rule for Transmitting

- *To send a 0-bit*:
  - Send the complement of the chip sequence
- *To send a 1-bit*:
  - Send the chip sequence
- *Example*: A’s chip sequence was

`A: ( -1 –1 –1 +1 +1 –1 +1 +1 )`

Then A sends a 1-bit by sending

`( -1 –1 –1 +1 +1 –1 +1 +1 )`

And a 0-bit by sending

`( +1 +1 +1 -1 -1 +1 -1 -1 )`

- Note that $(A \bullet A)/M = 1$, and $(A \bullet notA)/M = -1$

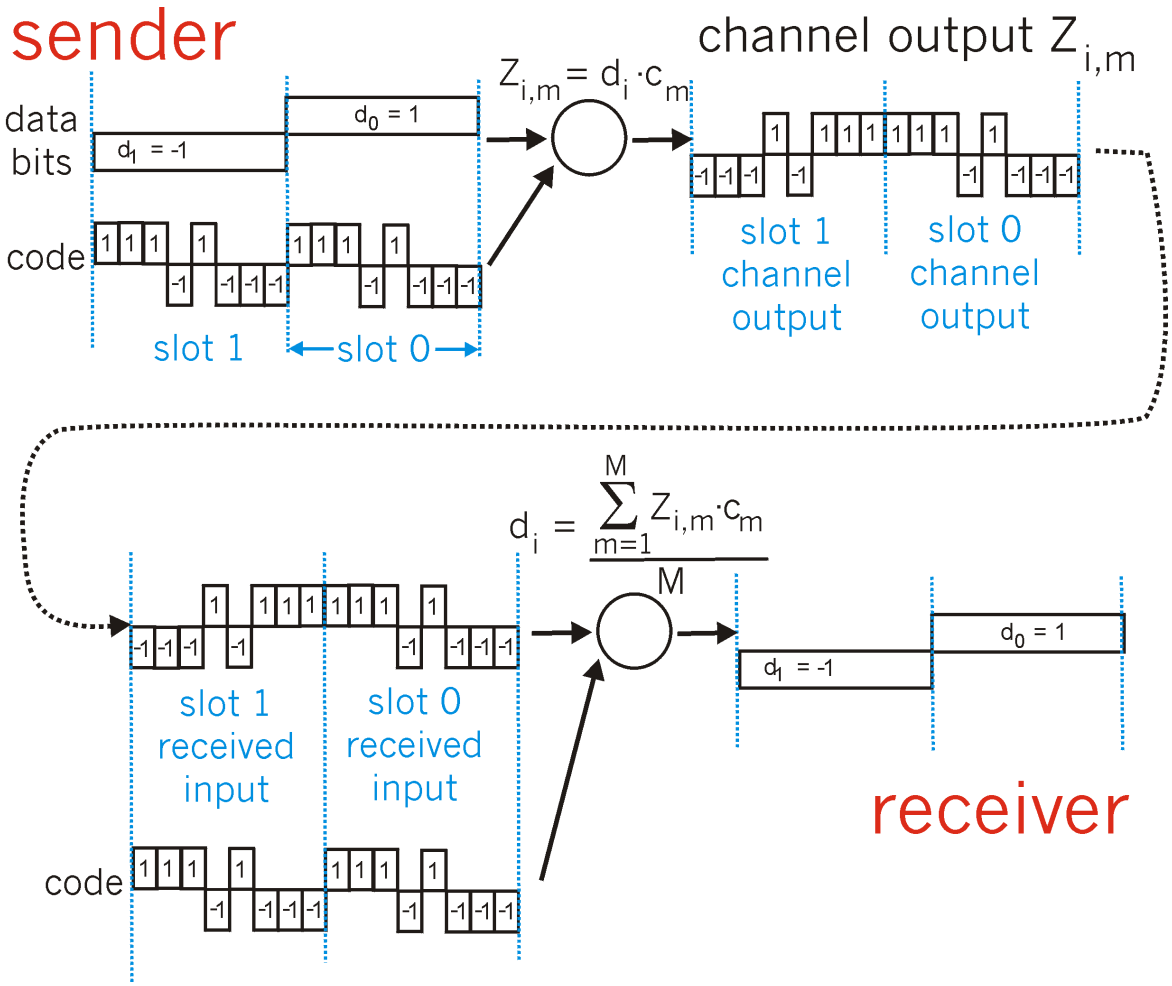
CDMA: Rule for Decoding

- At a bit slot, suppose the received vector is S.
- *To decode*, compute $S \bullet A$, $S \bullet B$, $S \bullet C$, $S \bullet D$
  - For any station X *in* $\{A, B, C, D\}$

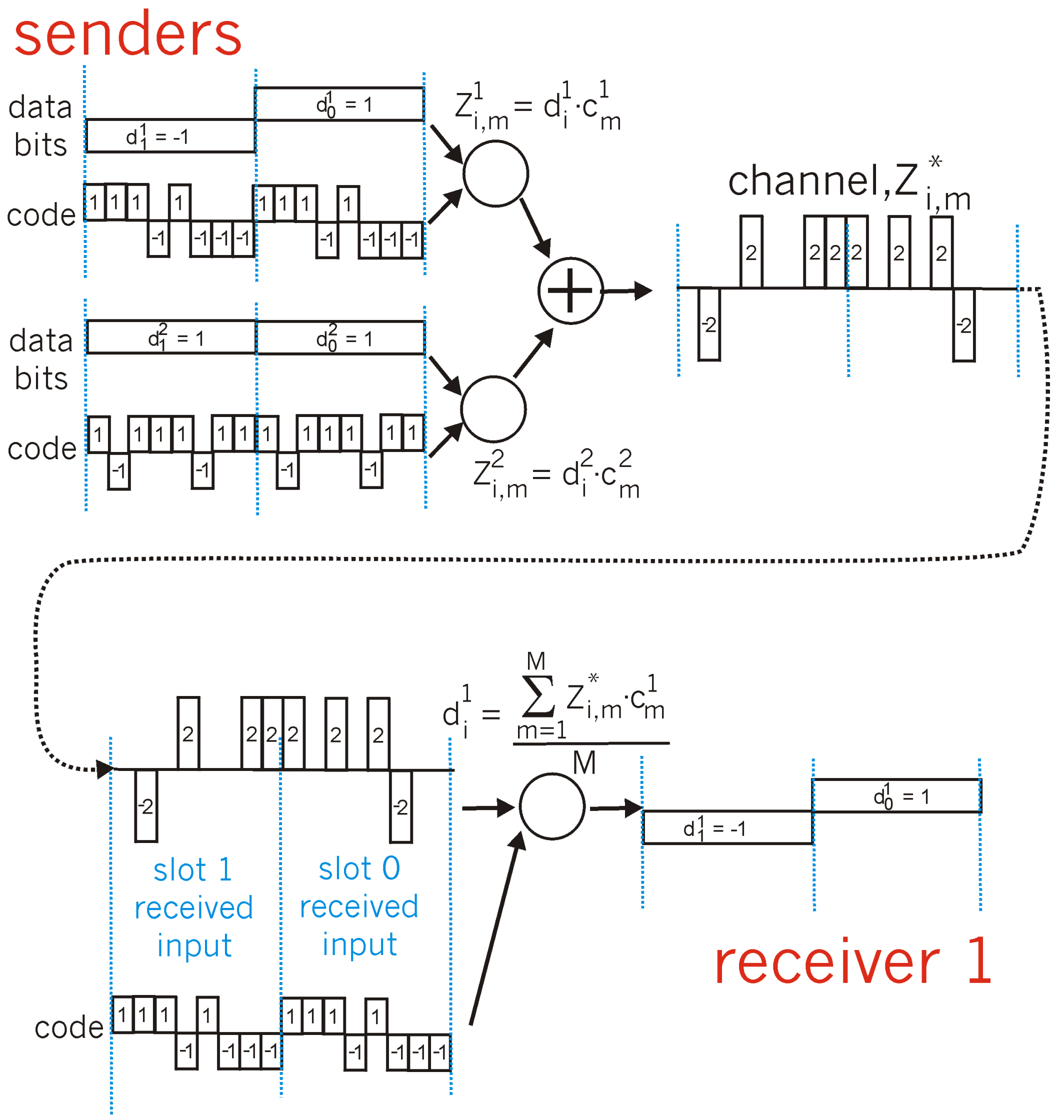
    If $(S \bullet X)/M = 1$, then X transmitted 1
    If $(S \bullet X)/M = -1$, then X transmitted 0
    If $(S \bullet X)/M = 0$, then X did not transmit

- *Assuming signals are additive*, it is now "easy" to see how this works.

CDMA Encode/Decode



CDMA: Two-Sender Interference



CDMA: More details

- Most companies did not think CDMA would be “the” technology, except for Qualcomm, who’s been very persistent on pushing the technology
- Now viewed as the best technical solution around
- Serves as the basis for 3G mobile systems

CDMA: Last Words

- Synchronization is a *huge* problem
- Senders may not have the same signal strength
  - the additive assumption is too strong
  - depending on how far senders are from receiver
- … (this is a maturing tech.)

- However, CDMA in normal mode supports many more users than GSM and D-AMPS

Three Broad Classes of MAC Protocols

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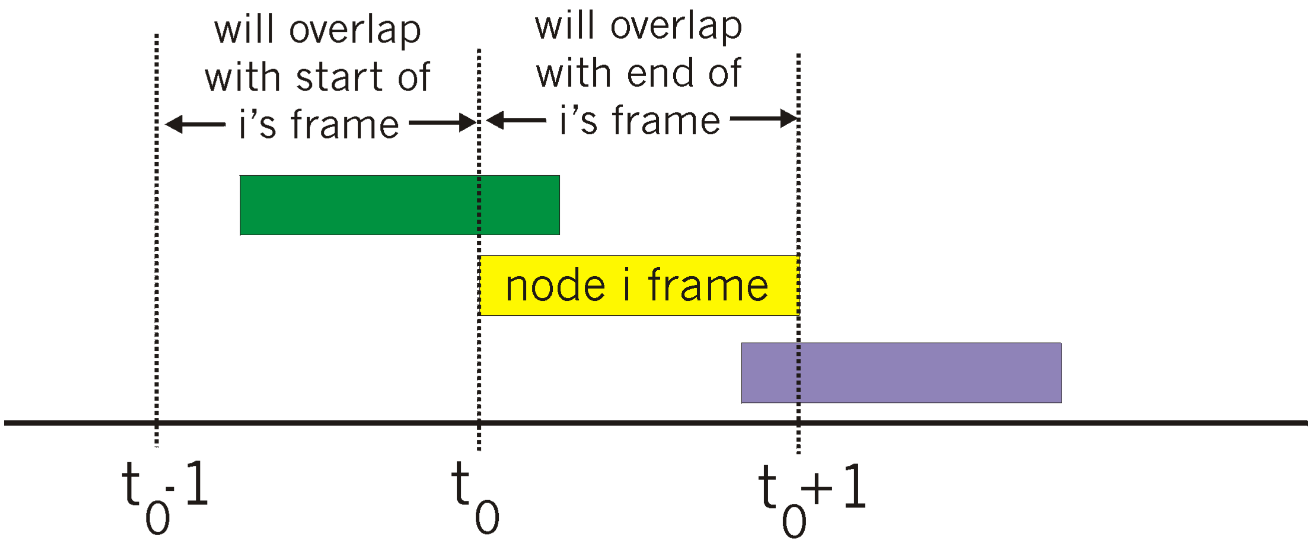
    - “Recover” from collisions
3) *“Taking turns” (or Round Robin)*
    - Tightly coordinate shared access to avoid collisions

Random Access Protocols

- When node has packet to send
  - Transmit at full channel data rate R.
  - No *a priori* coordination among nodes
- ≥ 2 simultaneous transmissions leads to "*collisions*"
- *Random access protocol* typically specifies:
  - How to *detect* collisions
  - How to *recover* from collisions (e.g., via delayed retransmissions)
- Examples of random access protocols:
  - Pure ALOHA
  - Slotted ALOHA
  - CSMA, CSMA/CD, CSMA/CA

Pure ALOHA (Norman Abramson)

- Developed for Packet Radio Systems in Hawaiian Islands (1970s)
- When frame first arrives: transmit immediately
- If collision occurs, wait for a random amount of time and retransmit



Poisson Distribution

- Network traffic in many cases follows the Poisson distribution
  - Arrival rate λ (packets/second)
  - The probability of having *k* packets arriving in an interval of length *t* is

$$\frac{(\lambda t)^k e^{-\lambda t}}{k!}$$

Exponential Distribution

- *Inter-arrival times* follow the exponential distribution with mean inter-arrival time 1/λ.

- Specifically, next arrival time is independent of the past.

$$\Pr[\text{nextarrival} \le t] = 1 - e^{\lambda t}$$

- We can think about Poisson distribution in either way

Analysis of Pure ALOHA

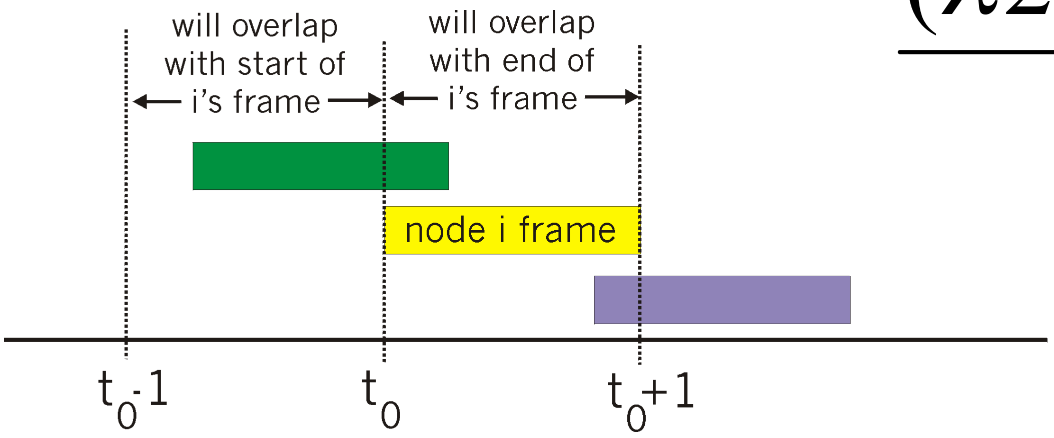
Input rate: λ frames per frame time (assumed 1 second)

Suppose we know probability of a successful transmission of a frame at time t_o is P

Throughput is then S = Pλ

The transmission is successful if no other transmission in 2 seconds, probability is

$$\frac{(\lambda 2)^0 e^{-\lambda 2}}{0!} = e^{-2\lambda}$$



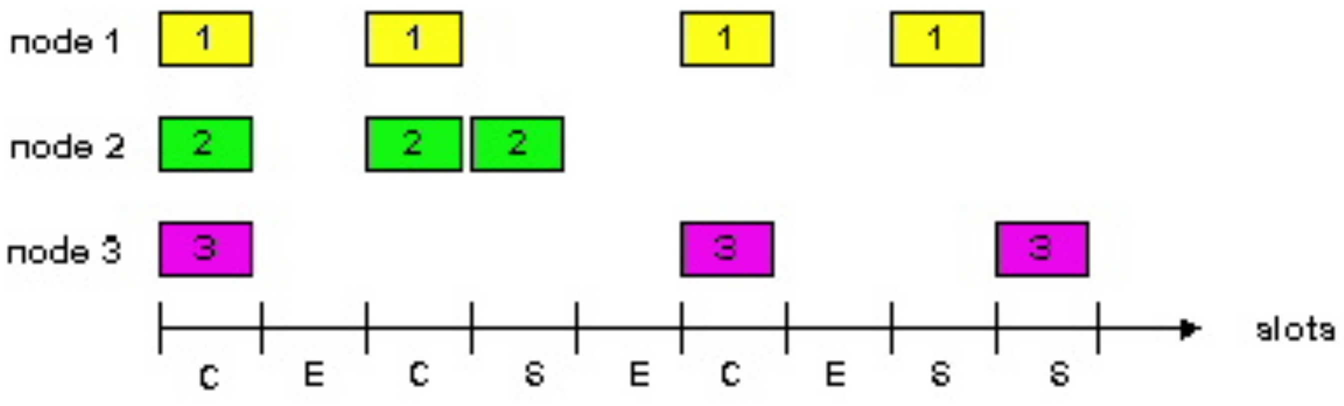
Analysis of Pure ALOHA

- The period of 2 frame times is called the "vulnerable" period
- Throughput is approximately $\lambda e^{-2\lambda}$
- This is maximized at $\lambda = 0.5$ for a throughput of $1/2e \approx 0.184 = 18.4\%$

Slotted ALOHA (Roberts, 1972)

- *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
  - *Nodes 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 can send new frame in next slot
  - 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
- Relatively 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

Slotted ALOHA Efficiency

Efficiency is the long-run fraction of successful slots when there's 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 1st node has success in a slot = $p(1-p)^{N-1}$
- Prob that some node is successful ≤ $Np(1-p)^{N-1}$
- 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!

A Different Analysis of Slotted ALOHA

- Vulnerable period is just 1 frame time
- Throughput is $\lambda e^{-\lambda}$
  which is maximized at $\lambda = 1$
  for a throughput of $1/e \approx 0.368 \approx 37\%$

Higher Arrival Rate

- Consider a transmission of a test frame
- Pr[success] = $e^{-\lambda}$
- Pr[collision] = $1 - e^{-\lambda}$
- Pr[success in k attempts] = $e^{-\lambda}(1 - e^{-\lambda})^{k-1}$
- E[# of attempts] = … = e^{λ}
- Small increase in channel load results in exponential decrease in efficiency

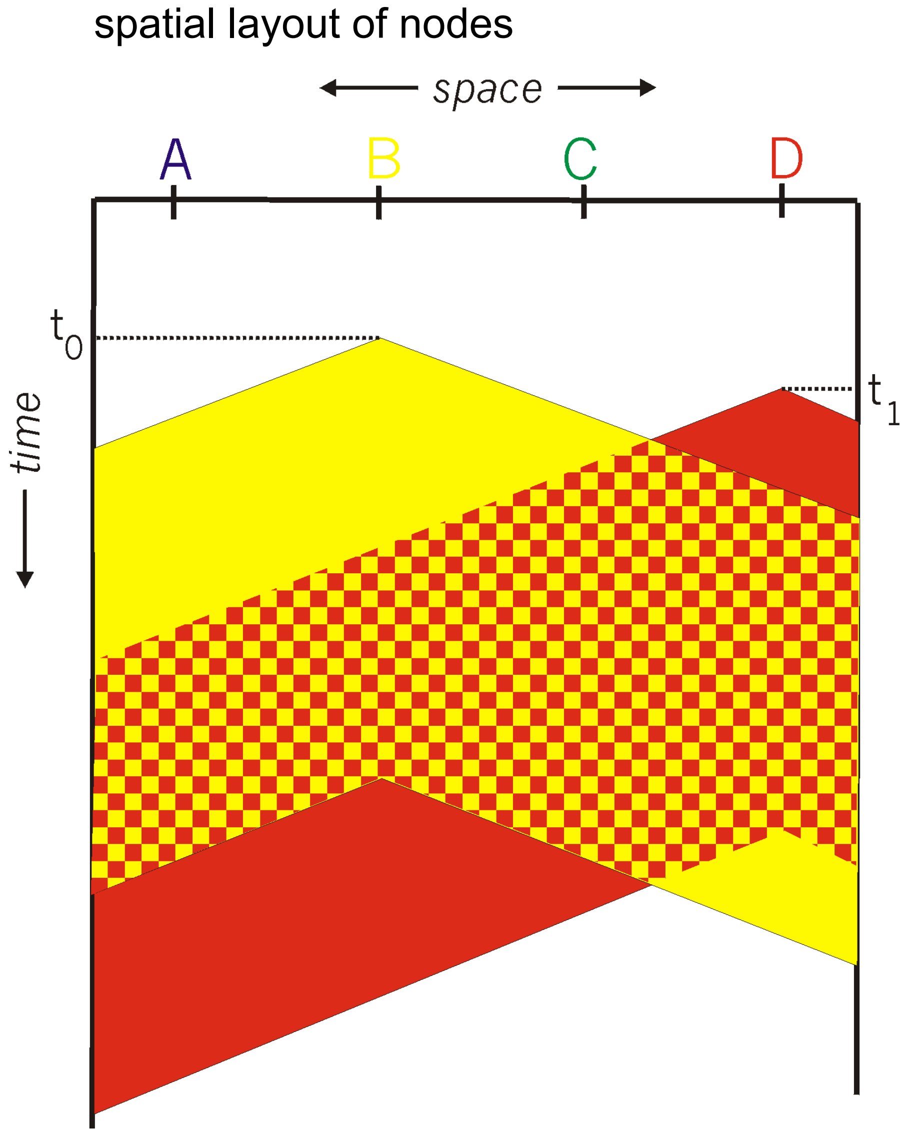
CSMA (Carrier Sense Multiple Access)

CSMA: *listen before transmit*

- If channel sensed idle: transmit entire frame
- If channel sensed busy, defer transmission

- There are several variations of this, which we won’t discuss:
  - Persistent CSMA
  - Non-persistent CSMA
  - P-persistent CSMA

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

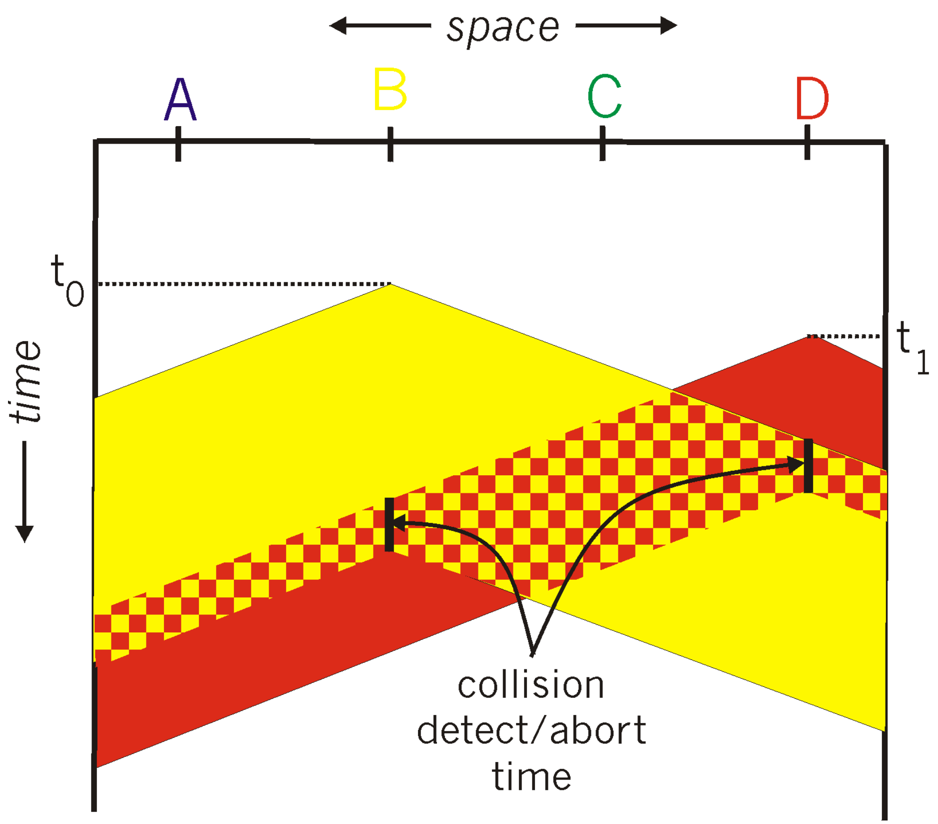
CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA

  - collisions *detected* within short time
  - colliding transmissions aborted (by the senders) → 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, hidden terminal problem, …

CSMA/CD Collision Detection



Collision Detection Time

- Suppose nodes share a straight cable
- Propagation delay between farthest nodes is τ
- A node senses collision if data read is different than data sent

- *At the maximum, how long does it take to detect collision?*

Collision Detection

- On a 1-km coaxial cable, τ ≈ 5μsec
- Thus, not until 10 μsec later a station is sure that no collision has occurred
- In fact, the station detecting the collision sends out a short "jam signal" to warn other stations of this
- Collision detection is an analog process
- Encoding must ensure that collision detection is possible
  - (e.g. collision of two 0-volt signals may be impossible to detect)

Minimum Frame Length

- At speed R bps, minimum frame length must be at least $2\tau R$
- To keep the protocol the same, increasing data rate implies reducing cable length
- Later, we'll see that max cable length
  - 10Base5: 500 meters
  - 10Base2: 185 meters
  - 10Base-T: 100 meters
  - 10Base-F: 2000 meters (fiber optics)
  - …

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“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!*

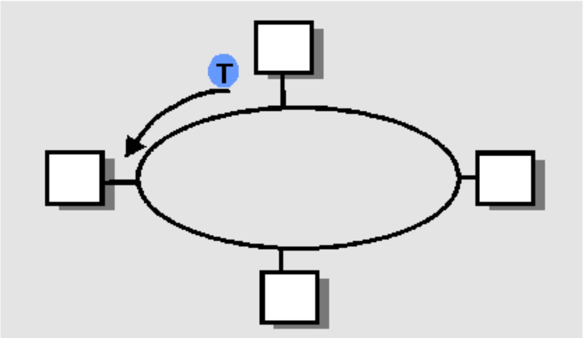
“Taking Turns” MAC protocols

Polling

- Master node “invites” slave nodes to transmit in turn
- Concerns:
  - Polling overhead
  - Latency
  - Single point of failure (master)

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,Code 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*
  - Taking Turns
    - polling from a central site, token passing