Hamming Code

- Gives a method for constructing a code with a distance of 3
  - Uses $n = 2^k - k - 1$, e.g., n=4, k=3
  - Put check bits in positions p that are powers of 2, starting with position 1
  - Check bit in position p is parity of positions with a p term in their values
- Plus an easy way to correct [soon]

Hamming Code (2)

- Example: data=0101, 3 check bits
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

_ _ _ _ _ _ _
1 2 3 4 5 6 7

Hamming Code (3)

- Example: data=0101, 3 check bits
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

$\underline{0}$	$\underline{1}$	0	$\underline{0}$	1	0	1	$\longrightarrow$
1	2	3	4	5	6	7	

$p_1 = 0+1+1 = 0$, $p_2 = 0+0+1 = 1$, $p_4 = 1+0+1 = 0$

Hamming Code (4)

- To decode:
  - Recompute check bits (with parity sum including the check bit)
  - Arrange as a binary number
  - Value (syndrome) tells error position
  - Value of zero means no error
  - Otherwise, flip bit to correct

Hamming Code (5)

- Example, continued

$$\longrightarrow \underline{0}\ \underline{1}\ 0\ \underline{0}\ 1\ 0\ 1$$

1 2 3 4 5 6 7

p_1= p_2=

p_4=

Syndrome =

Data =

Hamming Code (6)

- Example, continued

$$\longrightarrow \underline{0}\ \ \underline{1}\ \ 0\ \ \underline{0}\ \ 1\ \ 0\ \ 1$$

1 2 3 4 5 6 7

$p_1 = 0+0+1+1 = 0$, $p_2 = 1+0+0+1 = 0$,
$p_4 = 0+1+0+1 = 0$

Syndrome = 000, no error
Data = 0 1 0 1

Hamming Code (7)

- Example, continued

$$\longrightarrow \quad \underline{0}\ \ \underline{1}\ \ 0\ \ \underline{0}\ \ 1\ \ 1\ \ 1$$

1 2 3 4 5 6 7

p_1= p_2=

p_4=

Syndrome =

Data =

Hamming Code (8)

- Example, continued

$$\longrightarrow \quad \underline{0} \quad \underline{1} \quad 0 \quad \underline{0} \quad 1 \quad 1 \quad 1$$
$$\quad\quad\quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7$$

p_1= 0+0+1+1 = 0, p_2= 1+0+1+1 = 1,
p_4= 0+1+1+1 = 1

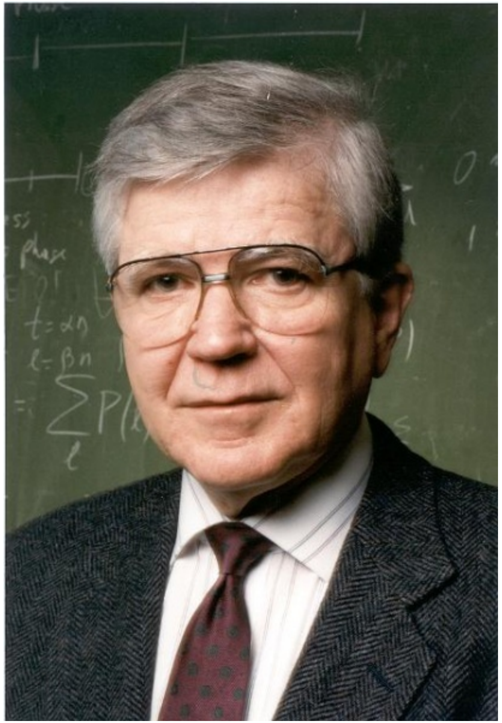
Syndrome = 1 1 0, flip position 6
Data = 0 1 0 1 (correct after flip!)

Other Error Correction Codes

- Codes used in practice are much more involved than Hamming
- Convolutional codes (§3.2.3)
  - Take a stream of data and output a mix of the recent input bits
  - Makes each output bit less fragile
  - Decode using Viterbi algorithm (which can use bit confidence values)

Other Codes (2) – LDPC

- Low Density Parity Check (§3.2.3)
  - LDPC based on sparse matrices
  - Decoded iteratively using a belief propagation algorithm
  - State of the art today
- Invented by Robert Gallager in 1963 as part of his PhD thesis
  - Promptly forgotten until 1996 …



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Detection vs. Correction

- Which is better will depend on the pattern of errors. For example:
  - 1000 bit messages with a bit error rate (BER) of 1 in 10000

- Which has less overhead?

Detection vs. Correction

- Which is better will depend on the pattern of errors. For example:
  - 1000 bit messages with a <u>bit error rate</u> (<u>BER</u>) of 1 in 10000

- Which has less overhead?
  - It still depends! We need to know more about the errors

Detection vs. Correction (2)

1. Assume bit errors are random
   - Messages have 0 or maybe 1 error

- Error correction:
  - Need ~10 check bits per message
  - Overhead:

- Error detection:
  - Need ~1 check bits per message plus 1000 bit retransmission 1/10 of the time
  - Overhead:

Detection vs. Correction (3)

2. Assume errors come in bursts of 100
   - Only 1 or 2 messages in 1000 have errors

- Error correction:
  - Need >>100 check bits per message
  - Overhead:

- Error detection:
  - Need 32? check bits per message plus 1000 bit resend 2/1000 of the time
  - Overhead:

Detection vs. Correction (4)

- Error correction:
  - Needed when errors are expected
  - Or when no time for retransmission
- Error detection:
  - More efficient when errors are not expected
  - And when errors are large when they do occur

Error Correction in Practice

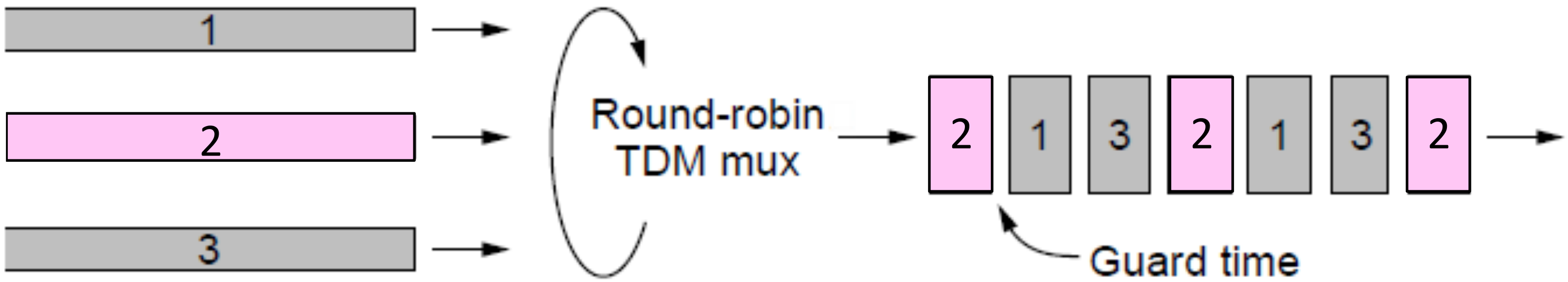
- Heavily used in physical layer
  - LDPC is the future, used for demanding links like 802.11, DVB, WiMAX, LTE, power-line, …
  - Convolutional codes widely used in practice
- Error detection (w/ retransmission) is used in the link layer and above for residual errors
- Correction also used in the application layer
  - Called Forward Error Correction (FEC)
  - Normally with an erasure error model
  - E.g., Reed-Solomon (CDs, DVDs, etc.)

Topic

- Multiplexing is the network word for the sharing of a resource
- Classic scenario is sharing a link among different users
  - Time Division Multiplexing (TDM) »
  - Frequency Division Multiplexing (FDM) »

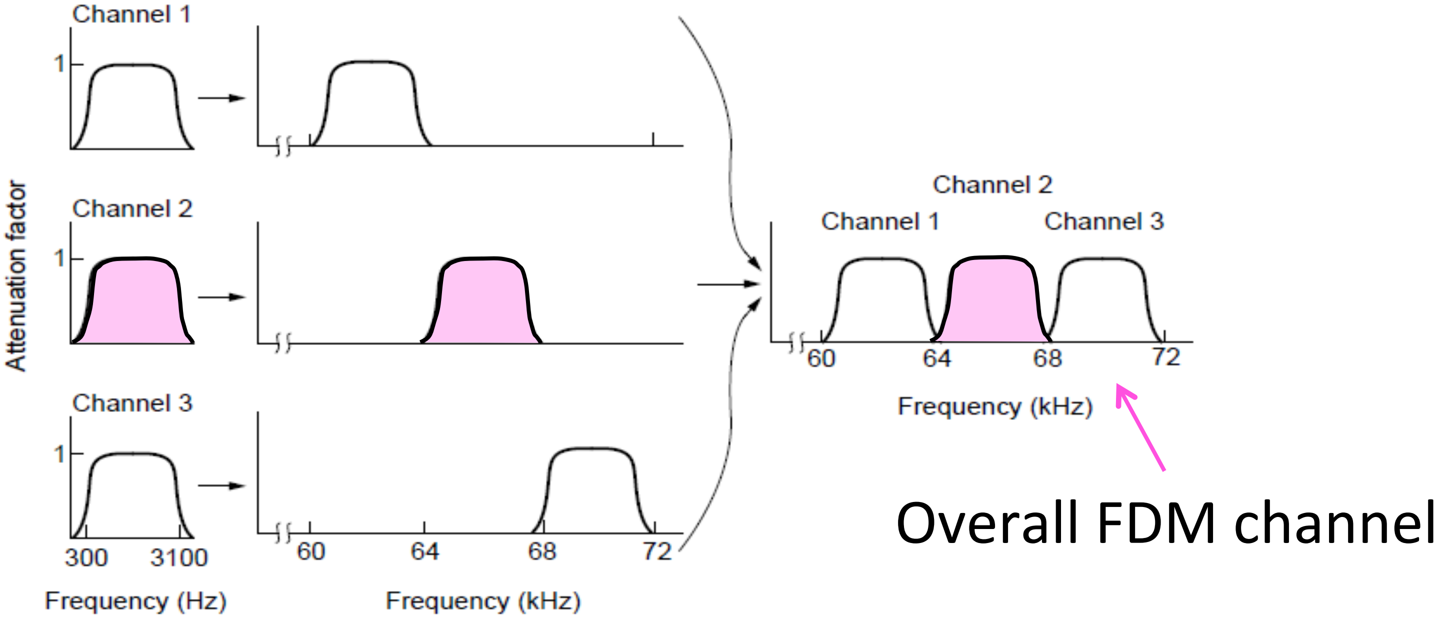
Time Division Multiplexing (TDM)

- Users take turns on a fixed schedule



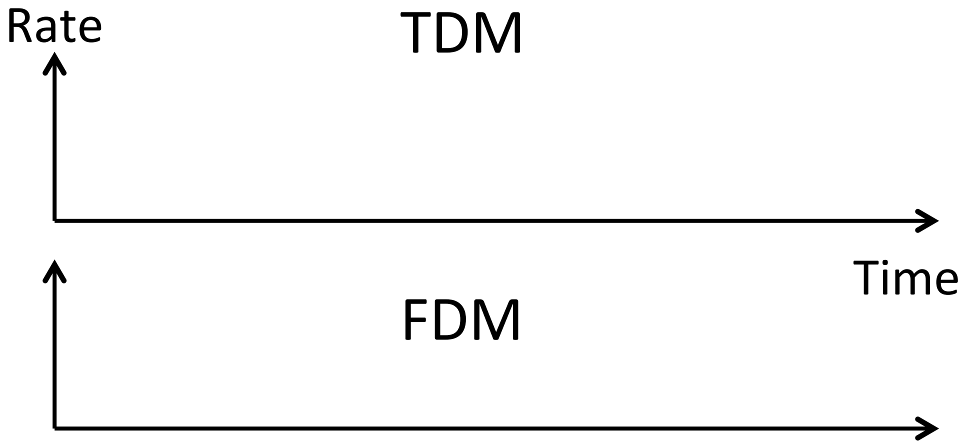
Frequency Division Multiplexing (FDM)

- Put different users on different frequency bands



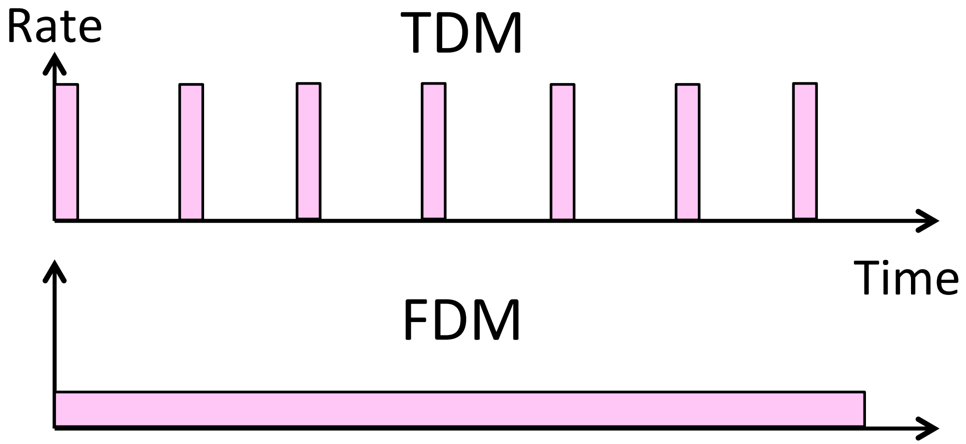
TDM versus FDM

- In TDM a user sends at a high rate a fraction of the time; in FDM, a user sends at a low rate all the time



TDM versus FDM (2)

- In TDM a user sends at a high rate a fraction of the time; in FDM, a user sends at a low rate all the time

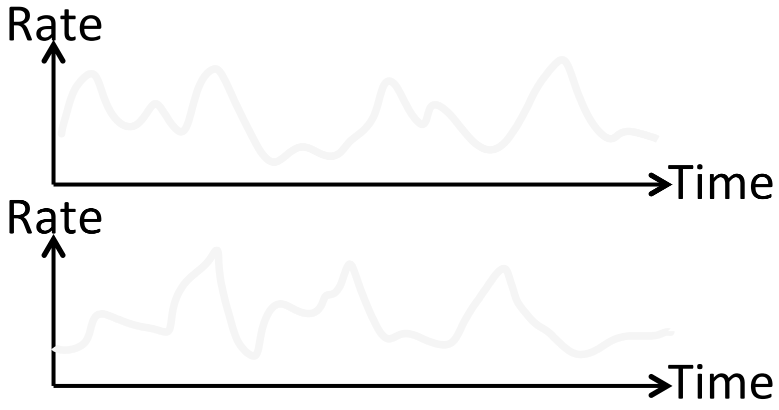


TDM/FDM Usage

- Statically divide a resource
  - Suited for continuous traffic, fixed number of users
- Widely used in telecommunications
  - TV and radio stations (FDM)
  - GSM (2G cellular) allocates calls using TDM within FDM

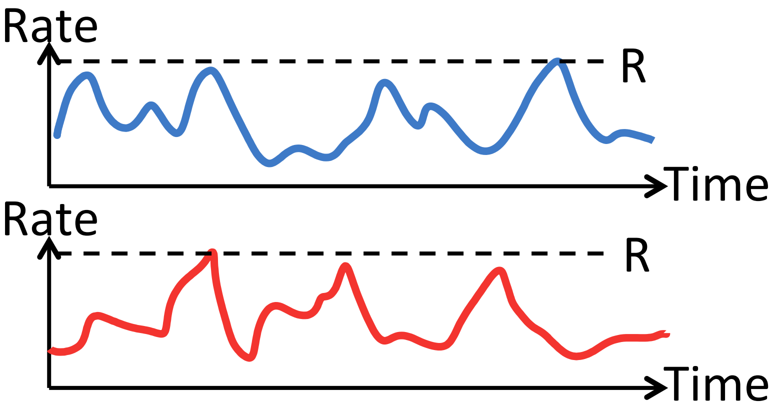
Multiplexing Network Traffic

- Network traffic is <u>bursty</u>
  - ON/OFF sources
  - Load varies greatly over time



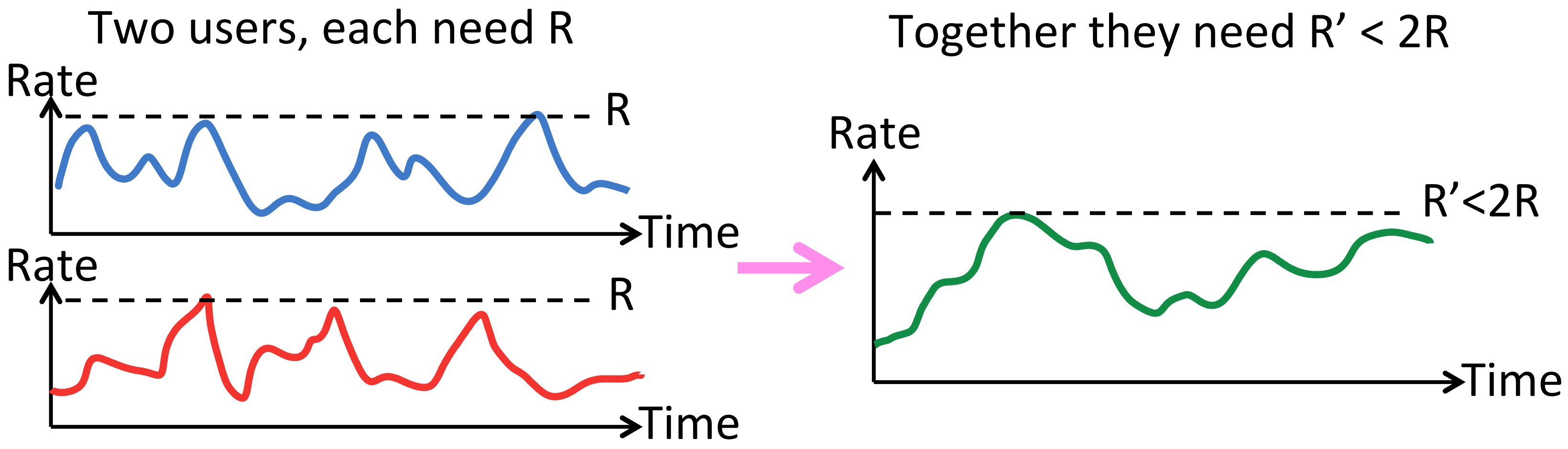
Multiplexing Network Traffic (2)

- Network traffic is <u>bursty</u>
  - Inefficient to always allocate user their ON needs with TDM/FDM



Multiplexing Network Traffic (3)

- Multiple access schemes multiplex users according to their demands – for gains of statistical multiplexing



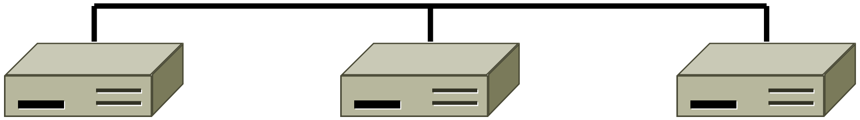
Multiple Access

- We will look at two kinds of multiple access protocols

1. Randomized. Nodes randomize their resource access attempts
   – Good for low load situations
2. Contention-free. Nodes order their resource access attempts
   – Good for high load or guaranteed quality of service situations

Topic

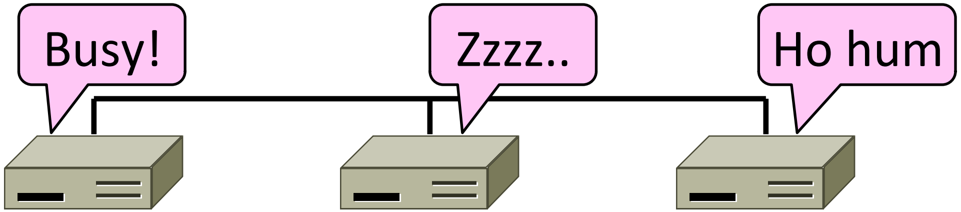
- How do nodes share a single link? Who sends when, e.g., in WiFI?
  - Explore with a simple model



- Assume no-one is in charge; this is a distributed system

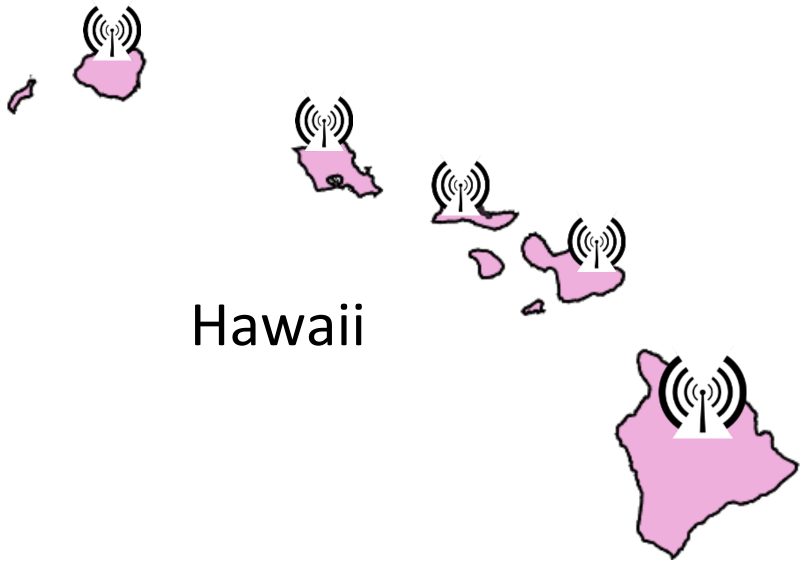
Topic (2)

- We will explore random multiple access control (MAC) protocols
  - This is the basis for classic Ethernet
  - Remember: data traffic is bursty



ALOHA Network

- Seminal computer network connecting the Hawaiian islands in the late 1960s
  - When should nodes send?
  - A new protocol was devised by Norm Abramson …

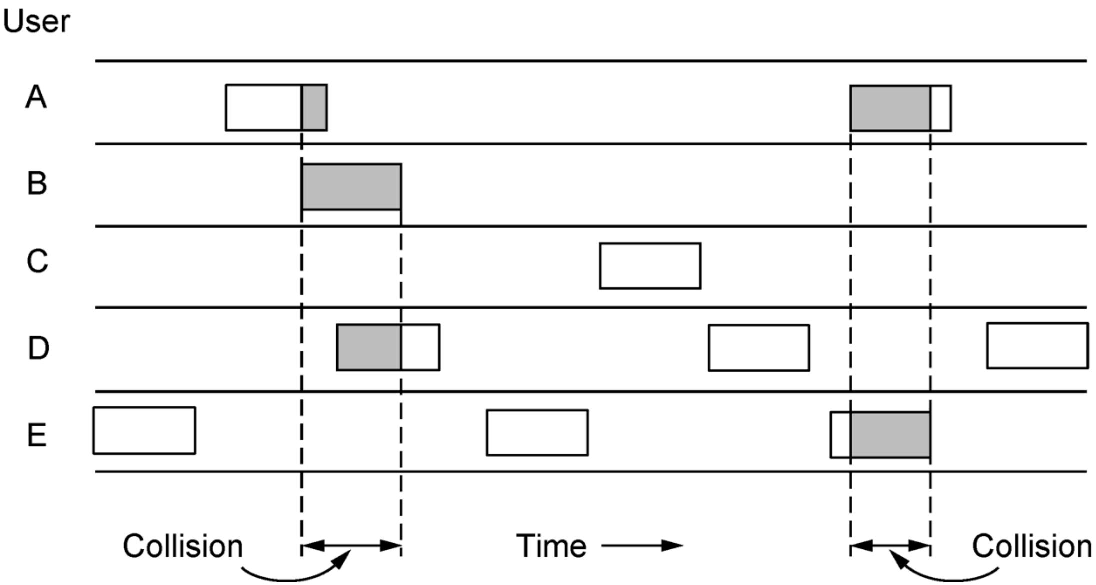


ALOHA Protocol

- Simple idea:
  - Node just sends when it has traffic.
  - If there was a collision (no ACK received) then wait a random time and resend
- That's it!

ALOHA Protocol (2)

- Some frames will be lost, but many may get through…
- Good idea?



ALOHA Protocol (3)

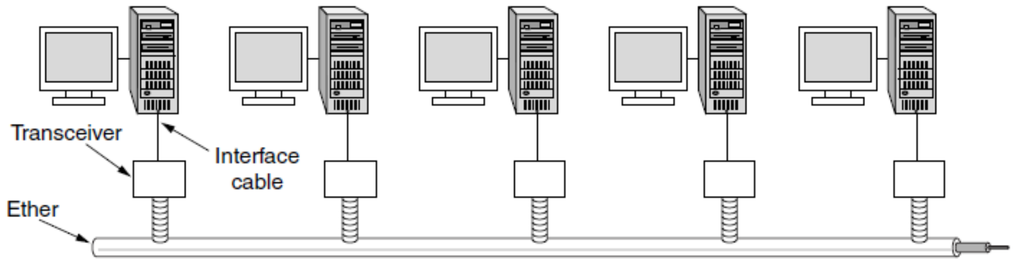
- Simple, decentralized protocol that works well under low load!

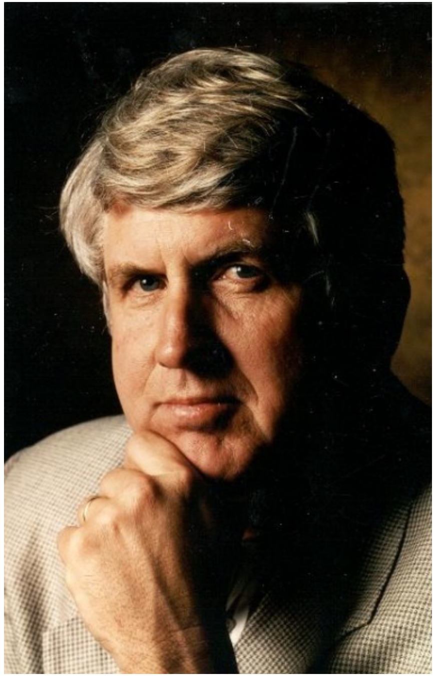
- Not efficient under high load
  - Analysis shows at most 18% efficiency
  - Improvement: divide time into slots and efficiency goes up to 36%

- We'll look at other improvements

Classic Ethernet

- ALOHA inspired Bob Metcalfe to invent Ethernet for LANs in 1973
  - Nodes share 10 Mbps coaxial cable
  - Hugely popular in 1980s, 1990s





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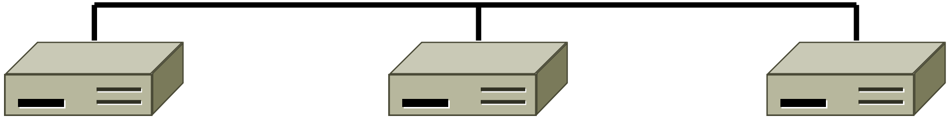
CSMA (Carrier Sense Multiple Access)

- Improve ALOHA by listening for activity before we send (Doh!)
  - Can do easily with wires, not wireless

- So does this eliminate collisions?
  - Why or why not?

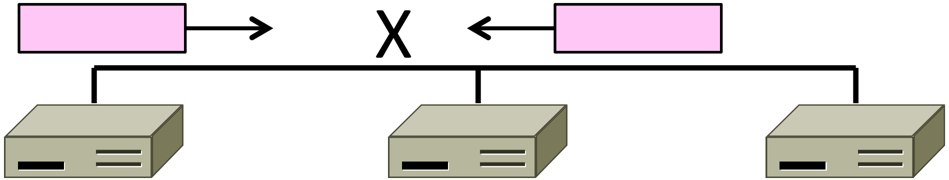
CSMA (2)

- Still possible to listen and hear nothing when another node is sending because of delay



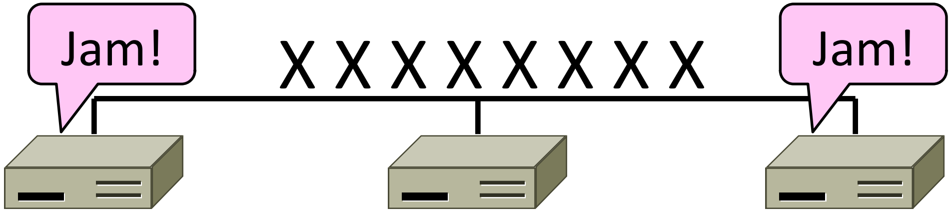
CSMA (3)

- CSMA is a good defense against collisions only when BD is small



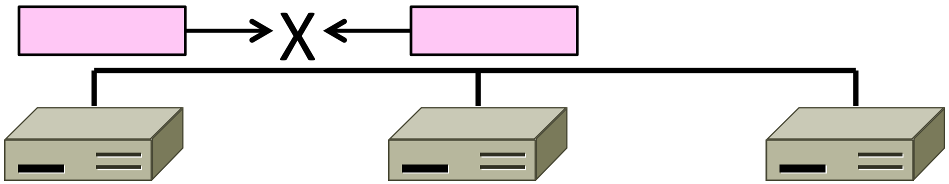
CSMA/CD (with Collision Detection)

- Can reduce the cost of collisions by detecting them and aborting (Jam) the rest of the frame time
  - Again, we can do this with wires



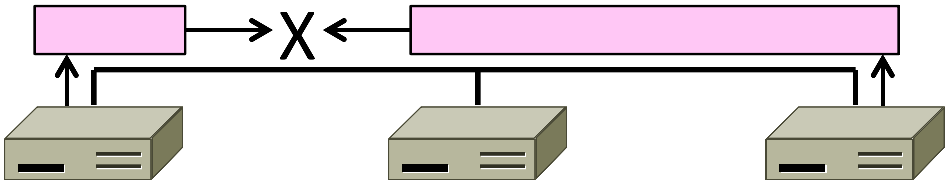
CSMA/CD Complications

- Want everyone who collides to know that it happened
  - Time window in which a node may hear of a collision is 2D seconds



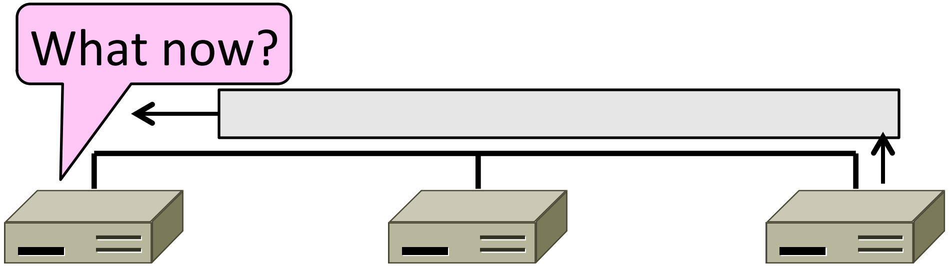
CSMA/CD Complications (2)

- Impose a minimum frame size that lasts for 2D seconds
  - So node can't finish before collision
  - Ethernet minimum frame is 64 bytes



CSMA "Persistence"

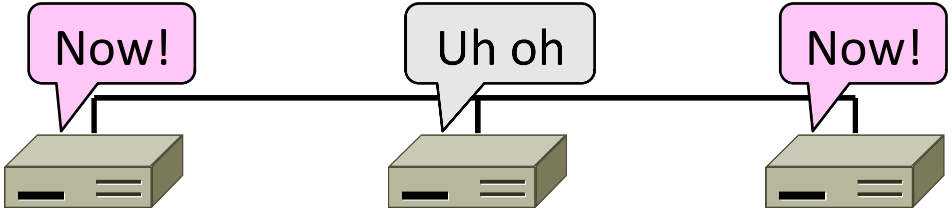
- What should a node do if another node is sending?



- Idea: Wait until it is done, and send

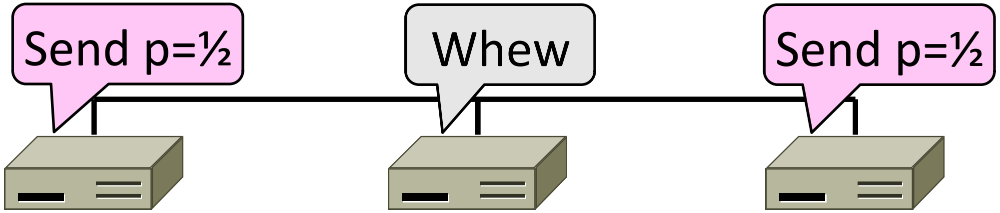
CSMA "Persistence" (2)

- Problem is that multiple waiting nodes will queue up then collide
  - More load, more of a problem



CSMA "Persistence" (3)

- Intuition for a better solution
  - If there are N queued senders, we want each to send next with probability 1/N

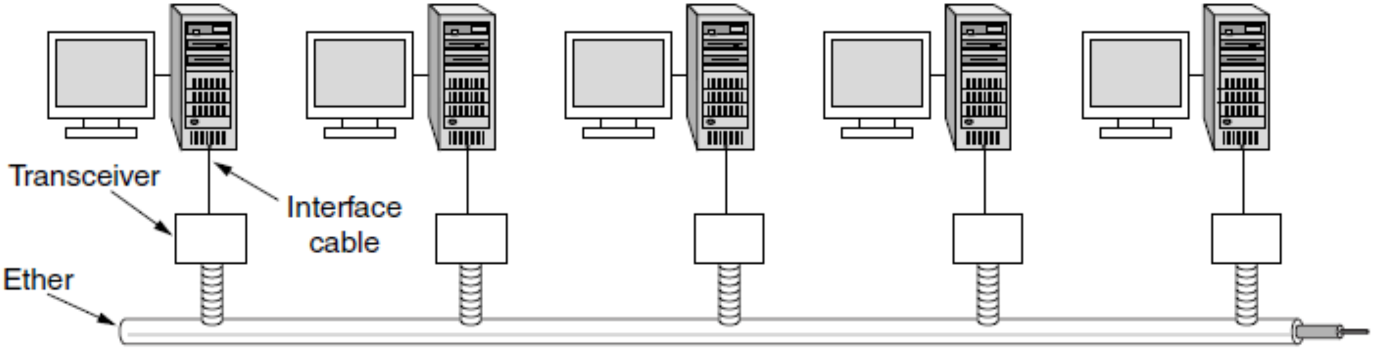


Binary Exponential Backoff (BEB)

- Cleverly estimates the probability
  - 1st collision, wait 0 or 1 frame times
  - 2nd collision, wait from 0 to 3 times
  - 3rd collision, wait from 0 to 7 times …
- BEB doubles interval for each successive collision
  - Quickly gets large enough to work
  - Very efficient in practice

Classic Ethernet, or IEEE 802.3

- Most popular LAN of the 1980s, 1990s
  - 10 Mbps over shared coaxial cable, with baseband signals
  - Multiple access with "1-persistent CSMA/CD with BEB"



Ethernet Frame Format

- Has addresses to identify the sender and receiver
- CRC-32 for error detection; no ACKs or retransmission
- Start of frame identified with physical layer preamble

Packet from Network layer (IP)

	Preamble	Destination address	Source address	Type	Data	Pad	Check-sum
Bytes	8	6	6	2	0-1500	0-46	4

Modern Ethernet

- Based on switches, not multiple access, but still called Ethernet
  - We'll get to it in a later segment