ECSE-4730: Computer Communication Networks (CCN)

Chapter 5: The Data Link Layer

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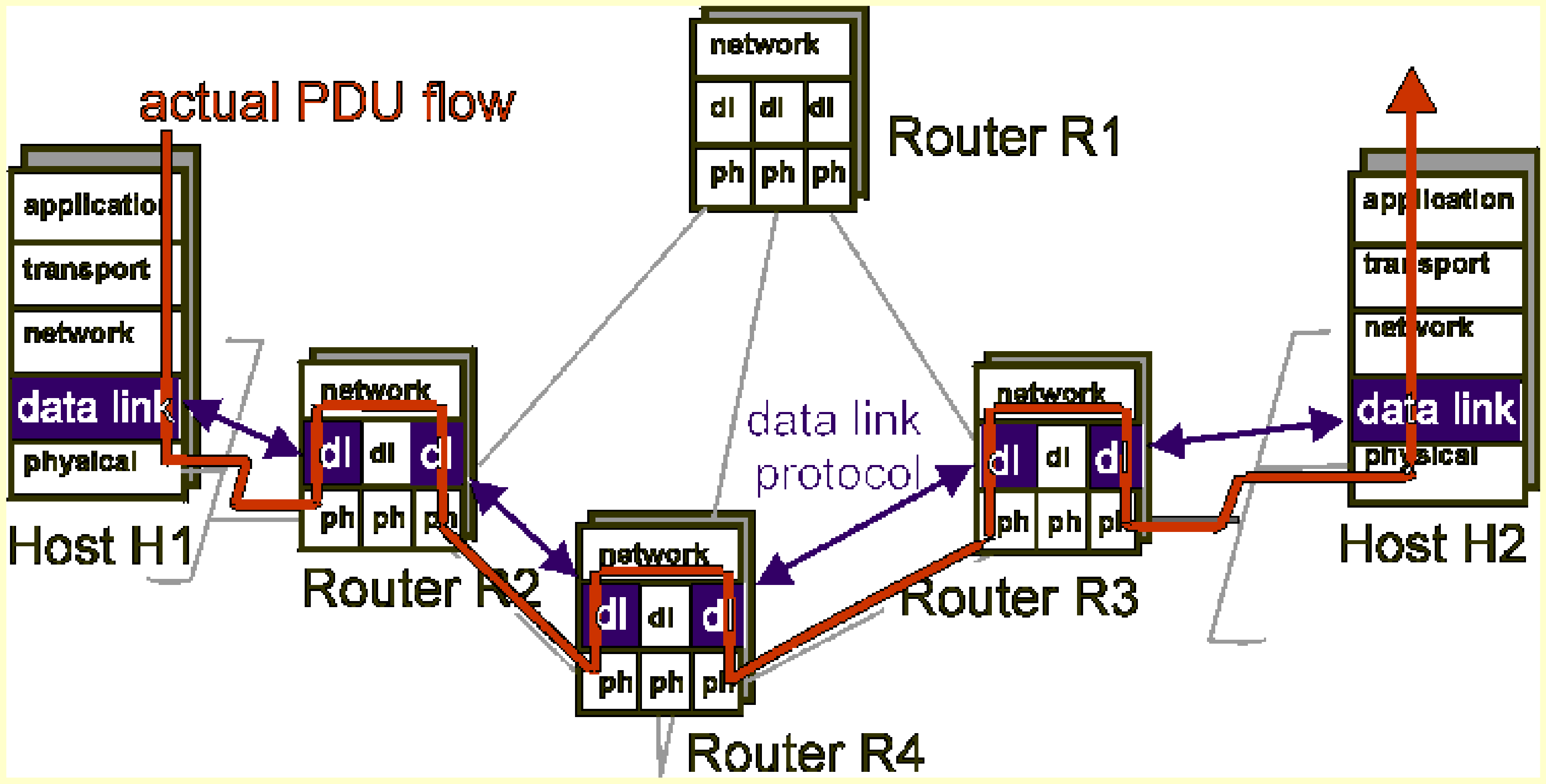
Understand principles behind data link layer services:
- error detection, correction
- sharing a broadcast channel: multiple access
- link layer addressing
- reliable data transfer, flow control: *done!*
- Instantiation and implementation of various link layer technologies

Overview

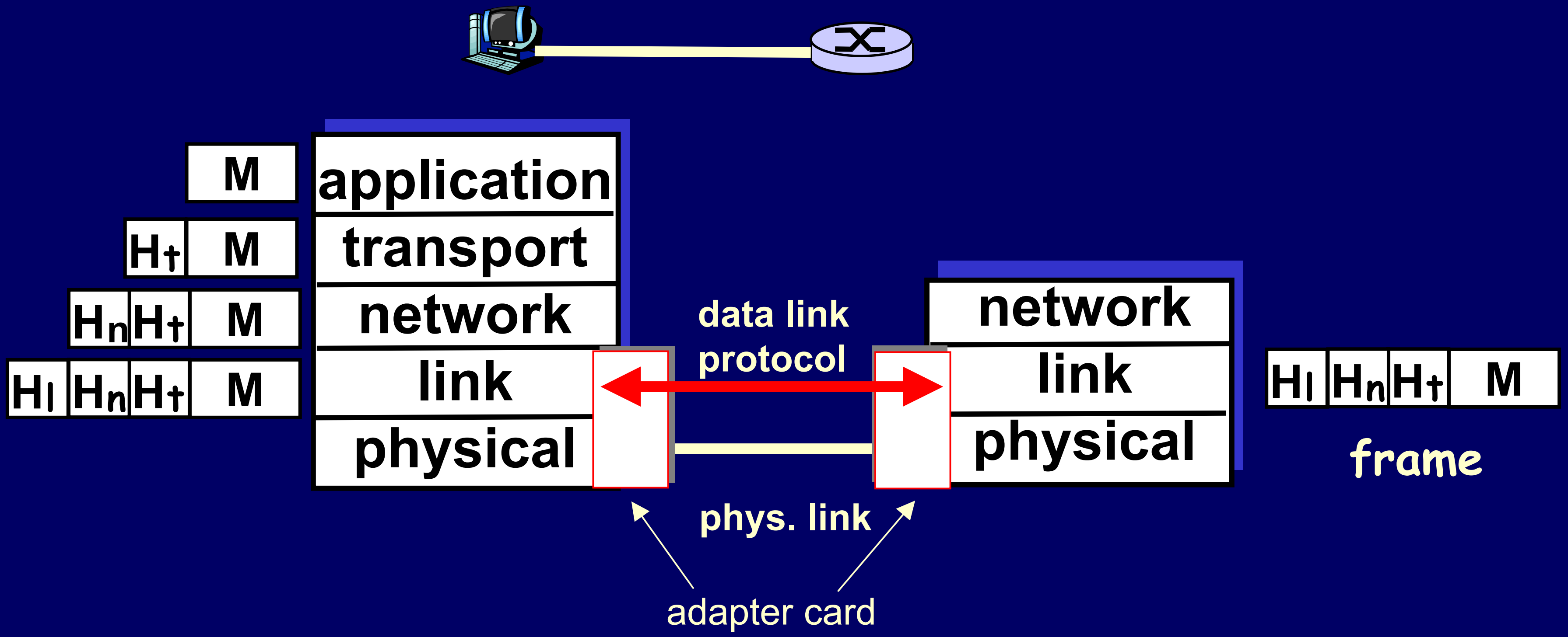
- link layer services
- error detection, correction
- multiple access protocols and LANs
- link layer addressing, ARP
- specific link layer technologies:
  - Ethernet
  - hibs, bridges, switches
  - IEEE 802.11 LANs
  - PPP
  - ATM

Link Layer: setting the context - 1



Link Layer: setting the context - 2

- two *physically connected* devices:
  - host-router, router-router, host-host
- unit of data: *frame*



M

H_t M

H_n H_t M

H_l H_n H_t M

application

transport

network

link

physical

data link protocol

network

link

physical

H_l H_n H_t M

frame

phys. link

adapter card

Link Layer Services - 1

- Framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - implement channel access if shared medium,
  - ‘physical addresses’ used in frame headers to identify source, dest
    - different from IP address!

Link Layer Services - 2

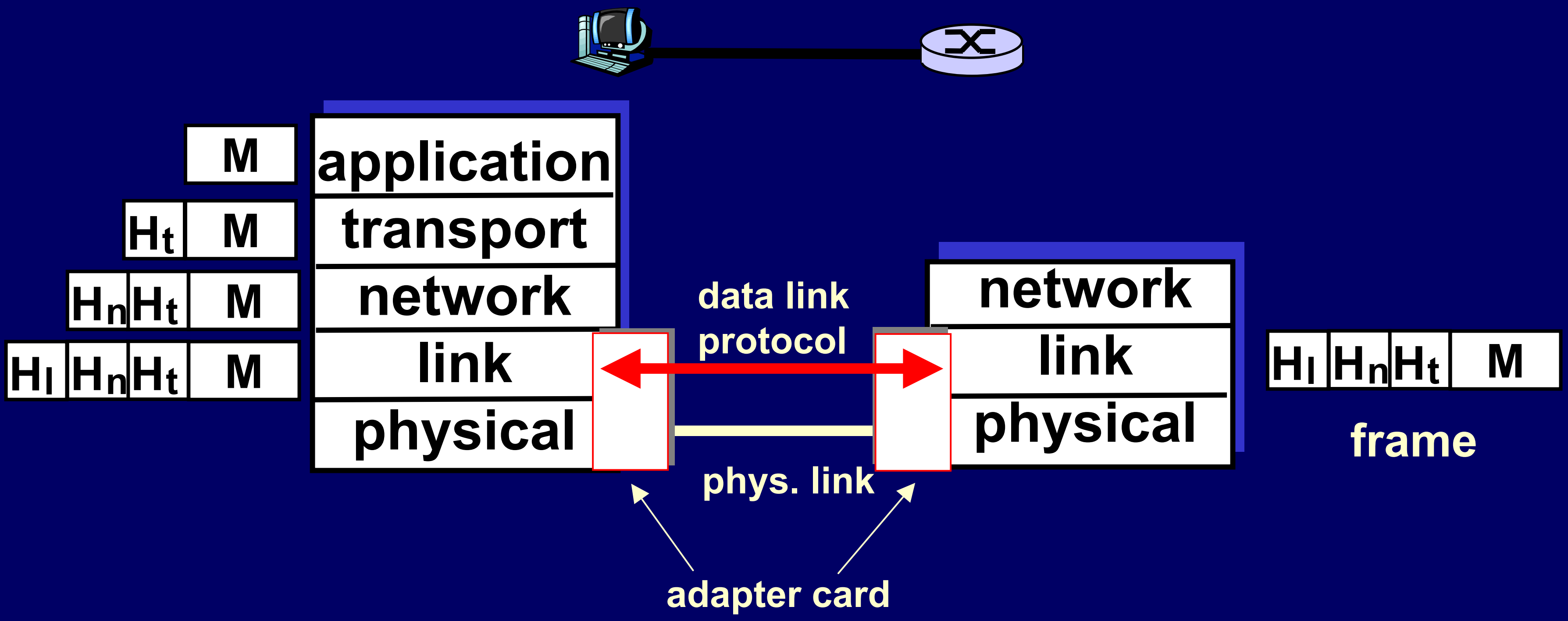
- Reliable delivery between two physically connected devices:
  - we learned how to do this already (chapter 3)!
  - seldom used on low bit error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?

Link Layer Services - 3

- **Flow Control:**
  - **pacing between sender and receivers**
- **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**

Link Layer: Implementation

- Implemented in “adapter”
  - e.g., PCMCIA card, Ethernet card
  - typically includes: RAM, DSP chips, host bus interface, and link interface



M

H_t M

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application

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data link protocol

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network

link

physical

H_l H_n H_t M

frame

adapter card

Error Detection - 1

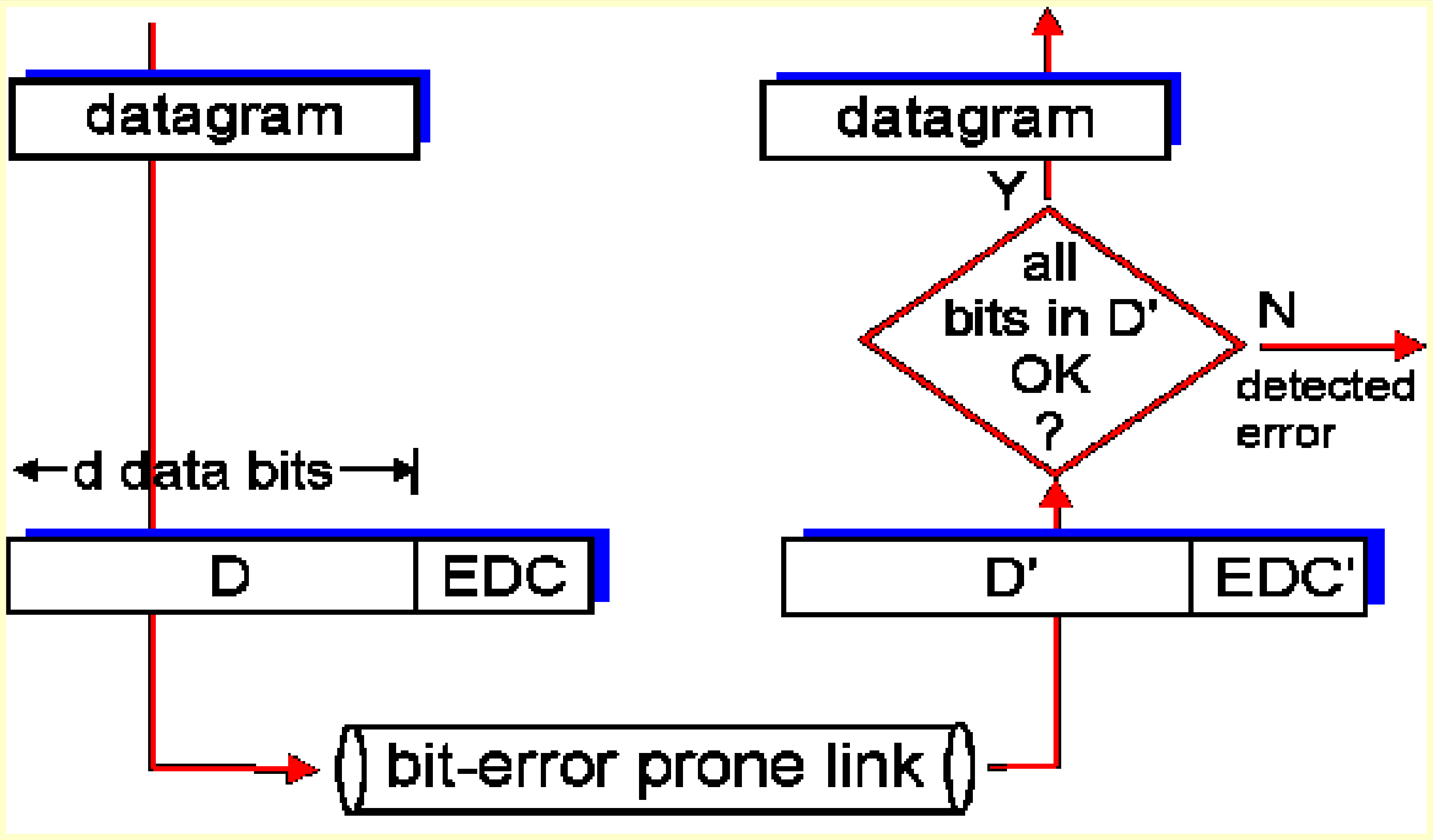
EDC= Error Detection and Correction bits (redundancy)

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

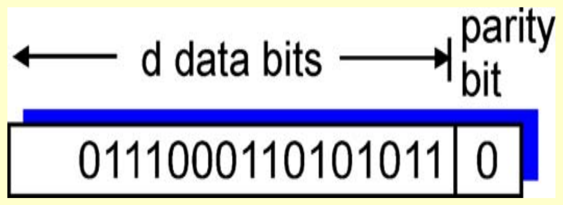
Error Detection - 2



Parity Checking

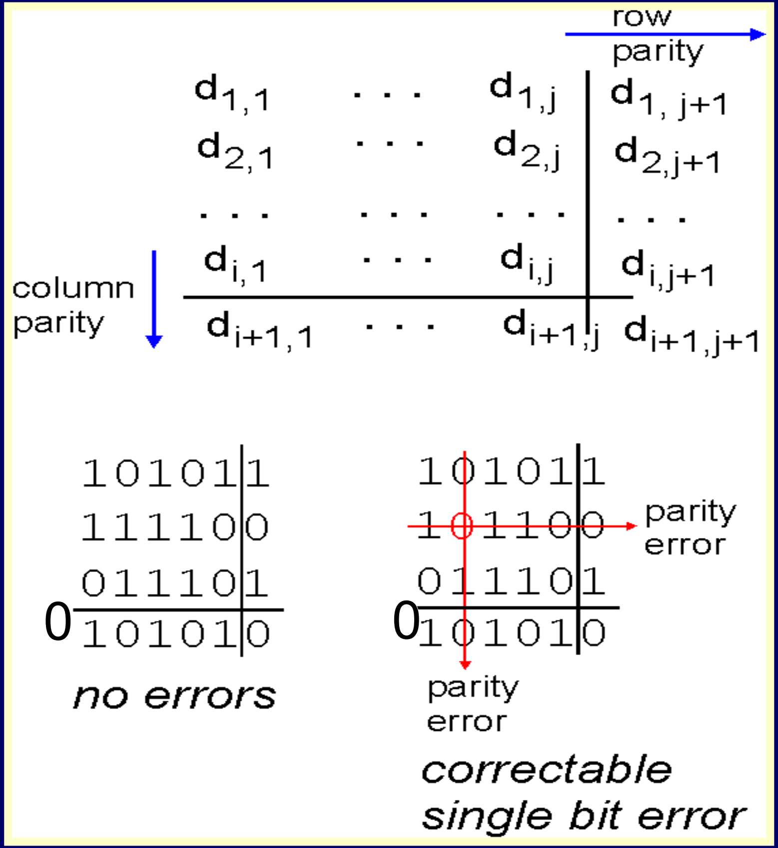
Single Bit Parity:

Detect single bit errors



Two Dimensional Bit Parity:

Detect and correct single bit errors



Internet checksum

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

Sender:

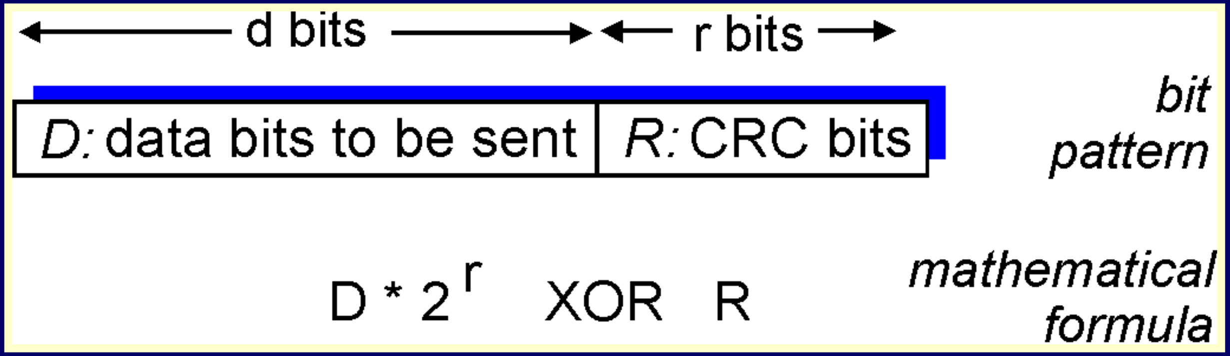
- treat segment contents as sequence of 16-bit integers
- checksum: addition (1’s complement sum) of segment contents
- sender puts checksum value into UDP checksum field

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, HDCL)



← d bits → ← r bits →

D: data bits to be sent | *R:* CRC bits

bit pattern

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

mathematical formula

CRC Example

Want:

D·2r XOR R = nG

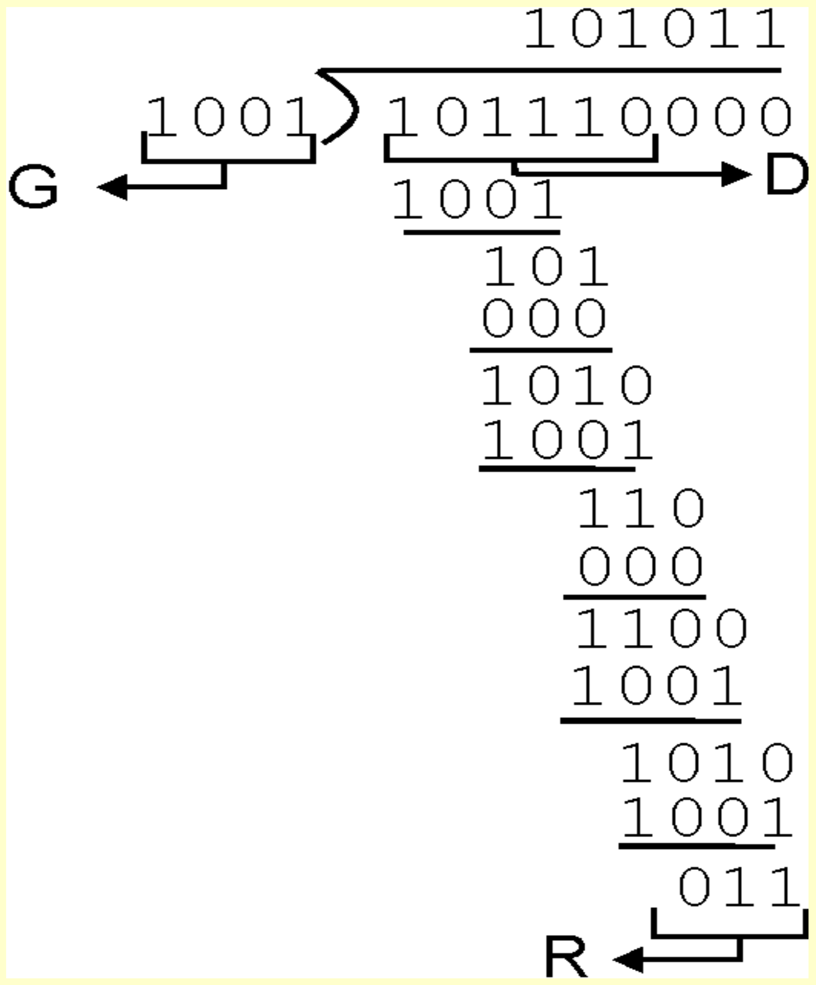
equivalently:

D·2r = nG XOR R

equivalently:

if we divide D·2r by G, want reminder R

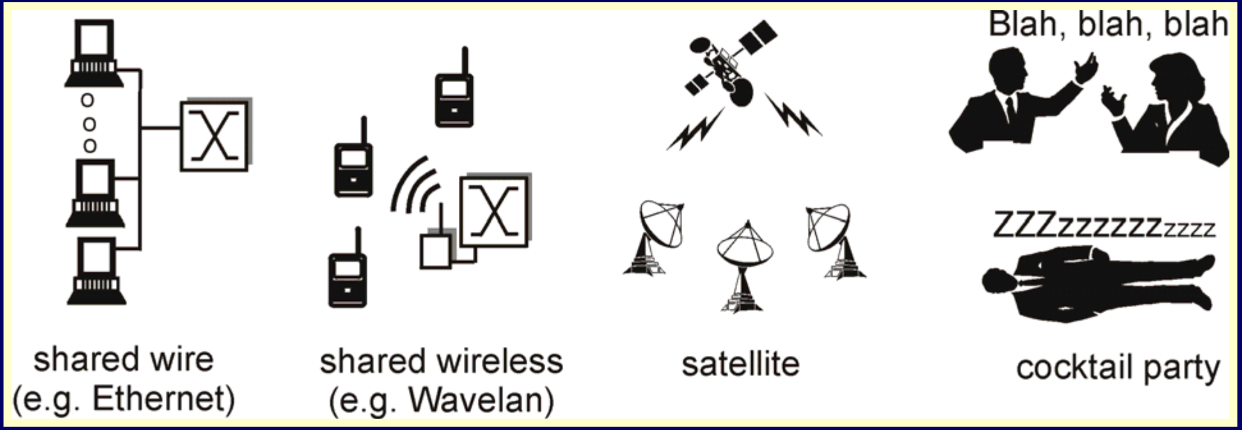
$$R = \text{remainder}\left[\frac{D\cdot 2r}{G}\right]$$



Multiple Access Links and Protocols

Three types of "links":

- Point-to-point (single wire, e.g. PPP, SLIP)
- **Broadcast** (shared wire or medium; e.g, Ethernet, Wavelan, etc.)



- Switched (e.g., switched Ethernet, ATM etc)

Multiple Access protocols - 1

- **single shared communication channel**
- **two or more simultaneous transmissions by nodes: interference**
  - **only one node can send successfully at a time**

- ***multiple access protocol:***
  - **distributed algorithm that determines how stations share channel, i.e., determine when station can transmit**

Multiple Access protocols - 2

- *multiple access protocol (cont.):*
  - communication about channel sharing must use channel itself!
  - What to look for in multiple access protocols:
    - synchronous or asynchronous
    - information needed about other stations
    - robustness (e.g., to channel errors)
    - performance

Multiple Access protocols - 3

- claim: humans use multiple access protocols all the time
- class can "guess" multiple access protocols
  - multiaccess protocol 1:
  - multiaccess protocol 2:
  - multiaccess protocol 3:
  - multiaccess protocol 4:

MAC Protocols: a taxonomy

Three broad classes:

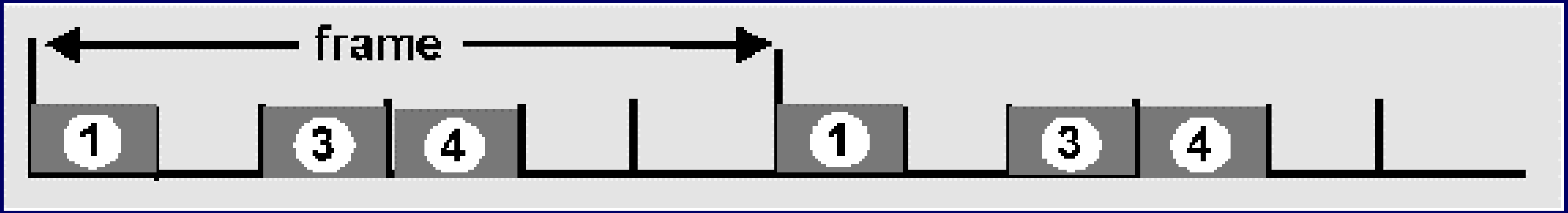
- **Channel Partitioning**
  - **divide channel into smaller "pieces" (time slots, frequency)**
  - **allocate piece to node for exclusive use**
- **Random Access**
  - **allow collisions**
  - **"recover" from collisions**
- **"Taking turns"**
  - **tightly coordinate shared access to avoid collisions**

Goal: efficient, fair, simple, decentralized

Channel Partitioning MAC protocols: TDMA - 1

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 MAC protocols: TDMA - 2

- TDM (Time Division Multiplexing): channel divided into N time slots, one per user; inefficient with low duty cycle users and at light load.

- FDM (Frequency Division Multiplexing): frequency subdivided.

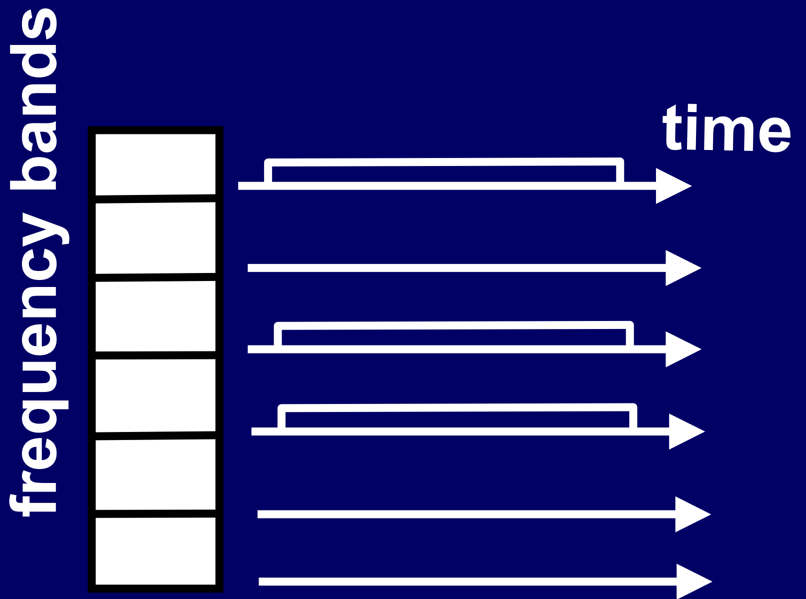
Channel Partitioning MAC protocols: FDMA - 1

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

Channel Partitioning MAC protocols: FDMA - 2

- Example: 6-station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle



Channel Partitioning
MAC protocols: FDMA - 3

- TDM (Time Division Multiplexing): channel divided into N time slots, one per user; inefficient with low duty cycle users and at light load.

- FDM (Frequency Division Multiplexing): frequency subdivided.

Channel Partitioning (CDMA) - 1

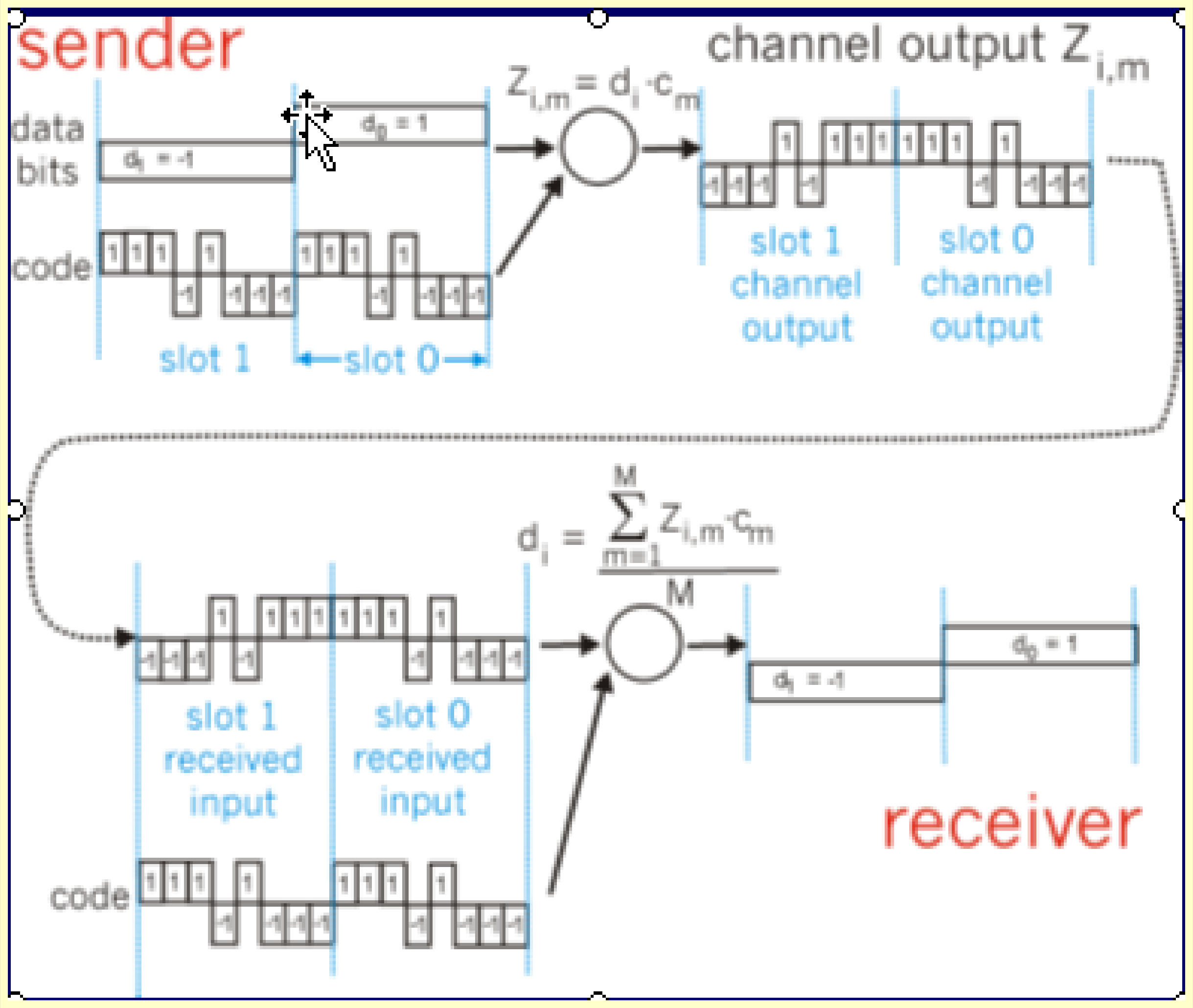
CDMA (Code Division Multiple Access)

- unique “code” assigned to each user; ie, code set partitioning
- used mostly in wireless broadcast channels (cellular, satellite, etc)
- all users share same frequency, but each user has own “chipping” sequence (ie, code) to encode data

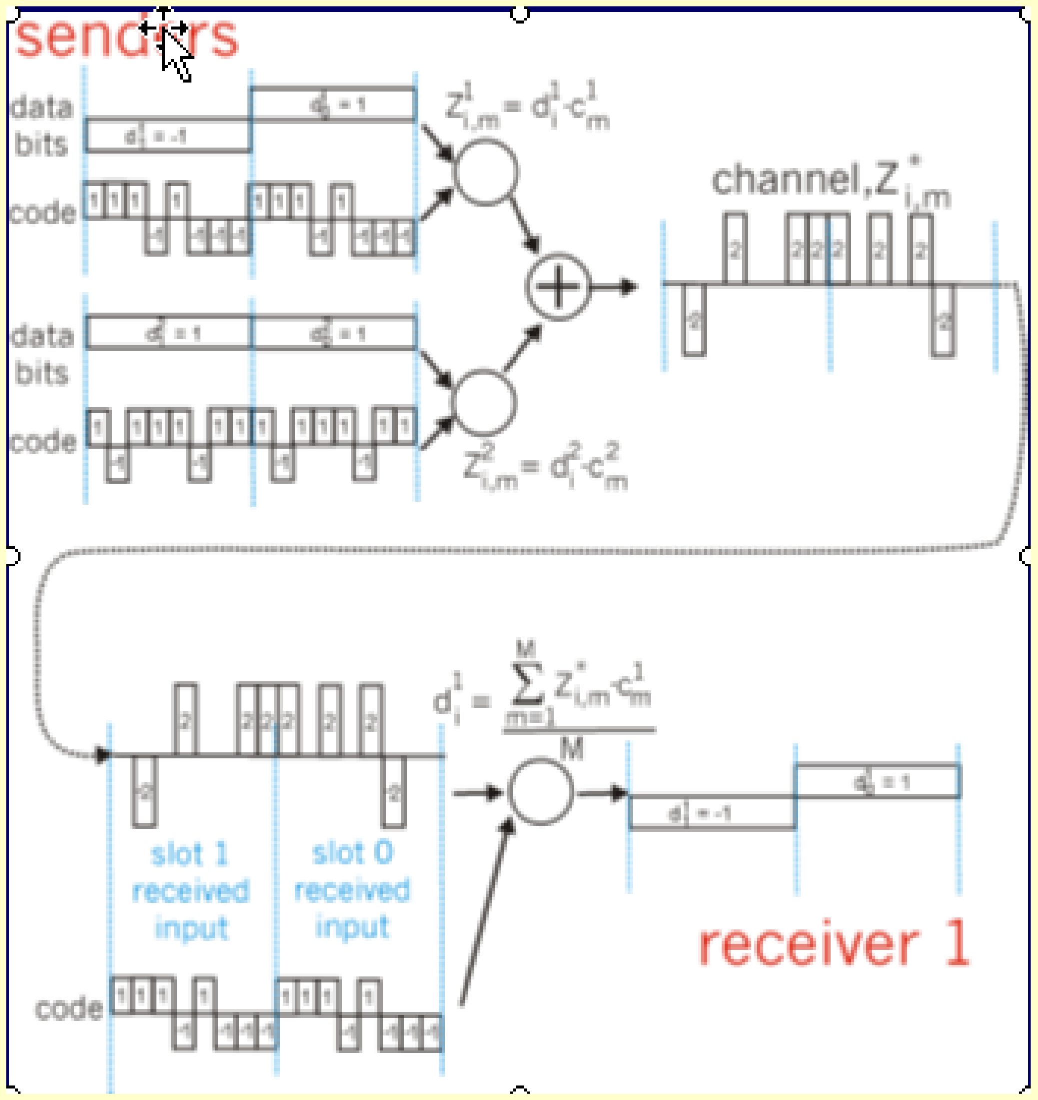
Channel Partitioning (CDMA) - 2

- **Encoded signal** = (original data) X (chipping sequence)
- **Decoding:** inner-product of encoded signal and chipping sequence
- allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")

CDMA Encode/Decode



CDMA: two-sender interference



Performance of Fixed Assignment Protocols - 1

- Fixed assignment protocols are ideal for continuous streams such as video or audio
- What about for packet switched data?
- A “perfect” multiple access scheme would always use the channel when there are packets waiting (statistical multiplexing)
- The mean delay for statistical multiplexing is just like for the M / M / 1 queue: $E(T) = \frac{1}{\mu - \lambda}$,

  where λ is the arrival rate and μ is the service rate

Performance of Fixed Assignment Protocols - 2

- OTOH fixed assignment protocols divide the channel into N separate independent, μ/N identical subchannels
- If each user has arrival rate λ/N, each user/subchannel pair can be modeled as a separate M / M / 1 queue
- And the mean delay for a packet is

$$E(T) = \frac{1}{\mu/N - \lambda/N} = \frac{N}{\mu - \lambda}$$

- So, if we use fixed assignment protocols for packet switched data, mean delay goes up by a factor of N!!

Performance of Fixed Assignment Protocols - 3

- This analysis is only appropriate for TDMA de to the discrete-time (slotted) nature of TDMA but the rough factor of N still holds
- Fixed assignment protocols are not appropriate for multiple access in a packet switched network with a large number of users
- Packet arrivals are fairly random, so there will be many times when packets are waiting at one user while other users are idle
- The idle resources (time slots or bandwidth or both are wasted in this case)

Random Access Protocols - 1

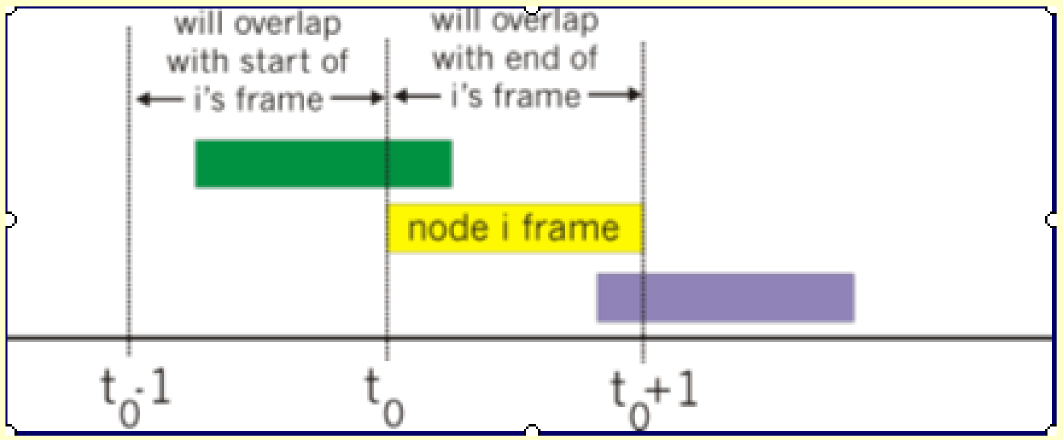
- When node has packet to send
  - transmit at full channel data rate R.
  - no *a priori* coordination among nodes
- Two or more transmitting nodes -> “collision”,
- Random access MAC protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)

Random Access Protocols - 2

- Examples of random access MAC protocols:
  - ALOHA
  - slotted ALOHA
  - CSMA and CSMA/CD

Pure (unslotted) ALOHA - 1

- Unslotted Aloha: simpler, no synchronization
- pkt needs transmission:
  - send without awaiting for beginning of slot
- Collision probability increases:
  - pkt sent at t_0 collide with other pkts sent in $[t_0-1, t_0+1]$



Pure (unslotted) ALOHA - 2

P(success by given node) = P(node transmits) .

P(no other node transmits in $[p_0-1,p_0]$.

P(no other node transmits in $[p_0-1,p_0]$

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

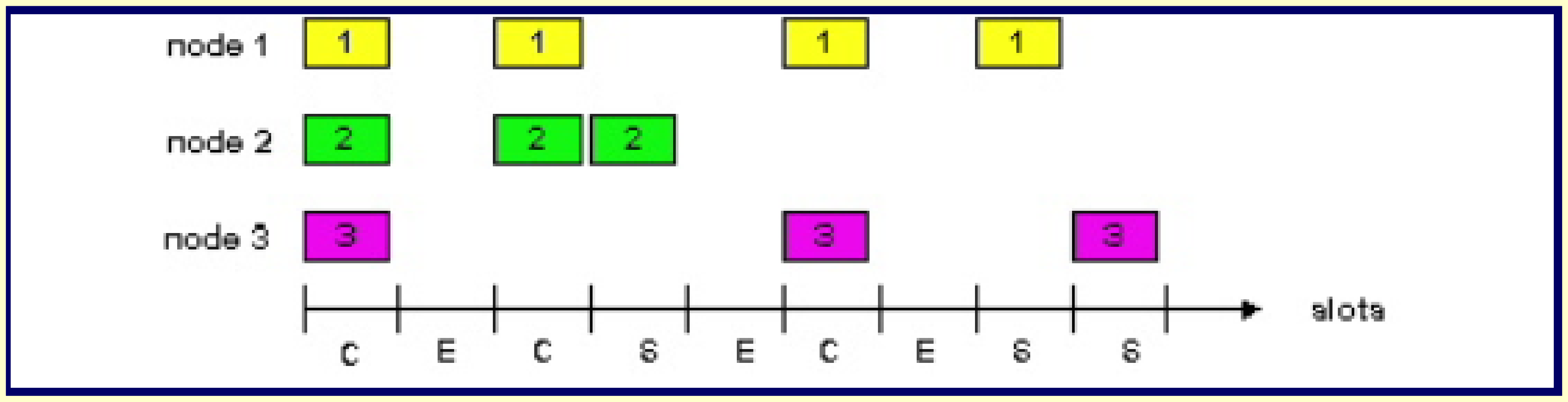
P(success by any of N nodes) = $N p \cdot (1-p)^{(N-1)} \cdot (1-p)^{(N-1)}$

… choosing optimum p as n -> infty ...

= 1/(2e) = .18

Slotted Aloha

- time is divided into equal size slots (= pkt trans. time)
- node with new arriving pkt: transmit at beginning of next slot
- if collision: retransmit pkt in future slots with probability p, until successful.



Success (S), Collision (C), Empty (E) slots

Slotted Aloha Efficiency

Q: What is max fraction slots successful?

A: Suppose N stations have packets to send

- each transmits in slot with probability p
- prob. successful transmission S is:

by single node: $S = p\,(1-p)^{(N-1)}$

by any of N nodes

S = Prob (only one transmits)

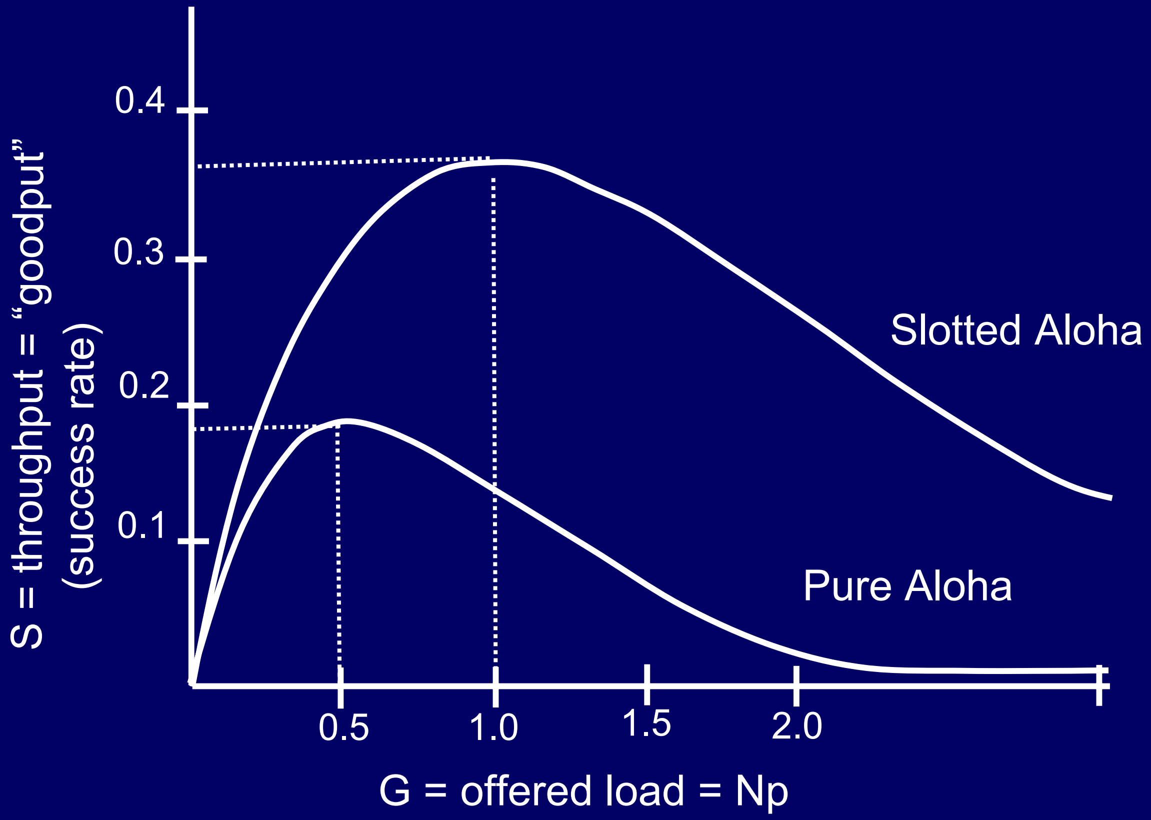
$= N p\,(1-p)^{(N-1)}$

… choosing optimum p as n -> infty …

= 1/e = .37 as N -> infty

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

Performance Comparison



***protocol* constrains effective channel throughput!**

Carrier Sense Multiple Access (CSMA) - 1

- In some shorter distance networks, it is possible to listen to the channel before transmitting
- In radio networks, this is called " sensing the carrier"
- The CSMA protocol works just like Aloha except: If the channel is sensed busy, then the user waits to transmit its packet, and a collision is avoided
- This really improves the performance in short distance networks!

Carrier Sense Multiple Access (CSMA) - 2

- How long does a blocked user wait before trying again to transmit its packet? Three basic variants:
- 1-persistent: Blocked user continuously senses channel until its idle, then transmits
- 0-persistent: Blocked user waits a randomly chosen amount of time before sensing channel again

Carrier Sense Multiple Access (CSMA) - 3

- P-persistent: Let T = end-to-end propagation delay
  - **If channel is idle then transmit packet**
  - **If channel busy then toss coin *[with P(heads) = P]***
  - **Heads: Transmit at first idle**
  - **Tails: wait until first idle plus *T*, sense, repeat**
- **Human analogy: Don’t interrupt others**

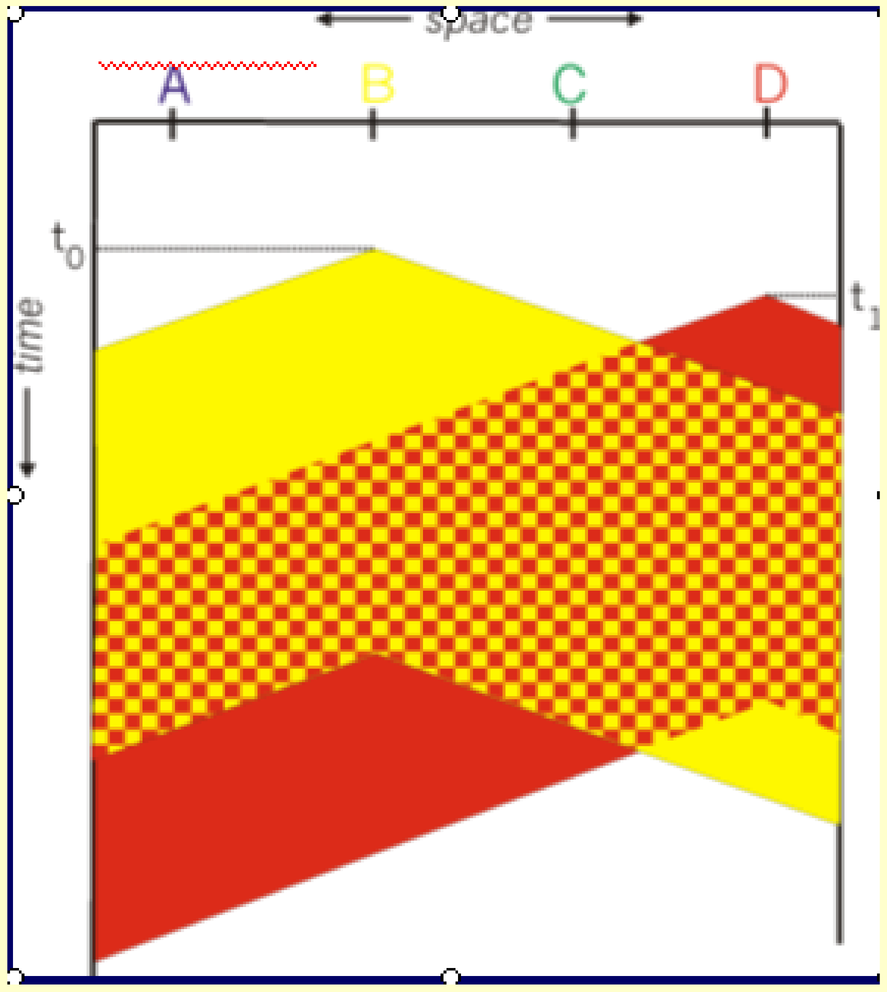
CSMA collisions

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

collision: entire packet transmission time wasted

note: role of distance and propagation delay in determining collision prob.

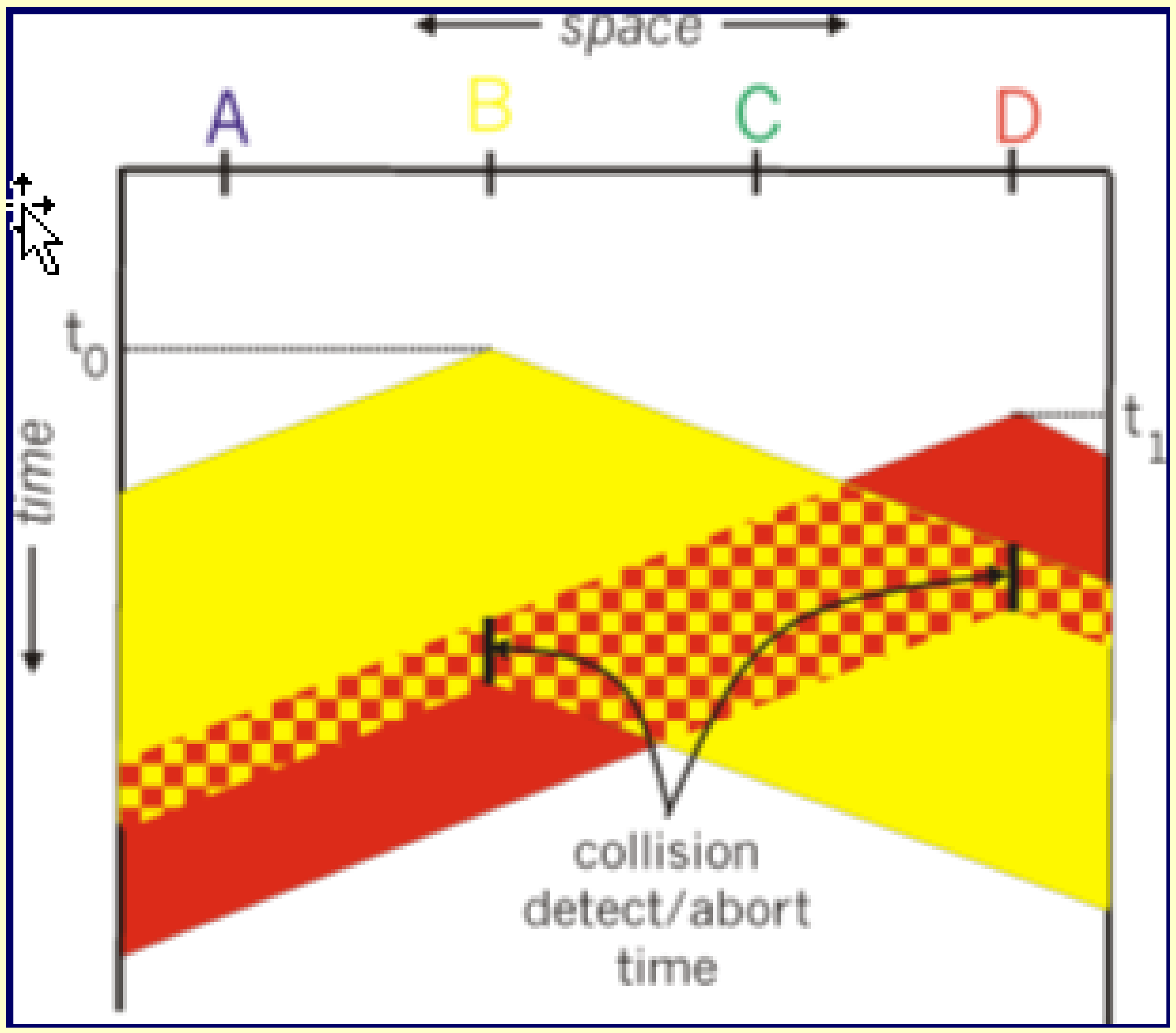
spatial layout of nodes along ethernet



CSMA/CD (Collision Detection)

- CSMA improves performance, but still it wastes the channel during collisions
- In some very short distance networks (e.g. coax LANs), it is possible to listen while transmitting (in addition to listening before transmitting)
- If we detect a collision while transmitting, we can abort the transmission and free up the channel sooner
- This idea was proposed by R. Metcalfe and Boggs at Xerox PARC in the mid 1970s under the name Ethernet.
- Human analogy: the polite conversationalist

CSMA/CD collision detection



Historical Aside on CSMA / CD

- While Metcalfe and Boggs are generally given credit for inventing Ethernet, some feel that the concept was first described by P. Townshend in 1968 under the name Magic Bus:

Everyday I get in the queue,
(too much, Magic Bus)
To get on the bus that takes me to you
(too much, Magic Bus)

“Taking Turns” MAC protocols - 1

Channel partitioning MAC protocols:

- share channel efficiently 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!

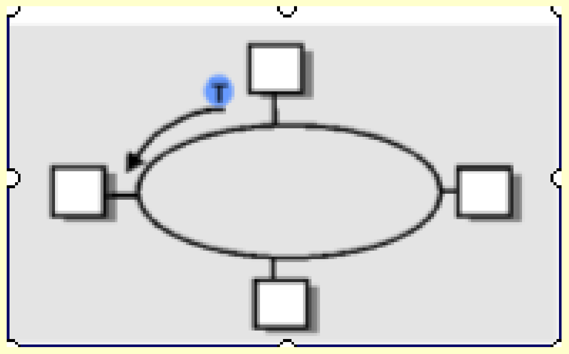
"Taking Turns" MAC protocols - 2

Polling:

- Master node "invites" slave nodes to transmit in turn
- Request to Send, Clear to Send messages
- 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)



Reservation-based protocols - 1

Distributed Polling:

- Time divided into slots
- Begins with N short **reservation slots**
  - reservation slot time equal to channel end-end propagation delay
  - station with message to send posts reservation
  - reservation seen by all stations

Reservation-based protocols - 2

- **After reservation slots, message transmissions ordered by known priority**