ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Chapter 5 part 1
LINK LAYER

Computer Networks

Timothy Roscoe

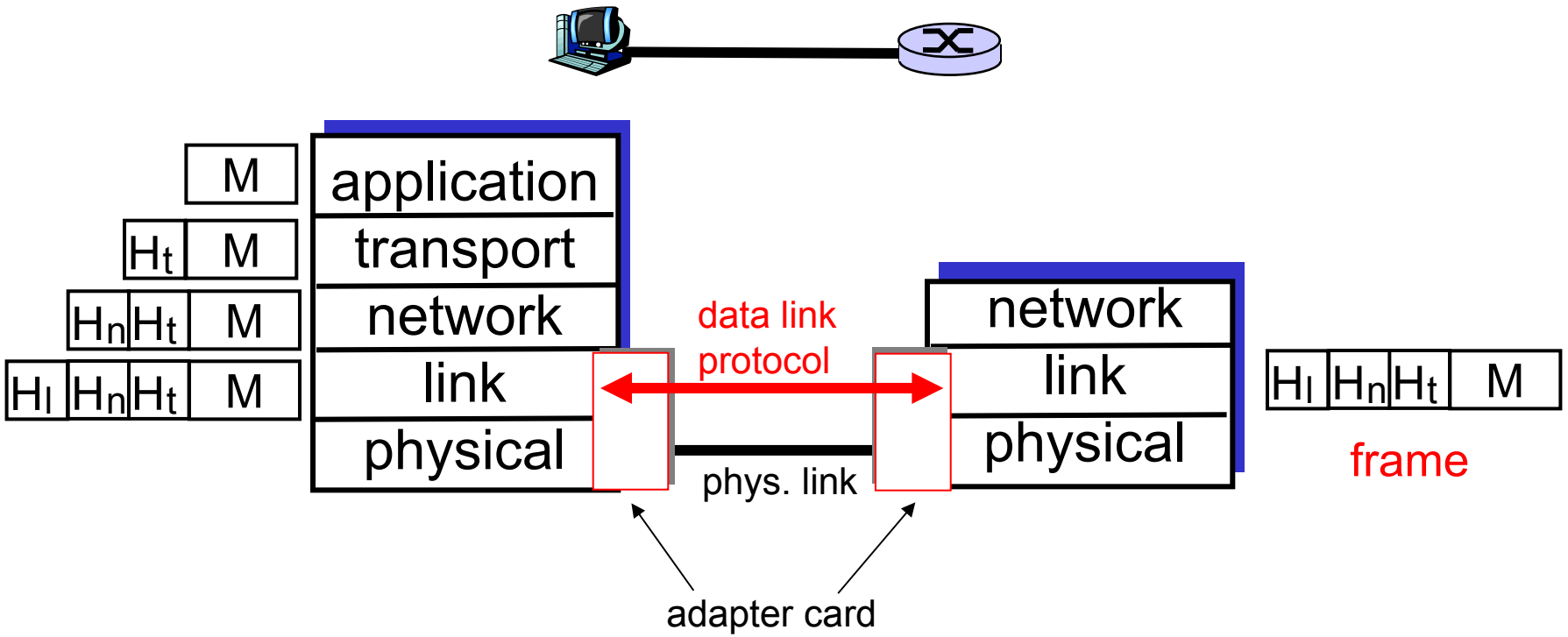
Summer 2007

Overview - today

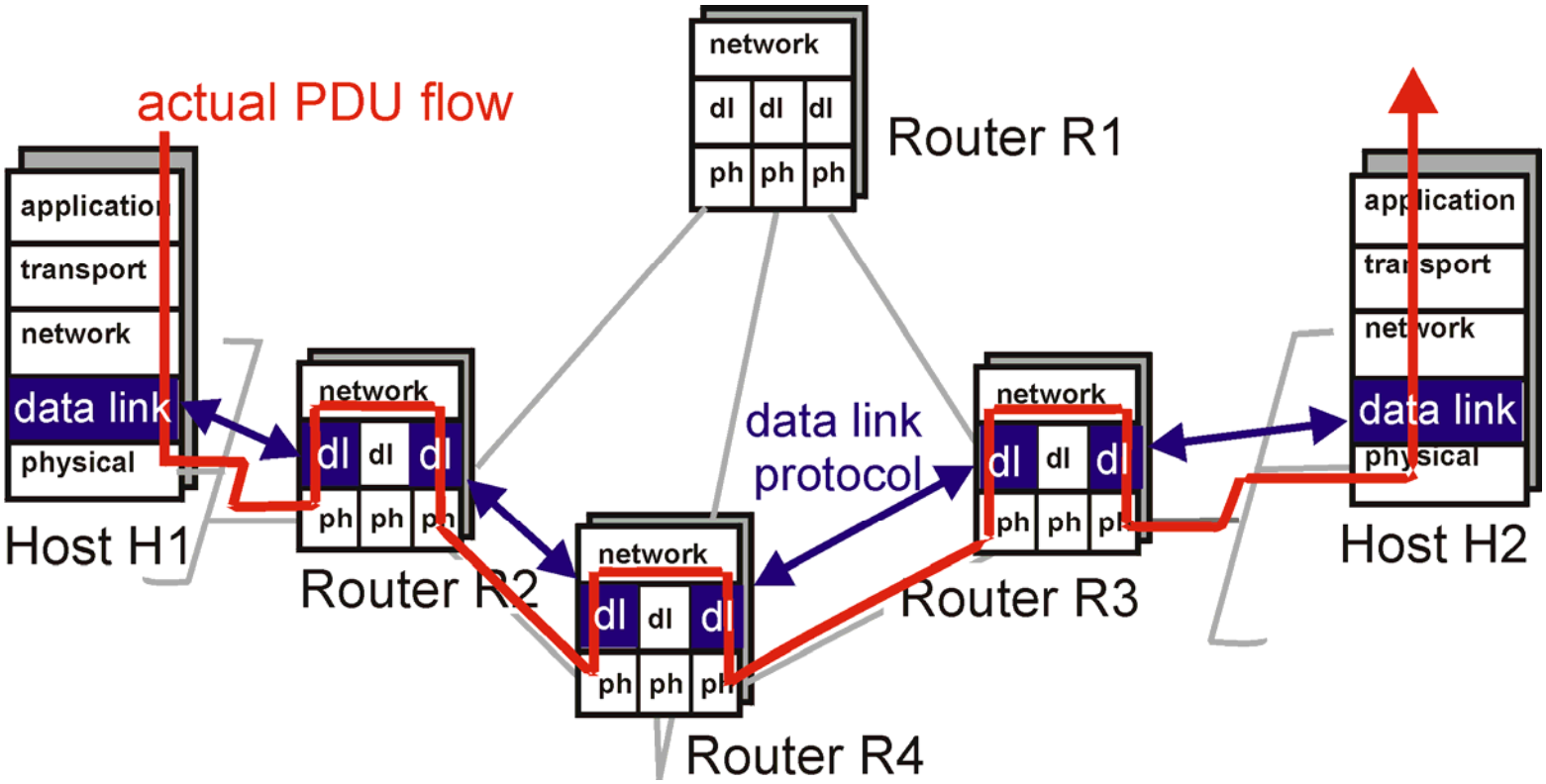
- Context
- Link layer services
  - Framing
  - Error detection and correction
  - Data Link layer protocols
- Multiple access protocols and LANs
  - Channel Partitioning
  - “Taking turns”
  - Random Access

Link Layer: setting the context

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

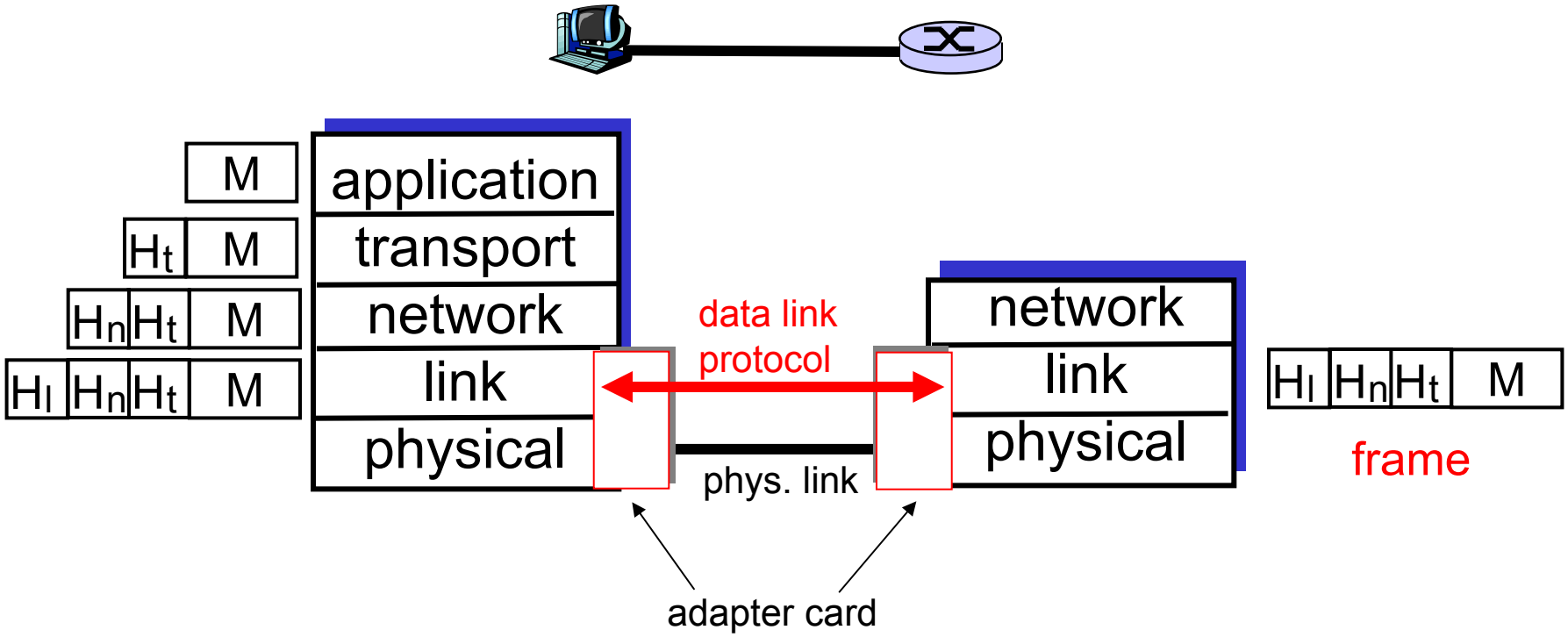


Link Layer: setting the context



Link Layer: Implementation

- Link layer implemented in “adapter” (a.k.a. NIC)
  - e.g., PCMCIA card, Ethernet card
  - typically includes: RAM, DSP chips, host bus interface, and link interface



Link Layer Services

- 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, destination
    - different from IP address!
- Error Detection
  - errors caused by signal attenuation, noise
  - receiver detects presence of errors:
    - receiver signals sender for retransmission or drops frame
- Error Correction
  - receiver identifies *and corrects* bit error(s) without resorting to retransmission

Link Layer Services (more)

- Flow Control
  - pacing between sender and receiver
- Half-duplex and full-duplex
  - with half duplex, nodes at both ends of link can transmit, but not at same time
- Reliable delivery between two physically connected devices:
  - we learned how to do this in chapter 3
  - seldom used on low error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?

Aside: The End-to-End Argument

"The function in question can completely and correctly be implemented only with the knowledge and help of the application standing at the end points of the communication system.

Therefore, providing that questioned function as a feature of the communication system itself is not possible.

(Sometimes an incomplete version of the function provided by the communication system may be useful as a performance enhancement.)"

"End-to-end arguments in system design",
J.H.Saltzer, D.P. Reed and D.D. Clark.
ACM Transactions in Computer Systems
vol.2, no.4, November, 1984, pages 277-288.

E2E and reliability

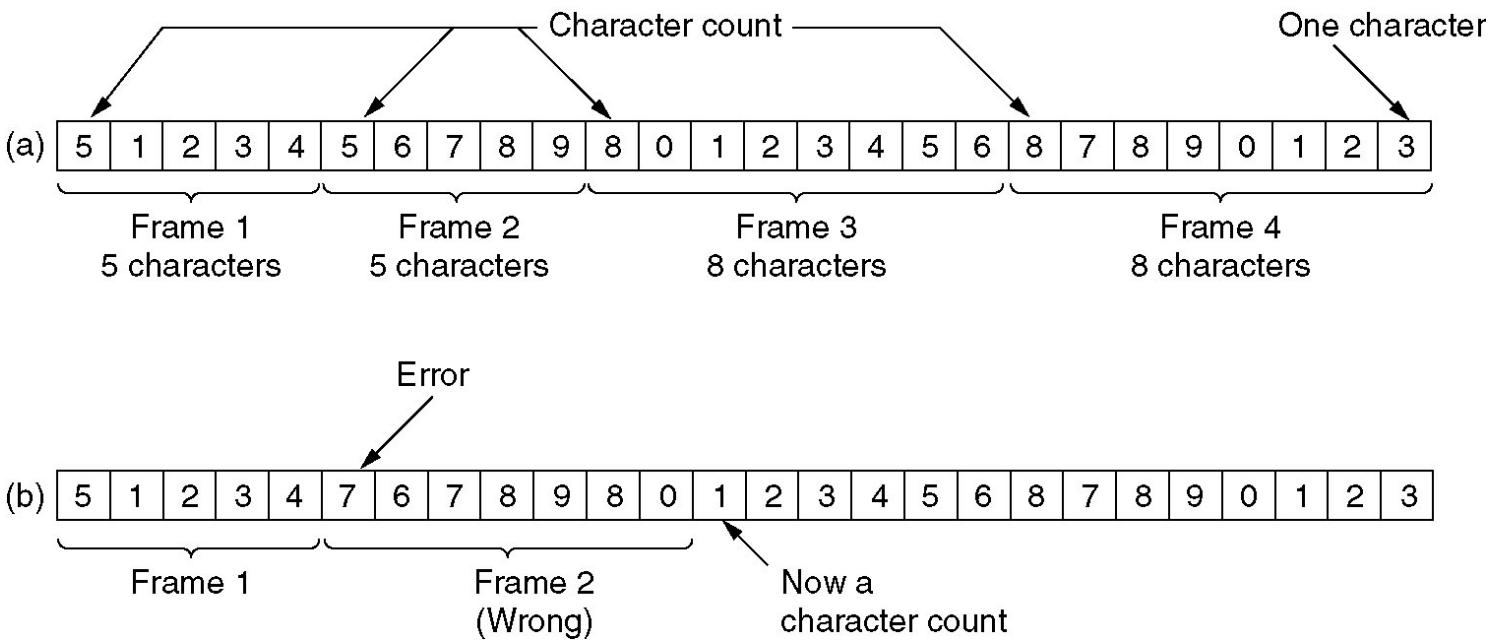
Something to ponder:

- Reliable delivery is a function
- Does reliable link-level transmission provide end-to-end reliability?

- Can it be worse than no link-level reliability?

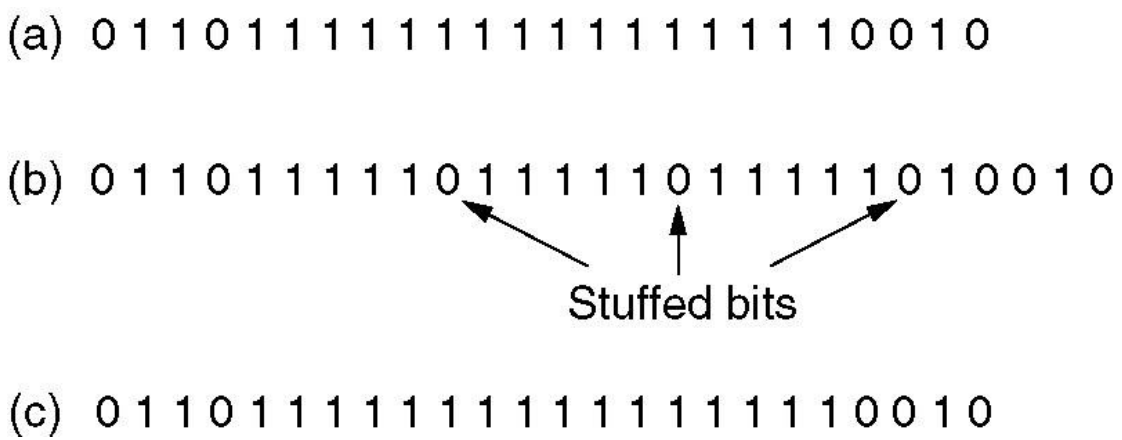
- When is it a good thing?

Framing



A character stream. (a) Without errors. (b) With one error.

Framing: bit-stuffing



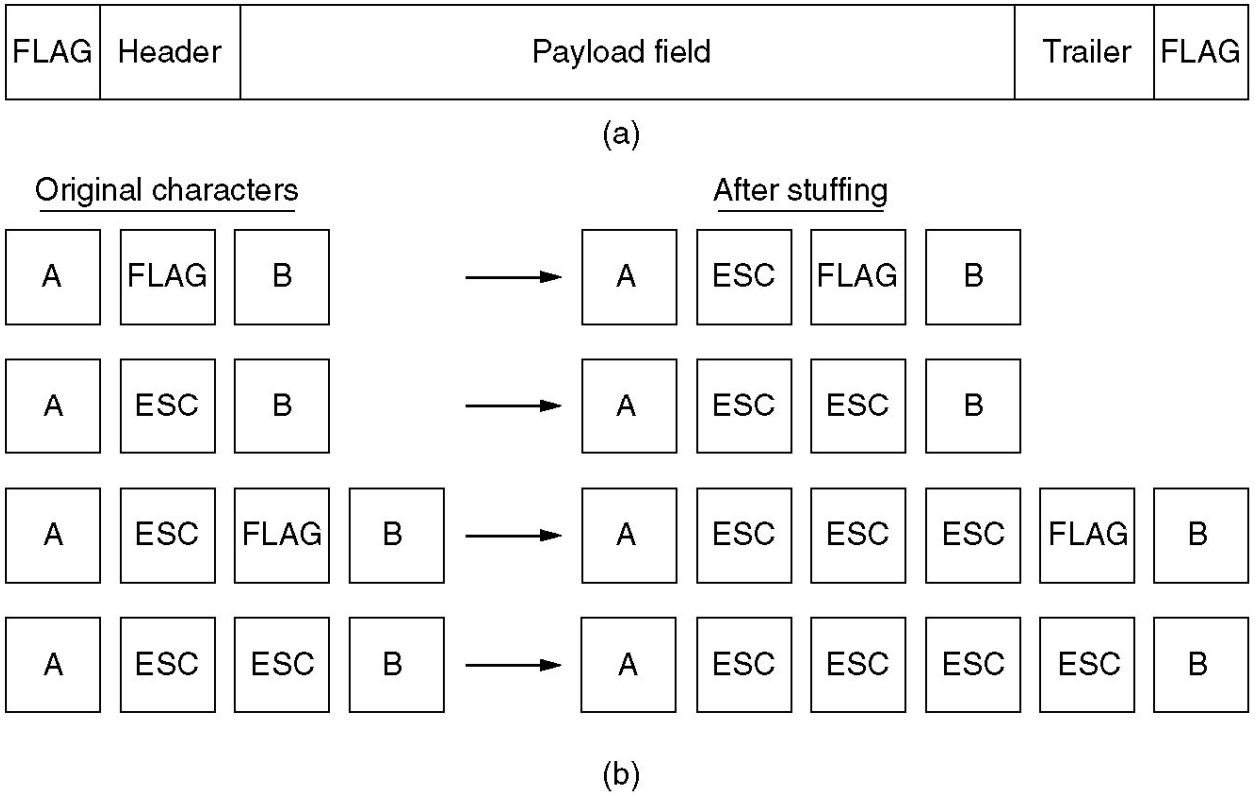
Bit stuffing

(a) The original data.

(b) The data as they appear on the line.

(c) The data as they are stored in receiver's memory after destuffing.

Framing: byte stuffing

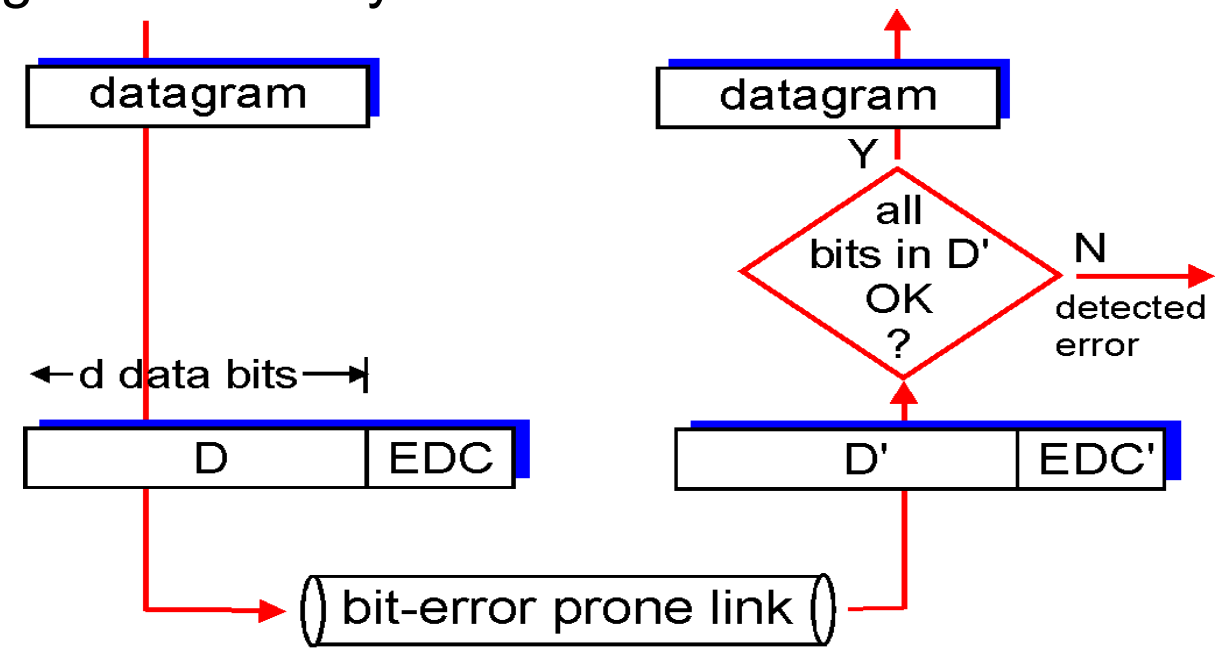


(a) A frame delimited by flag bytes.

(b) Four examples of byte sequences before and after stuffing.

Error Detection

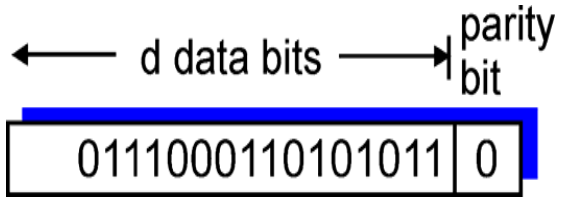
- EDC = Error Detection and Correction bits (redundancy)
- D = Data protected by error checking, may include header fields
- Error detection not 100% reliable!
  - protocol may miss some errors, but rarely
  - larger EDC field yields better detection and correction



Parity Checking

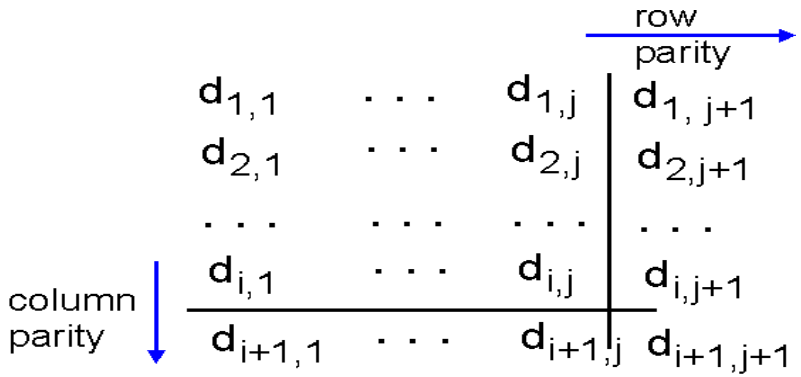
Single Bit Parity

Detect single bit errors



Two Dimensional Bit Parity

Detect *and correct* single bit errors



10101	1
11110	0
01110	1
10101	0

no errors

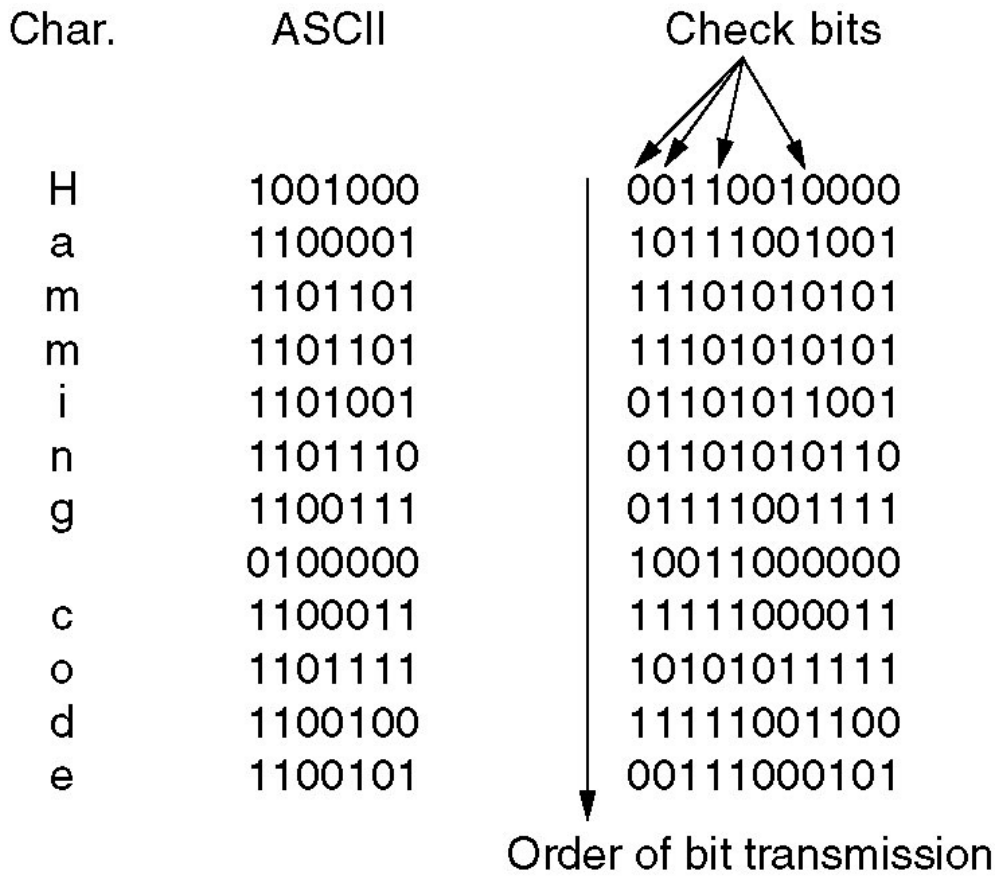
10101	1
10110	0
01110	1
10101	0

parity error

parity error

correctable single bit error

Error correcting codes



Internet checksum

Goal

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

Sender

- treat segment content as sequence of 16-bit integers
- checksum: addition (1’s complement sum) of segment content
- 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…

Cyclic Redundancy Check (CRC): Ring

- Polynomials with binary coefficients $b_k x^k + b_{k-1} x^{k-1} + \ldots + b_0 x^0$
- Order of polynomial: max i with $b_i \neq 0$

- Binary coefficients b_i (0 or 1) form a *field* with operations "+" (XOR) and "•" (AND).

- Polynomials form *ring* R with operations "+" and "•":
  - (R,+) is an abelian group, (R, ·) is an associative set,
  - Distributivity: $a \bullet (b+c) = (a \bullet b) + (a \bullet c)$
    and $(b+c) \bullet a = (b \bullet a) + (c \bullet a)$ for $a,b,c \in R$.

- Example:

$(x^3+1) \bullet (x^4+x+1)$	$1001 \bullet 10011$
$= x^3 \bullet (x^4+x+1) + 1 \bullet (x^4+x+1)$	$= \quad 10011$
$= (x^7+x^4+x^3) + (x^4+x+1)$	$+ \; 10011000$
$= x^7+x^3+x+1$	$= 10001011$

Cyclic Redundancy Check (CRC): Division

- Generator polynomial $G(x) = x^{16}+x^{12}+x^5+1$
- Let the whole frame (D+EDC) be polynomial T(x)

- Idea: fill EDC (CRC) field such that T(x) mod G(x) = 0
- How to divide with polynomials? Example with $G(x) = x^2+1$ (=101)

  11101100 / 101 = 110110, Remainder 10

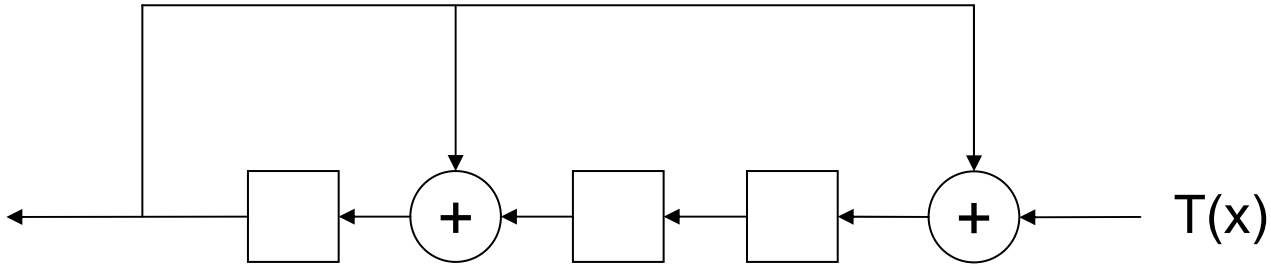
```
 100
  011
    111
     100
      010
```

- Idea: Fill EDC with remainder when dividing T(x) with EDC=00…0 by G(x). Then calculating and testing CRC is the same operation.

CRC calculation in Hardware

- Use cyclic shift register with r registers, where r is the order of G(x)
- Example

$G(x) = x^3 + x^2 + 1$



$\Rightarrow$ Remainder of the division ends up in the registers

CRCs: How to chose G(x)?

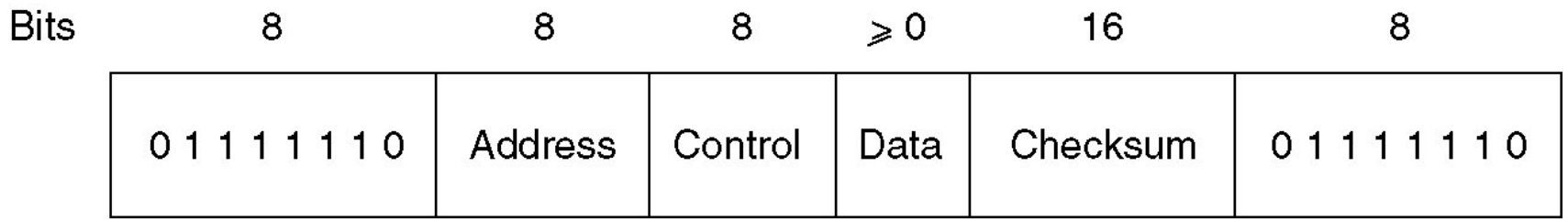
- Typical generator polynomial $G(x) = x^{16}+x^{12}+x^5+1$
- Why does G(x) look like this?

- Let E(x) be transmission errors: T(x) = M(x) + E(x)
- T(x) mod G(x) = (M(x) + E(x)) mod G(x)
  = M(x) mod G(x) + E(x) mod G(x)
- And recall M(x) mod G(x) = 0 …
- $\Rightarrow$ We can detect all transmission errors
  iff E(x) is not divisible by G(x) without remainder

CRCs: How to chose G(x)?

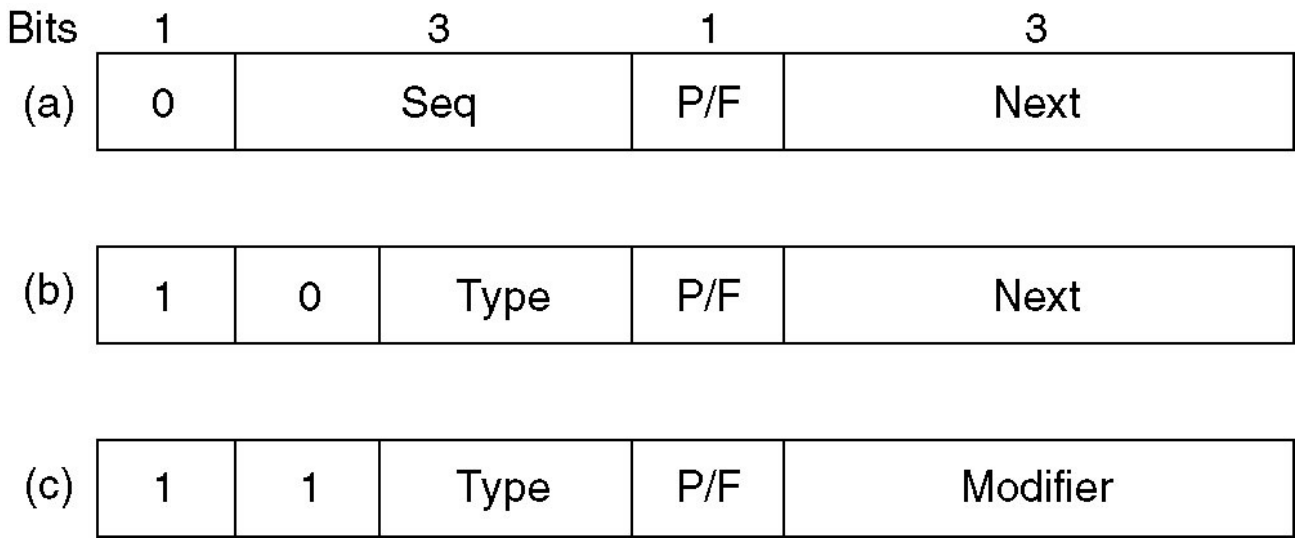
- One can show that G(x) of order r can detect
  - all single bit errors if G(x) has 2 or more coefficients
  - all bursty errors (k-bit long 1xxxx1 string) with $k \leq r$ (note: needs G(x) to include the term 1)
  - Any error with probability 2^{-r}

High-level Data Link Control Protocol (HDLC)



- Bit-oriented protocol ⇒ bitstuffing for framing
- Checksum for error detection

HDLC (2)



Control field of

(a) An information frame.

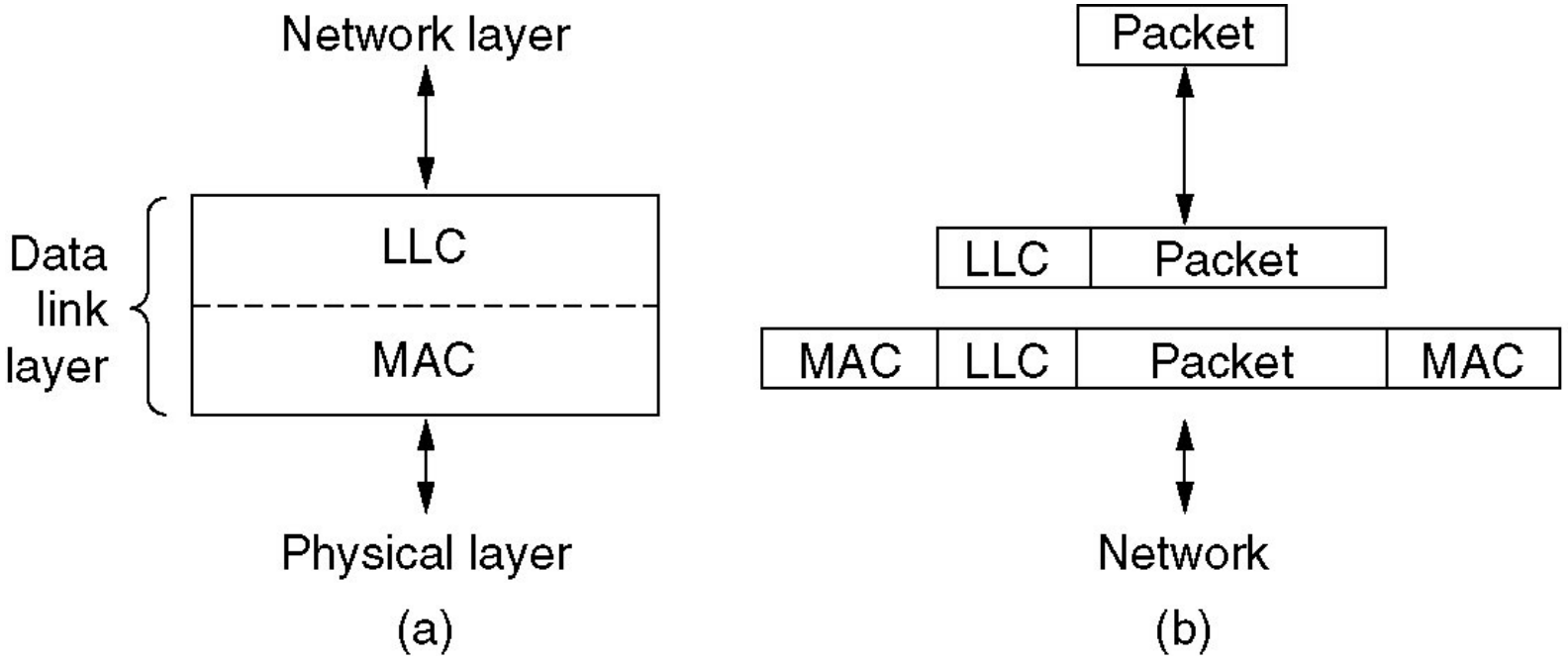
(b) A supervisory frame.

(c) An unnumbered frame.

(Some) IEEE 802 working groups

- 802.1: **Higher-layer LAN Protocols**
- 802.2: **Logical Link Control**
- 802.3: **Ethernet**
- 802.4: Token Bus (what?)
- 802.5: Token Ring (almost dead)
- 802.6: Metropolitan Area Network (DQDB…)
- 802.11: **Wireless LAN (WiFi)**
- 802.12: Demand Priority
- 802.14: Cable Modem
- 802.15: **Wireless Personal Area Network (Bluetooth)**
- 802.16: **Broadband Wireless Access (WiMax)**
- 802.17: Resilient Packet Ring (SONET without circuits)
- Etc…

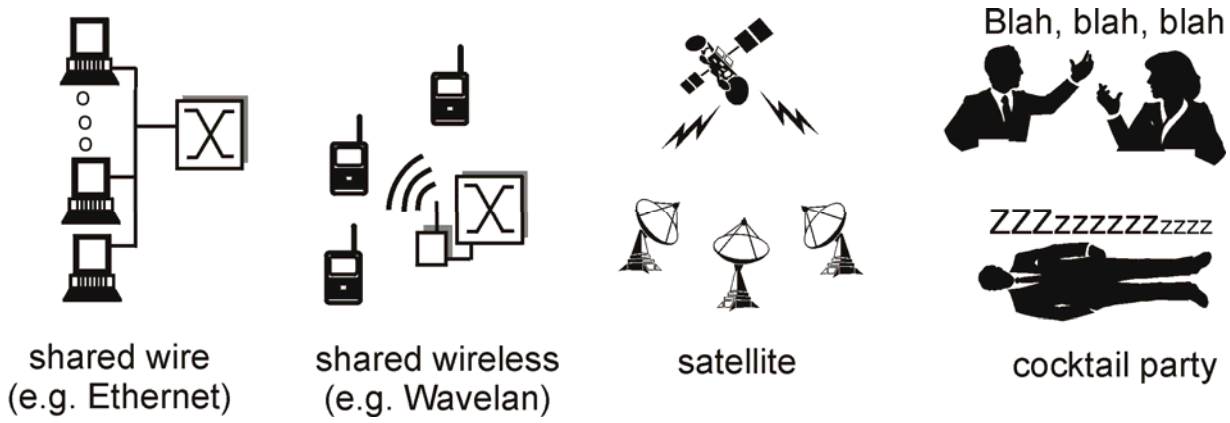
Sublayers: Link Control vs. Media Access



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, WLAN)
- switched (e.g. switched Ethernet, ATM)



Frequency Division Multiplexing (FDM)

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time

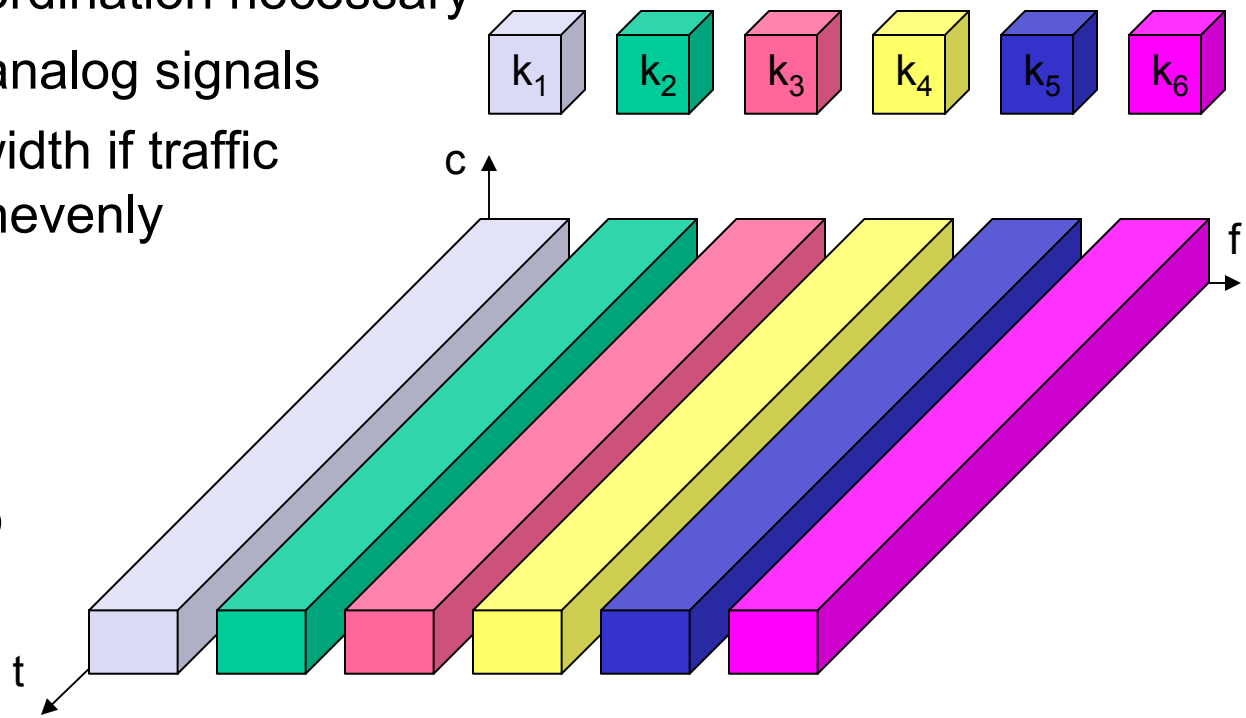
\+ no dynamic coordination necessary

\+ works also for analog signals

– waste of bandwidth if traffic is distributed unevenly

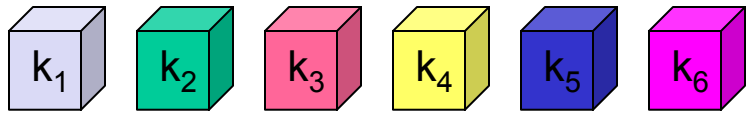
– inflexible

- Example: broadcast radio

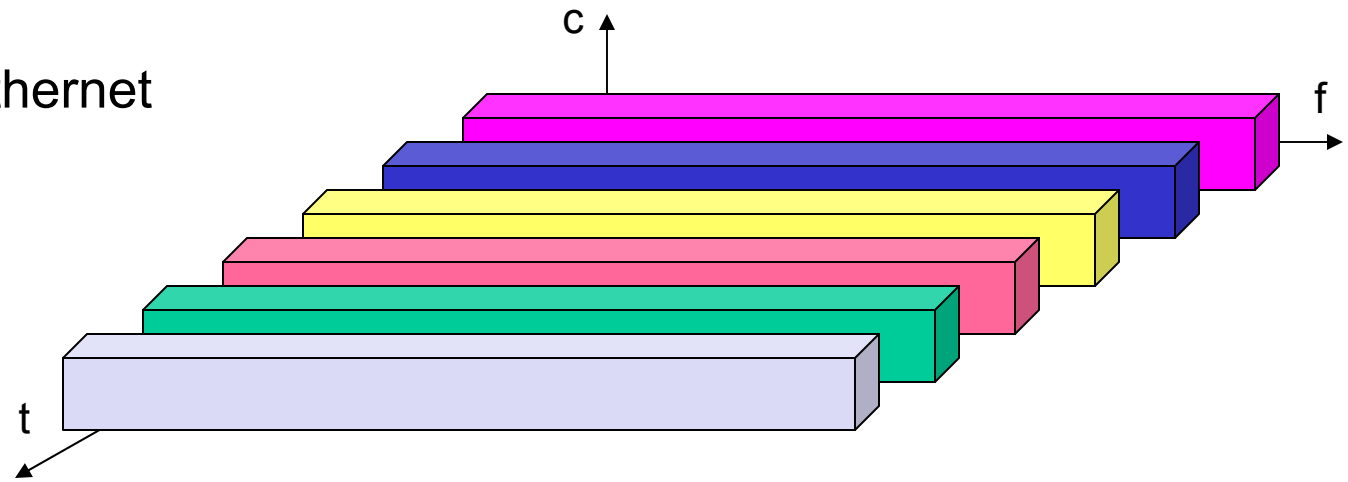


Time Division Multiplexing (TDM)

- A channel gets the whole spectrum for a certain amount of time
- \+ only one carrier in the medium at any time
- \+ throughput high even for many users
- – precise synchronization necessary



- Example: Ethernet



Time/Frequency Division Multiplexing

- Combination of both methods
- A channel gets a certain frequency band for some time

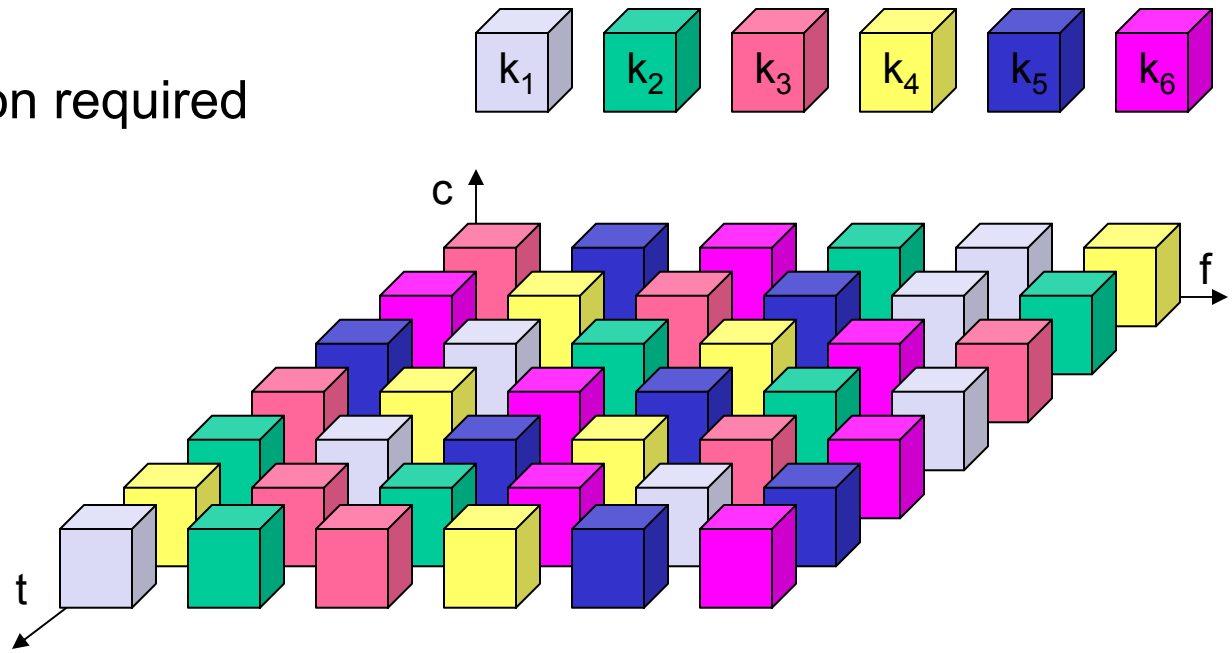
\+ protection against frequency selective interference

\+ protection against tapping

\+ adaptive

– precise coordination required

- Example: GSM



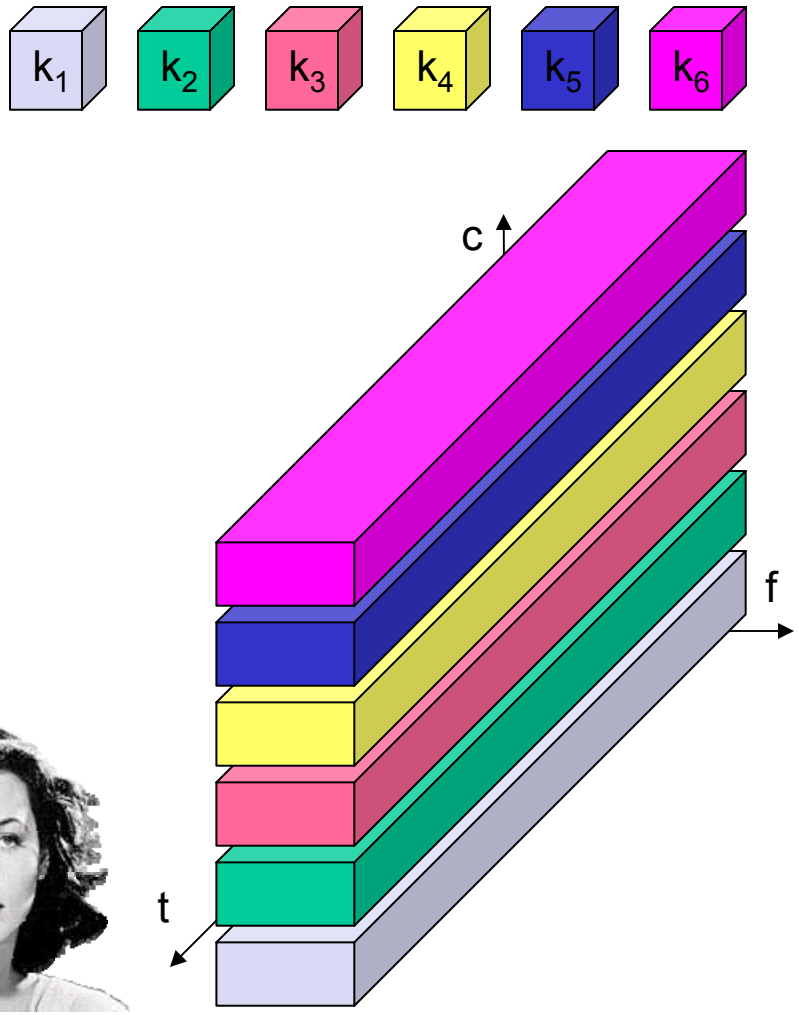
Code Division Multiplexing (CDM)

- Each channel has a unique code
- All channels use the same spectrum at the same time

+ bandwidth efficient
+ no coordination or synchronization
+ hard to tap
+ almost impossible to jam

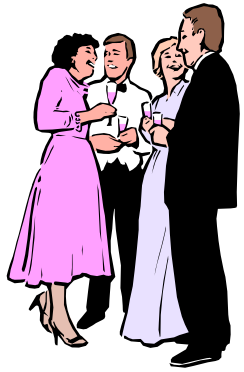
– lower user data rates
– more complex signal regeneration

- Example: UMTS
- Spread spectrum
- U. S. Patent 2‘292‘387, Hedy K. Markey (a.k.a. Lamarr or Kiesler) and George Antheil (1942)



Cocktail party as analogy for multiplexing

- Space multiplex: Communicate in different rooms
- Frequency multiplex: Use soprano, alto, tenor, or bass voices to define the communication channels
- Time multiplex: Let other speaker finish
- Code multiplex: Use different languages and hone in on your language. The “farther apart” the languages the better you can filter the “noise”: German/Japanese better than German/Dutch. Can we have orthogonal languages?



Media Access Protocols

- Single shared communication channel
- Two or more simultaneous transmissions by nodes: interference
  - only one node can send successfully at a time
- Media Access Control (MAC) Protocol
  - distributed algorithm that determines how stations share channel, i.e., determine when station can transmit
  - 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

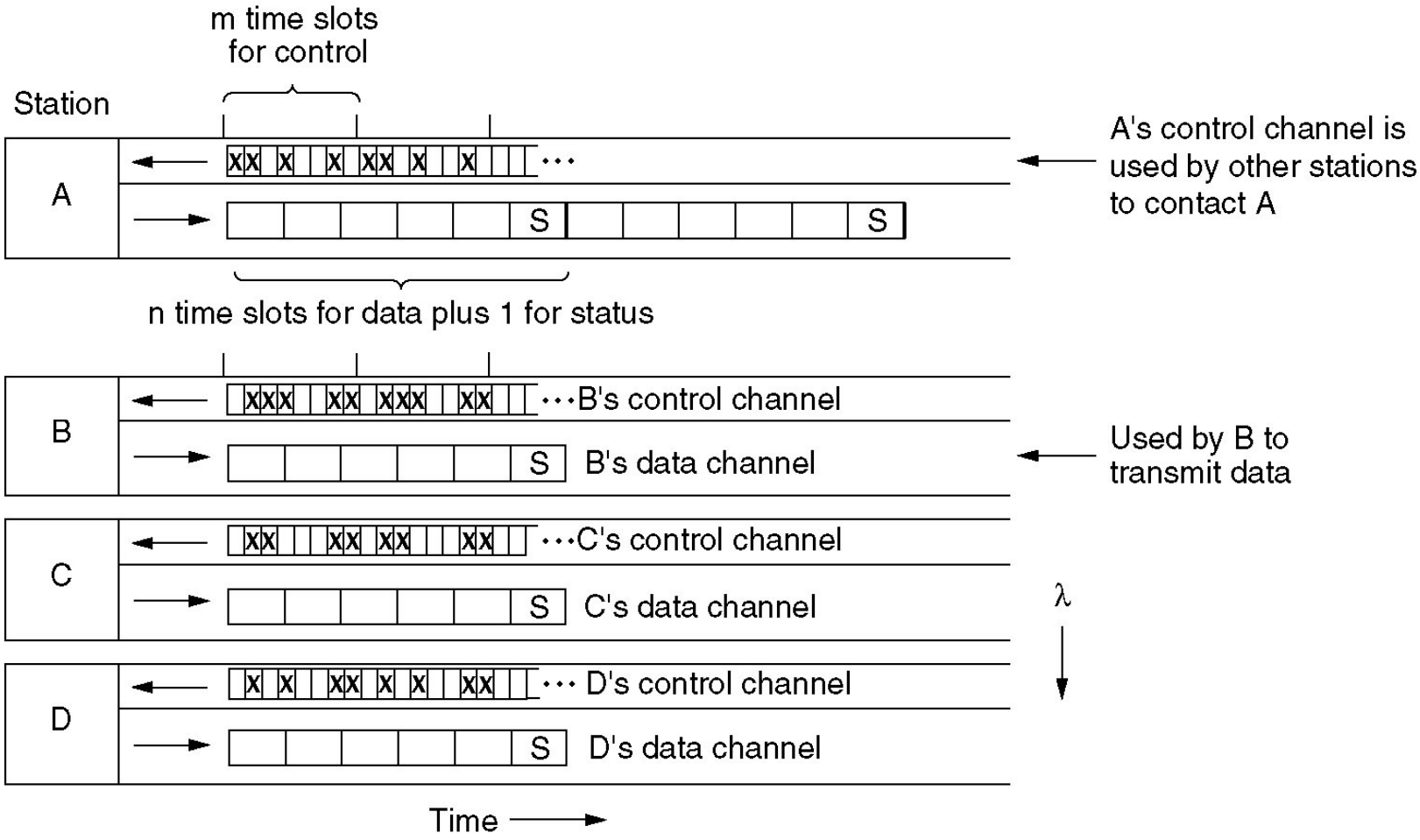
MAC Protocols: a taxonomy

Three broad classes

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

- Goals: decentralized, efficient, simple, fair

Wavelength-Division Multiple Access



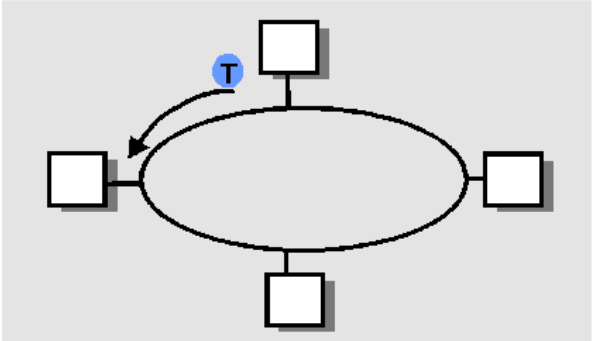
"Taking Turns" MAC protocols

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 (Token Ring)

- control token passed from one node to next sequentially
- token message
- concerns
  - token overhead
  - latency



"Taking Turns" Protocols: Round Robin

- Round robin protocol: station *k* sends after station *k*–1 (mod *n*)
- If a station does not need to transmit data, then it sends "ε"
- There is a maximum message size *m* that can be transmitted
- Is this different from token ring protocol?

- Questions
  - How efficient is round robin?
  - What if a station breaks or leaves?
  - Can a new station join?

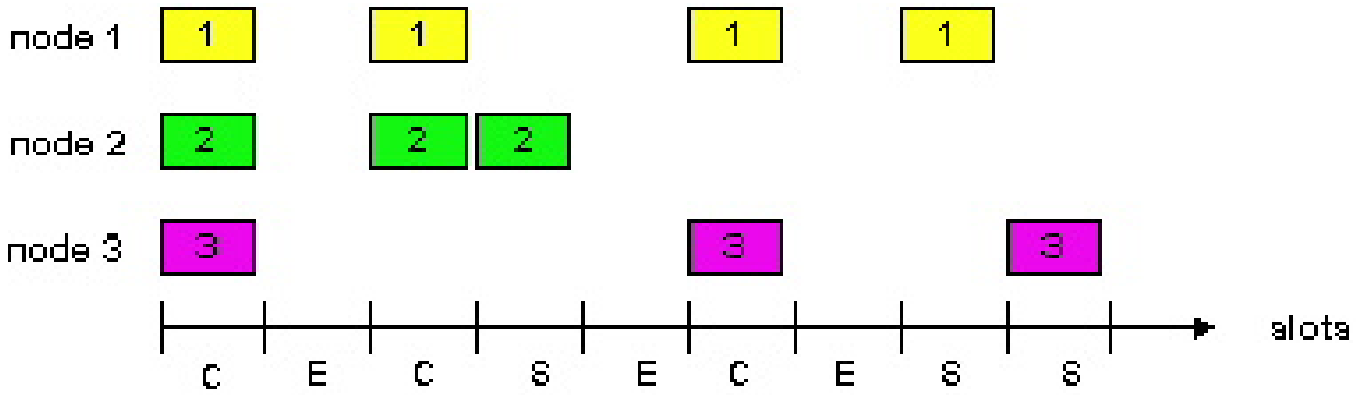
- All deterministic protocols have these (or worse) problems
  - Try randomized protocols instead!

Random Access protocols

- 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
    - via delayed retransmissions
- Examples of random access MAC protocols:
  - ALOHA and variants (slotted ALOHA, adaptive ALOHA)
  - Backoff protocols (CSMA, CSMA/CD, CSMA/CA)

Slotted Aloha

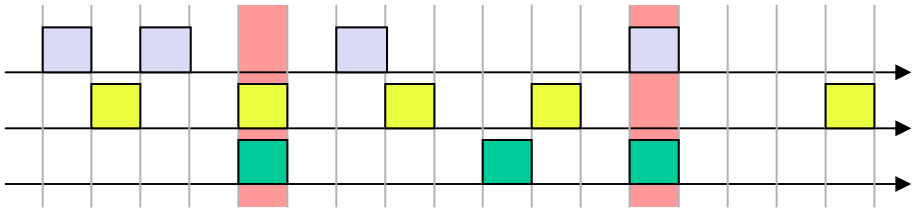
- Time is divided into equal size slots
  - A slot is equal to the packet transmission time
- Node with new arriving packet: transmit at beginning of next slot
- If collision: retransmit packet in future slots with probability p, until successful



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

Slotted Aloha (slightly simplified)

- We assume that the stations are perfectly synchronous
- In each time slot each station transmits with probability *p*



$$P_1 = \Pr[\text{Station 1 succeeds}] = p(1-p)^{n-1}$$

$$P = \Pr[\text{any Station succeeds}] = nP_1$$

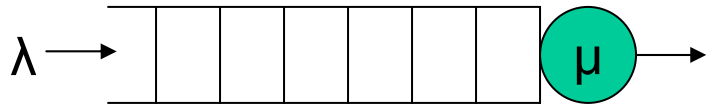
$$\text{maximize } P: \frac{dP}{dp} = n(1-p)^{n-2}(1-pn) \overset{!}{=} 0 \quad \Rightarrow \quad pn = 1$$

$$\text{then, } P = (1-\frac{1}{n})^{n-1} \geq \frac{1}{e}$$

- In slotted aloha, a station can transmit successfully with probability at least 1/*e*. How quickly can an application send packets to the radio transmission unit? Queuing Theory!

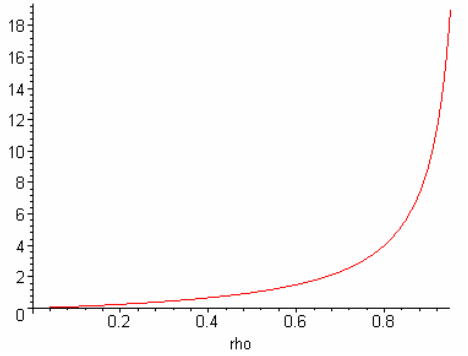
Queuing Theory (Remember Chapter 3?)

- Simplest M/M/1 queuing model (M=Markov):
- Poisson arrival rate λ, exponential service time with mean $1/\mu$



- In our time slot model, this means that the probability that a new packet is received by the buffer is λ; the probability that sending succeeds is $\mu = 1/e$, for any time slot. To keep the queue bounded we need $\rho = \lambda/\mu < 1$, thus $\lambda < 1/e$.

- In the equilibrium, the expected number of packets in the system is $N = \rho/(1-\rho)$, the average time in the system is $T = N/\lambda$.

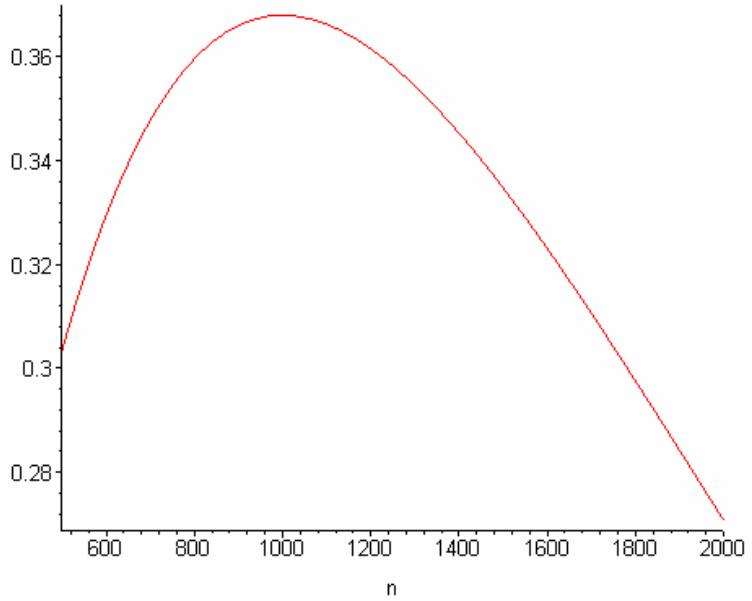


Slotted Aloha vs. Round Robin

– Slotted aloha uses not every slot of the channel; the round robin protocol is better in this respect.

\+ What happens in round robin when a new station joins? What about more than one new station? Slotted aloha is more flexible.

- Example: If the actual number of stations is twice as high as expected, there is still a successful transmission with probability 27%. If it is only half, 30% of the slots are successful.



Adaptive slotted aloha

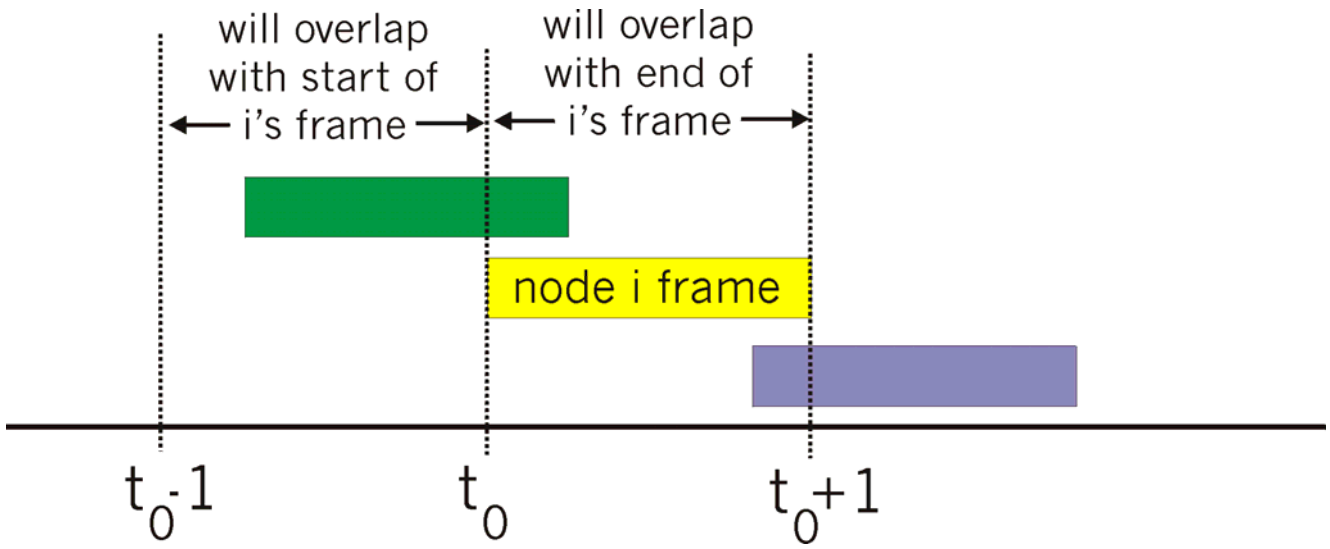
- Idea: Change the access probability with the number of stations
- How can we estimate the current number of stations in the system?
- Assume that stations can distinguish whether 0, 1, or more than 1 stations send in a time slot.

- Idea: Try to estimate the number of stations!
  - If you see that nobody sends, increase *p*.
  - If you see that more than one sends, decrease *p.*

- Analysis a little too tough for this course (unfortunately)

Pure (unslotted) ALOHA

- Unslotted Aloha: simpler, no synchronization
- Packet needs transmission
  - send without awaiting for beginning of slot
- Collision probability increases:
  - packet sent at t_0 collide with packets sent in (t_0-1, t_0+1)



Pure Aloha Analysis

- Partition each slot of size 1 into x "minislots" of size ε (then x = $1/\varepsilon$)
- Probability to start transmission in minislot is p_ε for each station

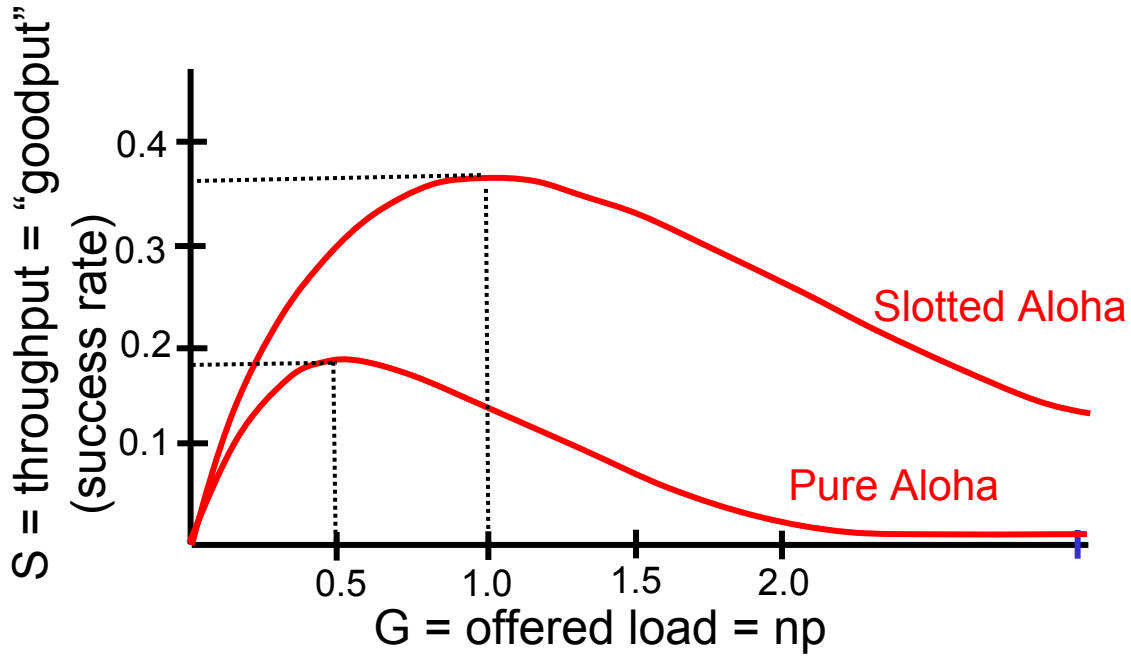
$$P_1 = \Pr[\text{Station 1 succeeds}] = p_\epsilon(1-p_\epsilon)^{(2x-1)(n-1)}$$
$$P = \Pr[\text{any station succeeds}] = n \cdot P_1$$

P can be maximized by choosing $p_\epsilon = \frac{\epsilon}{\epsilon+2n}$, which is $\frac{\epsilon}{2n}$ for $\epsilon \to 0^+$. Then

$$P = np_\epsilon(1-p_\epsilon)^{(2x-1)(n-1)} = \frac{\epsilon}{2}\left(1-\frac{\epsilon}{2n}\right)^{2n/\epsilon-\ldots} \geq \frac{\epsilon}{2e}$$

- Since there are x minislots in 1 slot, the success rate of a slot is about 1/2e, that is, half the rate of slotted aloha

Slotted Aloha vs. Pure Aloha



protocol constrains effective channel throughput!

Demand Assigned Multiple Access (DAMA)

- Channel efficiency only 36% for Slotted Aloha, and even worse for Aloha.

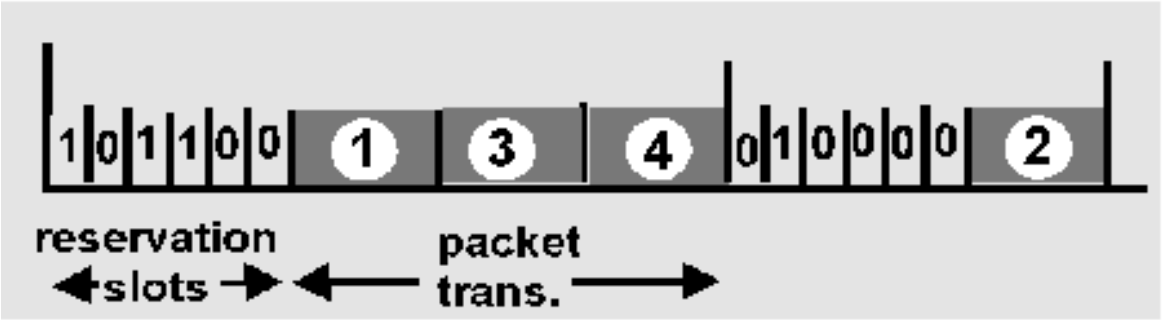
- Practical systems therefore use reservation whenever possible. But: Every scalable system needs an Aloha style component.

- Reservation
  - a sender *reserves* a future time-slot
  - sending within this reserved time-slot is possible without collision
  - reservation also causes higher delays
  - typical scheme for satellite systems

Example for reservation-based protocol

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
- after reservation slots, message transmissions ordered by known priority



Backoff Protocols

- Backoff protocols rely on acknowledgements only.
- Binary exponential backoff, for example, works as follows:
- If a packet has collided k times, we set $p = 2^{-k}$

  Or alternatively: wait from random number of slots in $[1..2^k]$

- It has been shown that binary exponential backoff is not stable for any $\lambda > 0$ (if there are infinitely many potential stations)
  - Intuition: there's a small chance things get bad. Once they're bad, they only get worse: more stations waiting $\Rightarrow$ more likelyhood of collisions $\Rightarrow$ more backlog…
- Interestingly when there are only finite stations, binary exponential backoff becomes unstable with $\lambda > 0.568$; Polynomial backoff however, remains stable for any $\lambda < 1$.

CSMA: Carrier Sense Multiple Access

Idea of CSMA: listen before transmit!

- If channel sensed idle: transmit entire packet
- If channel sensed busy, defer transmission. Two variants
  - *Persistent* CSMA
    - retry immediately with probability p when channel becomes idle (may cause instability)
  - *Non-persistent* CSMA
    - retry after random interval

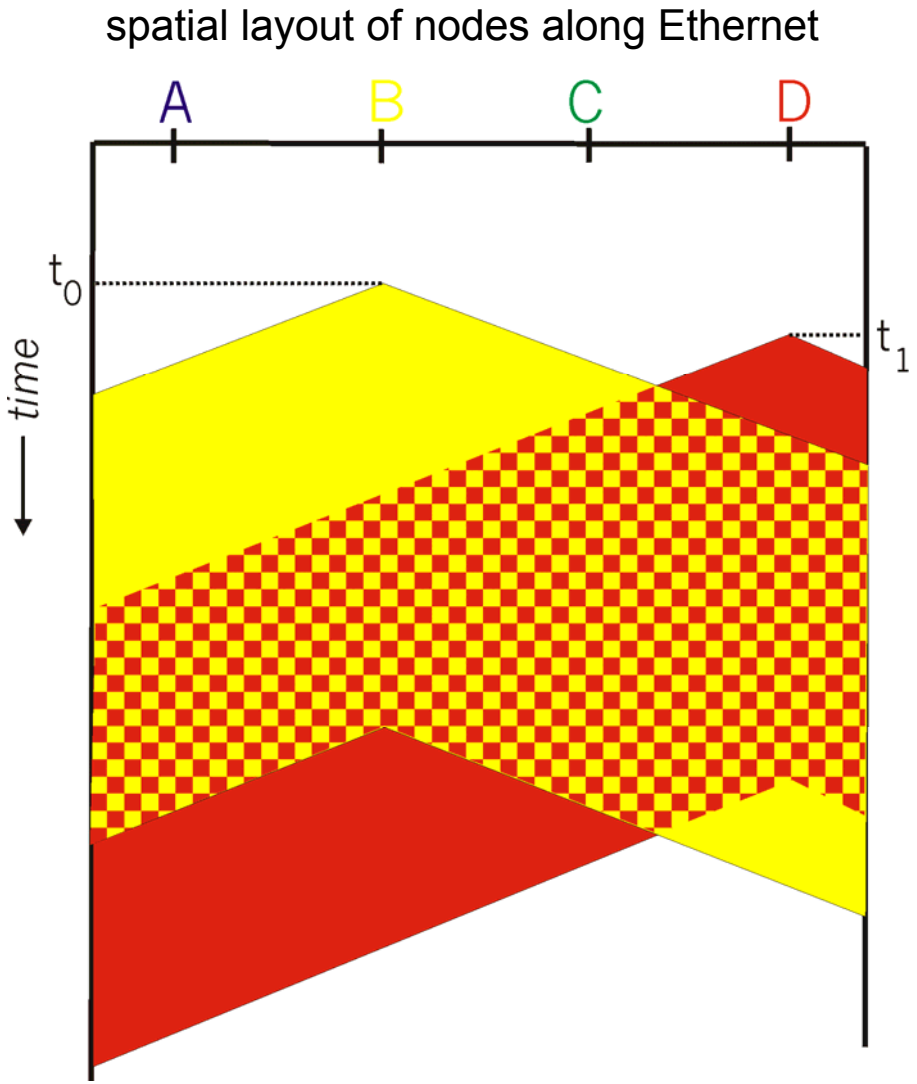
- Human analogy
  1. Don’t interrupt anybody already speaking

CSMA collisions

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

collision
entire packet transmission
time wasted

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



CSMA/CD (Collision Detection)

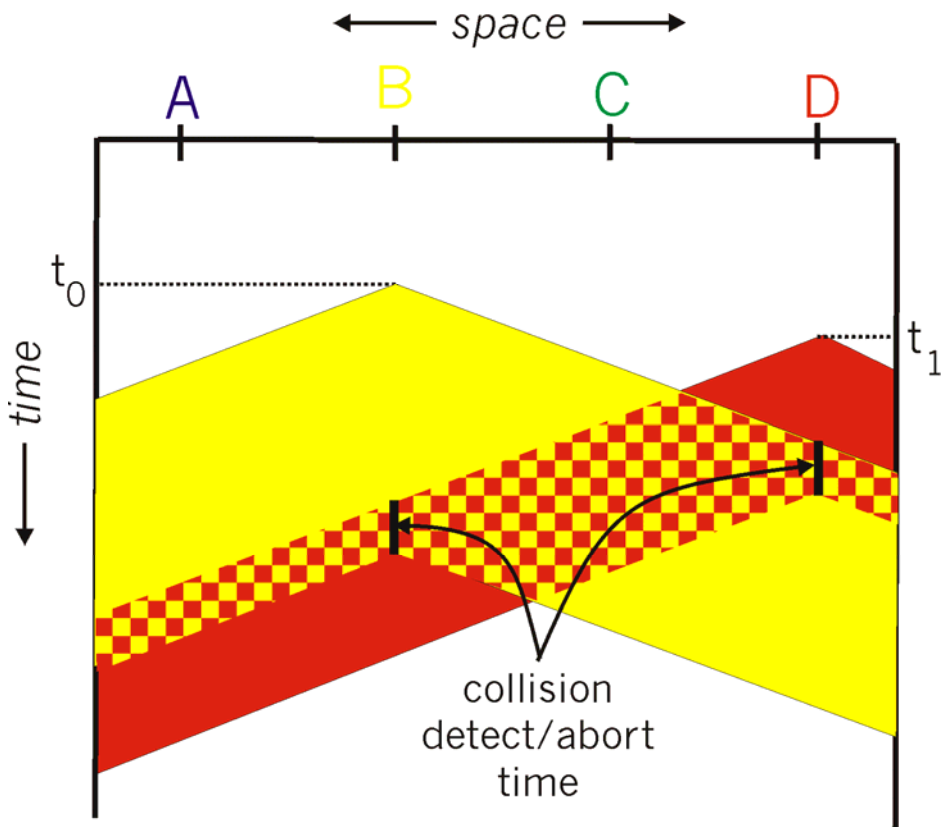
CSMA/CD: carrier sensing, as in CSMA

- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage
- persistent or non-persistent retransmission

- collision detection
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: receiver shut off while transmitting

- Human analogy (the polite conversationalist)
  1. Don't interrupt anybody already speaking
  2. If another starts speaking with you, then back off.

CSMA/CD collision detection



Summary of MAC protocols

- What do you do with a shared medium?
  - Channel Partitioning, by time, frequency or code
    - Time Division, Code Division, Frequency Division
  - Taking Turns
    - polling from a central site, token passing
  - 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

Next week:

- LAN addressing
- Ethernet!
- Bridges, Hubs, Switches
- PPP
- VLANS
- More philosophy…

- After that: Wireless.