CS 655 – System and Network Architectures and Implementation

Module 1 - Channels

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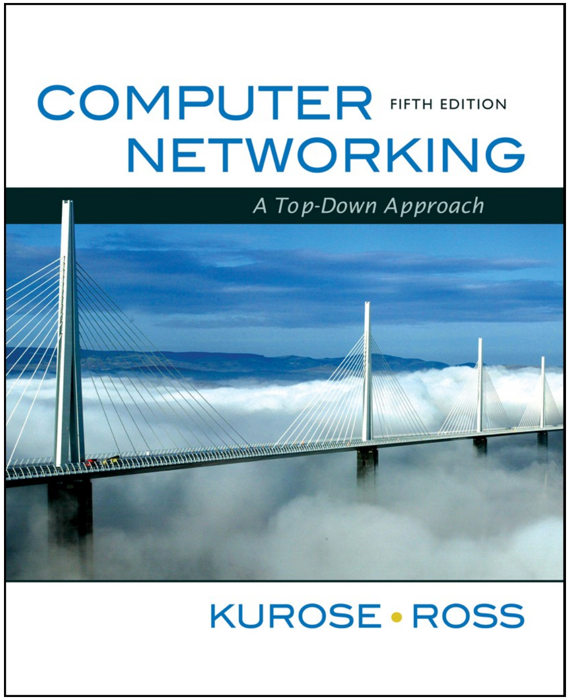

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Computer Networking: A Top Down Approach
5th edition.
Jim Kurose, Keith Ross
Addison-Wesley, April 2009.

Overview

- Signal Transmission
- Framing
- Error Detection / Correction
- Medium Access Control
- Principles
  - Encapsulation
  - Performance

Signal Transmission

- encode/decode binary information as
  - electrical signals
  - acoustic signals
  - optical signals
  - radio signals
  - etc.

Signals

- challenge: signal fading
  - signal level
  - transition edge
- binary vs. n-ary signals?
  - robustness vs. efficiency

- communication -> reconstruct original signal

Physical Media

- properties
    - capacity
    - shielding
    - propagation

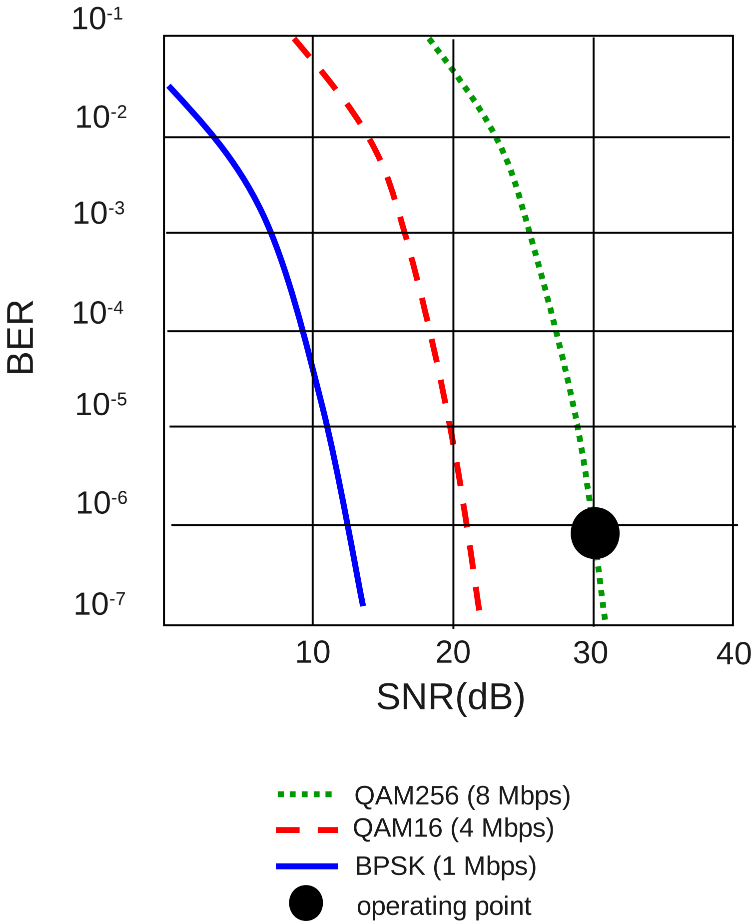
- cable
    - cost & quality: twisted pair < coax < fiber

Radio Transmission

- medium: electromagnetic spectrum
  - public good: regulated vs. unregulated bands
- no wire – no shielding
- propagation effects
  - obstruction (path loss)
  - reflection (multipath)
  - interference
- transmission pattern: base station – mobile
  - no ad-hoc or peer-to-peer communication

Radio Transmission – Adaption

- SNR: signal-to-noise ratio
- BER: bit error rate
- SNR vs. BER trade-offs
  - increase power -> increase SNR -> decrease BER
  - for fixed SNR: choose appropriate coding, such that BER is reasonable



Radio – Power Management

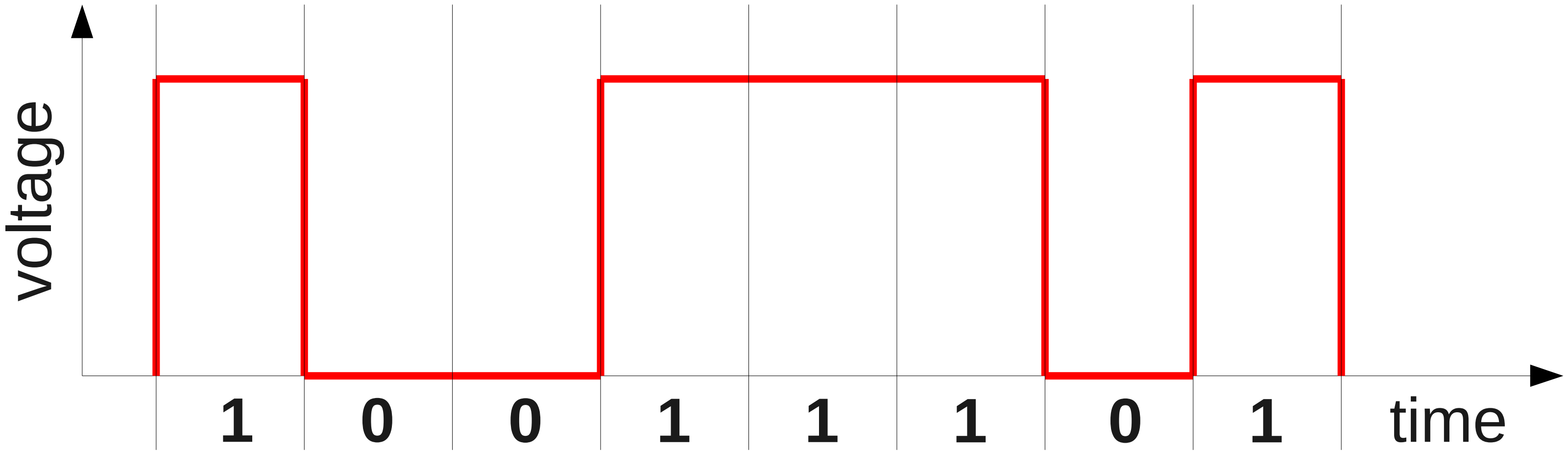
- radio ~ battery-powered devices
  - sending / receiving consumes significant power
- power savings mode: disable receiving
  - maybe hibernate device
- coordinate wake/sleep cycles with neighbor
  - fixed schedule or announce sleep periods
  - simple for base station scenarios, else difficult
- also: control sending power / interference

Optical Transmission

- computers are built using electrical components
- vs. much more efficient optical signals
  - “more efficient” -> more transitions per time
- electrical circuits (especially memory) have difficulty with keeping up...
- transmission pattern: point-to-point
- optical switches?
  - optical memory? optical delay lines

Binary Coding

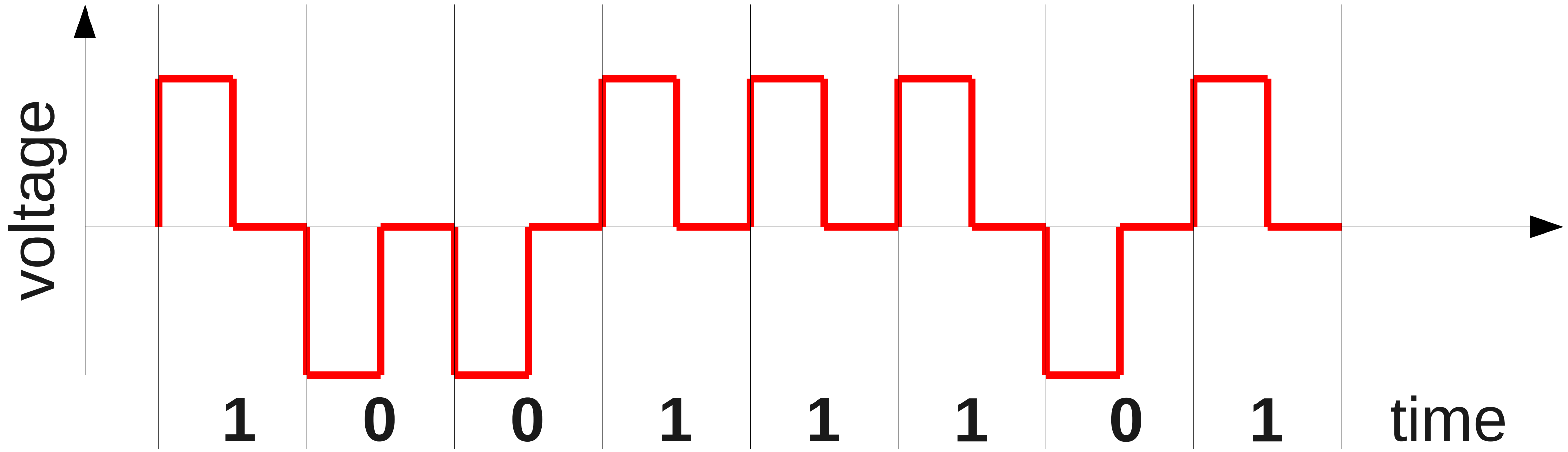
- simplest coding: unipolar, non-return-to-zero



- clock synchronization?
- direct current (DC) bias?

Self-Clocking

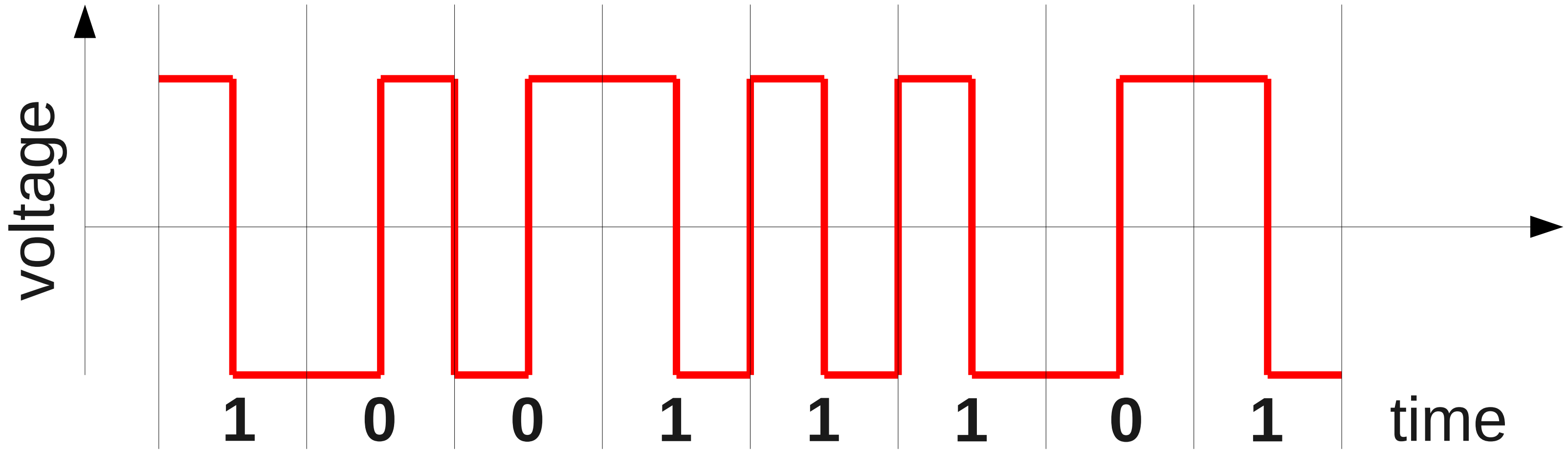
- bipolar, return-to-zero



- transition in middle of interval -> clock signal
  - but: only 50% efficient

Manchester Encoding

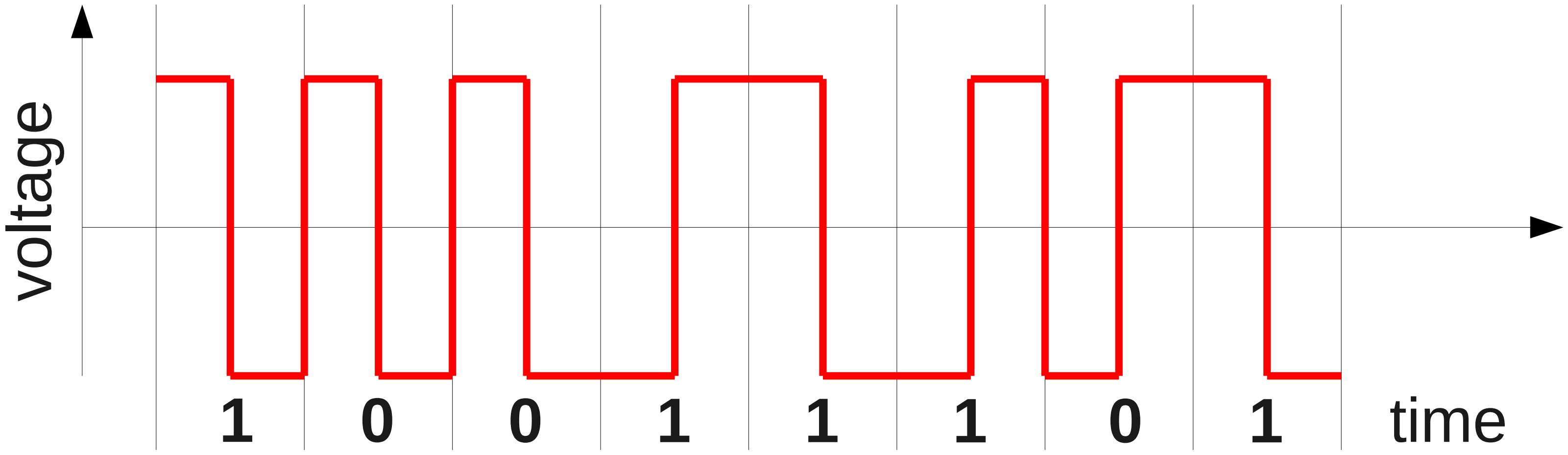
- direction of transition in middle of signal period



- no DC bias at all
- inversion (cable swapped)?
    - both versions exist in literature and standards

Differential Manchester Encoding

- presence of transition at start of period



- transition easier to detect than level
- robust against inversion

4B/5B Encoding

- encode 4 bits in 5 NRZ transitions
- fixed mapping dictionary
  - each code word encoded with at least 2 transitions
  - coding room for 'idle' and other control signals
- more recent: 64B/66B
  - use scrambler instead of dictionary
  - first two bits: preamble, guarantee transition
- dictionary and scrambling also limit DC bias

Framing

- split bit stream in discrete units
- signal start and end of message
  - basis for any kind of reliable communication
  - define unit for basic error detection and correction

- signal/code for 'idle'?
  - yes: can use frame length field
  - no: must use frame delimiter

Frame Delimiter

- example: PPP
- Point-to-Point Protocol (PPP)
  - transparency: transmit binary data over anything
  - assume 0- and 1-signal, but no 'idle' signal
  - operates on bytes

- designate special bit pattern as delimiter
  - e.g., 01111110 (for both start and end)
- what if 01111110 appears in data stream?

Byte Stuffing

- PPP sender algorithm

  if 01111110 appears in data stream:

  insert another 01111110 before

- PPP receiver algorithm

  if 01111110 appears in communication stream:

  followed by 01111110 -> remove one of them

  else -> 01111110 is a delimiter

Notes

- can have different start/end delimiters for robustness
- generalized sender algorithm

  insert *escape pattern* before any occurrence of control patterns in data (including escape itself)
- generalized receiver algorithm

  if escape pattern in stream:

  remove and treat next symbol as data

Escape Character

- e.g., in many programming languages:

  ```
  print “Tom said “Hello” to me.”;
  ```

  ... is a syntax error, because double quotation mark is the string delimiter token
- use *escape character* (backslash):

  ```
  print “Tom said \”Hello\” to me.”;
  ```

- same for regular expressions and related tools

Framing with Idle-Signal

- with 'idle'-signal: delimiters not strictly needed
- use 'length' field in message for robustness

- but: why does Ethernet define 'preamble'?
  - for channel cleanup (see medium access control),
  - ...and clock synchronization
    - self-clocking code

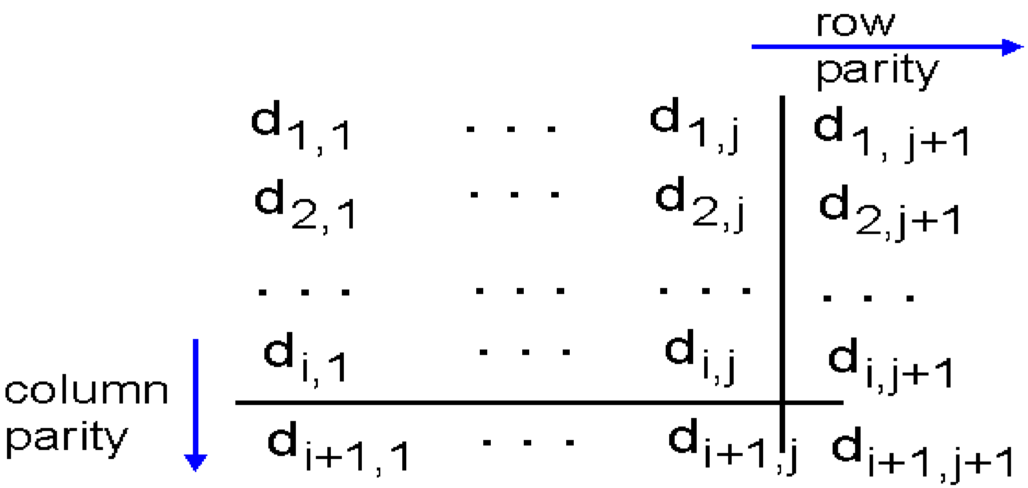
Error Control

- error detection: append parity bit to bit string
  - bit string can be codeword, message, etc.
  - add bit, such that number of 1s is odd
    - 'even' variant exists, as well

- 0111000110101011 -> append 0
- receiver can detect single-bit errors
- correction: *Automatic Repeat reQuest* (ARQ)
  - hold back ACK or send NAK

Forward Error Correction

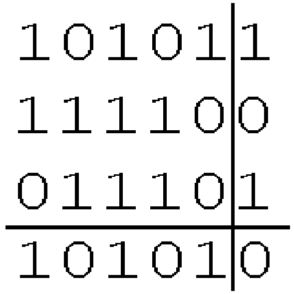
- matrix of parity bits



row parity

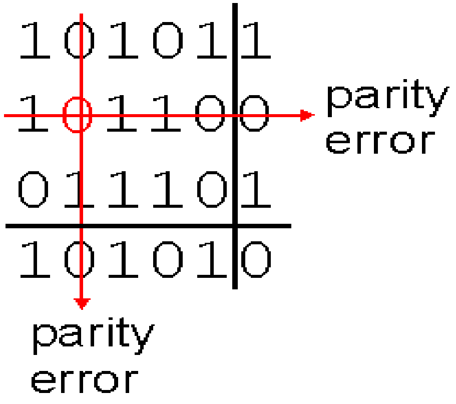
column parity

$$\begin{array}{ccc|c} d_{1,1} & \cdots & d_{1,j} & d_{1,j+1} \\ d_{2,1} & \cdots & d_{2,j} & d_{2,j+1} \\ \cdots & \cdots & \cdots & \cdots \\ d_{i,1} & \cdots & d_{i,j} & d_{i,j+1} \\ \hline d_{i+1,1} & \cdots & d_{i+1,j} & d_{i+1,j+1} \end{array}$$



$$\begin{array}{ccccc|c} 1&0&1&0&1&1 \\ 1&1&1&1&0&0 \\ 0&1&1&1&0&1 \\ \hline 1&0&1&0&1&0 \end{array}$$

no errors



$$\begin{array}{ccccc|c} 1&0&1&0&1&1 \\ 1&0&1&1&0&0 \\ 0&1&1&1&0&1 \\ \hline 1&0&1&0&1&0 \end{array}$$

correctable single bit error

Error Control: Redundancy

- what are we actually doing?
  - add redundancy to message (cf. natural language)
  - opposite of compression!

- data <-> code mapping
  - code properties determine error control capabilities

    -> *Hamming Distance*

Hamming Distance

- number of positions in which two strings of equal length are different

  h(a,b) for strings a, b

- assume code / set of fixed-length bit strings
- Hamming Distance of code C

  $H(C) = \min(h(a,b)\ \forall\ a,b \in C)$

Hamming Distance

- H(C) > n   => n-bit errors can be **detected**
- H(C) > 2n => n-bit errors can be **corrected**

- previous examples
  - simple Parity scheme: H(C) = 2 > 1
    - 1-bit errors can be detected
  - matrix Parity scheme: H(C) = 3 > 2 * 1
    - 1-bit errors can be corrected

- challenge: dictionary not feasible for messages

Internet Checksum

one's complement of sum of one's complements

  - process data as stream of 16-bit words
  - one's complement sum: add carry bit
  - not very strong: errors might go undetected

- why this format?
  - implementation in software
  - incremental update
  - independent of byte ordering
  - see RFC 1071 for discussion

Advanced Error Control

- Cyclic Redundancy Check (CRC)
  - error detection with small, fixed message overhead
  - simple in hardware – used, e.g., in Ethernet
- Erasure Codes
  - consider loss, instead of changes
  - parity -> e.g., in RAID systems
- Fountain Codes
  - any suitable subset of encoded symbols an recreate original message

Medium Access Control (MAC)

Goals

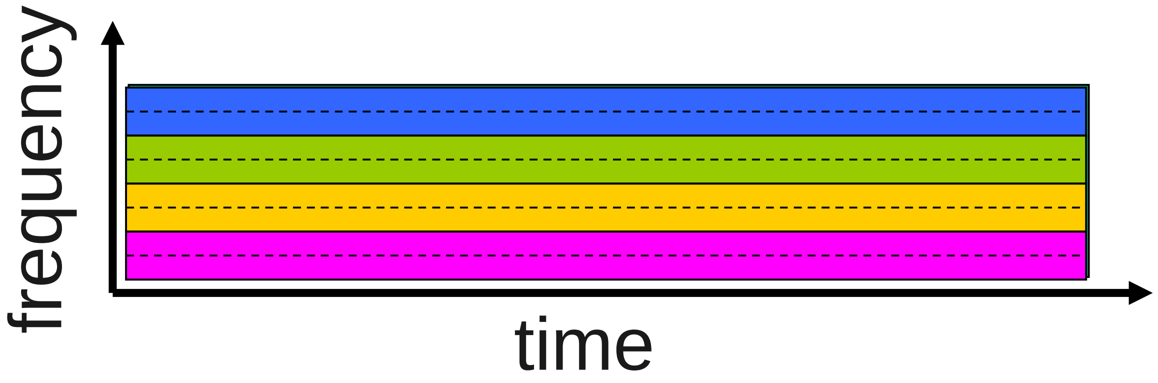
1. high channel utilization for single/few nodes
2. fair sharing for many nodes
3. decentralized, robust
4. simple

Medium Access Control Schemes

- channel partitioning
  - pessimistic: split channel into sub-channels
- random access
  - optimistic: uncoordinated access
  - distributed: handle collisions, resolve contention
- taking turns
  - distributed coordinated: avoid collisions
  - high complexity

Partitioning – Frequency

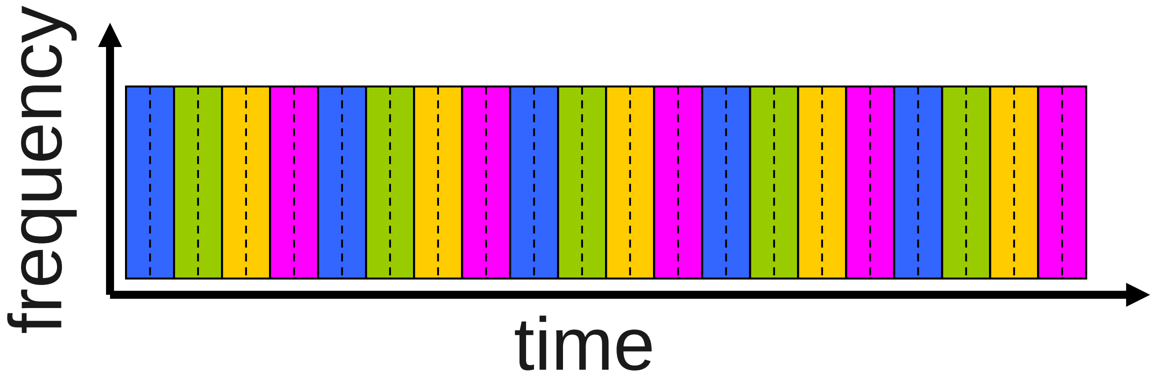
- Frequency Division Multiple Access (FDMA)
- channel spectrum divided into frequency bands
- each station assigned fixed frequency band



- unused capacity goes idle – utilization?

Partitioning – Time

- Time Division Multiple Access (TDMA)
- channel divided into “rounds”
- each station gets fixed length time slot



- unused slots go idle

Partitioning – Code

- Code Division Multiple Access (CDMA)
- ultimately uses multi-level signals
- each station is assigned chipping sequence
  - set of binary code vectors that are *orthogonal*
- downlink (from base station)
  - synchronous: signals add up, but can be decoded
- uplink (from mobile stations)
  - asynchronous: add pseudo-random “noise” signal

Partitioning

- need control functionality to manage channels
  - assign frequency or time slot or codes
  - mobile registration with base station
    - rare event (compared to message transmission)
  - ultimately: random access (bootstrapping problem)
    - truly global codes without collision not feasible

=> control overhead

- centralized
- utilization with few stations?

Random Access

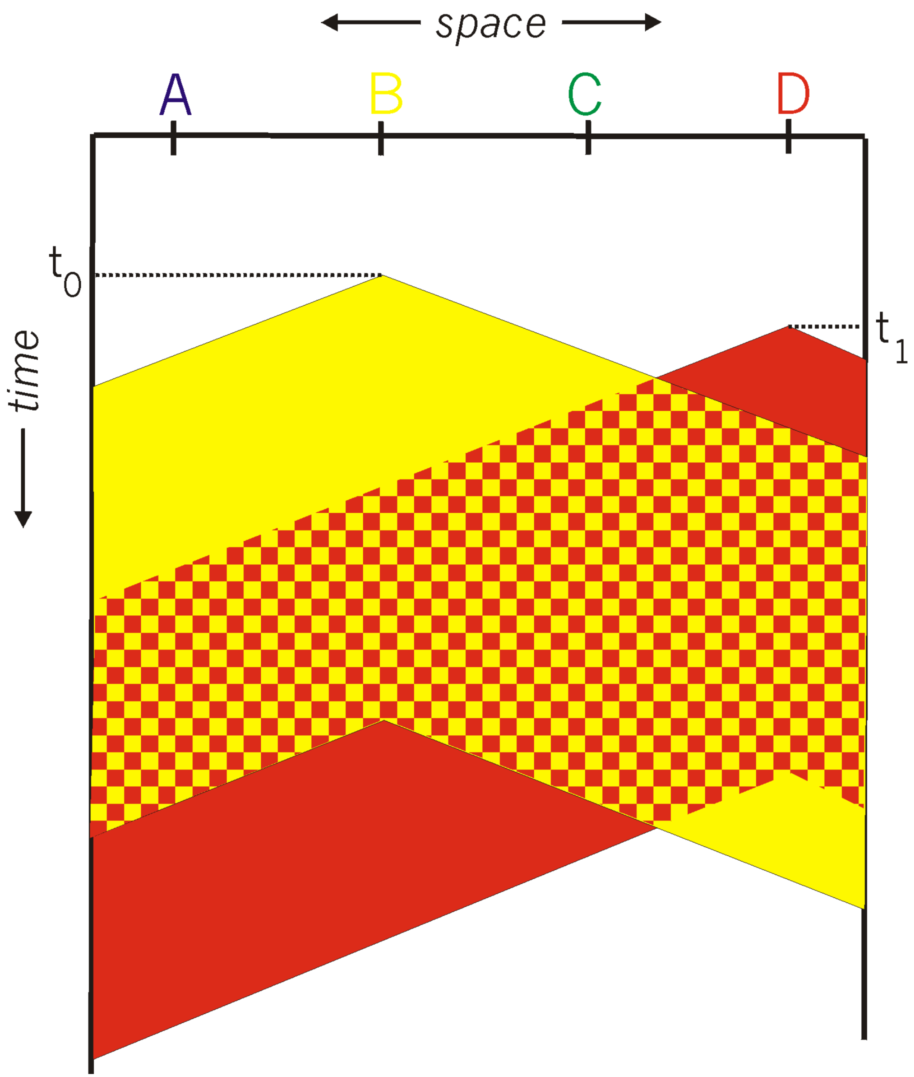
- assumption: signal overlap detectable as error
- potential collision not avoidable
- first approach: send any time (ALOHA)
  - fixed message length
  - detect collisions, random wait time, retransmit
  - best-case utilization: 18%
- next: send at slot intervals (slotted ALOHA)
  - best-case utilization: 36%

Carrier Sensing

- Carrier-Sense Multiple Access (CSMA)
  - listen to channel before transmission
  - if channel busy, wait
    - persistency – when to send after channel is sensed free?
- collisions? still possible...
  - non-zero propagation delay

CSMA – Collisions

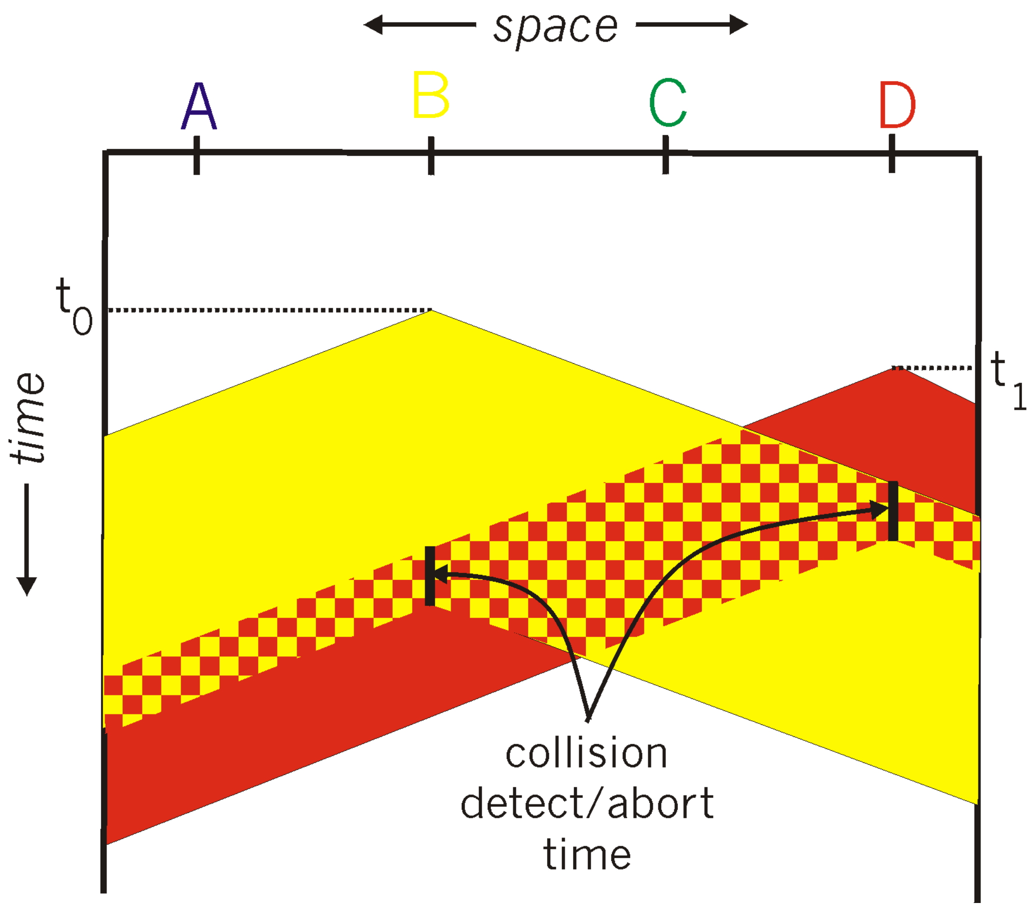
- propagation delay gap: two nodes do not hear each other
    - propagation speed
    - distance
- collision
    - entire message corrupt



Collision Detection

- compare signal on channel while own message
- detect collision locally -> abort transmission
  - reduce channel wastage
- easy in wired medium
  - compare signal strengths of transmitted/received signall
- difficult in radio networks
  - received signal strength overwhelmed by local transmission

Collision Detection



Minimum Message Size

- carrier sensing and minimum message size
  -> effective channel reservation scheme
- assume maximum distance d, prop speed v
  => maximum travel time: d/v
- remote station could transmit just before d/v
- if no collision after 2 * d/v -> channel reserved
- assume transmission rate b
  => minimum message size: b * 2 * d/v

Ethernet

- 1-persistent CSMA/CD, no ACKs
- minimum message size -> channel reservation
- but: message simply lost, if no receiver present
- collision -> randomized exponential backoff
  - increase wait time during continuous collisions
  - adaptive to level of load/contention
- modern versions: not much need for MAC
  star topology & network forwarding

Collision Avoidance

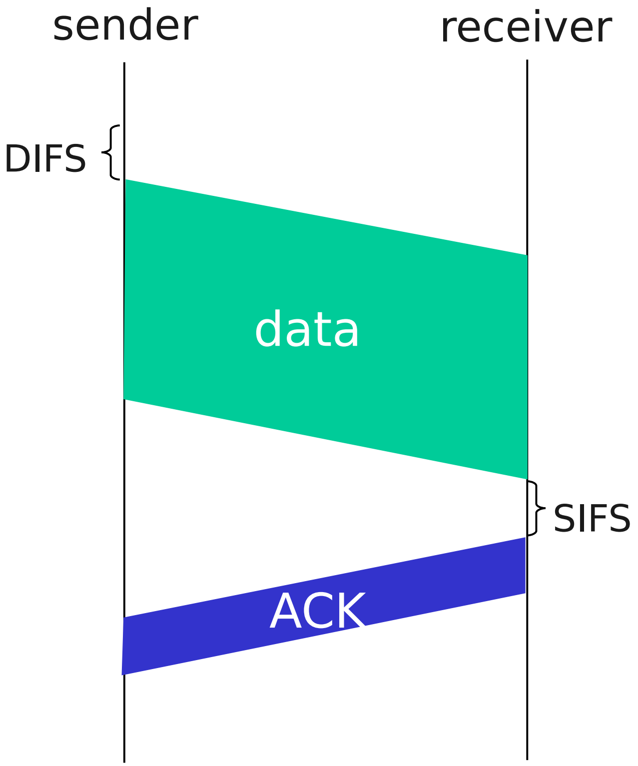
- radio: local collision detection not feasible
  - single radio cannot transmit/receive at same time
  - two radios: local signal would drown out remote
- hidden terminal problem

-> more conservative collision avoidance

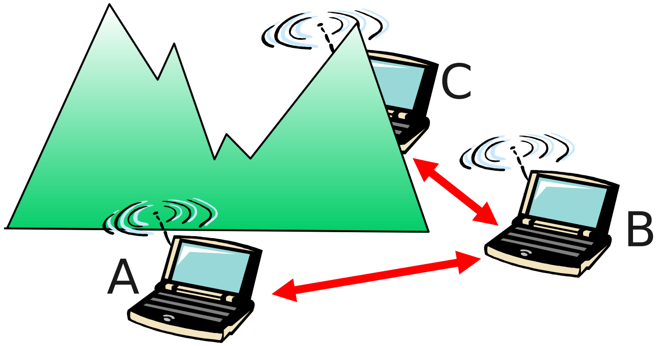
  - exponential backoff during CSMA
  - RTS/CTS mechanism to mitigate collision effect
  - ACKs to confirm successful transmission

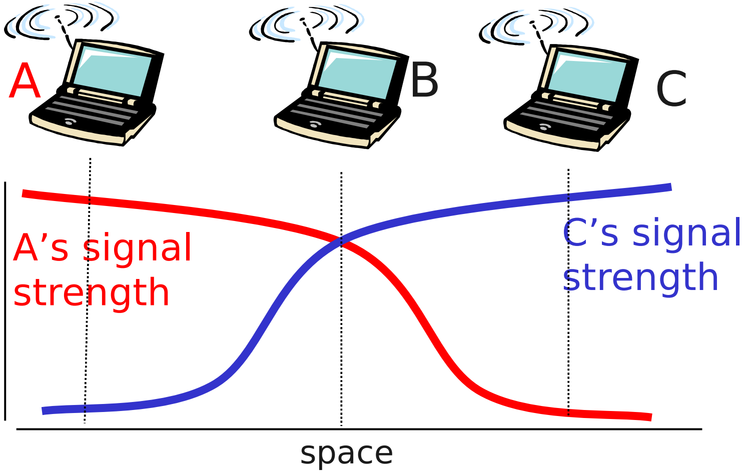
Priorities

- wait time counts down when medium is idle
- wait time priorities built into CSMA mechanism
    - SIFS – last receiver / ACK
    - PIFS – base station / control
    - DIFS – any station / data
- wait time includes backoff if applicable



Hidden Terminal

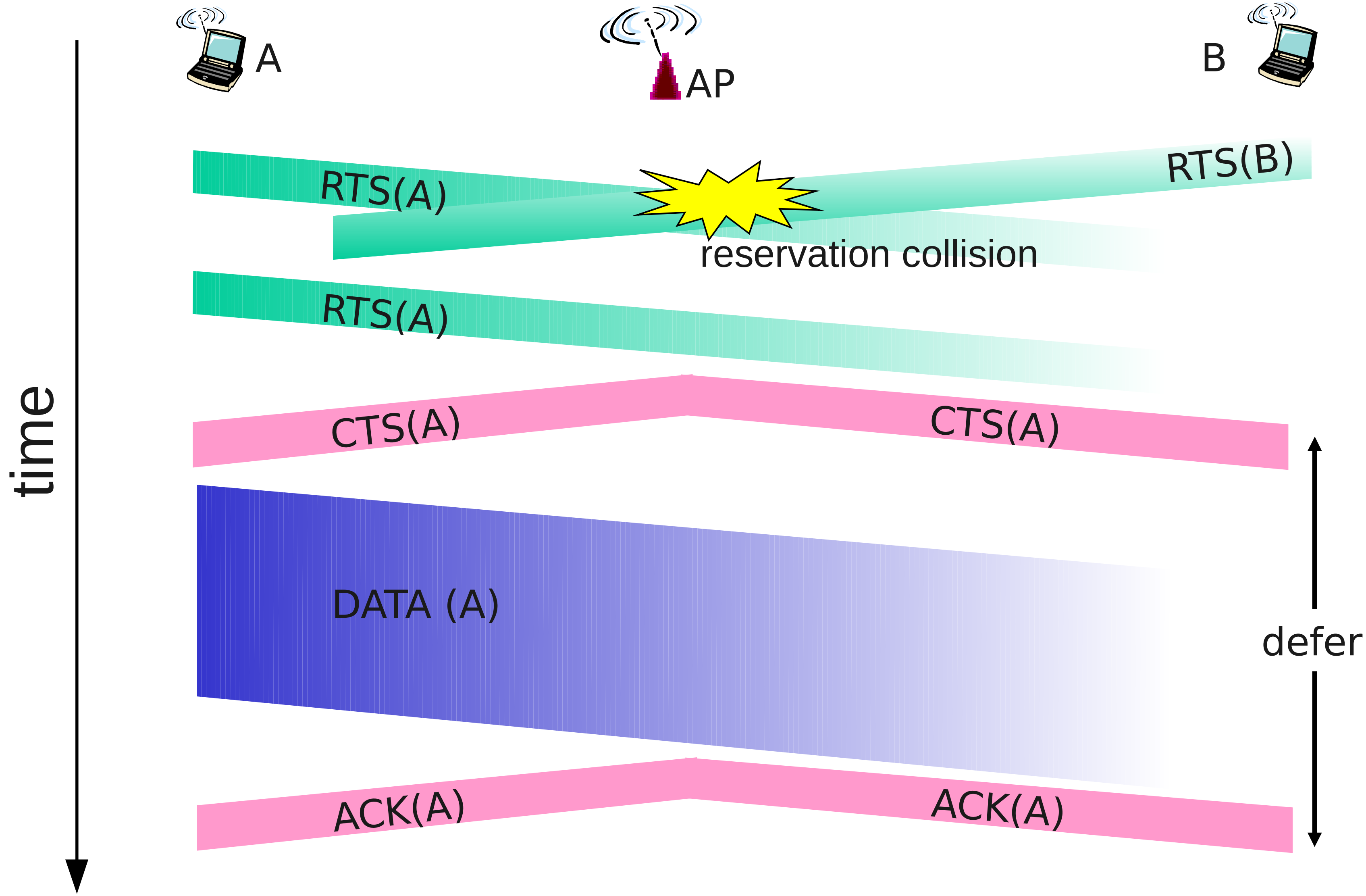




- obstruction
  - A,B hear each other
  - B,C hear each other
  - A,C can not

- signal attenuation
  - A,B hear each other
  - B,C hear each other
  - A,C can not

RTS/CTS


A
AP
B
RTS(A)
RTS(B)
reservation collision
RTS(A)
CTS(A)
CTS(A)
DATA (A)
defer
ACK(A)
ACK(A)
time

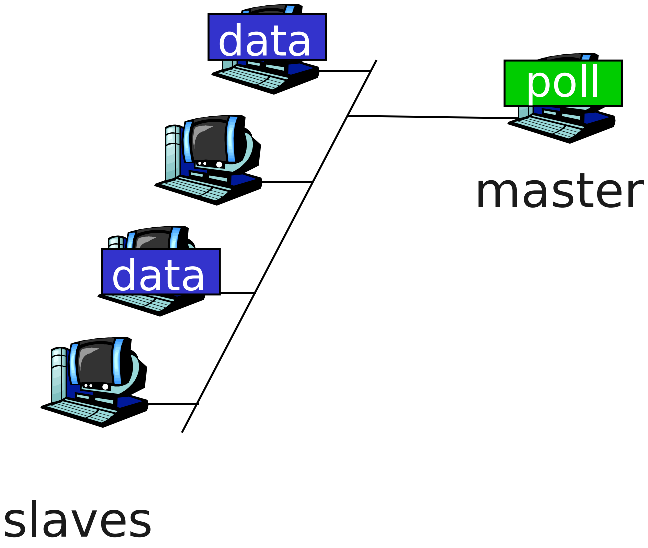
Taking Turns

- channel partitioning protocols:
  - static, coordinated
  - very efficient at high load
  - low utilization at low load
- random access
  - little a-priori coordination
  - very efficient at low load
  - collision overhead at high load

-> try dynamic, coordinated

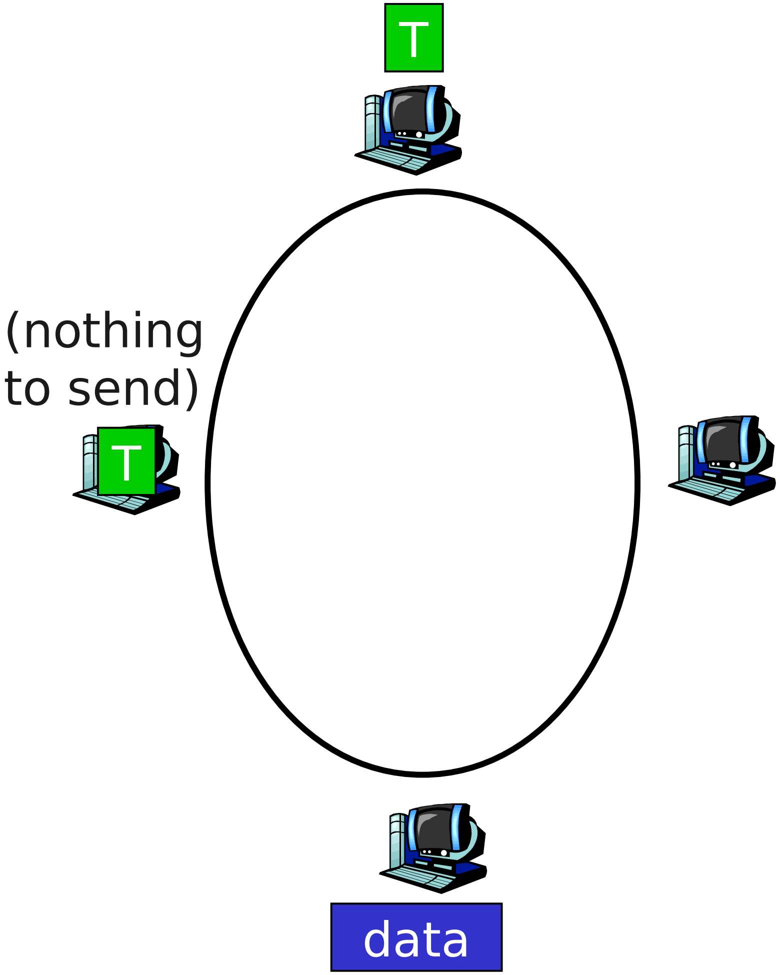
Centralized Polling

- master node "invites" slave nodes to transmit
- traditional scenario: host/terminal networks
- concerns
  - polling overhead
  - latency to send
  - single point of failure (master)



Token Passing

- control *token* passed from one station to next
- examples:
  Token Bus, Token Ring
- concerns
  - token overhead
  - latency
  - single point of failure (token)



Taking Turns

- efficient at low and high load
- manageability / control
    - minimum transmission rate
    - maximum latency
- but:
    - complexity
        - token passing: complexity in each station
    - obsolescence by point-to-point/switched Ethernet

Encapsulation

- wrap payload data into message format
- message header/trailer for control
- payload might be message itself

  -> encapsulation / layering
- typical header/trailer:
  - type, length, addresses, contro, checksuml

Performance

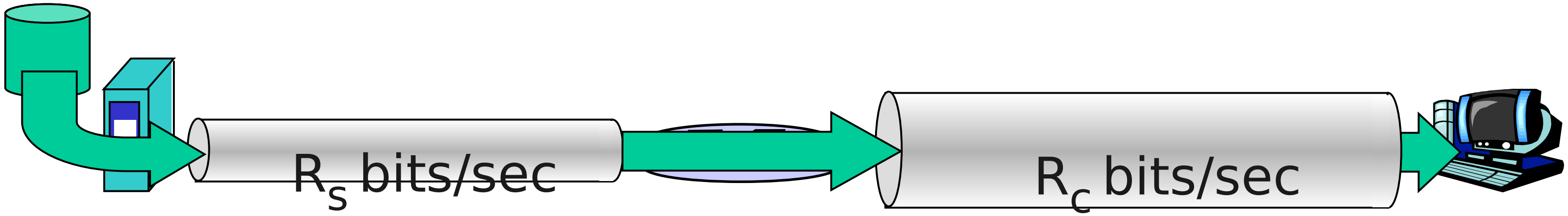
- throughput vs. delay vs. loss (later)
- example: Tim Hortons
  - number of served customers per hour
    - throughput
  - vs. time to wait for coffee
    - delay
- high throughput does not guarantee low delay
  - synchronous vs. asynchronous execution of job
  - high level of multiplexing: good for throughput

Throughput

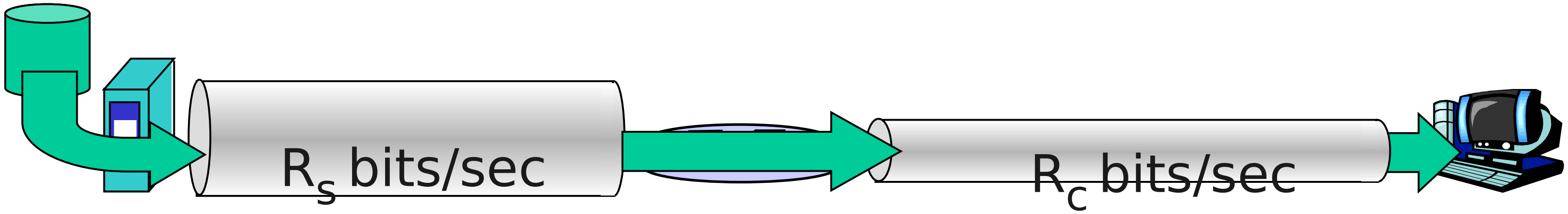
- transfer rate in bits/time
- always an average
  - different time scales relevant in different scenarios
    - streaming: minimum throughput needed “continuously”
      - i.e., over short time periods
    - download: average throughput
      - i.e., overall average throughput relevant
- capacity sharing: fairness vs. utility
  - consider two identical file downloads
  - sequential vs. concurrent download – utilities?

Throughput

- "width" of pipe
- multiple transmission segments
  - minimum throughput segment is *bottleneck*



- vs.



Delay

- processing delay
  - local processing at communication node
- queueing delay
  - later
- transmission delay (packetization)
  - message size / link throughput
- propagation delay
  - propagation speed / distance

Delay

- speed / length of pipe
- multiple transmission segments
    - total delay is sum of delays