Chapter 1

Introduction

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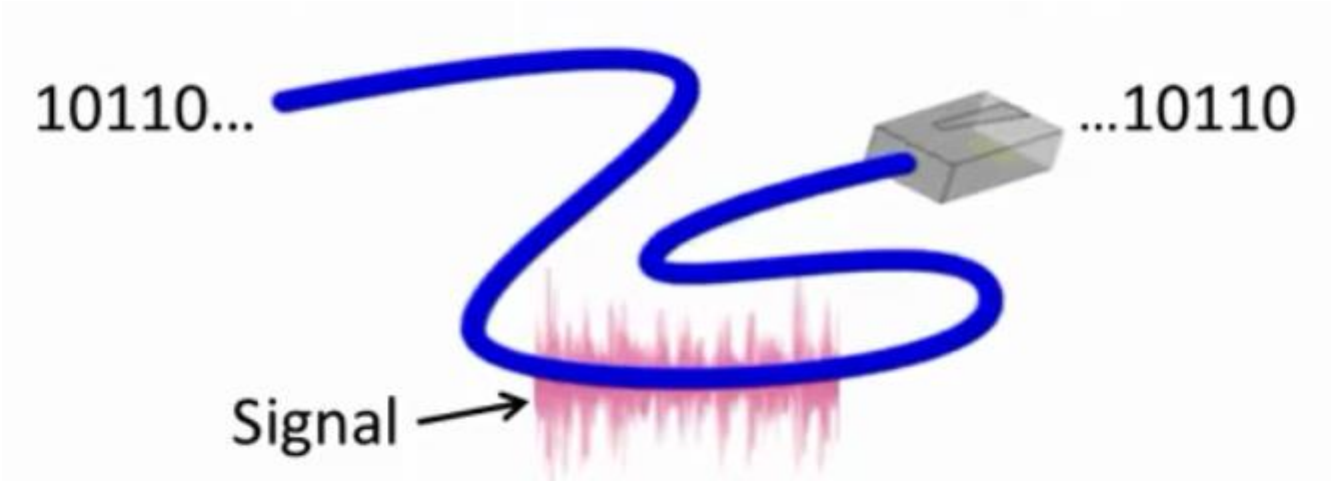
Chapter 1: roadmap

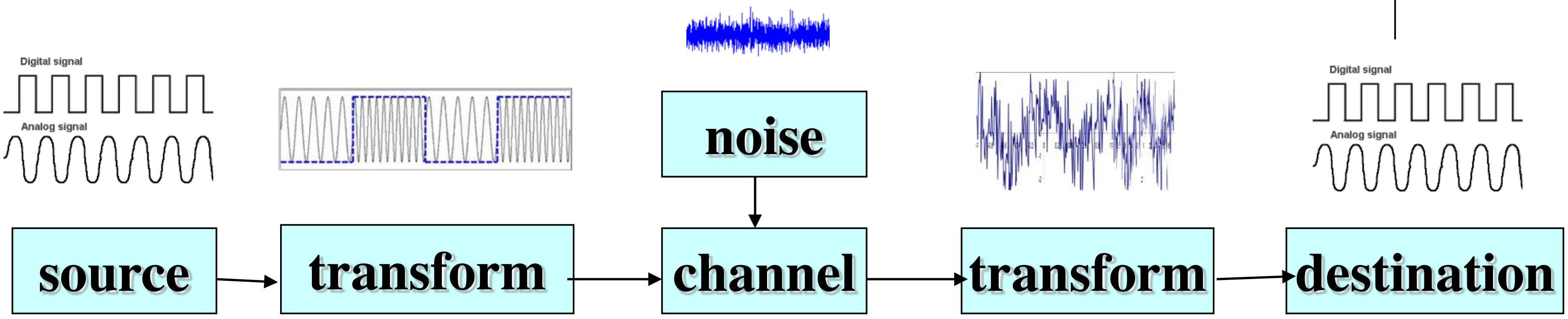
- What's Computer Network?
- protocol layers, service models
- basic concepts of data transmission:
  - bandwidth, delay, throughput, multiplexing, switching
- What's the Internet?
- network edge:
  - hosts, access net, physical media
- network core:
  - packet/circuit switching, Internet structure

Data Transmission and Physical Layer

- Physical layer Concerns how signals are used to transfer message bits over a link effectively
  - We want to send digital bits
  - Wires etc. carry analog/digital signals



Communication System



- source： analog signal, digital signal
- transformation： modulation, encoding, multiplexing,
- channel： bandwidth, noise, error-rate

Concepts of Data Transmission

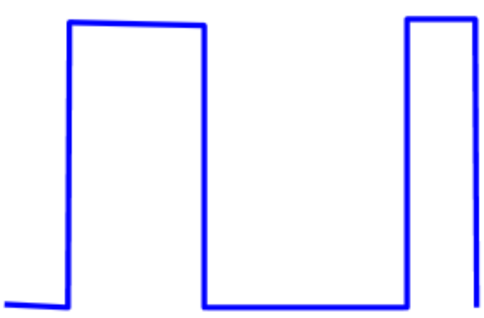
- Signals
- Bandwidth & Throughput
- Baud Rate and Bit Rate
- Synchronous/Asynchronous Communication
- Serial/Parallel Communication
- Data Encoding
- Multiplexing
- Switching
- Delay and Loss

Signals Over a Wire

What about Optical Signal?

- What happens to a signal as it passes over a wire?
  - The signal is delayed (propagates at ⅔c)
  - The signal is attenuated (energy lose)
  - The signal is distorted (high frequency lose)
  - Noise is added to the signal (causes errors)

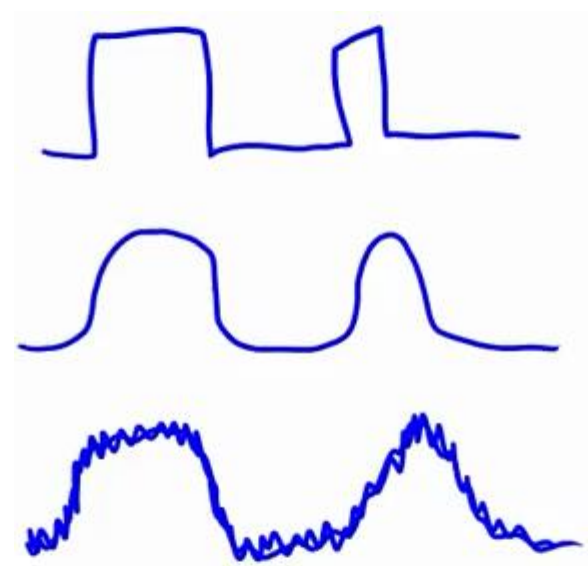
Signal sent



attenuation:

distortion:

noise:



Bandwidth

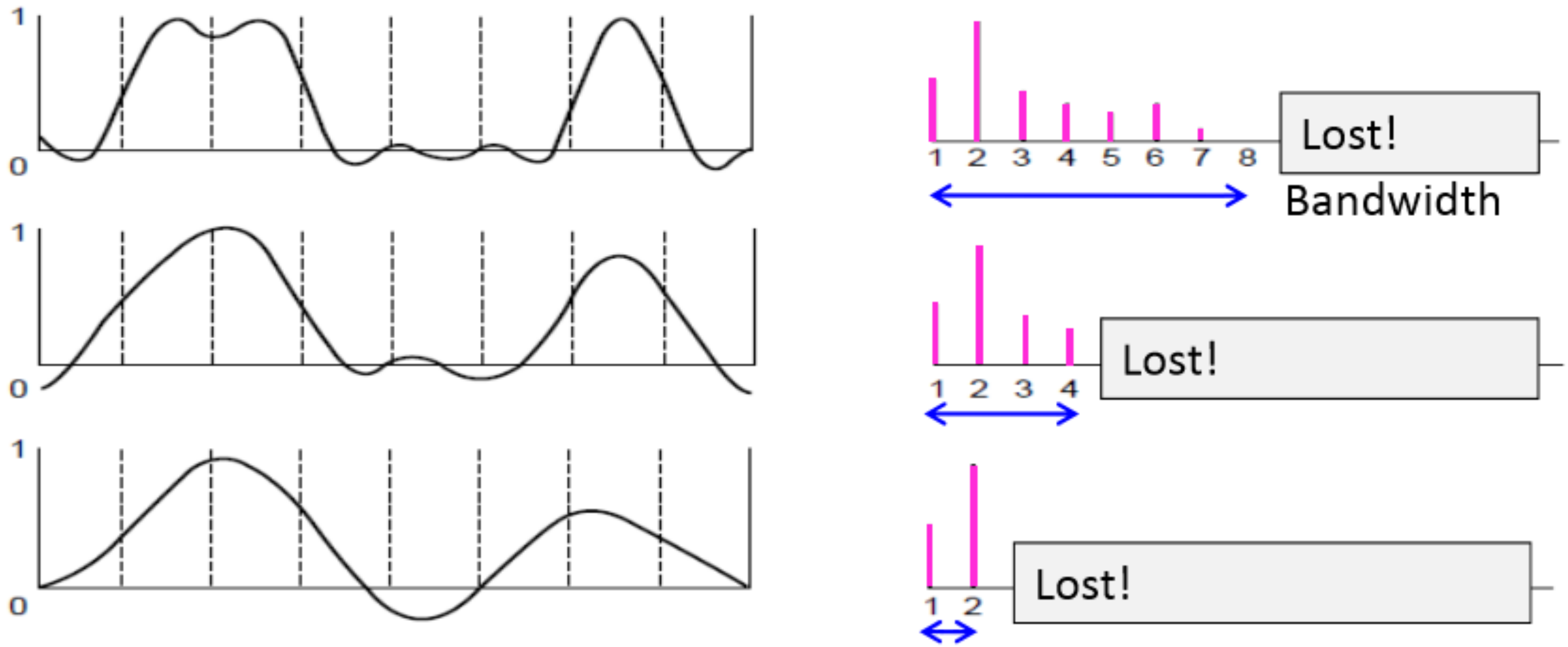
- Bandwidth (Hz): the range of frequencies transmitted without being strongly attenuated.
- The bandwidth is a physical property of the transmission medium and usually depends on the construction, thickness, and length of the medium.

EE: Bandwidth = width of frequency band, measured in Hz
CS: Bandwidth = information carrying capacity, in bits/sec

Bandwidth and Bandwidth-Limited Signals

- A Wide Band signal will be distorted when transmitted thru relatively narrower band channel with the higher harmonics cut off or hold back.

Demo



Baud Rate and Bit Rate

- The baud rate is the number of samples or symbols per second sent over the channel.
- The bit rate is the amount of information per second sent over the channel.
  - bit rate = baud rate x bits/symbol
  - The data encoding (e.g., QPSK) determines the number of bits/symbol

Metric Units

- The main prefixes we use:

Prefix	Exp.	prefix	exp.
K(ilo)	10^3	m(illi)	10^{-3}
M(ega)	10^6	μ(micro)	10^{-6}
G(iga)	10^9	n(ano)	10^{-9}

- Use powers of 10 for rates, 2 for storage.
  - 1 Mbps = 1,000,000 bps, 1 KB = 2^{10}bytes
- "B" is for bytes, "b" is for bits

Capacity / the maximum data rate

- **Nyquist's theorem**: the maximum data rate for a finite bandwidth noiseless channel is:

$$\text{Maximum data rate} = 2H\log_2 V,$$

Where H is the Bandwidth and V is the discrete levels of the signal.

- **Shannon's theorem**: the maximum data rate of a noisy channel with signal-to-noise ratio S/N is:

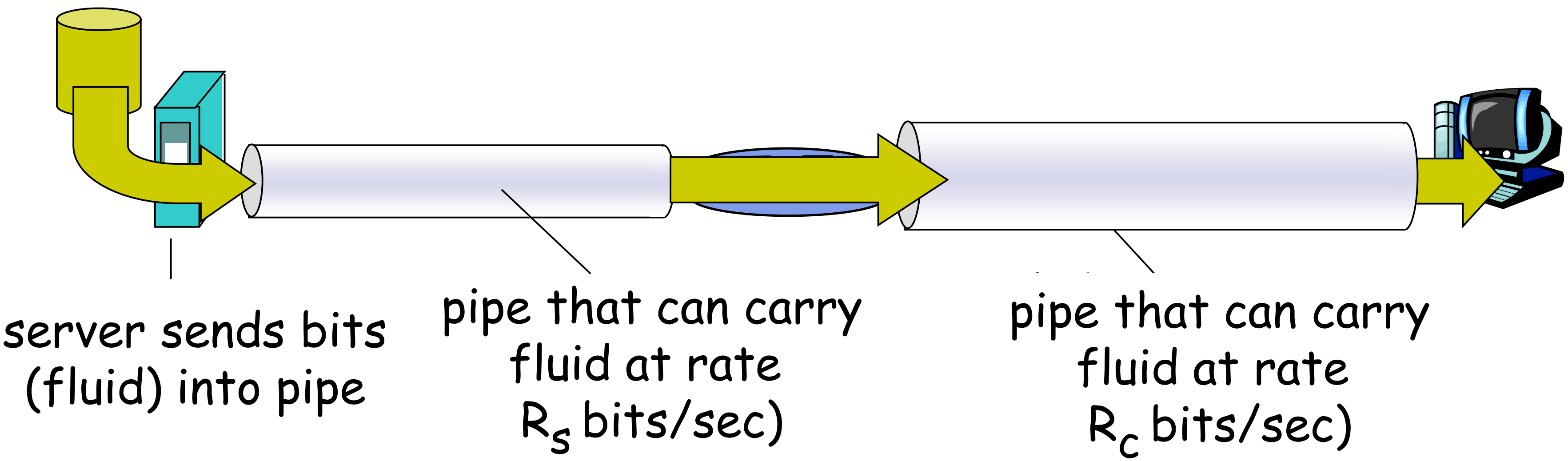
$$\text{Maximum data rate} = H\log_2(1+S/N)$$

$$S/N\text{（dB）} = 10\log_{10} S/N$$

E.g. telephone line
Bandwidth: H = 4kHz
V = 2
S/N = 30dB
Maximum date rate = min (Nyquist's, Shannon's)
Shannon: Max D = 4k * log2(1+1000) = 40kbps
Nyquist: 8kbps
→ 8kbps

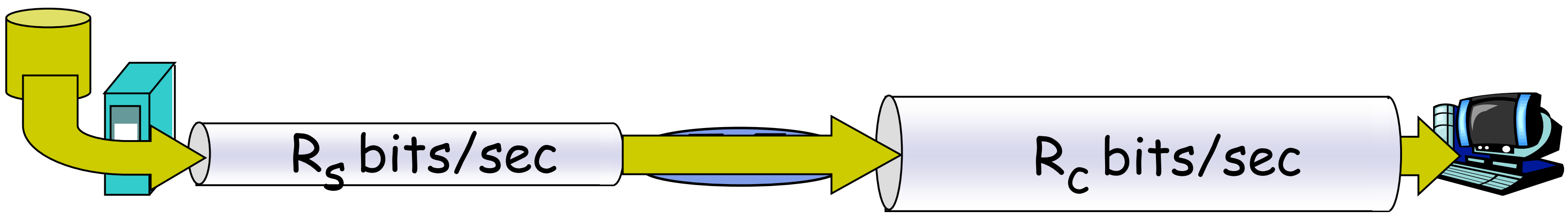
Throughput / the real data rate

- *throughput:* rate (bits/sec) at which bits transferred between sender/receiver
  - *instantaneous:* rate at given point in time, or
  - *average:* rate over longer period of time

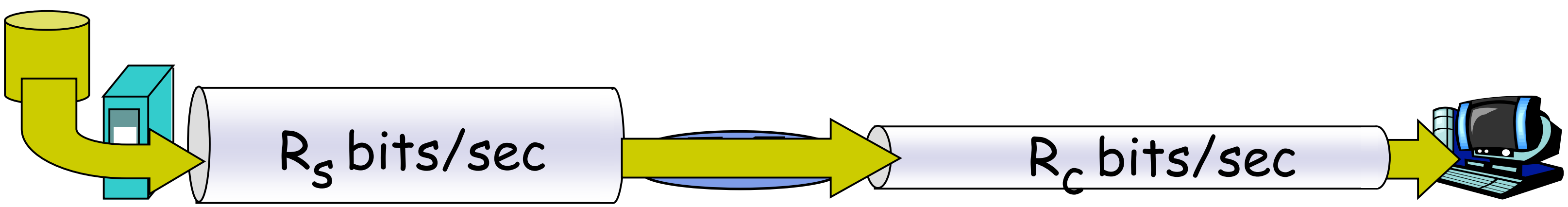


Throughput (more)

- $R_s < R_c$ What is average end-end throughput?



- $R_s > R_c$ What is average end-end throughput?

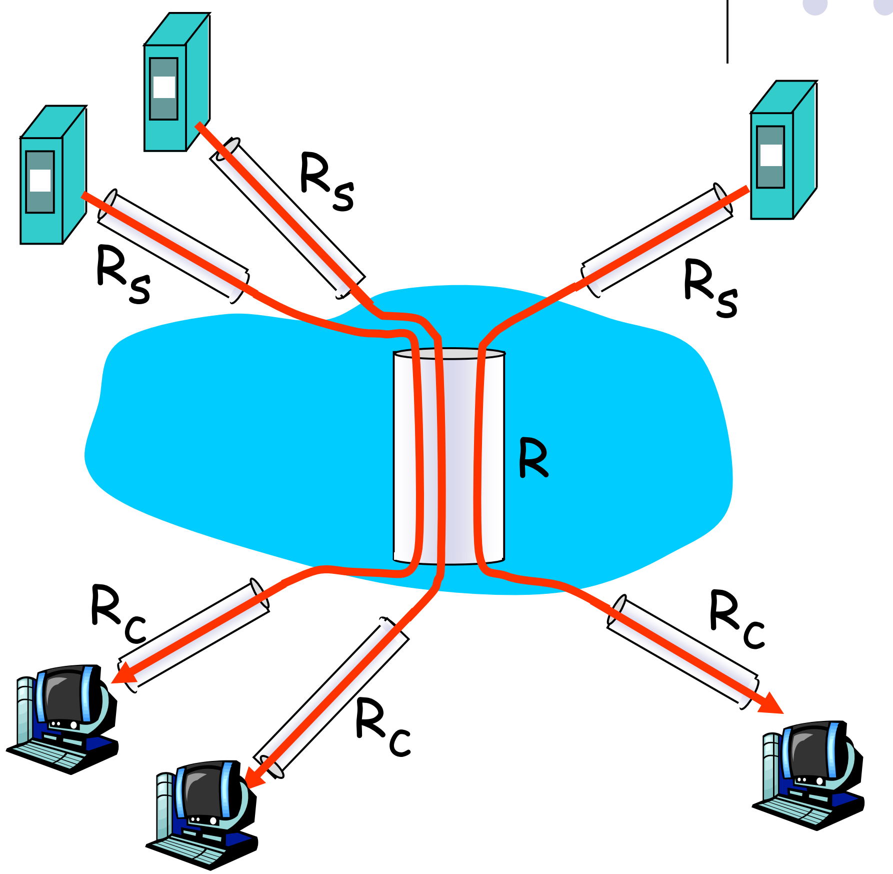


bottleneck link

link on end-end path that constrains end-end throughput

Throughput: Internet scenario

- per-connection end-end throughput? $\min(R_c, R_s, R/N)$
- in practice: R_c or R_s is often bottleneck



N connections (fairly) share backbone bottleneck link R bits/sec

Data Encoding
(from data to data)

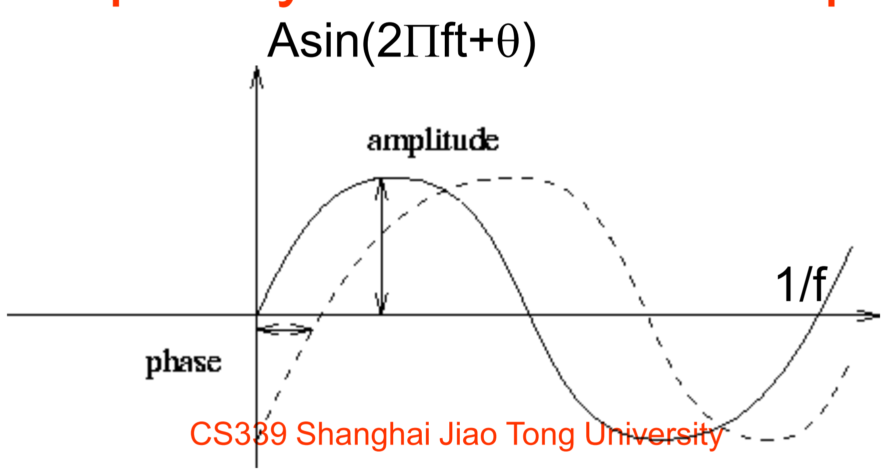
- To send text, need some way of encoding.
- ASCII and Unicode are two examples
  - ASCII is 8-bit (1 byte) unicode is 16-bit (2 byte)
  - "HELLO" in ASCII as an example
    - 72, 69, 76,76,79 (decimal)
    - 48, 45,4C,4C, 4F (hexidecimal)
    - 0100 1000 0100 0101 0100 1100 0100 1100 0100 1111 (binary)
  - "你好" in GB2312+ASCII as an example
    - C4, E3, BA, C3 (hex GB2312)
    - 1100 0100 1110 0011 1011 1010 1100 0011(binary)

Data Encoding
(from data to signal)

- Analog signals Transmission for digital data (Modulation):
  - ASK(Amplitude Shift Keying)
  - FSK(Frequency Shift Keying)
  - PSK(Phase Shift Keying)
  - QPSK(Quadrature Phase Shift Keying)
- Digital signals Transmission for digital data
  - Non-return-to zero encoding
  - Return-to zero encoding
  - Manchester encoding
  - 4B/5B
- Digital signals Transmission for analog data
  - Pulse Code Modulation

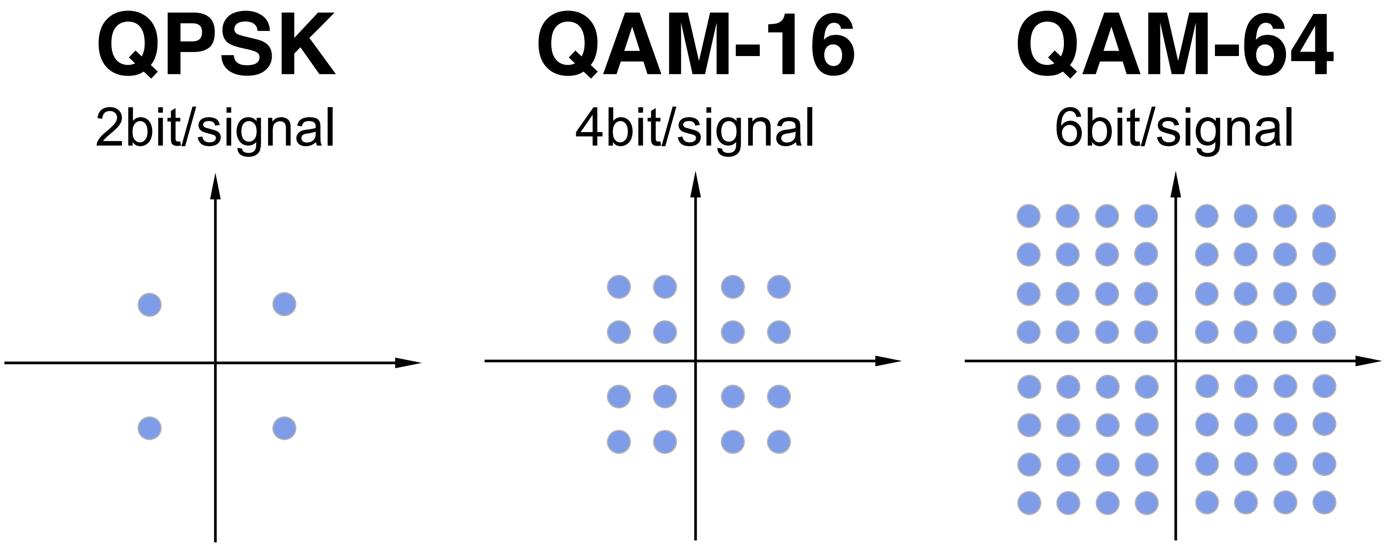
Modulation

- Baseband electrical signal is not suitable for long distance transmission because of its wide frequency spectrum.
- Modulation: a continuous tone called sine wave carrier is introduced. Its amplitude, frequency, or phase can be modulated to transmit information.
- Three basic forms of modulation: amplitude modulation, frequency modulation and phase modulation.



Demo

QPSK(Quadrature Phase Shift Keying)



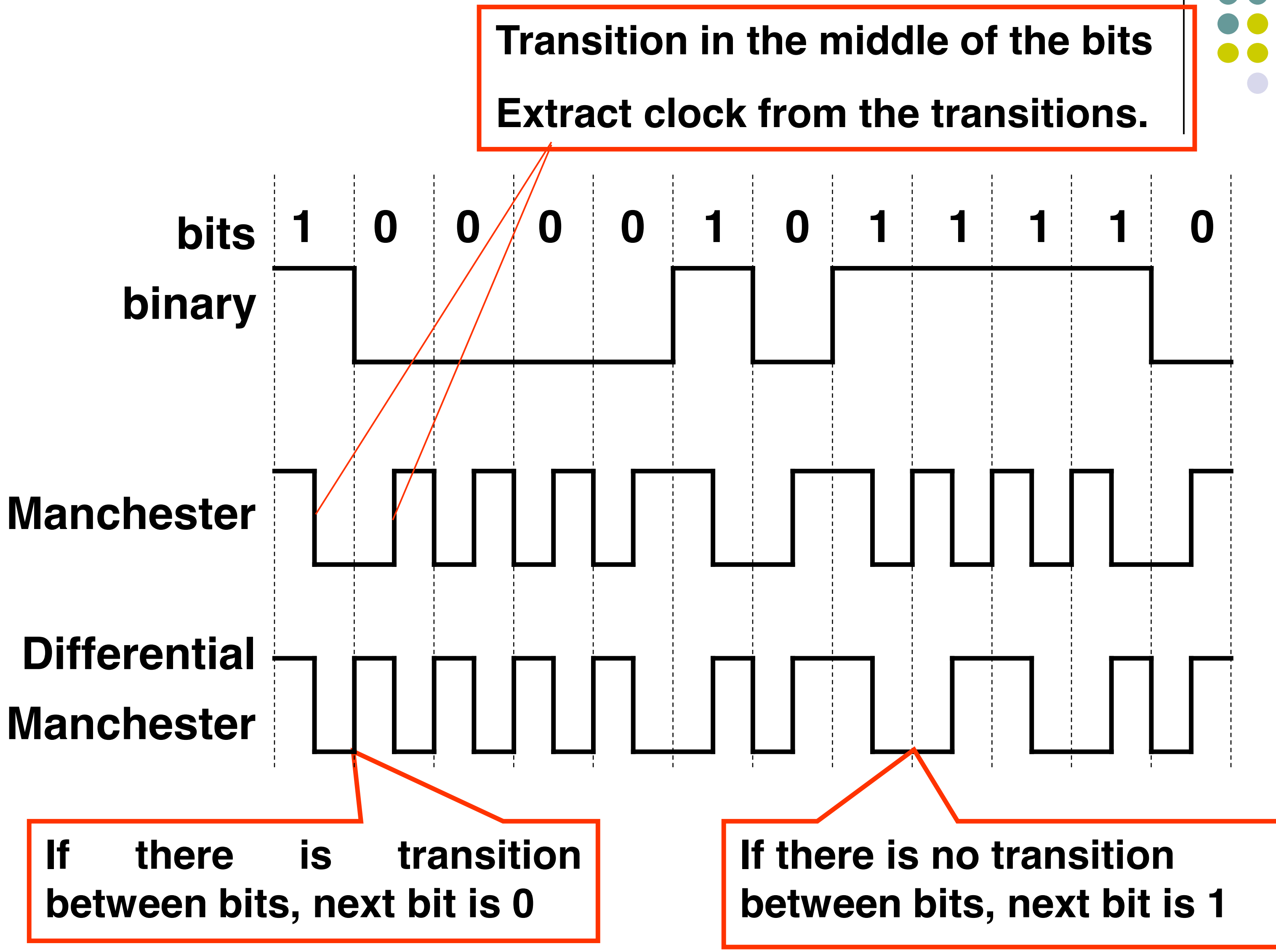
Bits/symbol

number of valid signal states determines the number of bits per symbol

Manchester encoding

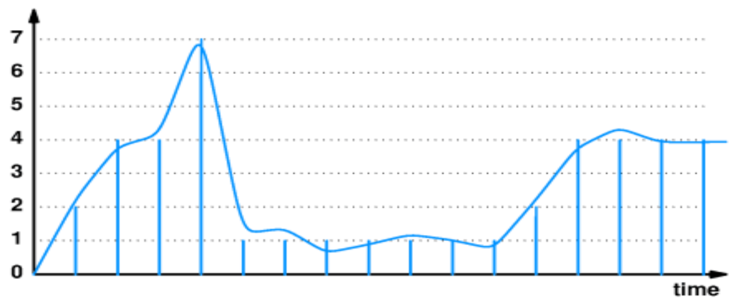
- Problems of baseband signal:
  - Straight binary encoding with 0 volts for a 0 bit and 5 volts for a 1 bit would lead to ambiguities.
  - Different clock speeds can cause the receiver and sender to get out of synchronization about where the bit boundaries are
- Manchester encoding is introduced for receivers to unambiguously determine the start, end, or middle of each bit without reference to an external clock.

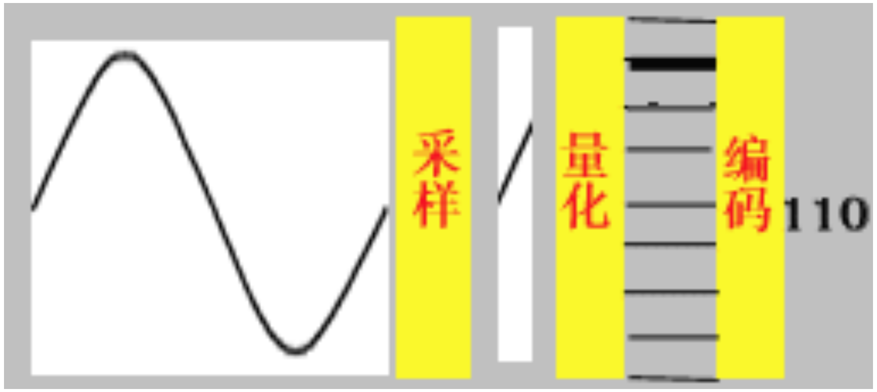
Manchester Encoding



Pulse Code Modulation

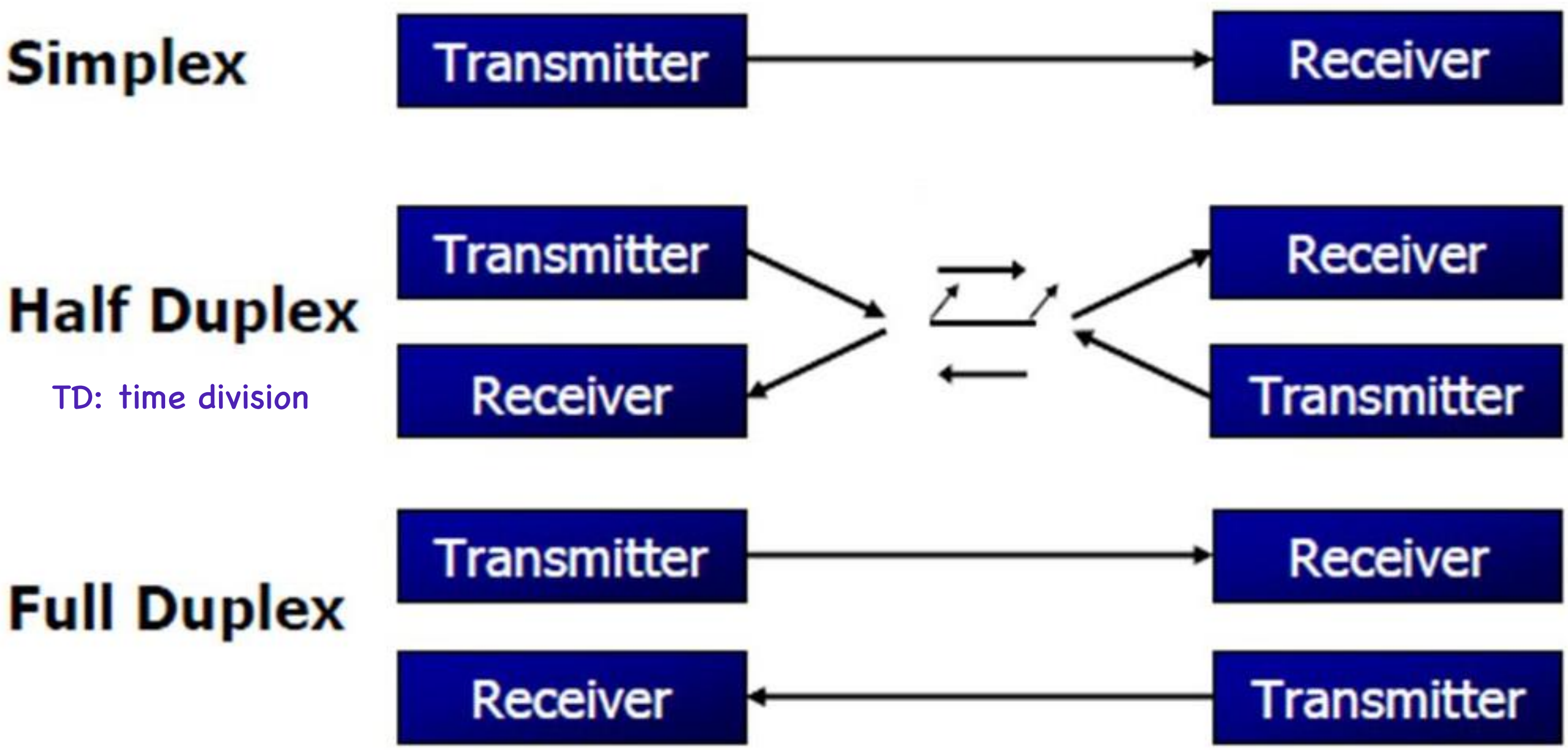
- AD Transformation: sampling、quantifying、encoding



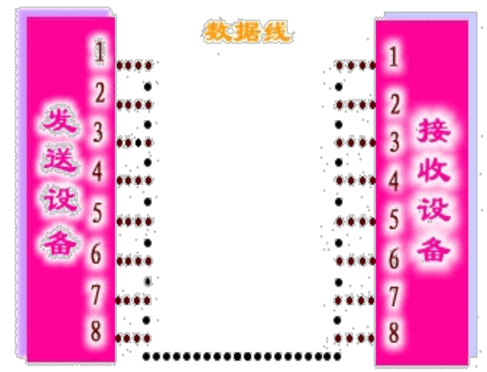


- **PCM** forms the heart of the modern telephone system.
  - sampling period :125us，256 level quantifying，
  - bit rate：8*8000=64Kbps

Type of Links/Channels



Serial and Parallel Communication



expensive

synchronization of signal

Serial: sent over a single channel one bit at a time

Parallel: send multiple bits at a time over multiple lines

Multiplexing

- Multiplexing: techniques of transmitting multiple signals over a single physical trunk simultaneously without interference.
- FDM: the frequency spectrum is divided into frequency bands for individual signals.
- TDM: the users take turns to use the entire bandwidth for a little burst of time.
- Wavelength Division Multiplexing is just FDM at very high frequencies
- CDMA (Code Division Multiple Access)

FDM

TDM

ATDM

Asynchronous TDM: distribute time slot on demand

WDM

CDMA

Code Division Multiple Access (CDMA)

- Used in several wireless broadcast channels (cellular, satellite, etc) standards
- Unique "code" assigned to each user; i.e., code set partitioning
- All users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data

CDMA Example

- The spreading code C_k must be unique for each user.
- Ideally, they are orthogonal to one another, i.e.

$$<C_i, C_k> = 0, \text{ unless } i = k$$
$$<C_i, C_k> = J, \quad \text{if } \ i = k$$

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

4-Ary Walsh Codes

$Suppose \quad user1 = 101, user2 = 011$

Encoding process :

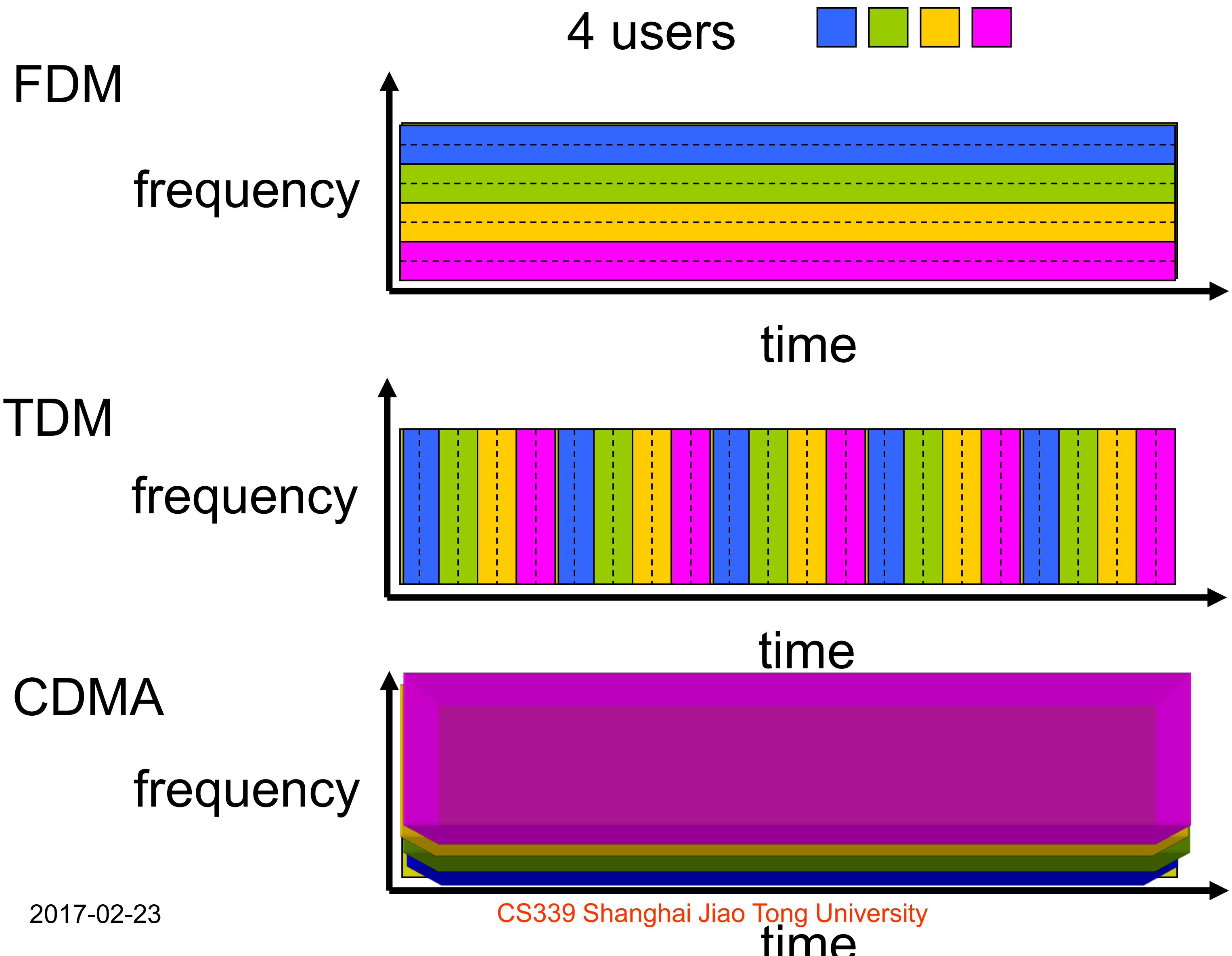
$$\begin{bmatrix} 1 & -1 \\ -1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 2 & 0 & 2 \\ -2 & -2 & 0 & -2 \\ 2 & 0 & 2 & 0 \end{bmatrix}$$

Decoding process :

$$\begin{bmatrix} 0 & 2 & 0 & 2 \\ -2 & -2 & 0 & -2 \\ 2 & 0 & 2 & 0 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} = \operatorname{sgn} \begin{bmatrix} 4 & -4 \\ -4 & 4 \\ 4 & 4 \end{bmatrix}$$

CDMA

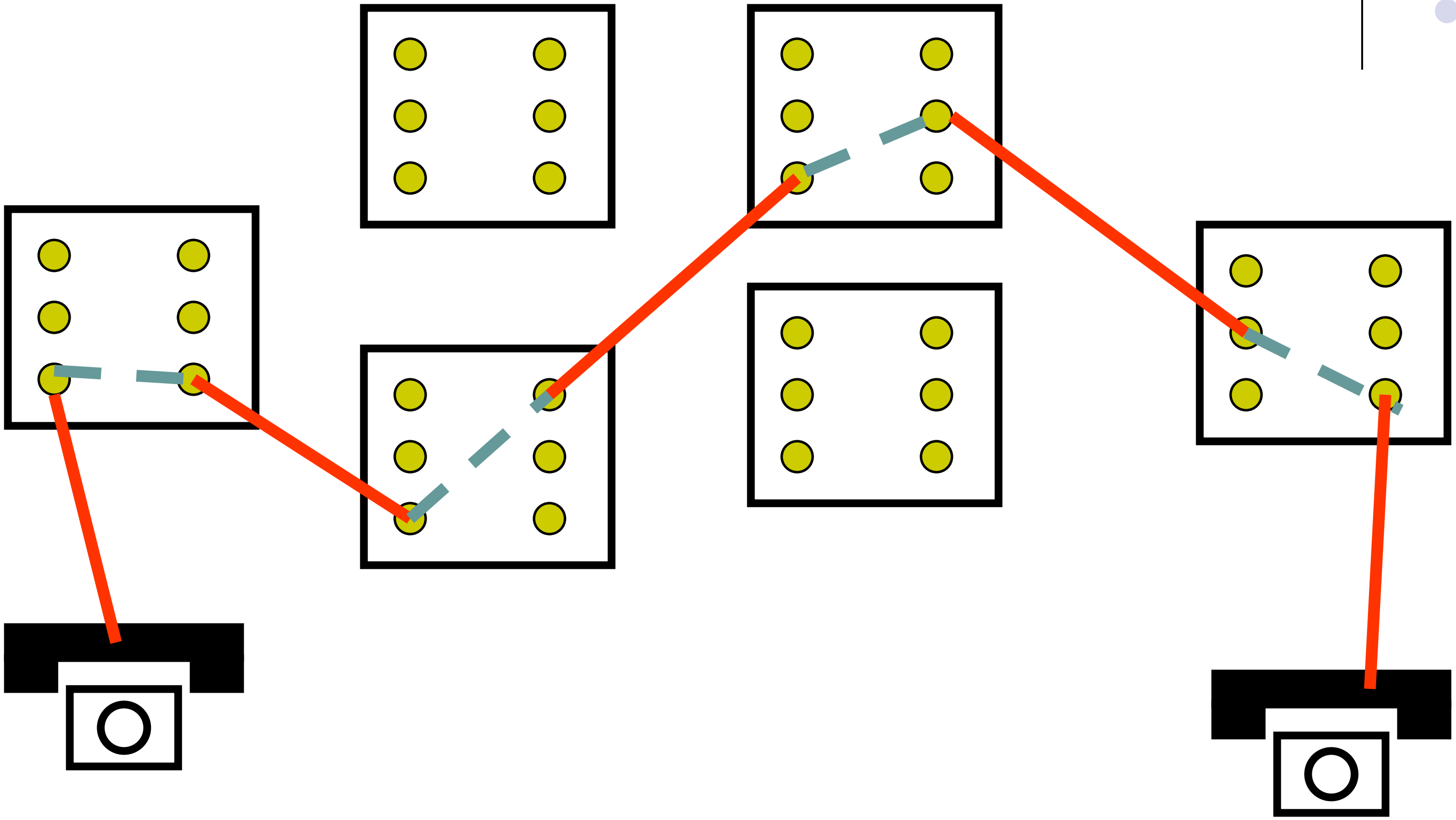
FDM ,TDM and CDMA



Switching

- Circuit switching
- Message switching
- Packet switching
  - Virtual Circuit switching

Circuit Switching -connection oriented



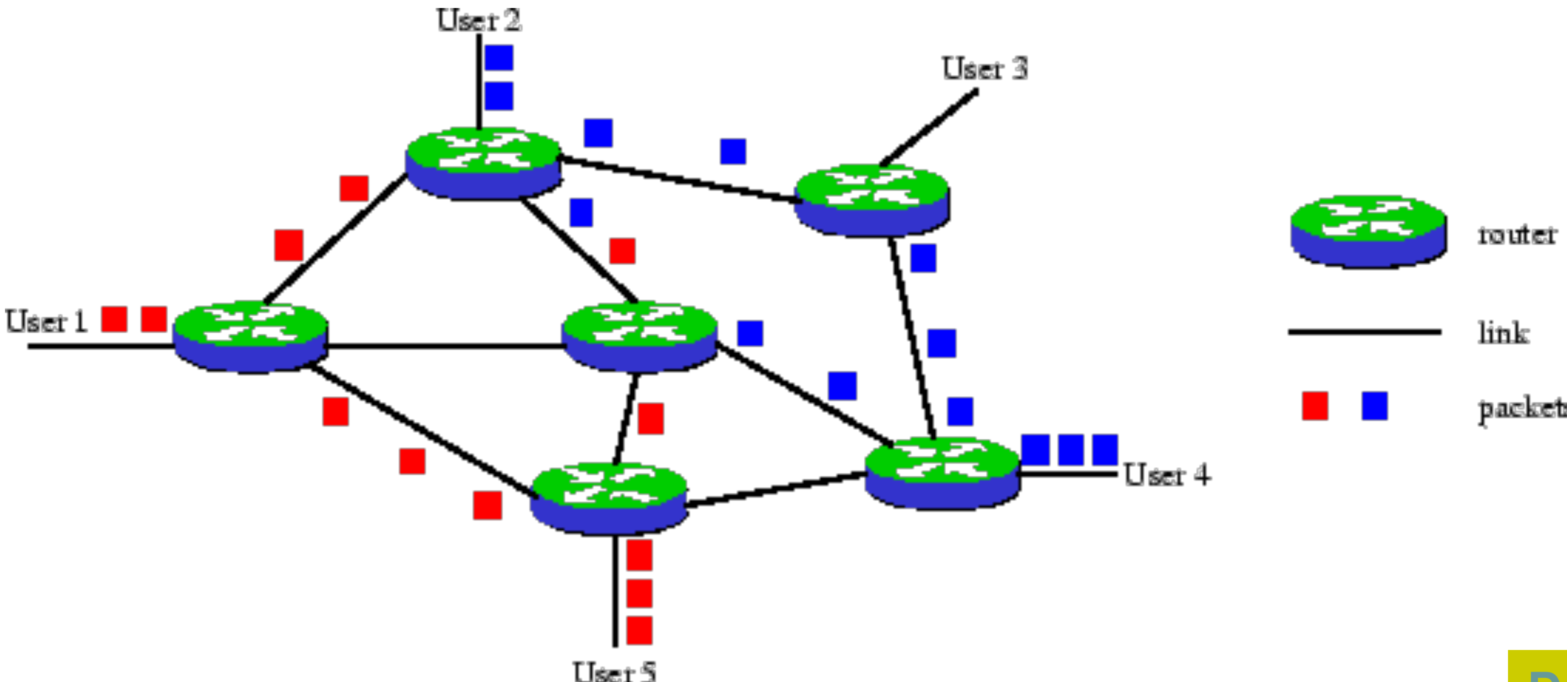
- A complete path is established prior to the call.
- It lasts for the duration

Circuit Switching

- Each session is allocated a fixed fraction of the capacity (FDM,TDM) on each link along its path
- Advantages
  - dedicated resources
  - fixed delays (real-time)
  - guaranteed continuous delivery
- Disadvantages
  - circuits are not used when session is idle
  - Inefficient for bursty traffic
  - fixed rate stream

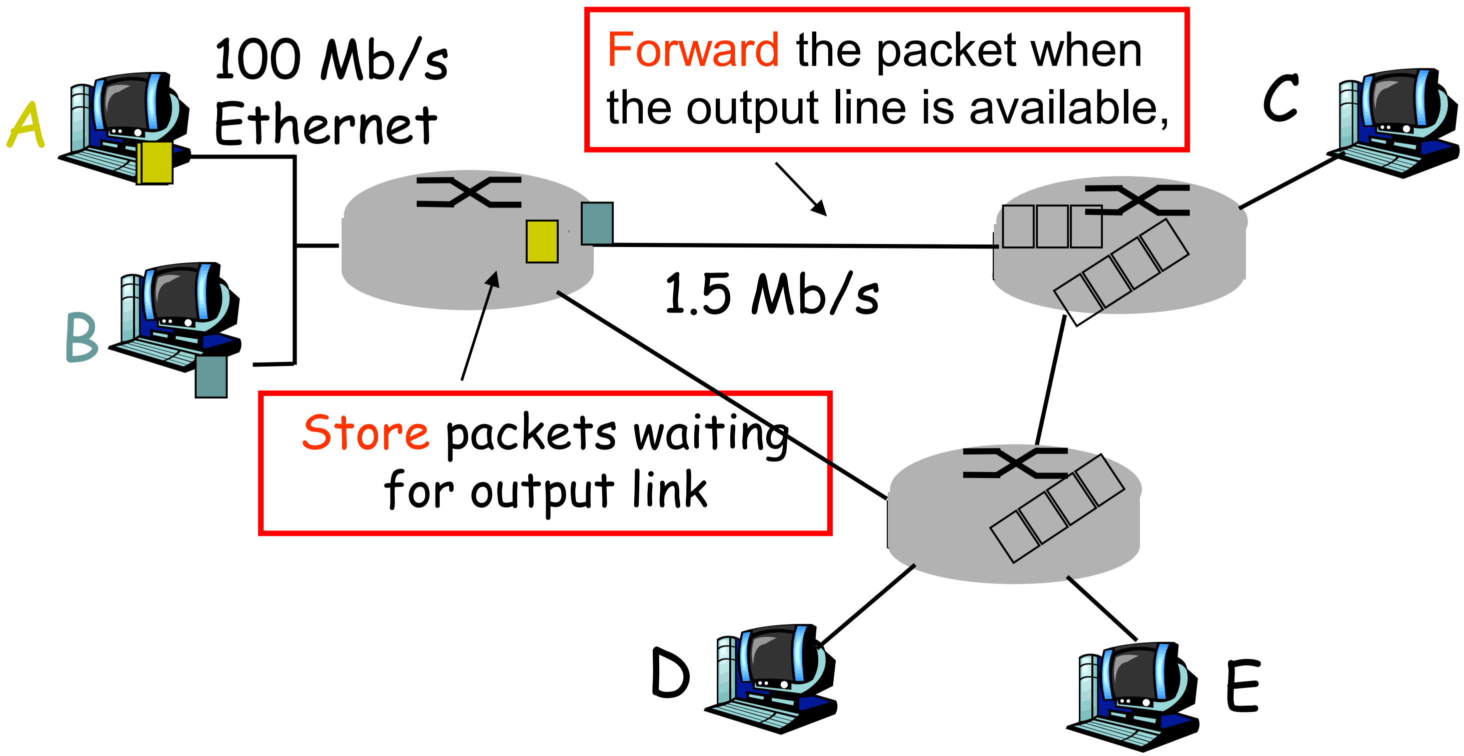
Packet Switching -connectionless

- data is divided into *packets.*
- users *share* network resources (link, router) with store-and-forward approach.
- route chosen on packet-by-packet basis



Demo

Packet Switching: Statistical Multiplexing

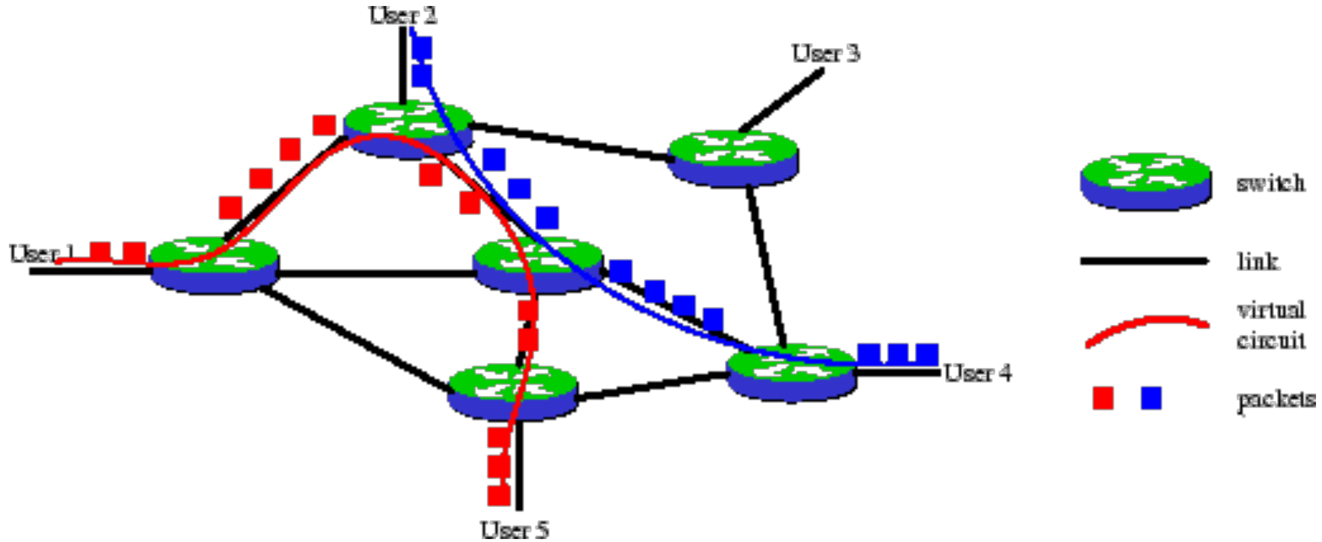


statistical multiplexing

Resource are allocated and shared on demand.

Packet Switching - Virtual Circuit

- All packets associated with a session follow the same path
- Route is chosen at start of session
- Packets are labeled with a VC# designating the route



Demo

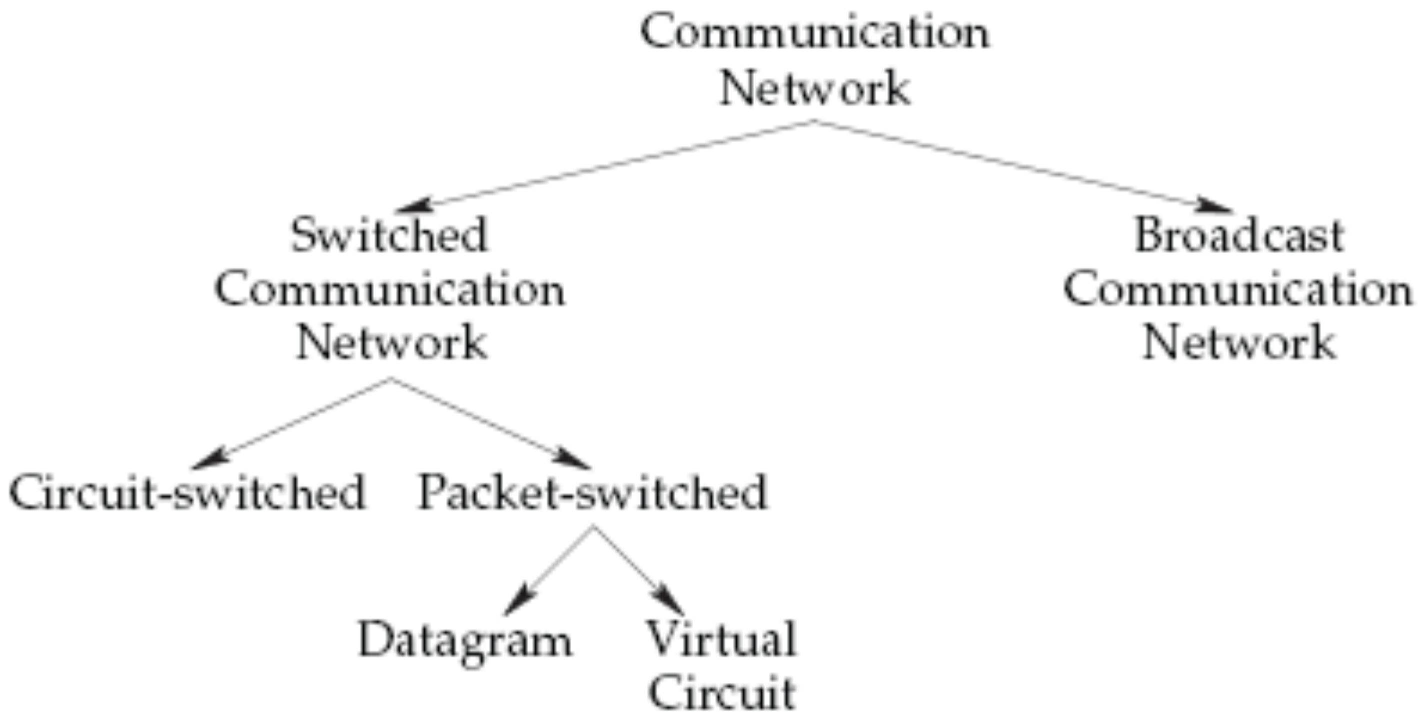
Virtual Circuit

Circuit switching over packet switching network

Packet Switching

- Advantages
  - efficient for bursty data
  - allows more users to use network!
  - easy to provide variable rates
- Disadvantages
  - variable delays
  - best-effort service
  - packets can arrive out-of-order
- Need for Quality of service (QoS)
  - guaranteed bandwidth
  - guaranteed delays
  - guaranteed delay variations
  - packet loss rate etc...

Recap: Big Picture

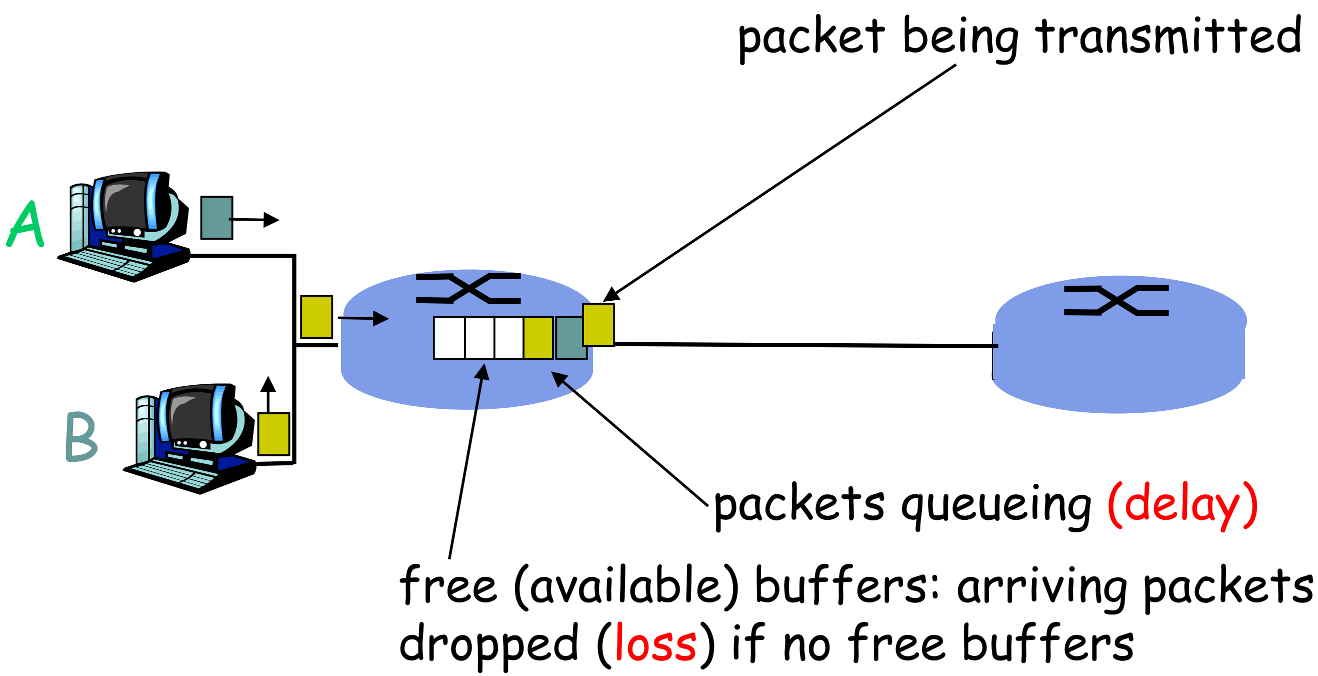


Switching Comparison

Item	Circuit-switched	Packet-switched	VC
			Y/N
Call setup	Required	Not needed	No
Dedicated physical path	Yes	No	Yes
Each packet follows the same route	Yes	No	Yes
Packets arrive in order	Yes	No	Yes
Is a switch crash fatal	Yes	No	Reserved
Bandwidth available	Fixed	Dynamic	setup
When can congestion occur	At setup time	On every packet	Yes
Potentially wasted bandwidth	Yes	No	Yes
Store-and-forward transmission	No	Yes	Yes
Transparency	Yes	No	*
Charging	Per minute	Per packet	

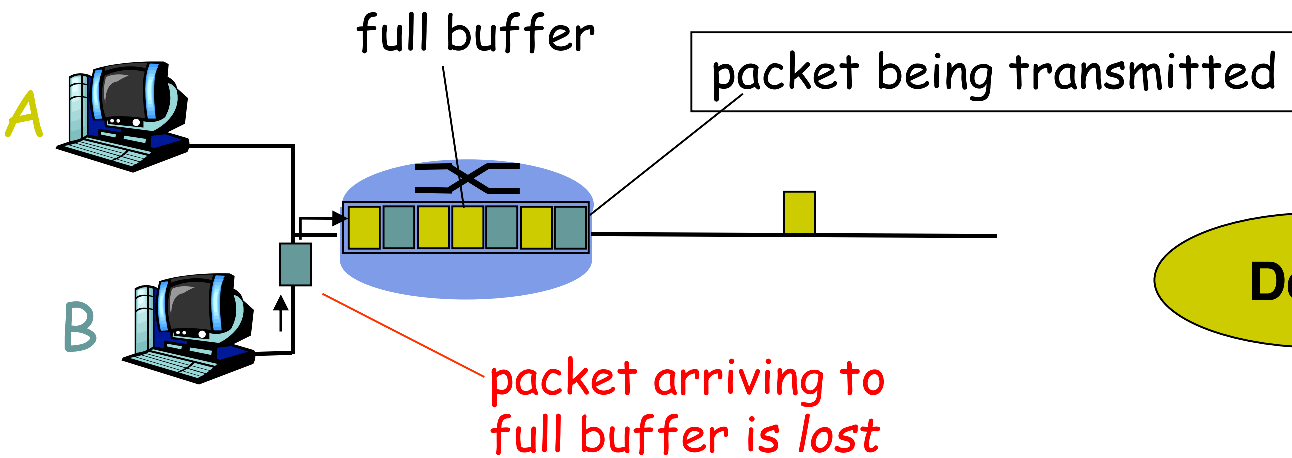
Queuing, delay and loss in packet-switched network

- packets *queue* in router buffers when packet arrival rate exceeds output link capacity
- packets queue, wait for turn to forward



Packet loss

- queue (buffer) has finite capacity
- packet arriving to full queue dropped (lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



Demo

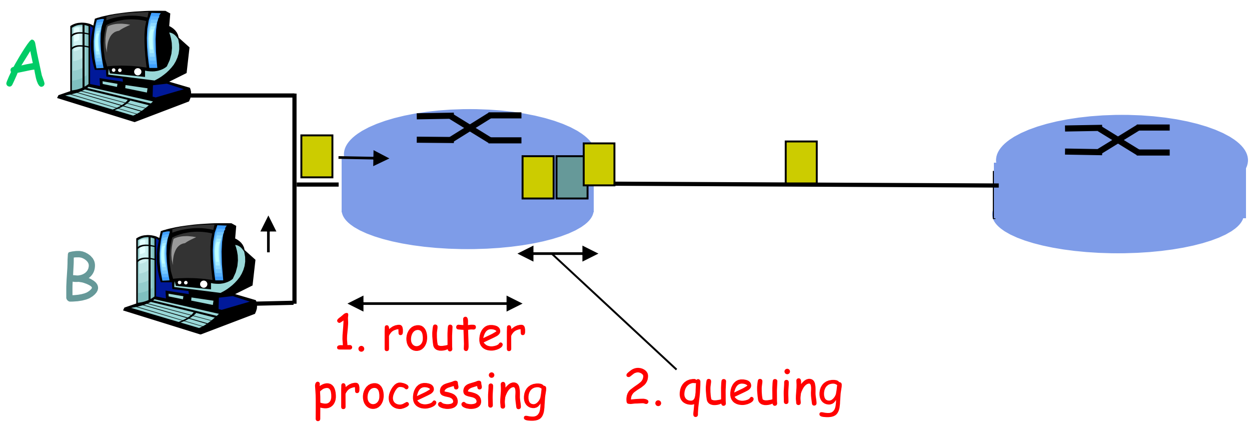
Four sources of packet delay

1. processing:

- check header
- check bit errors
- determine output link

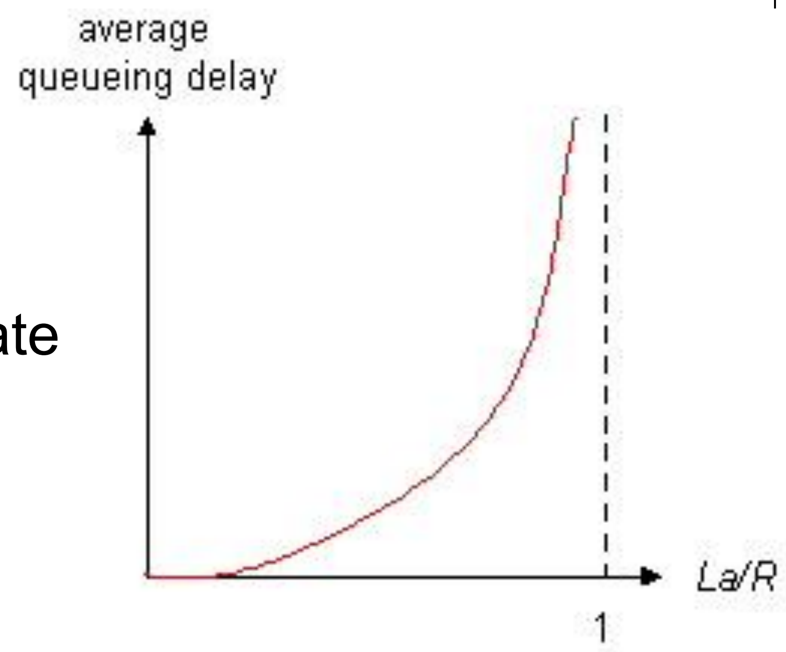
2. queuing

- time waiting at output link for transmission
- depends on congestion level of router



Queuing delay vs. traffic intensity

- R=link bandwidth (bps)
- L=packet length (bits)
- a=average packet arrival rate (packets/sec)



traffic intensity ρ = La/R

- La/R ~ 0: average queueing delay small
- La/R -> 1: delays become large
- La/R > 1: more "work" arriving than can be serviced, average delay infinite!

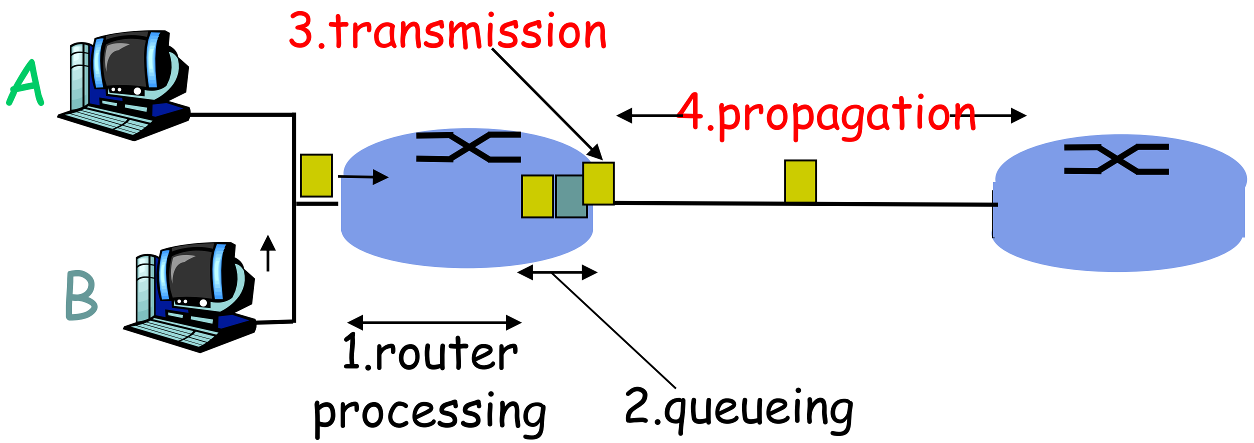
Four sources of packet delay con.

3. Transmission delay:

- R=link bandwidth (bps)
- L=packet length (bits)
- time to send bits into link = L/R

4. Propagation delay:

- d = length of physical link
- s = propagation speed in medium (~2×10^8 m/sec)
- propagation delay = d/s



Note

s and R are very different quantities!

Delay Examples

- "Dialup" with a telephone modem:
  - d= 1000km, R = 56 kbps, L = 1250 bytes

    1000km/(2*10^8m/s) + 1250B/56k = 200ms

    transmission delay: dominating
- Broadband cross-country link:
  - d =10000km, R = 10 Mbps, L = 1250 bytes
- A long link or a slow rate means high delay
  - Often, one delay component dominates

Demo

Router Nodal Delay

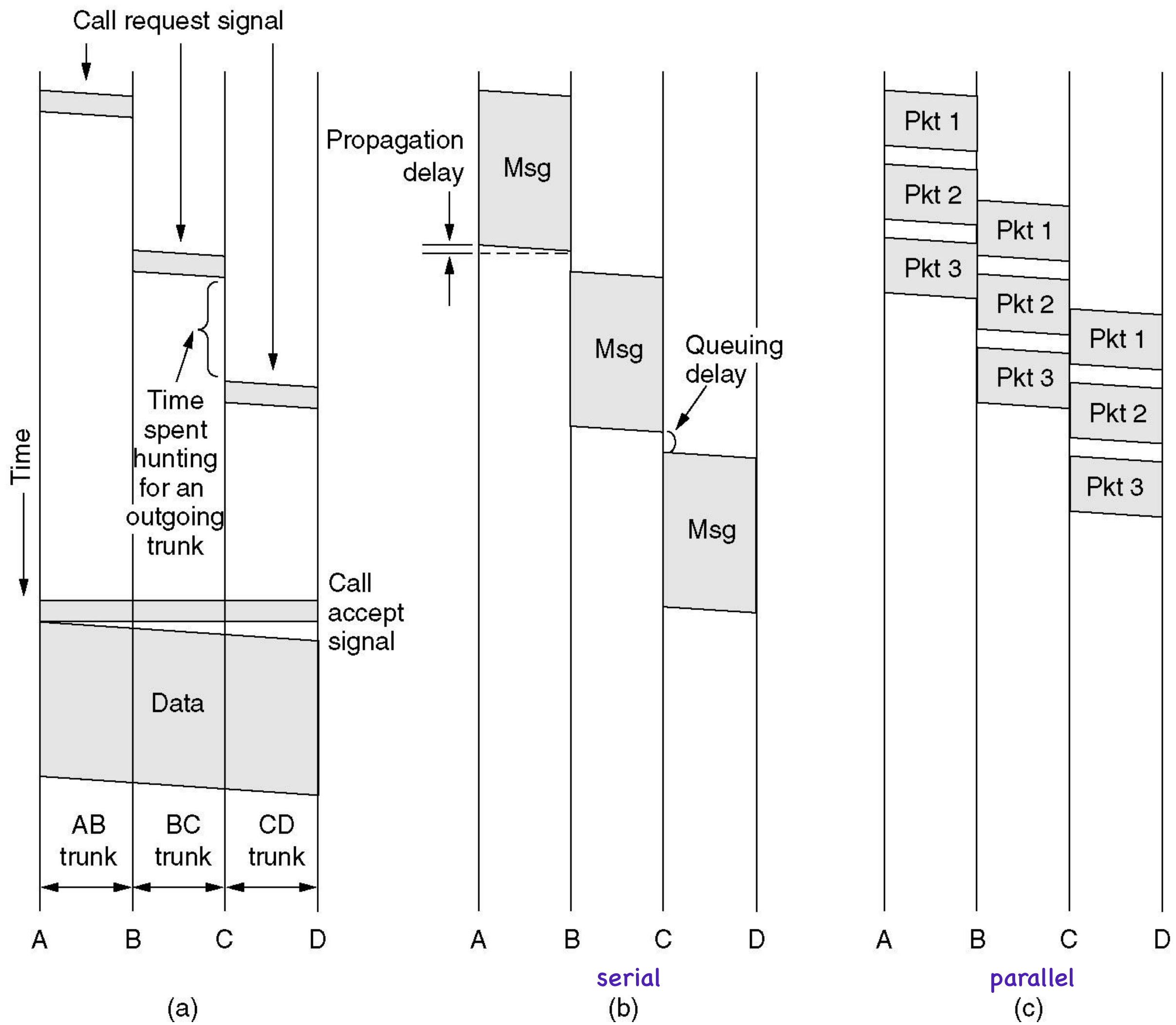
d_nodal = d_proc + d_queue + d_trans + d_prop

- d_{proc} = processing delay
  - typically a few microsecs or less
- d_{queue} = queuing delay
  - depends on congestion
- d_{trans} = transmission delay
  - = L/R, significant for low-speed links
- d_{prop} = propagation delay
  - a few microsecs to hundreds of msecs

End-to-End delay

- One packet
  - $d_{end\text{-}to\text{-}end} = \Sigma\, d_{nodal\text{-}i}$
- More than one packets pipelining
  - Packets transmitted in streamline.
  - $D_{end\text{-}to\text{-}end} \neq \Sigma\, d_{end\text{-}to\text{-}end\text{-}i}$ D_end-to-end = d_end-to-end-firstPacket + Σd_trans_i
- End system delay
  - Modulation, encoding, MAC, compression,encryption

Delay in Switching



Demo

(a) Circuit switching (b) Message switching (c) Packet switching

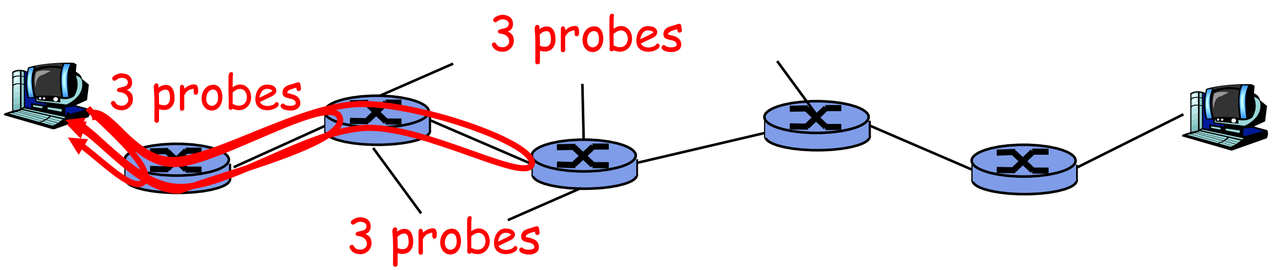
Bandwidth-Delay Product

- Messages take space on the wire!

- The amount of data in flight is the bandwidth-delay (BD) product
  - BD = R x D
  - Measure in bits, or in messages

Traceroute – a path and delay probe

- Traceroute: provides delay measurement from source to router along end-end Internet path towards destination. for all *i:*
  - sends three packets that will reach router *i* on path towards destination
  - router *i* will return packets to sender
  - sender times interval between transmission and reply.



"Real" Internet delays and routes

traceroute: cs.sjtu.edu.cn to www.mit.edu

1	1 ms	1 ms	1 ms	10.10.20.254
2	3 ms	2 ms	2 ms	202.120.38.254
3	2 ms	1 ms	1 ms	10.22.38.253
4	2 ms	1 ms	1 ms	10.3.2.77
5	2 ms	2 ms	2 ms	10.3.0.46
6	2 ms	2 ms	2 ms	10.255.38.35
7	3 ms	3 ms	3 ms	10.255.38.1
8	2 ms	2 ms	2 ms	10.255.38.254
9	3 ms	3 ms	4 ms	202.112.27.1
10	6 ms	2 ms	2 ms	101.4.115.174
11	27 ms	23 ms	23 ms	101.4.117.30
12	30 ms	31 ms	31 ms	101.4.116.117
13	28 ms	29 ms	28 ms	101.4.112.69
14	31 ms	31 ms	31 ms	101.4.116.134
15	29 ms	31 ms	31 ms	101.4.117.102
16	29 ms	28 ms	28 ms	101.4.117.182
17	197 ms	195 ms	195 ms	80.150.170.165
18	213 ms	214 ms	214 ms	tyo-sb1-i.TYO.JP.NET.DTAG.DE [62.154.5.198]
19	213 ms	280 ms	213 ms	xe-1-1-3.r23.tokyjp01.jp.bb.gin.ntt.net [129.250.8.217]
20	208 ms	212 ms	212 ms	ae-9.r24.tokyjp05.jp.bb.gin.ntt.net [129.250.3.159]
21	220 ms	225 ms	214 ms	ae-7.r22.osakjp02.jp.bb.gin.ntt.net [129.250.3.220]
22	*	*	*	
23	214 ms	214 ms	214 ms	a23-53-192-128.deploy.static.akamaitechnologies.com [23.53.192.128]

trans-oceanic link

* means no response (probe lost, router not replying)

Performance Definitions

Capacity/Bandwidth: the max data rate for a channel

√ improves with data encoding and S/N

- Throughput – Number of bits/time you can sustain at the receiver
  - Improves with technology
- Latency – How long for message to cross network
  - Propagation + Transmit + Queue
  - We are stuck with speed of light…10s of milliseconds to cross country
- Goodput – application level throughput, the number of useful information bits/time, FileSize/Latency

  √ depends on the size of protocol headers
- Jitter – Variation in latency

  √ important for streaming media
- What matters most for your application?
  - We'll look at network applications next lecture