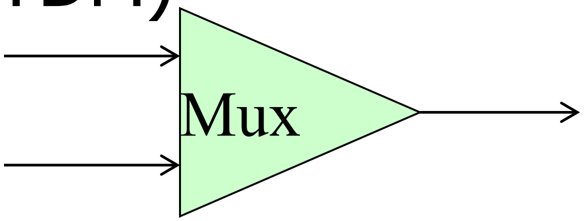
Networks Overview (Set 2)

- Topics:
  - Multiplexing
  - Switching
  - Addressing
  - Performance
  - Layered Architecture
- References
  - J.F. Kurose and K. W. Ross, "Computer Networking: A Top-Down Approach", 6th Edition, *Pearson*, 2012
  - Peterson and Davie, "Computer Networks: A Systems Approach", 4th Edition, *Morgan Kaufmann*, 2007

Multiplexing

Multiplexing Types

- How do we multiplex data/signal from different inputs to an output?
  - For eg., data from two input links (ports) of a switch (or router) needs to leave through the same output link (port).
- How do we share an output link between different input links (or users)?
- Frequency division multiplexing (FDM)
  - Cable TV, satellite
- Time division multiplexing (TDM)
  - Network switches

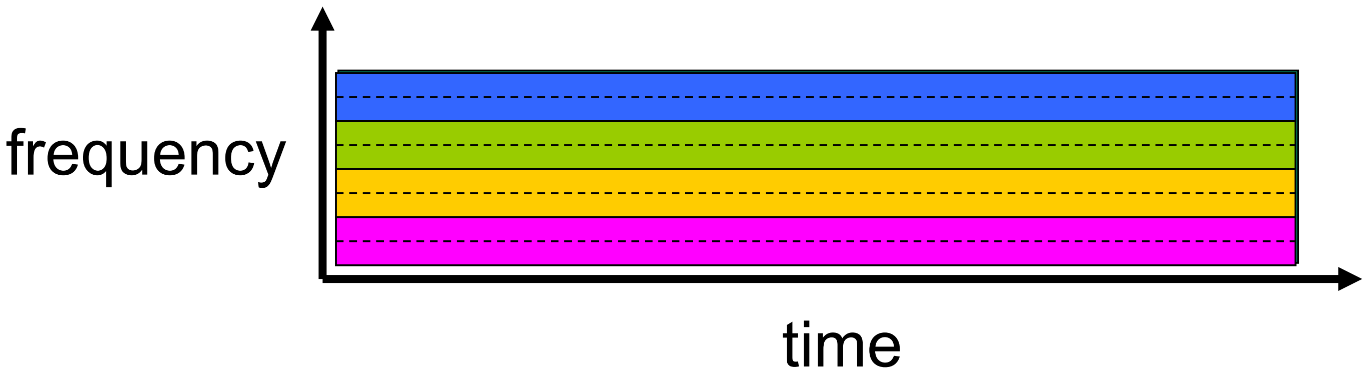


FDM versus TDM

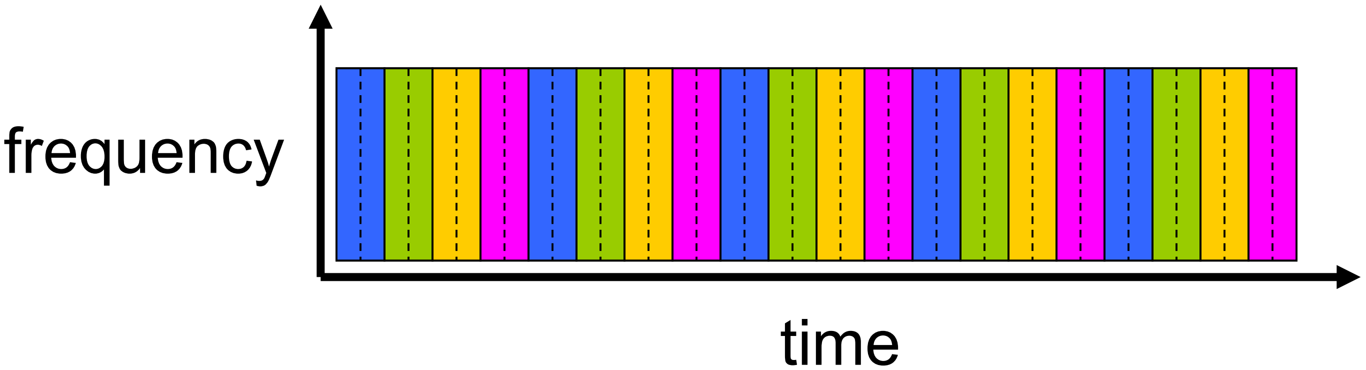
Example:

4 users

FDM



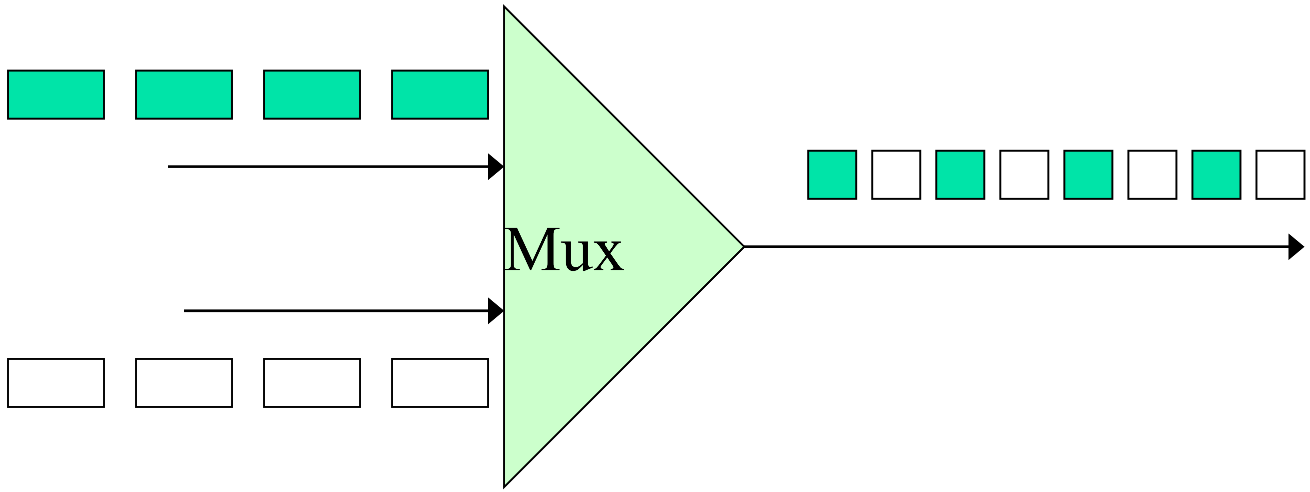
TDM



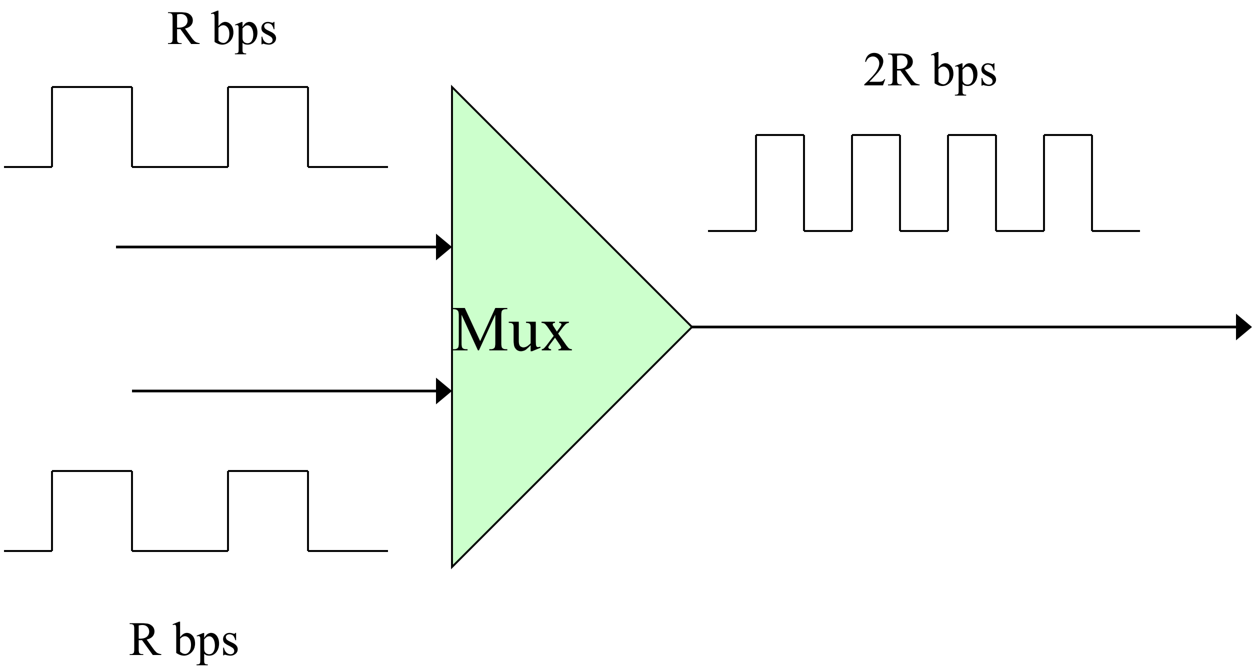
Time Division Multiplexing

- Consider a multiplexer with two input links and one output link
  - Data from input-1 will be transmitted on the output link during the odd-numbered slots
  - data from input-2 will be transmitted on the output link during the even-numbered slots
- Data rate of each input link is R bps requires the output link rate to be at least 2R bps
- If one byte is received at each input link for every T seconds, 2 bytes would be sent out at the output link for every T seconds

Time Division Multiplexing - Example



Time Division Multiplexing (input vs output data rate)



TDM Byte Interleaving

- For the example above, we can think of repeating frames sent on the output link.
  - Each frame carries two bytes (assuming byte interleaved multiplexing)
  - First byte comes from the top input link and second byte comes from the bottom input link

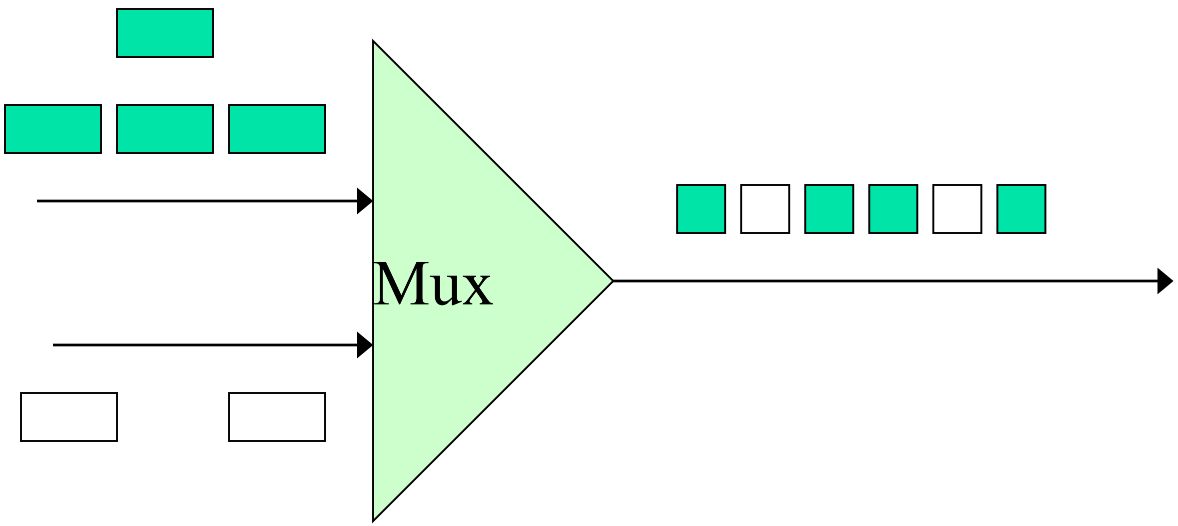
Fixed Time division multiplexing (FTDM)

- By default, TDM refers to fixed TDM
- Fixed and dedicated bandwidth is reserved
- Eg: two input sources, data rate 10 Mbps each
  - Output link rate at least 20 Mbps
  - Each input source is guaranteed 10 Mbps at the output link
- Guaranteed service (e.g. delay)
  - No queuing delay at the switch or multiplexer
- Inefficient bandwidth utilization
  - An input may not be active all the time; the output link bandwidth during the input inactivity period is not used

Statistical Time division multiplexing (STDM)

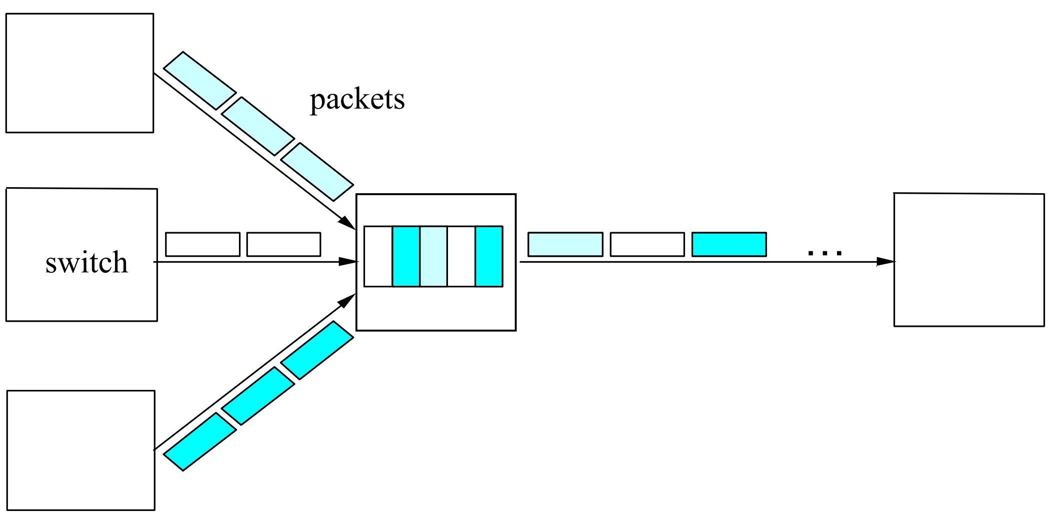
- No fixed slots or dedicated bandwidth reserved on an output link for the input links.
- The input link with more demand (more data) will use the output link more when compared to an input with less demand (See Figure)
- Eg: two input sources, data rate 10 Mbps each, active 60% of time on an average
    - Output link rate of 6+6=12 Mbps is OK. No guarantee of 10 Mbps (or other bandwidth) for each input source at the output link
    - If the sum of the input data arrival rates exceeds the data rate of the contending output link
        - Excess bits will be queued in the buffer
        - If the buffer overflows, bits will be lost, leading to congestion state.
        - If both inputs are active & sending at 10 Mbps rate, for every second 8 million excess bits arrive
- No service guarantee (e.g. delay)
    - Variable message transfer delay due to variable queuing delay at the multiplexer
- Efficient bandwidth utilization
    - Link is not idle when there is a demand, i.e. as long as there is some data (from any of the inputs) want to leave through the link.

Statistical Time Division Multiplexing Example



Statistical Multiplexing in Networks

- On-demand time-division, better resource sharing
- Schedule link on a per-packet basis
- Packets from different sources interleaved on link
- Buffer packets that are *contending* for the link
- Buffer (queue) overflow is called *congestion*



Switching

What is meant by Switching?

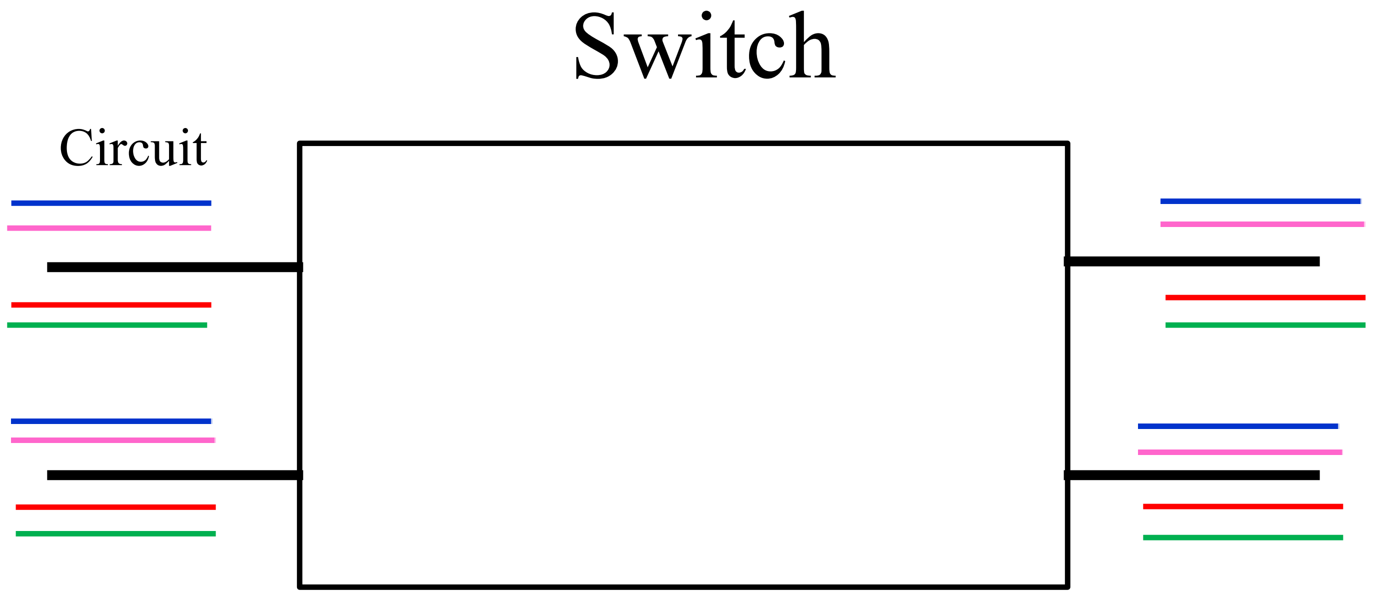
- A switch has a number of input ports (input links) and output ports (output links)
  - In practice, a port could serve as input/output port
- Switching is a process of forwarding data from an input port to an output port
- Switching is a functionality within a switch
- Circuit Switching (vs) Packet Switching

Circuit Switching

- Link bandwidth (capacity) is divided into fixed-size circuits
  - eg: telephone network, SONET, WDM
- Connect an input circuit to an output circuit; all data bits on the input circuit will be forwarded to the output circuit
  - Switching entity is a circuit
- Ex: A call or connection uses 1st circuit (blue) on top input link connected to 3rd circuit (red) on bottom output link (Figure in next slide)
- Uses Fixed TDM technique with circuits corresponding to time slots
- Uses WDM technique with circuits corresponding to wavelengths
- 3 distinct phases: circuit setup, data transmission, and circuit release phases

- A circuit has dedicated slot (hence dedicated bandwidth resource)
  - Advantage: guaranteed service
- A circuit is idle if not used by a call (or connection)
  - Drawback: bandwidth waste, low bandwidth utilization, circuit setup time overhead

Circuit Switch



Packet Switching

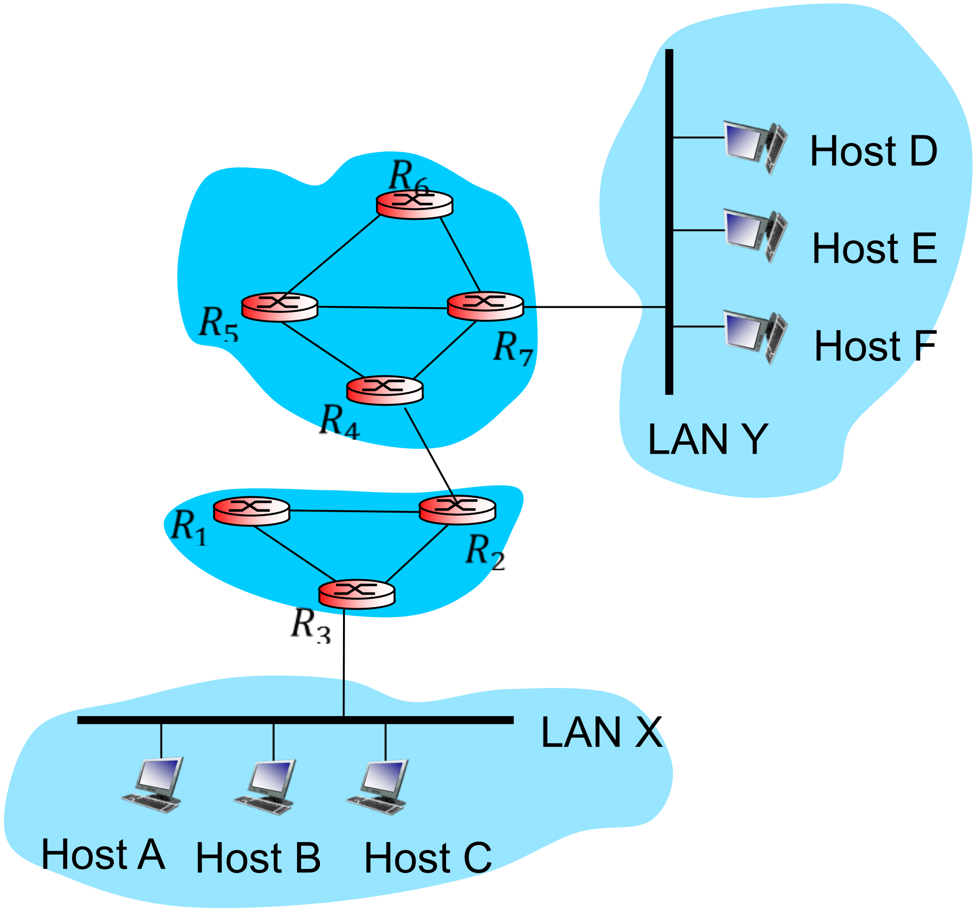
- store and forward technique employed
- A packet from a link is received in full, stored in a buffer, forwarded to an output link when free (see Fig. in slide 12)
  - based on the destination address or identifier carried in the packet header;
  - Local forwarding table is consulted to decide the output link
- switching entity is a packet. Statistical TDM is used.
  - High bandwidth utilization, possibility of buffer overflow/congestion
- Eg: Ethernet switch, IP router
  - Forwarding is based on destination address
  - Different packets of the same message may traverse different routes
    - possibility of out-of-order packet delivery
  - Difficult to provide guaranteed service, usually best-effort service

Addressing

Address and its Types

- Address: byte-string that identifies a node
  - usually unique
  - Carried as a part of the message
- Routing: process of forwarding messages to the destination node based on its address
- Types of addresses
  - unicast: node-specific
  - broadcast: all nodes on the network
  - multicast: some subset of nodes on the network

An Example Network



IP address vs MAC address

- A host (or router interface) has 4-byte IP address (format: x.y.z.w)
  - Hierarchical address; a part of address denotes network id (say,LAN); all hosts in a network has same network id
  - Host IP address from its ASCII name is obtained using DNS (Domain Name System)
- A host (or router) has network interface card (nic) connecting to the cable
- A host has 6-byte Ethernet (or hardware or MAC address) hardwired at nic (format: a:b:c:d:e:f)
  - Non-hierarchical address; When a host sees a packet carrying its own h/w address, it copies the packet onto itself
  - Hardware address corresponding to the IP address of each host on a LAN is known to hosts on the same LAN using ARP (Address Resolution Protocol)
  - ARP table (or ARP Cache) at every host and router
    - Entries of the form <IP address, h/w address> for each host & router in the same network

Packet Transfer Example 1 (Figure in slide 20)

- Host A at LAN X wants to transfer a packet to Host D at LAN Y
- At host A: obtain IP address of host D using DNS and attach to the packet
- Compare Network id part of host A's IP address with D's. Since they differ, hardware address of router (R3) interface at LAN X is attached to the packet
- Broadcast the packet on LAN X
- Router R3 at LAN X grabs the packet; uses IP address for routing the packet
- Packet reaches the router (R7) attached to LAN Y. Network id part of packet's destination IP address matches that of this router
  - This router R7 knows the corresponding hardware address of host D (from ARP table)
  - Router attaches the hardware address of host D with the packet
  - Router broadcasts the packet on LAN Y
  - Host D finds a match with its hardware address
  - Host D copies the packet

Packet Transfer Example 2
(Figure in slide 20)

- Host A at LAN X wants to transfer a packet to Host C at the same LAN X
- At host A, obtain IP address of host C using DNS and attach to the packet
- Compare Network id part of host A's IP address with C's. Since they match, Hardware address of host C at LAN X is attached to the packet
  - Hardware address of host C is known to host A from ARP table
- Broadcast the packet on LAN X
- Host C at LAN X takes the packet;

Performance: Delay and Throughput

Bandwidth and Throughput

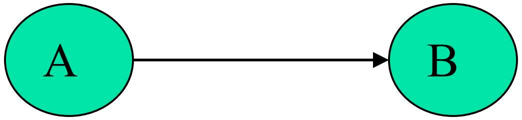
- Bandwidth, data rate, capacity
  - These terms might be used interchangeably as stated earlier
  - Number of bits that could be transmitted per time unit
  - link versus end-to-end connection
  - Bandwidth of a link (or end-to-end connection)
  - Notation: 1 Kbps bandwidth = 10^3 bits per second
  - Given for a link or channel
- Throughput or Effective throughput
  - Number of bits transferred per unit time (measured quantity)
  - Ratio between message size and message transfer time
  - Notation: message size 1 KB = 2^{10} bytes
  - Measured quantity refers to what we actually get.

Message Transfer time (delay, latency)

- Given a message of some size (in bits), how long does it take to transfer the message from a node to another node
  - Node: host or switch/router
  - over a link connecting a host and switch, two switches or two hosts
  - over a path connecting two end hosts traversing through a number of switches and links
  - some delay components of interest: transmission delay, queuing delay, and propagation delay
  - Other delay components: processing delay, packetization delay etc

Message Transfer Time

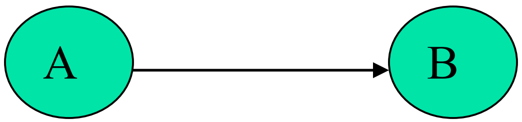
- Transmission time (T_t)
  - Time to transmit (or pump) message bits on to the link
  - i.e time elapsed between the beginning of transmission of the first bit and the end of transmission of the last bit
  - Message size / Bandwidth
- Propagation time (T_p)
  - Time to traverse from node A to node B
  - Distance / Propagation speed



- Queuing time (T_q)
  - Time for which a message is waiting in the queue at a node before the start of transmission (because the output link is not ready)
  - Depends on the load
- Message Latency $T_t + T_p + T_q$ for one-way unacknowledged message transfer
  - Time required to transfer a message from A to B

Calculation of Delay

- Consider a link connecting switches A and B
  - T_1: the message is ready/waiting for transmission at A
  - T_2: the first bit of the message starts transmission at A
  - T_3: the last bit of the message completes transmission at A
  - T_4: the last bit of the message is received at B
- Queuing time: $T_2 - T_1$
- Message transmission time: $T_3 - T_2$
- Link propagation time: $T_4 - T_3$
- Message Transfer Time: $T_4 - T_1$
  - Queuing time + transmission time + propagation time

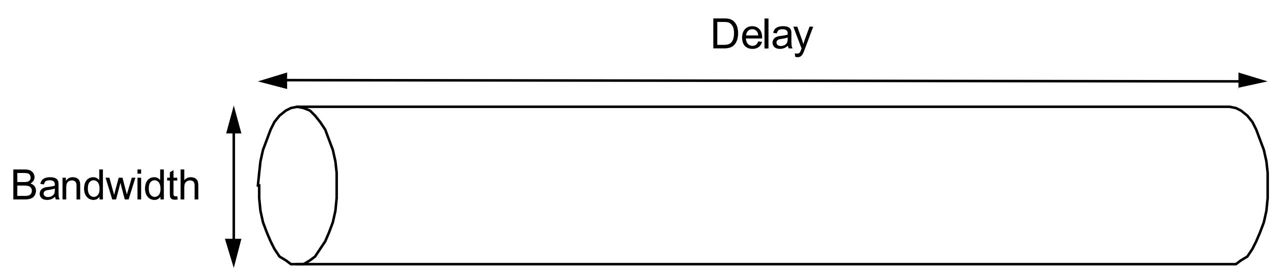


Acknowledged Message Transfer

- Round-Trip Time (RTT)
  - Time taken by a bit or short message to traverse from A to B then back to A
  - Usually the transmission time is excluded
- RTT is usually used in acknowledged services wherein data is transmitted in one direction and ACK is transmitted in the reverse direction
- Message Latency $T_t + 2T_p + T_q$ for one-way acknowledged message transfer
  - Time required to transfer a message from A to B + Time required to transfer ACK from B to A
  - Usually ACK packet size is very small; ACK transmission time can be assumed to be negligible unless specified otherwise

Delay x Bandwidth (D×B) Product

- Here, delay (D) refers to the propagation time on the link (pipe)
- Link is characterized by bandwidth B (→transmission time) and length (→ propagation delay)
- D×B product is equal to the amount of data "in the pipe"
- Consider a bit transmitted at t=0; the bit reaches the other end of the link at time t=D; by that time the transmitter would have transmitted D×B number of bits which are in transit inside the link
- Example: 100ms x 45Mbps = 4500 Kbits = 4.5 million bits in transit



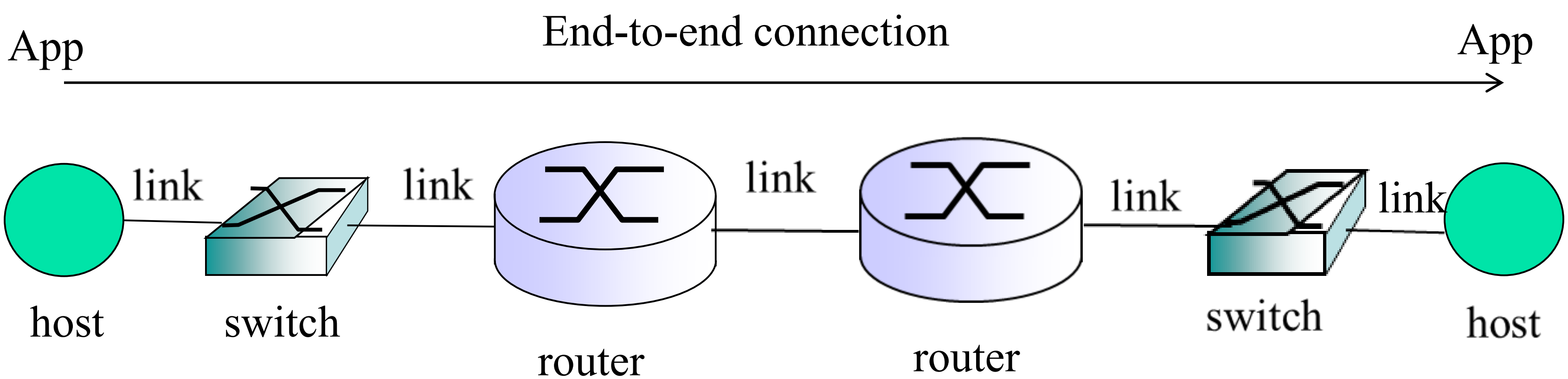
(Effective) Throughput

- Depends on RTT and transmission time
  - For unacknowledged one-way message transfer, one-way propagation time is used instead of RTT

- It is desirable that the throughput is close to the bandwidth
- Throughput rate = throughput/bandwidth

- RTT=10 ms, message size=1MB ($1024 \times 1024 \times 8$ bits), b/w=10 Mbps
  - Transfer time= 10+(1MB/10Mbps)=849 ms
  - Eff. Throughput= 1MB/849ms = 9.88 Mbps
  - Throughput rate = 9.88/10 = 0.988 = 98.8%

Network Layered Architecture



Layered Architecture

- Design of networks to carry out required functionalities
- Network is a complex structure with different kinds of elements such as host computers, server hosts, switches, and routers
- Task: Application data is required to be transferred between end hosts
- Several functionalities (or services) at various network elements need to be carried out to accomplish the task
  - Example: reliable data transfer between end hosts, routing of pieces of data (packets), detecting errors in the packets, retransmission on links etc.
  - These functions are organized into different groups called "layers"
  - A piece of data undergoes a set of functions at each layer vertically at network elements from top to bottom and also bottom to top

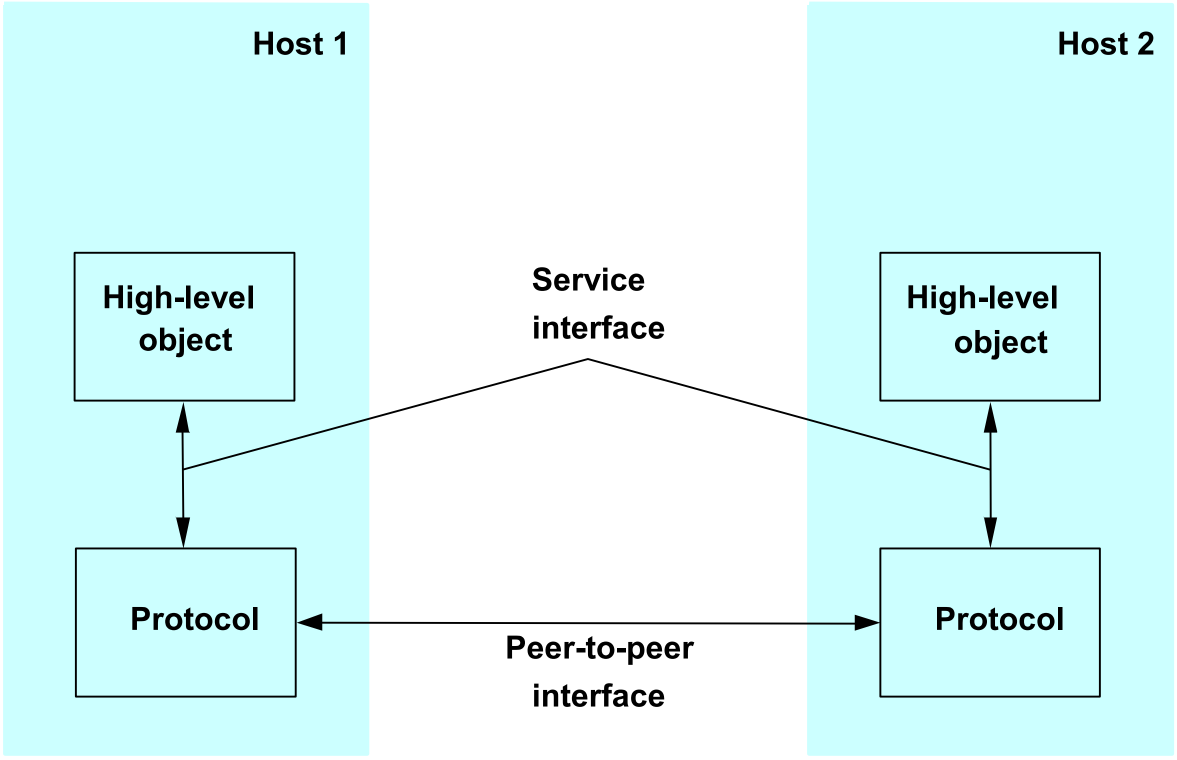
Advantages of Layering

- Layers use abstractions to hide complexity
- Abstraction naturally lead to layering
- Alternative abstractions at each layer
- Network design becomes easier as layering allows decomposing of the design problem into manageable components
- Layering aids modular design. New services can be added to a layer without modifying the functionality of other layers

Protocols

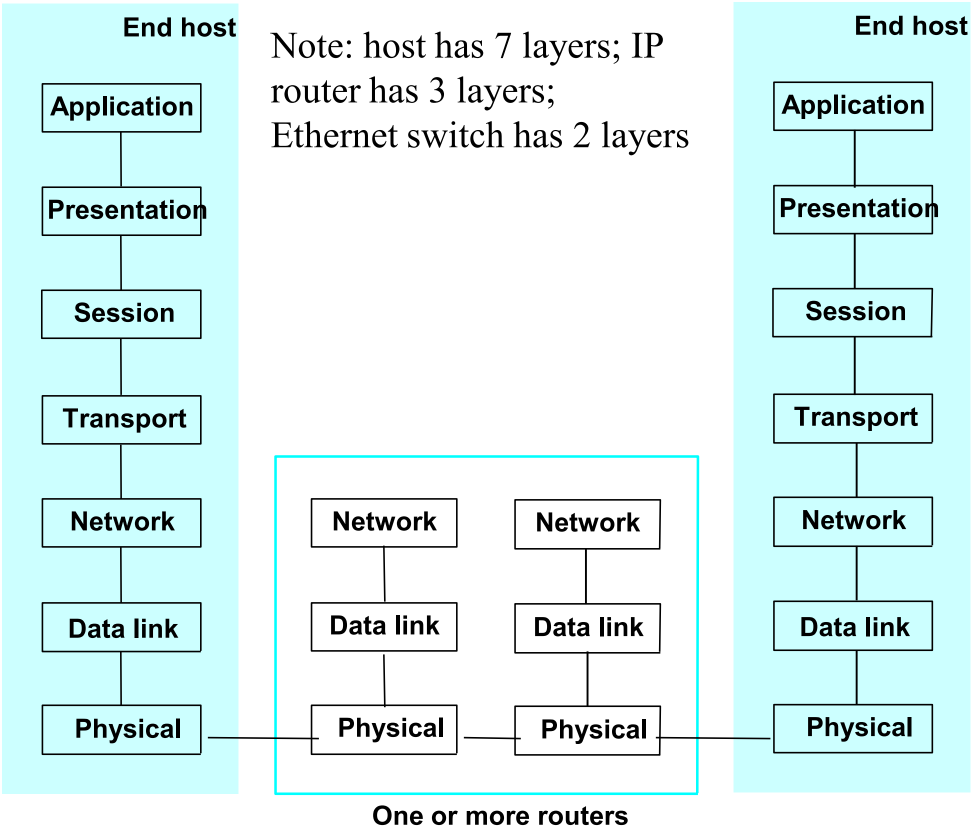
- Building blocks of a network architecture
- Protocols are associated with layers
  - protocol: services + messages
- Each protocol object has two different interfaces
  - *service interface*: operations on this protocol
  - *peer-to-peer interface*: messages exchanged with peer
- A protocol carries out its services making use of services at the lower layer
- A protocol provides services to the upper layer
- Messages are exchanged with appropriate header information between two network elements at the same layer

Interfaces


Host 1
Host 2
High-level object
High-level object
Service interface
Protocol
Protocol
Peer-to-peer interface

Seven-Layer ISO-OSI Architecture

Intl. Standards Organization-Open Systems Interconnection



Note: host has 7 layers; IP router has 3 layers; Ethernet switch has 2 layers

Functions of Layers

- Physical layer (Layer 1, L1)
  - Transmission of raw bits over a communication link
  - Electrical characteristics: voltage levels, signal durations
  - Mechanical characteristics: pluggable connector specifications
- Data link layer (Layer 2, L2)
  - Link-level, point-to-point and broadcast links
  - Aggregation of bits into frames, error and flow control (optional)
  - Medium access control (MAC), e.g. Ethernet
- Network layer (Layer 3, L3)
  - Routing packets between nodes, may do congestion control (IP routers do not do congestion control)
- Transport layer (Layer 4, L4)
  - Handles messages Process-to-process channel, end-to-end layer, end-to-end message transfer, reliable message delivery, congestion control, flow control

Functions of Layers (contd.)

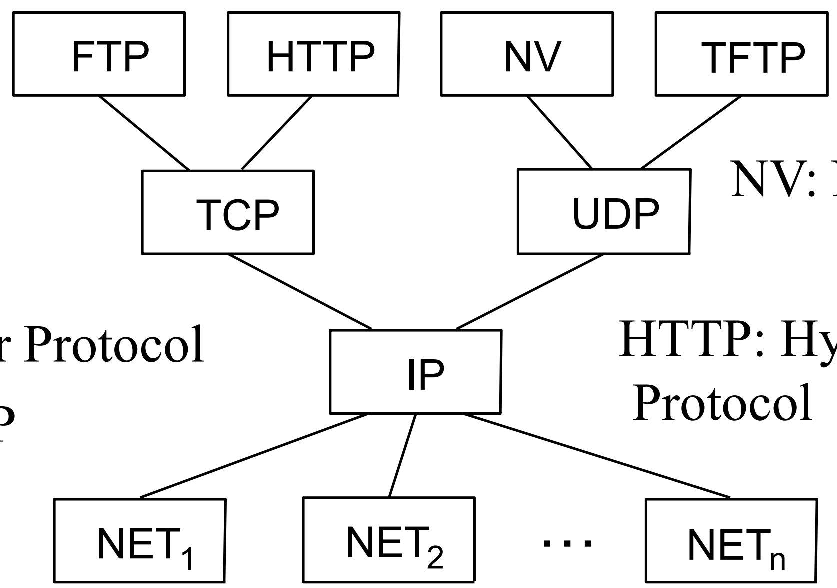
- Session layer (Layer 5, L5)
  - provide name space to collectively refer to different transport streams that are a part of a single application
  - eg. Video conferencing (audio and video streams)
- Presentation layer (Layer 6, L6)
  - data representation (integer, string)
  - how data is transmitted MSB first or LSB first.
  - Compression, encryption
- Application layer (Layer 7, L7)
  - Provides protocols to support different applications such as web browsing (http, hyper text transport protocol), email (SMTP, Simple Mail Transfer Protocol)

Five-Layer Internet Architecture

- Defined by Internet Engineering Task Force (IETF)
- Five Layers (no session layer or presentation layer)
  - Layer 5: Application layer (eg. http, smtp)
  - Layer 4: Transport layer
    - TCP(transmission control protocol): connection-oriented, reliable transport service
    - UDP(user datagram protocol): connectionless, unreliable transsport service
  - Layer 3: Network layer (eg IP)
  - Layer 2: Link layer (eg: Ethernet, Wifi)
  - Layer 1: Physical layer
- Functionalities of session layer and presentation layer to be included in Application layer as required

Internet Architecture

- Defined by Internet Engineering Task Force (IETF)
- Hourglass Design
- Application vs. Application Protocol (FTP, HTTP)



NV: Networked Video

FTP: File Transfer Protocol

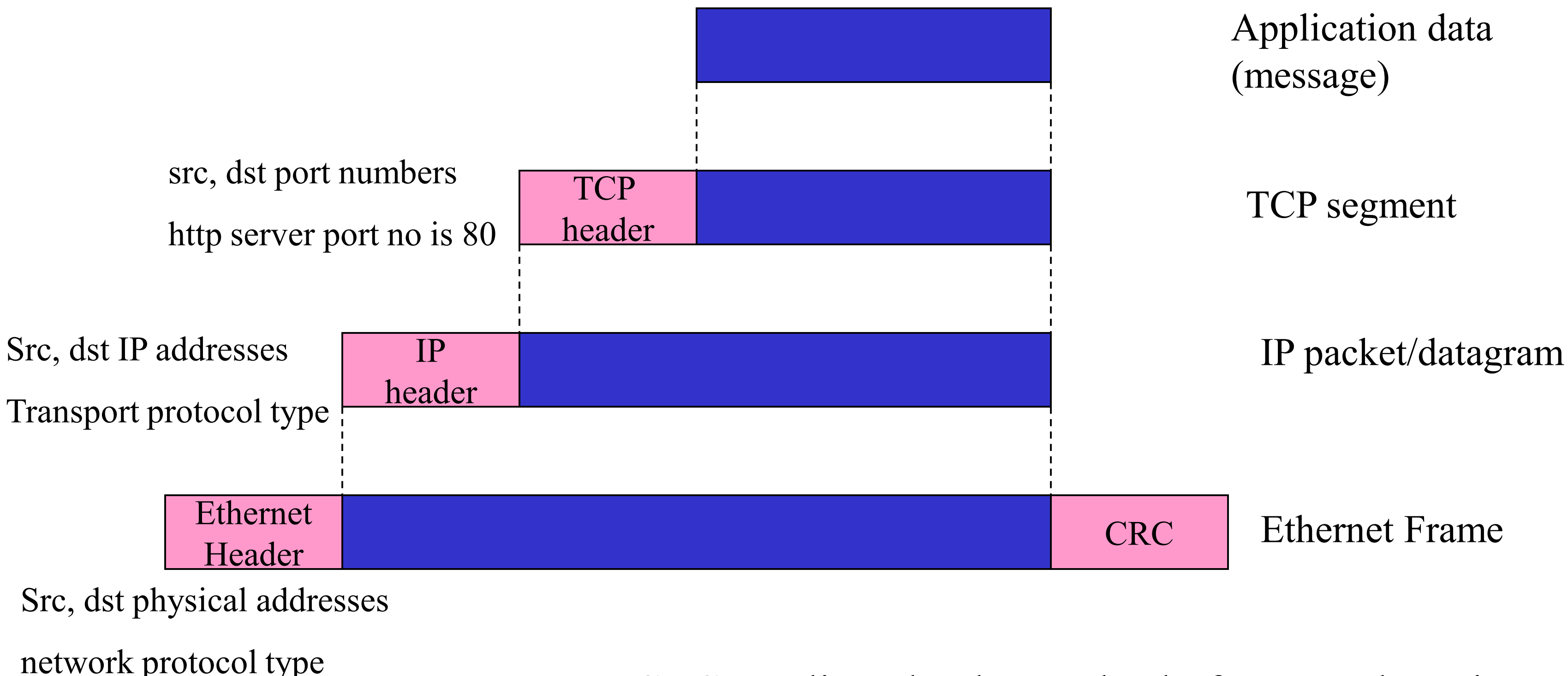
TFTP: Trivial FTP

HTTP: Hyper Text Transport Protocol

Protocol Data Units (PDUs) and Encapsulation

- Data Units used by a protocol at each layer has a name
  - Example: PDU at layer 3 (IP layer) is called packet (or datagram), PDU at layer 2 (Ethernet) is called a frame
- When a PDU is passed from an upper layer (say, layer i) to the lower layer (say layer i-1) , header information of layer i-1 is added to become a new PDU. This process is known as encapsulation
  - New PDU = header + payload (upper layer PDU)

Protocol Data Units in the TCP/IP Architecture



CRC: cyclic redundancy check; for error detection

Encapsulation