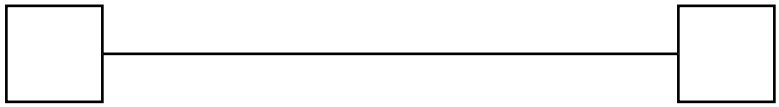
Perspective

- Network users: services that their applications need e.g., guarantee that each message it sends will be delivered without error within a certain amount of time
- Network designers: cost-effective design e.g., that network resources are efficiently utilized and fairly allocated to different users
- Network providers: system that is easy to administer and manage e.g., that faults can be easily isolated and it is easy to account for usage

Requirements

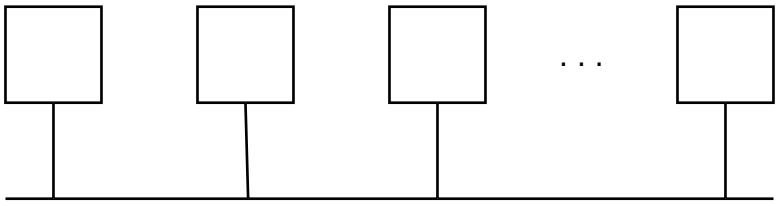
Connectivity

- Building Blocks
  - links: coax cable, optical fiber...
  - nodes: general-purpose workstations...
- Direct Links
  - point-to-point



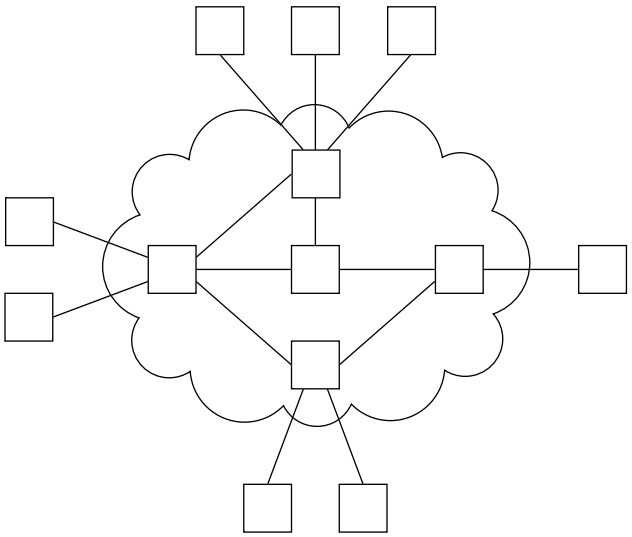
point-to-point network

  - multiple access

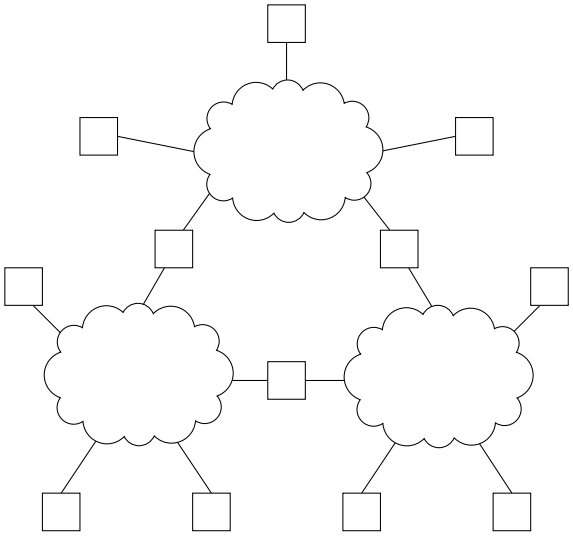


multiple access network

- Indirect Connectivity
  - switched networks



  - internetworks

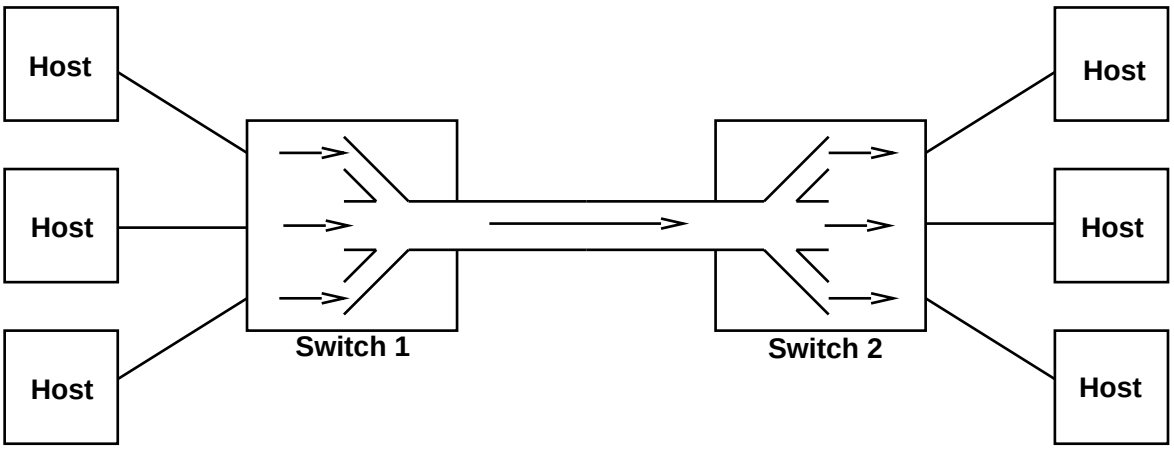


A network can be defined recursively as two or more nodes connected by a physical link, or by two or more networks connected by one or more nodes.

- Switching Strategies
  - circuit switching: dedicated circuit; send/receive a bit stream
  - packet switching: store-and-forward; send/receive messages (packets)
- Addressing and Routing
  - address: byte-string that identifies a node; usually unique
  - routing: process of determining how to forward messages towards 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

Cost-Effective Resource Sharing

Must share (*multiplex*) network resources (nodes and links) among multiple users.

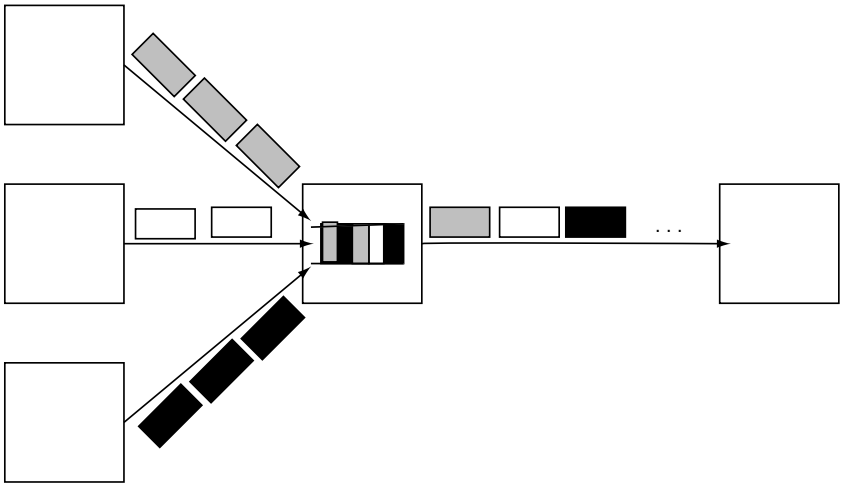


Common Multiplexing Strategies

- Time-Division Multiplexing (TDM)
- Frequency-Division Multiplexing (FDM)

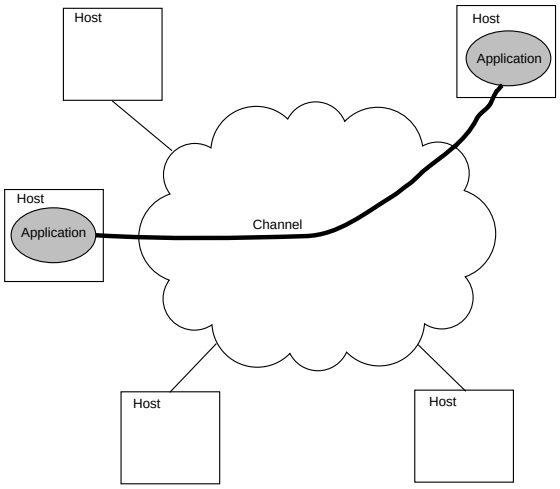
Statistical Multiplexing

- Time-division, but on demand rather than fixed
- Reschedule link on a per-packet basis
- Packets from different sources interleaved on the link
- Buffer packets that are *contending* for the link
- Packet queue may be processed FIFO, but not necessarily
- Buffer overflow is called *congestion*



Functionality

The application programs running on the hosts connected to the network must be able to communicate in a meaningful way.



Network supports common process-to-process channels; e.g.,

- Request/Reply: for file access and digital libraries
- Message Stream: for video applications
  - video: sequence of frames
  - resolution: 1/4 TV-size image = 352x240 pixels;
  - 24-bit color: frame = $(352 \times 240 \times 24)/8 = 247.5$KB;
  - frame rate: 30 fps = 7500KBps = 60Mbps
  - video on-demand versus video-conferencing

What Goes Wrong in the Network?

- Bit-level errors (electrical interference)
- Packet-level errors (congestion)
- Link and node failures

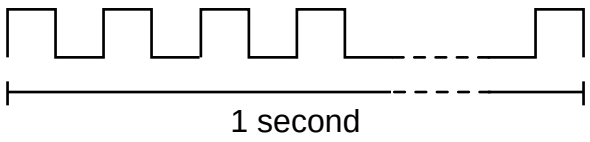
- Messages are delayed
- Messages are deliver out-of-order
- Third parties eavesdrop

The key problem is to fill in the gap between what applications expect and what the underlying technology provides.

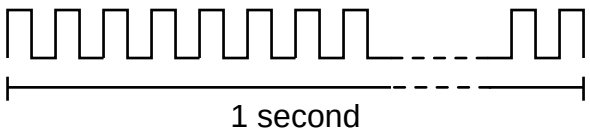
Performance

Bandwidth (throughput)

- Amount of data that can be transmitted per time unit
- Example: 10Mbps
- link versus end-to-end
- Notation
  - KB = 2^{10} bytes
  - Mbps = 10^6 bits per second
- Bandwidth related to "bit width"



1Mbps
(each bit 1 microseconds wide)



2 Mbps
(each bit 0.5 microseconds wide)

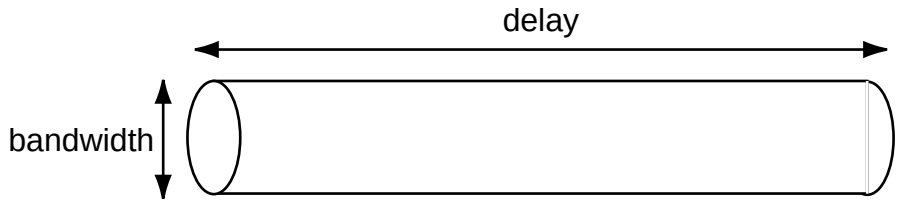
Latency (delay)

- Time it takes to send message from point A to point B
- Example: 24 milliseconds (ms)
- Sometimes interested in in round-trip time (RTT)
- Components of latency

  Latency = Propagation + Transmit + Queue
  Propagation = Distance / SpeedOfLight
  Transmit = Size / Bandwidth

- Speed of light
  - 3.0×10^8 meters/second in a vacuum
  - 2.3×10^8 meters/second in a cable
  - 2.0×10^8 meters/second in a fiber
- Notes
  - no queuing delays in direct link
  - bandwidth not relevant if Size = 1 bit
  - process-to-process latency includes software overhead
  - software overhead can dominate when Distance is small

- Relative importance of bandwidth and latency
  - small message (e.g., 1 byte): 1ms vs 100ms dominates 1Mbps vs 100Mbps
  - large message (e.g., 25 MB): 1Mbps vs 100Mbps dominates 1ms vs 100ms
- Delay $\times$ Bandwidth Product



  Example: 100ms RTT and 45Mbps Bandwidth = 560 KB of data
- Application Needs
  - bandwidth requirements: burst versus peak rate
  - jitter: variance in latency (inter-packet gap)