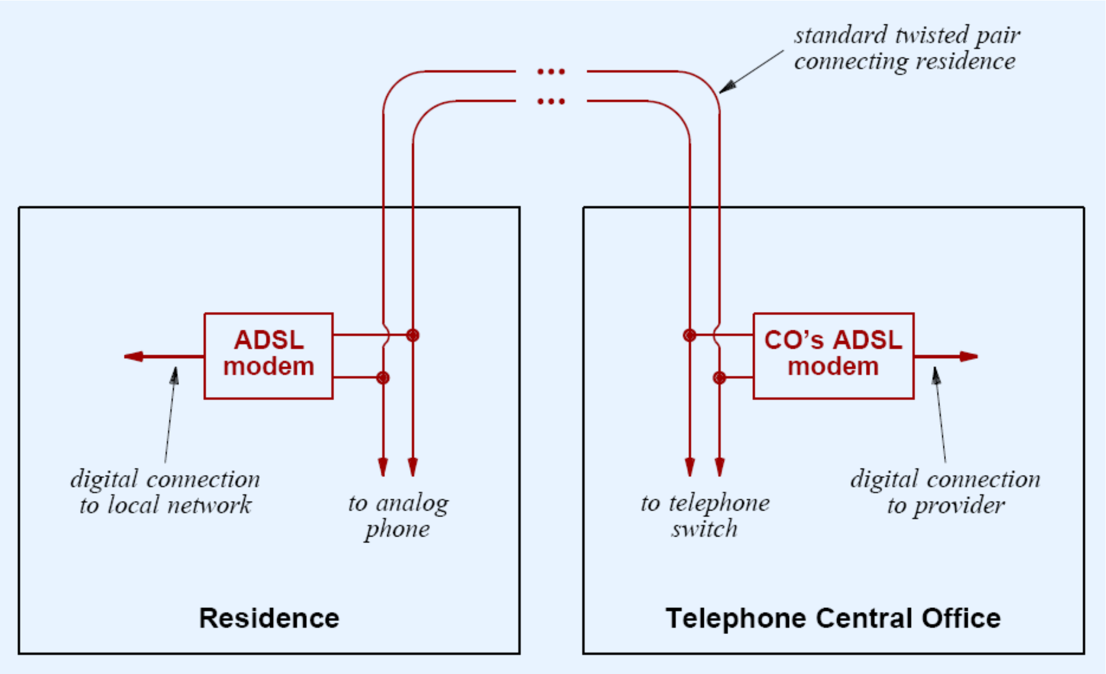
Digital Local Loop Technologies

- *Integrated Services Digital Network (ISDN)*
  - Handles voice and data
  - Relatively high cost for low bandwidth
- *Digital Subscriber Line (DSL)*
- *Cable modems*
- *Hybrid Fiber Coax*

Asymmetric Digital Subscriber Line (ADSL)

- Popular DSL variant
- Runs over conventional POTS wiring
- Higher capacity downstream
- Uses frequencies above POTS

Illustration Of ADSL Wiring



- Downstream can reach 6.4 Mbps
- Upstream can reach 640 Kbps

Cable Modems

- Send/receive over CATV wiring
- Use FDM
- Group of subscribers in neighborhood share bandwidth

Hybrid Fiber Coax

- Wiring scheme for cable to allow digital access Optical fiber
  – Highest bandwidth
  – Extends from central office to neighborhood concentration points
- Coaxial cable
  – Less bandwidth
  – Extends from neighborhood concentration point to individual subscribers (e.g., residence)

Summary

- Technologies exist that span long distances
  - Leased analog lines (require modems)
  - Leased digital circuits (require DSU/CSUs)
- Digital circuits
  - Available from phone company
  - Cost depends on distance and capacity
  - Popular capacities called T1 and T3
  - Fractional T1 also available

Summary (continued)

- High capacity circuits available
  - Popular capacities known as OC-3, OC-12
- Local loop refers to connection between central office and subscriber
- Local loop technologies include
  - DSL (especially ADSL)
  - Cable modems

PART VII

Wide Area Networks (WANs), Routing, and Shortest Paths

Motivation

- Connect multiple computers
- Span large geographic distance
- Cross public right-of-way
  - Streets
  - Buildings
  - Railroads

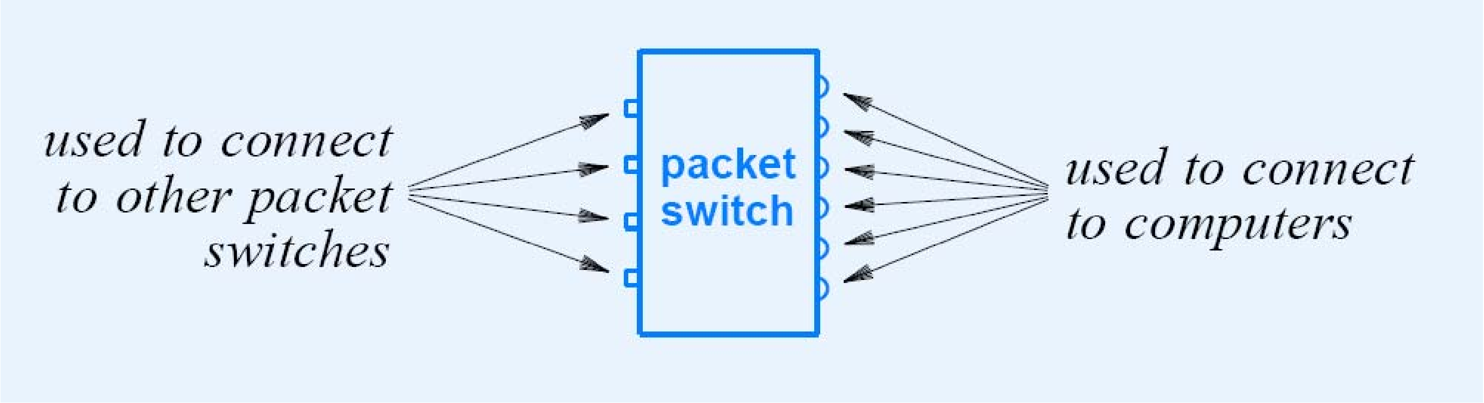
Building Blocks

- Point-to-point long-distance connections
- *Packet switches*

Packet Switch

- Hardware device
- Connects to
  - Other packet switches
  - Computers
- Forwards packets
- Uses addresses

Illustration Of A Packet Switch

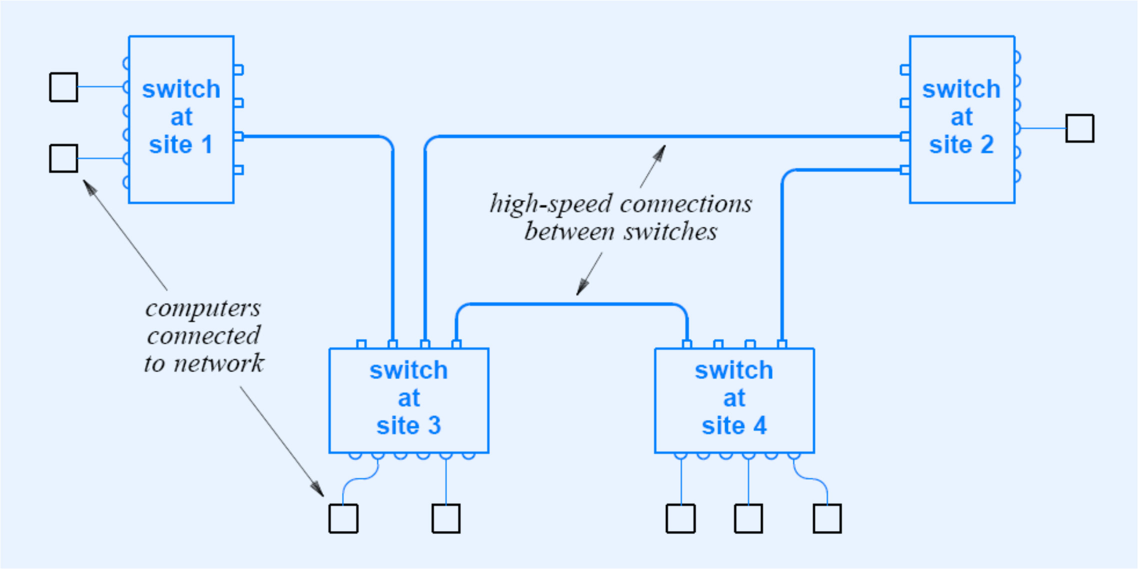


- Special-purpose computer system
  - CPU
  - Memory
  - I/O interfaces
  - Firmware

Building A WAN

- Place one or more packet switches at each site
- Interconnect switches
  - LAN technology for local connections
  - Leased digital circuits for long-distance connections

Illustration Of A WAN



- Interconnections depend on
  – Estimated traffic
  – Reliability needed

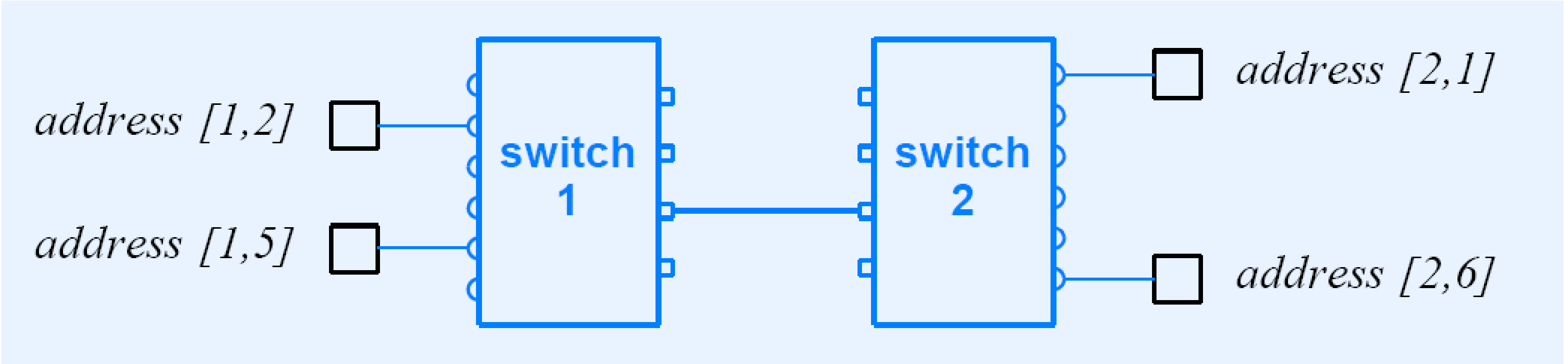
Store And Forward

- Basic paradigm used in packet switched network
- Packet
  - Sent from source computer
  - Travels switch-to-switch
  - Delivered to destination
- Switch
  - *Stores* packet in memory
  - Examines packet's destination address
  - *Forwards* packet toward destination

Addressing In A WAN

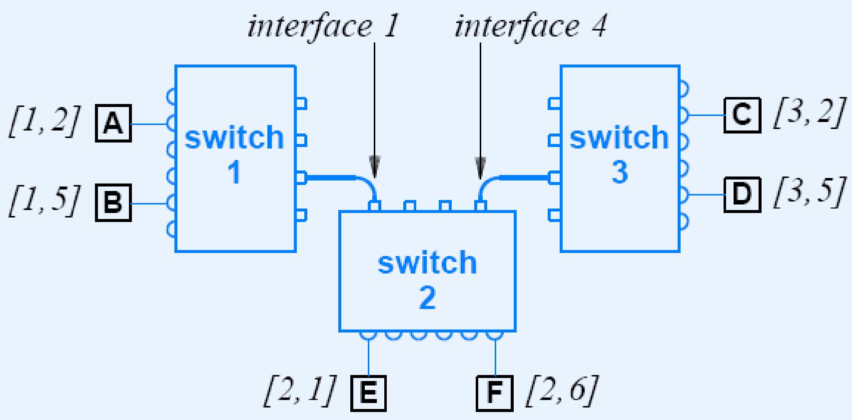
- Need
  - Unique address for each computer
  - Efficient forwarding
- Two-part address
  - Packet switch number
  - Computer on that switch

Illustration Of WAN Addressing



- Two-part address encoded as integer
  - High-order bits for switch number
  - Low-order bits for computer number

Next-Hop Forwarding



(a)

destination	next hop
[1,2]	interface 1
[1,5]	interface 1
[3,2]	interface 4
[3,5]	interface 4
[2,1]	computer E
[2,6]	computer F

(b)

- Performed by packet switch
- Uses table of routes
- Table gives *next hop*

Forwarding Table Abbreviations

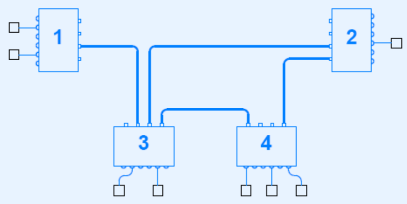
Destination	Next Hop
(1, anything)	interface 1
(3, anything)	interface 4
(2, anything)	local computer

- Many entries point to same next hop
- Can be condensed (*default*)
- Improves lookup efficiency

Source Of Routing Table Information

- Manual
  - Table created by hand
  - Useful in small networks
  - Useful if routes never change
- Automatic routing
  - Software creates/updates table
  - Needed in large networks
  - Changes routes when failures occur

Relationship Of Routing To Graph Theory



destin-ation	next hop
1	-
2	(1,3)
3	(1,3)
4	(1,3)

node 1

destin-ation	next hop
1	(2,3)
2	-
3	(2,3)
4	(2,4)

node 2

destin-ation	next hop
1	(3,1)
2	(3,2)
3	-
4	(3,4)

node 3

destin-ation	next hop
1	(4,3)
2	(4,2)
3	(4,3)
4	-

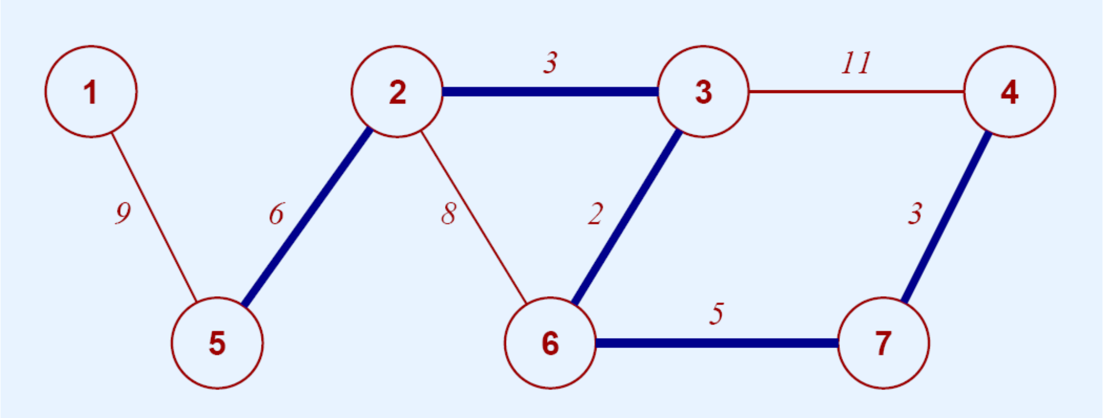
node 4

- Graph
  - *Node* models switch
  - *Edge* models connection

Shortest Path Computation

- Algorithms from graph theory
- No central authority (distributed computation)
- A switch
  - Must learn route to each destination
  - Only communicates with directly attached neighbors

Illustration Of Minimum Weight Path



- Label on edge represents “distance”
- Possible distance metric
  - Geographic distance
  - Economic cost
  - Inverse of capacity
- Darkened path is minimum *4* to *5*

Algorithms For Computing Shortest Paths

- *Distance Vector (DV)*
  - Switches exchange information in their routing tables
- *Link-state*
  - Switches exchange link status information
- Both used in practice

Distance Vector

- Periodic, two-way exchange between neighbors
- During exchange, switch sends
  - List of pairs
  - Each pair gives *(destination, distance)*
- Receiver
  - Compares each item in list to local routes
  - Changes routes if better path exists

Distance Vector Algorithm

Given:

a local routing table, a weight for each link that connects to another switch, and an incoming routing message

Compute:

an updated routing table

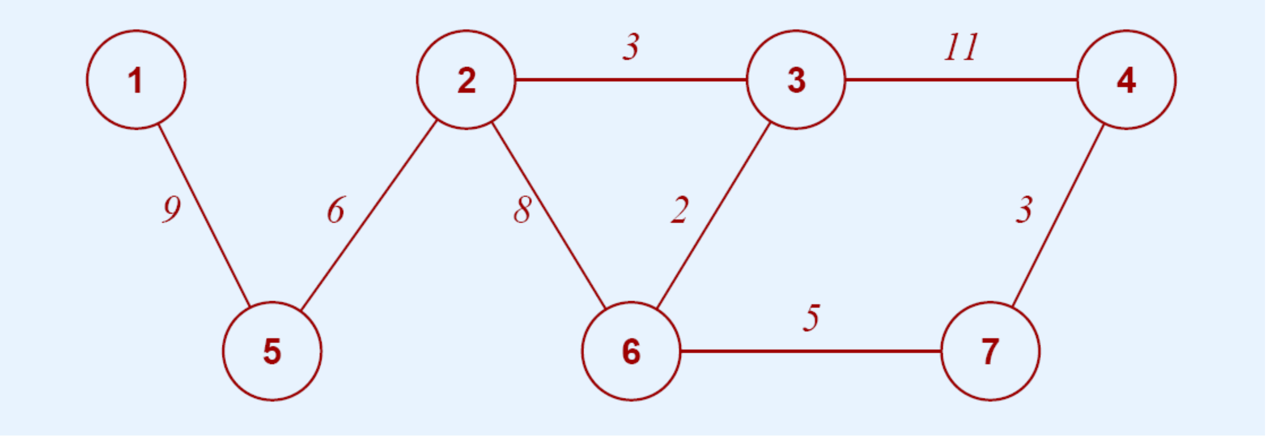
Method:

Maintain a *distance* field in each routing table entry;
Initialize routing table with a single entry that has the *destination* equal to the local packet switch,
the *next-hop* unused, and the *distance* set to zero;
Repeat forever {
    wait for the next routing message to arrive over the network from a neighbor; Let *N* be the sending switch; for each entry in the message {
        Let *V* be the destination in the entry and let *D* be the distance;
        Compute *C* as *D* plus the weight assigned to the link over which the message arrived;
        Examine and update the local routing table:
        if (no route exists to *V*) {
            add an entry to the local routing table for destination
            V with next-hop *N* and distance *C*;
        } else if (a route exists that has next-hop *N*) {
            replace the distance in existing route with *C*;
        } else if (a route exists with distance greater than *C*) {
            change the next-hop to *N* and distance to *C*;
        }
    }

Distance Vector Intuition

- Let
  - *N* be neighbor that sent the routing message
  - *V* be destination in a pair
  - *D* be distance in a pair
  - *C* be *D* plus the cost to reach the sender
- If no local route to *V* or local route has cost greater than *C*, install a route with next hop *N* and cost *C*
- Else ignore pair

Example Of Distance Vector Routing

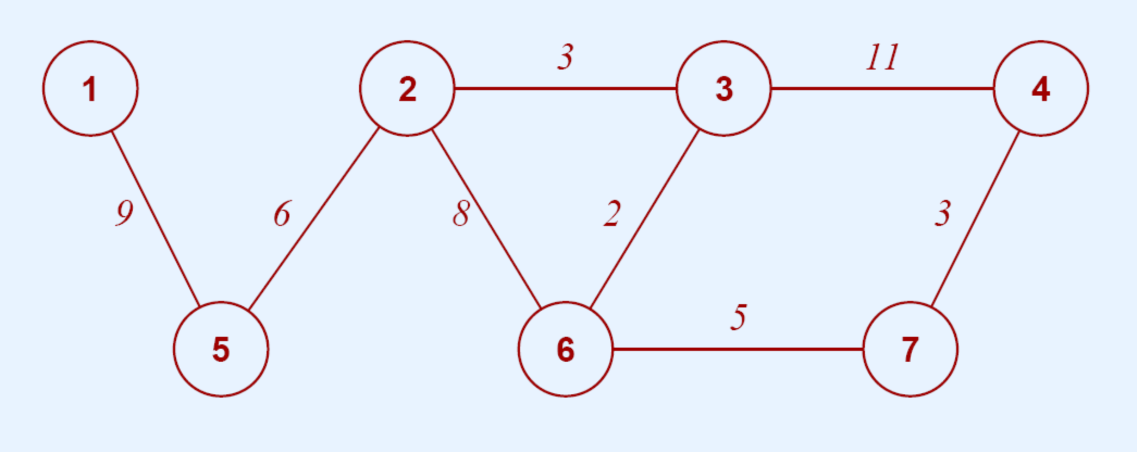


- Consider transmission of one DV message
- Node *2* sends to nodes *3, 5,* and *6*
- Node *6* installs cost *8* route to node *2*
- Later, node *3* sends update
- Node *6* changes route to make node *3* the next hop for destination *2*

Link-State Routing

- Overcomes instabilities in DV
- Pair of switches periodically
  - Test link between them
  - Broadcast link status message
- Switch
  - Receives status messages
  - Computes new routes
  - Uses Dijkstra's algorithm

Example Of Link-State Information



- Assume nodes *2* and *3*
  - Test link between them
  - Broadcast information
- Each node
  - Receives information
  - Recomputes routes as needed

Dijkstra's Shortest Path Algorithm

- Input
  - Graph with weighted edges
  - Node *n*
- Output
  - Set of shortest paths from *n* to each node
  - Cost of each path
- Called *Shortest Path First (SPF)* algorithm

Dijkstra's Algorithm

Given:

a graph with a nonnegative weight assigned to each edge and a designated source node

Compute:

the shortest distance from the source node to each other node and a next-hop routing table

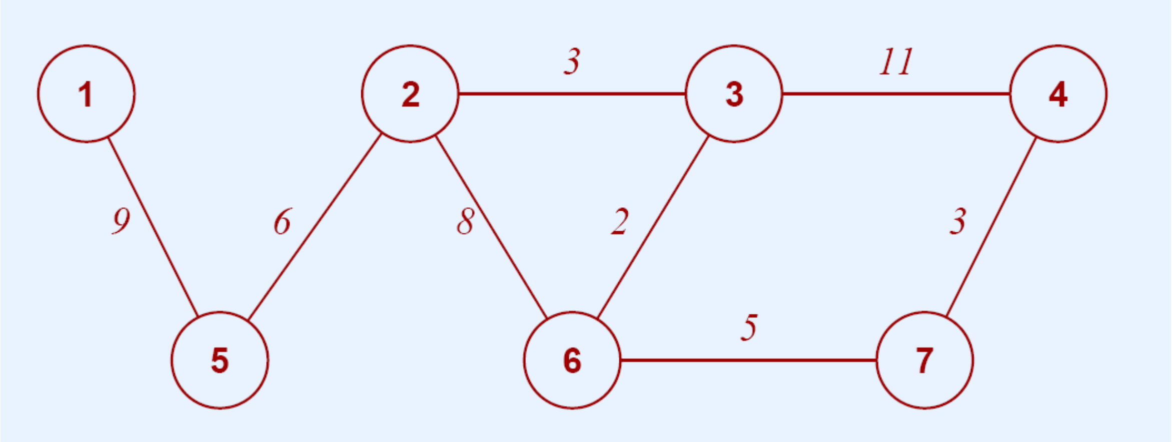
Method:

```
    Initialize set S to contain all nodes except the source node;
    Initialize array D so that D[v] is the weight of the edge from the source to v if such an edge exists, and infinity
otherwise;
    Initialize entries of R so that R[v] is assigned v if an edge exists from the source to v, and zero otherwise;
    while (set S is not empty) {
        choose a node u from S such that D[u] is minimum;
        if (D[u] is infinity) {
            no path exists to nodes in S; quit;}
}
        delete u from set S;
        for each node v such that (u,v) is an edge {
            if (v is still in S) {
                c = D[u] + weight(u,v);
                if (c < D[v]) {
                R[v] = u;
                D[v] = c;
                }
            }
        }
    }
```

Algorithm Intuition

- Start with self as source node
- Move outward
- At each step
  - Find node *u* such that it
    - Has not been considered
    - Is "closest" to source
  - Compute
    - Distance from *u* to each neighbor *v*
    - If distance shorter, make path from *u* go through *v*

Result Of Dijkstra’s Algorithm



- Example routes from node *6*
  - To *3*, next hop = *3*, cost = *2*
  - To *2*, next hop = *3*, cost = *5*
  - To *5*, next hop = *3*, cost = *11*
  - To *4*, next hop = *7*, cost = *8*

Early WAN Technologies

- ARPANET
  - Historically important in packet switching
  - Fast when invented; slow by current standards
- X.25
  - Early commercial service
  - Still used
  - More popular in Europe

Recent WAN Technologies

- SMDS
  - Offered by phone companies
  - Not as popular as Frame Relay
- Frame Relay
  - Widely used commercial service
  - Offered by phone companies
- ATM

Two Primary Performance Measures

- Delay
- Throughput

Delay

- Time required for one bit to travel through the network
- Three types (causes)
  - Propagation delay
  - Switching delay
  - Queuing delay
- Intuition: “length” of the pipe

Throughput

- Number of bits per second that can be transmitted
- Capacity
- Intuition: “width” of the pipe

Components Of Delay

- Fixed (nearly constant)
  - Propagation delay
  - Switching delay
- Variable
  - Queuing delay
  - Depends on throughput

Relationship Between Delay And Throughput

- When network idle
  - Queuing delay is zero
- As load on network increases
  - Queuing delay rises
- Load defined as ratio of throughput to capacity
  - Called utilization

Relationship Between Delay And Utilization

- Define
  - D0 to be the propagation and switching delay
  - U to be the utilization ($0 \leq U \leq 1$)
  - D to be the total delay
- Then

$$D = (1 - U) / D0$$

- High utilization known as congestion

Practical Consequence

Any network that operates with a utilization approaching 100% of capacity is doomed.

Delay–Throughput Product

- Delay
  - Time to cross network
  - Measured in seconds
- Throughput
  - Capacity
  - Measured in bits per second
- Delay ´ Throughput
  - Measured in bits
  - Gives quantity of data “in transit”

Summary

- Network can be
  - Public
  - Private
- Virtual Private Network
  - Uses public network
  - Connects set of private sites
  - Addressing and routing guarantee isolation

Summary (continued)

- Networks are
  - Connectionless
  - Connection-Oriented
- Connection types
  - Permanent Virtual Circuit
  - Switched Virtual Circuit
- Two performance measures
  - Delay
  - Throughput

Summary (continued)

- Delay and throughput interact
- Queueing delay increases as utilization increases
- Delay ´ Throughput
  - Measured in bits
  - Gives total data “in transit”

PART IX

Protocols and
Protocol Layering

Protocol

- Agreement about communication
- Specifies
  - Format of messages
  - Meaning of messages
  - Rules for exchange
  - Procedures for handling problems

Need For Protocols

- Hardware is low level
- Many problems can occur
  - Bits corrupted or destroyed
  - Entire packet lost
  - Packet duplicated
  - Packets delivered out of order