Chapter 7
Packet-Switching Networks

Network Services and Internal Network Operation
Packet Network Topology
Datagrams and Virtual Circuits
Routing in Packet Networks
Shortest Path Routing

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Network Services and Internal Network Operation
Network Layer

- Network Layer: the most complex layer
  - Requires the coordinated actions of multiple, geographically distributed network elements (switches & routers)
  - Must be able to deal with very large scales
    - Billions of users (people & communicating devices)
  - Biggest Challenges
    - Addressing: where should information be directed to?
    - Routing: what path should be used to get information there?

Packet Switching

- Transfer of information as payload in data packets
- Packets undergo random delays & possible loss
- Different applications impose differing requirements on the transfer of information
Network Service

- Network layer can offer a variety of services to transport layer
- Connection-oriented service or connectionless service
- Best-effort or delay/loss guarantees

Network Service vs. Operation

<table>
<thead>
<tr>
<th>Network Service</th>
<th>Internal Network Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectionless</td>
<td>Connectionless</td>
</tr>
<tr>
<td>- Datagram Transfer</td>
<td>- IP</td>
</tr>
<tr>
<td>Connection-Oriented</td>
<td>- Connection-Oriented</td>
</tr>
<tr>
<td>- Reliable and possibly constant bit rate transfer</td>
<td>- Telephone connection</td>
</tr>
<tr>
<td></td>
<td>- ATM</td>
</tr>
</tbody>
</table>

Various combinations are possible
- Connection-oriented service over Connectionless operation
- Connectionless service over Connection-Oriented operation
- Context & requirements determine what makes sense
Complexity at the Edge or in the Core?

The End-to-End Argument for System Design

- An end-to-end function is best implemented at a higher level than at a lower level
  - End-to-end service requires all intermediate components to work properly
  - Higher-level better positioned to ensure correct operation
- Example: stream transfer service
  - Establishing an explicit connection for each stream across network requires all network elements (NEs) to be aware of connection; All NEs have to be involved in re-establishment of connections in case of network fault
  - In connectionless network operation, NEs do not deal with each explicit connection and hence are much simpler in design
Network Layer Functions

Essential

- **Routing**: mechanisms for determining the set of best paths for routing packets requires the collaboration of network elements
- **Forwarding**: transfer of packets from NE inputs to outputs
- **Priority & Scheduling**: determining order of packet transmission in each NE

Optional: congestion control, segmentation & reassembly, security

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Packet Network Topology
End-to-End Packet Network

- Packet networks very different than telephone networks
- Individual packet streams are highly bursty
  - Statistical multiplexing is used to concentrate streams
- User demand can undergo dramatic change
  - Peer-to-peer applications stimulated huge growth in traffic volumes
- Internet structure highly decentralized
  - Paths traversed by packets can go through many networks controlled by different organizations
  - No single entity responsible for end-to-end service

Access Multiplexing

- Packet traffic from users multiplexed at access to network into aggregated streams
- DSL traffic multiplexed at DSL Access Mux
- Cable modem traffic multiplexed at Cable Modem Termination System
Oversubscription

- Access Multiplexer
  - N subscribers connected @ c bps to mux
  - Each subscriber active r/c of time
  - Mux has C=nc bps to network
  - Oversubscription rate: N/n
  - Find n so that at most 1% overflow probability

Feasible oversubscription rate increases with size

<table>
<thead>
<tr>
<th>N</th>
<th>r/c</th>
<th>n</th>
<th>N/n</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.01</td>
<td>1</td>
<td>10</td>
<td>10 extremely lightly loaded users</td>
</tr>
<tr>
<td>10</td>
<td>0.05</td>
<td>3</td>
<td>3.3</td>
<td>10 very lightly loaded user</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>4</td>
<td>2.5</td>
<td>10 lightly loaded users</td>
</tr>
<tr>
<td>20</td>
<td>0.1</td>
<td>6</td>
<td>3.3</td>
<td>20 lightly loaded users</td>
</tr>
<tr>
<td>40</td>
<td>0.1</td>
<td>9</td>
<td>4.4</td>
<td>40 lightly loaded users</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>18</td>
<td>5.5</td>
<td>100 lightly loaded users</td>
</tr>
</tbody>
</table>

Home LANs

- Home Router
  - LAN Access using Ethernet or WiFi (IEEE 802.11)
  - Private IP addresses in Home (192.168.0.x) using Network Address Translation (NAT)
  - Single global IP address from ISP issued using Dynamic Host Configuration Protocol (DHCP)
LAN Concentration

- LAN Hubs and switches in the access network also aggregate packet streams that flows into switches and routers

Campus Network

- Servers have redundant connectivity to backbone
- Departmental Server
- High-speed campus backbone net connects dept routers
- To Internet or wide area network
- Organization Servers
- Gateway
- Backbone
Connecting to Internet Service Provider

- Border routers
- Campus Network
- Autonomous system or domain
- LAN
- Internet service provider

Network administered by single organization

Internet Backbone

- National Service Provider A
- National Service Provider B
- National Service Provider C
- NAP

- Network Access Points: set up during original commercialization of Internet to facilitate exchange of traffic
- Private Peering Points: two-party inter-ISP agreements to exchange traffic
Key Role of Routing

How to get packet from here to there?

- Decentralized nature of Internet makes routing a major challenge
  - Interior gateway protocols (IGPs) are used to determine routes within a domain
  - Exterior gateway protocols (EGPs) are used to determine routes across domains
  - Routes must be consistent & produce stable flows
- Scalability required to accommodate growth
  - Hierarchical structure of IP addresses essential to keeping size of routing tables manageable
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Datagrams and Virtual Circuits

The Switching Function
- Dynamic interconnection of inputs to outputs
- Enables dynamic sharing of transmission resource
- Two fundamental approaches:
  - Connectionless
  - Connection-Oriented: Call setup control, Connection control
Packet Switching Network

Packet switching network
- Transfers packets between users
- Transmission lines + packet switches (routers)
- Origin in message switching

Two modes of operation:
- Connectionless
- Virtual Circuit

Message Switching

- Message switching invented for telegraphy
- Entire messages multiplexed onto shared lines, stored & forwarded
- Headers for source & destination addresses
- Routing at message switches
- Connectionless
**Message Switching Delay**

Minimum delay = $3\tau + 3T$

Additional queueing delays possible at each link

**Long Messages vs. Packets**

1 Mbit message

How many bits need to be transmitted to deliver message?

- Approach 1: send 1 Mbit message
- Probability message arrives correctly
  \[ P_e = (1 - 10^{-6})^{10^6} \approx e^{-10^6 10^{-6}} = e^{-1} \approx 1/3 \]
- On average it takes about 3 transmissions/hop
- Total # bits transmitted \( \approx 6 \text{ Mbits} \)

- Approach 2: send 10 100-kbit packets
- Probability packet arrives correctly
  \[ P'_e = (1 - 10^{-6})^{10^4} \approx e^{-10^4 10^{-6}} = e^{-0.1} \approx 0.9 \]
- On average it takes about 1.1 transmissions/hop
- Total # bits transmitted \( \approx 2.2 \text{ Mbits} \)
Packet Switching - Datagram

- Messages broken into smaller units (packets)
- Source & destination addresses in packet header
- Connectionless, packets routed independently (datagram)
- Packet may arrive out of order
- Pipelining of packets across network can reduce delay, increase throughput
- Lower delay than message switching, suitable for interactive traffic

Packet Switching Delay

Assume three packets corresponding to one message traverse same path

Minimum Delay = 3τ + 5(T/3) (single path assumed)
Additional queueing delays possible at each link
Packet pipelining enables message to arrive sooner
Delay for k-Packet Message over L Hops

3 hops
- $3\tau + 2(T/3)$ first bit received
- $3\tau + 3(T/3)$ first bit released
- $3\tau + 5 (T/3)$ last bit released

L hops
- $L\tau + (L-1)P$ first bit received
- $L\tau + LP$ first bit released
- $L\tau + LP + (k-1)P$ last bit released

where $T = kP$

Routing Tables in Datagram Networks

- Route determined by table lookup
- Routing decision involves finding next hop in route to given destination
- Routing table has an entry for each destination specifying output port that leads to next hop
- Size of table becomes impractical for very large number of destinations
Example: Internet Routing

- Internet protocol uses datagram packet switching across networks
  - Networks are treated as data links
- Hosts have two-port IP address:
  - Network address + Host address
- Routers do table lookup on network address
  - This reduces size of routing table

Packet Switching – Virtual Circuit

- Call set-up phase sets up pointers in fixed path along network
- All packets for a connection follow the same path
- Abbreviated header identifies connection on each link
- Packets queue for transmission
- Variable bit rates possible, negotiated during call set-up
- Delays variable, cannot be less than circuit switching
Connection Setup

- Signaling messages propagate as route is selected
- Signaling messages identify connection and setup tables in switches
- Typically a connection is identified by a local tag, Virtual Circuit Identifier (VCI)
- Each switch only needs to know how to relate an incoming tag in one input to an outgoing tag in the corresponding output
- Once tables are setup, packets can flow along path

Connection Setup Delay

- Connection setup delay is incurred before any packet can be transferred
- Delay is acceptable for sustained transfer of large number of packets
- This delay may be unacceptably high if only a few packets are being transferred
Virtual Circuit Forwarding Tables

<table>
<thead>
<tr>
<th>Input VCI</th>
<th>Output port</th>
<th>Output VCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>27</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>58</td>
<td>7</td>
<td>34</td>
</tr>
</tbody>
</table>

- Each input port of packet switch has a forwarding table
- Lookup entry for VCI of incoming packet
- Determine output port (next hop) and insert VCI for next link
- Very high speeds are possible
- Table can also include priority or other information about how packet should be treated

Cut-Through switching

- Some networks perform error checking on header only, so packet can be forwarded as soon as header is received & processed
- Delays reduced further with cut-through switching

Minimum delay $= 3t + T$
Message vs. Packet Minimum Delay

- **Message:**
  \[ L \tau + L T = L \tau + (L - 1) T + T \]

- **Packet**
  \[ L \tau + L P + (k - 1) P = L \tau + (L - 1) P + T \]

- **Cut-Through Packet (Immediate forwarding after header)**
  \[ = L \tau + T \]

Above neglect header processing delays

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Datagrams and Virtual Circuits

*Structure of a Packet Switch*