The Network Layer and Routers

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Network Layer

- deliver packets from sending host to receiving host
- must be on every host, router in the Internet – IP defines what it means to be a part of the Internet
- switch: processes only the link layer header
- router: processes the network layer header
Packet Forwarding versus Routing

- **forwarding**
  - accept packet on incoming interface
  - lookup outgoing interface from forwarding table
  - put packet into queue for outgoing interface

- **routing**
  - determine the path that packets should take
  - use these paths to create the forwarding table in a given router
How Should the Network Forward Packets?
Virtual Circuit

• setup a fixed path through the network like a telephone circuit
  • assign a flow to a path
  • packets carry virtual circuit identifiers to identify the path, rather than being forwarded based on the destination IP address

• advantages
  • can maintain multiple paths to a destination, each used by different flows
  • can set aside resources for each path, e.g. bandwidth
  • can isolate traffic, e.g. carry voice traffic separate from data traffic
Virtual Circuit Example

- VC table for R1:

<table>
<thead>
<tr>
<th>Incoming IF</th>
<th>Incoming VC</th>
<th>Outgoing IF</th>
<th>Outgoing VC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>63</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>1</td>
<td>97</td>
<td>3</td>
<td>87</td>
</tr>
</tbody>
</table>
Virtual Circuit Setup
Datagrams

- packets forwarded using only destination address in packet
  - each router sends packet to best next hop toward destination
  - packets sent from same source to same destination may take different paths
- advantages
  - simple
    - no connection setup in network layer
    - no connection state in routers
    - complexity (reliability and transport) at the edges
  - flexible: if a route fails, datagrams can take another path
- disadvantages
  - can only use one route per destination
  - forwarding table can be large
  - no performance guarantees
How Do Routers Work?
Routers

• key functions
  • run routing protocol (RIP, OSPF, BGP)
  • forward datagrams from incoming to outgoing link
  • schedule packets in outgoing link queues
Input Port Processing

- line termination - **physical layer** - bits
- data link processing - **link layer** - frames (e.g. Ethernet)
- lookup, forwarding, queueing - **network layer**
  - given a datagram destination address, lookup output port using forwarding table stored in input port memory
  - try to complete input port processing at link speed
  - if datagrams arrive faster than processing rate, they may be queued on input port
Switching Fabrics: Memory

- first-generation routers
- switching controlled by a CPU - packet copied to system memory and then out to output port
- memory contention: switching speed limited by memory bandwidth
Switching Fabrics: Bus

- copy datagram from input port memory to output port memory via shared bus
- **bus contention**: switching speed limited by bus bandwidth
- Cisco Catalyst 1900: 1 Gbps bus (old product)
  - sufficient speed for access and enterprise routers (not regional or backbone)
  - 3MB memory shared by all ports
  - 14,880 pps to 10-Mbps ports, 148,800 pps to 100-Mbps ports (64-byte packets)
Switching Fabrics: Interconnection Network

- overcome bus bandwidth limitation
- crossbar, Banyan networks, and others
- advanced design: fragment datagram into fixed length cells, switch cells through the fabric (cell switching)
- Cisco 12000 (December 2003)
  - 2.5 - 40 Gbps/slot
  - memory-less crossbar switching matrix
  - distributed processing
Output Port Processing

- buffering required: datagrams may arrive faster than link transmission speed – **delay and loss possible**
- scheduling discipline chooses order in which datagrams are transmitted
  - FIFO: service packets in order they arrive
  - priority queueing: service packets according to priority field in IP header
  - fair queueing: give every TCP flow a fair share of link bandwidth
Active Queue Management

- drop or mark a packet before the queue is full
  - sends a congestion signal to the sending host
  - causes hosts to slow down before buffer becomes full
  - to mark packets, need support from TCP to carry mark back to the source: TCP ECN

- Random Early Detection (RED)
  - use EWMA to track average queue length
  - if queue length < min_th, let packet in
  - if queue length > max_th, mark or drop
  - if queue length between min_th and max_th, mark or drop with probability = f(length)
    - this function increases from 0 to 1 as length moves from the minimum to maximum threshold

- AQM keeps the queue size low, which decreases overall queueing delay
Output Port Contention

- In this example, the switch fabric can deliver three packets to an output port in the time it takes for a single packet to be sent at the output port.
- Results in queueing delay at output port.
Head-of-Line Blocking

- In this example, the switch fabric can only deliver one packet a time to an output queue.
- Even though a second packet in the bottom input queue can be delivered to the middle output queue, it is blocked by a packet ahead of it.