Network Switching Technologies, Impairments, and Metrics

Outline

- Basic networking technologies
  - Circuit Switching
  - Packet Switching → Statistical Multiplexing
  - Virtual Circuit Switching
- Network impairments
  - The physical environment impacts network protocols
- Performance Metrics
Network Switching Technologies

- Switching transfers information from input ports to output ports

**Elements of Switches**
- Line cards (multiple interfaces/card)
- Switch fabric
- Control (mappings)
- Management
- Billing
Network Switching Technologies: Circuit Switching

- **On demand** call set up
- Dedicated fixed path
- Fixed network resources held for call duration

Phases of a call
- Call establishment
- Information transfer
- Call disconnect

If no network resources are available, the call blocks (fast busy signal)

Network resources can be easily defined: e.g., “Voice line”
Network Switching Technologies:
Circuit Switching

- The Public Switched Telephone Network (PSTN)
- Dense Wavelength Division (DWDM) Optical Networks
- Dial-up modems
- Customers can not use idle channels,
  → unused capacity is wasted

Network Switching Technologies:
Message Switching

- No Dedicated path
- Address information is added to the message
- Store if output port is busy
- Trade off delay for blocking
- If message is corrupted then retransmit entire message
TDM vs Statistical Multiplexing

- **TDM** →
  - Dwell time = one time slot
  - User 1 → Server
  - User N → Server

- **Statistical Multiplexing** →
  - Link Rate in b/s
  - User 1 → Server
  - User N → Server

If system empty then immediately TX packet at total link rate
Delay → wait for turn and then TX packet at total link rate
Loss → arrive and buffer is full

Example:
- Link rate = 1 Mb/s
- Message size = 5000 bits
- **TDM**
  - Frame size = 10 ms (1 Mb/s * 10 ms = 10,000 bits)
  - 10 times slots /frame (slot time = 1 ms, 1000 bits/slot)
  - Time to transmit 5000 bit message = 5 slot times @ 1 slot /frame = 50 ms
- **Statistical Multiplexing**
  - Assume arriving message finds the system empty
  - Time to transmit 5000 bit message = 5000 bits / (1Mb/s) = 5 ms
Network Switching Technologies: Message Switching

- If message arrives to empty system then it is transmitted at the FULL LINE RATE
- Transmission at the FULL LINE RATE is shared among the all the users
- If a message arrives to a busy system it waits

Message

Buffer

Server

This is called a Statistical Multiplexer

Network Switching Technologies: Packet Switching

- Break up messages into smaller units: **Packets**
- The process of “breaking up” larger information units into smaller parts is called: **Segmentation or Fragmentation**
- The process of “putting together” smaller parts into larger information units is called: **Reassembly**
- **Segmentation and Reassembly** (SAR) can happen multiple times to the same information stream, or flow
Network Switching Technologies:
Packet Switching

Packet Switch

Input Ports

Output Ports

Forwarding Table

Network Switching Technologies:
Packet Switching: Methods

- Datagram Packet Switching
  - Connectionless
- Virtual Circuit Packet Switching
  - Connection-oriented
Network Switching Technologies: Packet Switching --> Datagrams

- Each packet is treated independently
- Packets with same destination may take different routes through the network
- Each node makes independent forwarding decisions
- No call set up is required
- Nodes keep no “state” information
- No QoS is guaranteed
Network Switching Technologies: Packet Switching --> Datagrams

<table>
<thead>
<tr>
<th>Data</th>
<th>Destination Address</th>
<th>Source Address</th>
</tr>
</thead>
</table>

How do Packets find there way: Routing and Forwarding

Network Switching Technologies: Packet Switching --> Datagrams

- Datagram is an example of a connectionless service
- Internet Protocol (IP) provides a connectionless service

Network Switching Technologies: Virtual Circuit Packet Switching

- Virtual circuit packet switch is: connection oriented
- Connection oriented does not imply virtual circuits
- A “logical connection” is established between the source and destination
- All packets flow over the same route through the network
- Packets still “statistically share” link
Virtual circuits: signaling protocols

- used to setup, maintain, teardown VC
- used in ATM, frame-relay, X.25

Network Switching Technologies: Virtual Circuit Packet Switching

- Forwarding decisions are made based on a “virtual circuit identifier” not on the full address
- Packet share transmission facilities
- Switches save state/connection
- State is saved for duration of the connection
- QoS can be guaranteed
Network Switching Technologies:
Virtual Circuit Packet Switching

Virtual Circuit Switching
Client A on Host 1 wants to communicate with Server B on Host 2
Host 1 NIU is connected to port 7 on Switch 3
Host 2 NIU is connected to port 15 on Switch 22
Client A is assigned VCI #5
Server B is assigned VCI #11

*Note: Do not need the same VCI end-to-end

<table>
<thead>
<tr>
<th>Port In</th>
<th>VCI In</th>
<th>Port Out</th>
<th>VCI Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>5</td>
<td>1</td>
<td>55</td>
</tr>
</tbody>
</table>

Network Switching Technologies:
Virtual Circuit/Datagram Trade-offs

What is the Datagram VC switch performance trade-off between propagation time, and holding time?

Example:

Find the time to transmit a 1 Kbyte message coast-to-coast is the USA (3000Km) on a 600 Mb/s link. Propagation time = 3000km/c=10ms

a) Using Datagrams:

\[ \text{Clocking time} = \left( \frac{1 \times 8000}{600 \text{Mb/s}} \right) + 10 \text{ ms} \approx 10 \text{ms} \]

b) Using Virtual Circuits

30ms

Call Set-up

A          B

Data Transmission
Network Switching Technologies: Virtual Circuit/Datagram Trade-offs

Example:
Find the time to transmit a 37.5 Mbyte message coast-to-coast is the USA (3000Km) on a 600 Mb/s link

a) Using Datagrams:
510ms

b) Using Virtual Circuits
530ms

Key issue is holding time relative to call set-up time

Comparison

Network Switching Technologies:

- Permanent Virtual Circuits (PVC)
  - VC numbers assigned by management, usually manual
- Permanent Virtual Circuits are always up

Network Switching Technologies:

- Switched Virtual Circuits (SVC)
- Automatic user initiated call set-ups
- Call set up is on-demand
Network Switching Technologies: Switch State

- Circuit switched networks
  - Switches have “hard” state, they save knowledge of the connection throughout the duration of the call
- Pure datagram networks
  - Routers (switches) have no state of each connection or “flow”.
  - Can use a ‘label’ inside the packet for priority queuing

Network Switching Technologies: Soft state

- Often multiple related flows pass through a network element
- Implicit identification of what datagrams constitute a flow can be done based on source/destination addresses
- The states can be used for resource management --
  - RSVP (Resource Reservation Protocol)
- State of flows are temporarily saved
- Unused soft state is cleared by time outs
Network Switching Technologies:
Attributes of datagram transmission

- Decentralized control
- Simple hosts and switches
- No call processing
- Difficult to provide QoS
- Difficult to bill for services
- Difficult to manage resources to control congestion, note if no congestion then not an issue

Network Switching Technologies:
Attributes of Virtual Circuit Packet Networks

- Provides QoS
- Accommodates billing
- Centralized control
- Follows well known model of the PSTN
- Simpler switching
- Complex control
- Soft state is trying to give connectionless systems attributes of an connection oriented network
Datagram and VC networks

- Networks that only provide VC services at the network layer are typically called VC networks.
- Networks that only provide connectionless services at the network layer are typically called datagram networks.

Network Impairments

- **Propagation Delay:**
  - **The Speed of Light Limitation**
    
    \[ \text{Propagation delay} = \frac{\text{Distance (m)}}{\text{Speed of Light m/s}} \]

  - Example: 3000 km fiber link
    
    Speed of light in fiber = 0.66\*(3\times10^8 \text{m/s})
    
    Propagation delay = \(3000\times10^3 \text{m}/0.66\times(3\times10^8 \text{m/s}) = 15\text{ms}\)

  - Other Media
    - Speed of light in free space = 1.0\*(3\times10^8 \text{m/s})
    - Speed of light in coax = 0.88\*(3\times10^8 \text{m/s})

  - Effect of clocking time, L/C “putting the bits on the link”

  Example: Distance = 3000km, Data rate = 1 Mb/s, Packet size = 1000 bits

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clocking time = L/C = 1 ms</td>
<td>Propagation time = 15 ms</td>
</tr>
</tbody>
</table>

Section 3.1.2
## Network Impairments:
### Propagation Delay

- **Satellite Networks**
  - 500ms

- **Terrestrial Networks**

- **PAN: Personal Area Networks** [BAN: Body Area Network]
  - 3 m or 10ns

- **DAN.: Desk Area Networks**
  - 3 m or 10ns

- **LAN: Local Area Networks**
  - 3 Km or 10us

- **MAN: Metropolitan Area Networks**
  - 300 Km or 1ms

- **NAN: National Area Networks**
  - 3000 Km or 10ms

- **GAN: Global Area Networks**
  - 10,000 Km or 30ms
  - NANs and GANs are typically called WANs Wide Area Networks

- **Interplanetary Networks**
Network Impairments

- Error environment
  - Wired/Fiber/Cable
  - Wireless

Network Impairments: Error Environment

- Random, bit errors are independent
- Bursty, bit errors are correlated and come in groups,

*BER* = $10^{-12}$

*BER* = $10^{-1}$
Network Impairments:
Error Environment

- Random, bit errors are independent
- Bursty, bit errors are correlated and come in groups,

\[
\begin{align*}
\text{BER} &= 10^{-12} \\
\text{BER} &= 10^{-1}
\end{align*}
\]

Network Impairments:

- Example: Impact of delay and errors:
  - Link rate 600 Mb/s
  - Free Space
  - Link distance 3000 km $\rightarrow$ 10ms
  - Packet size:
    - Payload 48 bytes
    - Overhead 5 bytes
    - Total 53 bytes (424 bits)
Network Impairments:

14,285

1

424 bits/(600Mb/s) = .7us/packet
10ms/(0.7us/packet) = 14,285 packets in flight

Question: How do you cope with packets in error?

Network Impairments:

- **Example:**
  - Line rate = 600 Mb/s
  - Bit error rate (BER) = $10^{-9}$
- **What is the time between errors:**
  - On average see one error in $10^9$ bits
  - $(10^9$ bits/error)/(600 Mb/s) = 1.66 sec between errors
Network Impairments and Application Types

- Real time interactive applications
  - Require fixed or bounded delays
  - Large delay "variance" can degrade performance
  - Some real-time applications can tolerate some errors, e.g.,
    - Voice
    - Video

- Non Real time (elastic) applications
  - Can tolerate delay variance
  - Can not tolerate errors
    - E-mail
    - Telnet
    - FTP
    - www
  - Require accurate delivery of information
  - Does not require 'timely' delivery of data

- Some applications do not fit nicely into these categories

Network Performance Criteria: Response Time

Response time $T_R$: The time to "correctly" transmit a packet from Source to destination.
"correctly" implies Response time includes acknowledgments

Examine key components of delay
Network Performance Criteria: Response Time

- Time from source applications to NIC
- Waiting time in NIC to enter the network: buffering time
- Time to transmit the packet: clock the packet into the network
- Time for the network to deliver the packet to the destination’s NIC
- Time for destination’s NIC to generate an acknowledgment
- Time for the acknowledgment to reach the source host: repeating the above steps

Network Performance Criteria: Response Time Dependencies

- State of the network
  - Current topology
  - Active nodes
  - Active links
- State of the other users
  - Congestion
- Errors
- State of source/destination
- Link speeds
- Message sizes
- Message priorities

- Response time, $T_{R}$ is a random variable
  - Probability density function characterizes $T_{R}$
  - % packets observed with delays greater than $T$
  - Variance
  - Mean
Network Performance Criteria: Response Time

- Network designers focus on the components of response time that are a function of the network.
- Find the one-way delay as a function of:
  - traffic load
  - packet length
  - topology
- Focus on average response time or delay

Network Performance Criteria: Throughput

- Throughput in b/s, packets/sec, cells/sec
- Normalized throughput
  \[ S = \frac{R}{C} \]
  where
  
  \( R \) = Average error free rate (b/s) passing a reference point in the network
  
  \( C \) = Link Capacity (b/s)
  
  \( S \) = % time the network is carrying error free packets-goodput
Network Performance Criteria

- Channel (or link) utilization:
  - The % time the channel (or link is busy)
- Channel Efficiency
  - The % time the channel is carrying user information (impact of overhead)

Let

\[ D = \frac{\text{# user data bits}}{\text{packet}} \]
\[ H = \frac{\text{network overhead bits}}{\text{packet}} \]

then

\[ \text{Channel efficiency} = S \left( \frac{D}{D + H} \right) \]

Network Performance Criteria: Throughput

- Channel Capacity, \( S_{\text{max}} \), is the maximum obtainable throughput over the entire range of input traffic intensities, i.e., offered load.
Network Performance Criteria: Reliability

- Reliability: The reliability of a network can be defined as the probability that the functioning nodes are connected to working links.

  Reliability = 1 - Network Failure

- Here lets assume all nodes are working and analyze simple ring and tree networks
Network Performance Criteria: Reliability

5 links:
every node has two paths

4 links

Tree Network Topology

Ring Network Topology

NE=Network Element

Other Network Topologies

Full Mesh Network Topology

Bus Network Topology
Network Performance Criteria: Reliability

- Reliability for a 5 node tree network
- Any of the 4 links fail the network is down
- Let $p =$ probability of link failure and assume failures are statistically independent
- Then $\text{Prob}[\text{no link failure}] = (1-p)^4$
- $\text{Prob}[\text{network failure}] = 1 - (1-p)^4$

But

$$(1-p)^4 = 1 - 4p + 6p^2 - 4p^3 + p^4$$

$\text{Prob}[\text{network failure}] =
4p - 6p^2 + 4p^3 - p^4$

Assuming $p$ is small then for 5 node tree network the $\text{Prob}[\text{network failure}] \approx 4p$
Network Performance Criteria: Reliability

- Reliability for a 5 node ring network
- Ring network has 5 links
- Ring network can have one link failure and still be working, note one more link can fail
- Let $q = 1 - p$ = probability of link good
- $\text{Prob[network good]} = \text{Prob[all good or one failed and 4 good]} = q^5 + 5pq^4$
- So $\text{Prob[network failure]} = 1 - q^5 - 5pq^4$

Network Performance Criteria: Reliability

- Expanding $\text{Prob[network failure]} = 10p^2q^3 + 10p^3q^2 + 5p^4q + p^5$
- The dominant term (assuming $p$ small) is $10p^2q^3$

<table>
<thead>
<tr>
<th></th>
<th>Tree</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$4p$</td>
<td>$10p^2q^3$</td>
</tr>
<tr>
<td>0.01</td>
<td>0.04</td>
<td>0.00097</td>
</tr>
<tr>
<td>0.001</td>
<td>0.004</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$4 \times 10^{-5}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>$4 \times 10^{-7}$</td>
<td>$10^{-13}$</td>
</tr>
</tbody>
</table>
Other Network Performance Criteria

- **Blocking Probability**
  - Packet
  - Call
  *Will derive & apply blocking formulas later*

- **Fairness**

- **Security**

- **Reliability**

Network Performance Criteria: Example

<table>
<thead>
<tr>
<th>Traffic Data Type</th>
<th>Network Service</th>
<th>Typical Message Size</th>
<th>QoS</th>
<th>SoS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battle Command Data</td>
<td>IP Unicast &amp; Multicast</td>
<td>100-500 Bytes</td>
<td>&gt;95%</td>
<td>0.5sec</td>
</tr>
<tr>
<td>Situation Awareness</td>
<td>IP Broadcast</td>
<td>&lt;100 Bytes</td>
<td>&gt;95%</td>
<td>5 sec</td>
</tr>
</tbody>
</table>

QoS = Quality of Service = % IP packets successfully delivered
(for this RFP)

SoS = Speed of Service = Average time to deliver error free packets

From: DoD Proposal RFP October 1997
Network Performance Criteria: Example

<table>
<thead>
<tr>
<th>Generic service type</th>
<th>Virtual bandwidth</th>
<th>Tolerable error rate</th>
<th>Acceptable maximum delay</th>
<th>Tolerable delay variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real time video</td>
<td>&gt; 4Mb/s</td>
<td>&lt; 10^6</td>
<td>~100 ms</td>
<td>&lt;5 ms</td>
</tr>
<tr>
<td>Web browsing</td>
<td>&gt; 250 Kb/s</td>
<td>&lt; 10^5</td>
<td>~100 ms</td>
<td>&lt;10 ms</td>
</tr>
<tr>
<td>Multiparty network games</td>
<td>&gt; 100 Kb/s</td>
<td>&lt; 10^5</td>
<td>~50 ms</td>
<td>&lt;5 ms</td>
</tr>
<tr>
<td>Telecommuting</td>
<td>&gt; 1 Mb/s</td>
<td>&lt; 10^4</td>
<td>~1 sec</td>
<td>&lt;500 ms</td>
</tr>
</tbody>
</table>


Network Performance Perspective: User-Oriented

- Minimum application response time (Delay guarantee)
- Maximum application throughput (Throughput (b/s) guarantee)
- Low loss (Maximum packet loss guarantee)
- Highly reliable (Availability guarantee)
- Very flexible
- Secure
- Low cost
Network Performance Perspective:
Network Manager/Provider

- Maximum throughput for all users
- Effective congestion control
- Power = Throughput/Delay
- **Easy of management**
- Highly reliable
- Fairness
- Ease of billing
- Low cost

Network Performance Perspective:
Network Designer/Developer/Vendor

- Simple design
- Robust
- Scales
  - Number of users
  - Geographical distribution
  - Speed
- Efficient use of resources, CPU, links and memory
- Evolvable
Network Performance: What Can the Network Guarantee?

- Quality of Service (QoS)- Absolute/Contractual performance guarantees  
  Examples:  
  - Sustainable rate  
  - Peak rate  
  - Packet delay (average and standard deviation)  
  - Packet/Cell loss rate  
- Network must reserve resources to provide QoS

Network Performance: What Can the Network Guarantee?

- Class of Service (CoS)-Relative performance guarantees  
  Examples:  
  - Best Effort (lowest priority) [Current Internet is Best Effort]  
    - e-mail  
    - ftp  
  - Gold (medium priority)  
    - Point of sales transaction  
    - Telnet  
  - Platinum (highest priority)  
    - Voice  
    - Video  
- Network performs packet ‘labeling’ and priority queueing to provide CoS  
- Differential Services (IP-DiffServ) provides CoS in the Internet
Network Performance: What Can the Network Guarantee?

- Network engineering issues:
  - QoS
    - Reserving resources implies per connection processing and saving flow state information for each flow
    - Reserving resources implies call set-up
    - Reserving resource thus implies complex per flow processing in each switch
  - CoS
    - Relative services implies simplified router processing
      - only look at a label and queue appropriately
    - Relative services implies no unique per flow processing
  - Hybrids
    - QoS in the enterprise and CoS in the core network
    - QoS in the core network and CoS in the enterprise

How to Bill for it?

- Usage Tiers: Customers can choose how much bandwidth they expect to use and the price tier they are comfortable paying.
- Bandwidth Caps: All-you-can-eat — to a point. Requires a tool to let customers manage usage and give warnings when levels are close to being reached. Also includes the opportunity to buy additional bandwidth when needed.
- Bandwidth Credits: Like a cellular minutes rollover, how about crediting customers when they come in below their usage agreements, minimizing usage?
- Power Boast: Customers gain access to more bandwidth on an as-needed-basis — useful for one-time downloads or occasional requirements.
- Application-Specific Bandwidth: Price bandwidth reservations into specific applications, such as video-on-demand, carrier-provided or third-party VoIP, or online gaming.
How to Bill for it?

- **Third-Party Subsidies**: Charges for broadband are subsidized by other parties: advertisers, third-party VoIP operators, over-the-top Web content providers.
- **Ad-Supported**: Users gain access to bandwidth — or more bandwidth — in exchange for viewing advertising or sharing profile information.
- **User Controls**: Consumption is managed by giving a responsible party — parent, corporate IT department — control via preset usage and spending limits. Alerting and notifications leads to self-management of consumption.
- **Off-Peak Usage**: Set prices and policies to encourage off-peak usage, such as overnight delivery of cached video.
- **Priced-Right All-You-Can-Eat**: There's almost always a price at which unlimited access makes economic sense for carriers, aided by the fact that some unlimited customers will under-consume significantly, subsidizing biggest consumers.