Introduction II
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January 26, 2017
Chapter 1: Roadmap

1.1 What is the Internet?
1.2 Network edge
1.3 Network core
1.4 Network access and physical media
1.5 Internet structure and ISPs
1.6 Delay & loss in packet-switched networks
1.7 Protocol layers, service models
1.8 History
Internet: Network of Networks

- Roughly hierarchical
  - In the center: “tier-1” ISPs (e.g., Level3, Sprint, AT&T, Verizon), national/international coverage
  - Treat each other as equals, do not pay for upstream bandwidth
  - Form the backbone of the Internet

Tier-1 providers interconnect (peer) privately

Tier-1 providers also interconnect at public network access points (NAPs)
Internet: Network of Networks

- "Tier-2" ISPs: smaller (often regional) ISPs
  - Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs

Tier-2 ISP pays tier-1 ISP for connectivity to rest of Internet

Tier-2 ISP is customer of tier-1 provider

Tier-2 ISPs also peer privately with each other, or interconnect at NAPs
Internet Structure: Network of Networks

- “Tier-3” ISPs and local ISPs
  - Last hop (“access”) network (closest to end systems)

Local and tier-3 ISPs are customers of higher tier ISPs connecting them to rest of Internet
Internet Structure: Network of Networks

- A packet passes through many networks!
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How Do Loss and Delay Occur?

Packets *queue* in router buffers (typically FIFO queues)

- If packet arrival rate exceeds output link capacity:
  - Packets queue, wait for their turn
  - Analogy: 5 lanes of traffic merge into 1

  - packet being transmitted *(delay)*
  - packets queued *(delay)*
  - arriving packets dropped if no free buffers *(packet loss)*
Four Sources of Packet Delay

1. Router processing delay:
   - Check bit errors
   - Determine output link
   - Place packet in buffer

2. Queueing delay
   - Time waiting at output link for transmission
   - Depends on congestion level of router
3. Transmission delay:
   - $R = \text{link rate (bps)}$
   - $L = \text{packet length (bits)}$
   - Time to send bits into link $= \frac{L}{R}$

4. Propagation delay:
   - $d = \text{length of link (m)}$
   - $s = \text{propagation speed in medium (≈ 2x10^8 m/sec)}$
   - Propagation delay $= \frac{d}{s}$

Note: $s$ and $R$ are very different quantities!
Caravan Analogy

• Car ~ bit; caravan ~ packet
• Cars “propagate” at 100 mph
• Toll booth takes 12 sec to service a car (transmission time)
• Q: How long until caravan is lined up before the 2nd toll booth?

• Time to “push” entire caravan through toll booth onto highway = 12*10 = 120 sec
• Time for last car to propagate from 1st to 2nd toll both: 100 miles / (100 mph) = 1 hr
• A: 62 minutes
Caravan Analogy (more)

- Toll booth now takes 1 min to service a car
- Q: Will cars arrive to 2nd booth before all cars are serviced at 1st booth?

- Yes! After 7 min, 1st car at 2nd booth and 3 cars still at 1st booth
- 1st bit of packet can arrive at 2nd router before packet is fully transmitted from 1st router!
- Can a packet be at 3 routers simultaneously?
Nodal (Per-Router) Delay

\[ d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}} \]

- \( d_{\text{proc}} \) = processing delay
  - A few microseconds or less, usually fixed for all packets
- \( d_{\text{queue}} \) = queuing delay
  - Depends on congestion, randomly varies between packets
- \( d_{\text{trans}} \) = transmission delay
  - Equals \( \frac{L}{R} \), high for low-speed links, depends on packet size
- \( d_{\text{prop}} \) = propagation delay
  - A few microseconds to hundreds of milliseconds, depends on physical length of the link
Queueing Delay (Revisited)

- $R = \text{link bandwidth (bps)}$
- $L = \text{packet length (bits)}$
- $a = \text{average packet arrival rate (pkts/sec)}$
- Infinite buffer space

Traffic intensity $\rho = \frac{La}{R}$

- $\rho \approx 0$: average queueing delay is small
- $\rho \geq 1$: more “work” arriving than can be serviced, average delay is infinite
- $\rho \rightarrow 1$: delay quickly shoots up
“Real” Internet Delays and Routes

• What do “real” Internet delay & loss look like?
• **Traceroute (tracert in Windows):** provides delay measurement from source to all routers along end-end Internet path towards destination. For all $i$:
  - Sends three packets that reach router $i$ on path towards destination
  - Router $i$ returns packets to sender
  - Sender times interval between transmission and reply
### “Real” Internet Delays and Routes

**traceroute:** gaia.cs.umass.edu to www.eurecom.fr

<table>
<thead>
<tr>
<th>Hop</th>
<th>Host Name</th>
<th>Address</th>
<th>1st Hop</th>
<th>2nd Hop</th>
<th>3rd Hop</th>
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<tbody>
<tr>
<td>1</td>
<td>cs-gw</td>
<td>128.119.240.254</td>
<td>1 ms</td>
<td>1 ms</td>
<td>2 ms</td>
</tr>
<tr>
<td>2</td>
<td>border1-rt-fa5-1-0.gw.umass.edu</td>
<td>128.119.3.145</td>
<td>1 ms</td>
<td>1 ms</td>
<td>2 ms</td>
</tr>
<tr>
<td>3</td>
<td>cht-vbns.gw.umass.edu</td>
<td>128.119.3.130</td>
<td>6 ms</td>
<td>5 ms</td>
<td>5 ms</td>
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<tr>
<td>4</td>
<td>jn1-at1-0-0-19.wor.vbns.net</td>
<td>204.147.132.129</td>
<td>16 ms</td>
<td>11 ms</td>
<td>13 ms</td>
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<tr>
<td>5</td>
<td>jn1-so7-0-0-0.wae.vbns.net</td>
<td>204.147.136.136</td>
<td>21 ms</td>
<td>18 ms</td>
<td>18 ms</td>
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<tr>
<td>6</td>
<td>abilene-vbns.abilene.ucaid.edu</td>
<td>198.32.11.9</td>
<td>22 ms</td>
<td>18 ms</td>
<td>22 ms</td>
</tr>
<tr>
<td>7</td>
<td>nycm-wash.abilene.ucaid.edu</td>
<td>198.32.8.46</td>
<td>22 ms</td>
<td>22 ms</td>
<td>22 ms</td>
</tr>
<tr>
<td>8</td>
<td>62.40.103.253</td>
<td>62.40.103.253</td>
<td>104 ms</td>
<td>109 ms</td>
<td>106 ms</td>
</tr>
<tr>
<td>9</td>
<td>de2-1.de1.de.geant.net</td>
<td>62.40.96.129</td>
<td>109 ms</td>
<td>102 ms</td>
<td>104 ms</td>
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<tr>
<td>10</td>
<td>de.fr1.fr.geant.net</td>
<td>62.40.96.50</td>
<td>113 ms</td>
<td>121 ms</td>
<td>114 ms</td>
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<tr>
<td>11</td>
<td>renater-gw.fr1.fr.geant.net</td>
<td>62.40.103.54</td>
<td>112 ms</td>
<td>114 ms</td>
<td>112 ms</td>
</tr>
<tr>
<td>12</td>
<td>nio-n2.cssi.renater.fr</td>
<td>193.51.206.13</td>
<td>111 ms</td>
<td>114 ms</td>
<td>116 ms</td>
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<tr>
<td>13</td>
<td>nice.cssi.renater.fr</td>
<td>195.220.98.102</td>
<td>123 ms</td>
<td>125 ms</td>
<td>124 ms</td>
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<tr>
<td>14</td>
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<td>126 ms</td>
<td>124 ms</td>
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<tr>
<td>15</td>
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<td>193.48.50.54</td>
<td>135 ms</td>
<td>128 ms</td>
<td>133 ms</td>
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<tr>
<td>16</td>
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<td>194.214.211.25</td>
<td>126 ms</td>
<td>128 ms</td>
<td>126 ms</td>
</tr>
<tr>
<td>17</td>
<td>* * *</td>
<td>* * *</td>
<td>* * *</td>
<td>* * *</td>
<td>* * *</td>
</tr>
<tr>
<td>18</td>
<td>* * *</td>
<td>* * *</td>
<td>* * *</td>
<td>* * *</td>
<td>* * *</td>
</tr>
<tr>
<td>19</td>
<td>fantasia.eurecom.fr</td>
<td>193.55.113.142</td>
<td>132 ms</td>
<td>128 ms</td>
<td>136 ms</td>
</tr>
</tbody>
</table>

* * * means no response (probe lost, router not replying)
Packet Loss

- Queues have finite capacity
- When packets arrive to a full buffer, they are dropped (aka lost) – drop-tail queuing
- Lost packet may be retransmitted by previous router, by the source (end system), or not at all
- Loss rate: average fraction of data lost over a long period of time
- Example: link capacity $R = 10$ Mbps and total arrival rate of traffic is 11 Mbps
  - Q: What’s the average loss rate on the link?
  - A: About 9%
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Protocols “Layers”

Networks are complex!

- Many “pieces”
  - Hosts
  - Routers
  - Links of various media
  - Applications
  - Protocols

- Some type of modular organization is desirable

Solution: Layered structure

- Same host: each layer interacts only with adjacent (upper/lower) layers
- Remote host: each layer talks to identical layer on the other end-host
Layering

- Information travels **down** the protocol stack on the sender side and **up** on the receiver side
Layering

Layers: each layer implements a service

- Via its own internal-layer actions
- Relying on services provided by the layer below
- Talks to same layer on the other host
**Why Layering?**

Benefits of layered organization:

- Sufficient to specify only the *relationship* between the system’s pieces
  - Instead of defining one big protocol that does everything
  - Complexity reduced by *separately* standardizing individual components

- Modularization eases maintenance and upgrade
  - Change of implementation of layer’s service transparent to the rest of system
  - For example, change in FedEx truck routing doesn’t affect other layers
**Internet Protocol Stack**

- **Application**: interacts with user and supports network applications
  - FTP, SMTP, HTTP (ch 2)
- **Transport**: inter-process data transfer
  - TCP, UDP (ch 3)
- **Network**: routing of datagrams from source to destination host
  - IP, routing protocols (ch 4)
- **Link**: data transfer between neighboring network elements
  - 802.11b, Ethernet (ch 5)
- **Physical**: bits “on the wire”
  - Not covered in this class
Encapsulation