Introduction

Abusayeed Saifullah

CS 5600 Computer Networks

These slides are adapted from Kurose and Ross
Roadmap

1.1 what is the Internet?
1.2 network edge
   - end systems, access networks, links
1.3 network core
   - packet switching, circuit switching, network structure
1.4 delay, loss, throughput in networks
1.5 protocol layers, service models
1.6 networks under attack: security
1.7 history
The network core

- mesh of interconnected routers
- Two fundamental approaches to moving data through a network
  - Packet switching: forward packets from one router to the next, across links on path from source to destination
  - Circuit switching: dedicated source-destination path
Packet-switching: store-and-forward

- takes $L/R$ seconds to transmit (push out) $L$-bit packet into link at $R$ bps
- **store and forward:** entire packet must arrive at router before it can be transmitted on next link
- end-end delay = $2L/R$ (assuming zero propagation delay)

**one-hop numerical example:**
- $L = 7.5$ Mbits
- $R = 1.5$ Mbps
- one-hop transmission delay = 5 sec

more on delay shortly …
Two key network-core functions

**routing**: determines source-destination route taken by packets
- *routing algorithms*

**forwarding**: move packets from router’s input to appropriate router output

<table>
<thead>
<tr>
<th>header value</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100</td>
<td>3</td>
</tr>
<tr>
<td>0101</td>
<td>2</td>
</tr>
<tr>
<td>0111</td>
<td>2</td>
</tr>
<tr>
<td>1001</td>
<td>1</td>
</tr>
</tbody>
</table>

dest address in arriving packet’s header
Alternative core: circuit switching

end-end resources allocated to, reserved for “call” between source & dest:

- In diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call *(no sharing)*
- Commonly used in traditional telephone networks
Circuit switching: FDM versus TDM

Example:
4 users

FDM

frequency
time

TDM

frequency
time
Packet switching versus circuit switching
**Packet switching versus circuit switching**

*packet switching allows more users to use network!*

**example:**
- 1 Mb/s link
- each user:
  - 100 kb/s when “active”
  - active 10% of time

  - **circuit-switching:**
    - 10 users

  - **packet switching:**
    - with 35 users, probability > 10 active at same time is less than .0004 *

Q: how did we get value 0.0004?

Q: what happens if > 35 users?
Internet structure: network of networks

- End systems connect to Internet via access ISPs (Internet Service Providers)
  - Residential, company and university ISPs
- Access ISPs in turn must be interconnected.
  - So that any two hosts can send packets to each other
- Resulting network of networks is very complex
  - Evolution was driven by economics and national policies
- Let’s take a stepwise approach to describe current Internet structure
Internet structure: network of networks

**Question:** given *millions* of access ISPs, how to connect them together?
Internet structure: network of networks

Option: connect each access ISP to every other access ISP?

Connecting each access ISP to each other directly doesn’t scale: $O(N^2)$ connections.
Internet structure: network of networks

**Option:** connect each access ISP to a global transit ISP? *Customer and provider* ISPs have economic agreement.
Internet structure: network of networks

Global ISPs must be interconnected.
Internet structure: network of networks

... and regional networks may arise to connect access nets to ISPS.
Internet structure: network of networks

... and content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services, content close to end users.
Roadmap

1.1 what is the Internet?
1.2 network edge
   - end systems, access networks, links
1.3 network core
   - packet switching, circuit switching, network structure
1.4 delay, loss, throughput in networks
1.5 protocol layers, service models
1.6 networks under attack: security
1.7 history
How do loss and delay occur?

- packets queue in router buffers
  - packet arrival rate to link (temporarily) exceeds output link capacity
  - packets queue, wait for turn

- free (available) buffers: arriving packets dropped (loss) if no free buffers
Four sources of packet delay

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

- **\( d_{\text{proc}} \): nodal processing**
  - check bit errors
  - determine output link
  - typically < msec

- **\( d_{\text{queue}} \): queueing delay**
  - time waiting at output link for transmission
  - depends on congestion level of router
Four sources of packet delay

**Transmission Delay (d\text{\_trans})**
- \( L \): packet length (bits)
- \( R \): link bandwidth (bps)
- \( d_{\text{\_trans}} = \frac{L}{R} \)

**Propagation Delay (d\text{\_prop})**
- \( d \): length of physical link
- \( s \): propagation speed in medium (~2x10^8 m/sec)
- \( d_{\text{\_prop}} = \frac{d}{s} \)

\[ d_{\text{\_nodal}} = d_{\text{\_proc}} + d_{\text{\_queue}} + d_{\text{\_trans}} + d_{\text{\_prop}} \]
Caravan analogy

- Cars “propagate” at 100 km/hr
- Toll booth takes 12 sec to service car (bit transmission time)
- Car ~ bit; Caravan ~ packet
- Q: How long until caravan is lined up before 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 booth: 100km/(100km/hr) = 1 hr
- A: 62 minutes
“Real” Internet delays and routes

- what do “real” Internet delay & loss look like?
- **traceroute** program: provides delay measurement from source to router along end-end Internet path towards destination. For all $i$:
  - sends three packets that will reach router $i$ on path towards destination
  - router $i$ will return packets to sender
  - sender times interval between transmission and reply.
“Real” Internet delays, routes

traceroute: Rolla to www.louvre.fr
“Real” Internet delays, routes

traceroute: Rolla to www.louvre.fr

3 delay measurements from St Louis

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

- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all
Throughput

- **throughput**: rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous*: rate at given point in time
  - *average*: rate over longer period of time

Pipe diagram:
- Server sends bits (fluid) into pipe
- Pipe that can carry fluid at rate $R_s$ bits/sec
- Pipe that can carry fluid at rate $R_c$ bits/sec
- Client
Throughput (more)

- $R_s < R_c$ What is average end-end throughput?

- $R_s > R_c$ What is average end-end throughput?

bottleneck link
link on end-end path that constrains end-end throughput
Throughput: Internet scenario

- per-connection end-end throughput: min \((R_c, R_s, R/10)\)
- in practice: \(R_c\) or \(R_s\) is often bottleneck

10 connections (fairly) share backbone bottleneck link \(R\) bits/sec