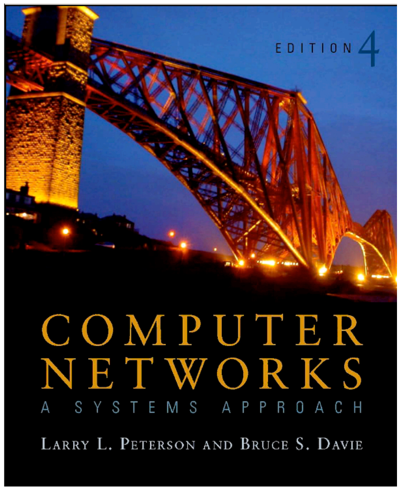
Networking



Introduction to Computer Science · Robert Sedgewick and Kevin Wayne · http://www.cs.Princeton.EDU/IntroCS

Lecture Outline

Client/Server Programming in Java

- Socket Abstraction
- TCP/IP Protocols

The Internet: The view from your laptop

- www.broadband.gov
- www.measurementlab.net
- traceroute, ping, dig

Some Important Concepts

- Statistical Multiplexing, Contention, and Congestion
- Congestion Control (AIMD Algorithm)
- Latency, Bandwidth, and Delay x Bandwidth Product
- Jitter and Audio/Video Playback

Internet

Internet.

- Global communication network containing million of computers.
- Computer networks communicate using TCP/IP protocols.
- Provides access to services: email, chat, world wide web, BitTorrent.
- Started by military around 1969 as ARPANET: survivability, robustness, efficiency. ← cost per bit
- Operating system and hardware independent.

Everybody but you grew up without it!

Client/Server

Stream socket.

- ADT for two-way communication over the Internet.
  - read from socket input and write to socket output
- IP address: identifies computer.
- Port number: identifies application.
- Ex: IP address = `128.112.129.71`, Port = `25`.

  ↑ smtp.princeton.edu mail server   ↑ smtp email application

- Purpose of a Socket is to communicate with another Socket.

Client/server model.

- Client = creates socket to communicate with specified server.
- Server = creates one socket to listen for connection requests; creates another socket to communicate with each client.

Ex: client = web browser, server = web server.

Echo Client

Echo client: connect with server, read text from standard input, send text to server, print whatever server sends back.

```
import java.net.Socket;
public class EchoClient {
   public static void main(String[] args) throws Exception {
      Socket socket = new Socket(args[0], 4444);
      In stdin = new In();
      In in     = new In(socket);
      Out out   = new Out(socket);

      String s;
      while ((s = stdin.readLine()) != null) {
         out.println(s);
         System.out.println(in.readLine());
      }

      out.close();
      in.close();
      socket.close();
   }
}
```

← open socket

↑ server name

← read from stdin

← send to server

← get from server

← close socket

Echo Server

Echo server: use `ServerSocket` to listen for connection requests; connect with a client; read text that client sends; and send it back.

```
public class EchoServer {
   public static void main(String[] args) throws Exception {
      ServerSocket serverSocket = new ServerSocket(4444);

      while (true) {
         Socket socket = serverSocket.accept();
         In  in  = new In (clientSocket);
         Out out = new Out(clientSocket);

         String s;
         while ((s = in.readLine()) != null)
            out.println(s);

         out.close();
         in.close();
         socket.close();
      }
   }
}
```

↖ open server socket and listen on port 4444

← listen and wait for client to request connection

← read data from client and echo it back

← close input streams and socket

Protocols

Internet Protocol (IP)

- Rules for routing packets from machine A to machine B.
- Each packet forwarded independently, possibly on different paths.
- No guarantee packets arrive in order, or even arrive.

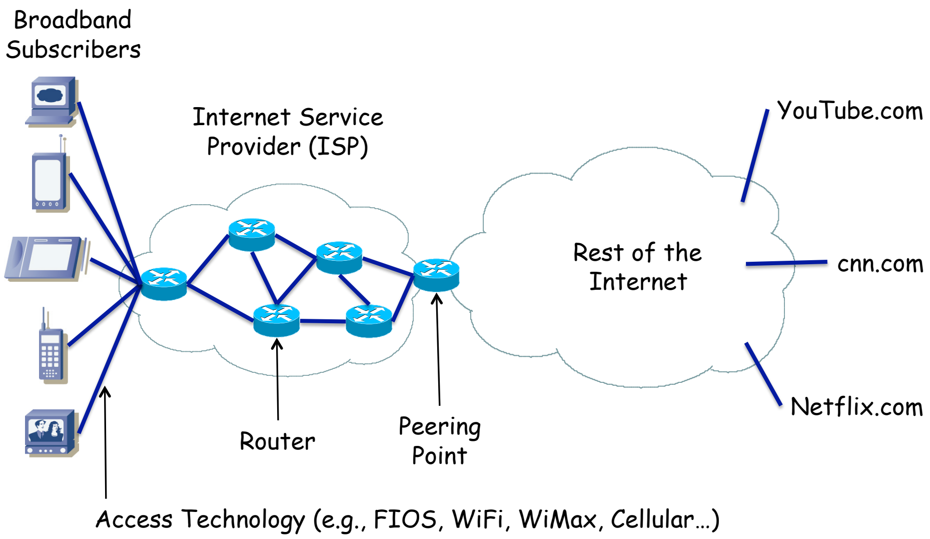
Transmission Control Protocol (TCP)

- Rules to provide communication between client/server programs.
- Fragment application data into packets and send using IP.
- Reassemble IP packets into ordered, reliable byte-stream.
- Acknowledge received packets; retransmit missing packets.

Application Layer Protocols

- Send/Receive user data using TCP/IP.
- HTTP (web), SMTP (email), SSH (secure login), RTMP (video)...

Internet: View from your laptop



Broadband Subscribers

Internet Service Provider (ISP)

YouTube.com

Rest of the Internet

cnn.com

Netflix.com

Router

Peering Point

Access Technology (e.g., FIOS, WiFi, WiMax, Cellular...)

Multiplexing

Network-speak for "resource sharing"

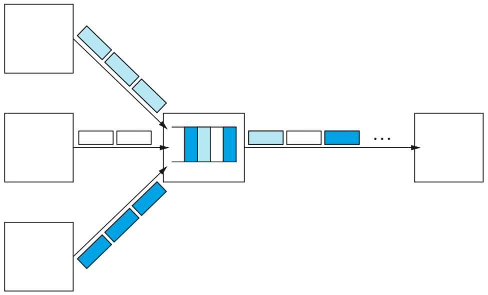
- time division multiplexing
- frequency division multiplexing
- statistical multiplexing

Contention – multiple packets want service at the same time

- packets wait in a queue (FIFO, Priority)

Congestion – too many packets waiting for service

- drop a packet (tail-drop, random drop)



TCP Congestion Control

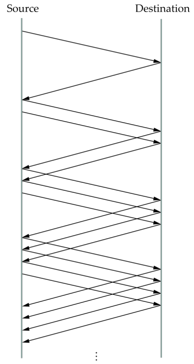
TCP source adjusts sending rate to match network's capacity

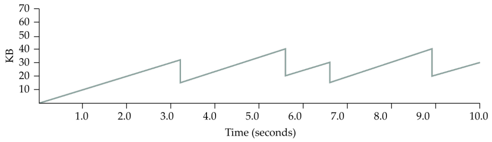
Sender reacts to implicit "signals" from the network

- Receiving an ACK for a packet says "send faster"
- Not receiving an ACK after a period of time says "send slower"

Speed-up conservatively & slow down aggressively

- Additive Increase / Multiplicative Decrease (AIMD)





Performance

Latency (aka Delay)

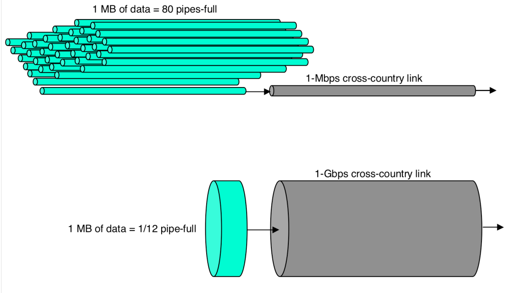
- Time it takes one bit to travel end-to-end (e.g.,300ms)
- Propagation delay (speed of light) + queuing delay
- Also interested in round-trip-time (RTT)

Bandwidth (aka Throughput)

- Number of bits that can be transmitted in a period of time (e.g., 1Mbps)

Delay-Bandwidth Product

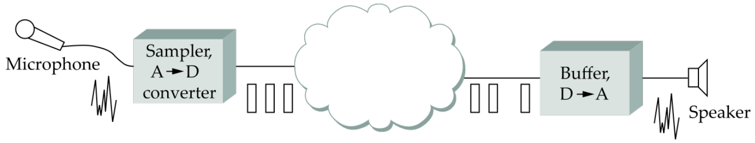
- Number of bits that can be "in flight" before sender hears back
- E.g., 100ms RTT x 1Gbps = 100Mb ~ 10MBytes

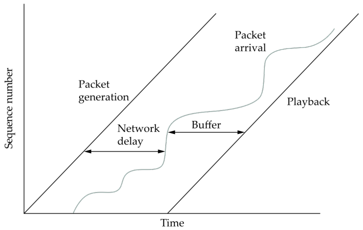

1 MB of data = 80 pipes-full
1-Mbps cross-country link
1-Gbps cross-country link
1 MB of data = 1/12 pipe-full

Audio/Video Applications

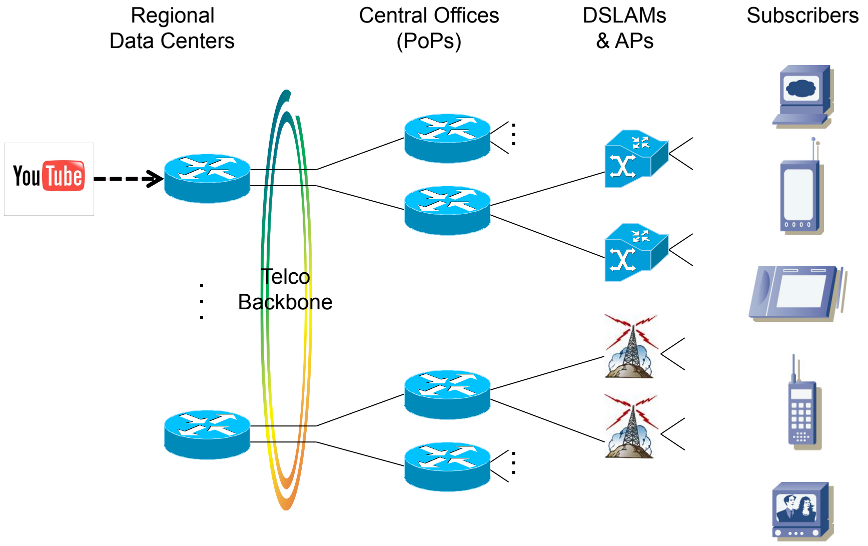
Jitter – Variations in network delay

Playback Buffer – Big enough to "absorb" variable delay





Access Network Revisited



Regional Data Centers

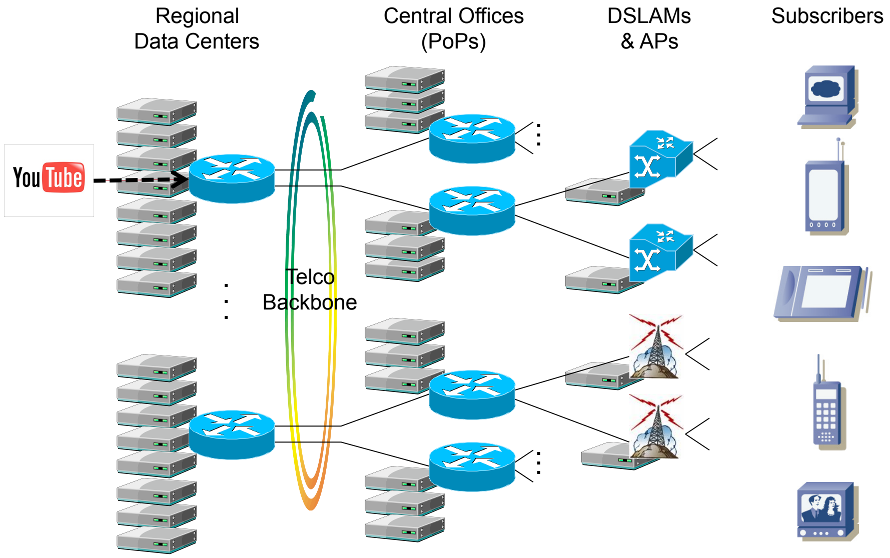
Central Offices (PoPs)

DSLAMs & APs

Subscribers

Telco Backbone

Content Distribution



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More Information

COS 318 Operating Systems

- How to write multi-threaded servers

COS 461 Computer Networks

- TCP, IP, and everything in between