Communication Networks

Telecommunications 1
P. Mathys

Overview

Communication Networks

Layout (Hardware)
- Nodes, Links
- Topology
- Media
- Capacity, Speed
- Connectivity
- Redundancy
- Switches, Routers
- Geographical Extent
- Backbone
- Wireless
- Satellite

Protocols (Software)
- Circuit Switching
- Packet Switching
- Multiplexing
- TCP/IP
- ATM, Frame Relay
- Protocol Stack
- Error Control, ARQ
- Conflict Resolution
- Point-to-point bit pipe
- Routing, Flow Control
- Encryption

Systems Level
- Throughput, Delay
- Reliability
- IP Network
- PSTN, DSL, ISDN
- LAN, MAN, WAN
- Ethernet, Token Ring
- Traffic: Voice, Data, Multimedia
- Gateways, Firewalls
- OSI Model

Nodes and Links

A network has nodes connected by links:

- **External nodes** are users and sometimes access points to other networks.
- **Internal nodes** are part of the network infrastructure and perform various tasks.
- **Links** provide interconnections between nodes. The goal is to have a path from any node to any other node without the need for an excessive number of links.

Topology

- **Fully connected**
- **Ring**
- **Star**
- **Bus**

Topology: Configuration formed by the connection between internal/external nodes of a network.

- **Tree**
- **Spanning Tree**
  In a spanning tree there is exactly one path from every node to every other node and there are no cycles.

- **Spanning Tree Topology**
  Uses the least amount of links to connect all nodes, but offers no redundancy.
**Example: Telephone Network**

EO: End office or local central office  
LATA: Local access and transport area  
LDN: Long distance network

**Example: Internet**

**Geographical Extent**

- **WAN** (wide area network), 100-1000 km  
- **MAN** (metropolitan area network), 10-100 km  
- **LAN** (local area network), 10-1000 m  
- **PAN** (personal area network), 1-10 m

**Example: Cable & Wireless USA Backbone**

**Internal Nodes**

- **Main function**: Connect incoming link to “right” outgoing link.  
- Telephone network: Internal nodes are called **switches**.  
- Internet: Internal nodes are called **routers**.  
- **Nodes** are computers that are program-med and adapt to network conditions.

**Internet Terminology**

- **Gateway**: A device which interconnects two or more networks.  
- **Firewall**: Security system to protect a network against external threats.  
- **Router**: An internal network device that forwards messages from incoming to outgoing links based on address and network state information.
What are Links Made From?

- Wire, twisted wire
  - e.g., telephone, Ethernet
- Coaxial cable
  - e.g., cable TV
- Optical fiber
  - e.g., backbone of Internet
- Wireless: AM, FM, microwave, optical
  - e.g., radio, satellite, IR beams

Link Characterization

- **Rate** or **speed** in bps (bits per second), kbps, Mbps, Gbps (kilo-, Mega-, Giga-bps).
- A single telephone channel without compression uses 64 kbps.
- 24 telephone channels plus overhead use $24 \times 64 + 8 = 1544$ kbps or 1.544 Mbps (T1).

T-Carrier Hierarchy

- T1 is a high speed digital network using pulse code modulation (PCM), developed and implemented by AT&T around 1960.
- T1: 1.544 Mbps (24 voice channels)
- T1C: 3.152 Mbps (48 voice channels)
- T2: 6.312 Mbps (96 voice channels)
- T3: 44.736 Mbps (1 video or 672 voice ch.)
- T4: 274.176 Mbps (6 video or 4032 voice)

Optical Carrier (OC) Levels

- OC-1: 51.84 Mbps (approx 1 video or 750 voice channels)
- OC-3: 155.52 Mbps
- OC-12: 622.08 Mbps
- OC-48: 2488.32 Mbps
- OC-192: 10 Gbps
- OC-768: 40 Gbps (approx 1000 video ch.)

IEEE 802.x Standards

- 802.3 CSMA/CD (carrier sense multiple access with collision detection) “Ethernet”
- 802.5 Token ring LANs
- 802.11 Wireless LANs
- 802.15 Wireless PANs (personal area networks)
- 802.16 Wireless stationary point-to-multipoint LANs/MANs

How to Transport Data

- Suppose you have data that needs to be transmitted from **user A to user B**.
- Should you ask the network to set up a **dedicated path** from user A to user B?
- Or should you break up the data into **standard size packets** and let the network decide “on the fly” how to best send the packets from user A to user B?
Circuit vs. Packet Switching

- The telephone network was optimized for analog voice communication. A direct path between two parties is established for each conversation session.
- Traffic between computers is usually bursty, i.e., short packets of data are exchanged rapidly, followed by relatively long periods of inactivity.

Example: Car Rental

- Suppose you’re on a vacation and rent a car for one week. You will have to pay the rental fee whether you actually drive the car or have it parked in a parking lot. But whenever you need to go somewhere, the car is right there and you can use it immediately. This is the essential idea behind circuit switching.

Example: Using the Bus

- Suppose you go downtown with the bus. You only pay the bus while you ride it. The fare is cheap because you can share the bus with many other people. But the bus route is fixed and you may have to change along the way to get to your destination. In addition, you may have to wait for the next available bus. This is similar to packet switching in networks.

Circuit Switching

- Telephone network: Fixed path between two users is established at beginning of telephone call.

Packet Switching

- Internet: Messages are broken into packets which travel individually over dynamically assigned paths.
Layered Network Architecture

- Data networks are rather complex to design and implement. To make the complexity manageable, most networks use a **layered architecture**.
- Each layer has specific, well defined tasks. Layers at the same level in different computers are referred to as **peers**.

Protocols

- The rules and conventions used in the peer-to-peer communications at a given layer are collectively called a **protocol**.
- Protocols used on the Internet are **TCP**, **IP**, and **UDP** (User Datagram Protocol).
- A list of protocols that is used at each layer in a certain network architecture is called a **protocol stack**.

Layers: Example

- You are the president of company B in Boulder and want to offer the services of your company to your peer, the president of company Y in New York.
- You write a letter, starting with "Dear Bob, may I …", and ending with "Sincerely yours, Jim". The phrases "Dear Bob" and "Sincerely yours" are part of the peer-to-peer protocol when writing letters.

Layers: Example (contd.)

- To actually get the letter to the president of company Y, you use the **services** of the next lower layer.
- Specifically, you ask your secretary to put a destination address, a return address, and a stamp onto an envelope, and to put the letter inside the envelope. The peer of the secretary in company B is the secretary in company Y.

Layers: Example (contd.)

- The secretary in turn uses the services of the next lower layer and brings the letter to the post office in Boulder. Its peer is the post office in New York.
- The post office in Boulder collects all letters for New York, brings them to the airport, and flies them to New York. The airplane represents the bottom layer, which is called **physical layer**.

The OSI 7 Layer Model

- In an attempt to standardize network architectures, the ISO (International Standards Organization) issued the OSI (Open Systems Interconnection) model in 1984 (ten years after the TCP/IP reference model was first defined in 1974).
- The OSI model has 7 layers which are shown on the following slide.
OSI 7 Layer Model

Open Systems Interconnect (OSI) Reference Model for computer networking

- **Application Layer:**
  - Level where applications access network services, e.g., e-mail, WWW
  
- **Presentation Layer:**
  - Intermediary format that specifies/handles presentation of data, e.g., html
  
- **Session Layer:**
  - Used to establish, use and sessions between applications, e.g., http
  
- **Transport Layer:**
  - Does packetizing, error recognition/recovery between end users, e.g., TCP
  
- **Network Layer:**
  - Physical/logical addressing, routing, switching, flow control, e.g., IP
  
- **Data Link Layer:**
  - Package bits into frames, media access, point-to-point comm, e.g., Ethernet
  
- **Physical Layer:**
  - Transmits bits over physical medium such as optical fiber, twisted pair wire, etc

WWW and Internet

- **Application:**
  - Web Browser/WWW Server

- **Presentation:**
  - HTML (Hypertext Markup Language)

- **Session:**
  - HTTP (Hypertext Transfer Protocol)

- **Transport:**
  - Telnet, ftp, SMTP

- **Network:**
  - TCP (Transmission Control Protocol)

- **Data Link:**
  - IP (Internet protocol)

- **Physical:**
  - Ethernet, ATM, PPP

Services Performed by Layers

- **Physical Layer (1):**
  - Transmit raw bits over physical medium
  - Convert bits to waveforms and vice versa

- **Data Link Layer (2):**
  - Transfer data frames reliably on point-to-point or multi-access links
  - Error detection/correction, ARQ (automatic repeat request), contention resolution

- **Network Layer (3):**
  - Transfer and route packets reliably between sub-networks
  - Routing algorithms, congestion control

- **Transport Layer (4):**
  - Transparent, reliable and cost-effective data transfer between end systems
  - Break messages into packets, flow control, additional end-to-end reliability.
Services Performed by Layers

- **Session Layer (5):**
  - Provide mechanism for organizing and structuring interactions between application processes (e.g., token management)

- **Presentation Layer (6):**
  - Provide independence from differences in data representations (e.g., ASCII vs. Unicode)
  - Data compression, code conversion

- **Application Layer (7):**
  - Provide uniform semantics for applications running in different environments
  - Terminal emulation, file conversion/transfer

**Note:** In practice the most important layers are 1…4, the others are seldom implemented explicitly within the network architecture.

TCP/IP Model

- The TCP/IP model grew out of the ARPA-NET project. Researchers recognized early on (1974) the importance of interconnecting networks of different makes and topologies.

- TCP/IP deliberately only specifies layers 3 and 4 of the OSI model; lower layers can be implemented in a variety of ways.

- TCP/IP is the most widely implemented model.

**Acronyms:**
- SMTP: Simple mail transfer protocol
- MIME: Multipurpose internet mail extensions
- FTP: File transfer protocol
- HTTP: Hypertext transfer protocol
- DNS: Domain name system
- SNMP: Simple network management protocol
- SNTP: Simple network time protocol

TCP/IP Model

- Acronyms:
  - TCP: Transmission control protocol
  - UDP: User datagram protocol
  - ARP: Address resolution protocol (IP <-> LAN)
  - IP: Internet protocol
  - FDDI: Fiber distributed data interface
  - ISDN: Integrated services digital network
  - ATM: Asynchronous transfer mode
Internet Protocol (IP)

- IP is the workhorse protocol of the TCP/IP protocol stack. It provides an unreliable connectionless datagram delivery service.
- IP implements layer 3 (network layer) of the OSI model.
- The main task of the IP is the routing and the fragmentation and reassembly of datagrams.

Data Transmission using the Internet Protocol (IP)

- How does data get transmitted on the Internet from one computer to another?
- Data is broken up into packets at the sender and reassembled at the receiver.
- Each data packet is individually labeled with a source and a destination address.
- Source and destination addresses are 32-bit numbers (under IP v4).

Internet Protocol (IP)

- To perform its functions and to communicate among peers, the IP layer adds a header to the data packets (called “payload”) that it receives for transmission, as shown in the next slide.
- The most important fields in the header are:
  - Source/destination IP address
  - Total length, TTL (time to live)

IP Header (for each packet)

```
<table>
<thead>
<tr>
<th>Bit</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>19</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ver</td>
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<tr>
<td></td>
<td>Len</td>
<td>Num</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>Time to Live</td>
<td></td>
<td>Protocol Number</td>
<td>Header Checksum</td>
</tr>
</tbody>
</table>
```

Network and Host Numbers

- **Network numbers** used to be globally administered by the InterNIC. Now there are several commercial agents (e.g., http://www.networksolutions.com).
- **Host numbers** are locally administered
- **Global routing** decisions can be made on the basis of the network numbers.
- **Local routing** decisions only need to take the host numbers into account.

IPv4 Address Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Network #</th>
<th>Host #</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8 bits</td>
<td>24 bits</td>
<td>Very large sites</td>
</tr>
<tr>
<td>B</td>
<td>16 bits</td>
<td>16 bits</td>
<td>Large sites</td>
</tr>
<tr>
<td>C</td>
<td>24 bits</td>
<td>8 bits</td>
<td>Small sites</td>
</tr>
<tr>
<td>D</td>
<td>n/a</td>
<td>n/a</td>
<td>Multicast address</td>
</tr>
<tr>
<td>E</td>
<td>n/a</td>
<td>n/a</td>
<td>Reserved</td>
</tr>
</tbody>
</table>

IP address = <network #><host #> (32 bits total)
IPv4 Address Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Network Numbers</th>
<th>Hosts/Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0 … 127</td>
<td>16,777,214</td>
</tr>
<tr>
<td>B</td>
<td>128.0 … 191.255</td>
<td>65,534</td>
</tr>
<tr>
<td>C</td>
<td>192.0.0 … 223.255.255</td>
<td>254</td>
</tr>
<tr>
<td>D</td>
<td>224.0.0.0 … 239.255.255</td>
<td>n/a</td>
</tr>
<tr>
<td>E</td>
<td>240.0.0.0 … 255.255.255</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Subnets

- In practice, individual subnets rarely consist of more than 100...200 computers.
- Thus, the original host # is subdivided (by the local network administration) into a subnet # and a new (shorter) host #.
- For example, 128.138.129.2 is interpreted as
  - Network #: 128.138 (administered globally)
  - Subnet #: 129 (administered locally)
  - Host #: 2 (administered locally)

Examples

- 192.149.89.61 is a class C address:
  - Network #: 192.149.89
  - Host #: 61
- 128.138.129.2 is a class B address:
  - Network #: 128.138
  - Subnet #: 129
  - Host #: 2
- 18.69.0.27 is a class A address:
  - Network #: 18
  - Subnet #: 69.0
  - Host #: 27

Exploring Network Topology

- Try to find the website of a network operator, e.g., www.cw.com (Cable & Wireless), and see if network maps are available.
- Examine the numerical IP address for network, subnet, and host numbers.
- Use tools such as tracert or traceroute.

traceroute

- traceroute (or tracert) probes the path that data packets take through the Internet, recording all the "hops" (routers) along the way.
- Using traceroute you can find out how to get to a site, where (approximately) it is located, where bottlenecks along the path are, and where packets are lost

TraceRoute Example

![TraceRoute Example](image)
(Almost) Fully Connected Example

“Weathermap” of TEN-155 core

Ring Topology Example

i-21 fiber-optic network

Star Topology Example

Centers in Prague and Brno

What is “Best” Topology?

- The network topology is determined by the internal/external nodes and how they are interconnected by links.
- There is no single “right” topology.
- Factors that determine topology choice:
  - Amount of traffic between locations.
  - Cost of links/nodes vs. revenue from users.
  - Delay requirements.

Optimization Criteria

- **Throughput** is the total number of (unit) messages that a communications system can transfer in a fixed time interval.
- Optimal for network: **Maximize** throughput.
- **Delay** is the average amount of time it takes for a message to be transferred from a source node to a destination node.
- Optimal for user: **Minimize** delay.

Example: Delay and Throughput for a Ski Lift

- **Throughput** is the total number of skiers transported from bottom to top per hour.
- **Delay** is the average amount of time it takes for a skier to go from bottom to top, including the time spent waiting in line.
- The ski lift operator wants to maximize throughput (= # of tickets sold), the skier wants to minimize delay (= time spent not skiing downhill). The two goals are contradictory.
- => **Compromise** is necessary.
Delay vs. Number of Links

<table>
<thead>
<tr>
<th>Node</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td></td>
<td>1</td>
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<tr>
<td>B</td>
<td>2</td>
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<td></td>
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<tr>
<td>C</td>
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<td>2</td>
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<td>D</td>
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<tr>
<td>E</td>
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<td></td>
<td>4</td>
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<td></td>
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<tr>
<td>F</td>
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<td>2</td>
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<td>G</td>
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<td>2</td>
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<tr>
<td>H</td>
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<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

# of links: 8
Avg delay: 16/7 = 2.3 hops

Compared to ring:
50% more links,
30% less delay (hops)

Hops
A -> B 1
A -> C 2
A -> D 3
A -> E 4
A -> F 3
A -> G 2
A -> H 1

# of links: 8
Avg delay: 2 hops
One additional node

Compared to ring:
50% more links,
30% less delay (hops)

Different Topology Features

- **Fully connected**
  - N nodes
  - N*(N-1)/2 links
  - Avg delay: 1 hop
  - Very robust with respect to link failures

- **Ring**
  - N nodes
  - N links
  - Avg delay: approx N/4 hops
  - Can survive loss of any single link

- **Star**
  - N+1 nodes
  - N links
  - Avg delay: 2 hops
  - Vulnerable: Cannot survive loss of central node

- **Bus**
  - N nodes
  - N+1 links
  - Avg delay: 1 hop (but collisions can occur)
  - Vulnerable: cannot survive loss of bus

- **Spanning Tree**
  - N nodes
  - N-1 links
  - Avg delay: proportional to log N
  - Has no cycles
  - Loss of any link splits network in two

What is “Best” Topology?

**Conclusions:**
- If links are very expensive, use more strategically placed (internal) nodes.
- If short delay is very crucial, use more links.
- **Quality of service (QoS)** differentiation:
  Connections with short delay (e.g., for two-way voice communication) can be requested from network if higher price is paid, similar to express mail.