Communications Landscape

Voice
Data: E-mail, Web, Network based applications, Images, Machine-to-Machine, IoT
Video, Streaming, Broadcast, Video on Demand, Mobile
Wired & wireless
Mobility
Separate Voice/Internet/Video networks have converged to:

An integrated packet network
Drivers: Customer Expectations

Sense of always connected
Instant response, high bandwidth
Ubiquitous connectivity
Multimedia (video) support
Conferencing (simultaneous communications with multiple users)

Drivers: Customer Expectations

Mobility support
Personalized information services
Context sensitive information services
Absolutely secure & private
Low-cost
The Value of the Net

Metcalf’s Law: The value of a network increases as the square of the number of connected users [some say nlog(n)]
The value of a network increases as the square of the access bandwidth
The value of a network increases as the square of computing power of end device
Number of connected users, bandwidth/user and device capabilities are increasing → Value of the Net ↑

Drivers: Technology
Traffic Growth

Internet still growing
Access rates increasing
- Cable/DSL ~ 10’s-100 Mb/s
- FTTH ~100’s to 1 Gb/s
- Wireless → Gb/s

Table 1. Internet users as a percentage of regional population

<table>
<thead>
<tr>
<th>Region</th>
<th>2018</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>51%</td>
<td>66%</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>52%</td>
<td>72%</td>
</tr>
<tr>
<td>Central and Eastern Europe</td>
<td>65%</td>
<td>78%</td>
</tr>
<tr>
<td>Latin America</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>Middle East and Africa</td>
<td>24%</td>
<td>35%</td>
</tr>
<tr>
<td>North America</td>
<td>90%</td>
<td>92%</td>
</tr>
<tr>
<td>Western Europe</td>
<td>82%</td>
<td>87%</td>
</tr>
</tbody>
</table>

Compound Annual Growth Rate = CAGR
Drivers: Technology

Moore’s Law

- Processing power doubles every 18 months
- Moore’s Law has been true since ~1965

Gilder’s Law (The Law of Telecoms)

- Total telecommunications system capacity (b/s) triples every three years


Connection Speeds

<table>
<thead>
<tr>
<th>Region</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>45.9</td>
<td>52.9</td>
<td>61.2</td>
<td>77.4</td>
<td>97.8</td>
<td>110.4</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>62.8</td>
<td>74.9</td>
<td>91.8</td>
<td>117.1</td>
<td>137.4</td>
<td>157.1</td>
</tr>
<tr>
<td>Latin America</td>
<td>15.7</td>
<td>19.7</td>
<td>24.5</td>
<td>31.3</td>
<td>51.5</td>
<td>59.3</td>
</tr>
<tr>
<td>North America</td>
<td>56.6</td>
<td>76.1</td>
<td>92.7</td>
<td>108.0</td>
<td>126.0</td>
<td>141.8</td>
</tr>
<tr>
<td>Western Europe</td>
<td>45.6</td>
<td>53.2</td>
<td>72.3</td>
<td>87.4</td>
<td>109.6</td>
<td>123.0</td>
</tr>
<tr>
<td>Central and Eastern Europe</td>
<td>35.0</td>
<td>37.2</td>
<td>37.0</td>
<td>65.5</td>
<td>77.8</td>
<td>87.7</td>
</tr>
<tr>
<td>Middle East and Africa</td>
<td>5.7</td>
<td>11.7</td>
<td>25.0</td>
<td>20.0</td>
<td>34.9</td>
<td>41.2</td>
</tr>
</tbody>
</table>

Table 7. Average mobile network connection speeds (in Mbps) by region and country

<table>
<thead>
<tr>
<th>Region</th>
<th>2018</th>
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<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global speed: All handsets</td>
<td>13.2</td>
<td>17.7</td>
<td>23.5</td>
<td>29.4</td>
<td>35.9</td>
<td>43.9</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>14.3</td>
<td>18.0</td>
<td>24.7</td>
<td>32.4</td>
<td>39.0</td>
<td>45.7</td>
</tr>
<tr>
<td>Latin America</td>
<td>8.0</td>
<td>11.2</td>
<td>15.7</td>
<td>21.1</td>
<td>24.8</td>
<td>28.8</td>
</tr>
<tr>
<td>North America</td>
<td>21.6</td>
<td>27.0</td>
<td>34.9</td>
<td>42.4</td>
<td>50.6</td>
<td>58.4</td>
</tr>
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<td>54.4</td>
<td>62.4</td>
</tr>
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<td>43.0</td>
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<td>9.4</td>
<td>13.3</td>
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**Speed Record**

July 14, 2021 “fastest internet speed, achieving a data transmission rate of 319 Terabits per second (Tb/s)”


“The new record was made on a line of fibers more than 1,864 miles (3,000 km) long.”

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**Drivers: Others**

**Economic**

**Public Policy/Regulatory**

- FCC opening of “White Space” to make use of additional spectrum
- Network Neutrality

**Local Laws and Culture**
Issues in Networking: Sharing

Example:

Business Offices

Link Rate = R b/s

Fiber

Internet

Business Campus Computer Center

D in meters

D = 2000m

What is shared:

- Link capacity
- Buffers (memory)
- Processing
- Common address (name) space
### Issues in Networking: Sharing

$R =$ Peak rate (link capacity) b/s
$L =$ Message Length (Bytes)
Packet clocking (serving) time (sec) = $L \times 8$ (bits) / $R$ (bits/sec)
One way propagation time (sec) = $D$ (meters) / (Propagation speed (meters/sec) = $\tau$ (sec)
  - Propagation speed = $c =$ speed of light = $3 \times 10^8$ meters/sec (in free space)
  - Propagation speed = $\approx 2 \times 10^8$ meters/sec (in fiber)
For $L = 9$ kBytes & $R = 100$ Mb/s $\rightarrow$ Packet clocking time $= 0.72$ ms
For $D = 2$ km $\rightarrow$ One way propagation time $= \tau = 10$ us
Round trip time (RTT) = $2\tau$ (Not including switching, forwarding, and processing times)

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### Issues in Networking: Sharing

Assume each customer and printer is connected using Ethernet, i.e. at 1 Gb/s
How fast does the link between the offices and the computer center have to be to guarantee all the customers can use the 1 Gb/s.
$R =$ Rate $= 55$ Gb/s
Too expensive
Issues in Networking: Sharing

Solution: Gamble

Assume:
- Each host computer breaks up messages into ‘smallish’ units called packets
- Packets from each customer are sent to a waiting line, buffer, to wait their turn to use the link
- Packets arriving to a full buffer are discarded
- Discarded packets are retransmitted later

Customer information now experiences:
- Queueing Delay, waiting in line
- Loss

Network resources are shared, e.g.,
- Transmission capacity
- Addresses
- Buffer (memory)

Customer performance requirements:
- Delay < 100ms and Loss < 10%

Assume customer traffic:
- \( L \) (bytes) = Average packet length = 9000 bytes
- \( \lambda \) (packets/sec/device) = Packets are generated at a rate of 2 per second/device

Using basic queueing theory
- \( R = 8.6 \text{ Mb/s} \ll 55 \text{ Gb/s} \)
- System size > 7 packets

What happens when you lose your gamble:
- Packet Loss
- Delay

See the current Internet performance @ 
Issues in Networking: Sharing

What happens when you lose your gamble:
- Packet Loss
- Delay

From: Tenth Measuring Broadband America Fixed Broadband Report
A Report on Consumer Fixed Broadband Performance in the United States,
FCC, January 2021

Packet Loss

Issues in Networking: Protocols

Protocols are the rules, implemented as algorithms, that govern the interactions between network elements, e.g.,
- Routing
- Media Access
- Resource Allocation

Protocols are algorithms implemented software or hardware
Protocols must run in “real time”

- Assume R = 40 Gb/s and L = 1500 Bytes
- Router must process a packet in 0.3 μs
Issues in Networking: Protocols

Peer protocols
- Executed at both ends of the connection
- Run on geographically distributed network elements
- Use memory to save state
- Packet events (arrival) to change state based on data in packet headers
- Packets arrive asynchronously

Protocols must work with inaccurate or imperfect knowledge
- Packets are lost due to bit errors or traffic congestion
- Instantaneous demands for network resources are unknown
- Out-of-date information due to queueing and finite propagation delay

Protocols must be standardized

Issues in Networking:

Routing → finding path from source to destination
Addressing (naming & identifiers)

Resource Allocation
- Call admission control (CAC)
- Congestion control
- Flow control

Time scales: Control of network resources at time scales ranging from $10^{-9}$ sec to months

Management, e.g.,
- ISP need to add/delete users
- Carriers/ISPs need to add/delete and administer their equipment

Need for cooperation among competing companies
**Issues in Networks**

**Specific Protocols and Acronyms**
- E.g., TDM, FDM, IP, TCP, ARP, DNS, DHCP, ICMP, IPv6.....

**Header Formats....**

**Boxes (Network Elements-NEs)**
- E.g., Router, switch, repeater, firewalls, "middleboxes", headend, base station, user equipment (UE)

**Tools,**
- E.g., Ping, traceroute, wireshark,....

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**Networks**

Real time distributed systems
- Owned by different companies, governments, agencies, enterprises.....
- Must meet constraints, e.g.,
  - Quality of Experience (QoE),
  - Security,
  - Privacy,
- Large scale, e.g.,
  - Geographic
  - Number of devices (Internet of Things)
  - Range of data rates
- Must cope with a wide variety of impairments
- Must cope with imperfect knowledge