Communication Networks

Part 1: General overview

#1 What is a network made of?

#2 How is it shared?

#3 How is it organized?

#4 How does communication happen?

#5 How do we characterize it?
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What is a network made of?

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How does communication happen?

How do we characterize it?
The Internet should allow

processes on different hosts
to exchange data

everything else is just commentary…
How do you exchange data in a network as complex as this?
To exchange data, Alice and Bob use a set of network protocols.
A protocol is like a conversational convention: who should talk next and how they should respond.
Each protocol is governed by a specific interface

Alice

while (...) {
    message = ...;
    send(message, ...);
}

Bob

while (...) {
    message = receive(...);
}

WoW server

WoW client

Application Programming Interface
In practice, there exists a lot of network protocols. How does the Internet organize this?
How standards proliferate:
(See: A/C chargers, character encodings, instant messaging, etc.)

**Situation:**
There are 14 competing standards.

14?! Ridiculous!
We need to develop one universal standard that covers everyone's use cases.

Yeah!

**Soon:**

**Situation:**
There are 15 competing standards.

https://xkcd.com/927/
Modularity is a key component of any good system

Problem

- Can’t build large systems out of spaghetti code
- Hard (if not, impossible) to understand, debug, update
- Need to bound the scope of changes
- Evolve the system without rewriting it from scratch

Solution

- Modularity is how we do it
- …and understand the system at a higher-level
Modularity, based on abstraction, is the way things get done

— Barbara Liskov, MIT

Photo: Donna Coveney
To provide structure to the design of network protocols, network designers organize protocols in layers
To provide structure to the design of network protocols, network designers organize protocols in layers and the network hardware/software that implement them.
Internet communication can be decomposed into 5 independent layers (or 7 layers for the OSI model)

- **L5** Application
- **L4** Transport
- **L3** Network
- **L2** Link
- **L1** Physical
Each layer provides a service to the layer above

<table>
<thead>
<tr>
<th>Layer</th>
<th>Service Provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>Application: network access</td>
</tr>
<tr>
<td>L4</td>
<td>Transport: end-to-end delivery (reliable or not)</td>
</tr>
<tr>
<td>L3</td>
<td>Network: global best-effort delivery</td>
</tr>
<tr>
<td>L2</td>
<td>Link: local best-effort delivery</td>
</tr>
<tr>
<td>L1</td>
<td>Physical: physical transfer of bits</td>
</tr>
</tbody>
</table>
Each layer provides a service to the layer above by using the services of the layer directly below it.

Applications
...built on...

Reliable (or unreliable) transport
...built on...

Best-effort global packet delivery
...built on...

Best-effort local packet delivery
...built on...

Physical transfer of bits
Each layer has a unit of **data**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>Application exchanges <em>messages</em> between processes</td>
</tr>
<tr>
<td>L4</td>
<td>Transport transports <em>segments</em> between end systems</td>
</tr>
<tr>
<td>L3</td>
<td>Network moves <em>packets</em> around the network</td>
</tr>
<tr>
<td>L2</td>
<td>Link moves <em>frames</em> across a link</td>
</tr>
<tr>
<td>L1</td>
<td>Physical moves <em>bits</em> across a physical medium</td>
</tr>
</tbody>
</table>
Each layer (except for L3) is implemented with different protocols

<table>
<thead>
<tr>
<th>layer</th>
<th>protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5 Application</td>
<td>HTTP, SMTP, FTP, SIP, …</td>
</tr>
<tr>
<td>L4 Transport</td>
<td>TCP, UDP, SCTP</td>
</tr>
<tr>
<td>L3 Network</td>
<td>IP</td>
</tr>
<tr>
<td>L2 Link</td>
<td>Ethernet, Wifi, (A/V)DSL, WiMAX, LTE, …</td>
</tr>
<tr>
<td>L1 Physical</td>
<td>Twisted pair, fiber, coaxial cable, …</td>
</tr>
</tbody>
</table>
The Internet Protocol (IP) acts as an unifying, network, layer

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<td>L5</td>
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<td>L1</td>
<td>Physical</td>
</tr>
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</table>
Each layer is implemented with different protocols and technologies.
Each layer takes messages from the layer above, and *encapsulates* with its own header and/or trailer.
GET google.ch

your laptop

Application
HTTP(S)

Transport
TCP/UDP

Network
IP

Link
Ethernet

Header
Message

HA
GET google.ch
In practice, layers are distributed on every network device.
Since when bits arrive they must make it to the application, all the layers exist on a host.
Routers act as **L3 gateway** as such they implement L2 and L3
Switches act as **L2 gateway** as such they only implement L2
Let’s see how it looks like in practice on a host, using Wireshark https://www.wireshark.org
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A network *connection* is characterized by its delay, loss rate and throughput.

- **Delay**
- **Loss**
- **Throughput**

How long does it take for a packet to reach the destination?

What fraction of packets sent to a destination are dropped?

At what rate is the destination receiving data from the source?
A network *connection* is characterized by its delay, loss rate and throughput.
Each packet suffers from several types of delays at *each node* along the path.

\[
\begin{align*}
\text{transmission delay} & \quad \text{due to link properties} \\
\oplus \quad \text{propagation delay} \\
\oplus \quad \text{processing delay} & \quad \text{due to traffic mix & switch internals} \\
\oplus \quad \text{queuing delay} \\
\hline \\
= \quad \text{total delay}
\end{align*}
\]
Overall, the main culprits for the overall delay are the transmission, propagation and queuing delays tend to be tiny
The transmission delay is the amount of time required to push all of the bits onto the link.

Transmission delay = \( \frac{\text{packet size}}{\text{link bandwidth}} \) [sec]

Example:

\[ \frac{1000 \text{ bits}}{100 \text{ Gbps}} = 10 \text{ ns} \]
The propagation delay is the amount of time required for a bit to travel to the end of the link.

\[
\text{Propagation delay} = \frac{\text{link length}}{\text{propagation speed}} \quad \text{[sec]}
\]

\[
\frac{30\,000\,\text{m}}{2 \times 10^8\,\text{m/sec}} = 150\,\mu\text{sec}
\]

Example:

- Link length: 30,000 m
- Propagation speed: \(2 \times 10^8\,\text{m/sec}\) (speed of light in fiber)
How long does it take for a packet to travel from A to B? (not considering queuing for now)
How long does it take to exchange 100 Bytes packet?

- Time to transmit one bit = $10^{-6}$s
- Time to transmit 800 bits = $800 \times 10^{-6}$s
- Time when that bit reaches B: $10^{-6} + 10^{-3}$s
- The last bit reaches B at $(800 \times 10^{-6}) + 10^{-3}$s = 1.8ms
If we have a 1 Gbps link, the total time decreases to 1.0008 ms.
If we now exchange a 1GB file split in 100B packets

The last bit reaches B at:

\[
\begin{align*}
(10^7 \times 800 \times 10^{-9}) + 10^{-3}s \\
= 8001ms
\end{align*}
\]
Different transmission characteristics imply different tradeoffs in terms of which delay dominates

In the Internet, we *can’t know* in advance which one matters!

<table>
<thead>
<tr>
<th>Data Size</th>
<th>Packet Size</th>
<th>Link Speed</th>
<th>Delay Dominance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^7 \times 100$ B</td>
<td>pkt</td>
<td>1Gbps link</td>
<td>transmission delay dominates</td>
</tr>
<tr>
<td>1x100B</td>
<td>pkt</td>
<td>1Gbps link</td>
<td>propagation delay dominates</td>
</tr>
<tr>
<td>1x100B</td>
<td>pkt</td>
<td>1Mbps link</td>
<td>both matter</td>
</tr>
</tbody>
</table>
The queuing delay is the amount of time a packet waits (in a buffer) to be transmitted on a link.

Queuing delay is the hardest to evaluate as it varies from packet to packet.

It is characterized with statistical measures, e.g., average delay & variance, probability of exceeding $x$. 
Queuing delay depends on the traffic pattern
Queuing delay depends on the traffic pattern.

Transient overload!
Transient overload!
Queues absorb transient bursts, but introduce queueing delays.
The time a packet has to sit in a buffer before being processed depends on the traffic pattern.

Queueing delay depends on:

- arrival rate at the queue
- transmission rate of the outgoing link
- traffic burstiness
average packet arrival rate \( a \) [packet/sec]

transmission rate of outgoing link \( R \) [bit/sec]

fixed packets length \( L \) [bit]

average bits arrival rate \( La \) [bit/sec]

traffic intensity \( La/R \)
When the traffic intensity is $>1$, the queue will increase without bound, and so does the queuing delay.

**Golden rule**

Design your queuing system, so that it operates far from that point.
When the **traffic intensity is \(\leq 1\)**, queueing delay depends on the burst size.
A network *connection* is characterized by its delay, loss rate and throughput.
In practice, queues are not infinite. There is an upper bound on queuing delay.

\[
\text{queuing delay upper bound: } N \times \frac{L}{R}
\]
If the queue is persistently overloaded, it will eventually drop packets (loss)
A network *connection* is characterized by its delay, loss rate and throughput.
The throughput is the instantaneous rate at which a host receives data

\[
\text{Average throughput} = \frac{\text{data size}}{\text{transfer time}} \quad \text{[#bits/sec]}
\]
To compute throughput, one has to consider the bottleneck link.

Average throughput

\[ \text{Average throughput} = \min(R_S, R_L) \]

= transmission rate of the bottleneck link
To compute throughput, one has to consider the bottleneck link… and the intervening traffic.

If $4 \times \min(R_S, R_L) > R$, the bottleneck is now in the core, providing each download $R/4$ of throughput.
A network *connection* is characterized by its delay, loss rate and throughput.
As technology improves, throughput increases and delays are getting lower except for propagation (speed of light).

source: ciena.com
Because of propagation delays, Content Delivery Networks move content closer to you.
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Materials inspired from Scott Shenker & Jennifer Rexford