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?

The Internet should allow processes on different hosts to exchange data. Everything else is just commentary...

http://www.opte.org

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.

In practice, there exists a lot of network protocols. How does the Internet organize this?

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

To provide structure to the design of network protocols, network designers organize protocols in layers.

Photo: Donna Coveney

Modularity, based on abstraction, is the way things get done.

— Barbara Liskov, MIT
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 in 5 independent layers (or 7 layers for the OSI model):

<table>
<thead>
<tr>
<th>Layer</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5 Application</td>
<td>Network access</td>
</tr>
<tr>
<td>L4 Transport</td>
<td>End-to-end delivery (reliable or not)</td>
</tr>
<tr>
<td>L3 Network</td>
<td>Global best-effort delivery</td>
</tr>
<tr>
<td>L2 Link</td>
<td>Local best-effort delivery</td>
</tr>
<tr>
<td>L1 Physical</td>
<td>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>
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</tr>
</thead>
<tbody>
<tr>
<td>L5 Application</td>
<td>Exchanges messages between processes</td>
</tr>
<tr>
<td>L4 Transport</td>
<td>Transports segments between end systems</td>
</tr>
<tr>
<td>L3 Network</td>
<td>Moves packets around the network</td>
</tr>
<tr>
<td>L2 Link</td>
<td>Moves frames across a link</td>
</tr>
<tr>
<td>L1 Physical</td>
<td>Moves bits across a physical medium</td>
</tr>
</tbody>
</table>

The Internet Protocol (IP) acts as an unifying, network layer:

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<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, Wi-Fi, (A/V)DSL, Cable, LTE, ...</td>
</tr>
<tr>
<td>L1 Physical</td>
<td>Twisted pair, fiber, coaxial cable, ...</td>
</tr>
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</table>

Each layer is implemented with different protocols and technologies:

<table>
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Each layer takes messages from the layer above, and *encapsulates* with its own header and/or trailer.

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

| Application | HTTP(S) | | HTTP(S) |
| Transport | TCP/UDP | | TCP/UDP |
| Network | IP | switch | IP |
| Link | Ethernet | | Ethernet |

Let’s see how it looks like in practice **on a host**, using Wireshark  
[https://www.wireshark.org](https://www.wireshark.org)

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**How do we characterize it?**

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?

Each packet suffers from several types of delays at *each node* along the path

- transmission delay  
- propagation delay  
- processing delay  
- queuing delay

\[
\text{total delay} = \text{due to link properties} + \text{due to traffic mix & switch internals}
\]

The main culprits for the overall delay are the transmission, propagation and queuing delays

- transmission delay  
- propagation delay  
- processing delay  
- queuing delay

\[
\text{total delay} = \text{due to link properties} + \text{due to traffic mix & switch internals}
\]

- **transmission** delay  
- **propagation** delay  
- **processing** delay  
- **queuing** delay  
- **total delay**
The transmission delay is the amount of time required to push all of the bits onto the link.

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

Example:
- 1000 bits
- 100 Gbps
- 10 ms

The propagation delay is the amount of time required for a bit to travel to the end of the link.

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

Example:
- 30,000 m
- \(2 \times 10^8\) m/sec (speed of light in fiber)
- 150 \(\mu\)sec

How long does it take for a packet to travel from A to B? (not considering queuing for now)

If we have a 1 Gbps link, the total time decreases to 1.0008 ms.

If we now exchange a 1 GB file split in 100B packets:

The queuing delay is the amount of time a packet waits (in a buffer) to be transmitted on a link.

Different transmission characteristics imply different tradeoffs in terms of which delay dominates:

- \(10^9\) x 100B pkt 1 Gbps link: transmission delay dominates
- 1 x 100B pkt 1 Gbps link: propagation delay dominates
- 1 x 100B pkt 1 Mbps link: both matter

In the Internet, we can’t know in advance which one matters!
Queuing delay depends on the traffic pattern

![Diagram showing queuing delay]

No overload

![Diagram showing no overload]

Transient overload!

![Diagram showing transient overload]

Queue

Queues absorb transient bursts, but introduce queueing delays

![Diagram showing queue absorption and delay]
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

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.

A network connection is characterized by its delay, loss rate and throughput.

If the queue is persistently overloaded, it will eventually drop packets (loss).

In practice, queues are not infinite. There is an upper bound on queuing delay.

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...

\[
\text{Average throughput} = \min(R_S, R_L) \quad \text{transmission rate of the bottleneck link}
\]

A network connection is characterized by its delay, loss rate and throughput

As technology improves, throughput increase & delays are getting lower except for propagation (speed of light)

Because of propagation delays, Content Delivery Networks move content closer to you

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