Lugging a torrent of bits
From here to there
And through thin air

With fidelity ... for an error
begs a retransmission and then another

What's done to a bit, is done to the next
Be it a blockchain or a simple text

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Frequently asked questions from the previous class survey

- Do sockets act like threads to take bytes from stream?
- How are regular sockets created?
- Ports vs sockets?
- Number of connections:
  - Connection is refused when the number of connections exceeds threshold
- Do we use serverSocket and sockets for our peer-to-peer assignment?
- Several on port numbers, why the limit, MapReduce/Spark, BitCoin
  - Please hold on ... we will get there
Topics covered in this lecture

- Encoding
- Bandwidth and Latency
- Multiplexing
- Network Architecture
- Encapsulation

Communications & Networking:
Topics that we will cover

- Data transmission
- Switched Networks
- Bandwidth and Latency
- Multiplexing
- Internet Architecture
- IP routing
- The TCP and UDP protocols
Communications & Networking
{How data is sent}

How is the data sent?

- Are we sending 1’s and 0’s?
- Whatever the physical medium, we use signals
  - Electromagnetic waves traveling at the speed of light
  - Speed of light is different in different mediums
Components of encoding binary data in a signal

- Modulation
- Duplexity

Encoding binary data: Modulation

- Objective is to send a pair of distinguishable signals
- Vary frequency, amplitude, or phase of the signal to transmit information
  - E.g. vary the power (amplitude) of signal
  - $x(t) = A \sin(2\pi ft + \theta)$
Encoding binary data: Duplexity

- How many bit streams can be encoded on a link at a time?
  - If it is one: nodes must share access to link

- Can data flow in both directions at the same time?
  - Yes → full-duplex
  - No → half-duplex

For our purposes, let’s ignore details of modulation

- Assume we are working with two signals
  - High and low

- In practice:
  - Different voltages on a copper-based link
  - Different power-levels on an optical link
Let’s do the obvious thing

- Map 1 to a high signal
- Map 0 to a low signal

Non-return to zero (NRZ)
Problems with NRZ because of consecutive 1’s and 0’s: **BASELINE WANDER**

- Receiver keeps *average* of the signal seen so far
- Average is used to *distinguish* between low and high
- Lots of consecutive 1/0’s will make it difficult to detect a significant change

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Problems with NRZ because of consecutive 1’s and 0’s: **CLOCK RECOVERY**

- Every clock cycle, sender transmits and the receiver receives
- Sender and receiver’s clocks must be perfectly *synchronized*
  - Otherwise, it is not possible to decode the signal
Manchester encoding

- 0 is a low-to-high transition
- 1 is a high-to-low transition

Manchester encoding and NRZ

```
NRZ
0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0
```

Manchester Encoding
Some more about Manchester encoding

- Doubles the rate at which signal transitions are made on the link
  - Receiver has ½ the time to detect each pulse
- Rate of signal changes: baud rate
- Bit rate is ½ the baud rate
  - Encoding is considered 50% efficient

NRZI (Non return to zero inverted)

- Make a transition from current signal to encode a 1
  - *Stay* at current signal to encode a 0
- Solves the problem of consecutive 1’s
  - But does nothing for consecutive 0’s
4B/5B encoding

- Attempts to address inefficiencies in Manchester encoding
  - Without suffering from problems due to extended high/low signals
- The crux here is to insert extra bits into bitstream
  - Breakup long sequences of 1s or 0s
  - 4 bits of actual data encoded in a 5-bit code
  - 5-bit codes are carefully selected
    - No more than 1 leading 0 & no more than 2 trailing 0s

<table>
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<th>5B</th>
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<td>0000</td>
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<td>0001</td>
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<tr>
<td>1111</td>
<td>11101</td>
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</table>
4B/5B: Rules for the conversion of 4-bit codes to 5-bit codes

- Objective is to ensure that in each translation there is:
  - No more than one leading 0
  - No more than two trailing 0's
  - When sent back-to-back:
    - No pair of 5-bit codes results in more than 3 consecutive 0's being transmitted

- 5-bit codes are transmitted using NRZI
  - This is why they are so concerned with consecutive 0's

Networking: Expectations and Links
Expectations that we have of a network

- Application **programmer**
  - Error-free and timely delivery of messages

- Network **designer**
  - Cost effective design
  - Effective and fair allocation of resources

- Network **provider**
  - Easy to administer and manage
  - Isolate faults and account for usage

A network must provide connectivity among a set of computers

Physical medium: Link

Nodes

Multiple-access
Multiple access links are limited in size

- Geographical distances that can be covered
- Number of nodes that can be connected

Connectivity between nodes need not imply a direct physical connection. Otherwise …

- Networks would be very limited in the number of nodes they could connect
- Number of wires out the back of a node
  - Unmanageable
  - Very expensive
Switched networks: Indirect connectivity among cooperating nodes

- Nodes with at least two links
  - Run software that forwards data on one link out on another

- Types
  - Circuit switched
  - Packet switched
Switched networks: Circuit switched networks

- Establish a **dedicated** circuit
  - Across a set of links
  - No one else can use this till termination

- Allows source to send a stream of bits
  - **Across circuit** to the destination node

- Employed by the telephone system
  - Also known as POTS (Plain Old Telephone System)

Switched networks: Packet switched networks

- Nodes in the network send **discrete** data blocks to each other

- Use **store-and-forward**
  1. Receive complete packet over some link
  2. Store packet in internal memory
  3. Forward complete packet to another node

- Used by the **overwhelming majority** of computer networks
Interconnection of networks

Router/Gateway forwards messages between networks

Addressing: A node must be able to say which nodes it wishes to communicate with

- Assign an address (byte string) to each node
  - Distinguish node from other nodes in the network
- Source specifies address of the destination node
- Switches and routers use address to forward messages towards the destination node
  - Routing
Cost effective resource sharing

How do all hosts that want to communicate share the network ...

- At the same time?
- How about sharing links?
  - Hosts want to use it at the same time

- Multiplexing ...
  - Analogy: Sharing CPU among multiple processes
Data sent by multiple users can be multiplexed over the physical links

Multiplexing data onto a physical link

- Synchronous time division multiplexing (STDM)
  - Divide time into quanta
  - Assign quanta in round-robin fashion

- Frequency division multiplexing (FDM)
  - Transit data flows at different frequencies
Problems with STDM and FDM

- {Problem-1} **Limited** to specific situations
  - Max number of flows is **fixed**
  - Known **ahead** of time

- {Problem-2} If one of the flows does not have data?
  - Its share of the physical link remains **idle**

- In computer communications:
  1. Amount of time a link is idle can be very large
  2. Data flows are fluid

Statistical multiplexing

- Physical link is shared over time

- Data is transmitted from each flow **on demand**
  - Not a predetermined slot
  - When there is only one flow?
    - **No need to wait** for quantum to come around
Limiting transmissions so that other flows can have a turn

- Upper bound on **size** of data block that each flow is allowed to transmit
  - Packet

- Larger application messages
  - Fragmented into several packets
  - Receiver reassembles these

- Each flow sends packets over the link
  - Decision made on a **packet-by-packet basis**

Multiplexing packets from multiple sources onto a shared link
Deciding which packet to send over a shared link

- In some cases, decision is made by switches
- Service packets using
  - FIFO
  - Round robin
    - Ensure flows receive a certain share of the bandwidth
    - Maximum threshold for delays for certain packets
- Networks that allow special treatment of flows
  - Quality of Service

Bandwidth and Latency
Network performance is measured in two fundamental ways

- **Bandwidth**
  - Number of bits transmitted over the network in a given time (e.g., 10 million bits per second; 10 Mbps)
  - Also called *throughput*

- **Latency**
  - How long it takes for a message to go from one end of the network to another?

Components of latency

- **Speed-of-light propagation delay**
  - $3 \times 10^8$ m/sec in vacuum
  - $2.3 \times 10^8$ m/sec in cable

- **Amount of time to transmit** a unit of data

- **Queuing delays**
The Delay x Bandwidth product

The product gives us information about *how many bits fit* in the pipe.

- Transcontinental channel:
  - 50 ms one-way latency
  - Bandwidth: 45 Mbps
  - Can hold: \(50 \times 10^{-3} \text{ seconds} \times 45 \times 10^6 \text{ bits/second}\)
    - \(2.25 \times 10^6 \text{ bits} = 280 \text{ KB}\)
The Delay x Bandwidth product

- Corresponds to how many bits the sender must send
  - Before first bit arrives at the receiver
- Bits in the pipe are said to be in flight

Bandwidth and latency improvements are not in lockstep

- Over past 35-40 years approximately
  - Bandwidth improvements: 220-1200 times
  - Latency improvements: 4-20 times
- Ethernet 802.3 (1978)
  - 10 Mbps
  - Latency 3 millisecond
- Ethernet 802.3ae (2003)
  - 10,000 Mbps (1000 times)
  - Latency 0.19 millisecond (15 times)
What does not change as the bandwidth increases?

- Speed of light

- High-speed does not mean that latency improves at the same rate as bandwidth
  - Transcontinental delays of 100 ms for
    - 1-Mbps/1-Gbps link

Sending 1 MB data over a cross country link. Delay 100 ms

- 1 Mbps link
  - Pipe: $100 \times 10^{-3} \times 10^6 = 100 \text{ Kb} = 0.1 \text{ Mb}$
  - So you need 80 pipes to transmit 1 MB
    - $8 \text{ Mb}/0.1 \text{ Mb} = 80$

- 1 Gbps
  - Pipe: $100 \times 10^{-3} \times 10^9 = 100 \text{ Mb}$
  - So you need $8 \text{ Mb}/100 \text{ Mb} = \text{approx} \ 1/12$th of the pipe is utilized
More accurate to think of network as allowing applications to communicate

- When 2 applications need to communicate
  - Lot of things need to happen
  - Beyond just sending messages between the hosts

- Build all functionality into each app?

- Identify and build right set of common services
  - Hide complexity without constraining functionality
Processes communicating over an abstract channel

Guarantees provisioned in the channel

- Guaranteed delivery?
- Ordered delivery?
- Thwart eavesdropping?
Not just *which* functionality, but _where_ they will be provided

- View network as a **bit pipe**
  - High-level communication semantics provided by end hosts
  - Keeps switches in the middle _very simple_

- Alternative: Push functionality **onto** switches
  - End hosts are dumb devices
    - Telephones

Mask failures so that the network appears more reliable than it really is

- Bit errors
- Burst errors: Consecutive bits are corrupted
- Packet failures
  - Discarded because the switch buffer is full
    - **Congested**
  - Routing mistakes
- Node and link failures
  - Route around failed nodes and links
All communications in distributed systems based on sending/receiving messages

- **No shared memory**

- Sending message from A to B
  - Build message in A’s address space
  - Send message over the network
  - Reconstruct message at B
But A and B must agree on the meaning of the bits

- Signaling 1's and 0's
- What is the last bit of the message?
- Detect if the message is lost or damaged
  - Respond to problems
- Representation of data types

Layering and Protocols

- Start with services provided by hardware
- Add a sequence of layers
  - Each providing higher level of service
- Services at higher layers implemented in terms of lower layers
Advantages of layering

- Decomposes problem into **manageable** components
- Provides **modular** design
  - Adding functionality may result only in minor modifications

Advantages of layering

- Each layer can be changed **independently** of the other
  - Change as technology improves
Layered Architectures: Requests go down the hierarchy; results flow upward

Layer N

Layer N - 1

Layer 2

Layer 1

Component at layer \( L_i \) can call components at layer \( L_{i-1} \)

Request flow

Response flow

Example of a layered network system

- Application programs
- Process-to-process channels
- Host-to-Host connectivity
- Hardware
Layered system with alternative abstractions at a given layer

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<td>Hardware</td>
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Abstract objects that comprise layers of a network system are called **protocols**

- Provides a **service interface** to other objects on the same computer
  - Wishing to use its communication services
- Defines the **form** and **meaning of messages** exchanged by protocol peers
- Protocol also refers to modules that implement a specification
The contents of this slide-set are based on the following references