Lecture 14: Communication of information

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TUESDAY, MARCH 5, 2019
A big cell tower such as that pictured above is a critical element of modern communication infrastructure, as it connects nearby cellular phones with the “backbone” telephone and data networks.
Communication networks

A wide array of communication networks are used to distribute information among users, over a range of distances:

Wired: public switched telephone network, internet fiber network, undersea cables connecting islands and continents

Wireless: WiFi, cellular communications, packet radio networks, broadcast radio, TV, maritime and aviation radio, satellite communications
  ◦ China even put up a satellite so people can talk to the dark side of the moon...
  ◦ “Organic” wireless communications can be performed with pigeons (https://en.wikipedia.org/wiki/IP_over_Avian_Carriers)

Image credit: NASA/GSFC/Arizona State University
Communication networks

A communication network consists of a set of physical devices interacting through a medium or channel. These devices go through a series of operations to prepare and transmit information on one end and receive and process the information on the other.

- The process of preparing a message to transmit is called encoding.
- The process of recovering a message from received coded bits is called decoding.

Such processing/coding can be used for data compression, encryption, error correction, multiple access communication, and other important tasks.
Communication networks

Of course, communication networks are more than a single link or connection. Much of the sophistication of modern networks deals with efficiently managing multiple connections or links simultaneously.

Some considerations at a network level include:
- Quality of service
- Network utilization (e.g., load balancing)
- Traffic priorities
- Security and privacy (and robustness to network attacks like DOS)
- ...

Image credit: Wikipedia/user:SilverStar
Communications limitations

For a given link or connection, multiple factors limit the flow of information:

- Delay in information reception (*latency*)
- Spectral range of channel (*bandwidth*)
- Corruption by outside sources (*noise*)

Consider the following analogy of water flowing through a pipe:

- The latency is the length of the pipe. The longer the pipe, the longer it takes for water to travel from one end to the other. But, once it gets there, it continues to flow.
- The bandwidth is the diameter of the pipe. The bigger the pipe is, the more water we can push through at once.
- Noise are like little holes or leaks in the pipe. Some of the water leaks out before reaching the end.
More about latency

Latency is time lag, or time delay.

Suppose a message is transmitted at $t = 0$
- When is it received? Delay = latency
- Remember: velocity = distance/time, so time = distance/velocity.
- We’re usually talking about EM waves with velocity = speed of light $c$ (recall: what is $c$?)

**Example:** iPhone conversation between Washington DC and Tokyo.
- Cable at ground level: $d = 11,000$ km
  - Assume $v = c = 3 \times 10^5$ km/s
  - $t = \frac{(11,000 \text{ km})}{(3 \times 10^5 \text{ km/s})} \approx 36$ ms
- Link through geosynchronous satellite: $d = 76,000$ km (why so much bigger?)
  - $t = 255$ ms

These are one-way delay figures. For a real conversation, we have to wait for the reply as well.
Latency of materials

In real channels, the latency often depends on the channel medium. For instance, light propagates slightly slower through air than in a vacuum.

General types of channels:

- Free space (air/vacuum): Shared channel may contain many signals and sources of noise; need to transmit/receive using antenna structures; the signal radiates causing its power to decrease according to the inverse square law with regard to distance: power $\sim 1/r^2$
- Wires: Not effective over long distances due to costs and power loss; can be shielded against interference; very cheap interface for transmitter/receiver
- Glass/fiber: Can transmit optical signal with less loss over long distances; can be shielded against interference; can be expensive to deploy (just ask Google!)
Latency of materials

Speed of light in a vacuum:

- Permeability \( \mu_0 = 1.26 \times 10^{-8} \frac{Wb}{A \cdot cm} \)
- Permittivity \( \varepsilon_0 = 8.85 \times 10^{-14} \frac{F}{cm} \)
- Speed of light is \( c_0 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^{10} \frac{cm}{s} \)

When light is not in a vacuum, \( \varepsilon = \kappa \varepsilon_0 \), where kappa is the dielectric constant of the material.

- Air has a dielectric constant of close to 1
- SiO\(_2\) has a constant of 3.8; fiberglass has a constant between 4.1 to 7.2
- Water has a constant of 80

Then, \( c = \frac{1}{\sqrt{\mu_0 \kappa \varepsilon_0}} = \frac{c_0}{\sqrt{\kappa}} \)
Latency of materials

This latency also affects the efficiency of electronic circuits, since the signal takes time to propagate along the pathways in a chip. For instance, in an integrated circuit with SiO2,

- The speed of light is \( c = \frac{c_0}{\sqrt{k}} = 0.51c_0 \).
- If a processor has a clock speed of 3 GHz, then each clock cycle between instructions is 33 ns apart. In this period of time, a signal can travel at most 5 cm. Electrons are much slower than light, so the signal will actually travel even less distance.

This also has implications for conventional spinning-disk hard drives, and the latency of hard drives was a major factor in the overall performance of conventional computers until the advent of solid state storage. Imagine if iPhones had to rely on spinning disk hard drives!
Bandwidth and the channel

Recall: bandwidth is the highest frequency in the spectrum of a bandlimited analog signal. It represents the range of frequencies characterizing the signal.

We can also characterize a channel or medium according to the usable frequency spectrum available for communication. This is the channel bandwidth.

- Most communication channels can be modeled as a linear, time invariant system. We already observed that linear, time invariant systems can be described in terms of a frequency response or spectrum.
- The characteristic range of frequencies depends highly on the medium and the presence of interference. Although a channel frequency response can vary a bit over time, it usually does so slowly enough to make estimation of the channel frequency response useful in many applications.
Bandwidth and the channel

If we transmit outside the channel's permissible frequency range, we essentially filter our signal. What does this filter do to the information present?
Bandwidth and the channel

Frequently, a signal will not use the entire frequency range or channel bandwidth. Instead, especially in wireless communications, where the channel is a shared resource, the channel bandwidth will be divided and assigned to different users. Certain parts may even be divided further and reallocated over time according to demand.

The FCC regulates bandwidth assignments over free space communications. These spectrum licenses are incredibly expensive, with Verizon and AT&T spending over $16 billion in 2008 on 700 MHz spectrum auctioned for use in 4G communications. Spectrum made available for 5G communications will be auctioned using a similar process.
Noise in the channel

In addition to the time delay and bandwidth considerations, we must account for noise or interference that would appear in the received signal.

Noise comes from many sources:
- Power lines (hum)
- Motors and electrical appliances (radiating EM waves)
- Fluorescent lights
- Radio, TV, radar transmitters
- Computers, monitors, printers
- Other cell phones, cordless phones
Noise in the signal

What does noise look like? Usually, some kind of random perturbation of the underlying signal:

Note: noise is usually reserved for *random* phenomena, not deterministic changes in the signal.
Noise distributions

Noise is random, so we can't predict it (deterministically). But we can make statistical observations.

So far, we have mainly talked about probabilities for discrete random variable, and discrete probability distributions. But noise takes values from a continuous set, for example the set of real numbers. The noise probabilities are represented by their cumulative distribution function (cdf):

\[ F_N(n) = P(N \leq n) \]

If we compute the derivative of this cumulative distribution function, we get a nonnegative function called the probability density function, or pdf. The height of this function \( f_n(n) \) is the derivative of the cdf, and is proportional to relatively how likely values are close to \( n \).

- The most common noise distribution is called the Normal or Gaussian distribution. The distribution is centered around its mean \( \mu \) and has a spread determined by its standard deviation \( \sigma \). The cdf does not have a closed form, but the pdf does:

\[
 f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad \text{pdf is valid over the entire real line.} 
\]
Normal distribution

The Normal distribution has many powerful properties.

If we add two Normal random variables, we get another Normal random variable.

- So if our source is also Normal distributed, then the received result will be Normal as well.

If we have lots of data, statistics tend towards that of a normal distribution.
Expected values

Recall: for discrete distributions, the expected value or mean is the weighted average

\[ E_X\{x\} = \sum_x x \ p(x) \]

The variance and other expectations can be computed similarly. The notion of expected value also extends to continuous random variables. Here, we replace the sum with an integral:

\[ E_X\{x\} = \int x \ f_X(x) \ dx \]

Thus, the probability density function serves a similar purpose for continuous random variables as the probability mass function does for discrete random variables.

We won’t worry too much about computing these integrals except maybe in very simple cases; the Normal distribution parameters give us the mean and variance directly.
Signal and noise power

Given the mean and variance of a noise or signal source, we can compute its power statistically:

\[
\text{Power} = (\text{Mean})^2 + \text{Variance}
\]

In practice, we can estimate the average power of a given signal by adding up the squared magnitudes of the signal values:

\[
\text{Power} = \frac{1}{N} \sum_{n=1}^{N} |x[n]|^2
\]

We can also talk about power at a given frequency range by measuring the squared magnitude frequency spectrum of the signal:

\[
\text{Power}(f) \propto |X(f)|^2
\]

- Note: there are some scaling constants here. To learn more, take digital signal processing (ECE 4750).
Signal to noise ratio

Given estimates for the input signal and noise power, we can measure the signal-to-noise ratio of the received signal combining these two:

\[ SNR = \frac{\text{signal power}}{\text{noise power}} \]

For instance, if our signal has amplitude \( A \), its power is \( A^2 \). If our noise has zero mean and variance \( \sigma^2 \), then its power is also \( \sigma^2 \). The SNR for this setting is then \( (A/\sigma)^2 \).

Generally, the lower our SNR, the more random perturbations in our received signal, and the less information is preserved. We will make this more precise later in this lecture.
If higher SNR is better, how do we increase it?

- Boost signal level (increase $A$)
- Decrease noise level (decrease $\sigma$)

A more powerful transmitter can boost the signal (i.e., an amplifier). Being located closer to the source also can help (especially with inverse square law for wireless radiation).

Improving the shielding or filtering processing can reduce the noise level, but it can be difficult to shield wireless transmissions from noise or interference, especially in free space.

- Intelligent coding can also help; one approach is called signal differencing.
Signal differencing

Consider noise $n(t)$ adding to a transmitted analog wave $s(t)$ to produce $y(t) = s(t) + n(t)$.

We observe the noise level is substantial. In signal differencing, we instead construct an inverted version of $s(t)$, and transmit both $s(t)/2$ and $-s(t)/2$. Each will be corrupted by noise $n(t)$, which allows us to take the difference between the two received signals to recover $s(t)$:

- Observe: $(s(t)/2 + n(t)) - (-s(t)/2 + n(t)) = s(t)$
Signal differencing

What does this method rely upon?
When would the noise added be the same?

Ways to ensure similar noise sources:
◦ Twisted-pair cabling – this is what is used in ethernet cable
◦ Multiple antennas – transmit/receive simultaneously
Signal to noise ratio

SNR is usually represented in decibels (dB), a logarithmic scale:

\[ SNR \ (dB) = 10 \log_{10}(SNR) \]

For example:

<table>
<thead>
<tr>
<th>SNR</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-20 dB</td>
</tr>
<tr>
<td>1</td>
<td>0 dB</td>
</tr>
<tr>
<td>2</td>
<td>3 dB (classic in engineering)</td>
</tr>
<tr>
<td>10</td>
<td>10 dB</td>
</tr>
<tr>
<td>1000</td>
<td>30 dB</td>
</tr>
</tbody>
</table>
Noise and digital signals

As noise increases, the effects on a digital signal become more significant:

**Effect of increasing noise**

![Graphs showing effect of increasing noise](image-url)
Noise and digital signals

Normally, if we sample and threshold the values to the closed quantized bit, we can reduce the noise effect significantly:

Sampling + Thresholding restores original data
Noise and digital signals

The probability of the threshold producing an error increases slowly at low SNR:
Back to channel capacity

We showed that mutual information leads to an expression for capacity, or maximum information transmission, along a channel with a certain error probability:

$$C = 1 - H_b(e) = 1 + e \log e + (1 - e) \log(1 - e)$$
Shannon-Hartley Law

When communicating over a channel, the channel capacity is the maximum rate of information:

**Fundamental Tenet V:**

Given a channel with bandwidth $B$ and signal-to-noise ratio $S/N$, the channel capacity $C$ is

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

This is called the Shannon-Hartley Law and describes an upper limit on information transmission as a function of bandwidth and noise limitations. It does not account for latency.
Announcements

Next time: Review of vectors and matrices