Introduction to Communications

Communication System: Transfers info from a source to a destination through a transmission medium (channel)

Example: Telephone System

You talking → telephone → telephone network → telephone → Your buddy listening

We are interested in those communication systems that utilize electromagnetic (EM) signals as the means of conveying info.

Q: The question we will address (very briefly) in this course is "how to design the Tx & Rx so that we can convey info efficiently through a channel?"
To preview the "answer" to the question, let's look at the simplest possible comm. system (if interest):

Eg: The Tx is connected directly to the Rx and the whole circuit is submerged in liquid helium!

In this case, we can assume that the channel does nothing to the signal from the Tx and hence the Rx sees exactly the same signal.

Q: The next question to ask is what kind of info we'd like to convey through this comm. system?

A: There are basically 2 types of info:

1. Analogy info: e.g. voice
2. Digital info: e.g. a stream of bits with values "0" or "1"

Q: So how should we send these two types of info from the Tx to the Rx by means of EM signals (we only electric signal for simplicity)?

A: 1. Analogy info:
   
   (i) convert analogy info to electrical signal and Tx sends the signal to Rx → Analog communications
   
   e.g. Telephone handset converts voice to voltage signal
Analog info (cont.)

(iii) "digitize" analog info into digital info, then....
I will talk about this process later.

2. Digital info

Represent "0" by a voltage pulse and "1" by another voltage pulse.
Tx sends a sequence of pulses to convey a stream of bits.
Rx maps seq. of pulses back to bit stream.
This method is usually called line coding.
The resulting system is called a digital communication system.

Summary:

- Analog communications - convey analog info
- Digital communications - convey digital info (or digitized analog info)
- We're interesting mainly in digital comm.
- Some commonly used line coding techniques
  are given on the following page.
Typical Communication Channels (Media)

1) Twisted Pairs
   - Two copper wires twisted together with external sheathing (non-metallic).
   - Mostly used in lower frequency (e.g. telephone) communication systems, e.g. POTS, DSL, etc.
   - Poor high freq. response due to skin effect.
   - Suffer from cross-talk and external interference.
   - Termination & bridges cause echoes (multipaths) due to reflection of electrical signal.

2) Coaxial Cables
   - An inner wire shielded by a concentric conductor ring.
   - Work for higher frequencies.
   - Immunity to cross-talk & interference because of the shielding effect of external conductor ring.
   - Used in TV, measurement equipments and etc.
   - Provides higher data rates than the twisted pairs.
3. **Atmosphere**

- Radiate EM waves through atmosphere using antennas.
- To efficiently radiate energy, antennas need to be at least a fraction of wavelength in size. This is only practical when freq. high enough.
  
  e.g.) at 30 MHz, \( \lambda = 10 \text{m} \)
  
  at 300 MHz, \( \lambda = 1 \text{m} \)
  
  at 3 GHz, \( \lambda = 0.1 \text{m} \)

- Different modes of transmission depending on freq. (wavelength)

**Diagram:**

- Ionosphere
- Sky waves
- Tropospheric wave
- Direct wave
- Reflected wave
- Transmitter antenna
- Receiving antenna

**VLF - Atmosphere & earth act as waveguide**
**LF - Surface wave, earth as transmission line**
**HF, VHF - Sky waves**

**VHF and higher - direct wave (tropospheric wave sometimes) (Direct line of sight)**
- Power radiated from a Tx antenna and a Rx antenna picks up signal. Power loss resisted because of isotropic radiation.

\[ P_{\text{Rx}} = \frac{G_r G_t}{L} P_{\text{Tx}} \]

where \( P_{\text{Rx}} \) & \( P_{\text{Tx}} \) are the transmit & receive powers,
\( g_r \) & \( g_t \) are the antenna gains of transmit & receive antennas
\( \frac{4 \pi A e^2}{\lambda^2} \)
\( L = \left( \frac{4 \pi d}{\lambda} \right)^2 \)
\( \text{Distance between Tx & Rx} \)

i.e., path loss is inversely proportional to distance square
- As a result, may need repeaters for longer-haul transmission.

4) Optic fibers
- Thin glass (pure) core surrounded by thicker layer cladding with different refractive index.
- Operate at optical freq.
- Can provide tera-bit data rates
- Used in Internet backbone
Baseband vs. Carrier Communications.

As discussed before, some comm. channels act like low-pass filters and some other act like bandpass filters.
To design a comm. system over a specific comm. channel, we need to take into account the characteristics of the channel.

For a low-pass channel like those in twisted pairs and coaxial cables, we can directly send the information-bearing signal (EM wave) to the channel. This form of comm. is called baseband communication.

For a bandpass channel, like the atmosphere and optic fiber, if we send the lowpass info-bearing signal directly to the channel, most of the signal energy will be filtered out by the channel.

The usual way to solve this problem is to "mix" the lowpass info-bearing signal up to the operating freq. of the channel. The "mixing" operation is performed by multiplying the info-bearing signal with a sinusoidal signal at the operating freq. of the channel.
To understand the mixing operation, we can employ the freq. shift property of Fourier Transform:

\[ g(t) \cos(wc t + \theta) \overset{F}{\to} \frac{1}{2} \left[ G_I(w-w_c)e^{j\theta} + G_I(w+w_c)e^{-j\theta} \right] \]

where \( g(t) \leftrightarrow G(w) \)
\( wc = 2\pi fc \) is the angular freq. of the sinusoid in radians. \((fc \text{ is the freq. in Hz})\).
\( \theta \) is the phase of sinusoid.

Pictorially, we have in time domain

\[ g(t) \cos(wc t + \theta) \]

In freq. domain

\[ \mid F(g(t) \cos(wc t + \theta)) \mid \]

So multiplying the info-bearing signal by a sinusoid of freq. \( fc \) effectively shifts the freq. components of the signal to the freq. \( fc \). Now we can pass the resulting BP signal (product of info-bearing signal & sinusoid) to channel.
Terminology:
(i) The sinusoid in the mixing operation is usually called the carrier and its freq is hence called the carrier freq.

(ii) As a result, this form of comm. is called carrier communication.

(iii) The mixing process is sometimes called modulation and the resulting signal is called the modulated signal.

In addition to matching to the operating freq. of the channel, mixing (modulation) can be employed to let multiple transmitters to share the use of the channel simultaneously by mixing different info-bearing signals to different freqs so that the freq components from different signals do not overlap. This approach is called freq-division multiplexing (FDM) and is used in many applications, such as radio and TV broadcasting, cell phone systems, etc.

Question: How to convert the modulated signal at the receiver back to the original info-bearing signal?
Channel Distortions

Not only do most comm. channels act as LP or BP filters, they also introduce distortions to the transmitted signals via many different physical mechanisms. Moreover, the non-ideal nature of the transmitter & receiver circuitry can also introduce noises and distortions to the transmitted signal.

Before we study some of these distortions & noises, let's investigate the condition of the channel under which there will be no distortion on the transmitted signal.

First, we need to clarify what a distortion-less channel is. We will not consider simple scaling and delay of the transmitted signal $s(t)$ as distortion (why?).

This means that if the received signal $r(t)$ is given by

$$r(t) = A s(t - T),$$

where $A > 0$ is the gain/attenuation and $T$ is the delay, the we will say the channel is distortionless.

Taking Fourier Transform, we have

$$R(w) = A S(w) e^{-jwT}.$$
Rearranging, we get:

\[ R(w) = \frac{A e^{-j\omega T}}{H(w)} \]

Recognizing that \( R(w) \) is the product of \( H(w) = A e^{-j\omega T} \) and \( S(w) \), we see that the effect of scaling & delay can be described by passing \( S(w) \) through a LTI filter with transfer function \( H(w) = A e^{-j\omega T} \).

(What is the impulse response of the channel?)

Hence, to be distortion-less, the channel should be a LTI filter with constant amplitude response and linear phase response over the pass band of the transmitted signal.

**Linear Distortion**

Linear distortion results when the amplitude response is non-constant and/or the phase response is non-linear over the pass band of the transmitted signal.

This type of distortion is usually caused by multiple delayed replica of the transmitted signal arriving at the receiver. The resulting signal is the superposition of all these replicas. The replica are generated from reflections due to e.g. reflection by cladding in optic fiber, reflector at terminations in twisted & coaxial cables, reflections by mountains or tall buildings in atmospheric transmissions.
Example: Two-ray channel

\[ h(t) = s(t-t_0) + 0.8s(t-2t_0) \]

Impulse response of channel

\[ H(f) = e^{-j2\pi f t_0} + 0.8e^{-j2\pi f 2t_0} \]

Direct LOS

\[ H(f) = \sqrt{1 + 0.64 \cos(2\pi ft_0)} e^{-j2\pi ft_0} \]

Reflected path

So both amplitude & phase responses are nonideal.

Now suppose that we send the following signal (neglecting whether it is practically doable for now) into the channel:

\[ \begin{array}{c}
-1 \\
0 \\
1 \\
\end{array} \]

where \( T = 2T \)

In this case, it is easy to get the received signal in time domain:

Direct LOS

\[ \begin{array}{c}
0 \\
1 \\
0 \\
\end{array} \]

Reflected

\[ \begin{array}{c}
0.8 \\
0 \\
-0.8 \\
0 \\
\end{array} \]
As can be seen from the example above, the usual effect of linear distortion is the "smeary" of the transmitted signal in time. This smeary effect can cause significant problems in both analog & digital communication systems.

Nonlinear Distortion

- Nonlinear distortions are usually caused by the nonlinear nature of practical electronic circuits in the transmitter & receiver, e.g. the nonlinear amplifier used in the transmitter.

- The effect of nonlinear distortion is usually the extension of the spectrum of the transmitted signal beyond the original design limit.

- See example 3.18 from textbook.

Noises & Interferences

- Here we focus on thermal noise only.
**Thermal Noise**

Next, we look at a little bit more realistic case:

**Q:** What happens if the circuit is not submerged in liquid helium?

**A:** The electrons in the circuit will have enough energy to move around (jitter), adding a random signal, called thermal noise, to the transmitted signal.

Hence, the signal received by the RX would be:

\[ r(t) = s(t) + n(t) \]

\[ \text{received signal} \quad \uparrow \quad \text{transmitted signal} \]

\[ \text{thermal noise} \]

* Usually, the thermal noise \( n(t) \) is modelled by a **White Gaussian random process**.

We will not go deep into defining what a white Gaussian process is. It suffices to mention some properties of the process:

i. If we sample \( n(t) \) at time \( t \), the \( n(t) \) is a Gaussian random variable with zero mean and infinite variance.

ii. The samples \( n(t_0), n(t_2), \ldots, n(t_k) \) are jointly Gaussian and independent for any \( k \).

iii. Define \( n = \int_{t_0}^{T_e} n(t) dt \) is a Gaussian random variable with zero mean and variance \( \frac{N_0}{2} (T_e - T_0) \) for all \( T_e > T_0 \).
White Gaussian process (cont.)

The parameter $\frac{N_0}{2}$ is crucial in specifying the thermal noise. It is usually referred to as the two-sided power spectral density of the noise.

Remark: To say $n$ is a Gaussian random variable with zero mean and variance $\sigma^2$, it means that the value taken by $n$ is random (can range from $-\infty$ to $\infty$) with $P(n \leq a) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{a} e^{-\frac{x^2}{2\sigma^2}} \, dx$.

Example: Suppose we use Unipolar NRZ.

$$E(t) = \begin{cases} 1 & \text{for } t \in (0,1) \\ 0 & \text{else} \end{cases}$$

$$n(t) = \begin{cases} 0 & \text{for } t \in (0,1) \\ \text{noise} & \text{else} \end{cases}$$

$$r(t) = E(t) + n(t)$$

For sampled voltages:

-0.1V, -0.2V, 0V, 0.1V, 0.2V, 0.3V, 0.4V

Decisions:

- $0$ for range $-0.1V$ to $-0.2V$, $0.1V$ to $0.2V$
- $1$ for range $0.1V$ to $0.3V$

Wrong decisions (errors)!

Conclusion: Noise causes errors!

Q: Can we do better? How?
Putting all together, a reasonably simple but representative model of a communication channel is as below:

\[ y(t) = g(x(t)) \ast R(t) + n(t) \]

where \( g(\cdot) \) models nonlinear distortion, \( R(t) \) models the impulse response of linear distortion, and \( n(t) \) is the thermal noise.

Notice that the LP or BP effect of the channel is included in \( R(t) \).

In many situations, we will ignore some of the distortion and noise effects in the model above (when these effects are not very significant or just for the sake of simplicity). For example, we may ignore the nonlinear distortion \( g(\cdot) \) and obtain a linear distortion model:

\[ y(t) = s(t) \ast R(t) + n(t) \]

Or we may sometimes ignore the linear distortion effect when it is not very significant and get

\[ y(t) = g(s(t-z)) + n(t) \]

The simplest model is to ignore both the nonlinear & linear distortion effect:

\[ y(t) = As(t) + n(t) \quad \text{(AWGN)} \]

This model is called the additive white Gaussian noise model.