Data Transmission

- A **signal** is an electrical or electromagnetic encoding of data

- **Signaling** is the act of propagating a signal along a medium
  - **guided** media: signals are sent along a physical path (e.g., wire, cable, fiber)
  - **unguided** media: signals are broadcast (e.g., air, vacuum)

- A guided medium may be either
  - **point-to-point**: direct link between two devices
  - **multipoint**: more than two devices share the medium
A Mathematical View of Signals

- A signal is a function of time.
- A signal $x(t)$ is periodic if and only if
  \[ x(t + T) = x(t), \text{ for } -\infty < t < \infty \]
  Otherwise, it is aperiodic.
- Three characteristics of a periodic signal are
  - amplitude: the value of the signal at a time
  - frequency: inverse of the period $T$
  - phase: measure of the relative position in time within a signal period of a signal

Examples of Periodic Signals
Examples of Aperiodic Signals

Any periodic signal can be represented as a sum of sinusoids, known as Fourier series:

$$x(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(2\pi n f_0 t) + \sum_{n=1}^{\infty} b_n \sin(2\pi n f_0 t)$$

where

$$a_0 = \frac{1}{T} \int_{0}^{T} x(t) dt$$

$$a_n = \frac{2}{T} \int_{0}^{T} x(t) \cos(2\pi n f_0 t) dt$$

$$b_n = \frac{2}{T} \int_{0}^{T} x(t) \sin(2\pi n f_0 t) dt$$
**Fourier Analysis**

- $f_0$ is known as the **fundamental frequency**
- $T = 1/f_0$ is the **period** of the signal
- Multiples of $f_0$ are referred to as **harmonics**.
- The formula can be generalized to accommodate aperiodic signals

*Speak “English,” please:*

- We see any signal as the combined result of a (infinite) sequence of sinusoid functions, called **frequency components**.

**Components of a Square Wave**

$$x(t) = \sin(2\pi \times ft) + \frac{1}{3}\sin(2\pi \times 3ft) + \frac{1}{5}\sin(2\pi \times 5ft) + \cdots$$

![Graph of a digital signal](image-url)
**First Sin() Component**

A graph showing a sine wave with the label "fundamental freq. f".

**Third Component**

A graph showing a sine wave with the label "3f".
The more high-frequency harmonics we include, the more faithful the result is to the original.
Even More Components

Some Terminologies

- The spectrum of a signal is the range of frequencies that it contains.
- The absolute bandwidth is the width of the spectrum.
  - The absolute bandwidth of the square wave is infinite.
- Due to the limitations of real-world media, a signal must be represented in a limited band of frequencies. This band is referred to as the effective bandwidth, or just bandwidth.
- The exact range of this “limited band” is largely an engineering issue.
Examples

- Consider a square wave \( x(t) \) whose fundamental frequency \( f=1 \text{M Hz} \).
- If the representation of \( x(t) \) by harmonics \( 1f+3f+5f \) is good enough, then the (effective) bandwidth of \( x(t) \) is \( 5\text{M} - 1\text{M} = 4\text{M Hz} \).
- A more faithful representation that uses up to \( 9f \) will have the bandwidth of \( 9\text{M}-1\text{M} = 8\text{M Hz} \).

Bandwidth of Human Voice

- Typically, a baby can hear from 20 Hz to 20 KHz.
- Many adults, especially males, are not as capable.
  - Can you hear the 15 KHz noise produced by the CRT of your TV set?
- Telephone systems pass frequencies from 300 Hz to 3300 Hz (bandwidth = 3000 Hz)
  - a transmission medium meeting this specification is called voice grade.
**Nyquist Theorem**

- Given a bandwidth \( H \), the highest signal rate (the number of signaling elements per second) that can be carried is \( 2H \).
- If each signal element contains \( V \) distinct values, then

\[
\text{maximum data rate} = 2H \log_2 V \text{ bits/sec}
\]

- This theorem assumes that the underlying medium is free of noises and, thus, gives an upper bound of the data rate.

**Examples**

- Consider a voice-grade line.
  - \( H = ? \)
- Using binary encoding, where each signal element could be either 0 or 1:
  - Max data rate = \( \text{bits/sec} \)
- Using a QAM encoding (studied later) that has 16 distinct values in each signaling element:
  - Max data rate = \( \text{bits/sec} \)
Transmission Impairment

- **Attenuation**
  - signal strength falls off with distance
  - attenuation increases with frequency

- **Delay distortion**
  - different frequency components propagate at different speeds over guided media

- **Noise**
  - cross talk: unwanted coupling between parallel signal paths
  - impulse noise: due to, for example, lighting

Signal-to-Noise ratio is measured in **decibels**:

\[
(S/N)_{dB} = 10 \times \log_{10} \frac{\text{signal power}}{\text{noise power}}
\]

- **Consequences**
  - limited data rate or limited distance
  - errors in transmission inevitable
Shannon Theorem

$$\text{maximum data rate} = H \log_2(1 + S/N) \text{ bits/sec}$$

- Notice that we need the direct S/N ratio (not in decibel) in the formula.
- Example: $H=3000\,\text{Hz}$, $S/N_{dB}=30$
  - $S/N$ = ?
  - $\text{Max data rate} = ?$
- Like Nyquist theorem, Shannon’s theorem gives an upper bound.

More Examples

- Consider a voice grade communication link with $S/N_{dB}=30$ and $V=4$.
- According to Nyquist’s theorem,
  - $\text{max data rate} = ?$
- According to Shannon’s theorem,
  - $\text{max data rate} = ?$
- The maximum data rate of the link = ?
- If $V=64$, then the max data rate = ?
- The lesson: