What does the Physical Layer Do?

- A possibly faulty, single-hop, bit pipe that connects a sender to possibly multiple receivers
Morse Code Analogy

Example bit pipe: sending Morse Code to receivers using a flashlight. Issues:

- **Fundamental Limits**: Brain-eye system processing limits leads to Inter Symbol Interference
- **Media Issues**: Flashlight, semaphore
- **Coding**: Morse code, getting in synch, knowing receiver rate.
PHYSICAL LAYER: SUBLAYERS

Input Stream 01010000

Coding Sublayer

Coded Stream

Media Transmission Sublayer

Input Signal

Signal Transmission Sublayer
(SHANNON AND NYQUIST LIMITS)

Media Reception Sublayer

Coded Stream

Decoding Sublayer

Output Stream 01010000

Output Signal
Why understand the Physical Layer in Sublayers?

- The bottom sublayer is really describing the essential properties of the media (frequency response, bit error rate). These influence data transmission rates (Nyquist, Shannon limits). This lecture.

- The middle sublayer describes properties of particular media — e.g., satellites, coaxial cable, fibre.

- The top sublayer is about things like clock recovery, synchronization etc.

Sublayers can be studied independently. Separate concerns. Each sublayer exacts its price!
Sending bits to a receiver

- **Goal:** to send a sequence of 0’s and 1’s from a sender to a receiver by sending energy (e.g., light, electricity) over a channel (e.g., fiber, cable). One coding: 0 = no energy, 1 = energy.

- **Problem:** Real channels distort input energy signals. Leads to two questions.
  
  - **Q1:** How can we predict what a given channel will do to an input signal given some properties of the channel. **Answer:** Fourier Analysis.
  
  - **Q2:** How does distortion affect maximum bit rate? **Answer:** Nyquist (sluggishness) and Shannon (noise) limits.
Signals, and channels

- **Signal**: energy (e.g., voltage, light) that varies with time. Continuous and Discrete. Periodic. Period and frequency.

- **Channel**: physical medium that conveys energy from a sender to a receiver (e.g., a fiber link) with possible distortion.
• Sine waves are special because all signals can be rewritten in terms of sine waves.

• Mathematically: \( A \sin(2\pi ft + \theta) \), \( A \) is max value, \( f \) is frequency, is initial phase shift

• Example: Frequency 1 Hz, \( \theta = 0 \). Values at \( t = 0 \) and \( t = 1/4 \). Use calculator but express angle in radians!
Fourier Analysis: the big picture

• If we forget about noise, most channels are “nice” to sine waves. A sine wave of frequency $f$ is always scaled by a fixed factor $s(f)$ and phase shifted by a fixed amount $p(f)$ regardless of amplitude.

• Thus we can completely describe a channel by plotting the values of $s(f)$ (frequency response) and $p(f)$ (phase response) for all values of frequency $f$.

• To find what happens to arbitrary signal $S$, we i) Use Fourier Analysis to rewrite $S$ as a sum of sine waves of diff frequencies ii) Use frequency and phase response to see effect of each sine wave iii) Add scaled sine waves to find output signal.
Frequency and Phase Response Examples

- Bandwidth: range of frequencies for which channel passes signal through. Not very precise.
Sluggishness and Noise

• Most channels are sluggish (they take time to respond) because they turn a deaf ear to higher frequencies in the input signal. Thus lower bandwidth channels are more sluggish.

• What about noise? Different models for different channels. Simplest and common model: white noise (uniformly distributed at all frequencies and normally distributed within a frequency)
Sampling Bits

• Receivers recover the bits in the input signal by *sampling* output signal close to middle of bit period.

• Two limits to bit rate: channel bandwidth (Nyquist) and noise (Shannon).
Bandwidth and Intersymbol Interference

- We know that a channel that cannot pass frequencies beyond \( f \) cannot respond fast enough if signals are sent at a rate faster than \( f \).

- If we do so, then when the first signal is still “settling”, the energy of the second signal will start mixing in. If first signal is a 0 and second is a 1, receiver may decode incorrectly.

- Technically, we say that signalling at a rate higher than the channel bandwidth causes Inter Symbol Interference or ISI.
Signal frequency = $1/T = f$
Maximum Signal Rate = $2/T = 2f$
Works only if we have removed frequency components above $f$
Baud Rate and Bit Rate

• To prevent ISI, we cannot signal at faster than $2f$ times per second. Baud rate is max signalling rate.

• But each symbol in a signal can carry multiple bits. For example: 0, 2, 4 and 5V. 4 possible values and 2 bits per symbol.

• With $L$ signal levels, bit rate is $\log L$ times baud rate.

• So why can’t we transmit at terabits over a phone line? Noise.
THE SHANNON BOUND

\[ S = \text{Maximum Signal Amplitude} \]
\[ N = \text{Maximum Noise Amplitude} \]
\[ \log(S/2N) \text{ bits per signal} \]
\[ 2 \text{ B signals/sec (Nyquist)} \]
\[ \text{Naive Bound} = 2 \text{ B } \log(S/2N) \]
\[ \text{Shannon Bound} = B \log(1 + S/2N) \]