

What does the Physical Layer Do?



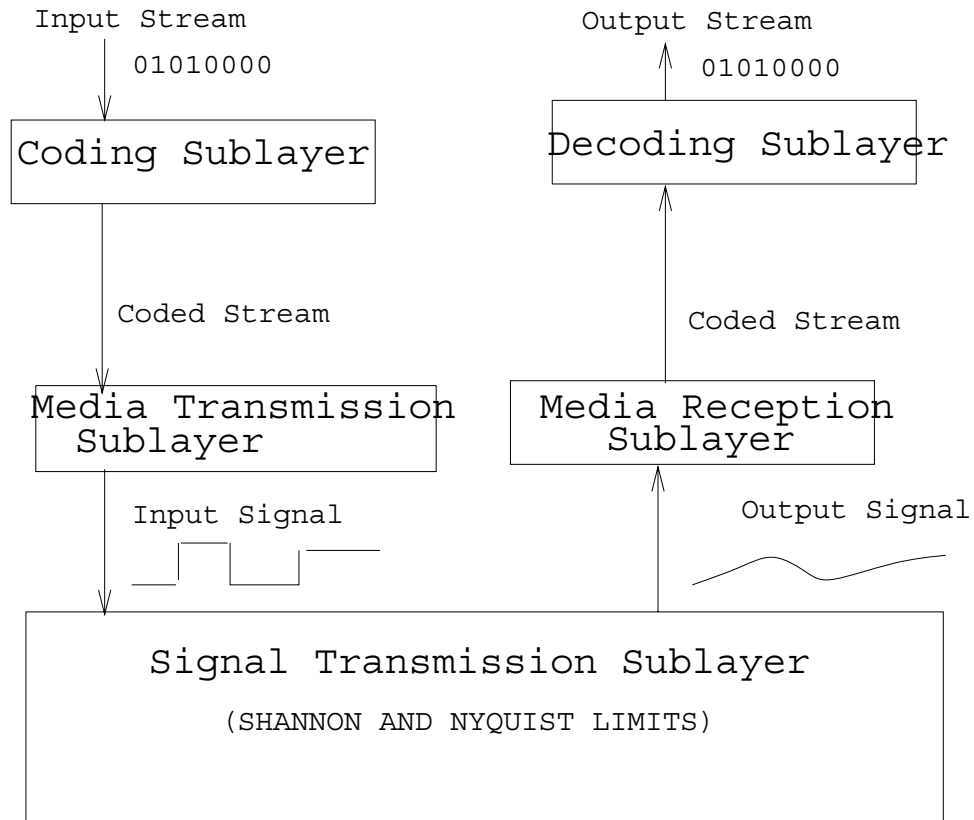
- A possibly faulty, single-hop, bit pipe that connects a sender to possibly multiple receivers

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



Why understand the Physical Layer in Sublayers?

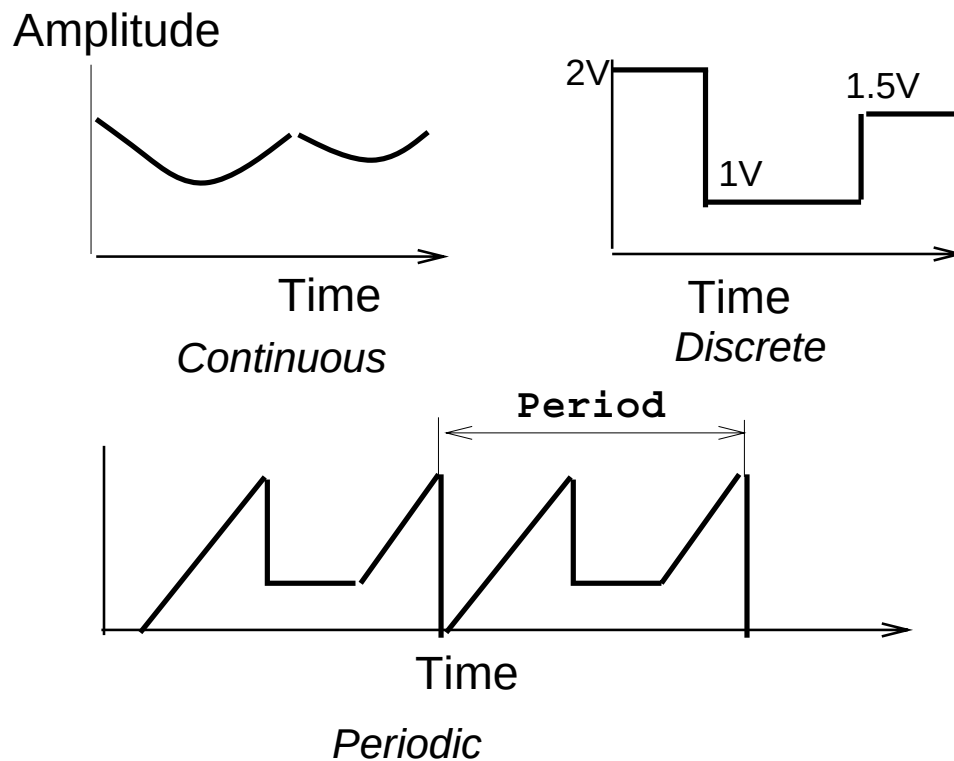
- The bottom sublayer is really describing the essential properties of the media (frequency response, bit error rate). These influence data transmission rates (Nyquist, Shannon limits). This lecture.
- The middle sublayer describes properties of particular media — e.g.. satellites, coaxial cable, fibre.
- 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

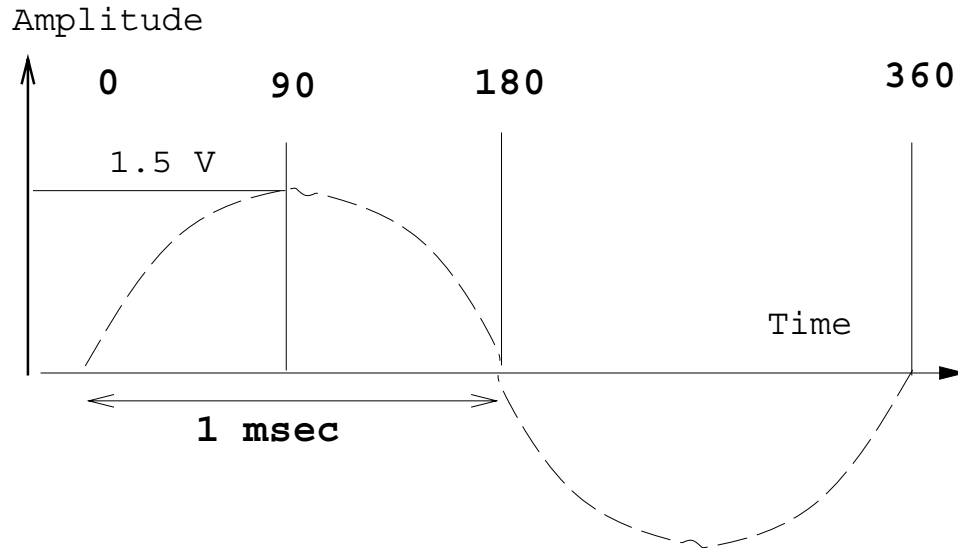
- **Goal:** to send a sequence of 0's and 1's from a sender to a receiver by sending energy (e.g., light, electricity) over a channel (e.g., fiber, cable). One coding: 0 = no energy, 1 = energy.
- **Problem:** Real channels distort input energy signals. Leads to two questions.
 - **Q1:** How can we predict 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

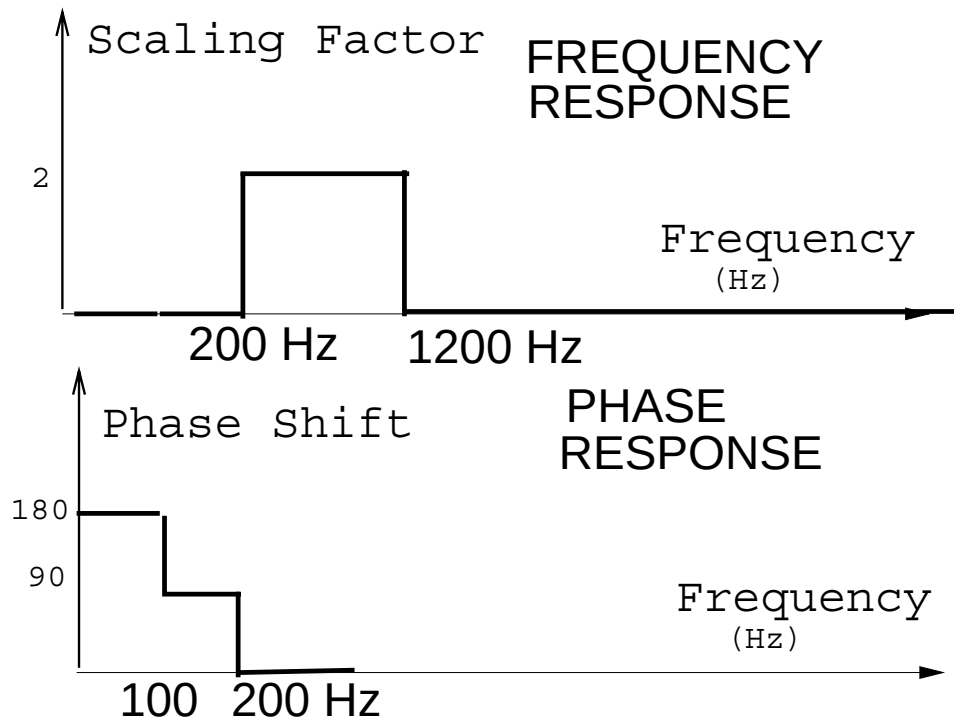


- Sine waves are special because all signals can be rewritten in terms of sine waves.
- Mathematically: $A \sin(2\pi ft + \theta)$, A is max value, f is frequency, θ is initial phase shift
- Example: Frequency 1 Hz, $\theta = 0$. Values at $t = 0$ and $t = 1/4$. Use calculator but express angle in radians!

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

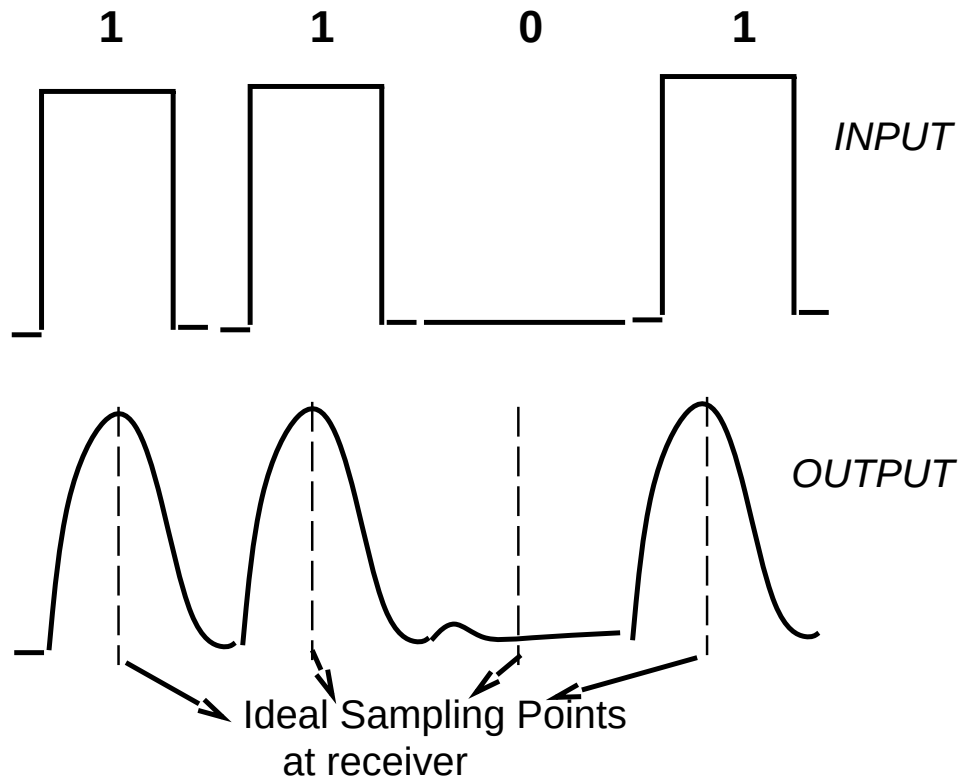


- Bandwidth: range of frequencies for which channel passes signal through. Not very precise.

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

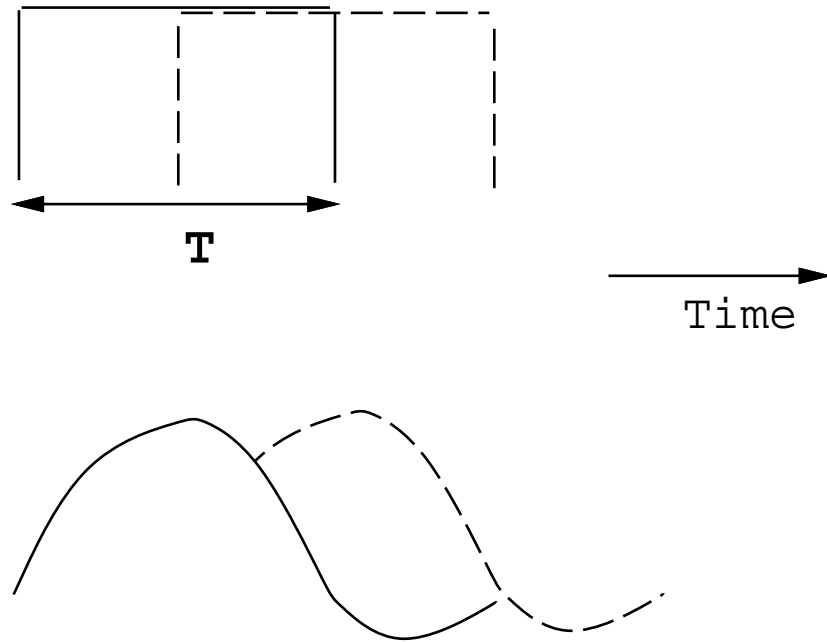


- Receivers recover the bits in the input signal by *sampling* output signal close to middle of bit period.
- Two limits to bit rate: channel bandwidth (Nyquist) and noise (Shannon).

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.

NYQUIST LIMIT



Signal frequency = $1/T = f$

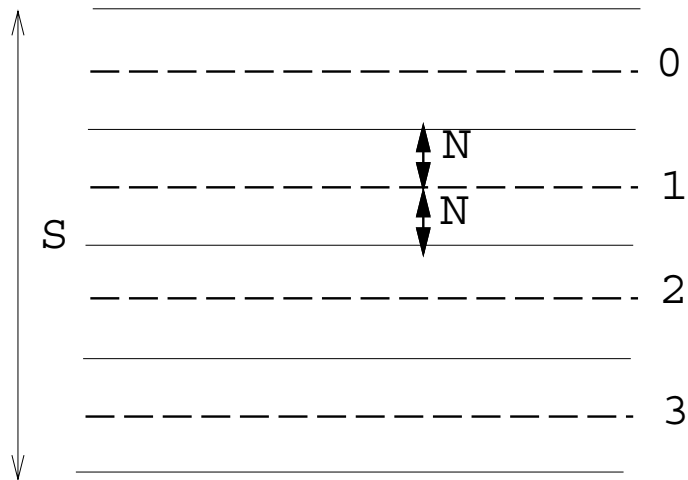
Maximum Signal Rate = $2/T = 2f$

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 = Maximum Signal Amplitude

N = Maximum Noise Amplitude

$\log(S/2N)$ bits per signal

2 B signals/sec (Nyquist)

Naive Bound = $2 B \log(S/2N)$

Shannon Bound = $B \log(1 + S/2N)$