1 Human communication

- Human communication
  - What? Process of exchanging information
  - Why? Convey thoughts, idaes, feelings using open vocal and larger bank of symbols
  - Barriers? distance , language
  - Electronic communication has allowed access and application of information in a timely way
- Milestones in electronic communication
  - Telegraph. Samuel Morse. 1843
  - Telephone. Alexander Bell. 1876
  - Radio. Guglielmo Marconi. 1887
- How to transmit information wirelessly?
  1. Point-to-point
  2. Sharing channel
  3. Network

2 Point-to-point communication

2.1 Converting information to bits

- Transfer of information
  - Transmitter. takes a sequence of bits and creates physical signal or waveform that is carried over a channel
  - Channel. medium of transferring information. the channel may modify the signal as the channel caries the signal
  - Receiver. tries to figure out what the transmitted bits were from the received signal
- Analog-to-Digital Conversion (ADC). analog signal $\rightarrow$ [sampling $\rightarrow$ quantization $\rightarrow$ coding] $\rightarrow$ digital signal.
- Signal. any physical quantity that varies with time, space, or any other independent variables
- Electrical transducer. physical device capable of converting the physical quantity to proportional electrical quantity.
- Continuous time signal (analog). defined for every value to time and value
- Discrete time signal. can be derived by selecting values of an analog signal at discrete time instants, a process known as **sampling**
- Sample. the sampler is a switch that connects the analog signal input to the discrete time signal output for a brief instant at a rate of F_s (sampling frequence) $= \dfrac{1}{T_s}$ (1/sampling period)
- Sampling theorem. if the highest frequency content of an analog signal is $F_{\max}$, the sampling rate is selected such as $F_s > 2F_{\max}$
- Nyquist rate. $F_N = 2F_{\max}$
- number of samples. $N = \dfrac{T_w \text{ (signal length)}}{T_s \text{ (sample period)}}$
- tradeoff: higher sample frequency has less information lost but requires more storage
- Aliasing. misidentification of a signal frequency due to undersampling
- Continuous valued signal. takes all possible values in a finite or infinite range
- Discrete valued signal. has a set of discrete values

- Quantization. process of converting a discrete time continuous valued signal to a digital signal by expressing each sample as a finite number of digits
- Digital signal. a signal that is both discrete time and discrete valued
- Quantization error. difference between sampled analog signal and digital signal
- Quantization step size or resolution. distance between two quantization levels
- Dynamic range. difference between maximum and minim value of the discrete time signal
- Coding. assignment of a unique binary number to each quantization level. requires at least L binary numbers to L quantization levels
- ASCII. **A**merical **S**tandard **C**ode for **I**nformation **I**nterchange. an 8-bit code to represent text symbols
- Bit time. measures the length of time it takes to send one bit. bit time $= SPB \cdot T_s = \dfrac{SPB}{F_s}$
- Bit rate. measures the number of bits sent in a given unit of time. bit rate $= \dfrac{1}{\text{bit time}} = \dfrac{1}{SPB \cdot T_s} = \dfrac{F_s}{SPB}$
- Unit step function. $u(n) = \begin{cases} 1, & n \geq 0 \\ 0, & n < 0 \end{cases}$. can be delayed by d by substituting $n - d$ to n
- Bit waveforms can be represented as a sum of unit step functions
  - for a bit change from 0 to 1 at sample D, add $u(n - D)$
  - for a bit change from 1 to 0 at sample D, subtract $u(n - D)$

2.2 Propagating the signal through a channel

- Types of Physical Media
  - Guided media
    * Twisted pair. consists of two solid copper conductors encased in a polyvinylchloride (PVC) sheath. least expensive and most common guided media. susceptible to *electromagnetic interference* (EMI) - which is mitigated by twisting. cables have 4 pairs. up to 100 meters and can carry 10 Mbps to 10 Gbps
    * Coaxial cable. has an inner and outer conductor separated by a *dielectric insulator*. it is more robust to EMI due to shielding. higher data rate and bandwidth than twisted pair. allows shared access
    * Fiber optic. thin, flexible (high purity glass) that conduct pulses of light. has bit rate of 10s to hundreds of Gbps. immune to EMI. low signal attenuation up to 100 km. hard to tap. useind in long distance telephone network and Internet backbone. most expensive guided media.
  - Unguided media.
    * Terrestrial radio. Carry signals in the electromagnetic spectrum. require no physical wire to be installed. can penetrate walls. provide connectivity to a mobile user. can potentially carry a signal for long distances. characteristics of channel depend on the propagation environment and the distance:
      1. path loss and shadow fading
      2. multipath fading
      3. interference
    * Satellite radio. links two or more Earth-based microwave transmitter/receivers, known as ground stations. the satellite receives transmissions on one frequency band, regenerates the signal using a repeater, and transmits the signal on another frequency. two types of satellites are used in communications:
      1. geostationary
      2. low-earth orbiting (LEO)
  - Mathematical models. a good model happens if the model and actual response are similar ($y_m(n) \approx y_a(n)$)and the relationship of model response and input is simple. models are used to understand the operation of the system, predict the performance of the system, and develop modifications to the system to improve performance.

- Effects of the channel. channel may cause the received signal $y(n)$ to differ from the transmitted signal $x(n)$ in several ways:
  - attenuation (decrease in amplitude)
  - delay
  - offset
  - blurring of transitions
    - transducer that creates the physical waveform
    - electronics that drive the transducer
    - physical medium that carries the waveform
    - sensor that senses the waveform
    - electronics that process the sensor signal
  - noise
- Model for attenuation, delay, and offset: $y(n) = kx(n-d) + c$. k is the attenuation ($k < 1$), d is the delay, c is the offset.
- Linear functions. in the form $y = ax$. has two properties:
  - Homogeneity. $x \to ax \to y \implies cx \to ax \to cy$
  - Additivity. $\begin{array}{l} x_1 \to ax \to y_1 \\ x_2 \to ax \to y_2 \end{array} \implies x_1 + x_2 \to ax \to y_1 + y_2$
- Systems. takes in an input waveform $x(n)$ and produces and output $y(n)$. $x(n) \to \text{system} \to y(n)$
- Linear system. a system with properties of linear function.
  - Homogeneity. $x(n) \to \text{system} \to y(n) \implies cx(n) \to \text{system} \to cy(n)$
  - Additivity. $\begin{array}{l} x_1(n) \to \text{system} \to y_1(n) \\ x_2(n) \to \text{system} \to y_2(n) \end{array} \implies x_1(n) + x_2(n) \to \text{system} \to y_1(n) + y_2(n)$

- Time invariant. if the input is delayed by d, the output is the the same but also delayed by d
- Linear Time Invariant (LTI) Systems. a system that is both linear and time invariant
- Step response. the output to a unit step function input
- Exponential step response. $s(n) = k(1 - a^{n+1})u(n)$ with k as the change in amplitude and a as blurring of transitions
- Protocol. an agreement on set of rules or procedures to follow during communication. some example of protocols in data communication system:
  - representation of text characters. ASCII vs Unicode
  - order of bit sequence. LSB or MSB first
  - representation of bits. 1 = on, 0 = off or 1 = off, 0 = on
  - bit time or bit rate
  - training sequence
  - synchronization method
- Thresholding. in the model system, 1 is close to $c + k$ and 0 is close to c. hence we compare the values received to a **threshold** T which is between c and $c + k \implies T = c + \frac{k}{2}$. if $r(n)$ is the received signal at time n, we can model the thresholded signal $b(n)$ as

$$b(n) = \begin{cases} 1, & r(n) \geq T \\ 0, & r(n) < T \end{cases}$$

- Bit rate vs Bit Error Rate (BER). we want bit rate to be as high as possible but BER increases as bit rate increases
- Intersymbol interference (ISI). response to a "zero" or "one" bit depends upon what bits were transmitted before it. the smaller bit time to the time for channel to respond $\to$ greater ISI
- Minimizing ISI. make the channel faster (costly), increase the bit time (reduced bit rate)
- Eye diagram. summarizes the effects of the ISI by showing all responses to "zeros" and "ones" simultaneously. generated by overlaying plots of the channel response for **two** bit times

2.3 Recovering the Information

- Received signal. response to the input (computed using the step response with LTI assumption) + signals introduced by the environment (such as offset and noise)
- Noise. a random signal. it comes from nature and most common is *thermal noise*. thermal noise is due to the ambient heat. the amount of noise determine the minimum signal that one can understand, and the minimum signal that can be decoded by radios and receivers.
- Additive noise. moves the received signals away from the channel output without noise
- Assumptions for BER analysis:
  - Perfect synchronization. we know exactly where to sample the output to decode for each bit
  - Single sample decoding. each bit is decoded by comparing one output sample bit with a threshold
  - No ISI. channel response depends only on current bit, not on past bits.
  - Additive "White" Gaussian Noise (AWGN). white: noise varies fast enough that its value at different samples are unrelated to each other
- Binary channel model. further assumptions: we ignore the details of the noise and received signal levels r_{min} or r_{max} and only look at input and output bits
- Binary channel. both input and output have two possible values: 0 or 1
- BER. the probability of error P_e given by

$$P_e = P_{e0} \cdot P[IN = 0] + P_{e1} \cdot P[IN = 1]$$

- Power consumption. we are interested in how the signals differ from their average: $\Delta r = r - r_{\text{average}}$. the average value of Δr is $(\Delta r)_{\text{average}} = \dfrac{1}{N}\sum_{n=1}^{N} \Delta r(n) = 0$ for very large N
- Average power. $P_{\text{average}} = \dfrac{1}{N}\sum_{n=1}^{N} (\Delta r(n))^2$
- if 0's and 1's are equally likely, the average power is $P = \dfrac{(r_{\max} - r_{\min})^2}{4}$
- Signal-to-noise ratio (SNR). we consider the SNR and not the absolute signal or noise power.

$$SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}}$$

$$SNR(dB) = 10 \log_{10} \frac{P_{\text{signal}}}{P_{\text{noise}}}$$

- Factors affecting SNR
  - received power decreases as receiver moves away
  - decrease in received signal power leads to decrease in SNR
  - once SNR falls below $10dB$, the receiver stops functioning. this happens at 10^{-14} W
- BER is high for low signal power; it is low for low noise power
- Channel coding. a way to detect or correct bit errors by adding redundancy to the transmission
- Claude Elwood Shannon. Father of Information Theory.
- Shannon's Noisy Channel Coding Theory: a noisy channel has a capacity C, the maximum rate at which useful information can be transmitted. For any data rate $R < C$, there exists a way to encode the data such that the probability of error is arbitrarily small.
- (n, k, d) block codes. split the message into k bit blocks and add $(n-k)$ extra bits on each block. note that the added bits is computed based on the message bits. d is the minimum **Hamming Distance** between codewords

- Code rate. fraction of bits that contain useful information. for the (n, k, d) block code, the

$$\text{code rate} = \frac{k}{n}$$

- Gross bit rate or Data signaling rate. rate that all bits are sent $= \dfrac{F_s}{SPB}$
- Net bit rate. rate that useful bits are send = code rate $\times$ gross bit rate
- Hamming distance. between two codewords, it is the number of bit positions where the corresponding bits are different.
- Error detection. errors can be known but don't know how to fix
- Error correction. errors can be know AND fixed
- Error detection/correction capability. if the minimum hamming distance is d, the receiver can either *detect but not correct* at most $d-1$ bits OR *detect and correct* at most $\dfrac{d-1}{2}$ bits
- Single parity bit code. given a $k-$bit message, create a $(k+1, k, 2)$ block code by adding a **parity bit** that ensures the the sum of bits is *even*. if the received signal has odd parity, assume single bit error. otherwise, no bit errors occurred. this method fails to correct even number of bit error