Chapter 3
The Physical Layer

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Outline
- The physical layer provides a service:
  -- It transfers bits across a link.
- Digital representation of information – Why? How?
- Characterization of communication channels.
- Fundamental limits – a taste of information theory.
- Error control codes.
- Transmission media.

Source
- Analog signal
- Digital signal
  010001001110101
  L:aksdfjoiqwqweu;ikajsdfl
**Digital Transmission of Analog Information**

- **Analog source**
- **Sampling (A/D)**
- **Quantization**
- **Transmission or storage**
- **Display or playout**

Bandwidth $W$

**Original signal**

$\text{Bandwidth } W$

**Approximation** $y(t)$

- **Sampling Theorem**
  - (The Kupfmuller-Nyquist-Kotelnikov Sampling Theorem)
  - Consider an analog signal which is limited to bandwidth $W_s$
  - The signal can be perfectly reconstructed from its discrete-time samples if the sampling rate is $1/T > 2W_s$

**Digitization of Analog Signal**

- **Sampling** (continuous-time to discrete-time)
- **Quantization** (continuous value to discrete value)

$R_s = \text{Bit rate} = \# \text{bits/sample} \times \# \text{samples/second}$
Bit Rate

Bit rate = # bits/sample x # samples/second

Recall the Sampling Theorem
- Bandwidth $W_s$ Hertz: how fast the signal changes
- Nyquist Sampling Theorem: Minimum sampling rate = $2 \times W_s$

Telephone voice
- $W_s = 4$ kHz
- $R_s = 8$ bits/sample x 8000 samples/sec = 64 kbps

CD Audio
- $W_s = 22$ kHz
- $R_s = 16$ bits/sample x 44000 samples/sec = 704 kbps

Theory of Information

- What is information?
  - Answer: uncertainty.
- How much information?
  - Answer: entropy.
- Entropy
  - Consider a source $X_1 X_2 X_3 ...$
    - $X_i$ are independent and identically distributed with distribution $P(X_i = m) = q_m$, $m = 1,...,M$.
  - $H(X) = - \sum q_m \log(q_m)$

Data Compression

- Also known as source coding.
- Noiseless
  - The original information can be recovered exactly.
  - Can compress to the entropy.
  - E.g. zip, GIF.
- Noisy
  - Noisy: recover information approximately
  - JPEG
  - Tradeoff: # bits vs. quality
A Transmission System

Transmitter

Communication channel

Receiver

Bits $s(t)$

Communication Channel
- Pair of copper wires
- Coaxial cable
- Radio
- Optical fiber
- Light, infrared

Transmission Impairments
- Attenuation
- Distortion
- Spurious noise
- Interference

$\text{r}(t)$ bits

Analog vs. Digital Transmission

Analog transmission: difficult to reproduce all details accurately

Sent

Digital transmission: only discrete levels need to be reproduced

Distortion

Attenuation

Sent

Simple Receiver: Was original pulse positive or negative?

Received

Distortion

Attenuation

Received
Transmission Delay

- \( L \) number of bits
- \( R \) speed of transmission (bits/sec)
- \( t_{\text{prop}} \) propagation time
- \( d \) distance
- \( c \) speed of light (\( 3 \times 10^8 \) m/s in vacuum)

\[
\text{Delay} = t_{\text{prop}} + \frac{L}{R} = \frac{d}{c} + \frac{L}{R} \text{ seconds}
\]

Signaling

Digital Binary Signal

\[ +A \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \]
\[ -A \quad 0 \quad 1 \quad 2T \quad 3T \quad 4T \quad 5T \quad 6T \]

\[ \text{Bit rate} = 1 \text{ bit} / T \text{ seconds} \]

Speed vs. reliability.
Synchronization

Clock drift causes a loss of synchronization

Asynchronous Transmission

- Specify a short maximum length for the bit sequences and resetting the clock in the beginning of each bit sequence.

Recommended Standard (RS) 232

- Serial line interface between computer and modem or similar device
- Data Terminal Equipment (DTE): computer
- Data Communications Equipment (DCE): modem

![Diagram of Synchronization](image)

![Diagram of Asynchronous Transmission](image)

![Diagram of Recommended Standard (RS) 232](image)
Synchronous Transmission

- Sequence contains data + clock information (line coding)
  - i.e. Manchester encoding, self-synchronizing codes, is used.
- PLL (phase-lock loop)

```
+1 0 0 0 1 1 0 1 0
```

- Voltage
- Time

Line coding

Mapping bits into digital signal that enters the channel

- Unipolar NRZ
- Polar NRZ
- NRZ-inverted (differential encoding)
- Bipolar encoding
- Manchester encoding
- Differential Manchester encoding

Spectrum of Line codes

- Assume 1s & 0s independent & equiprobable
- NRZ has high content at low frequencies
- Bipolar tightly packed around T/2
- Manchester wasteful of bandwidth
**Bandwidth of a Channel**

- Bandwidth $W_c$ is range of frequencies passed by channel
- Maximum pulse transmission rate $2 \times W_c$ pulses/second

$$X(t) = \cos(2\pi ft) \rightarrow \text{Channel} \rightarrow Y(t) = A(t) \cos(2\pi ft)$$

**Multilevel Pulse Transmission**

- If pulses amplitudes are either $-A$ or $+A$,
  $R = 2W_c$ bps
- If $M = 2^m$ amplitude levels,
  $R = 2^mW_c$ bps

*In the absence of noise, $R$ can be arbitrarily high. Noise places a limit.*

**Signal-to-Noise Ratio**

$$\text{SNR} = \frac{\text{Average signal power}}{\text{Average (in band) noise power}}$$

*High SNR*

*Low SNR*
Bandpass Channels

- Modulate a sinusoid
  1. Amplitude modulation
  2. Frequency modulation
  3. Phase modulation

Phase-Shift-Keying

Information
Baseband Signal
Modulated Signal $x(t)$

$x(t) = A_k \cos(2\pi f_c t)$

Demodulate by multiplying by $2\cos(2\pi f_c t)$ and lowpass filtering

$Y(t) = A_k \cos(2\pi f_c t)$

Lowpass Filter (Smother)

$X(t) = 2A_k \cos^2(2\pi f_c t) = A_k (1 + \cos(4\pi f_c t))$
Example of Demodulation

After multiplication at receiver
\[ x(t) \cos(2\pi f_c t) \]

Baseband signal discernable after smoothing

Recovered Information

| 1 | 0 | 1 | 1 | 0 | 1 |

Fundamental Limits

Discrete-time Noisy channel

- \[ Y = \alpha X + \sigma N \]
- If \( X = -1 \) or \( +1 \), \( N \) is standard Gaussian
- Signal-to-noise ratio \( g = (\alpha/\sigma)^2 \)
- Then the probability of error is
  \[ P_e = P(N > \sqrt{g}) = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{g}}^{\infty} e^{-t^2/2} dt \]
- Reliability can be improved by "coding" over a block of bits and adding appropriate redundancy
The Shannon Capacity of the discrete-time channel:
The maximum reliable transmission rate of the channel
\[ Y_i = a X_i + \sigma N_i \] is
\[ C = \frac{1}{2} \log_2 \left( 1 + g \right) \text{ bits/channel use} \]

- Arbitrarily reliable communication possible if transmission rate \( R < C \); otherwise not.
- Reliable communication means that, given any \( \epsilon > 0 \), the error rate can be made to be smaller than \( \epsilon \) by using a sufficient error-control code.

The Shannon Capacity of a continuous-time channel:
The maximum reliable transmission rate over the continuous-time additive white Gaussian noise channel
\[ Y(t) = X(t) + N(t) \] with bandwidth \( W \) Hz, power \( P \) (watts) and noise spectrum density \( N_0 \) watts/Hz is
\[ C = W \log_2 \left( 1 + \frac{P}{W N_0} \right) \text{ bits/second} \]

Example: Capacity
- Channel capacity for a telephone channel with \( W_c = 3400 \) Hz and \( \text{SNR} = 30 \) dB
\[ C = 3400 \log_2 (1 + 1000) \approx 33,888 \text{ bps} \]
Media

Electromagnetic Spectrum

Attenuation

- Wireline
  - Exponential decay (absorption): \( L = 10^{kd} \)
  - Attenuation in \( \text{dB} = kd \)

- Wireless
  - Power law (spread out): \( L = \beta d^\gamma \)
  - Space communications possible

- Amplifier
  \( L = \text{Pout/Pin} \)
Twisted Pair

- Insulated copper wires arranged in a regular spiral pattern to minimize interference
  - E.g., telephone subscriber loop to central office
  - Local area network (LAN)
- High bit rates at short distances
- Asymmetric Digital Subscriber Loop (ADSL)
  - High-speed Internet Access
  - Lower 3 kHz for voice, upper band for data
  - 64 kbps inbound, 640 kbps outbound
- Much higher rates possible at shorter distances

Coaxial Cable

- Cylindrical braided outer conductor surrounds insulated inner wire conductor
- High interference immunity
- Higher bandwidth than twisted pair, hundreds of MHz
  - Cable TV
  - Long distance telephone network
  - Original Ethernet LAN medium

Optical Fiber

- Light sources (lasers, LEDs) generate pulses of light
  - Very long distance (>1000 km)
  - Very high speed (>40 Gbps/wavelength)
  - Nearly error-free (BER of 10^{-15})
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services
Radio Transmission

- Signal transmitted by antenna and radiates in air/space
- Wireless communications
  - Cellular phones
  - Satellite transmissions
  - Wireless LANs
- Spectrum regulated by national & international regulatory organizations
- Impairments
  - Multipath propagation causes fading
  - Interference from other users