Chapter 3: Data Transmission

Terminology (1)

- Transmitter
- Receiver
- Medium
  - Guided medium
    - e.g. twisted pair, optical fiber
  - Unguided medium
    - e.g. air, water, vacuum
Terminology (2)

- Direct link
  — No intermediate devices
- Point-to-point
  — Direct link
  — Only 2 devices share link
- Multi-point
  — More than two devices share the link

Terminology (3)

- Simplex
  — One direction
    - e.g. Television
- Half duplex
  — Either direction, but only one way at a time
    - e.g. police radio
- Full duplex
  — Both directions at the same time
    - e.g. telephone
Frequency, Spectrum and Bandwidth

- Time domain concepts
  - Analog signal
    - Varies in a smooth way over time
  - Digital signal
    - Maintains a constant level then changes to another constant level
  - Periodic signal
    - Pattern repeated over time
  - Aperiodic signal
    - Pattern not repeated over time

Analogue & Digital Signals

(a) Analog

(b) Digital
Periodic Signals

Sine Wave

- Peak Amplitude ($A$)
  - maximum strength of signal, in volts
- Frequency ($f$)
  - Rate of change of signal, in Hertz (Hz) or cycles per second
  - Period = time for one repetition ($T$), $T = 1/f$
- Phase ($\phi$)
  - Relative position in time
- Periodic signal $s(t + T) = s(t)$
- General wave $s(t) = A \sin(2\pi ft + \Phi)$
Periodic Signal: e.g. Sine Waves

\[ s(t) = A \sin(2\pi ft + \Phi) \]

Wavelength

- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- Wavelength \( \lambda \)
- Assuming signal velocity \( v \)

\[ \lambda = vT \quad \text{[unit is m]} \]
\[ \lambda f = \nu \]
\[ c = 3 \times 10^8 \text{ m/s (speed of light in free space)} \]
**Frequency Domain Concepts**

- Signal is usually made up of many frequencies
- Components are sine waves
- It can be shown (Fourier analysis) that any signal is made up of component sine waves
- One can plot frequency domain functions

**Building block for waves**

- What is a square wave?
  - What frequency components are digital signals composed of?
  - How many components do I need to recreate a square wave?
  - What is a realistic spectrum?
  - Where is the main energy of the signal?
  - Below is a representation of a square wave with amplitude $A$:

$$s(t) = \frac{A4}{\pi} \sum_{k=1, k \text{ odd}}^{\infty} \frac{1}{k} \sin(2\pi kt)$$
Physical Aspects

• Limited Bandwidth
  — Fourier Analysis

\[ v(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t \]

\[ a_0 = \frac{1}{T} \int_{0}^{T} v(t) dt \]

\[ a_n = \frac{2}{T} \int_{0}^{T} v(t) \cos(n\omega_0 t) dt \]

\[ b_n = \frac{2}{T} \int_{0}^{T} v(t) \sin(n\omega_0 t) dt \]

\[ v(t) = \text{voltage as a function of time} \]

\[ \omega_0 = \text{fundamental frequency component in radians / second} \]

\[ f_0 = \text{fundamental frequency in Hz} \]

\[ T = 1/f_0 = \text{period in seconds} \]

Physical Aspects

• Limited Bandwidth (cont.)
  — Unipolar

\[ v(t) = \frac{V}{2} + \frac{2V}{\pi} \{ \cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \ldots \} \]

— Bipolar

\[ v(t) = \frac{4V}{\pi} \{ \cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \ldots \} \]

How much bandwidth do we need?
What are the trade-offs if we compromise bandwidth?
Addition of Frequency Components \((T=1/f)\)

Spectrum of previous example

Single pulse: between \(-X/2\) and \(X/2\)
Spectrum & Bandwidth

- Spectrum
  - range of frequencies contained in signal
- Absolute bandwidth
  - width of spectrum
- Effective bandwidth
  - Often just bandwidth
  - Narrow band of frequencies containing most of the energy
- DC Component
  - Component of zero frequency

Signal with DC Component
Data Rate and Bandwidth

- Any transmission system has a limited band of frequencies
- This limits the data rate that can be carried
- Issues
  - The more bandwidth the less distortion
  - Where is the bulk of the energy?

Analog and Digital Data Transmission

- Data
  - Entities that convey meaning
- Signals
  - Electric or electromagnetic representations of data
- Transmission
  - Communication of data by propagation and processing of signals
Analog and Digital Data

- **Analog**
  - Continuous values within some interval
  - e.g. sound, video
- **Digital**
  - Discrete values
  - e.g. text, integers

Acoustic Spectrum (Analog)
Analog and Digital Signals

- Means by which data are propagated
- Analog
  - Continuously variable
  - Various media
    - wire, fiber optic, space
  - Speech bandwidth 100Hz to 7kHz
  - Telephone bandwidth 300Hz to 3400Hz
  - Video bandwidth 4MHz
- Digital
  - Use two DC components

Advantages & Disadvantages of Digital

- Cheaper
- Less susceptible to noise
- Greater attenuation
  - Pulses become rounded and smaller
  - Leads to loss of information
Components of Speech

- Frequency range (of hearing) 20Hz-20kHz
  - Speech 100Hz-7kHz
- Easily converted into electromagnetic signal for transmission
- Sound frequencies with varying volume converted into electromagnetic frequencies with varying voltage
- Limit frequency range for voice channel
  - 300-3400Hz
**Video Components**

- USA - 483 lines scanned per frame at 30 frames per second
  - 525 lines but 42 lost during vertical retrace
- So 525 lines x 30 scans = 15750 lines per second
  - 63.5µs per line, (11µs for retrace, so 52.5 µs per video line)
- Max frequency if line alternates black and white
- Horizontal resolution is about 450 lines giving 225 cycles of wave in 52.5 µs
- Max frequency of 4.2MHz

**Binary Digital Data**

- From computer terminals etc.
- Two dc components
- Bandwidth depends on data rate
Conversion of PC Input to Digital Signal

- as generated by computers etc.
- has two dc components
- bandwidth depends on data rate

```
0 1 1 1 0 0 0 1 0 1
```

+5 volts

-5 volts

0.02 msec

User input at a PC is converted into a stream of binary digits (1s and 0s). In this graph of a typical digital signal, binary one is represented by -5 volts and binary zero is represented by +5 volts. The signal for each bit has a duration of 0.02 msec, giving a data rate of 50,000 bits per second (50 kbps).

Data and Signals

- Usually use digital signals for digital data and analog signals for analog data
- Can use analog signal to carry digital data
  — Modem
- Can use digital signal to carry analog data
  — Compact Disc audio
**Analog Signals Carrying Analog and Digital Data**

Analog Signals: Represent data with continuously varying electromagnetic wave

- Analog Data (voice sound waves)
  - Telephone

- Digital Data (binary voltage pulses)
  - Modem

**Digital Signals Carrying Analog and Digital Data**

Digital Signals: Represent data with sequence of voltage pulses

- Analog Signal
  - Codec

- Digital Data
  - Digital Transceiver
Transmission Impairments

- Signal received may differ from signal transmitted causing:
  - analog - degradation of signal quality
  - digital - bit errors
- Most significant impairments are
  - attenuation and attenuation distortion
  - delay distortion
  - noise

Attenuation

- Signal strength falls off with distance
- Depends on medium
- Received signal strength:
  - must be enough to be detected
  - must be sufficiently higher than noise to be received without error
- Attenuation is an increasing function of frequency
Delay Distortion

- Only in guided media
- Propagation velocity varies with frequency

Noise (1)

- Additional signals inserted between transmitter and receiver
- Thermal
  - Due to thermal agitation of electrons
  - Uniformly distributed
  - White noise
- Intermodulation
  - Signals that are the sum and difference of original frequencies sharing a medium
Noise (2)

- Crosstalk
  - A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes
  - e.g. External electromagnetic interference
  - Short duration
  - High amplitude

Digital Transmission

- Concerned with content
- Integrity endangered by noise, attenuation etc.
- Repeaters
  - Repeater receives signal
  - Extracts bit pattern
  - Retransmits
  - Attenuation is overcome
  - Noise is not amplified
Analog Transmission

- Analog signal transmitted without regard to content
- May be analog or digital data
- Attenuated over distance
- Use amplifiers to boost signal
- Also amplifies noise

Advantages of Digital Transmission

- Digital technology
  - Low cost LSI/VLSI technology
- Data integrity
  - Longer distances over lower quality lines
- Capacity utilization
  - High bandwidth links economical
  - High degree of multiplexing easier with digital techniques
- Security & Privacy
  - Encryption
- Integration
  - Can treat analog and digital data similarly
Channel Capacity

- Data rate
  - In bits per second, bps (not Bps)
  - Rate at which data can be communicated
- Bandwidth
  - In cycles per second of Hertz, Hz
  - Constrained by transmitter and medium
- Convention: not all k’s are equal
  - data rates are given as power of 10
    - e.g., kHz is 1000Hz
  - data is given in terms of power of 2
    - e.g., KByte is 1024 Bytes

Nyquist Bandwidth

- If rate of signal transmission is 2B then a signal with frequencies no greater than B is sufficient to carry the signal rate.
  - Why? Assume we have a square wave of repeating 101010. If a positive pulse is a 1 and a negative pulse is 0, then each pulse lasts 1/2 T_1 (T_1 = 1/f_1) and the data rate is 2f_1 bits per second.
Nyquist Bandwidth

- If we limit the components to a maximum frequency (restrict the bandwidth) we need to make sure the signal is accurately represented.
- Based on the accuracy we require, the bandwidth can carry a particular data rate. The theoretical maximum communication limit is given by the **Nyquist** formula:

\[ C = 2B \log_2 M \]

- \( C \) = capacity or data transfer rate in bps
- \( B \) = bandwidth (in hertz)
- \( M \) = number of possible signaling levels

Signal Strength

- An important parameter in communication is the strength of the signal transmitted. Even more important is the strength being received.
- As signal propagates it will be **attenuated** (decreased)
- **Amplifiers** are inserted to increase signal strength
- Gains, losses and relative levels of signals are expressed in decibels
  - This is a logarithmic scale, but strength usually falls logarithmically
  - Calculation of gains and losses involves simple addition and subtraction
- Decibel measure of difference in two power levels is

\[ N_{dB} = 10 \log_{10} \frac{P_1}{P_2} \]
Physical Aspects

- Signal Attenuation and Distortion
  - As a signal propagates across a transmission medium its amplitude decreases. This is known as **signal attenuation**.
  - A typical signal consists of a composition of many frequency components (Fourier Analysis). Due to the limited transmission bandwidth of a medium, the higher frequency components may not be able to be transmitted.
    - Recall the **Nyquist** formula
      \[ C = 2B \log_2 M \]
      \[ \log_2 (x) = \frac{\ln (x)}{\ln (2)} \]

Delay Distortion

- Different frequency components of a signal
  - are attenuated differently, and
  - travel at different speeds through guided media

- This may lead to **delay distortion**
Shannon capacity

A transmission line may experience interference from a number of sources, called noise. Noise is measured in terms of signal to noise power ratio, expressed in decibels:

$$\left(\frac{S}{N}\right)_{dB} = 10 \log_{10}\left(\frac{S}{N}\right)_{dB}$$

The effects of noise on channel capacity can be seen using the Shannon-Hartley Law:

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \text{ bps}$$

Where:
- $C$ = data transfer rate in bps
- $B$ = bandwidth (in hertz)

Cross Talk -- NEXT canceling

Near-end crosstalk (NEXT), cross talk of strong transmit (output) signal to weak receive (input) signal.

Adaptive NEXT canceling using op-amp
Noise

- Impulse Noise
  - impulse caused by switching, lightning etc.

- Thermal Noise
  - present irrespective of any external effects
  - caused by thermal agitation of electrons

Noise

- White Noise
  - random noise – entire spectrum

- Pink Noise
  - “realistic spectrum”
  - the power spectral density is inversely proportional to the frequency
Combined Effects

- Attenuation
- Limited Bandwidth
- Noise

It all adds up!

![Diagram showing combined effects](image)

Hal96 fig.2.6

Thermal Noise

- Energy (in joules = watts x seconds) per bit in a signal:
  \[ E_b = ST_b \]
  \[ S = \text{signal power in watts} \]
  \[ T_b = \text{time period for 1 bit in seconds} \]

- Data Transmission rate \( R = 1/T_b \)

- Thermal noise \( N_0 \) in a line is: \( T \) is temperature in K
  \[ N_0 = kTW \]
  \[ k = 1.3803 \times 10^{-23} \text{ joule K}^{-1} \]
  \( k \) is Boltzmann constant

\[ W = \text{the bandwidth} \]

\[ \frac{E_b}{N_0} = \frac{S}{R} \]

\[ \frac{N_0}{kTW} \]
Signal Delay

—There exists a **transmission propagation delay** in any medium
  - Speed of light $3 \times 10^8 \text{ ms}^{-1}$
  - Speed of EM in cable/wire $2 \times 10^8 \text{ ms}^{-1}$
—Important parameter is **round-trip-delay**
  (time from first bit sent to last bit acknowledged)

Signal Delay

—Propagation delay $T_p$ and transmission delay $T_x$

$$ T_p = \frac{d}{V}, \quad T_x = \frac{n}{R} $$

—Important ratio $\frac{T_p}{T_x}$

$d$ = distance in meters
$V$ = EM speed
$n$ = number of bits transmitted
$R$ = link bit rate in bits per second