Transmission Fundamentals

Prelude to Chapter 3 on Noise Limited Systems
Electromagnetic Signals

- Function of time \( t \)
- Can also be expressed as a function of frequency \( 2\pi ft \)
  - All useful signals consist of components of different frequencies
Time-Domain Concepts

- **Analog signal** - signal intensity varies in a smooth fashion over time
  - No breaks or discontinuities in the signal
- **Digital signal** - signal intensity maintains a constant level for some period of time and then changes to another constant level
- **Periodic signal** - analog or digital signal pattern that repeats over time
  - \( s(t + T) = s(t) \quad -\infty < t < +\infty \)
  - where \( T \) is the period of the signal
Figure 2.3 \( s(t) = A \sin (2 \, ft + \phi) \)
Sine Wave Parameters

- General sine wave
  - \( s(t) = A \sin(2\pi ft + \phi) \)

- Figure shows the effect of varying each of the three parameters
  - (a) \( A = 1, f = 1 \text{ Hz}, \phi = 0; \text{ thus } T = 1\text{s} \)
  - (b) Reduced peak amplitude; \( A = 0.5 \)
  - (c) Increased frequency; \( f = 2, \text{ thus } T = \frac{1}{2} \)
  - (d) Phase shift; \( \phi = \frac{\pi}{4} \text{ radians (45 degrees)} \)

  note: \( 2\pi \text{ radians} = 360^\circ = 1 \text{ period} \)
Time vs. Distance

- When the horizontal axis is *time*, as in waveform figure, graphs display the value of a signal at a given point in *space* as a function of *time*.

- The same graphs can apply with the horizontal axis in *space* (change in scale), then the graphs display the value of a signal at a given point in *time* as a function of *distance*.

  - At a particular instant of time, the intensity of the signal varies as a function of distance from the source.
Frequency-Domain Concepts

- **Fundamental frequency** - when all frequency components of a signal are integer multiples of one frequency, it’s referred to as the **fundamental frequency**.

- **Spectrum** - range of frequencies that makeup a signal, e.g., the frequency content of the signal.

- **Absolute bandwidth** - width of the spectrum of a signal.

- **Effective bandwidth** (or just bandwidth) - narrow band of frequencies that most of the signal’s energy is contained within (3 dB down points).
Frequency-Domain Concepts

- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies and phases. (Fourier Analysis)

- The period of the total signal is equal to the period of the fundamental frequency (the lowest frequency).
Relationship between Data Rate and Bandwidth

- The greater the bandwidth, the higher the information-carrying capacity

Conclusions

- Any digital waveform will have infinite bandwidth
- BUT the transmission system will limit the bandwidth that can be transmitted
- AND, for any given medium, the greater the bandwidth transmitted, the greater the cost (use of xmit resources)
- HOWEVER, limiting the bandwidth creates distortions and makes detection more difficult (ability to distinguish between 0’s and 1’s)
Data Communication Terms

- **Data** - entities that convey meaning, or information
- **Signals** - electric or electromagnetic representations of data
- **Transmission** - communication of data by the propagation and processing of signals
Examples of Analog and Digital Data

- Analog (continuous)
  - Video
  - Audio (acoustic based information)
- Digital (discrete)
  - Text
  - Integers
Analog Signals

- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency

- Examples of media:
  - Copper wire media (twisted pair and coaxial cable)
  - Fiber optic cable (light)
  - Atmosphere or space propagation (wireless)

- Analog signals can propagate analog and digital data (e.g. via a modem)
Audio Spectrum

Figure 2.6 Acoustic Spectrum of Speech and Music [CARN99a]
Digital Signals

- A sequence of voltage pulses that may be transmitted over a copper wire medium
- Generally cheaper than analog signaling
- Less susceptible to noise interference
- Suffers more from attenuation (higher frequency content)
- Digital signals can propagate analog (by digitizing data) and digital data
Analog Signals: Represent data with continuously varying electromagnetic wave

Analog Data (voice sound waves) → Telephone → Analog Signal

Digital Data (binary voltage pulses) → Modem → Analog Signal (modulated on carrier frequency)
Digital Signaling

Digital Signals: Represent data with sequence of voltage pulses

Example - PCM
Reasons for Choosing Data and Signal Combinations

- Digital data, digital signal
  - Equipment for encoding is less expensive than digital-to-analog equipment

- Analog data, digital signal
  - Conversion permits use of modern digital transmission, computational resources and switching equipment

- Digital data, analog signal
  - Transmission media will only propagate analog signals
  - Examples include optical fiber and POTS (3 kHz bandwidth limited)

- Analog data, analog signal
  - Analog data easily converted to an analog signal via some form of modulation (AM, FM, etc.)
Analog Transmission

- Transmit analog signals without regard to content (don’t care if signal is used to represent analog data or digital data)
- Attenuation limits length of transmission link
- Cascaded amplifiers boost signal’s energy for longer distances but cause distortion (cumulative in an analog path)
  - Analog data can tolerate distortion (less fidelity)
  - However distortion introduces errors if analog signal is being used to convey digital data
Digital Transmission

- Concerned with the content of the signal
- Attenuation endangers integrity of data
- Digital Signal
  - Repeaters used to achieve greater distance
  - Repeaters recover the signal and retransmit. Simple decision process, it’s either a 0 or a 1. (Non-cumulative errors)
  - Computers work in the digital domain
- Analog signal carrying digital data
  - Retransmission device recovers (demodulates) the digital data from analog signal
  - Generates new, clean analog signal
Channel Capacity

- Impairments, such as noise, limit the data rate that can be achieved.
- For digital data, to what extent do these impairments limit the data rate?
- Channel Capacity – the maximum rate at which data can be transmitted over a given communication path (channel), under given conditions.
Concepts Related to Channel Capacity

- **Data rate** - rate at which data can be communicated (bps)
- **Bandwidth (B)** - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- **Noise** - average level of noise over the communications path (non-correlated energy)
- **Error rate** - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1
Nyquist Bandwidth

- For binary signals (two voltage levels representing 0 and 1) the channel capacity
  - \( C = 2B \) (noise free medium)
  - \( B = \) bandwidth in Hz \( C = \) Channel Capacity in bps
  - The basis of digital sampling

- With multilevel signaling
  - \( C = 2B \log_2 M \)
  - \( M = \) number of discrete signal or voltage levels
  - \( B = \) bandwidth in Hz \( C = \) Channel Capacity in bps
  - Places additional burden on receiver and is limited in practice (ability to distinguish, no longer a simple on or off decision process).
Signal-to-Noise Ratio (SNR)

- Ratio of the power in a signal to the power contained in the noise that’s present at a particular point in the transmission.
- Typically measured at a receiver.
- Signal-to-noise ratio (SNR or S/N)

\[(SNR)_{dB} = 10 \log_{10} \left( \frac{\text{signal power}}{\text{noise power}} \right)\]

- A high SNR means a high-quality signal, high signal energy and/or low noise; SNR can be negative.
- SNR sets the upper bound on achievable data rate.
Shannon Capacity Formula

- Equation for \( C \) in bps:
  \[
  C = B \log_2(1 + \text{SNR})
  \]
  (not in dB, a ratio)

- Represents the theoretical maximum that can be achieved

- In practice, only much lower rates achieved
  - Formula assumes white noise (thermal noise) thus as \( B \) is increased, SNR will decrease
  - Factors not accounted for:
    1. Impulse noise
    2. Attenuation distortion or delay distortion – not constant over frequency range of signal
Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz; $\text{SNR}_{\text{dB}} = 24$ dB

  \[ B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz} \]
  \[ \text{SNR}_{\text{dB}} = 24 \text{ dB} = 10 \log_{10}(\text{SNR}) \]
  \[ \text{SNR} = 251 \]

- Using Shannon’s formula

  \[ C = 10^6 \times \log_2 (1 + 251) \approx 10^6 \times 8 = 8 \text{ Mbps} \]
Nyquist and Shannon Formulations

- How many signaling levels are required? (assuming Shannon’s theoretical limit can be achieved)

- Using the Nyquist Criterion

\[ C = 2B \log_2 M \]

\[ 8 \times 10^6 = 2 \times \left(10^6\right) \times \log_2 M \]

\[ 4 = \log_2 M \]

\[ M = 16 \]

- For a digital wordlength, how many bits are required?
The sampling theorem was implied by the work of Harry Nyquist in 1928 ("Certain topics in telegraph transmission theory"), in which he showed that up to $2B$ independent pulse samples could be sent through a system of bandwidth $B$. He did not explicitly consider the problem of sampling and reconstruction of continuous signals.

The sampling theorem, essentially a dual of Nyquist's result, was proved by Claude E. Shannon in 1949 ("Communication in the presence of noise").

Nyquist–Shannon sampling theorem: Exact reconstruction of a continuous-time baseband signal from its samples is possible if the signal is bandlimited and the sampling frequency is greater than twice the signal bandwidth.

The condition for exact reconstructability from samples at a uniform sampling rate (in samples per unit time) is $f_s > 2B$ or equivalently $B < f_s / 2$ where $2B$ is called the Nyquist rate and is a property of the bandlimited signal, while $f_s$ is called the Nyquist frequency and is a property of the sampling system.

The theorem naming nomenclature (why Nyquist?) is a historical oddity.
Classifications of Transmission Media

- Transmission Medium
  - Physical path between transmitter and receiver

- Guided Media
  - Waves are guided along a solid medium, loss varies logarithmically with distance
  - e.g., copper twisted pair, heliax (hardline coax), fiber

- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals, loss varies as the square of the distance
  - Usually referred to as wireless transmission
  - e.g., atmosphere, vacuum of outer space
Unguided Media

- Transmission and reception are achieved by means of an antenna (rcvr + xmtr)

- Configurations for wireless transmission
  - Directional (infers gain)
  - Omnidirectional
  - Polarization (vertical, horizontal, circular)
Electromagnetic Spectrum

Figure 2.10  Electromagnetic Spectrum for Telecommunications
Broadcast Radio

- Description of broadcast radio antennas
  - Omnidirectional (HF-vertical polarization, VHF/UHF-horizontal polarization)
  - Antennas not required to be dish-shaped
  - Antennas need not be rigidly mounted to a precise alignment

- Applications
  - Broadcast radio
    - VHF and part of the UHF band; 30 MHz to 1GHz
    - Covers FM radio and UHF and VHF television
    - Below 30 MHz transmission (AM radio) is subjected to propagation effects so not reliable for point-to-point communications (MUF or max usable freq)
Characteristics of some Frequencies

- **Microwave frequency range**
  - 1 GHz to 40 GHz
  - Directional beams possible (small)
  - Suitable for point-to-point transmission
  - Used for satellite communications

- **VHF/UHF Radio frequency range**
  - 30 MHz to 1 GHz (no atmospheric propagation, LOS)
  - Suitable for omnidirectional applications

- **Infrared frequency range**
  - Roughly $3 \times 10^{11}$ to $2 \times 10^{14}$ Hz
  - Useful in local point-to-point multipoint applications within confined areas
Terrestrial Microwave

- **Description of common microwave antenna**
  - Parabolic "dish", 3 m in diameter
  - Fixed rigidly which focuses a narrow beam
  - Achieves a line-of-sight (LOS) transmission path to the receiving antenna
  - Located at substantial heights above ground level

- **Applications**
  - Long haul telecommunications service (many repeaters)
  - Short point-to-point links between buildings
Satellite Microwave

- Description of communication satellite
  - Microwave relay station
  - Used to link two or more ground-based microwave transmitter/receivers
  - Receives transmissions on one frequency band (uplink), amplifies or repeats the signal and transmits it on another frequency (downlink)

- Applications
  - Television distribution (e.g., Direct TV)
  - Long-distance telephone transmission
  - Private business networks