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

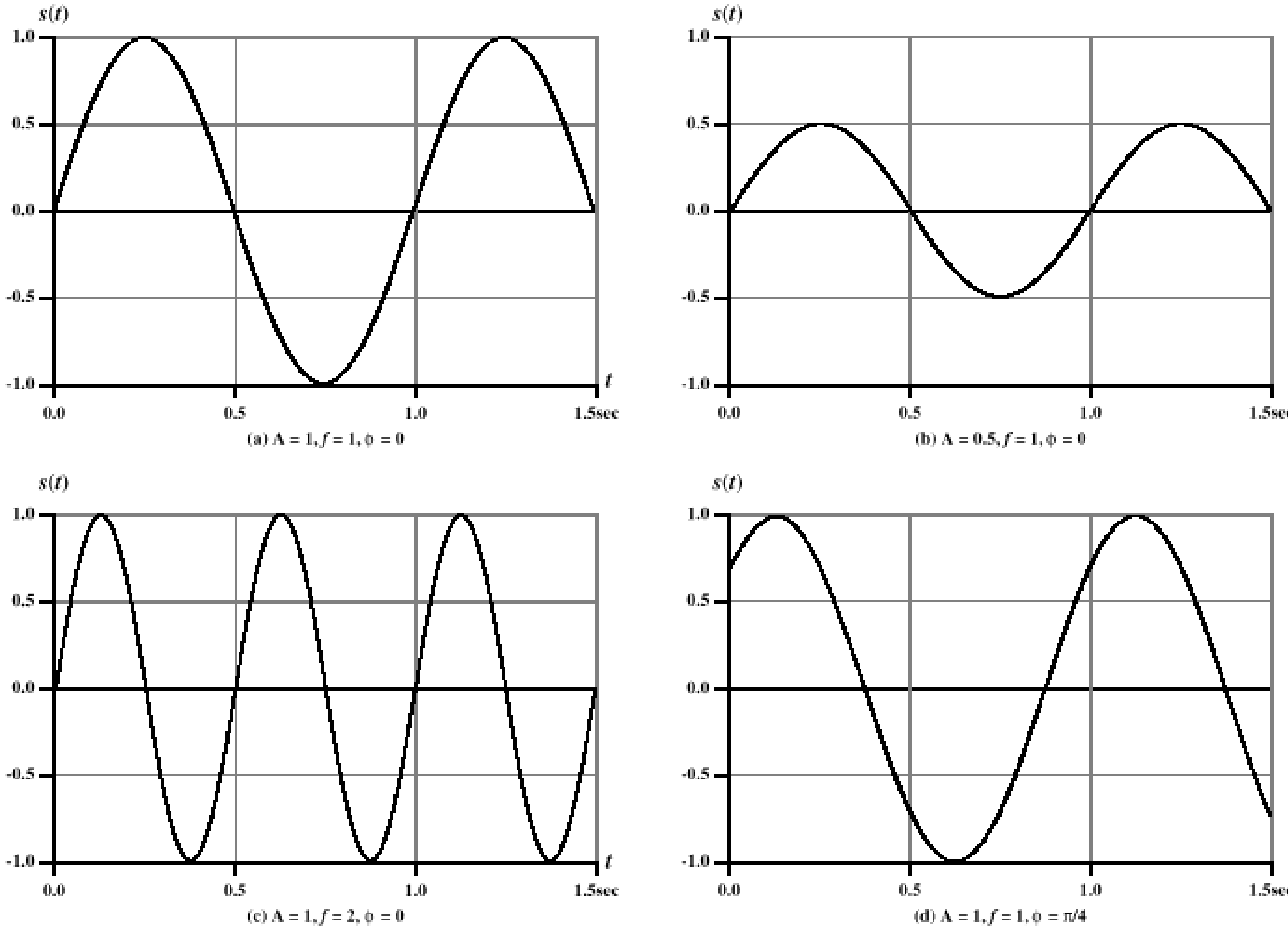


Figure 2.3 $s(t) = A \sin(2\ ft + \phi)$

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi f t + \phi)$
- Figure shows the effect of varying each of the three parameters
  - (a) $A = 1$, $f = 1$ Hz, $\phi = 0$; thus $T = 1$s
  - (b) Reduced peak amplitude; A=0.5
  - (c) Increased frequency; $f = 2$, thus $T = ½$
  - (d) Phase shift; $\phi = \pi/4$ radians (45 degrees)

    note: 2π radians = 360° = 1 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

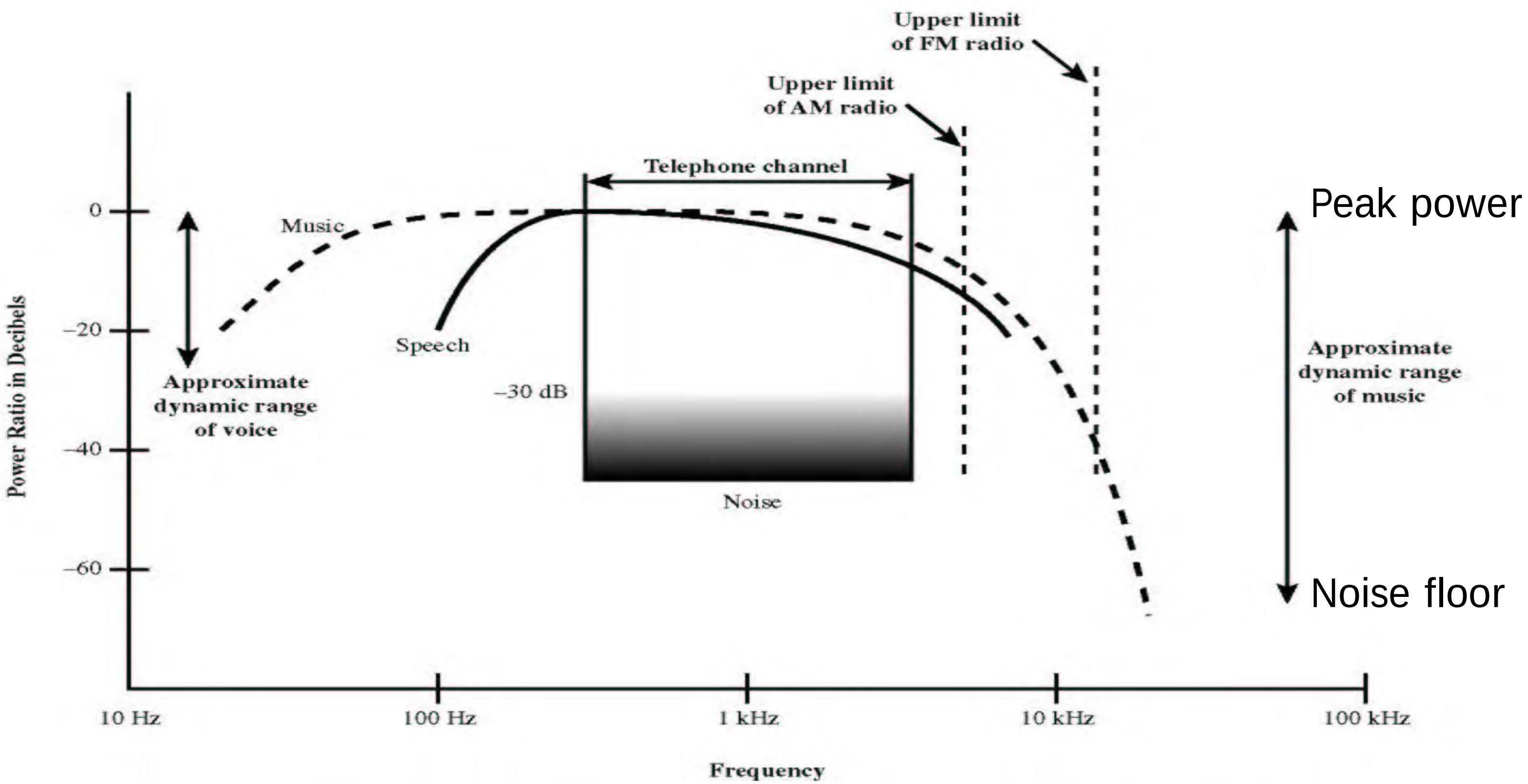


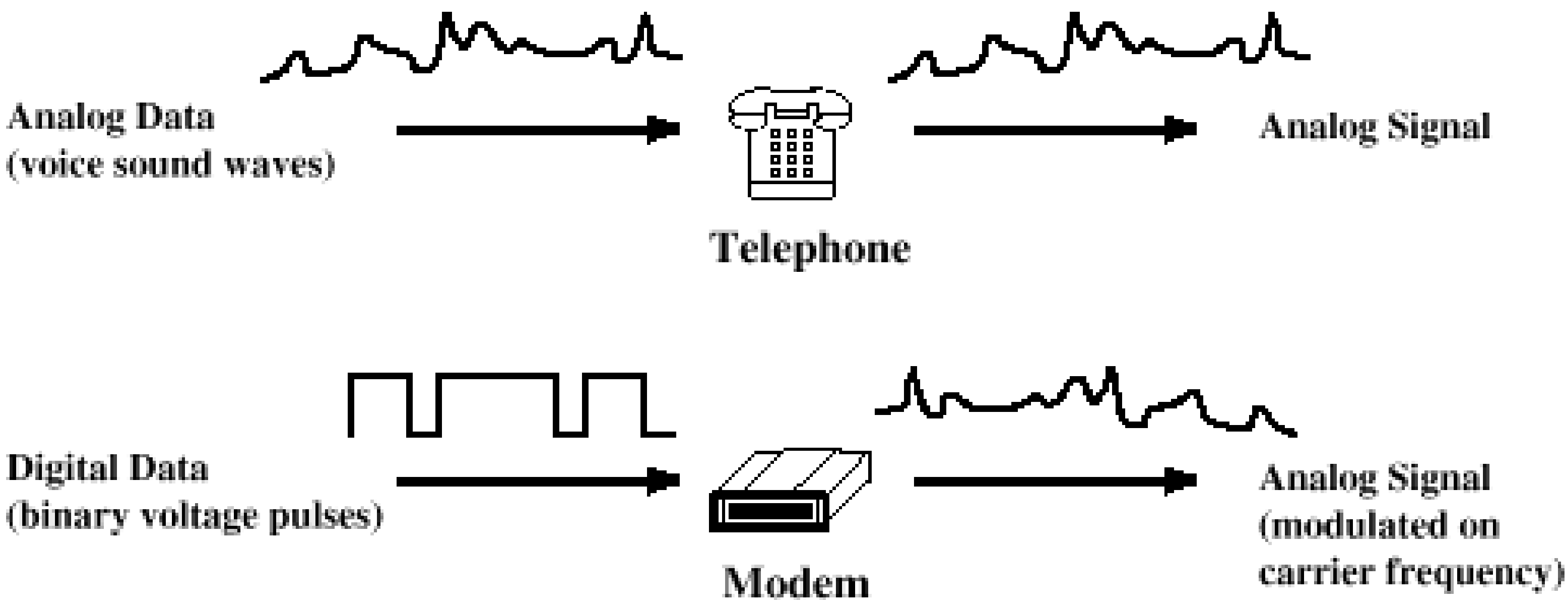
Figure 2.6 Acoustic Spectrum of Speech and Music [CARN99a]

Digital Signals

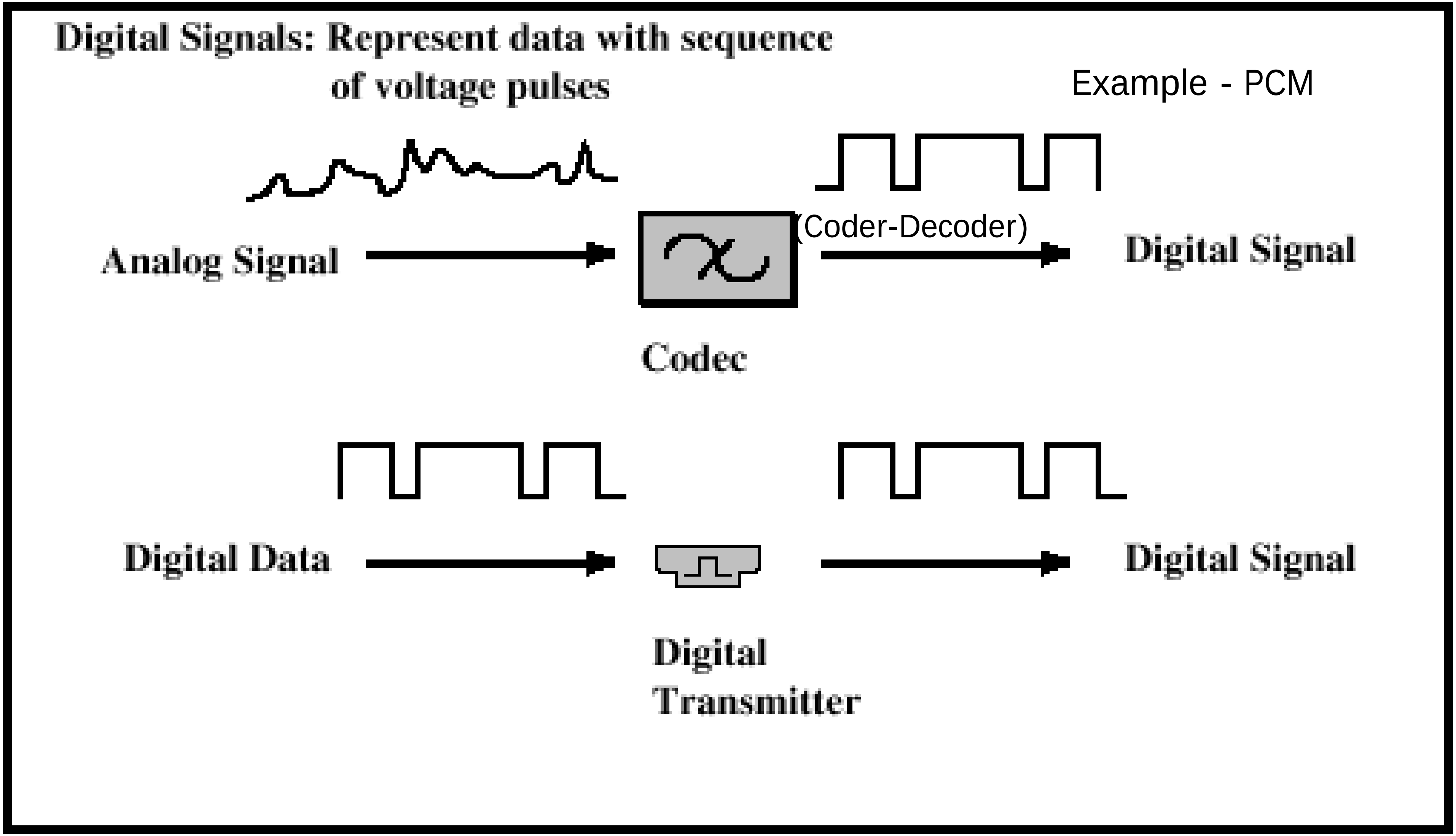
- A sequence of voltage pulses that may be transmitted over a copper wire medium
- Generally cheaper than analog signaling
- Less susceptible to noise interference
- Suffers more from attenuation (higher frequency content)
- Digital signals can propagate analog (by digitizing data) and digital data

Analog Signaling

Analog Signals: Represent data with continuously varying electromagnetic wave



Digital Signaling



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* = 2*B*** *(noise free medium)*
    - B = bandwidth in Hz C = Channel Capacity in bps
    - The basis of digital sampling
- With multilevel signaling
  - $\boldsymbol{C = 2B \log_2 M}$
    - *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)

$$(SNR)_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- 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:

not in dB, a ratio

$$C = B\log_2\left(1+\mathrm{SNR}\right)$$

- 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 ; $SNR_{dB} = 24$ dB

$$B = 4\,\text{MHz} - 3\,\text{MHz} = 1\,\text{MHz}$$

$$SNR_{dB} = 24\,\text{dB} = 10\log_{10}(SNR)$$

$$SNR = 251$$

- 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

$$C = 2B\log_2 M$$

$$8\times10^6 = 2\times\left(10^6\right)\times\log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

- For a digital wordlength, how many bits are required?

Relationship of the Nyquist and Shannon Theorems

- 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.

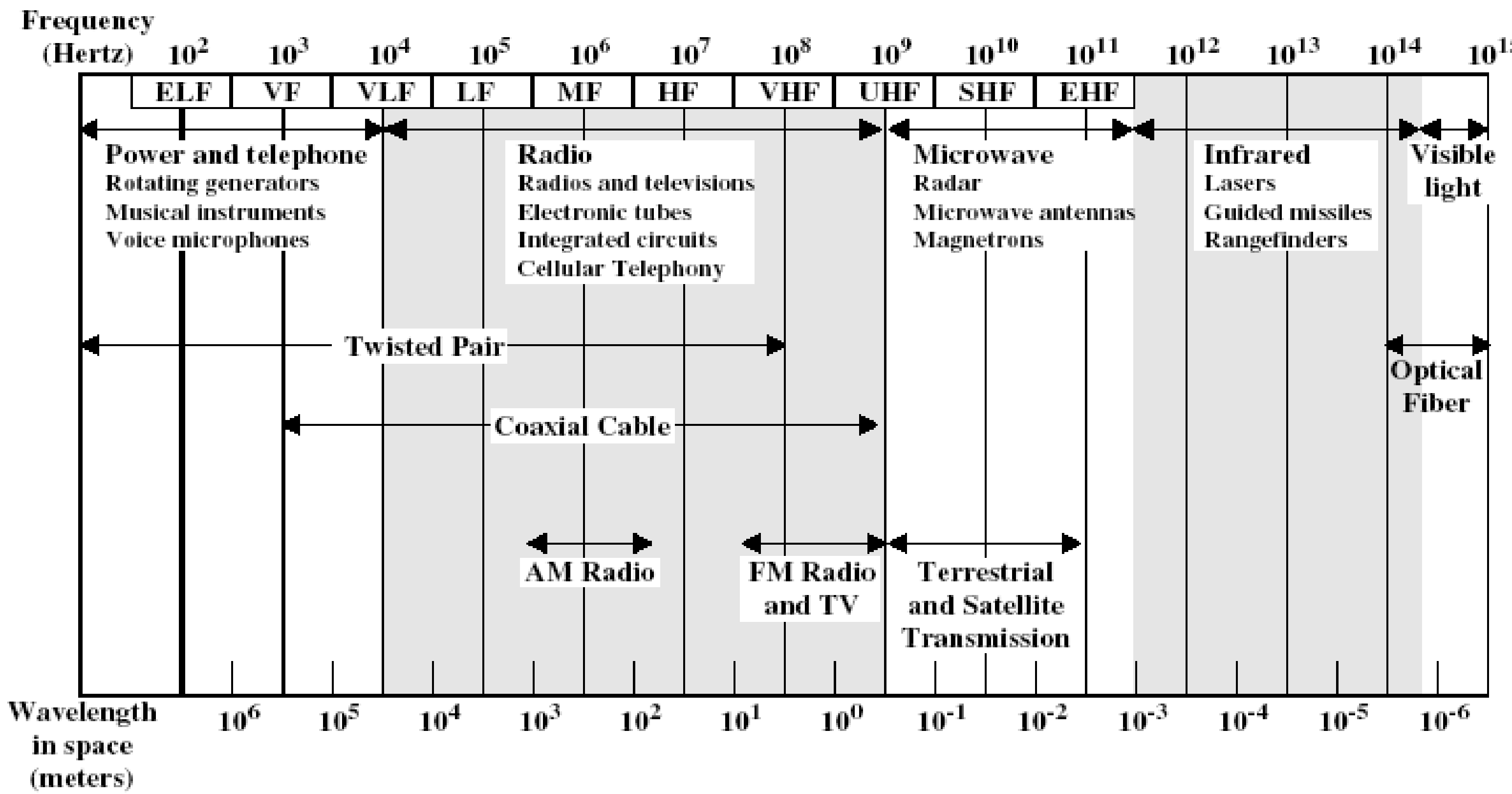
Classifications of Transmission Media

- 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



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

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 $3x10^{11}$ to $2x10^{14}$ 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