Transmission Fundamentals

Chapter 2 (Stallings Book)

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Electromagnetic Signal

- is a function of time
- can also be expressed as a function of frequency
  - Signal consists 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
- Aperiodic signal - analog or digital signal pattern that doesn't repeat over time

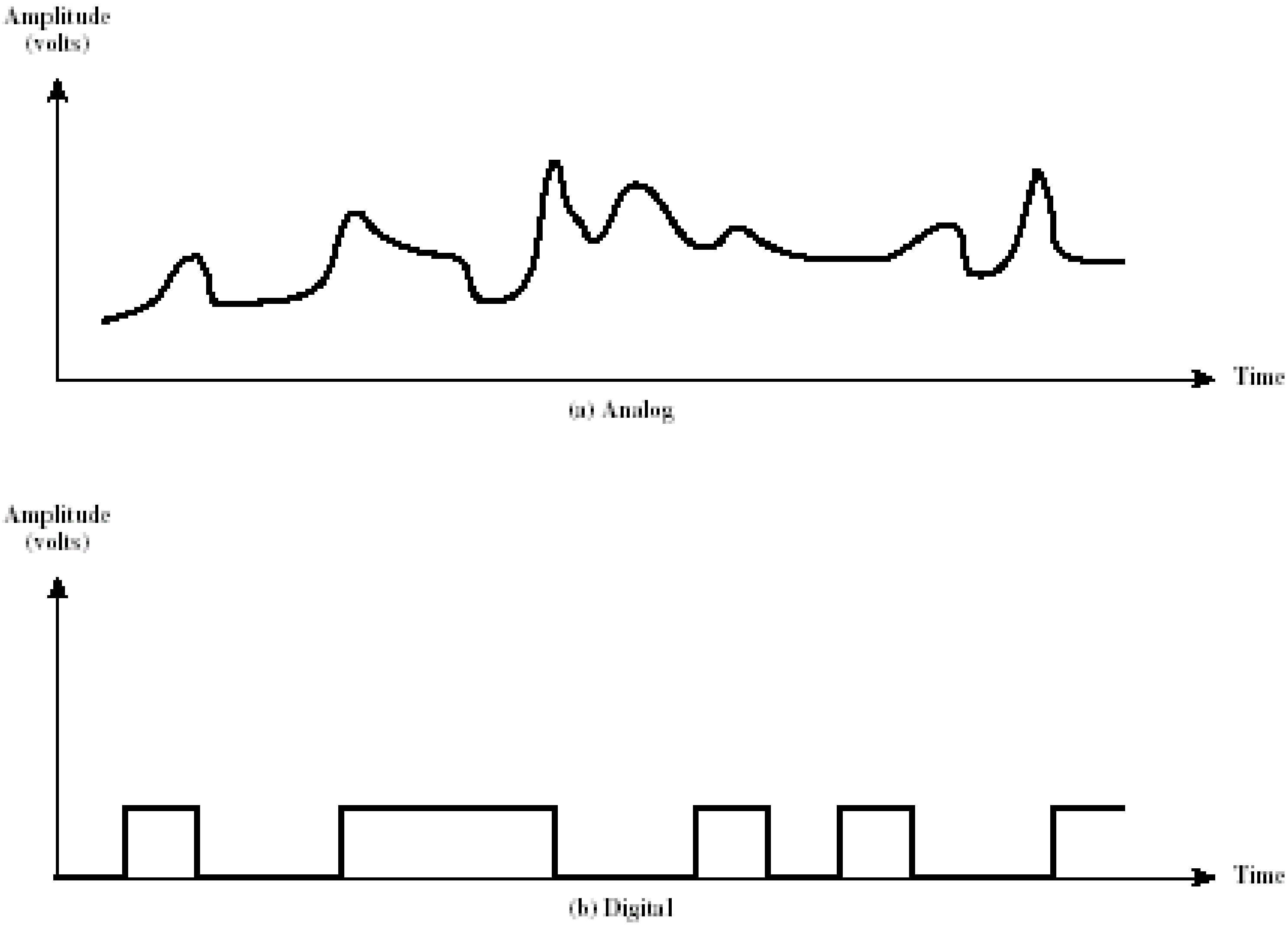


Figure 2.1 Analog and Digital Waveforms

Time-Domain Concepts (cont.)

- Peak amplitude (*A*)
  - maximum value or strength of the signal over time
  - typically measured in volts
- Frequency (*f*)
  - Rate, in cycles per second, or Hertz (Hz), at which the signal repeats

Time-Domain Concepts (cont.)

- Period (T)
  - amount of time it takes for one repetition of the signal
  - $T = 1/f$
- Phase (ϕ) - measure of the relative position in time within a single period of a signal
- Wavelength (λ) - distance occupied by a single cycle of the signal
  - Ex: Speed of light is $v = 3 \times 10^8$ m/s. Then the wavelength is $\lambda f = v$ (or $\lambda = vT$)

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi f t + \phi)$
  - note: 2π radians = 360° = 1 period
- Figure 2.3 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)

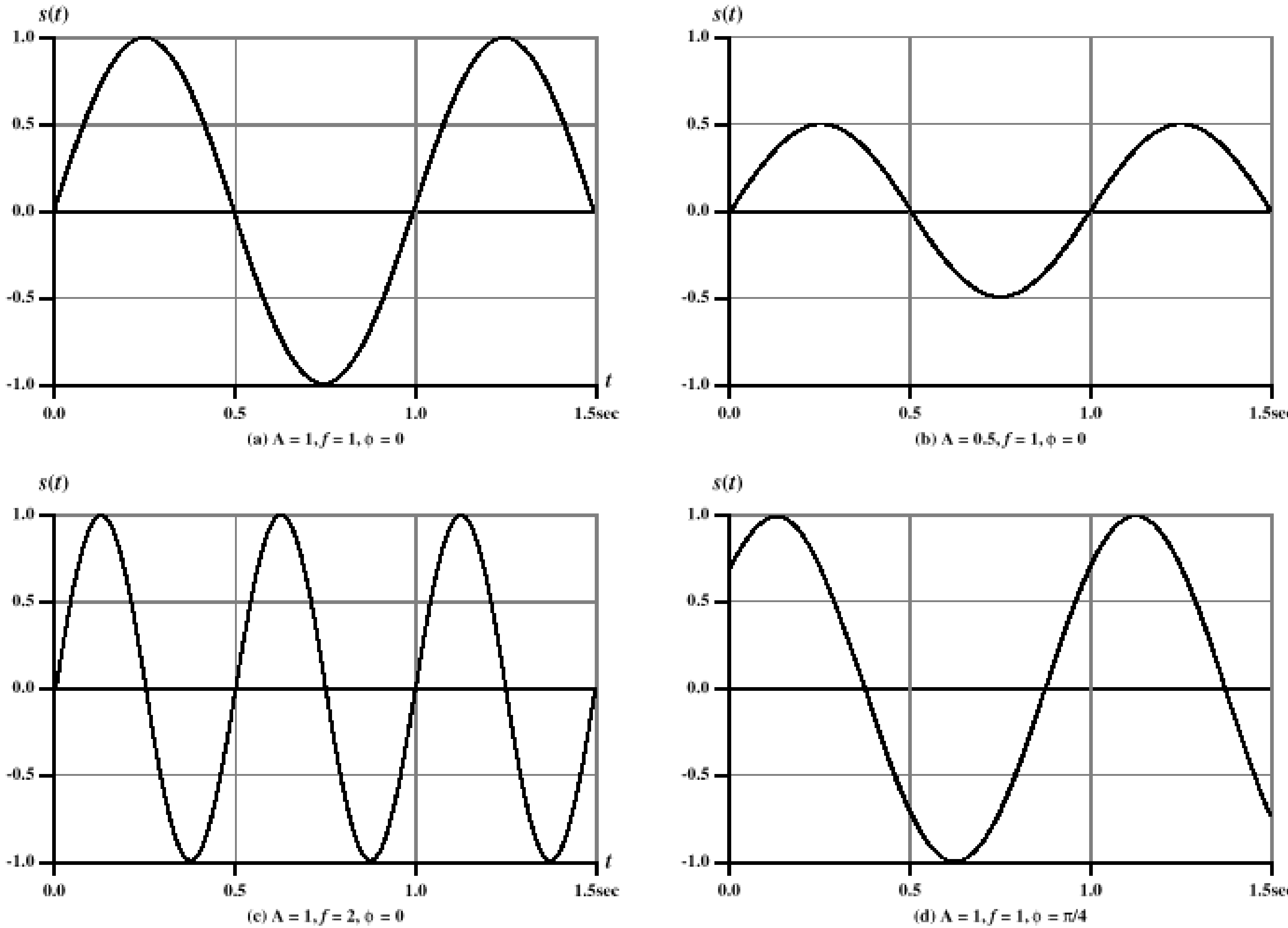
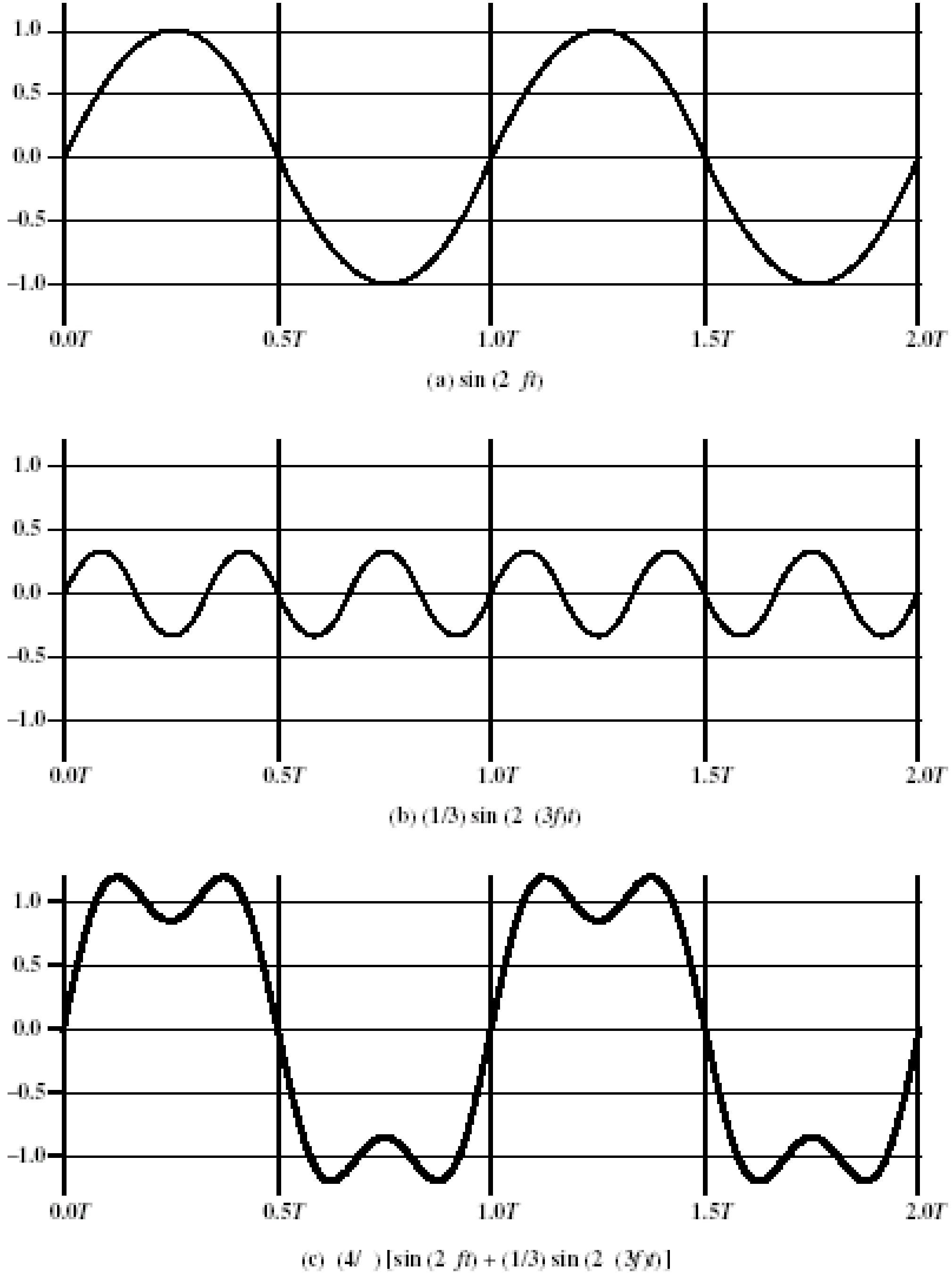


Figure 2.3 $s(t) = A \sin (2\ ft + \phi)$

Frequency-Domain Concepts

- An electromagnetic signal can be made up of many frequencies.
  - Example: $s(t) = (4/\pi)x(\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t))$
    - Fig. 2.4(a) + Fig. 2.4(b) = Fig. 2.4(c)
    - There are two component frequencies: f and 3f
  - Based on Fourier analysis, any signal is made up of components at various frequencies,
    - in which each component is a sinusoid wave
    - at different amplitudes, frequencies, and phases.



$$s(t) = A \times \frac{4}{\pi} \sum_{k \text{ odd}, k=1}^{\infty} \frac{\sin(2\pi k f t)}{k}$$

Figure 2.4 Addition of Frequency Components ($T = 1/f$)

Frequency-Domain (cont.)

- Spectrum - range of frequencies that a signal contains
  - In Fig. 2.4(c), spectrum extends from f to 3f
- Absolute bandwidth - width of the spectrum of a signal
  - In Fig. 2.4(c), it is 3f – f = 2f
- Effective bandwidth –
  - A signal may contain many frequencies
  - But most of the energy may concentrate in a narrow band of frequencies
  - These frequencies are effective bandwidth

Frequency-Domain (cont.)

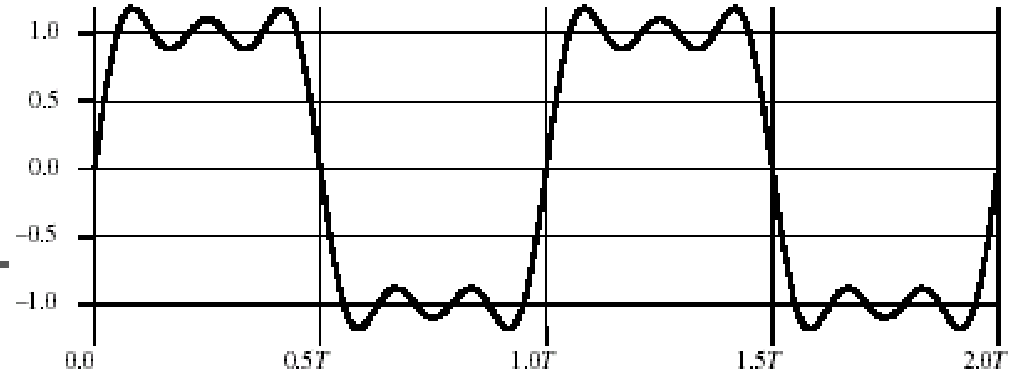
- Fundamental frequency –
  - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
  - (earlier example) f and 3f → fund. freq = f
- The period of the total signal is equal to the period of the fundamental frequency
  - refer to Fig. 2.4 again!

Data vs. Signal

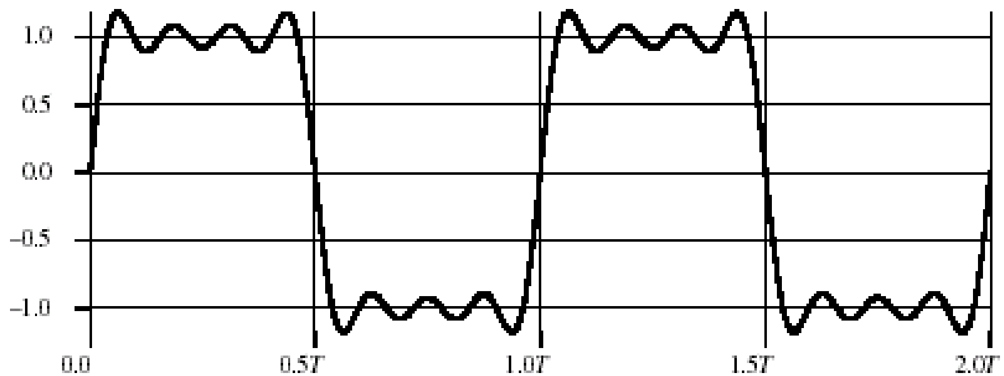
- Data - entities that convey meaning, or information
- Signals - electric or electromagnetic representations of data
- Transmission - communication of data by the propagation and processing of signals

Approximating Square Wave by Signals

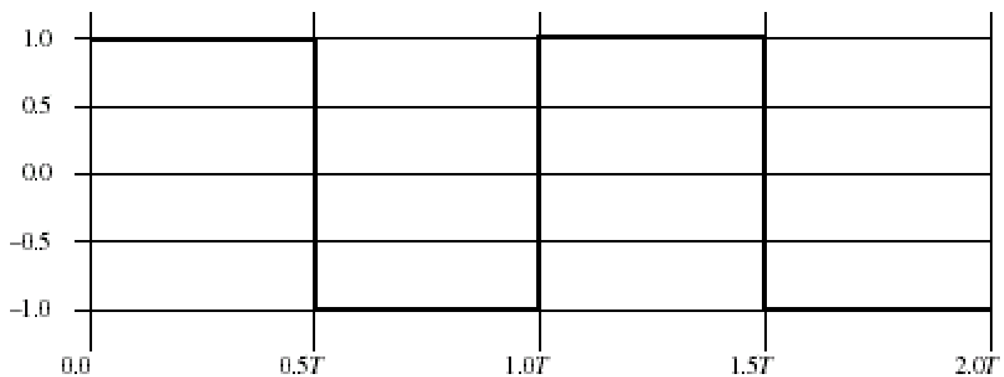
- adding a frequency of 5f to Fig. 2.4(c) → Fig. 2.5(a)
- adding a frequency of 7f to Fig. 2.4(c) → Fig. 2.5(b)
- adding all frequencies of 9f, 11f, 13f, ... → Fig. 2.5(c), a square wave
  - This square wave has an infinite number of frequency components, and thus infinite bandwidth



(a) (4/) [sin (2 ft) + (1/3) sin (2 (3f)t) + (1/5) sin (2 (5f)t)]



(b) (4/) [sin (2 ft) + (1/3) sin (2 (3f)t) + (1/5) sin (2 (5f)t) + (1/7) sin (2 (7f)t)]



(c) (4/) ∑ (1/k) sin (2 (kf)t), for k odd

Figure 2.5 Frequency Components of Square Wave (T = 1/f)

Data Rate vs. Bandwidth

- Case I: (Fig. 2.5(a))
  - Let f = 10^6 cycles/sec = 1 MHz
  - frequency components: 1f, 3f, 5f
  - absolute bandwidth = 5f – 1f = 4f = 4 MHz
  - Note that for $f = 1$ *MHz, the period of the* fundamental frequency is $T = 1/10^6 = 1\ \mu s$
  - If we treat this waveform as a bit string of 1s and 0s, one bit occurs every 0.5 μs
  - data rate = 2×10^6 = 2 Mbps (1 bit per 0.5 μs)
    - 1 bit per 0.5 μs, means 2 bits per 1 μs
    - Mean 2 x 10^6 bps = 2 Mbps

Data Rate vs. Bandwidth

- Case II: (Fig. 2.5(a))
  - Let f = 2×10^6 cycles/sec = 2 MHz
  - frequency components: 1f, 3f, 5f
  - absolute bandwidth = 10MHz – 2MHz = 8 MHz
  - $T = 1/f = 1/2.10^6 = 0.5\ \mu s$
  - one bit occurs every 0.25 μs
    - Means 4 bits per 1 μs
    - Means 4×10^6 bps
  - data rate = 4×10^6 = 4 Mbps

- Case III: (Fig. 2.4(c))
  - Let f = 2×10^6 cycles/sec = 2 MHz
  - frequencies: 1f, 3f
  - absolute bandwidth = 6MHz – 2MHz = 4MHz
  - $T = 1/f = 1/2.10^6 = 0.5\ \mu s$
  - one bit occurs every 0.25 μs
    - Means 4 bits per 1 μs
    - Means 4×10^6 bps
  - data rate = 4×10^6 = 4 Mbps
- ** compare the absolute bandwidth and data rate in the above examples!

- Bandwidth=4 MHz; data rate = 2 Mbps
- Bandwidth=8 MHz; data rate = 4 Mbps
- Bandwidth=4 MHz; data rate = 4 Mbps
  - In general, any digital waveform will have infinite bandwidth
  - If we attempt to transmit this waveform as a signal over any medium, the transmission system will limit the bandwidth that can be transmitted
    - for any given medium, the greater the bandwidth transmitted, the greater the cost
  - digital information be approximated by a signal of limited bandwidth
    - economic and practical reasons, vs.
    - creates distortions, which makes the task of interpreting the received signal more difficult

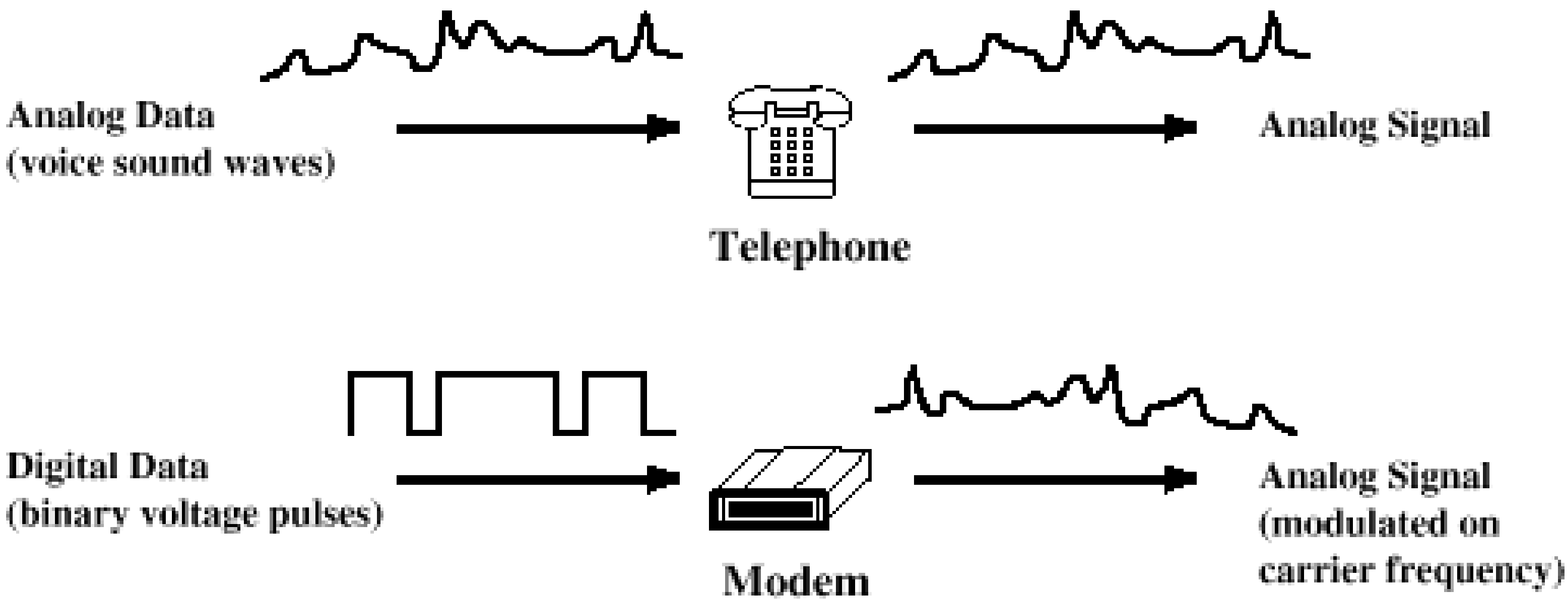
Examples of
Analog and Digital Data

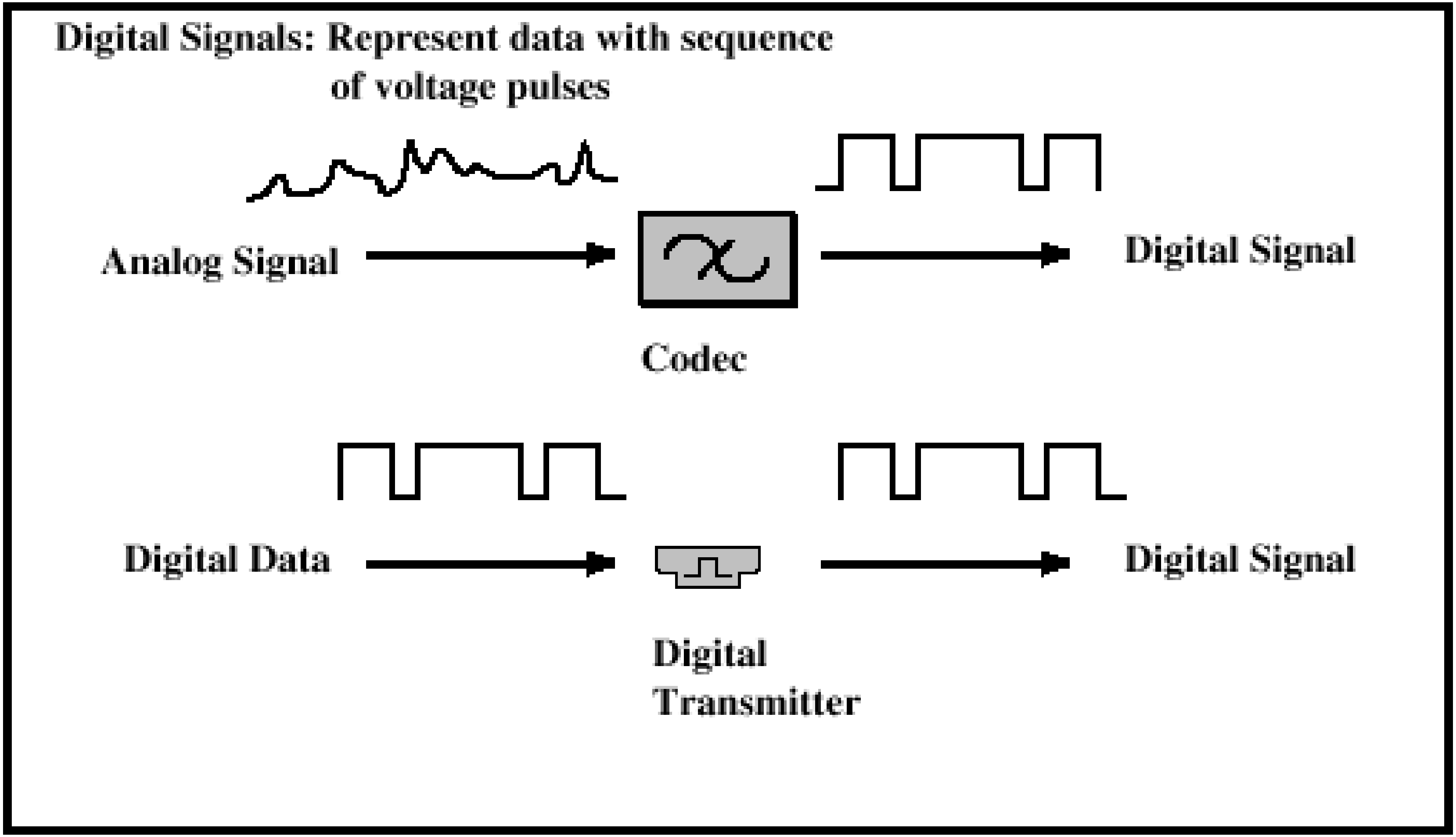
- Analog
  - Video
  - Audio
- Digital
  - Text
  - Integers

Analog vs. Digital Signals

- Analog
  - 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
    - Atmosphere or space propagation
  - Analog signals can propagate analog and digital data
- Digital
  - A sequence of voltage pulses that may be transmitted over a copper wire medium
  - Generally cheaper than analog signaling
  - Less susceptible to noise interference
  - Suffer more from attenuation
  - Digital signals can propagate analog and digital data

Analog Signals: Represent data with continuously varying electromagnetic wave




Digital Signals: Represent data with sequence of voltage pulses
Analog Signal
Codec
Digital Signal
Digital Data
Digital Transmitter
Digital Signal

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 and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - Examples include optical fiber and satellite
- Analog data, analog signal
  - Analog data easily converted to analog signal

Concepts Related to Channel Capacity

- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise
- Channel Capacity – the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions
- Error rate - rate at which errors occur

Nyquist Bandwidth

- Given a bandwidth of B, the highest signal transmission rate is 2B:
  - $C = 2B$
  - *Ex: B=3100 Hz; C=6200 bps*
- With multilevel signaling
  - $C = 2B \log_2 M$, where M is the number of discrete signal or voltage levels

Signal-to-Noise Ratio

- 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)

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

  - $= 10 \log_{10} \mathrm{SNR}$
  - A high SNR means a high-quality signal
  - SNR sets an upper bound on the achievable data rate

Shannon Capacity Formula

- The max. channel capacity:

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

  - note: SNR not in db
- In practice, only much lower rates achieved
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
    - Short duration "on/off" noise pulses
  - Attenuation distortion or delay distortion not accounted for

Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz ; $SNR_{dB} = 24$ dB

- By Shannon's formula, What is the max. channel capacity?

Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB

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

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

$$\text{SNR} = 251$$

- By Shannon's formula, the max. capacity:

$$C = 10^6 \times \log_2(1+251) \approx 10^6 \times 8 = 8\text{Mbps}$$

- To achieve the max. capacity of 8 Mbps, how many signaling levels are required?

- To achieve the max. capacity of 8 Mbps, how many signaling levels are required?

$$C = 2B\log_2 M$$

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

$$4 = \log_2 M$$

$$M = 16$$

Classifications of Transmission Media

- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
  - E.g., atmosphere, outer space

General Frequency Ranges

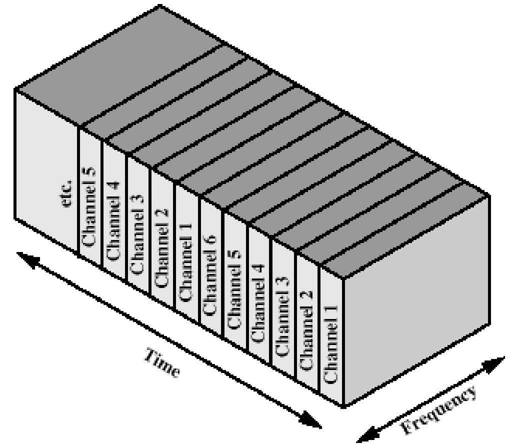
- Microwave frequency range
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for long-distance, point-to-point transmission
  - Used for satellite communications
- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- Infrared frequency range
  - Roughly, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point multipoint applications within confined areas

Multiplexing

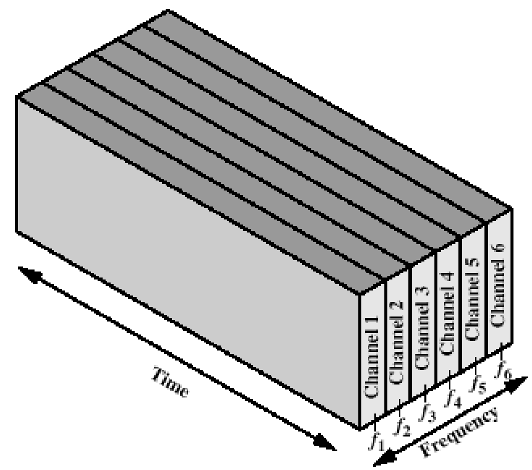
- Capacity of transmission medium usually exceeds the required capacity
- Multiplexing - carrying multiple signals on a single medium
  - More efficient use of transmission medium

Multiplexing Techniques

- Frequency-division multiplexing (FDM)
  - Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal



- Time-division multiplexing (TDM)
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal



Summary

- signal
- analog vs. digital transmissions
- channel capacity
- transmission media
- multiplexing