Data Transmission

Basic terminology

- Transmission medium: guided and unguided
- Link: point-to-point, multi-point
- Transmission: simplex, half-duplex, full-duplex
- Data: analog, digital – block-oriented, stream
- Block-oriented
  - 8x10 in color picture scanned at 400x400 pixels/sq. in = 38.4 MB
- Stream information
  - Audio sampled 8000 samples/sec. 8 bits/sample = 64 kbps
  - CD quality: 44,000 samples/sec. 16 bits/sample x 2 = 1.4 Mbps

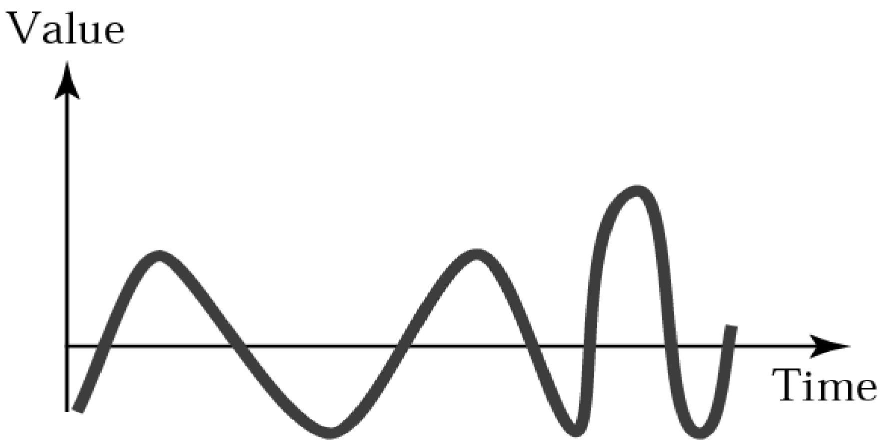
Signal

- A variable (or multiple variables) that changes in time
  - Speech or audio signal: A sound amplitude that varies in time
  - Temperature readings at different hours of a day
  - Stock price changes over days
- More generally, a signal may vary in 2-D space and/or time
  - A picture: the color varies in a 2-D space
  - A video sequence: the color varies in 2-D space and in time
- Continuous vs. Discrete
  - The value can vary continuously or take from a discrete set
  - The time and space can also be continuous or discrete

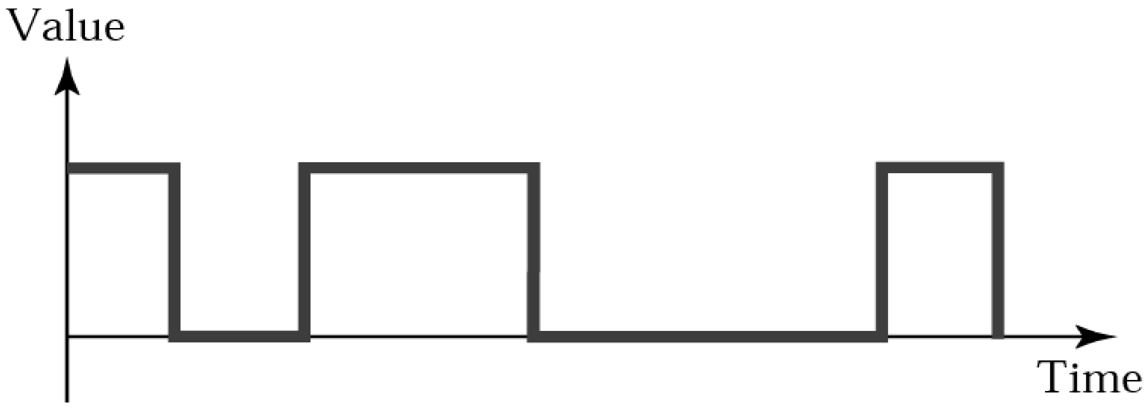
Characterization of Signals

- Signal: Representation of a set of data as function of time
  - e.g. packet RTTs measured at source (discrete,aperiodic,analog)
  - e.g. no. of HTTP requests at server/sec (discrete,aperiodic,digital)
- Analog: signal takes continuous real values
- Digital: signal takes values from a quantized set
- Periodic: signal repeats itself over time
- Aperiodic: cannot determine a period
- Sine wave: fundamental periodic signal
  - Peak amplitude, frequency, phase, wavelength

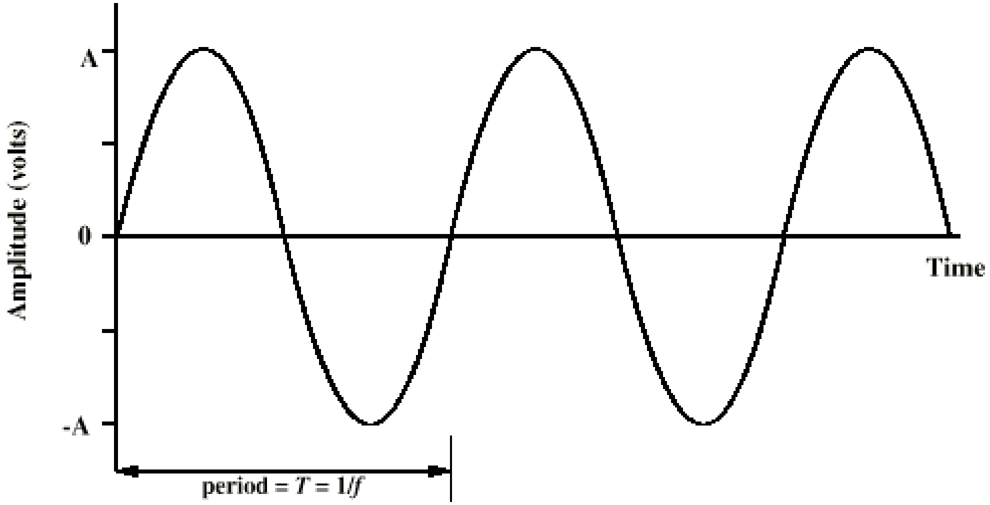
Types of Signals



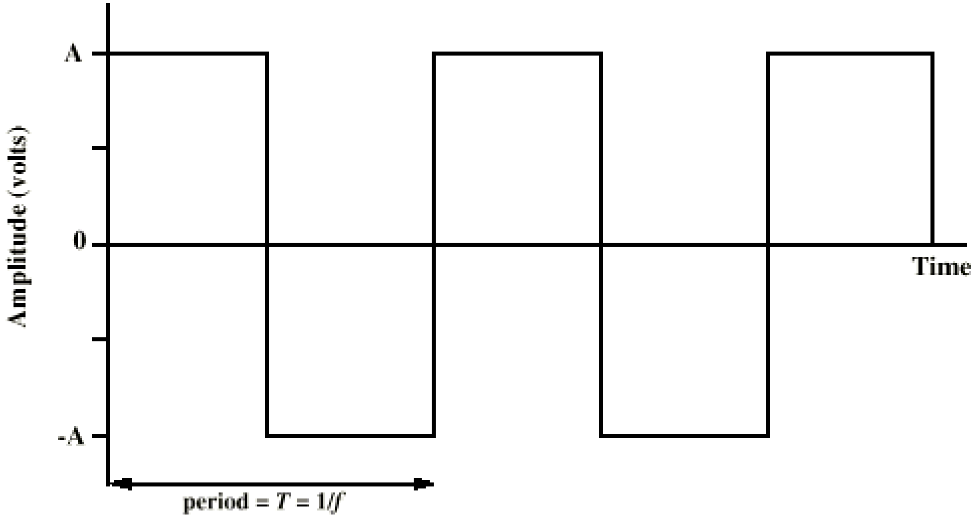
a. Analog signal



b. Digital signal

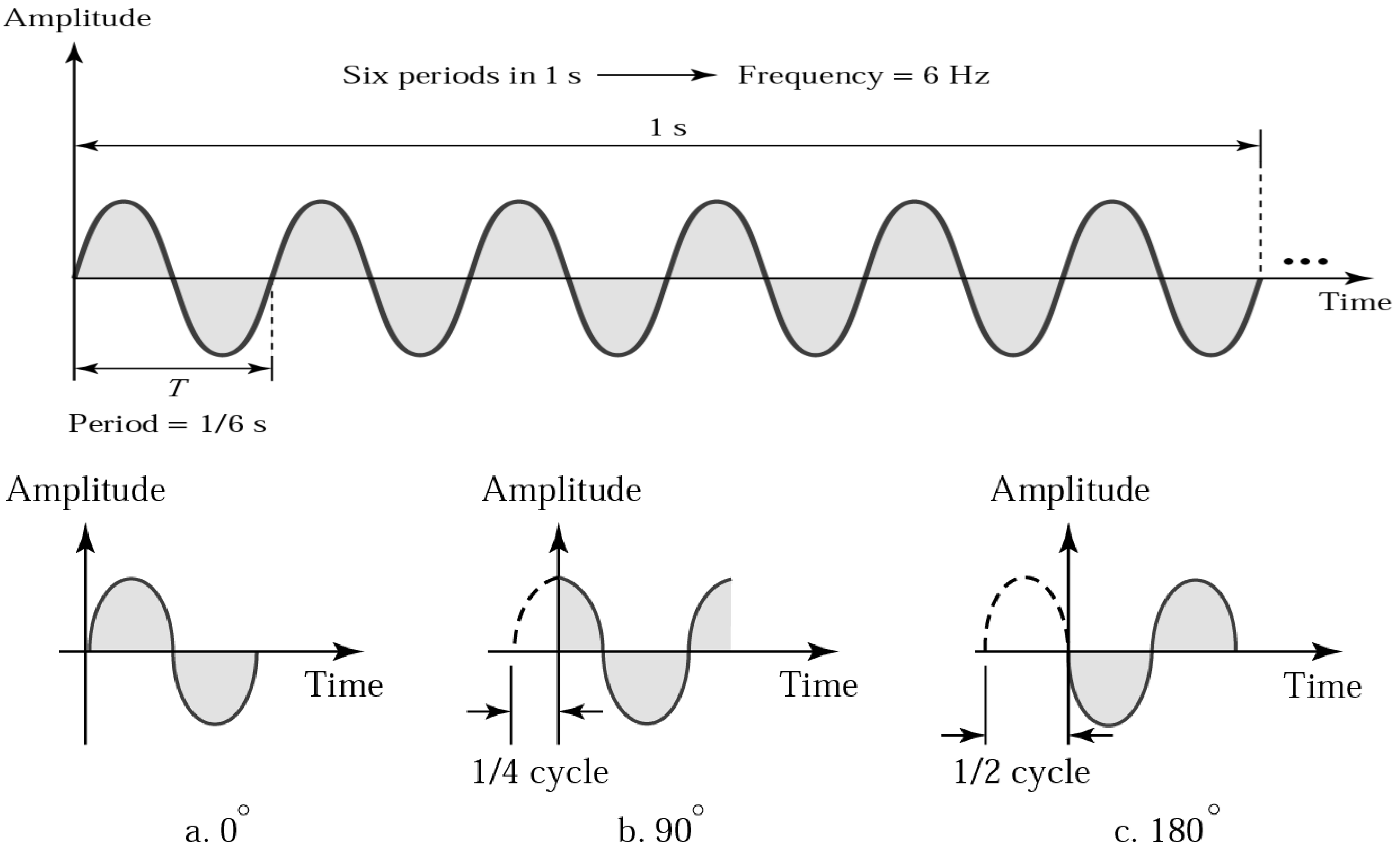


(a) Sine wave

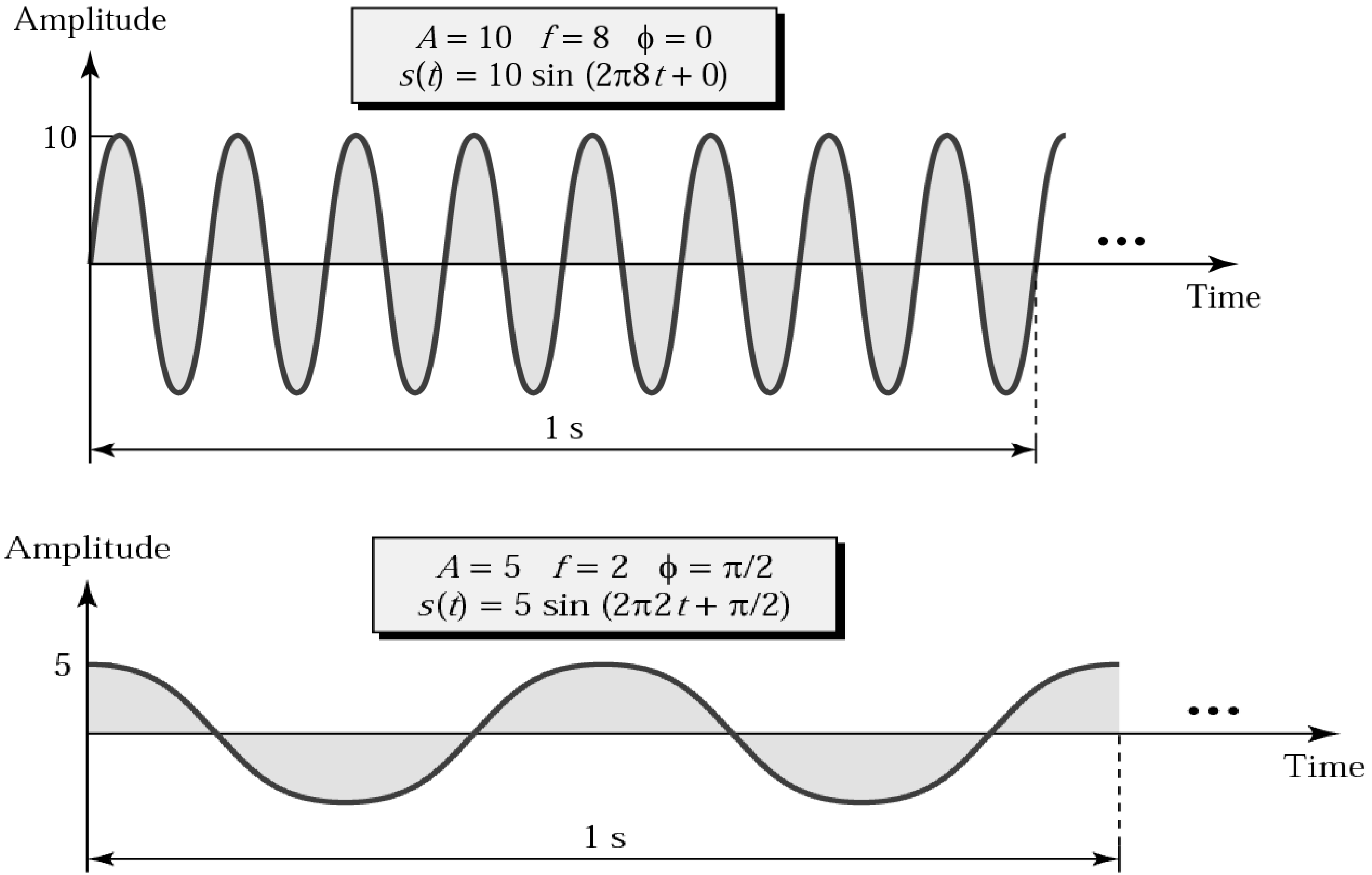


(b) Square wave

Illustration

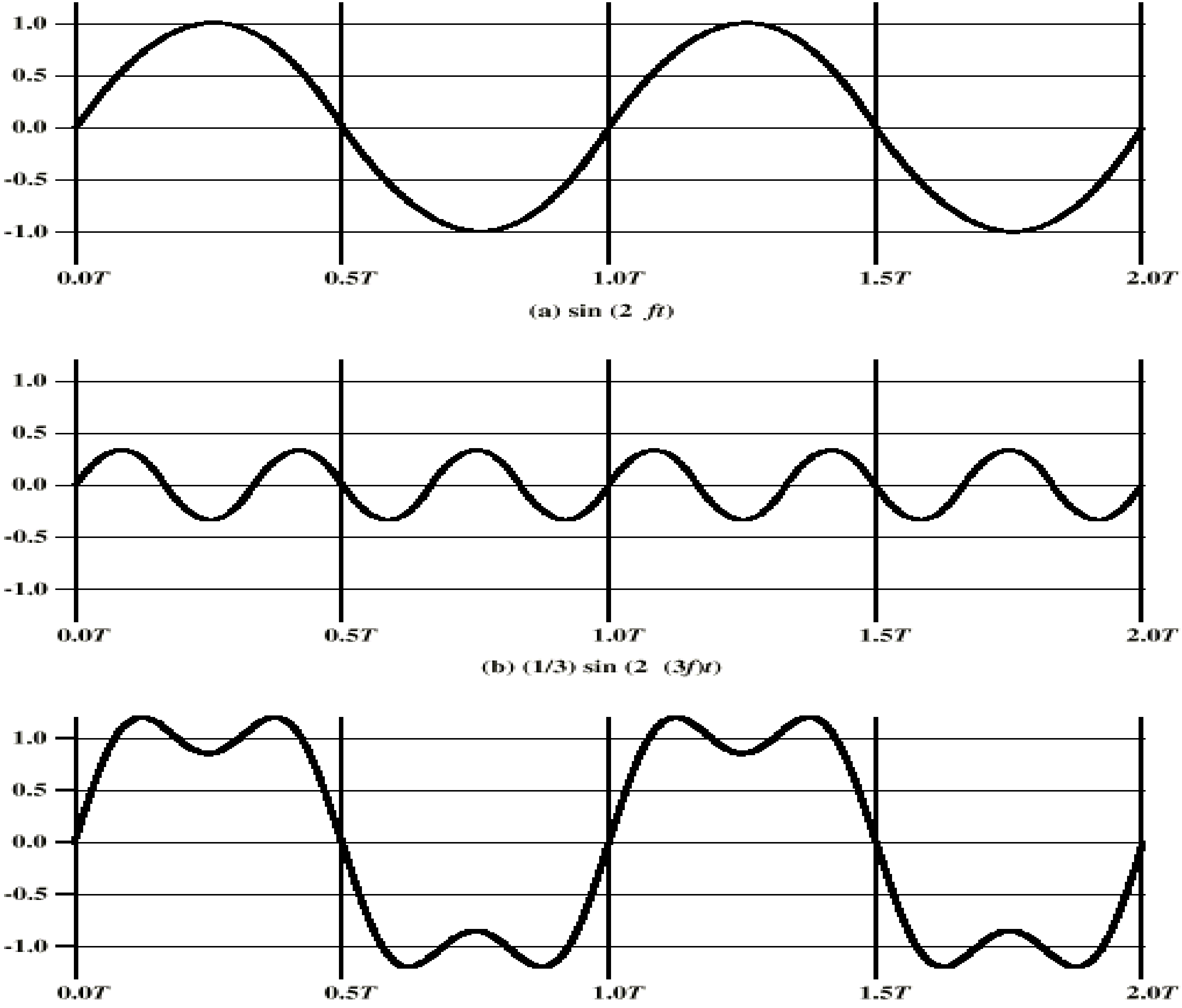


Illustration



Composite Signal

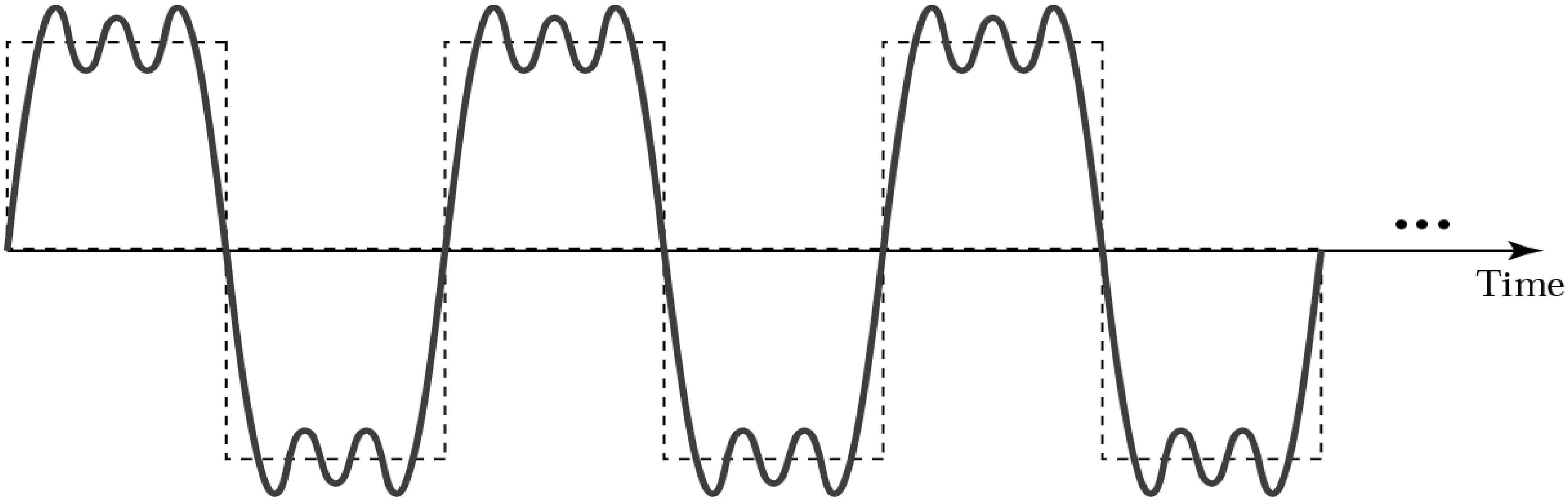
- Fundamental frequency
- Harmonics
- Period of signal equals that of fundamental frequency
- Fourier analysis used to derive component signals



(a) sin (2 ft)

(b) (1/3) sin (2 (3f)t)

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



b. Frequency spectrum of an approximation with only three harmonics

Fourier Analysis

- Any composite signal can be expressed as combination of sinusoids
  - Periodic: finite number of discrete frequencies
  - Aperiodic: infinite number of continuous frequencies
  - Fundamental frequency and harmonics
- Digital signal: composite analog signal approximation
  - Contains frequencies between zero and infinity
  - Periodic: infinite number of discrete frequencies
  - Aperiodic: infinite number of continuous frequencies
- Spectrum: frequencies present in signal
- Bandwidth: width of the spectrum

Fourier Series and Transform

- Every composite periodic signal can be represented with a series of sine and cosine functions.
- The functions are integral harmonics of the fundamental frequency “f” of the composite signal.
- Using the series we can decompose any periodic signal into its harmonics.

- Fourier Transform gives the frequency domain of a nonperiodic time domain signal.

Fourier Series: Representation

- Sine-cosine representation

$$x(t) = a_0 + \sum_{n=1}^{\infty} \left[a_n \cos(2\pi f_0 n t) + b_n \sin(2\pi f_0 n t) \right]$$

$$a_0 = \frac{1}{T} \int_0^T x(t)\,dt$$

$$a_n = \frac{2}{T} \int_0^T x(t) \cos(2\pi n f_0 t)\,dt$$

$$b_n = \frac{2}{T} \int_0^T x(t) \sin(2\pi n f_0 t)\,dt$$

Fourier Series: Representation

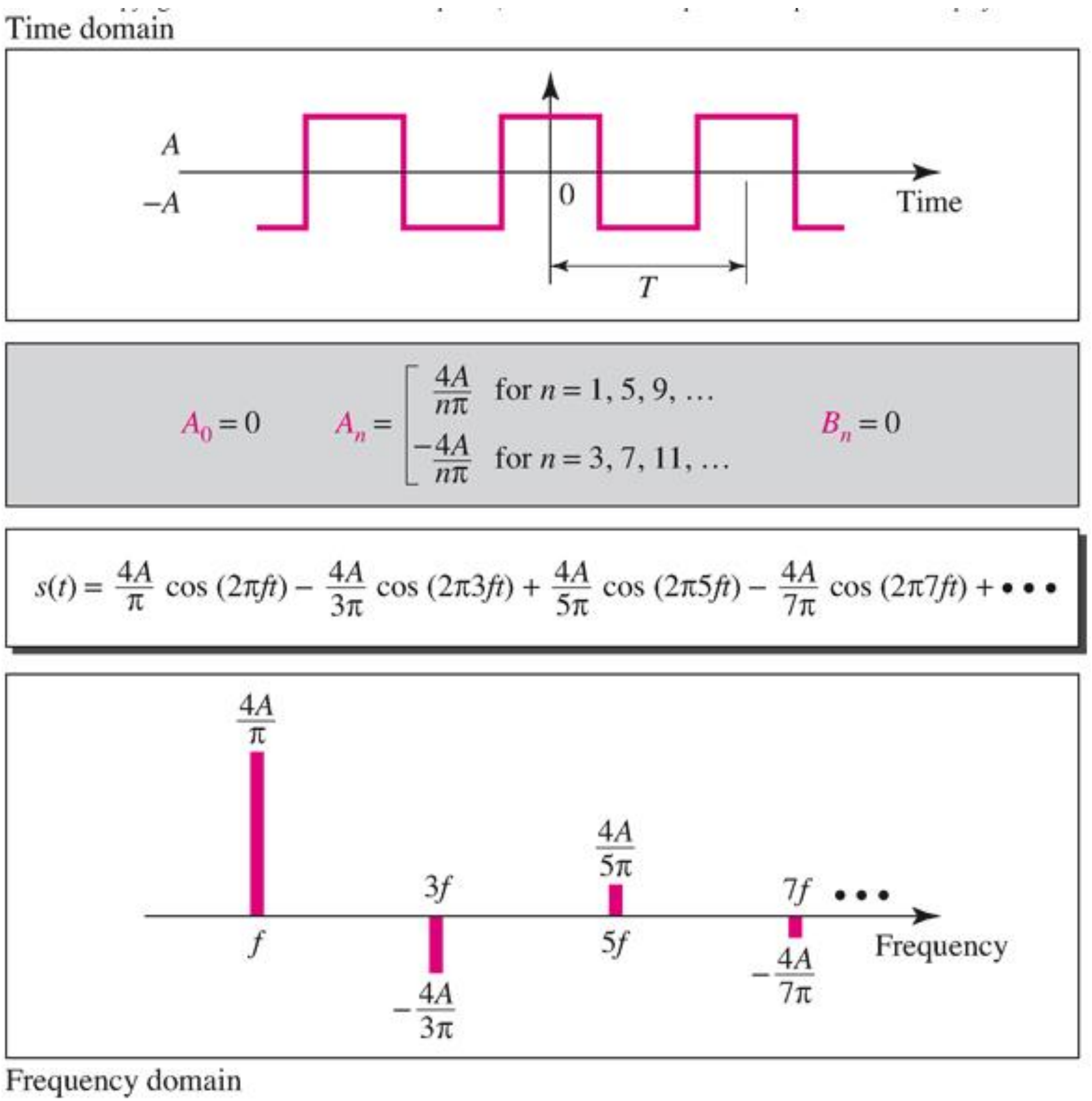
- Amplitude-phase representation

$$\boxed{x(t) = c_0 + \sum_{n=1}^{\infty} \left[c_n \cos(2\pi f_0 n t + \phi_n) \right]}$$

$$\boxed{\begin{aligned} c_0 &= a_0 \\ c_n &= \sqrt{a_n^2 + b_n^2} \\ \phi_n &= -\tan^{-1}\left(\frac{b_n}{a_n}\right) \end{aligned}}$$

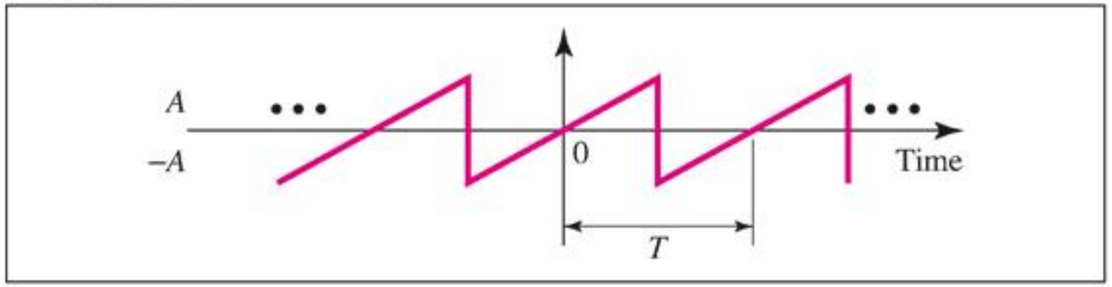
Examples of Signals and the Fourier Series Representation

- Coefficient A_0 indicates DC component of signal
- Component of zero frequency
- Non-zero average amplitude in time domain



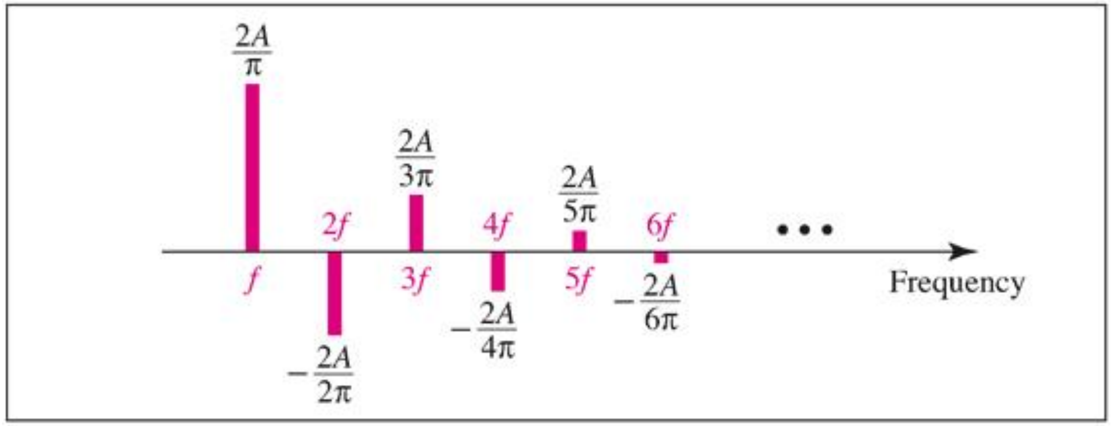
Sawtooth Signal

Time domain



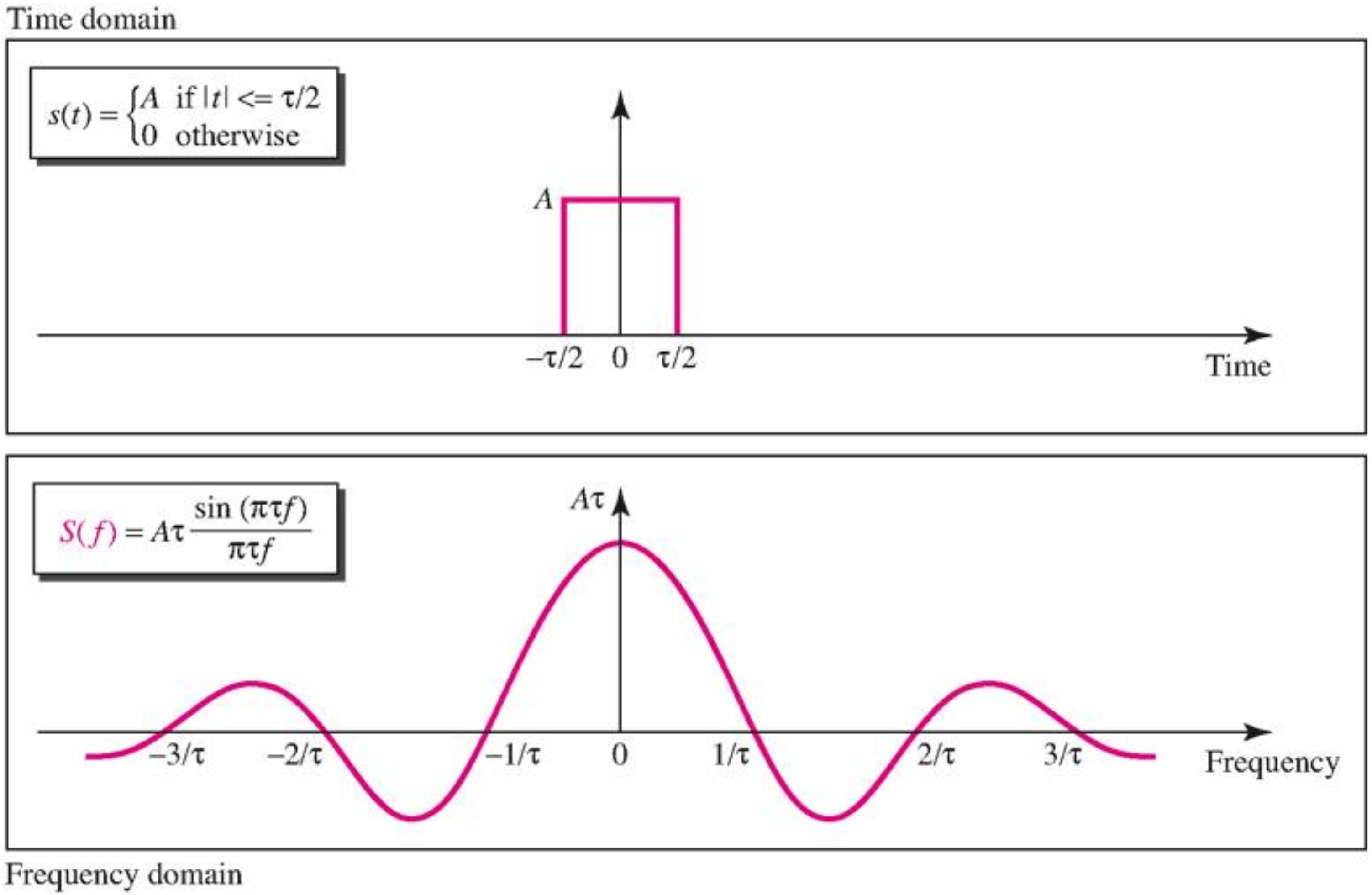
$$A_0 = 0 \qquad A_n = 0 \qquad B_n = \begin{cases} \dfrac{2A}{n\pi} & \text{for } n \text{ odd} \\ -\dfrac{2A}{n\pi} & \text{for } n \text{ even} \end{cases}$$

$$s(t) = \frac{2A}{\pi}\sin(2\pi ft) - \frac{2A}{2\pi}\sin(2\pi 2ft) + \frac{2A}{3\pi}\sin(2\pi 3ft) - \frac{2A}{4\pi}\sin(2\pi 4ft) + \cdots$$



Frequency domain

Example of a Fourier Transform



Inverse Fourier Transform

$$S(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft}\, dt$$

Fourier transform

$$s(t) = \int_{-\infty}^{\infty} S(f)e^{j2\pi ft}\, dt$$

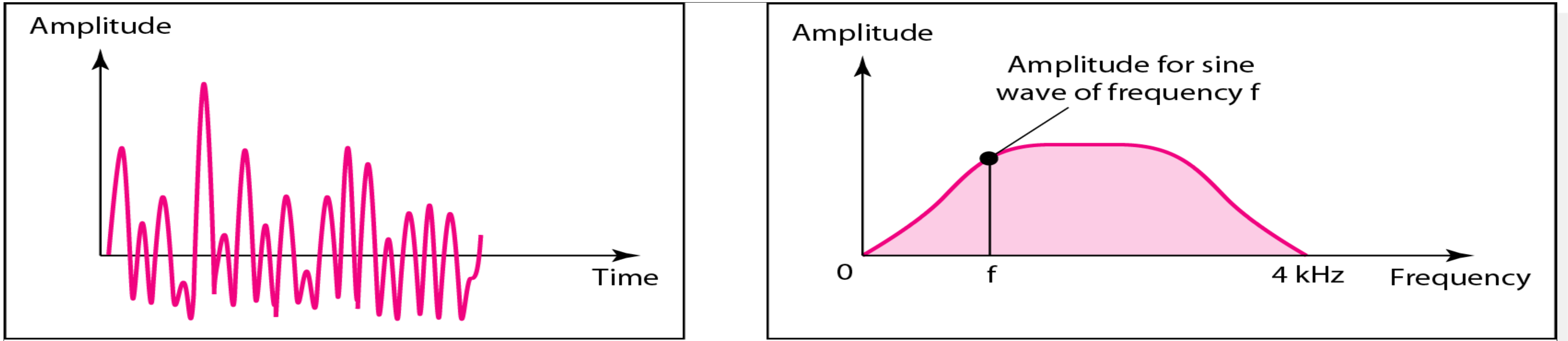
Inverse Fourier transform

Time-limited and Band-limited Signals

- A time-limited signal is a signal, where $s(t) = 0$ for $t < T_1$ and $t > T_2$
- A band-limited signal is a signal, where $S(f) = 0$ for $f < F_1$ and $f > F_2$

- Absolute bandwidth of any time-limited signal is infinite!
- But, power of signal limited to some bandwidth – effective bandwidth

The time and frequency domains of a nonperiodic signal



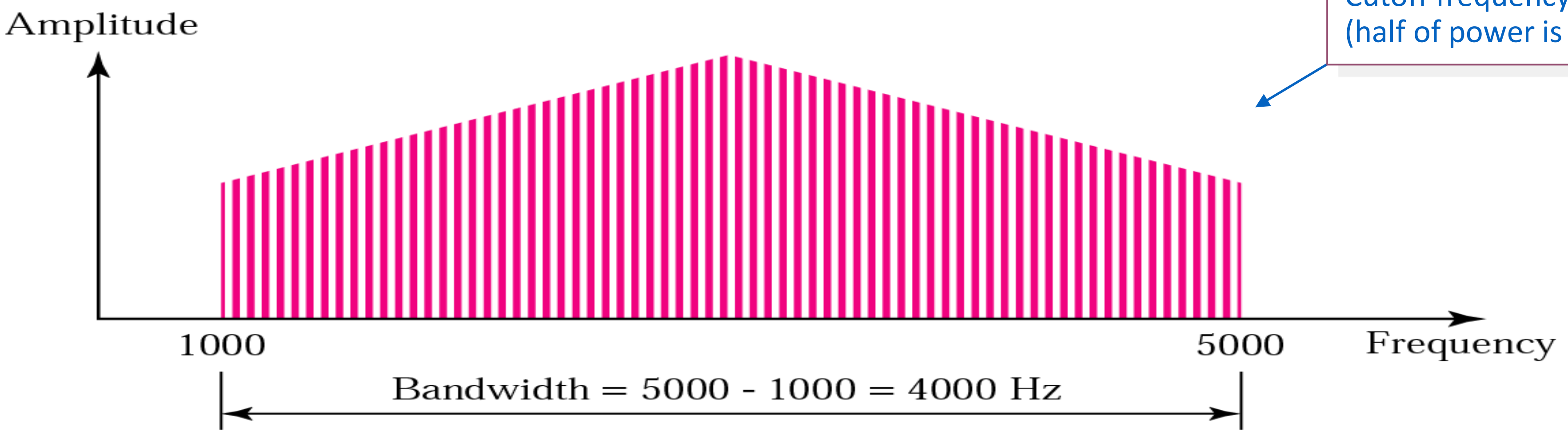
a. Time domain

b. Frequency domain

Bandwidth

- A property of the medium
  - Indicates the difference between the highest and the lowest frequencies allowed to pass
  - *<highest freq allowed> – <lowest freq allowed>*

Cutoff frequency
(half of power is lost)



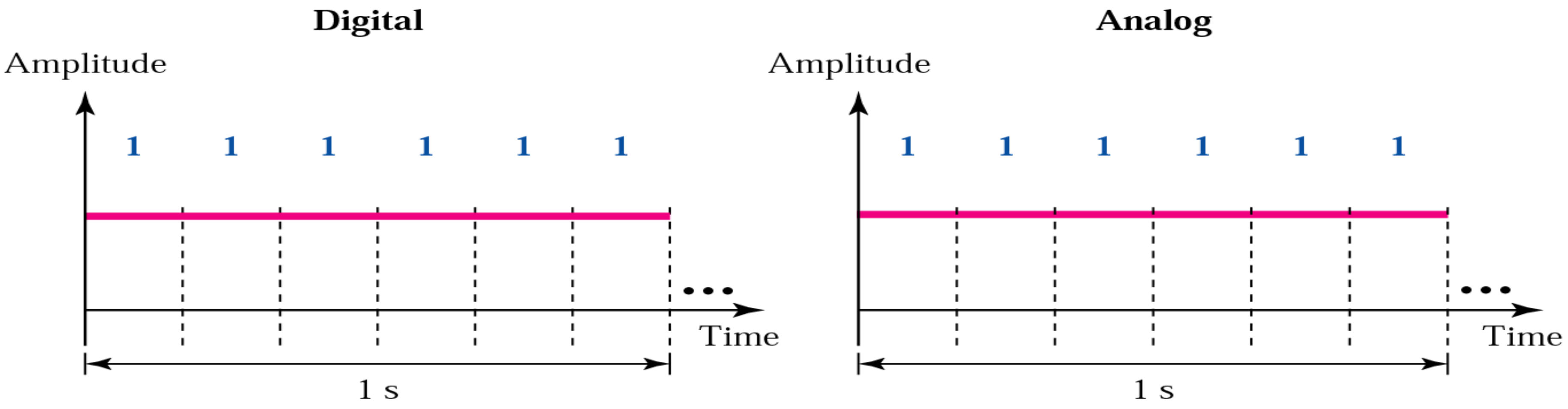
Bandwidth

- Width of the spectrum of frequencies that can be transmitted
- Greater bandwidth leads to greater costs
- Limited bandwidth leads to distortion
- Analog measured in Hertz, digital measured in baud

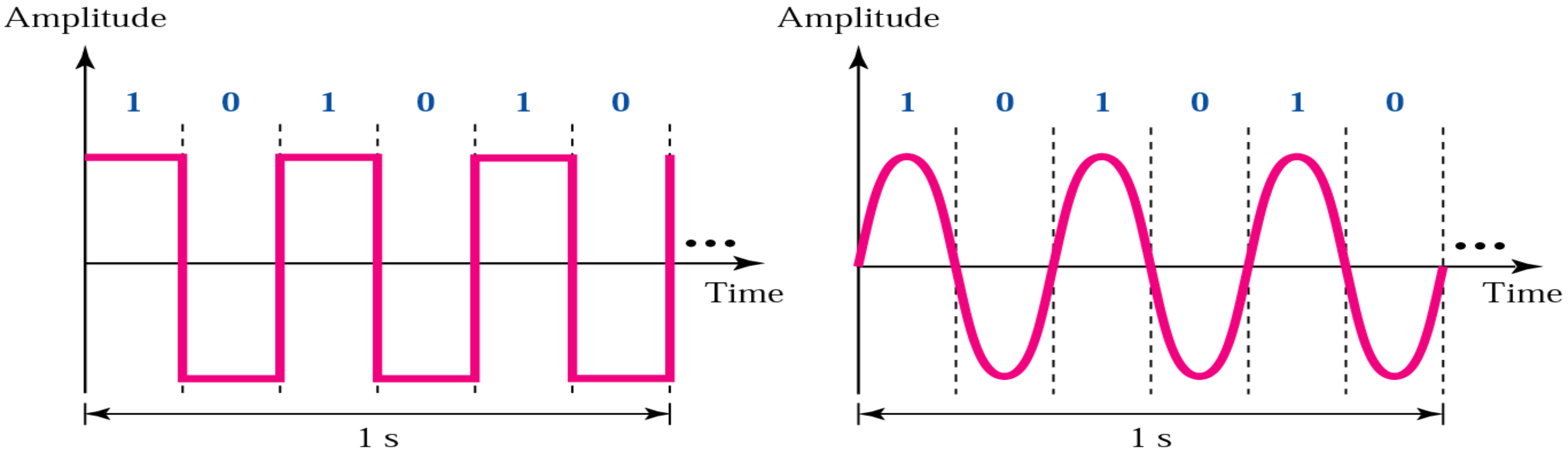
BPS vs. Baud

- BPS=bits per second
- Baud=# of signal changes per second
- Each signal change can represent more than one bit, through variations on amplitude, frequency, and/or phase

Illustration of Bit rate



a. Best case, bit rate = 6, $f = 0$



b. Worst case, bit rate = 6, $f = 3$

How many harmonics?

- For a square wave with amplitudes A and –A:

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

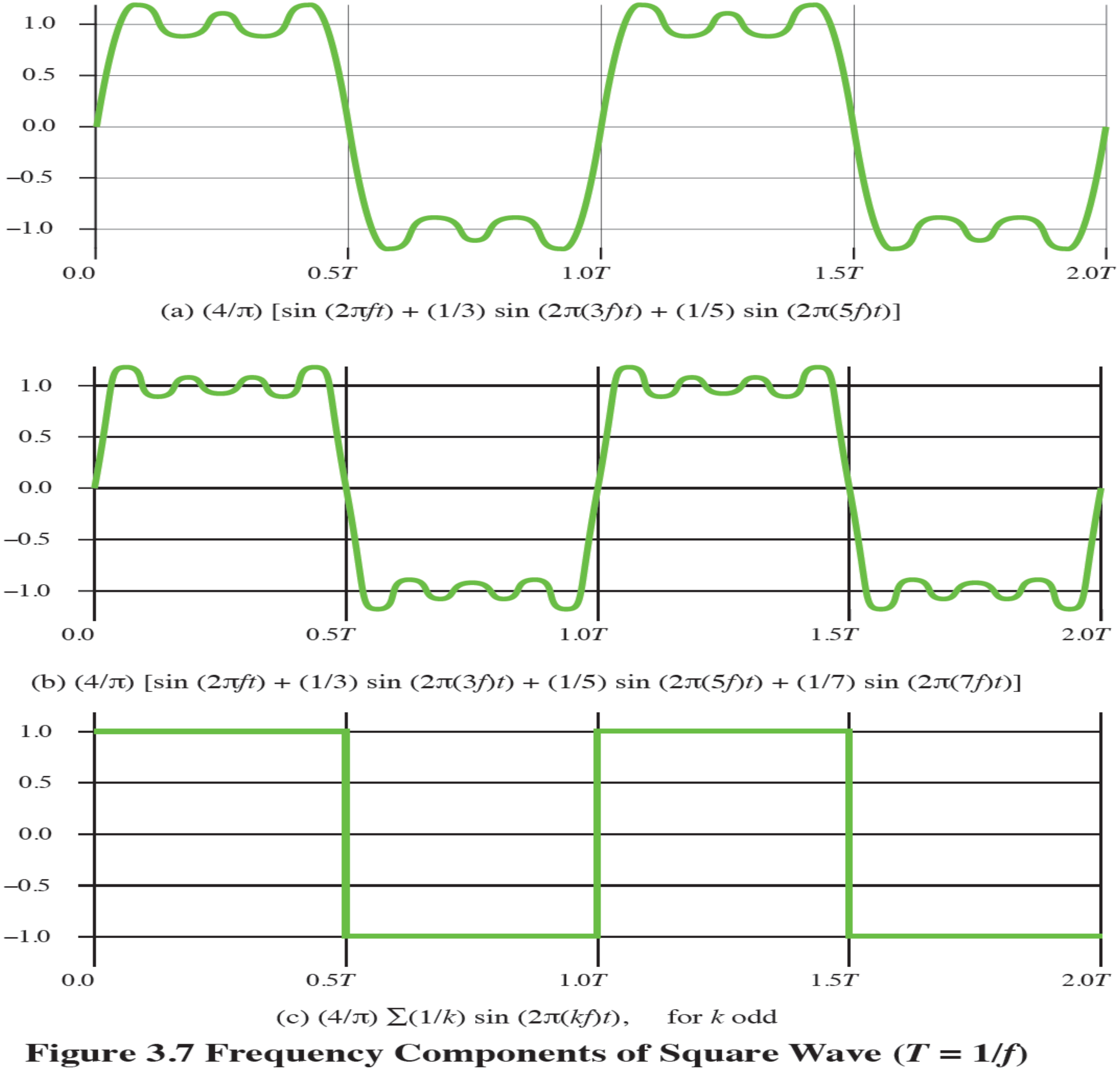
- Power spectral density: power content of signal as function of freq.

$$S(f) = \sum_{n=-\infty}^{\infty} |C_n|^2 \delta(f - nf_0)$$

- Half-power bandwidth – take upto j^{th} harmonic where PSD is half of maximum

$$P = \frac{1}{4}C_0^2 + \frac{1}{2}\sum_{n=1}^{j} C_n^2$$

How many harmonics



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

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

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

Figure 3.7 Frequency Components of Square Wave (T = 1/f)

Data Rate Calculation

Consider 101010.... T=1/f; 2 bits in each period. Bit duration is 0.5 T

- Case 1
  - Bandwidth 4MHz, use the sine wave f = 1MHz
  - 4MHz = 5f – f
  - Data rate = 2 Mbps
- Case 2
  - Bandwidth 8MHz, use the sine wave of f = 2MHz
  - 8MHz = 5f – f
  - Data rate = 4 Mbps
- Case 3
  - Bandwidth 4MHz, use the sine wave of f = 2MHz
  - 4MHz = 3f – f
  - Data rate = 4 Mbps

Data Rate vs. Bandwidth

- Bandwidth ↑
  - Data rate ↑ (compare case 1 & 2)
  - Same signal quality
- Same bandwidth
  - Higher signal quality → lower data rate
  - Compare case 1 & 3
- Same data rate
  - Bandwidth ↑ → better signal quality
  - Compare case 2 & 3

Analog and Digital Data Transmission

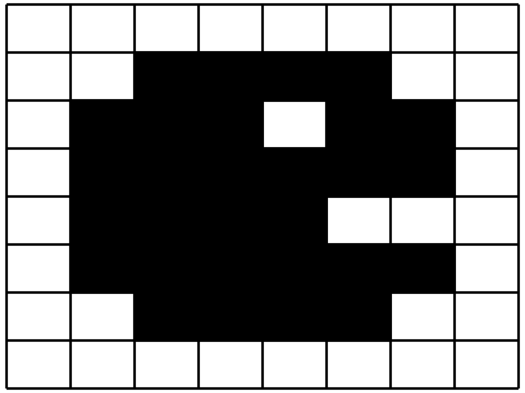
- data
  - entities that convey meaning
- signals & signaling
  - electric or electromagnetic representations of data, physically propagates along medium
- transmission
  - communication of data by propagation and processing of signals

Digital Text Signaling

- Transmission of electronic pulses representing the binary digits 1 and 0
- How do we represent letters, numbers, characters in binary form?
- Earliest example: Morse code (dots and dashes)
- Most common current form: ASCII
  - Use 8 bits of data (1 byte) to transmit one character
  - 8 binary bits has 256 possible outcomes (0 to 255)
  - Represents alphanumeric characters, as well as “special” characters

Digital Image Signaling

- Pixelization and binary representation

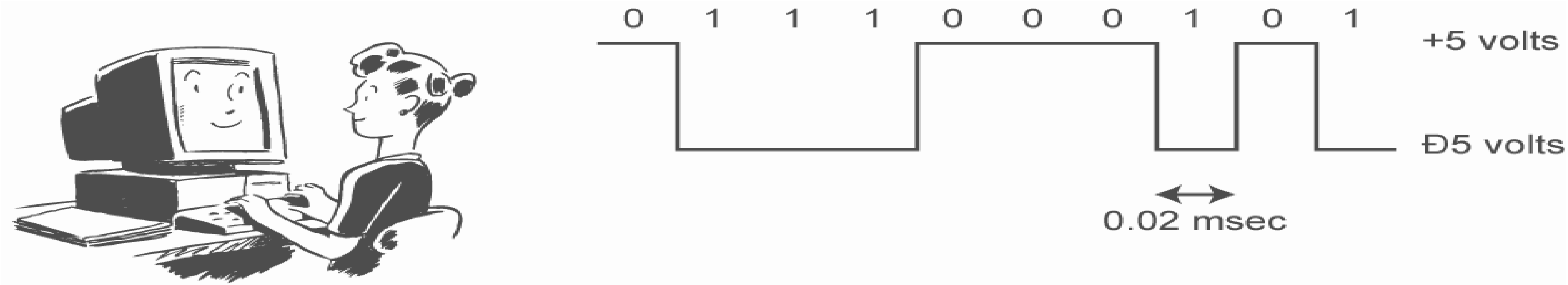


Code:

```
00000000
00111100
01110110
01111110
01111000
01111110
00111100
00000000
```

Digital Data

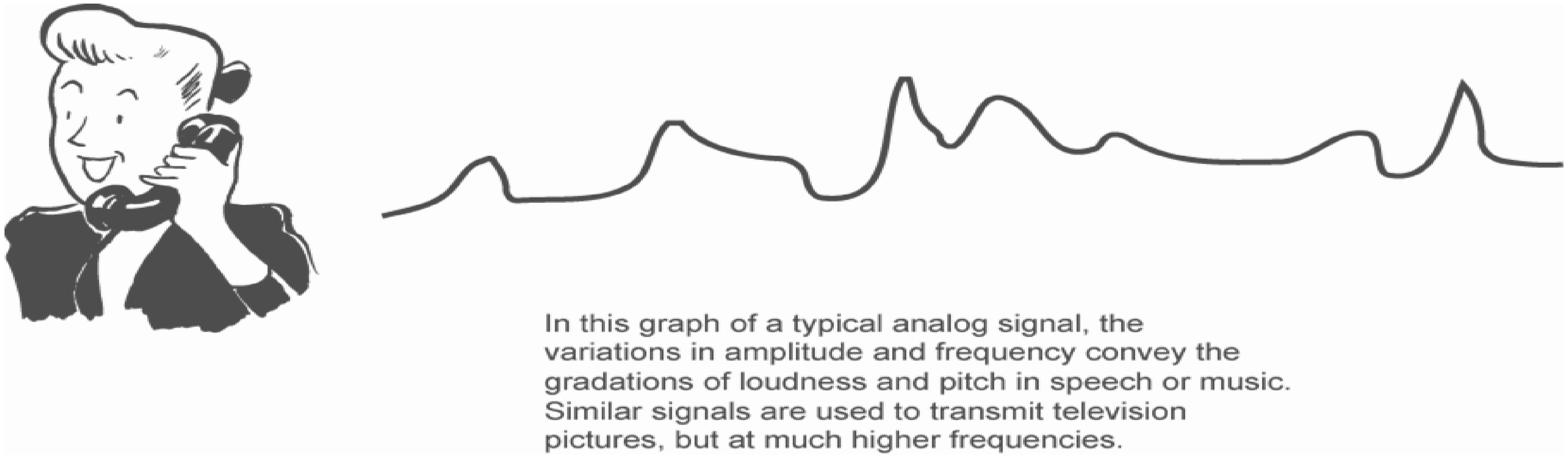
- as generated by computers etc.
- has two dc components
- bandwidth depends on data rate



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 Ð5 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).

Audio Signals

- freq range 20Hz-20kHz (speech 100Hz-7kHz)
- easily converted into electromagnetic signals
- varying volume converted to varying voltage
- can limit frequency range for voice channel to 300-3400Hz



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

Digital Transmission

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

Advantages of Digital Transmission

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

Impairments and Capacity

- Impairments exist in all forms of data transmission
- Analog signal impairments result in random modifications that impair signal quality
- Digital signal impairments result in bit errors (1s and 0s transposed)
- Bitrate achievable depends on the bit error rate and channel bandwidth

Transmission Impairments

- Signal received may differ from signal transmitted
- Analog - degradation of signal quality
- Digital - bit errors
- Caused by
  - Attenuation and attenuation distortion
  - Delay distortion
  - Noise

Transmission Impairments

- Attenuation
  - loss of signal strength over distance
- Attenuation Distortion
  - different losses at different frequencies
- Delay Distortion
  - different speeds for different frequencies
- Noise

Channel Characterization

- Attenuation: Ratio of output power to input power
  - Function of frequency, increases with frequency
  - Measured in decibels
  - Amplitude response function measured to determine attenuation
  - Less important for digital signals
- Bandwidth of a channel: width of frequencies passed by channel
  - Theoretically infinite, but practically finite
  - Bandpass channel: passes between some f1 and f2.
- Filters used to modify the frequencies suitable for transmission

Frequency domain characterization

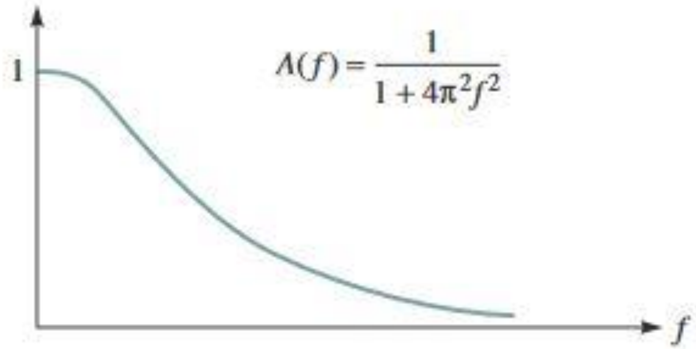
- Effect of channel on sinusoid with varying frequency

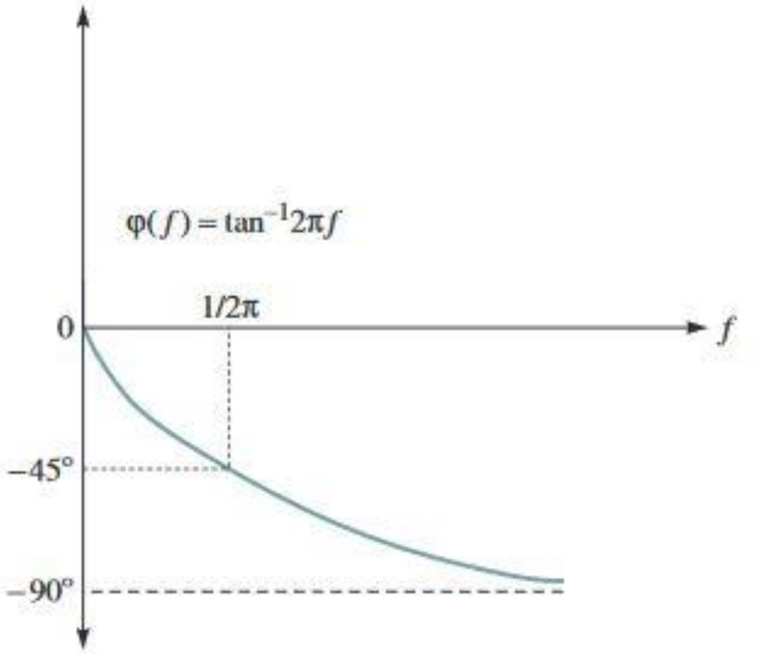
$A_f = A_{out} / A_{in}$

$$y(t) = A(f)\cos(2\pi ft + \varphi(f)) = A(f)\cos(2\pi f(t - \tau(f))).$$

- Effect of channel on digital signal

$$y(t) = \sum a_k A(kf_0)\cos(2\pi kf_0 t + \varphi(kf_0)).$$





Effect of lowpass

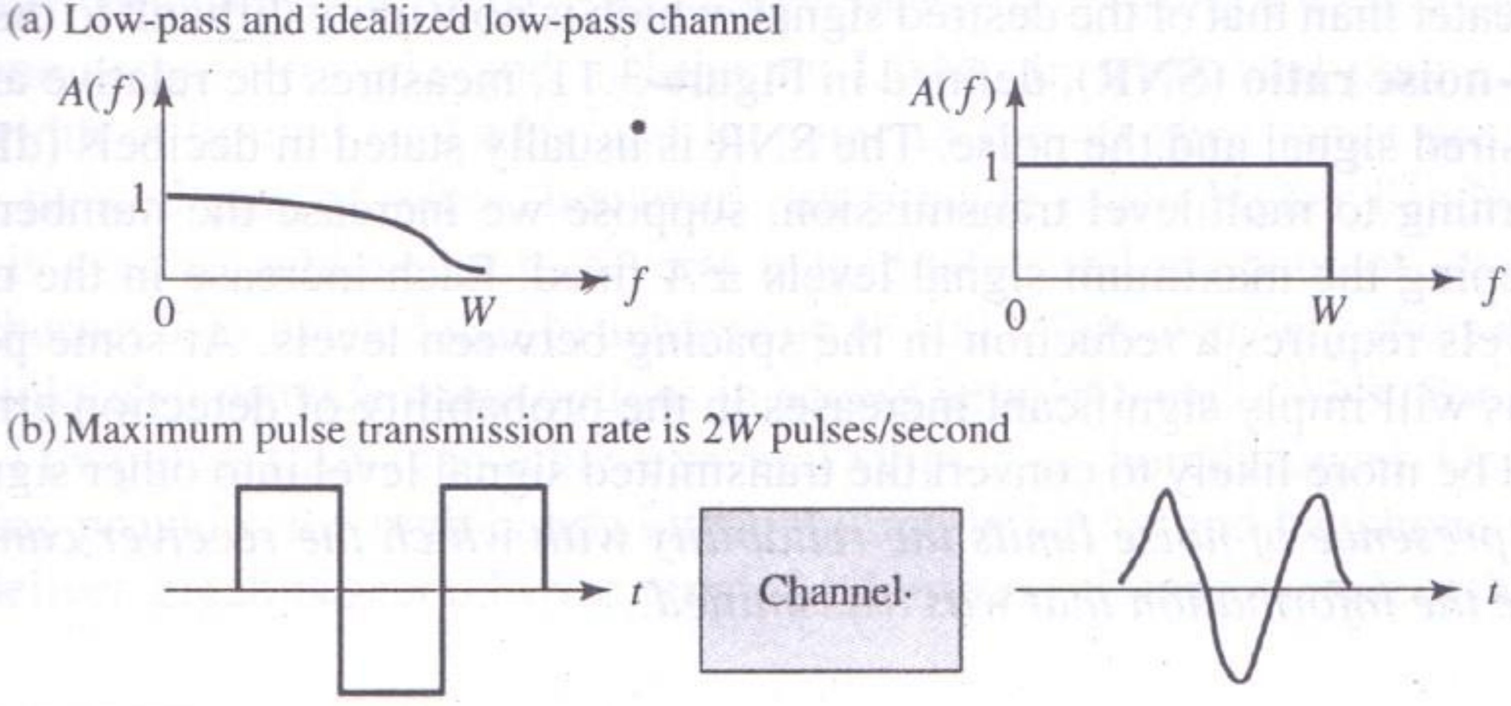


FIGURE 3.10 Typical amplitude-response functions.

Channel effects on signal: Distortion

- Delay distortion
  - Mainly concern in guided media
  - Different frequencies have different phase shifts
  - Velocity of propagation varies with frequency
  - Critical for digital signals
  - Inter-symbol interference (ISI) caused by delay distortion
  - Pulse spreading in time : Impulse response of a channel

Effect of channel bandwidth

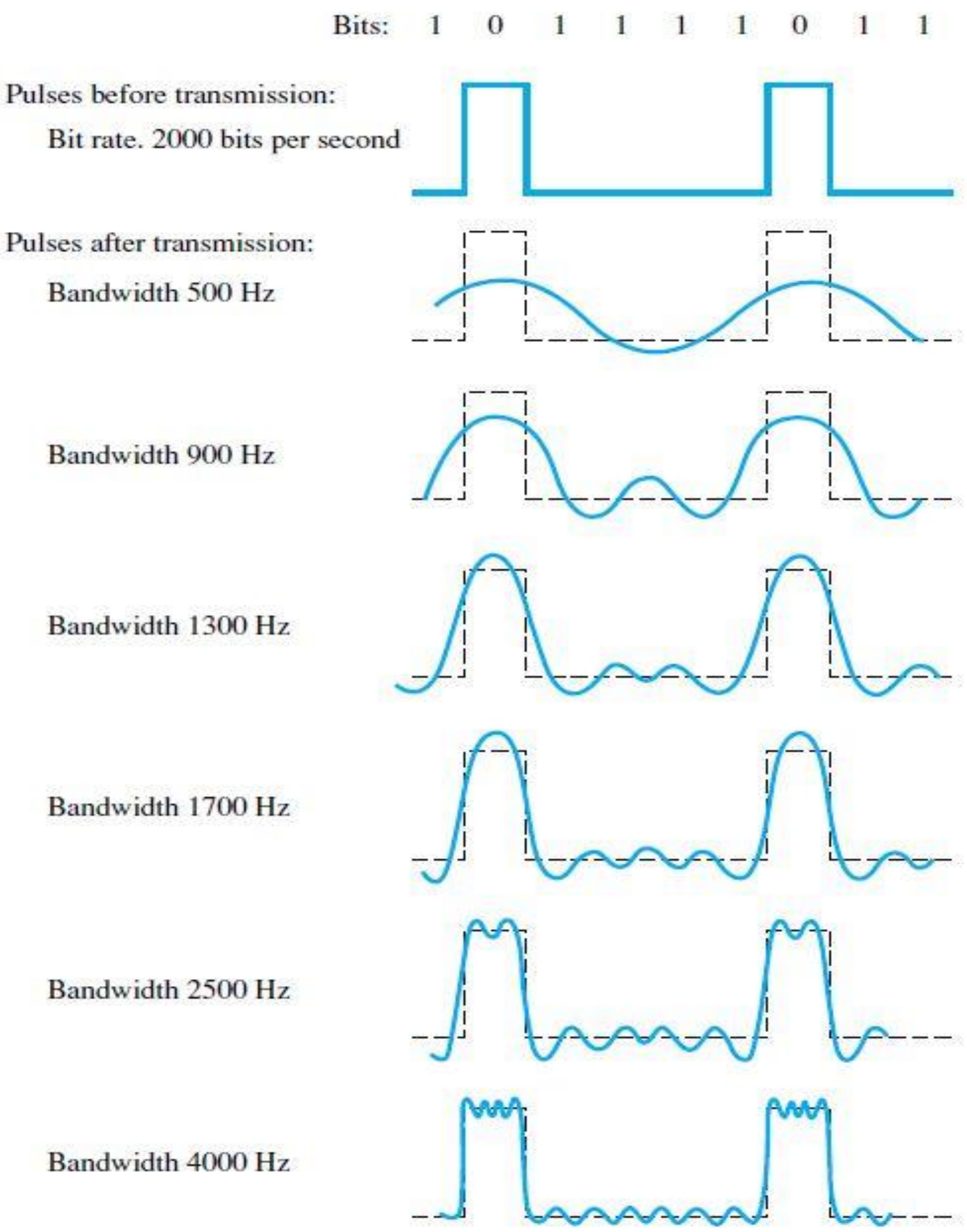


Figure 3.8 Effect of Bandwidth on a Digital Signal

Types of Noise

- Thermal noise
  - Due to thermal agitation of electrons
  - Electronic devices and channels contribute
- Intermodulation noise
  - Signals with different frequencies produce new frequencies
  - Due to non-linear effects of the medium
  - Typically at high power transmissions
- Crosstalk
  - Coupling between adjacent signal paths in guided medium
  - Antenna picks up unwanted signals
- Impulse noise
  - Random spikes due to electromagnetic interference
  - Primary source of bit errors in digital transmission

Digital signal with noise

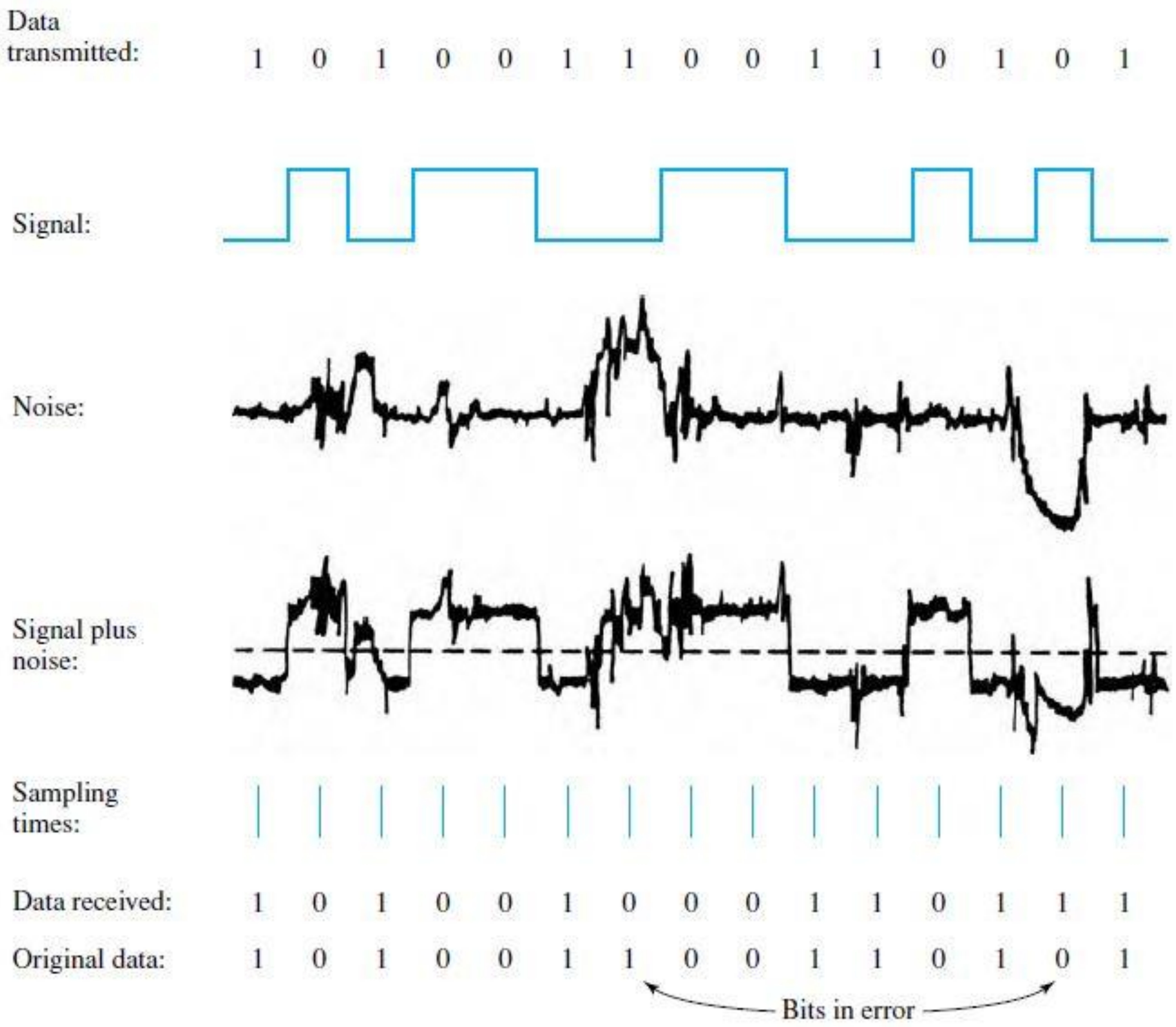


Figure 3.16 Effect of Noise on a Digital Signal

Channel capacity

- Max. data rate over a transmission system under given conditions
- Relate data rate, bandwidth, noise, bit error rate
- Nyquist rate (ideal noiseless lowpass channel)
  - If rate of signal transmission is 2B, then signal with frequency no greater than B is sufficient to carry the information
  - Noiseless channel, only limitation due to ISI from delay distortion
  - $C = 2B \log_2 M$

Channel capacity

- Shannon capacity (ideal lowpass channel)
  - Given SNR at the receiver, the maximum data rate over a channel with bandwith B is C = B log (1+SNR)
  - Assumes only white noise, practical capacity is much lower
- As B increases SNR decreases
- As S increases, nonlinear effects increase
- How to find coding scheme that achieves Shannon capacity?

Summary

- How fast can bits be transmitted reliably over a given transmission system?
  - Amount of energy put in transmitting the system
  - Amount of noise that receiver has to deal with
  - Distance that the signal has to be transmitted over
  - Bandwidth of the transmission channel
- If bandwidth of channel is B, max rate of transmission is 2B pulses/sec
- Infinite data rate by increasing number of bits/pulse
- Practically limited by SNR, non-linear effects, receiver sensitivity, transmitter capability, choice of medium.