Chapter 3

DATA AND SIGNALS

Introduction

- Physical layer moves data in the form of electromagnetic signals across a transmission medium
- Data must be changed to a form that transmission media can accept

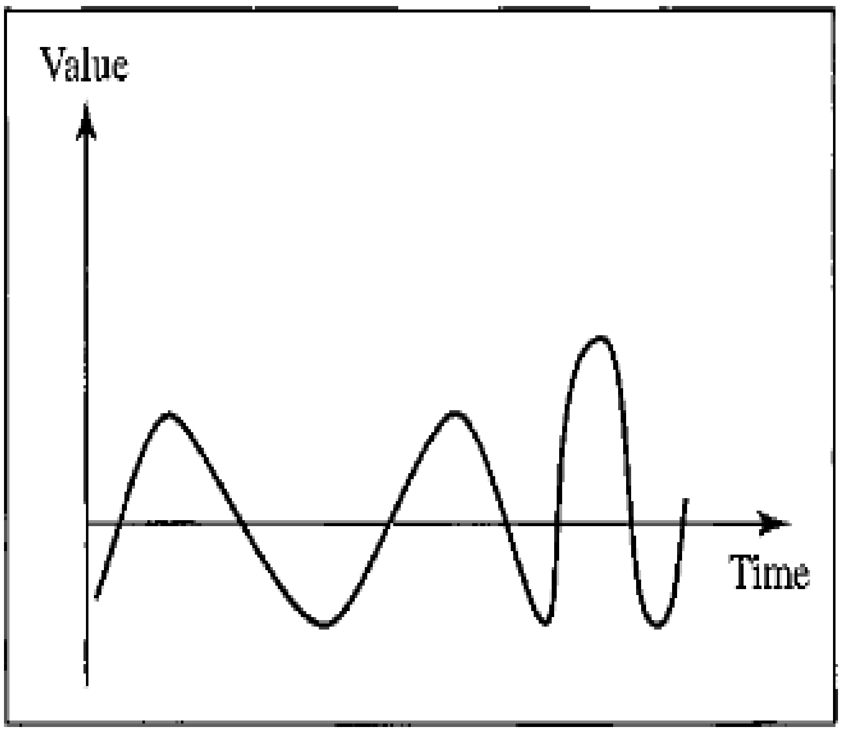
Analog and Digital Data

- Analog data
  - Continuous
  - ex. analog clock, human voice
  - Can be converted to analog or digital signals
- Digital data
  - Discrete
  - ex. digital clock, data produced by computers
  - Can be converted to analog or digital signals

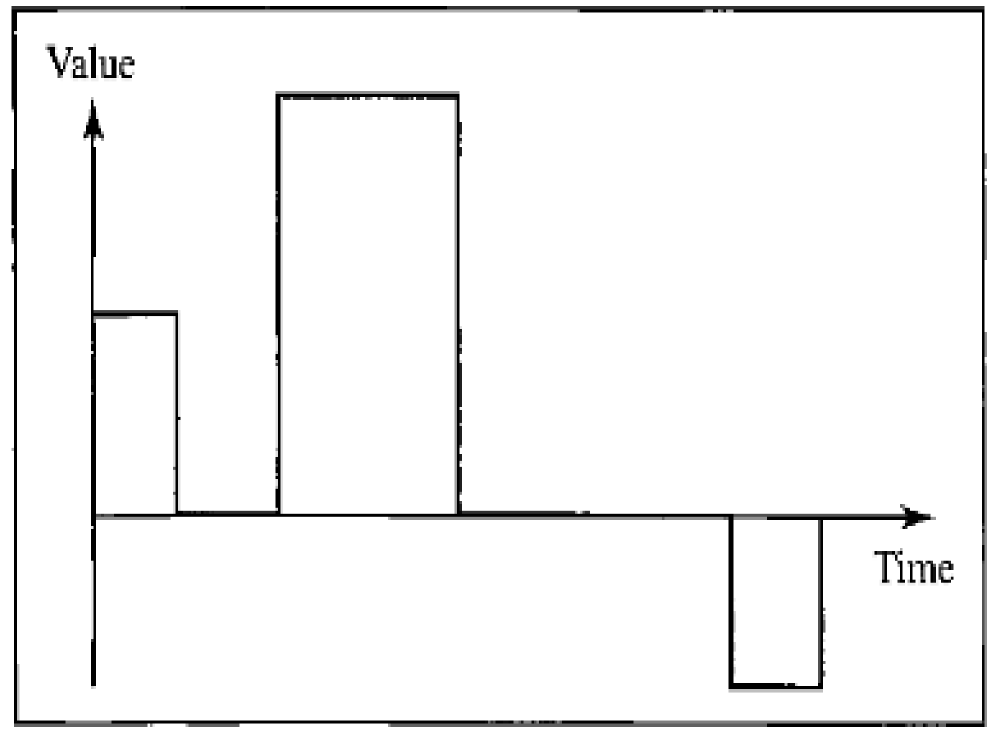
Analog and Digital Signal

- Analog signal
  - Infinitely many levels of intensity over a period of time
- Digital signal
  - Have a limited number of defined values (1 and 0)

Analog and Digital Signal



a. Analog signal



b. Digital signal

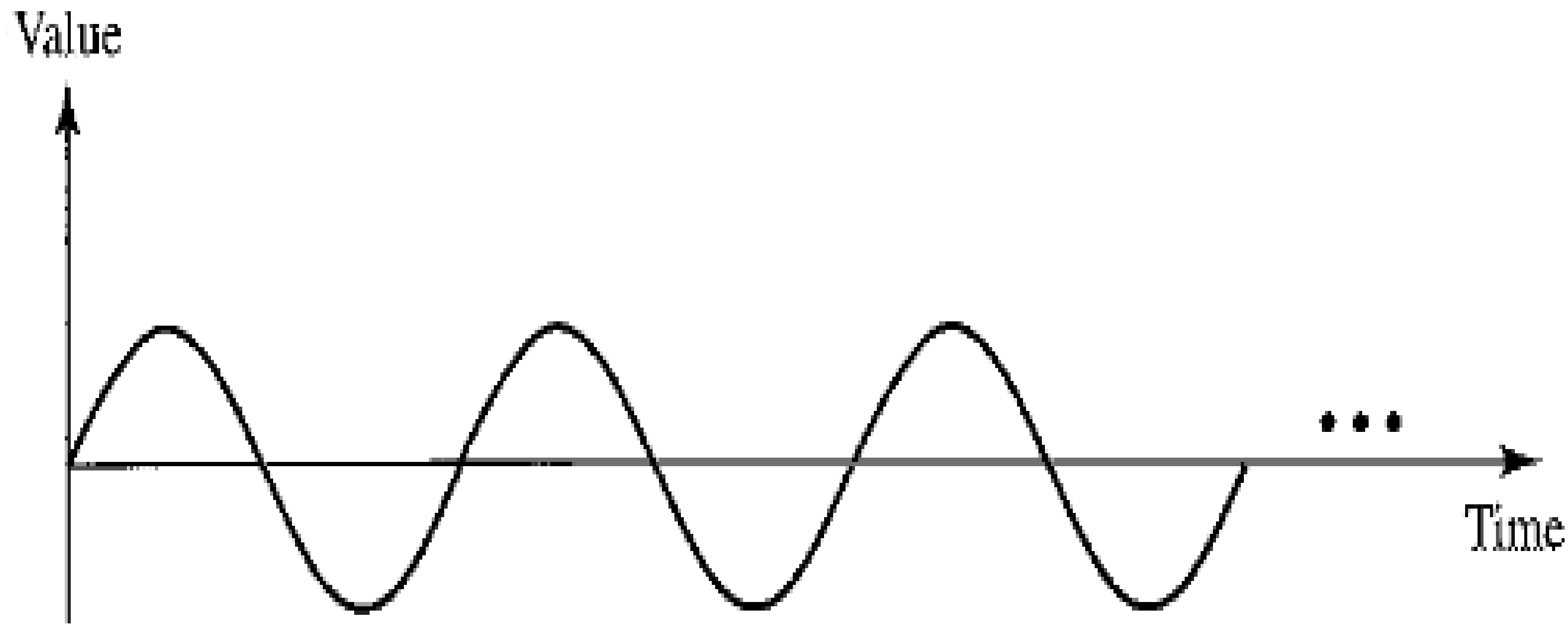
Periodic and Nonperiodic Signals

- Periodic signal
  - Completes a pattern within a measurable time frame (period)
  - Cycle – completion of one full pattern
  - Need less bandwidth
- Nonperiodic signal(aperiodic)
  - Changes without exhibiting a pattern or cycle that repeats over time
  - Can represent variation in data

Periodic Analog Signal (1)

- Sine wave
  - Most fundamental form of a periodic analog signal
- Peak amplitude
  - Absolute value of a signal's highest intensity, proportional to the energy it carries
- Ex. power in US homes has actual peak amplitude of 155-170V. Commonly 110-120V (Root Mean Squared).
- Ex. AA Baterry is 1.5 V

Periodic Analog Signal (2)

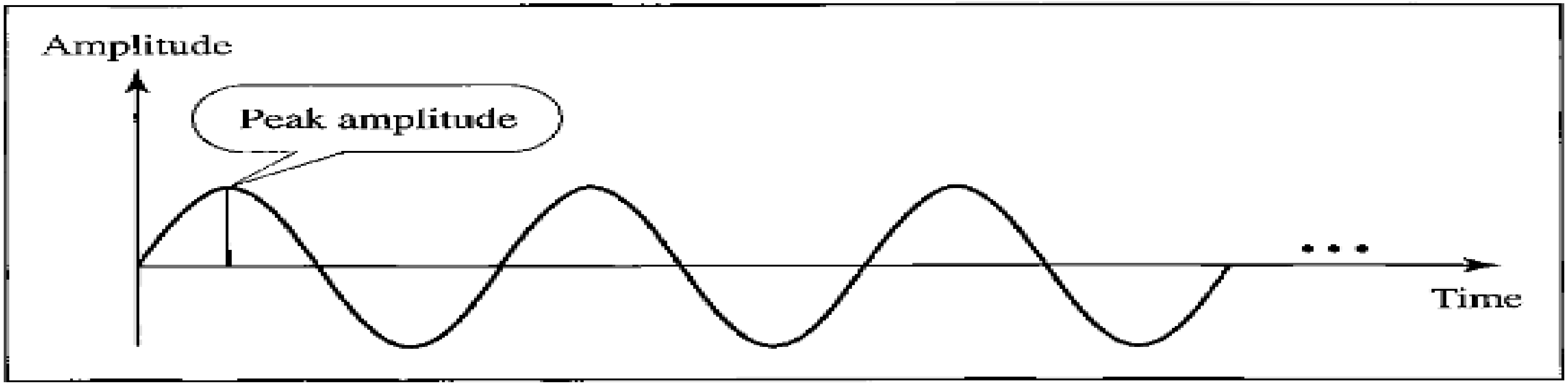


Periodic Analog Signal (2)

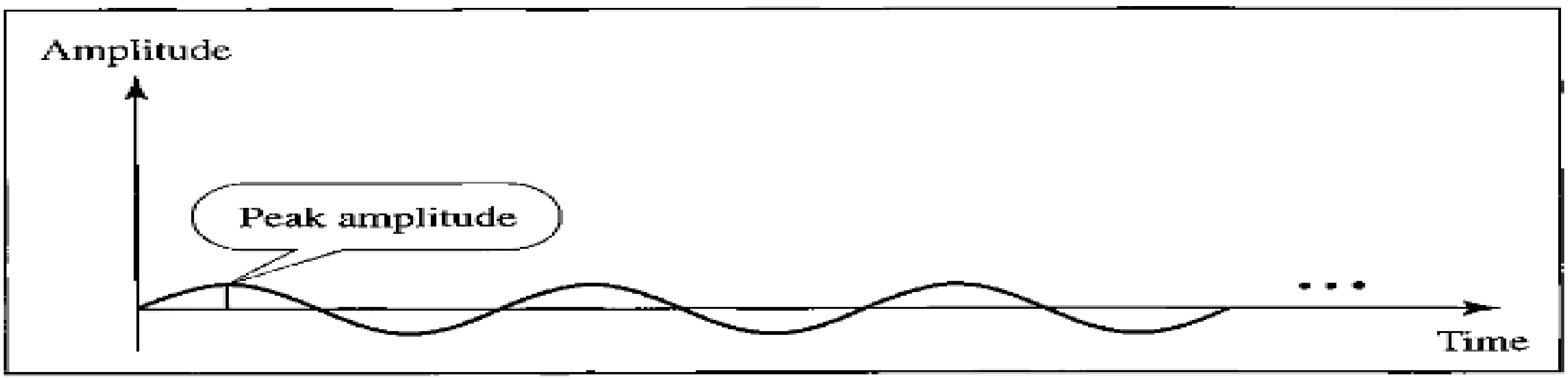
- Period (T)
  - Amount of time in seconds a signal needs to complete 1 cycle.
- Frequency (f)
  - Number of periods(or cycles) in 1 second, hertz
  - Measure of the rate of change of a signal with respect to time
- T and f are inverse of each other:

$$f = \frac{1}{T} \qquad T = \frac{1}{f}$$

Periodic Analog Signal (3)



a. A signal with high peak amplitude

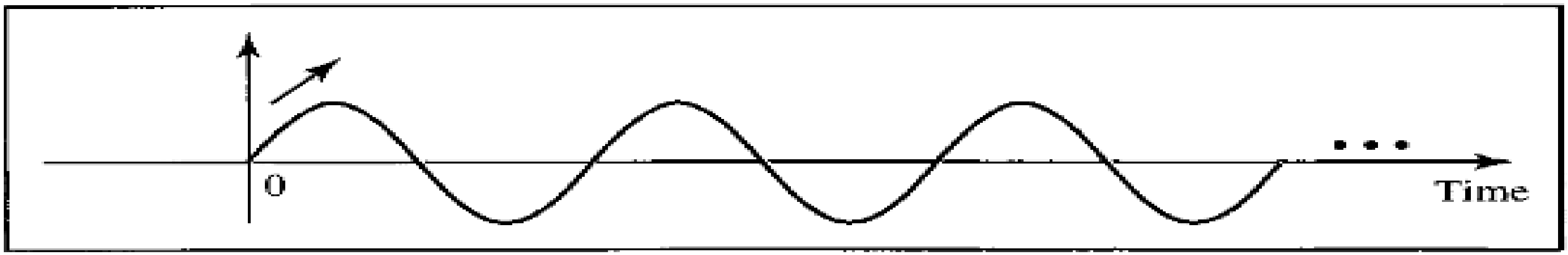


b. A signal with low peak amplitude

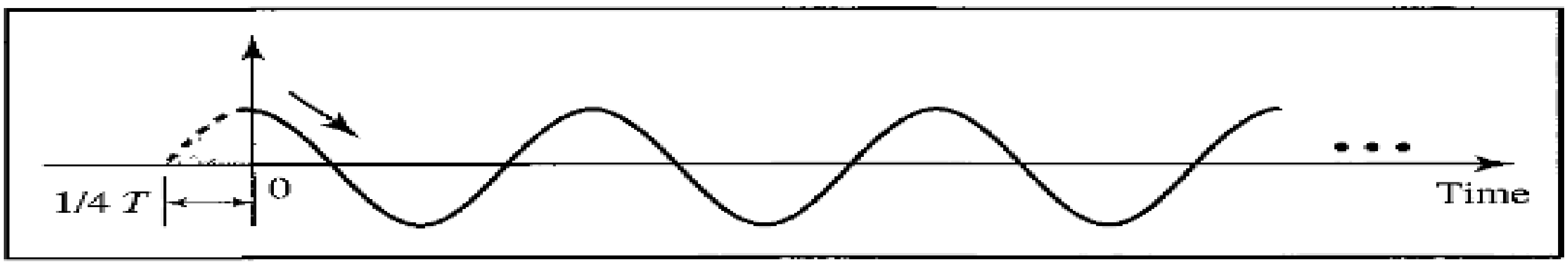
Periodic Analog Signal (4)

- What if a signal does not change?
  - f is zero
- What if a signal changes instantaneously?
  - f is infinite
- Phase
  - Position of waveform relative to time 0
  - The amount of shift in the time axis (x-axis)
  - Measured in degrees or radians
    - $360\,deg = 2\,\Pi\,rad$

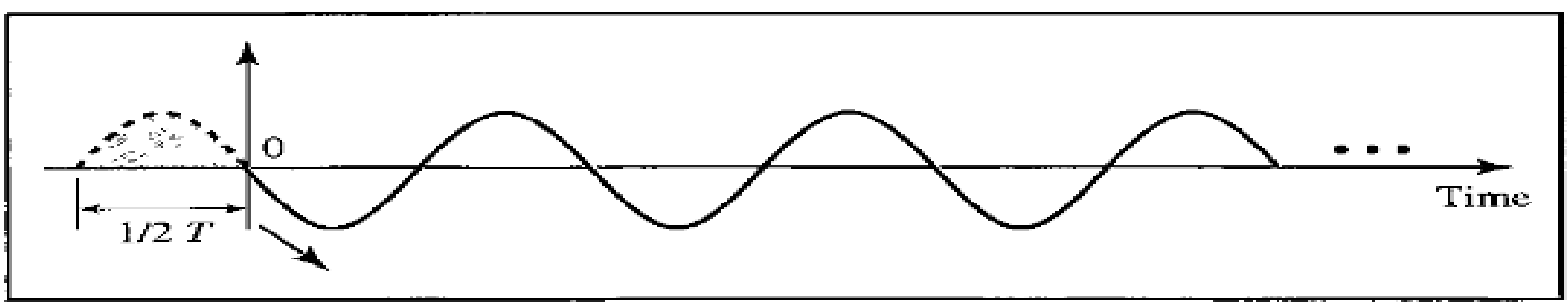
Periodic Analog Signal (5)



a. 0 degrees



b. 90 degrees

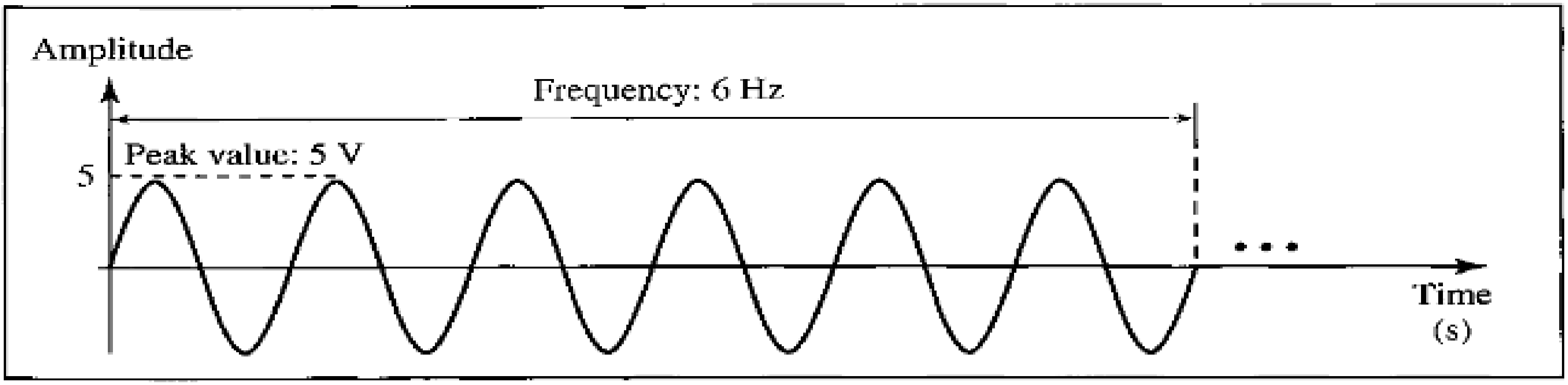


c. 180 degrees

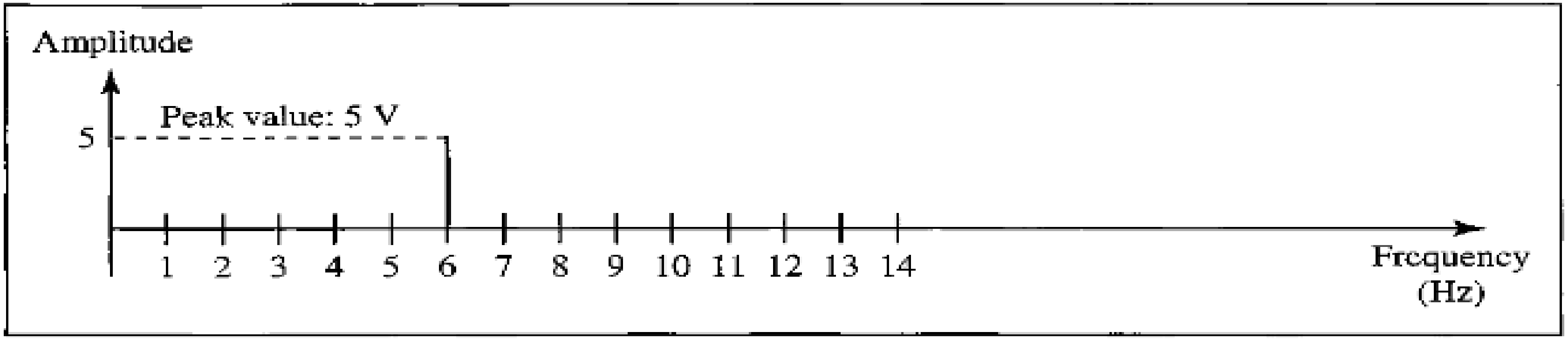
Periodic Analog Signal (6)

- Wavelength(λ)
  - Binds T or f of a simple sine wave to the propagation speed of the medium
  - $\lambda = cT = \frac{c}{f}$
  - where c = propagation speed of light = $3\,x\,10^{8}\,m/s$
  - Unit is micrometers (microns)
  - Ex. λ of red light on air is $\frac{(3\,x\,10^{8})}{(3\,x\,10^{14})} = 0.75\,microns$

Time and Frequency Domains



a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

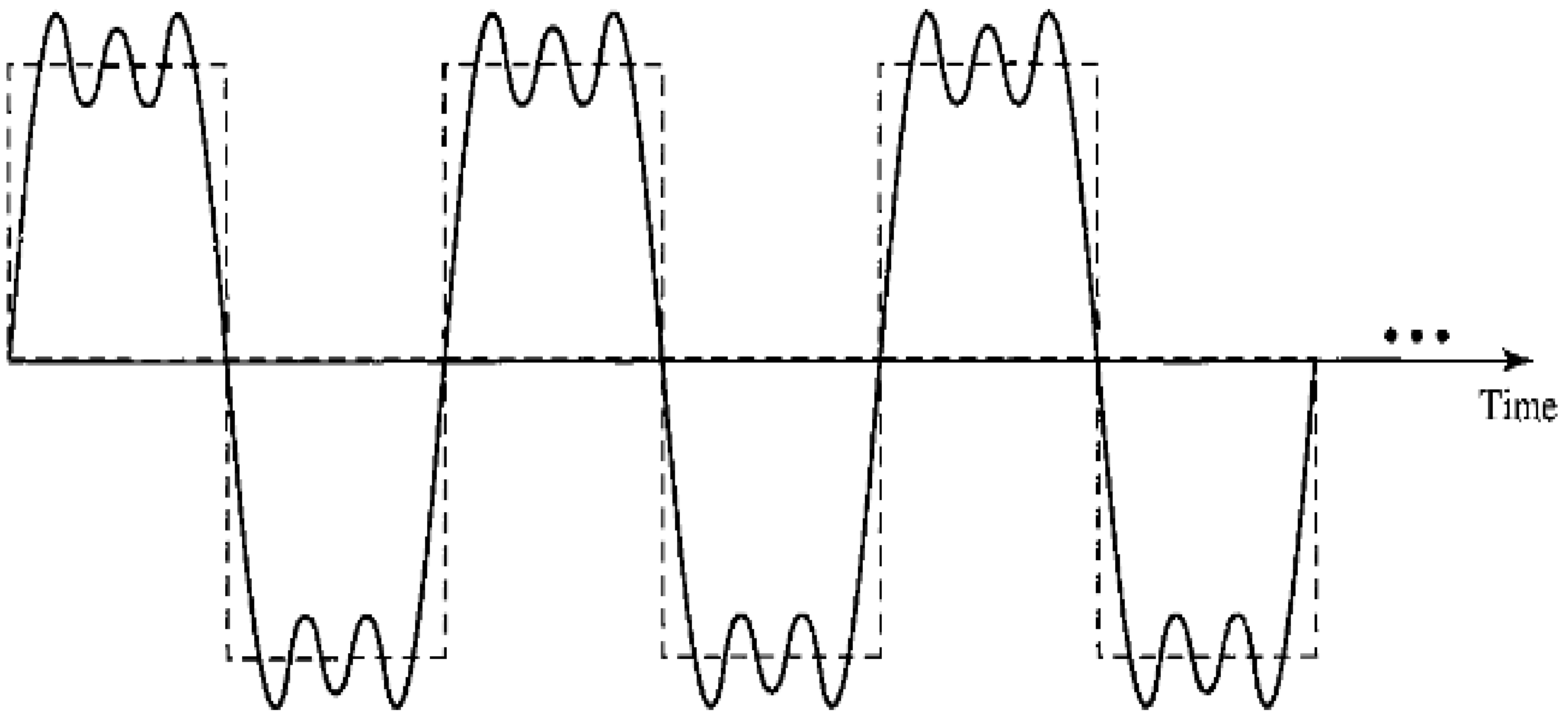


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

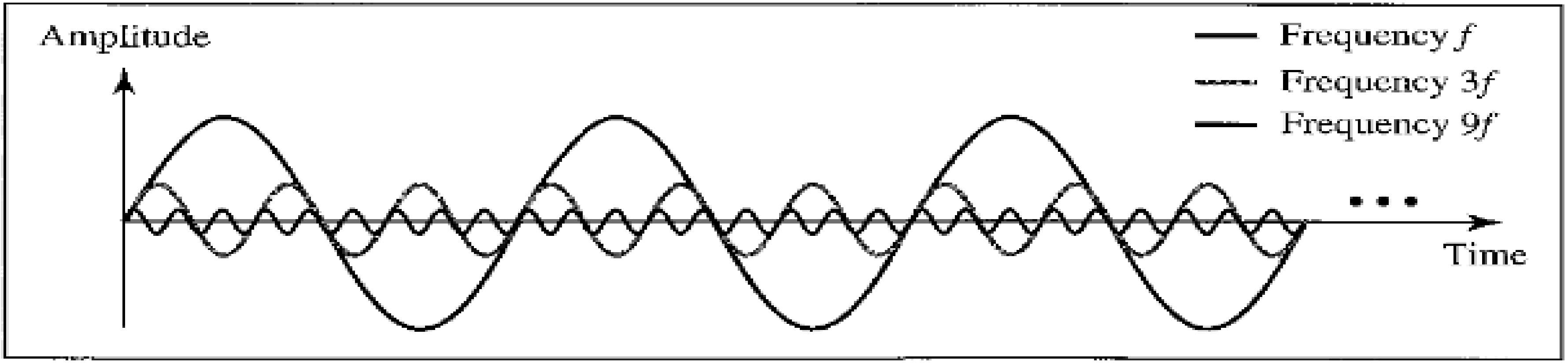
Composite Signals

- Electricity distributed in homes is a single sine wave with a frequency of 60 Hz
- Composite signals, made up of many simple sine waves, are used in data communications
- Jean-Baptiste Fourier - any composite signal is actually a combination of simple sine waves
- Periodic composite signals – signals with discrete frequencies
- Nonperiodic – signals with continuous frequencies

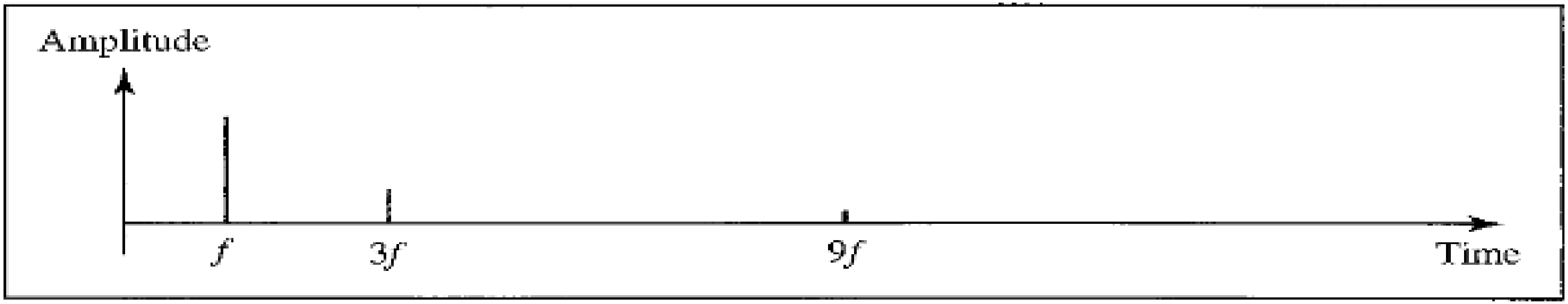
Composite Signals (Periodic)



Composite Signals (Periodic)

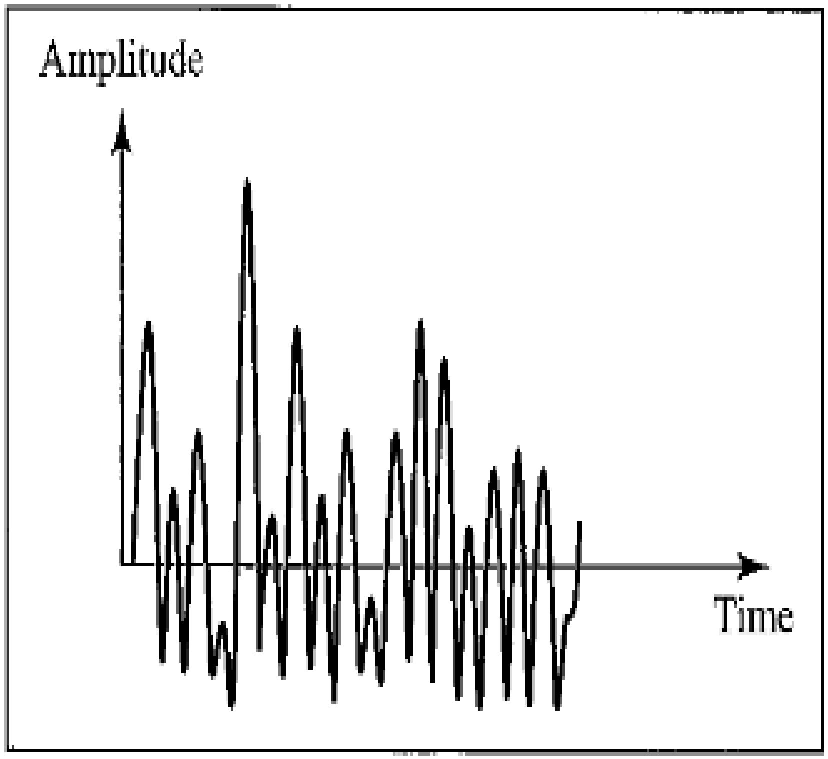


a. Time-domain decomposition of a composite signal

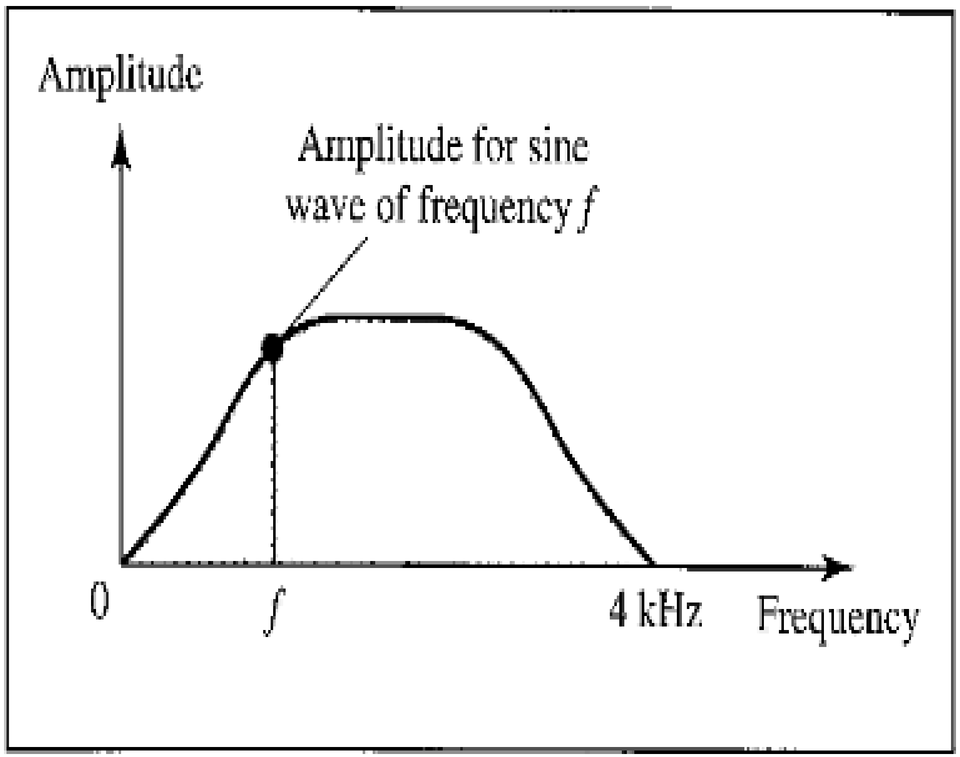


b. Frequency-domain decomposition of the composite signal

Composite Signals (Nonperiodic)



a. Time domain



b. Frequency domain

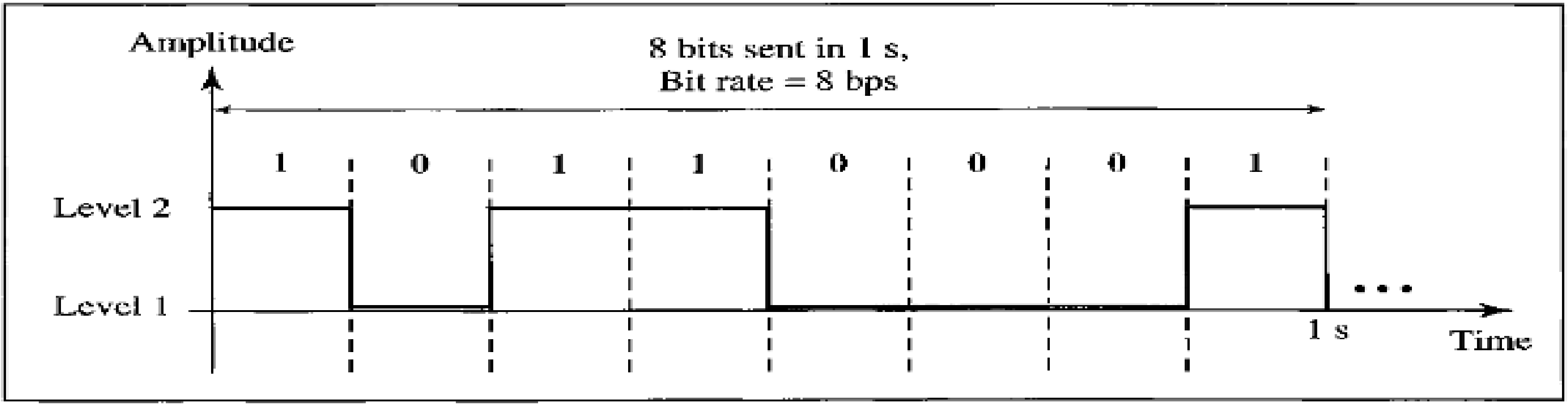
Bandwidth

- **Bandwidth** – range of frequencies contained in a composite signal
  - Ex. Given a composite signal with frequencies between 1000 Hz and 5000 Hz
    - Bandwidth = 5000-1000=4000 Hz

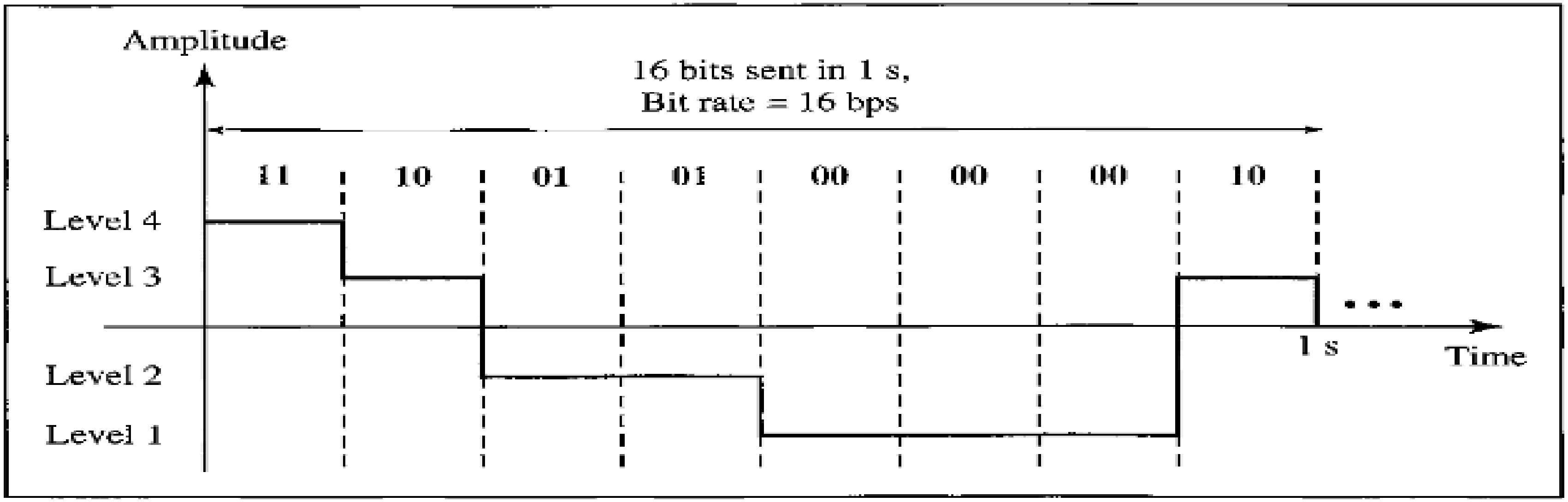
Digital Signals

- A "1" can be encoded as a positive voltage and a "0" as zero voltage
- A digital signal can have more than two levels
  - We can send more than 1 bit for each level
- If a signal has L levels, each level needs $\log_2 L$ bits

Digital Signals



a. A digital signal with two levels



b. A digital signal with four levels

Bit Rate

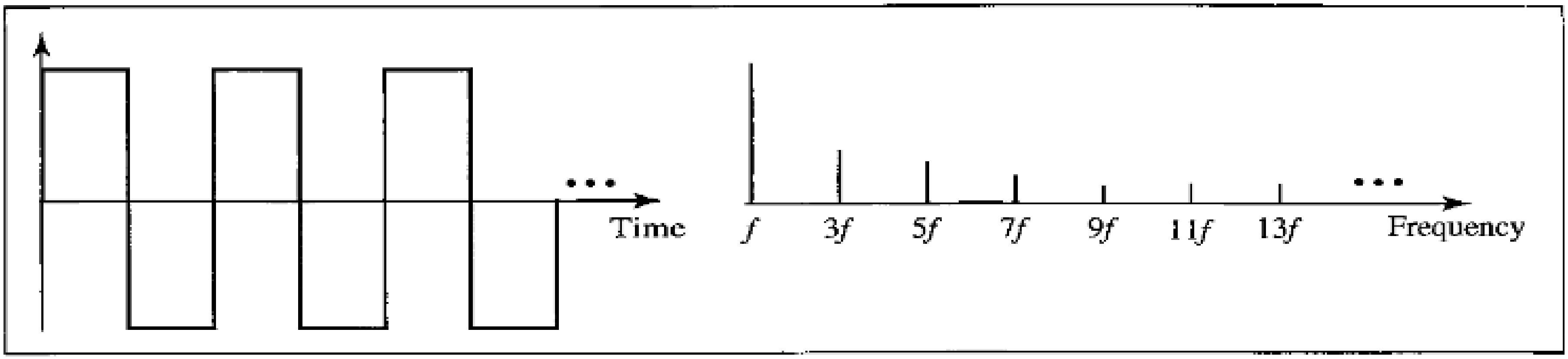
- Most digital signals are nonperiodic
- Bit rate – number of bits sent in 1 second, expressed as bits per second (bps)

Bit Length

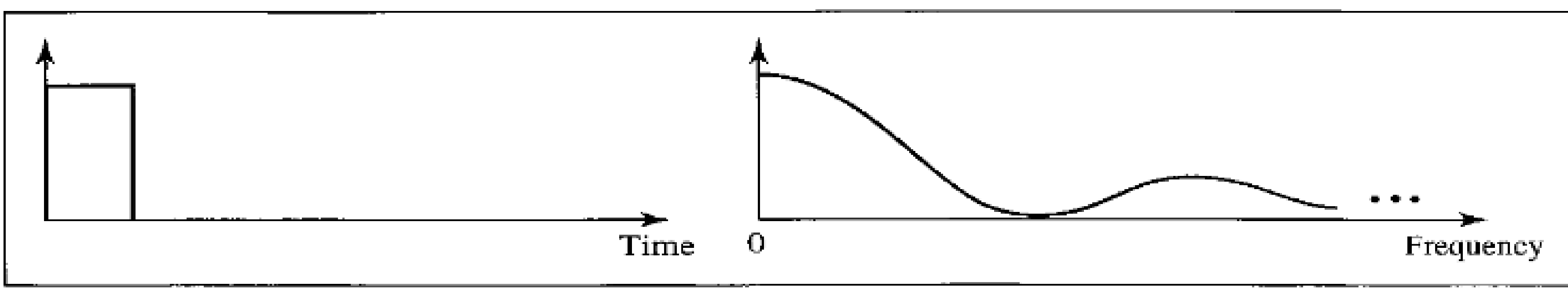
- Similar to wavelength
- Bit length = distance one bit occupies on the transmission medium

$$bit\ length = propagation\ speed \times bit\ duration$$

Digital Signal as a Composite Analog Signal



a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

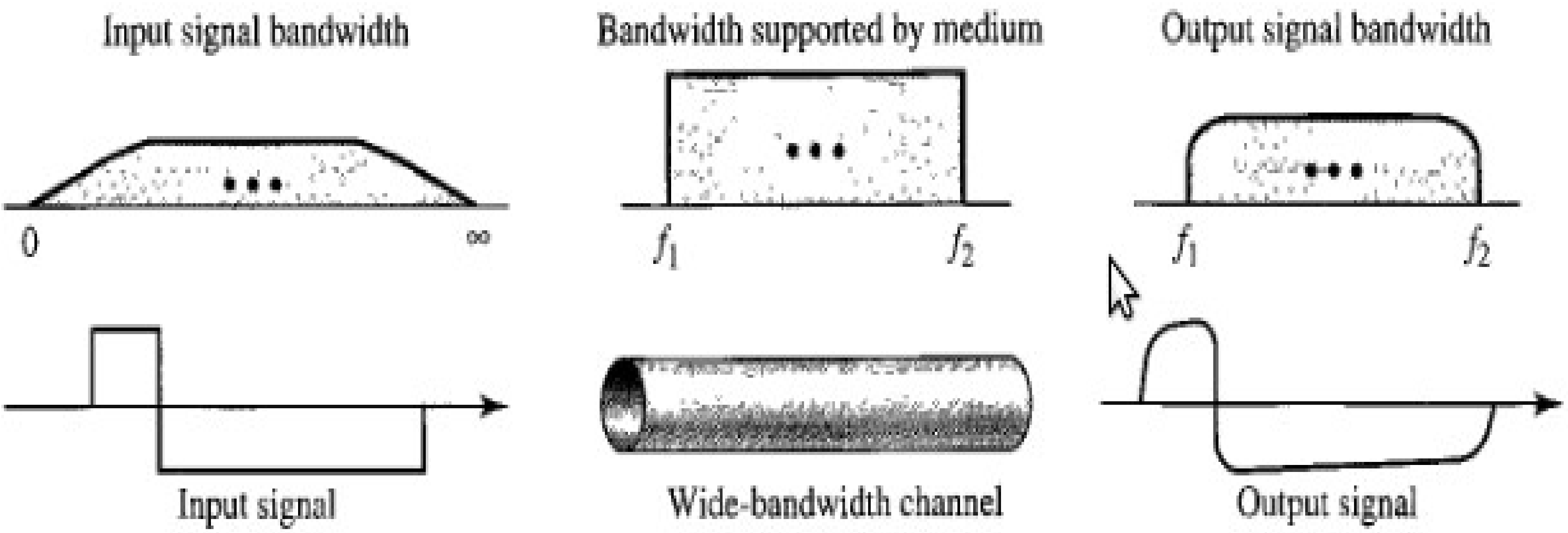
Transmission of Digital Signals

- How can we send a digital signal from point A to point B?
- Data communications use nonperiodic digital signal
  - Infinite bandwidth, continuous frequencies
- baseband and broadband

Baseband Transmission

- Sends a digital signal without changing it to analog signal
- Requires a dedicated low-pass channel, a channel with a bandwidth that starts from zero
- Low-Pass Channel with Wide Bandwidth
  - Preserves the shape of the digital signal
- Low-Pass Channel with Limited Bandwidth
  - Approximate the digital signal with an analog signal

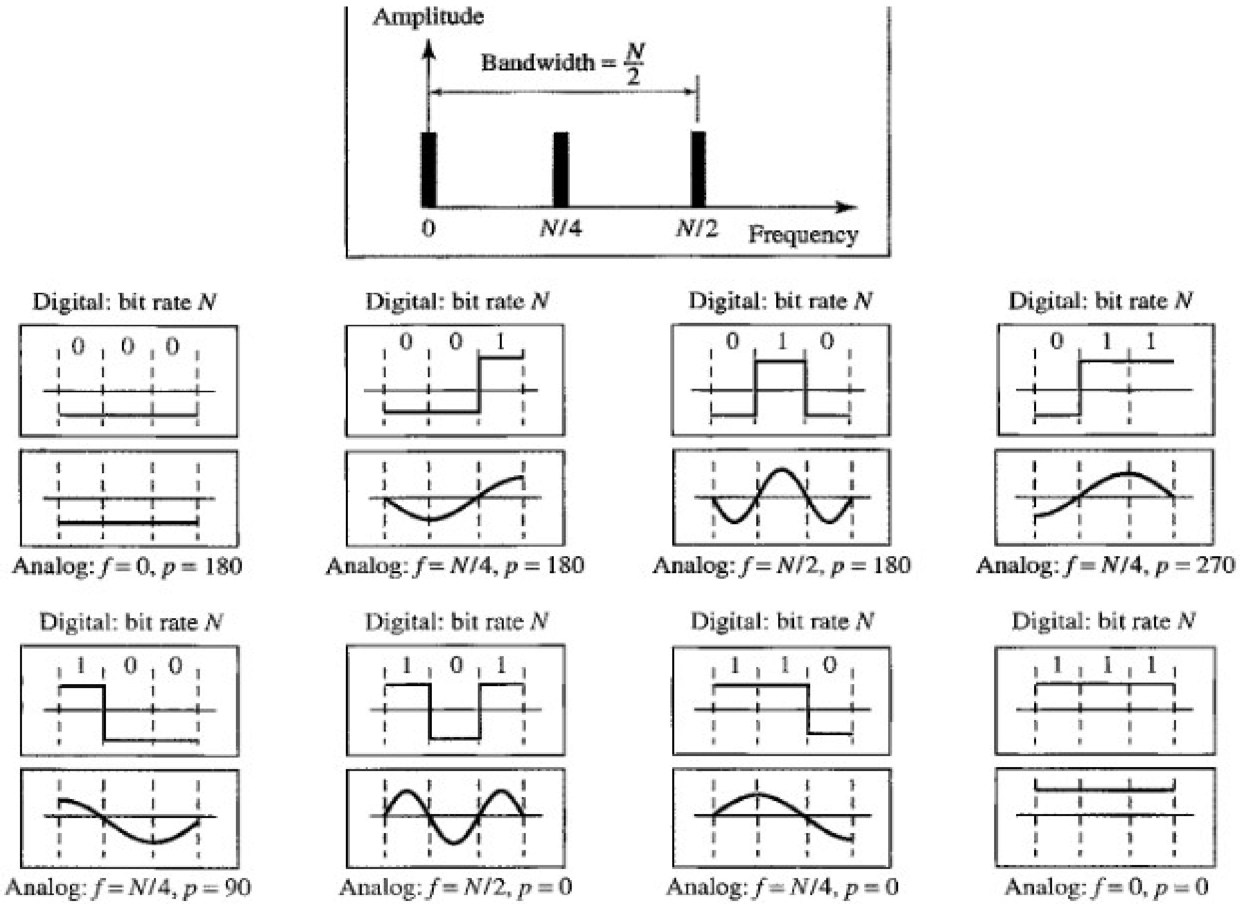
LPC-WB



Input signal bandwidth
0
∞
Bandwidth supported by medium
f_1
f_2
Output signal bandwidth
f_1
f_2
Input signal
Wide-bandwidth channel
Output signal

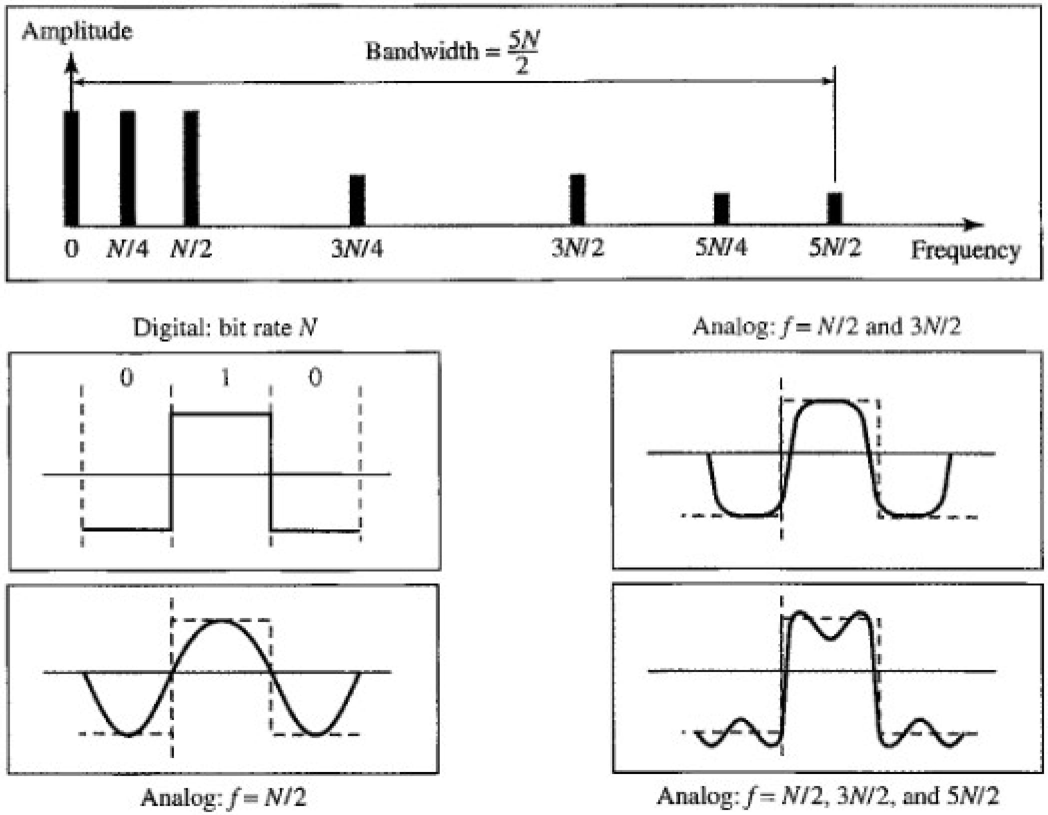
LPC-LB

- Rough approximation



LPC-LB

- Better approximation



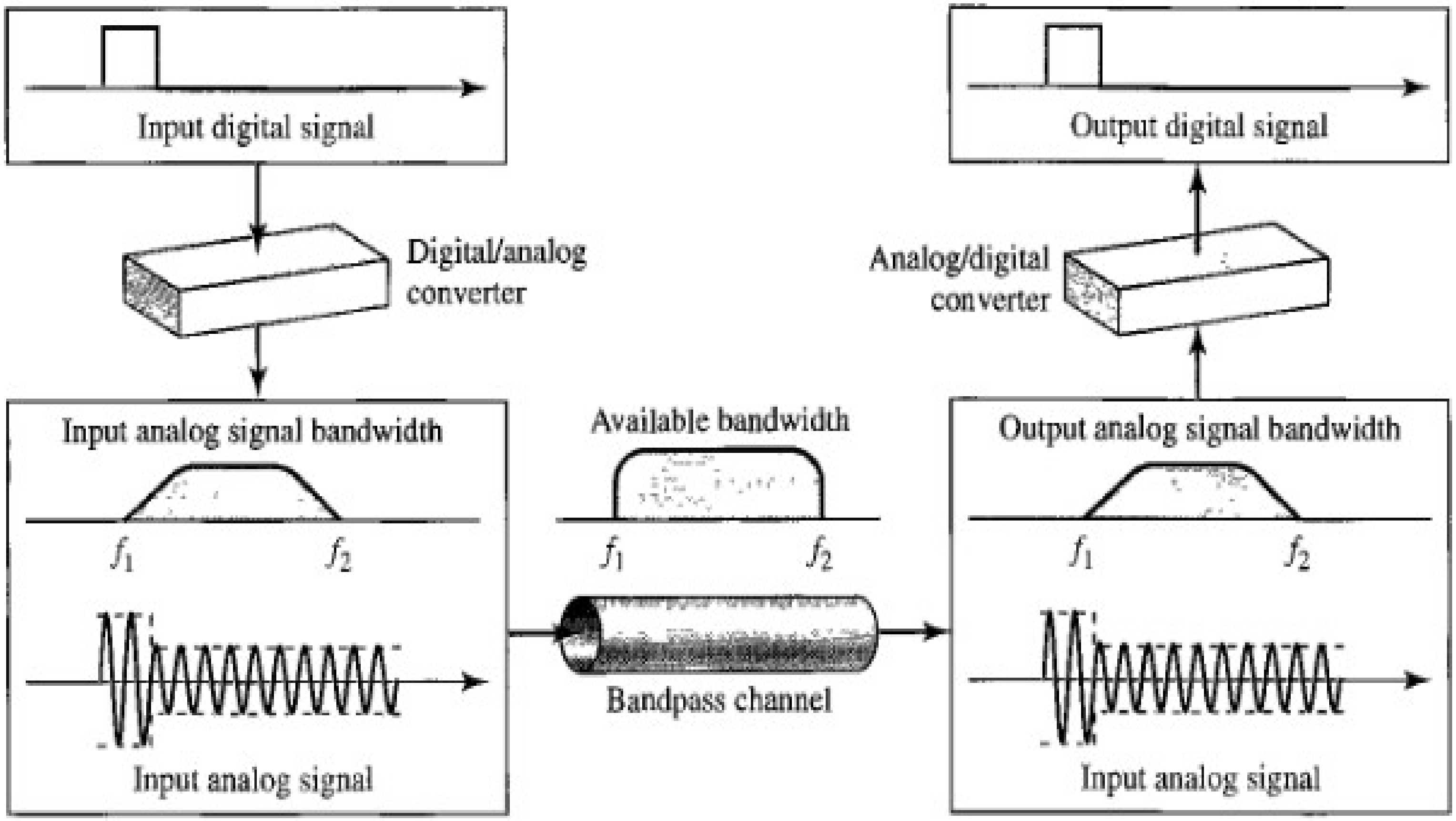
LPC-LB

- What is the required bandwidth of a LPC if we need to send 1Mbps using baseband transmission?
  - B=bit rate / 2 = 500kHz, minimum bandwidth
- We have a LPC with B=100 kHz. What is the maximum bit rate of this channel?
  - Bit rate = 2 x B = 200 kbps

Broadband Transmission

- Changes the digital signal to analog signal for transmission
- Allows the use of bandpass channel – a channel with a bandwidth that does not start from zero

Broadband Transmission



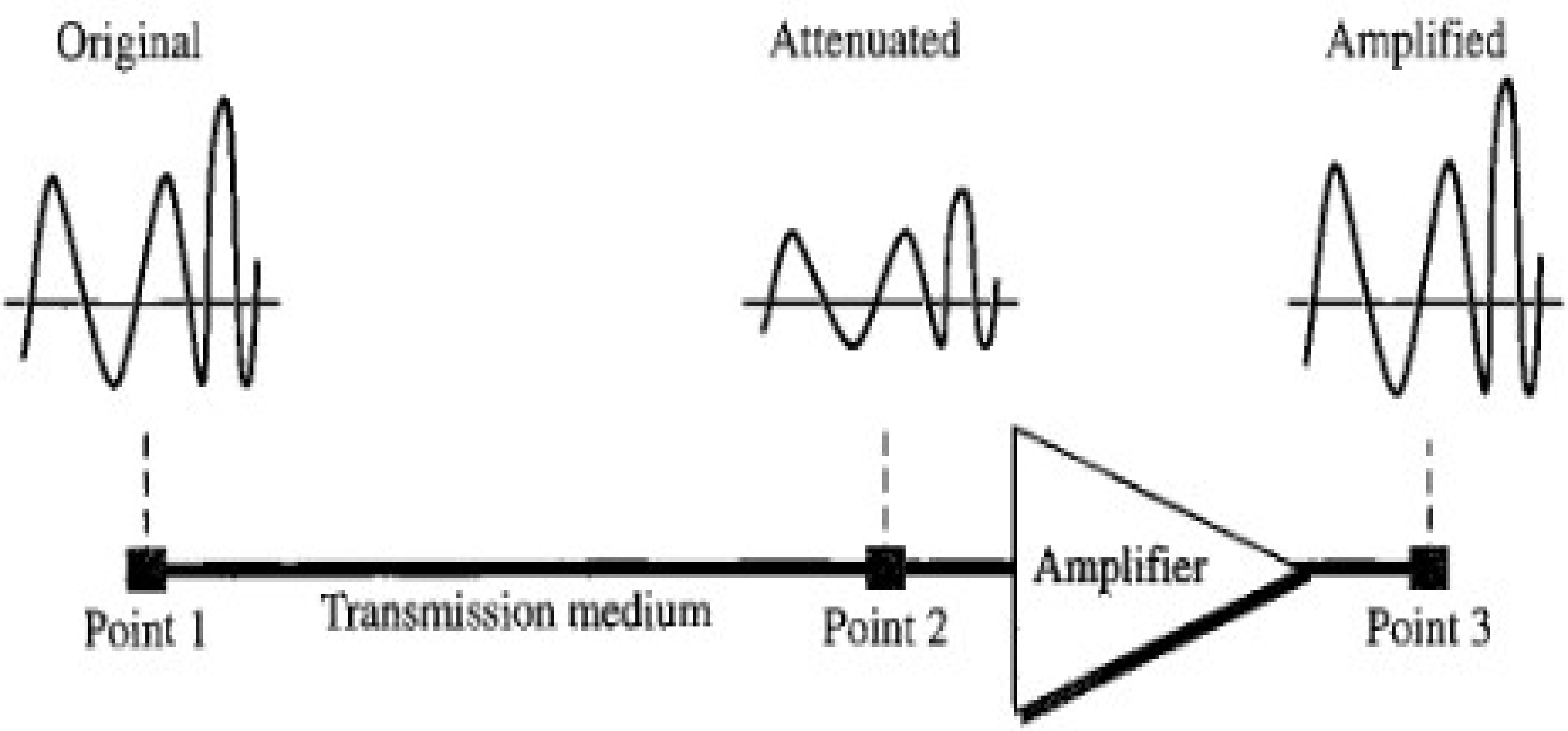
TRANSMISSION IMPAIRMENT

Attenuation

- Energy of a signal decreases as it travels through a medium
- Amplifiers are used to increase the signal
- Decibel (dB) – measures the relative strengths of two signals or one signal at two different points

$$dB = 10 \log_{10} \frac{P_2}{P_1}$$

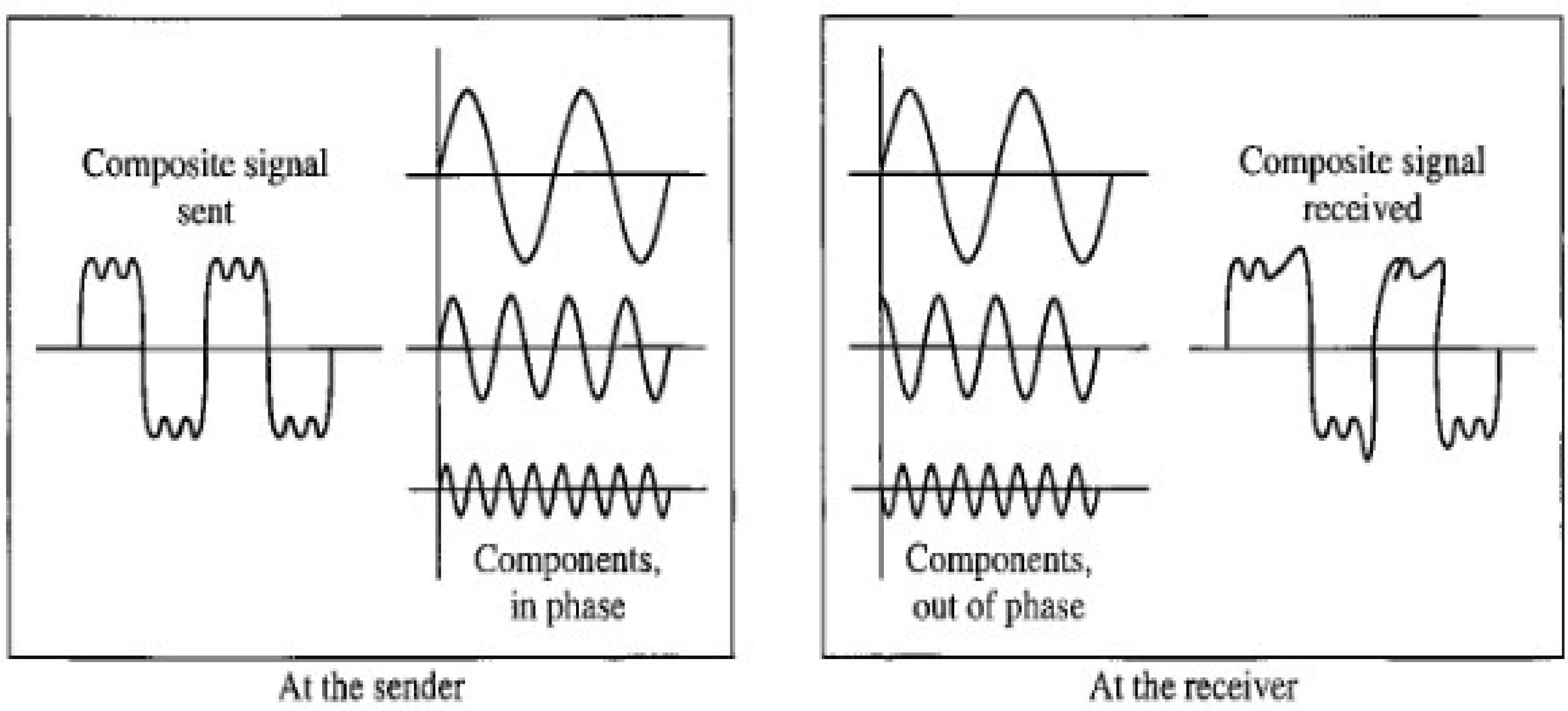
Attenuation



Distortion

- Signal changes its form or shape
- Each signal component has its own propagation speed, components may be out of phase

Distortion


Composite signal
sent
Components,
in phase
At the sender
Composite signal
received
Components,
out of phase
At the receiver

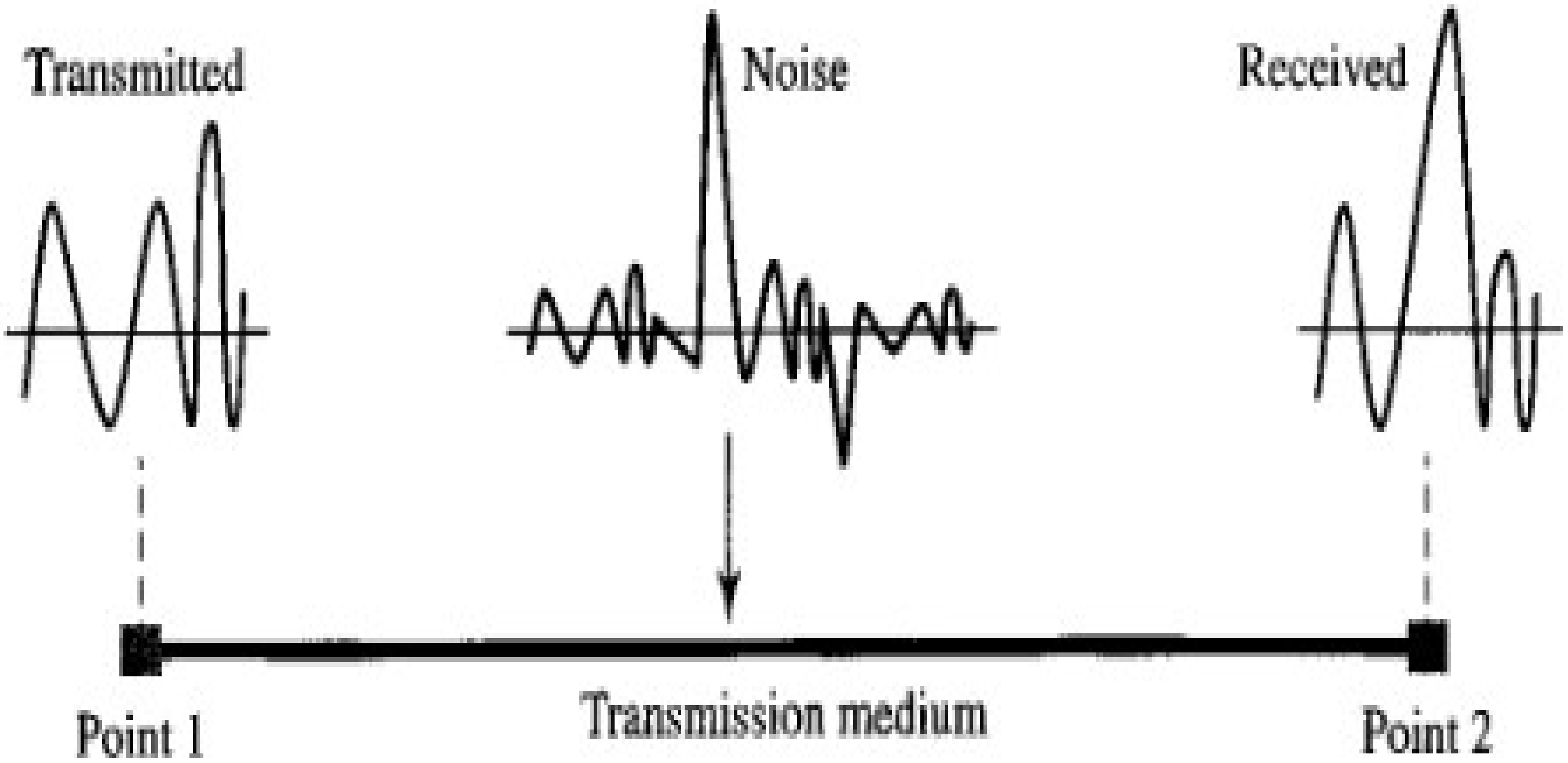
Noise

- Types
  - Thermal – random motion of electrons
  - Induced – external sources
  - Crosstalk – one wire on the other
  - Impulse – spike noise (ex. Lightning)
- Signal-to-Noise Ratio (SNR)

$$SNR = \frac{(average\ signal\ power)}{(average\ noise\ power)}$$

$$SNR_{dB} = 10 \log_{10} SNR$$

Noise


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Data Rate Limits

- Depends on:
  - Bandwidth available
  - Level of the signals we use
  - Quality of the channel (level of noise)
- Noiseless Channel: Nyquist Bit Rate (bps), L is number of signal levels

$$Bit\ Rate_{Nyquist} = 2 \times bandwidth \times \log_2 L$$

- Noisy Channel: Shannon Capacity (bps)

$$Capacity = bandwidth \times \log_2 (1 + SNR)$$

Examples

- What is the maximum bit rate of a noiseless channel with a bandwidth of 3 kHz transmitting with two signal levels?

$$BitRate = 2 \times 3000 \times \log_2 2 = 6000\ bps$$

- How many signal levels are needed to send at 265 kbps over a noiseless channel with a bandwidth of 20 kHz?

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$
$$\log_2 L = 6.625$$
$$L = 2^{6.625} = 98.7\ levels$$

Examples

- A telephone line has a typical bandwidth of 3000 Hz (300 to 3300 Hz) for data communications. SNR is 3162. What is the capacity?

$$C = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$

$$3000 \times 11.62 = 34,860 \; bps$$

Performance

- Bandwidth – in hertz or in bps
- Throughput – how fast we can actually send data through a network
- Latency (Delay) – how long it takes for an entire message to completely arrive at the destination from the first bit
  - Propagation time + transmission time + queuing time + processing delay

Performance

- Propagation Time – time required for a bit to travel from source to the destination

$$Propagation\, time = \frac{(Distance)}{(Propagation\, speed)}$$

- Transmission Time – time to transmit all the bits

$$Transmission\, time = \frac{msize}{bandwidth}$$

- Queuing Time – time to hold the message before it is processed

Examples

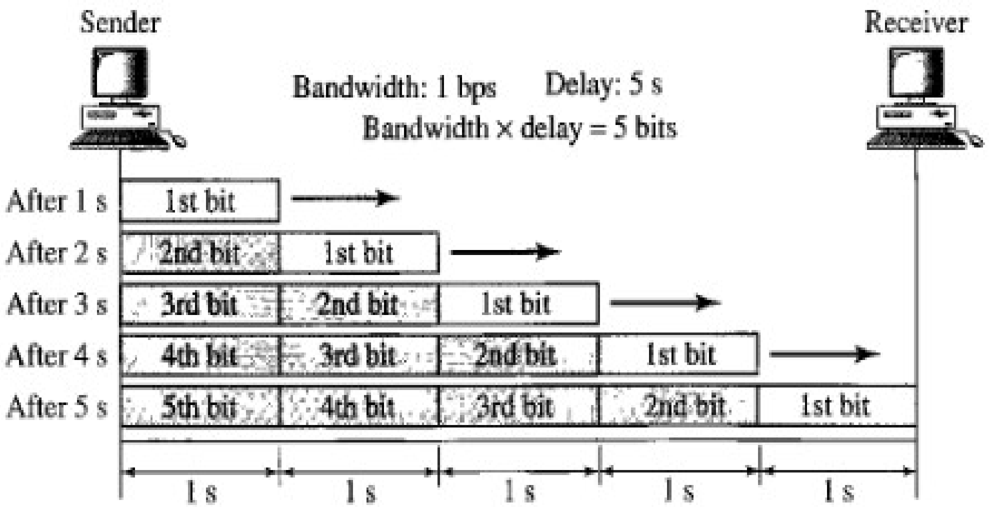
- What are the propagation time and the transmission time for a 2.5-kbyte email if the bandwidth is 1 Gbps? Assume the distance between the sender and the receiver is 12,000 km and light travels at $2.4 \times 10^8 m/s$

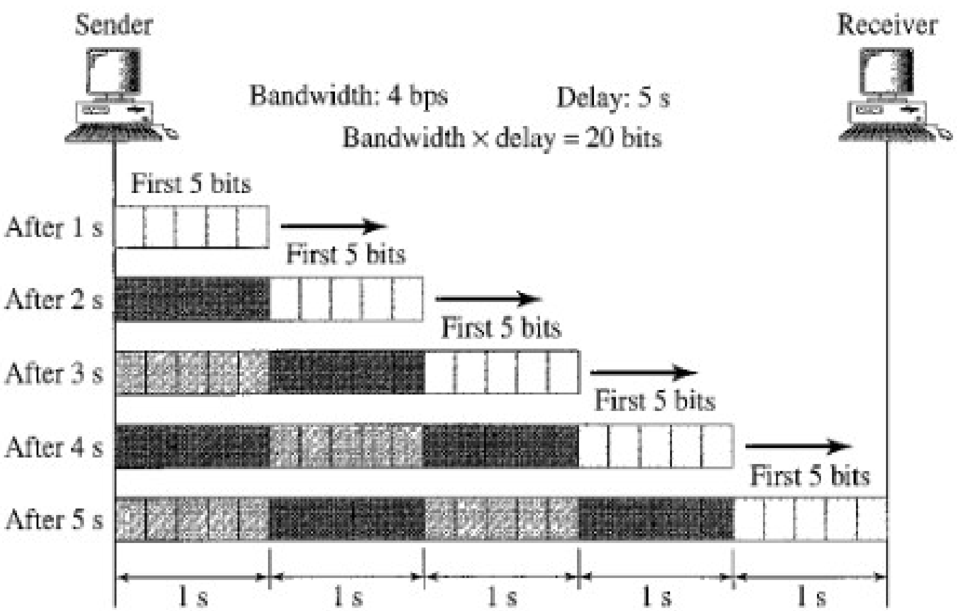
$$Propagation\ time = \frac{(12{,}000 \times 1000)}{(2 \times 10^8)} = 50\ ms$$

$$Transmission\ Time = \frac{(2500 \times 8)}{(10^9)} = 0.020\ ms$$

Performance

- Bandwidth-Delay Product
  - Defines the number of bits that can fill the link





Jitter

- Delays in transmitting time sensitive data

Enjoy! :)