Data Communications and Networking Fourth Edition

Forouzan

Chapter 3

Data and Signals

Introduction

- Physical layer is responsible to perform various functions.
- One of its major functions is to move data in form of electromagnetic signals across a transmission medium.
- Data must be transformed to electromagnetic signals to be transmitted.

Analog and Digital Data

- Data can be analog or digital.
- The term analog data refers to information that is continuous.
- Digital data refers to information that has discrete states.
- Example 1: Analog and digital clock
- Example 2: Speech signal and data stored in computer memory in form of 0s and 1s.

Analog and Digital Signal

- Signals can be analog or digital.
- Analog signals can have an infinite number of values in a range.
- Digital signals can have only a limited number of values.

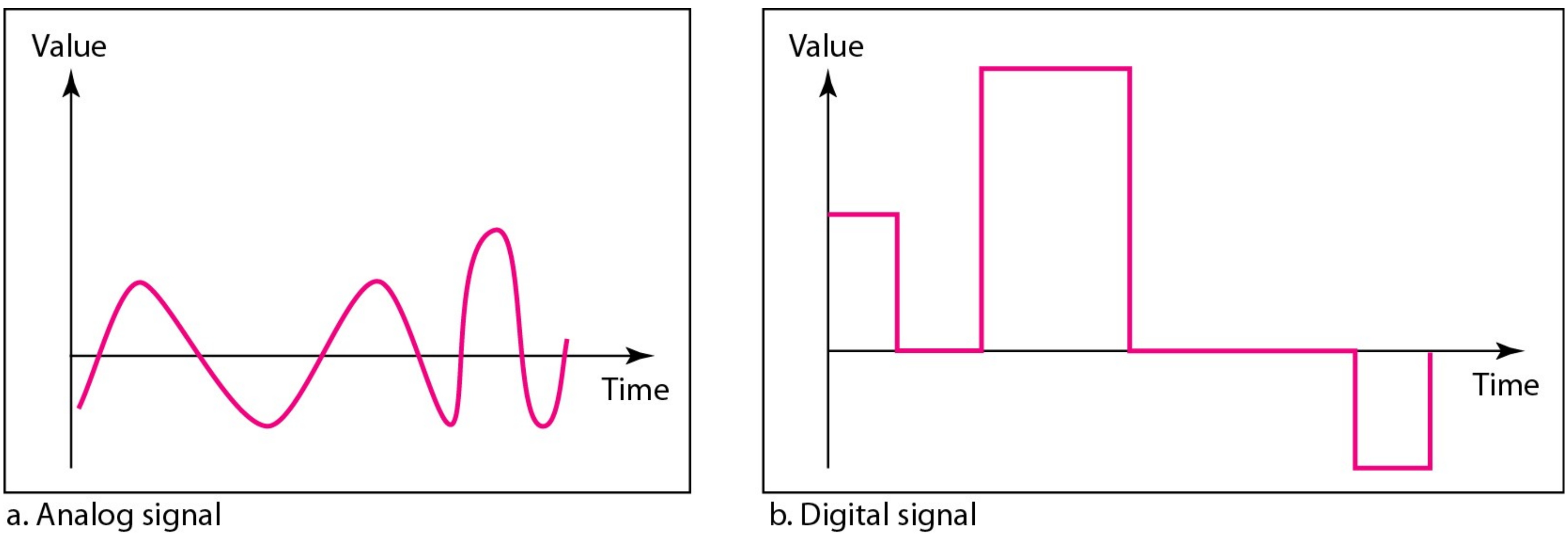


Figure 3.1 *Comparison of analog and digital signals*

Periodic and Non-periodic Signals

- Both analog and digital signals can take one of the two forms:
  - Periodic
  - Non-periodic (aperiodic)
- A periodic signal complete a pattern within a measurable time called period and repeats that pattern over time.
- The completion of one full pattern is called a cycle.
- A non-periodic signal change without exhibiting a pattern or cycle that repeats over time

Periodic Analog Signals

- In data communications, we commonly use periodic analog signals and non-periodic digital signals.
- Periodic analog signals can be classified as simple or composite.
- A simple periodic analog signal, a sine wave, cannot be decomposed into simpler signals.
- A composite periodic analog signal is composed of multiple sine waves.

Sine Wave

- The sine wave is the most fundamental form of a periodic analog signal.
- A sine wave can be represented by three parameters: peak amplitude, frequency, and phase.

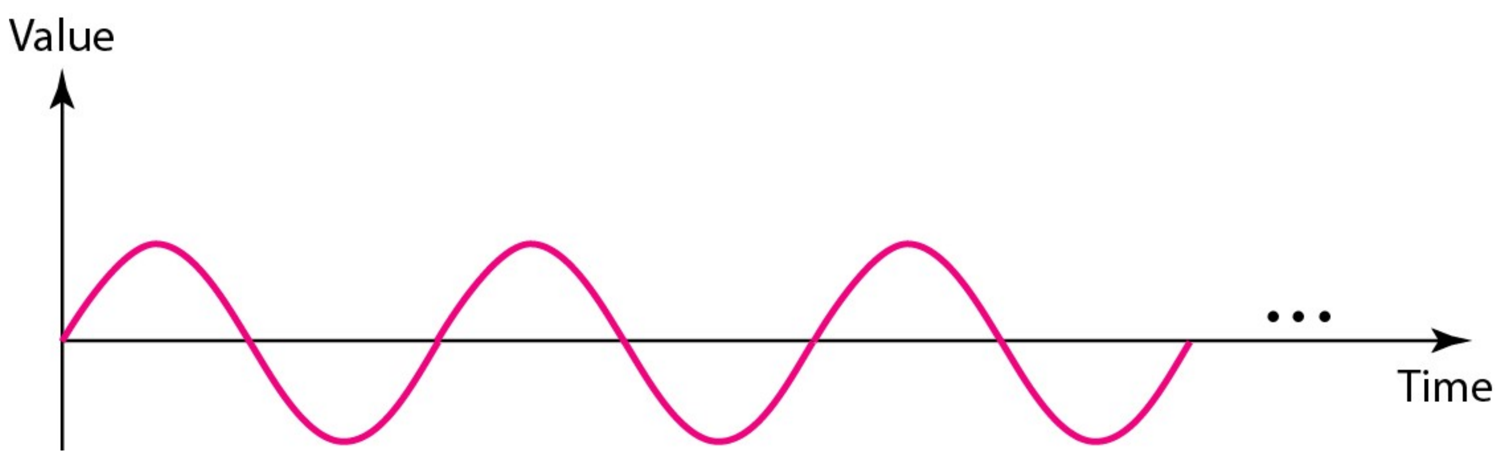


Figure 3.2 *A sine wave*

Peak Amplitude

- The peak amplitude of a signal is the absolute value of its highest intensity, proportional to the energy it carries.
- For electric signals, peak amplitude is normally measured in volts.
- Example 3.1: In Pakistan the power can be represented by a sine wave with peak amplitude of 170 to 220 volts, however in US it is 110 to 120 volts.
- Example 3.2: The voltage of battery is constant which is considered as sine wave. The peak value of an AA battery is 1.5 volts.

Peak Amplitude (Conti…)

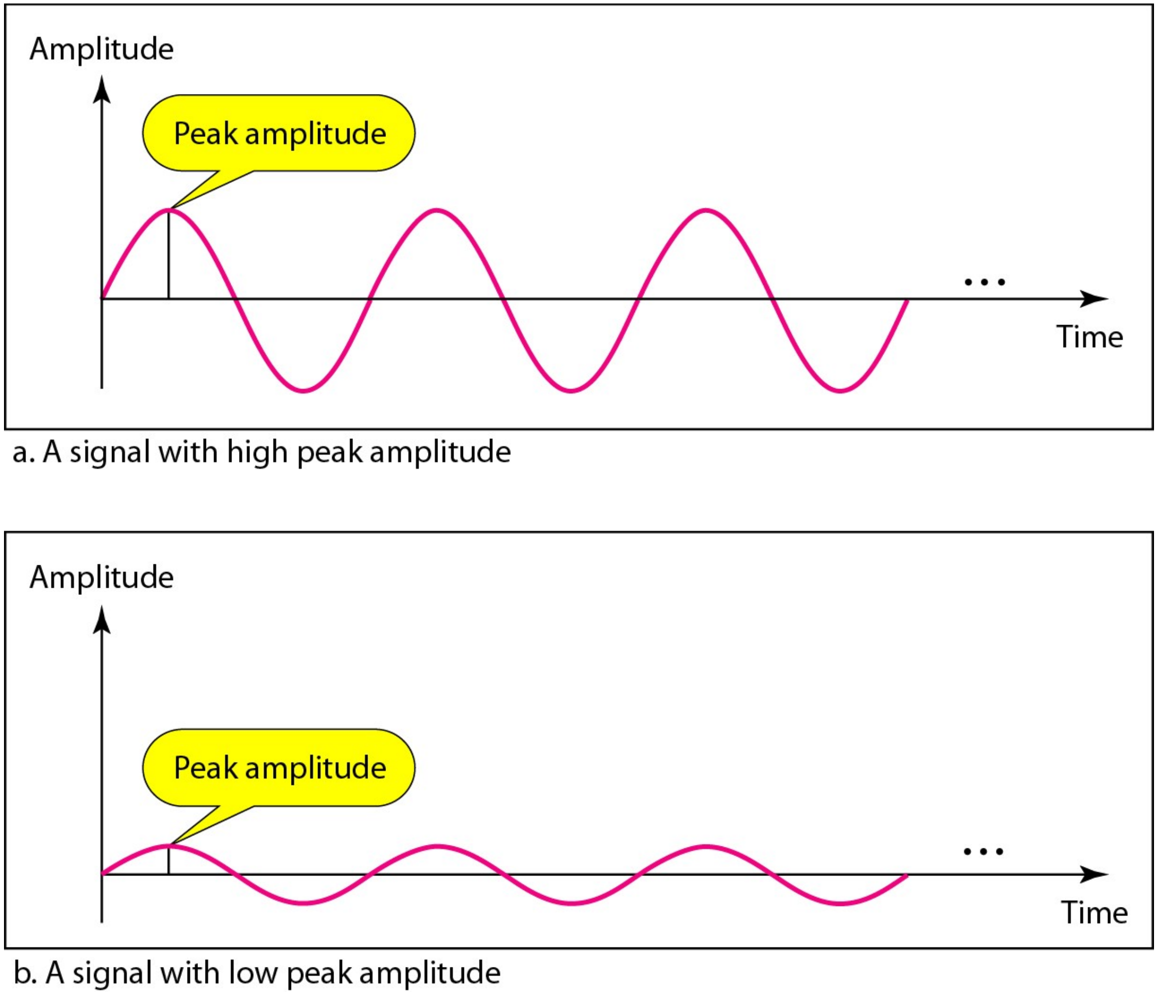


Figure 3.3 *Two signals with the same phase and frequency, but different amplitudes*

Period and Frequency

- Period (T) or time period refers to the amount of time (in seconds) a single needs to complete 1 cycle.
- Frequency (f) refers to the number of periods in 1 sec.
- Note: Both period and frequency are just one characteristic defined in two ways.
- Periods is express in seconds while frequency in Hertz (Hz) or cycle per second
- Frequency and period are inverse of each other.

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

Period and Frequency (Conti…)

Table 3.1 *Units of period and frequency*

Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	10^{-6} s	Megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	Gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz

Period and Frequency (Conti…)

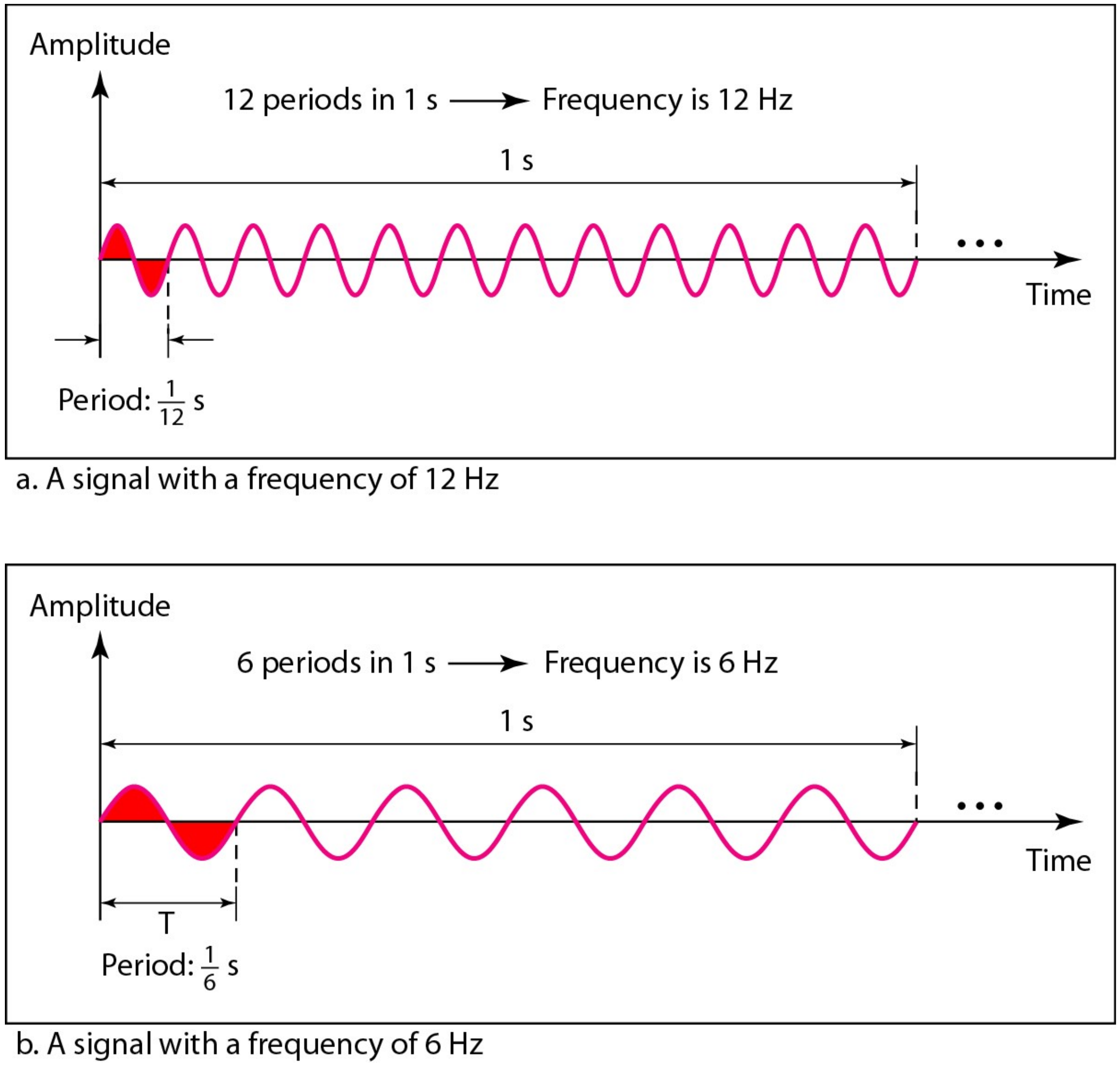


Figure 3.4 *Two signals with the same amplitude and phase, but different frequencies*

Period and Frequency (Conti…)

Example 3.3: The power we use at home has a frequency of 60 Hz. The period of this sine wave can be determined as follows:

Solution:

$$T = \frac{1}{f} = \frac{1}{60} = 0.0166 \text{ s} = \boxed{16.6 \times 10^{-3} = 16.6 \text{ ms}}$$

Period and Frequency (Conti…)

Example 3.4: Express a period of 100 ms in microseconds.

Solution:

We know that:

$$1 \text{ ms} = 10^{-3} \text{ s and } 1 \text{ s} = 10^{6} \ \mu\text{s}$$

So

$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 100 \times 10^{-3} \times 10^{6} \ \mu\text{s}$$
$$= 10^{2} \times 10^{-3} \times 10^{6} \ \mu\text{s}$$
$$= 10^{5} \ \mu\text{s}$$

Period and Frequency (Conti…)

Example 3.5: The period of a signal is 100 ms. What is its frequency in kilohertz?

Solution

First we change 100 ms to seconds, and then we calculate the frequency from the period (1 Hz = 10^{-3} kHz).

$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 10^{-1} \text{ s}$$

$$f = \frac{1}{T} = \frac{1}{10^{-1}} \text{ Hz} = 10 \text{ Hz} = 10 \times 10^{-3} \text{ kHz} = 10^{-2} \text{ kHz}$$

Period and Frequency (Conti…)

- Frequency is the rate of change with respect to time.
- Change in a short span of time means high frequency.
- Change over a long span of time means low frequency.
- If a signal does not change at all, its frequency is zero.
- If a signal changes instantaneously, its frequency is infinite.

Phase

- The term phase describes the position of the waveform relative to time 0.
- It indicates the status of the first cycle.
- Phase is measured in degrees or radians
  - 360 degrees = 2π rad
  - 1 degree = $2\pi/360$ rad
  - 1 rad = $360/2\pi$ rad
- Phase shift of 360 degrees – complete period shift
- Phase shift of 180 degree – one-half period shift
- Phase shift of 90 degree – one-quarter period shift

Phase (Conti…)

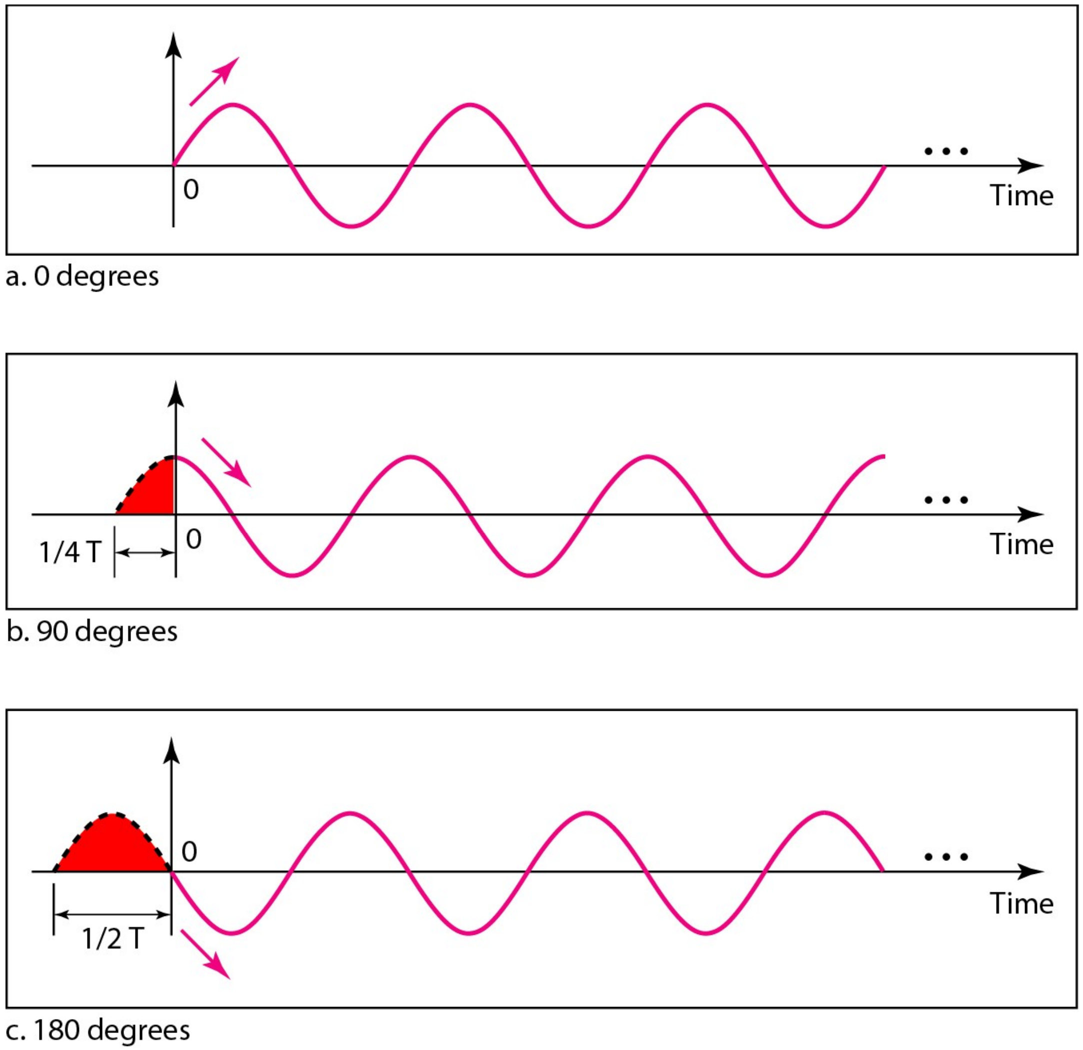


Figure 3.5 *Three sine waves with the same amplitude and frequency, but different phases*

Phase (Conti…)

Example 3.6: A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

Solution

We know that 1 complete cycle is 360°. Therefore, 1/6 cycle is

$$\frac{1}{6} \times 360 = 60^{\circ} = 60 \times \frac{2\pi}{360} \text{ rad} = \frac{\pi}{3} \text{ rad} = 1.046 \text{ rad}$$

Wavelength

- Wavelength is another of a signal traveling through a transmission medium.
- It binds the period or frequency of a simple sine wave to the propagation speed of the medium.
- Frequency is independent of the medium but wavelength depends on both frequency and medium.
- Wavelength is the distance a simple signal can travel in one period.
- Wavelength is measured normally in micrometers (μm) instead of meters.

Wavelength (Conti…)

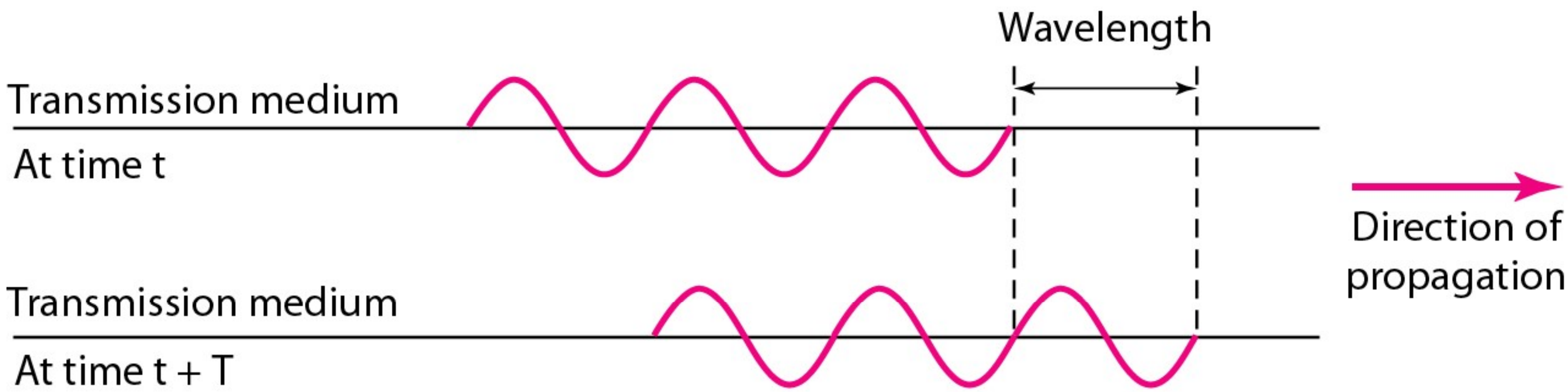


Figure 3.6 *Wavelength and period*

Wavelength (Conti…)

- Wavelength can be calculated if propagation speed (speed of light) and period or frequency of the signal are known.

Wavelength = Propagation Speed x period = Propagation Speed/Frequency

$$\lambda = c / f$$

Example: The wavelength of a red light (frequency is 4×10^{14}) in air is:

Solution:

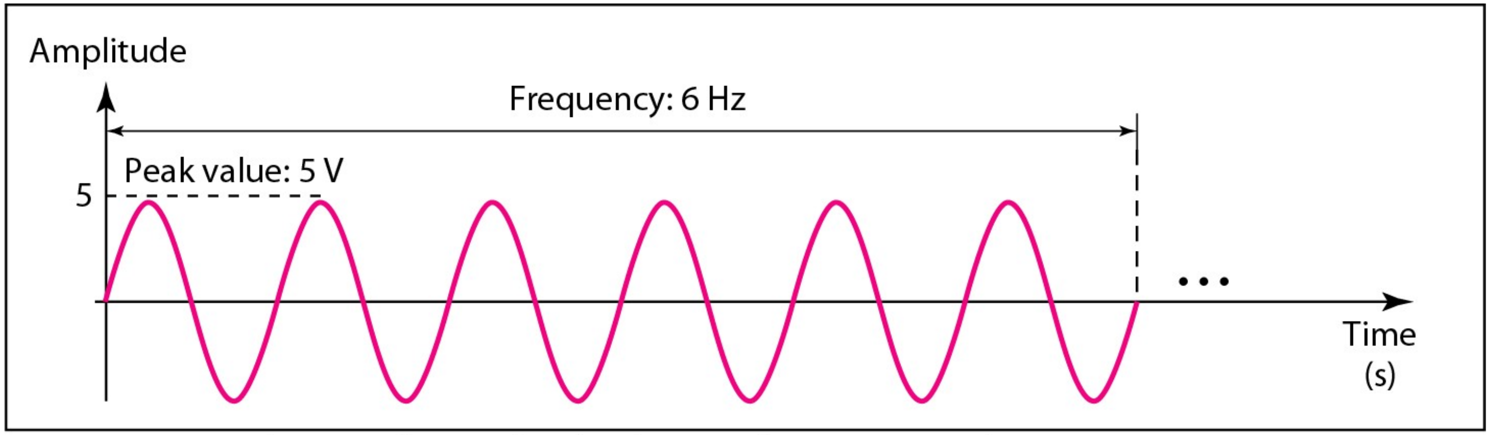
$$\lambda = c / f = 3 \times 10^{8} / 4 \times 10^{14}$$

$$= 0.75 \times 10^{-6} \text{ m} = 0.75 \ \mu\text{m}$$

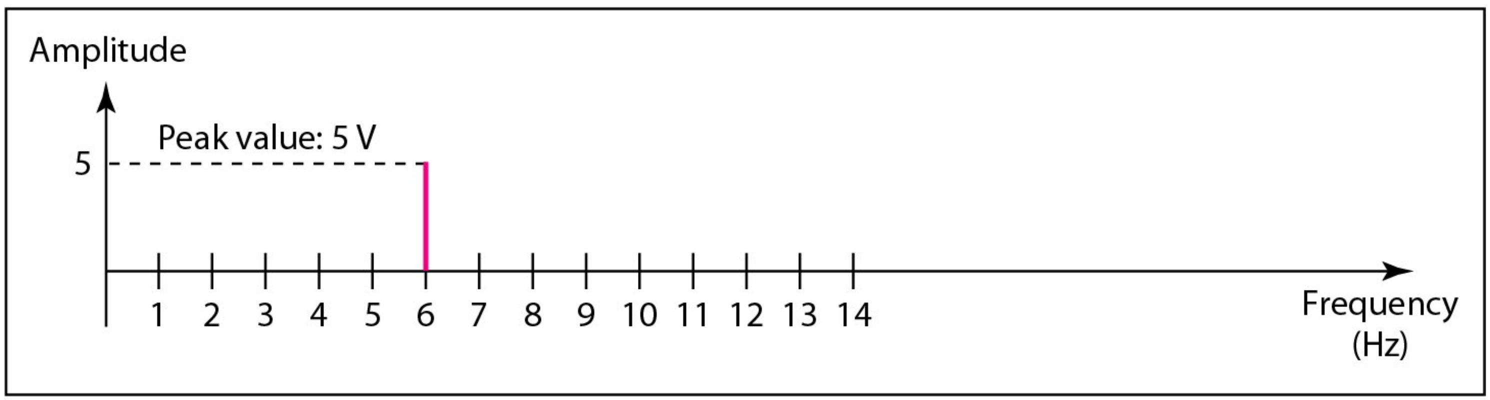
Time and Frequency Domains

- A sine wave is defined by its amplitude, frequency, and phase.
- Time-domain plots are used to show the changes in signal amplitude with respect to time i.e. amplitude-versus-time plot).
- Phase is not explicitly shown on time-domain plots.
- Frequency-domain plots are used to show the relationship between amplitude and frequency.
- It is concerned with only the peak value and frequency.
- A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

Time and Frequency Domains (Conti…)



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



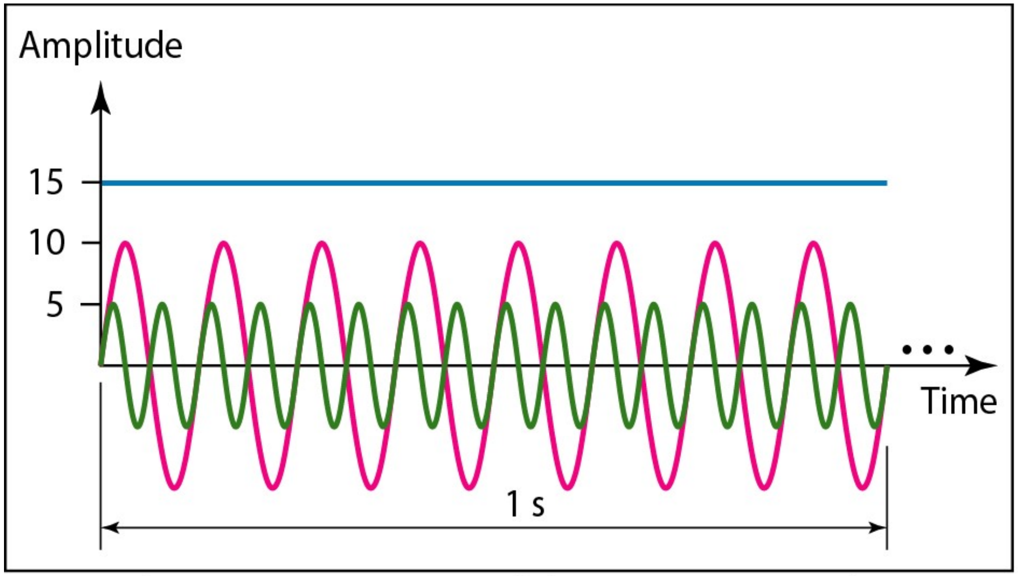
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Figure 3.7 *The time-domain and frequency-domain plots of a sine wave*

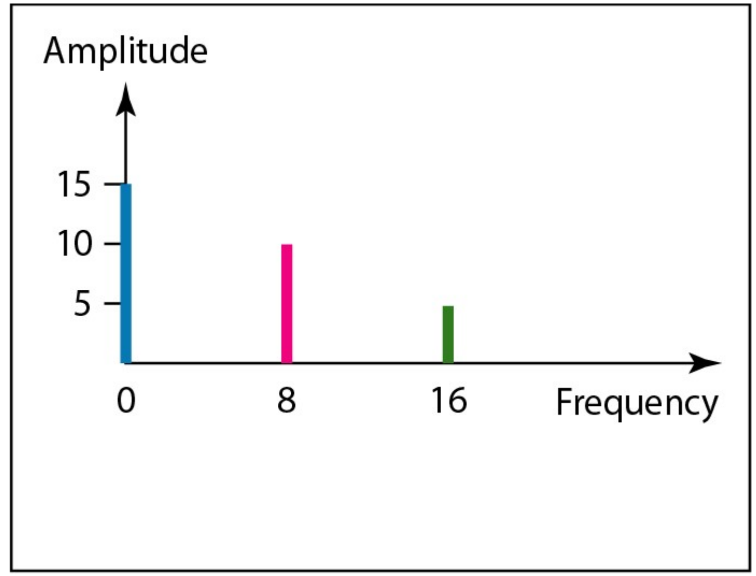
Time and Frequency Domains (Conti…)

Example 3.7: The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.8 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

Time and Frequency Domains (Conti…)



a. Time-domain representation of three sine waves with frequencies 0, 8, and 16



b. Frequency-domain representation of the same three signals

Figure 3.8 *The time domain and frequency domain of three sine waves*

Composite Signals

- A single-frequency sine wave is not useful in data communications.
- We need to send a composite signal, a signal made of many simple sine waves.
- In early 1900s, the French mathematician Jean-Baptiste Fourier showed that any composite signal is actually a combination of simple sine waves with different frequencies, amplitudes, and phases.

Composite Signals (Conti…)

- A composite signal can periodic or aperiodic.
- If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies.
- If the composite signal is aperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

Composite Signals (Conti…)

Example 3.8: Figure 3.9 shows a periodic composite signal with frequency f. This type of signal is not typical of those found in data communications. We can consider it to be three alarm systems, each with a different frequency. The analysis of this signal can give us a good understanding of how to decompose signals.

Composite Signals (Conti…)

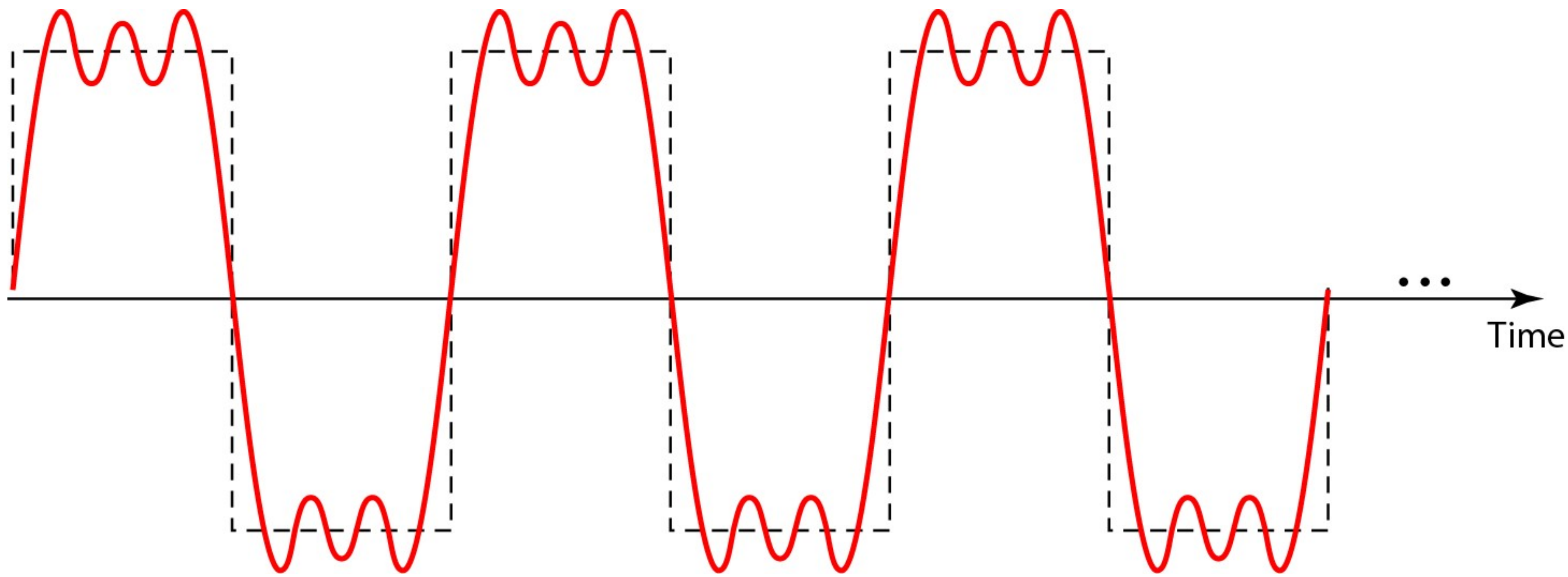


Figure 3.9 *A composite periodic signal*

Composite Signals (Conti…)

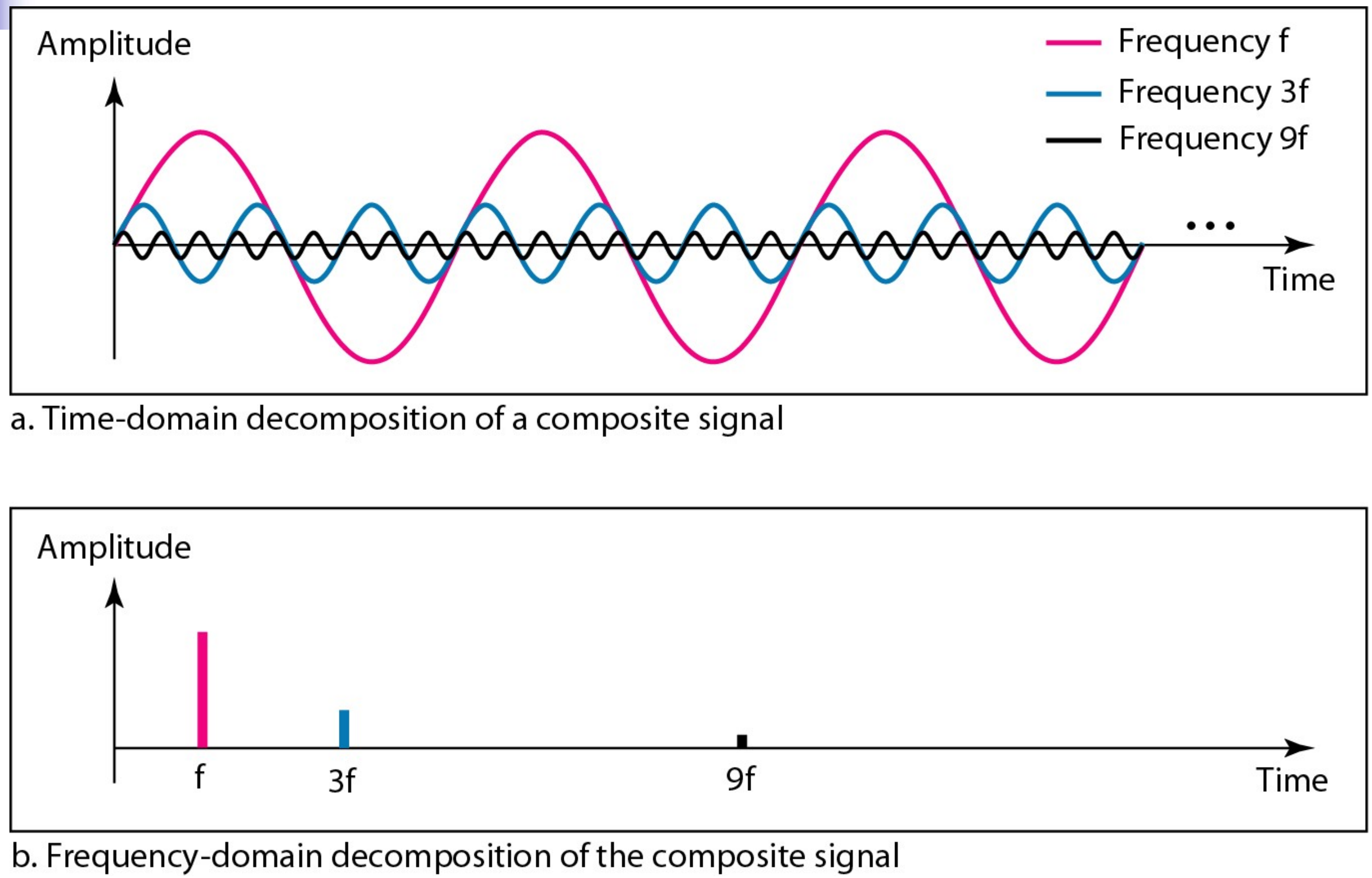


Figure 3.10 *Decomposition of a composite periodic signal in the time and frequency domains*

Composite Signals (Conti…)

- The frequency of sine wave with frequency *f* is the same as the frequency of the composite signal, known as fundamental frequency or first harmonic.
- Sine wave with frequency *3f* has a frequency 3 times of the fundamental frequency known as 3rd harmonic.
- The third sine wave with frequency *9f* has a frequecy of 9 times the fundamental frequency, known as 9th harmonic.

Composite Signals (Conti…)

Example 3.9: Figure 3.11 shows a aperiodic composite signal. It can be the signal created by a microphone or a telephone set when a word or two is pronounced. In this case, the composite signal cannot be periodic, because that implies that we are repeating the same word or words with exactly the same tone.

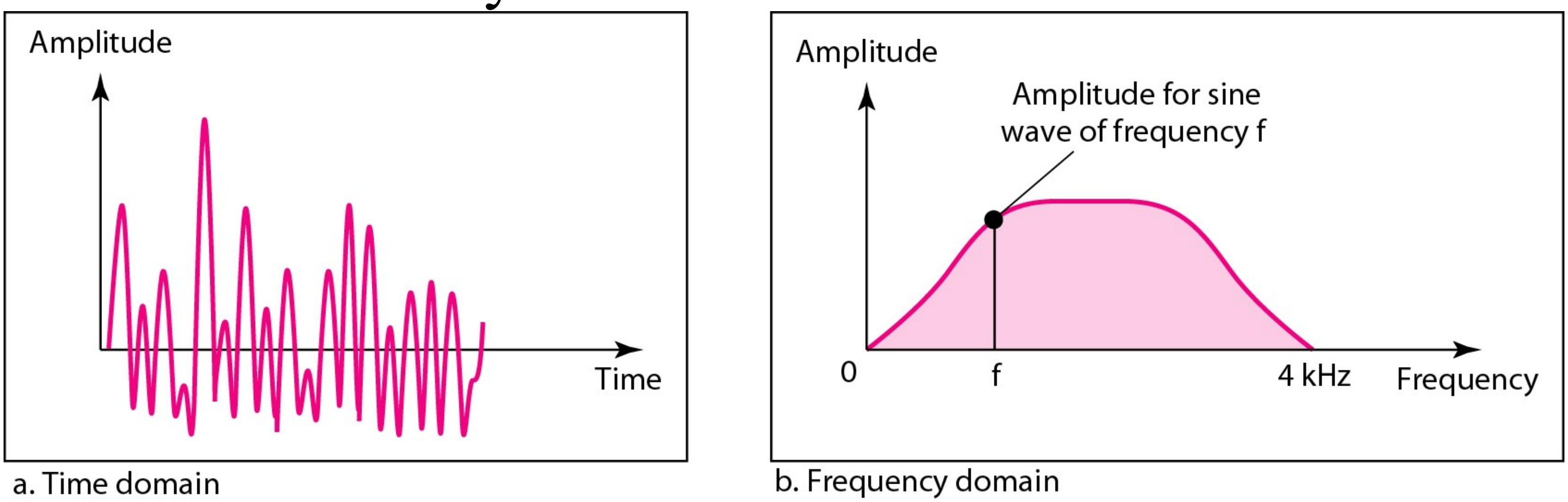


Figure 3.11 *The time and frequency domains of a nonperiodic signal*

Composite Signals (Conti…)

- In time-domain representation of this composite signal, there are an infinite number of simple sine frequency.
- Although the number of frequencies in human voice is infinite, but the range is limited.
- A normal human being can create a continuous range of frequencies between 0 to 4 KHz.

Bandwidth

- The range of frequencies contained in a composite signal is its bandwidth.
- The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.
- For Example: If a composite signal contains frequencies between 1000Hz and 5000 Hz, then its bandwidth is 5000Hz – 1000Hz = 4000Hz.

Bandwidth (Conti…)

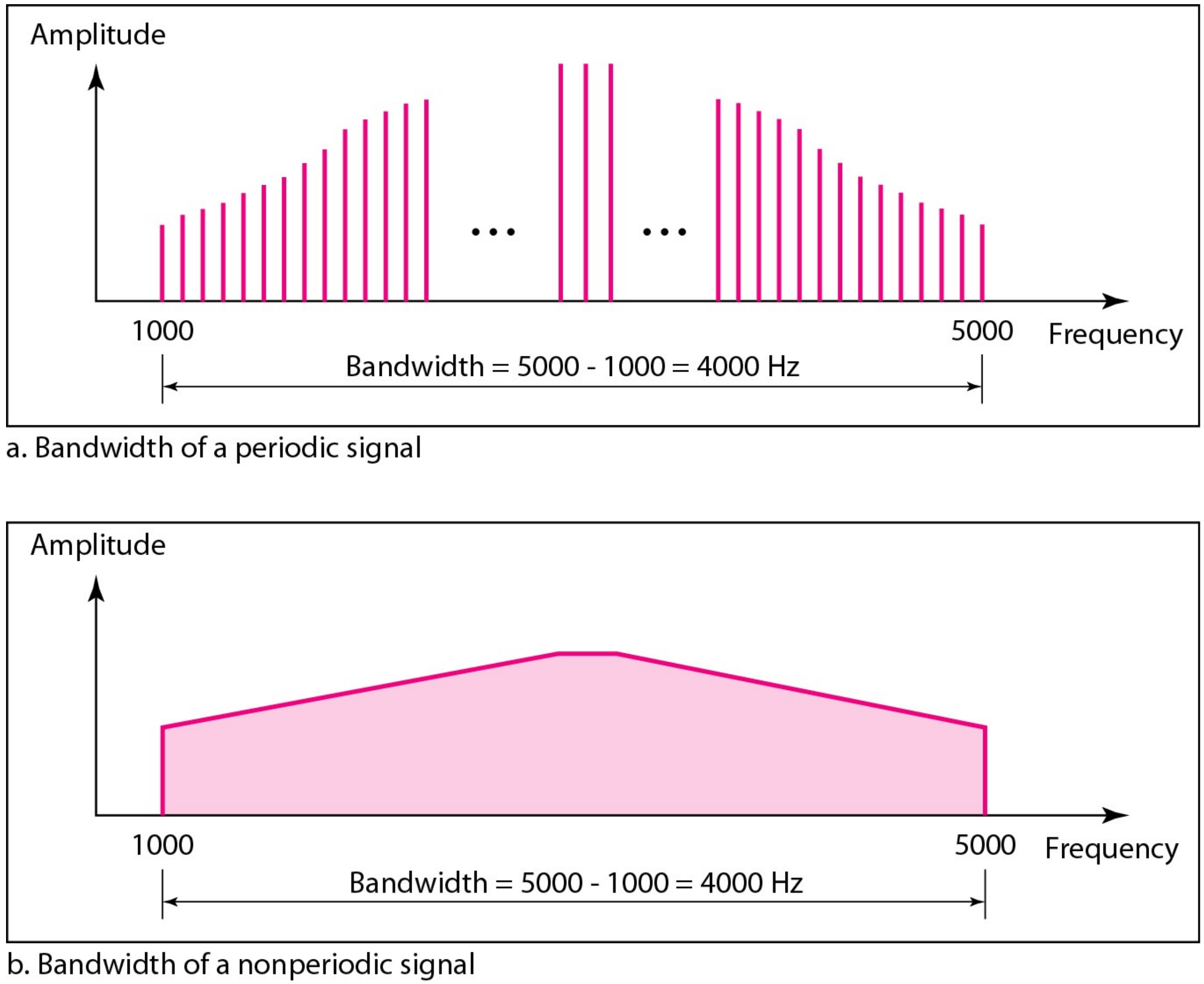


Figure 3.12 *The bandwidth of periodic and nonperiodic composite signals*

Bandwidth (Conti…)

Example 3.10: If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

Solution

Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

$$B = f_h - f_l = 900 - 100 = 800 \text{ Hz}$$

Bandwidth (Conti…)

The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz (see Figure 3.13).

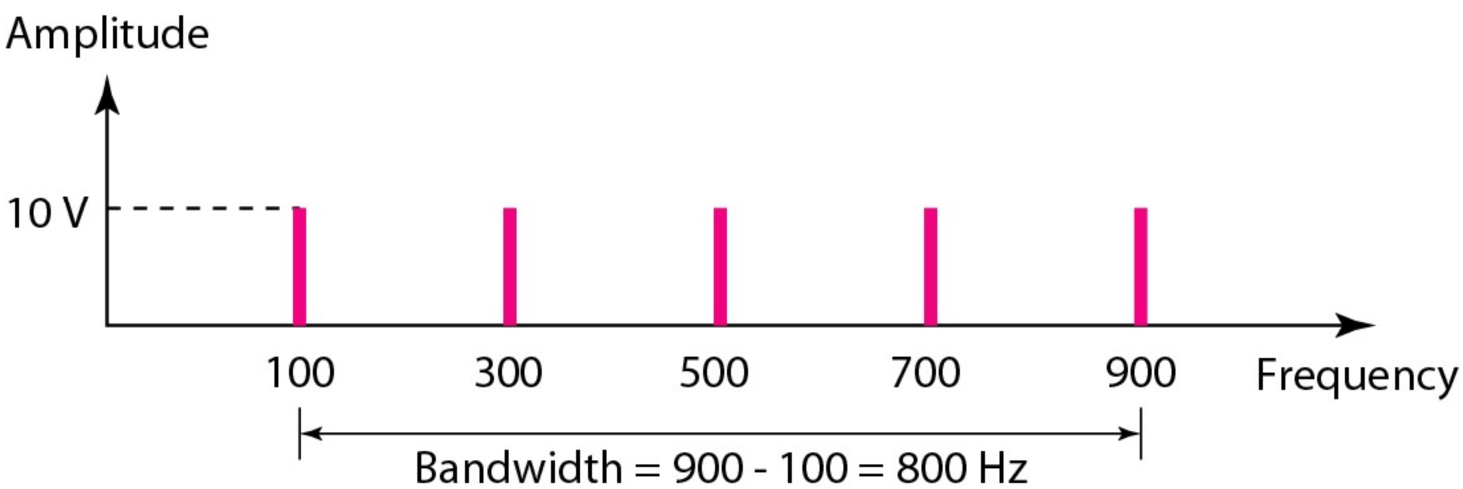


Figure 3.13 *The bandwidth for Example 3.10*

Bandwidth (Conti…)

Example 3.11: A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all frequencies of the same amplitude.

Solution

Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

$$B = f_h - f_l \quad \Rightarrow \quad 20 = 60 - f_l \quad \Rightarrow \quad f_l = 60 - 20 = 40 \text{ Hz}$$

Bandwidth (Conti…)

The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.14).

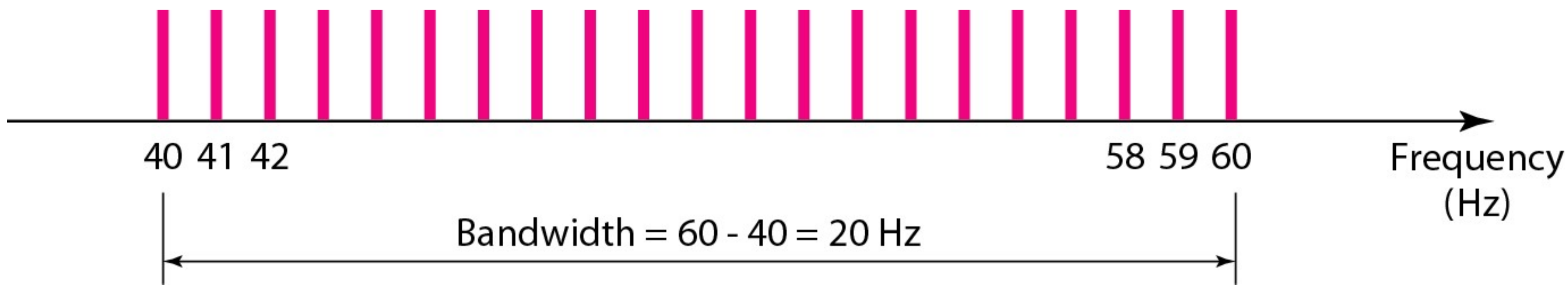


Figure 3.14 *The bandwidth for Example 3.11*

Example 3.12: A non-periodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20 V. The two extreme frequencies have an amplitude of 0. Draw the frequency domain of the signal.

Solution

The lowest frequency must be at 40 kHz and the highest at 240 kHz. Figure 3.15 shows the frequency domain and the bandwidth.

Bandwidth (Conti…)

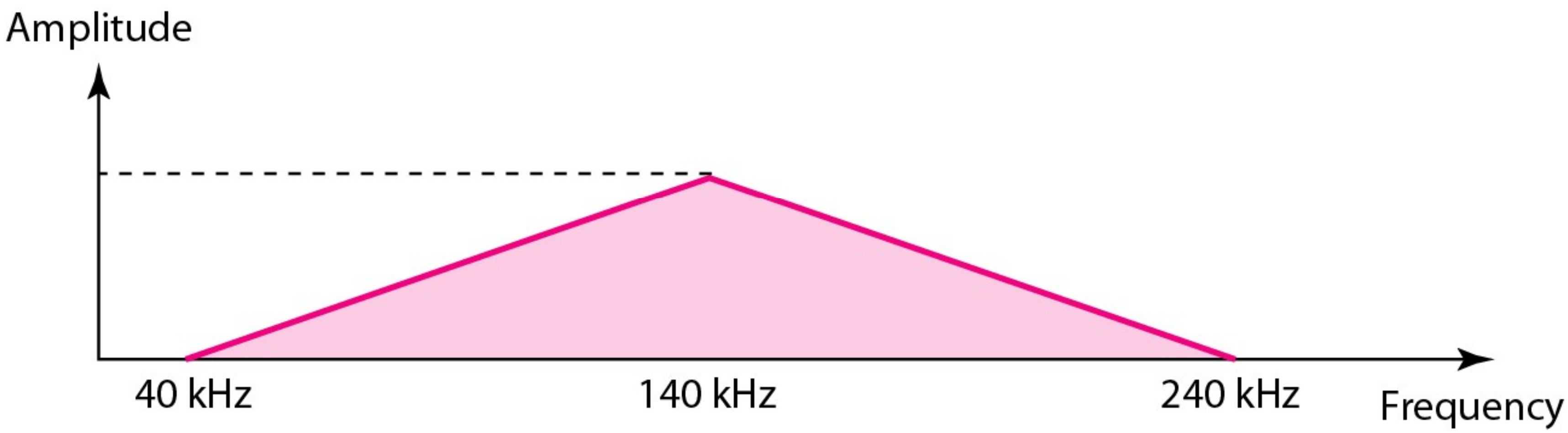


Figure 3.15 *The bandwidth for Example 3.12*

Bandwidth (Conti…)

Example 3.13: An example of a non-periodic composite signal is the signal propagated by an AM radio station. In the United States, each AM radio station is assigned a 10-kHz bandwidth. The total bandwidth dedicated to AM radio ranges from 530 to 1700 kHz.

Example 3.14: Another example of a non-periodic composite signal is the signal propagated by an FM radio station. In the United States, each FM radio station is assigned a 200-kHz bandwidth. The total bandwidth dedicated to FM radio ranges from 88 to 108 MHz.

Bandwidth (Conti…)

Example 3.15: Another example of a nonperiodic composite signal is the signal received by an old-fashioned analog black-and-white TV. A TV screen is made up of pixels. If we assume a resolution of 525 × 700, we have 367,500 pixels per screen. If we scan the screen 30 times per second, this is 367,500 × 30 = 11,025,000 pixels per second. The worst-case scenario is alternating black and white pixels. We can send 2 pixels per cycle. Therefore, we need 11,025,000 / 2 = 5,512,500 cycles per second, or Hz. The bandwidth needed is 5.5125 MHz.

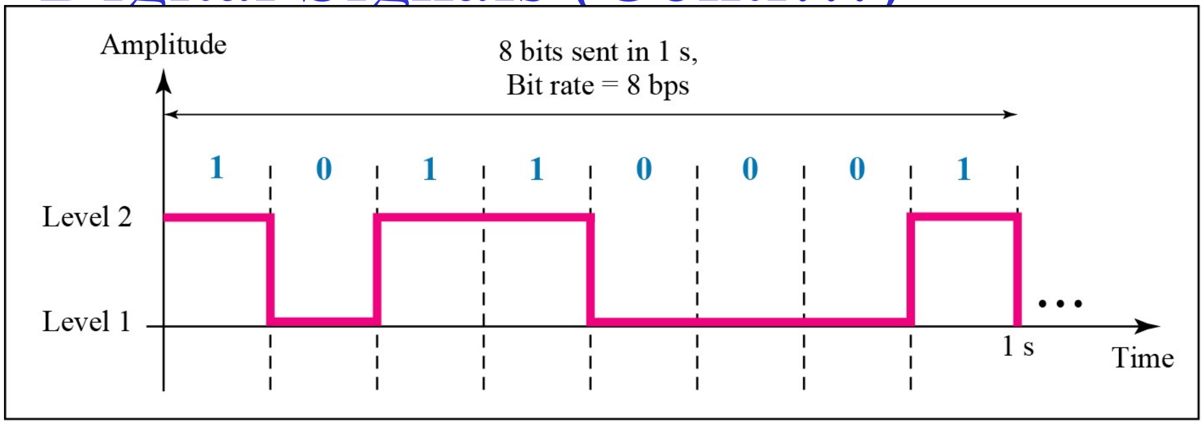
Note

Fourier analysis is a tool that changes a time domain signal to a frequency domain signal and vice versa.

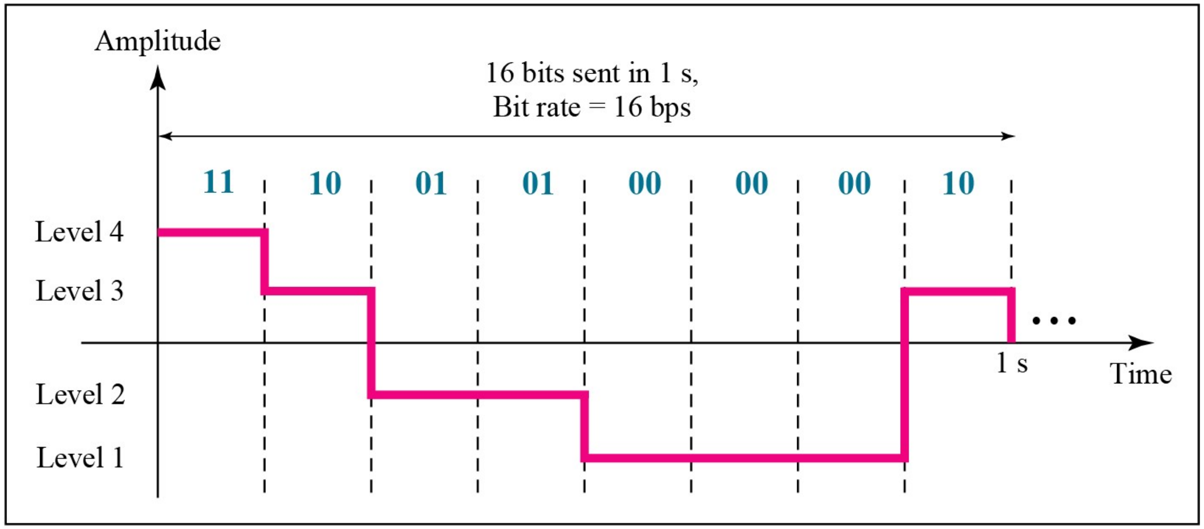
Digital Signals

- In addition to being represented by an analog signal, information can also be represented by a digital signal.
- For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage.
- A digital signal can have more than two levels to send more than 1 bit for each level.
- In general, if a signal has *L* levels, each level needs *log2L* bits.

Digital Signals (Conti…)



a. A digital signal with two levels



b. A digital signal with four levels

Figure 3.16 *Two digital signals: one with two signal levels and the other with four signal levels*

Digital Signals (Conti…)

Example 3.16: A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula discussed.

$$\text{Number of bits per level} = \log_2 8 = 3$$

Each signal level is represented by 3 bits.

Digital Signals (Conti…)

Example 3.17: A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula. Each signal level is represented by 3.17 bits. However, this answer is not realistic. The number of bits sent per level needs to be an integer as well as a power of 2. For this example, 4 bits can represent one level.

Bit Rate

- Most digital signals are non-periodic, thus frequency and period are not appropriate characteristics.
- Another term bit-rate (instead of frequency) is used to describe digital signals.
- The bit-rate is the number of bits sent in one second.
- It is expressed in bits per second (bps).

Bit Rate (Conti…)

Example 3.18: Assume we need to download text documents at the rate of 100 pages per sec. What is the required bit rate of the channel?

Solution

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits (ASCII), the bit rate is:

$$100 \times 24 \times 80 \times 8 = 1,636,000 \text{ bps} = 1.636 \text{ Mbps}$$

Bit Rate (Conti…)

Example 3.19: A digitized voice channel, as we will see in Chapter 4, is made by digitizing a 4-kHz bandwidth analog voice signal. We need to sample the signal at twice the highest frequency (two samples per hertz). We assume that each sample requires 8 bits. What is the required bit rate?

Solution

The bit rate can be calculated as:

$$2 \times 4000 \times 8 = 64{,}000 \text{ bps} = 64 \text{ kbps}$$

Bit Rate (Conti…)

Example 3.20: What is the bit rate for high-definition TV (HDTV)?

Solution

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel.

$$1920 \times 1080 \times 30 \times 24 = 1{,}492{,}992{,}000 \text{ or } 1.5 \text{ Gbps}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression

Bit Length

- As discussed that wavelength (for an analog signal) is the distance one cycle occupies on the transmission medium.
- Bit length is similar to wavelength defined for digital signals.
- Bit length is the distance one bit occupies on the transmission medium.

Bit Length = Propagation Speed * Bit Duration

Transmission Impairment

- Signals travel through transmission media, which are not perfect.
- The imperfection causes signal impairment.
- This means that the signal at the beginning of the medium is not the same as the signal at the end of the medium. What is sent is not what is received.
- Three causes of impairment are attenuation, distortion, and noise.

Transmission Impairment (Conti…)

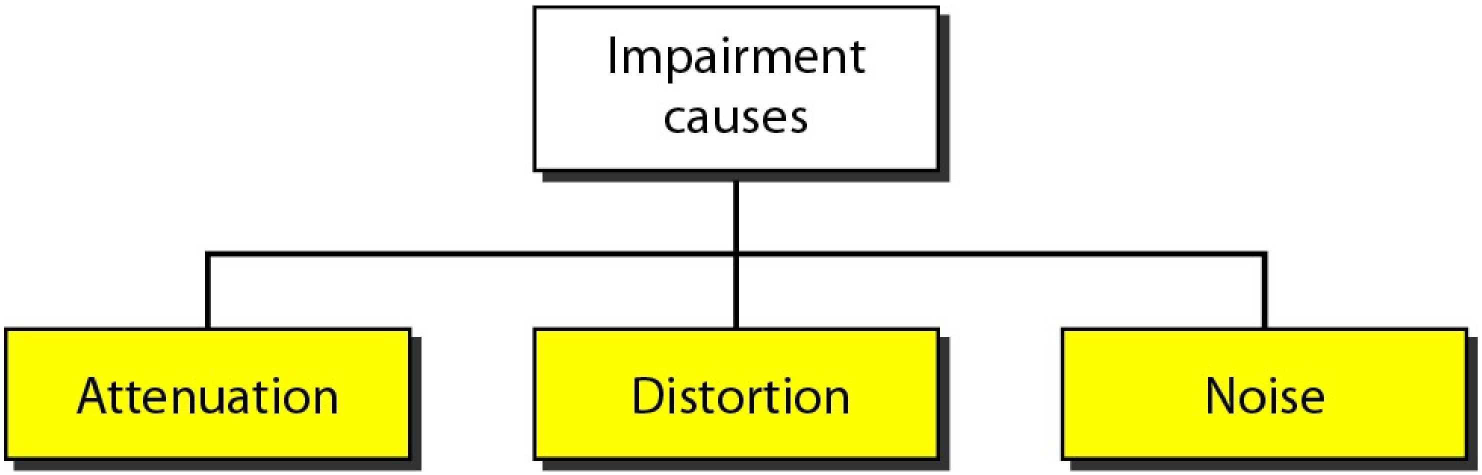


Figure 3.25 *Causes of impairment*

Attenuation

- Means loss of energy -> weaker signal.
- When a signal travels through a medium it loses energy overcoming the resistance of the medium.
- Wire carrying electrical signals gets warm i.e. some of the electrical energy is converted to heat.
- Amplifiers are used to compensate for this loss of energy by amplifying the signal.

Attenuation (Conti…)

- To show the loss or gain of energy the unit decibel (dB) is used.
- The decibel measures the relative strengths of two signals or one signal at two different points.

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

P_1 – Power of input signal

P_2 – Power of output signal

Attenuation (Conti…)

- Some engineering books define the decibel in terms of voltage instead of power.

$$dB = 20\log_{10} V_2/V_1$$

V_1 – Voltage of input signal

V_2 – Voltage of output signal

- Note: The decibel is negative if a signal is attenuated and positive if a signal is amplified.

Attenuation (Conti…)

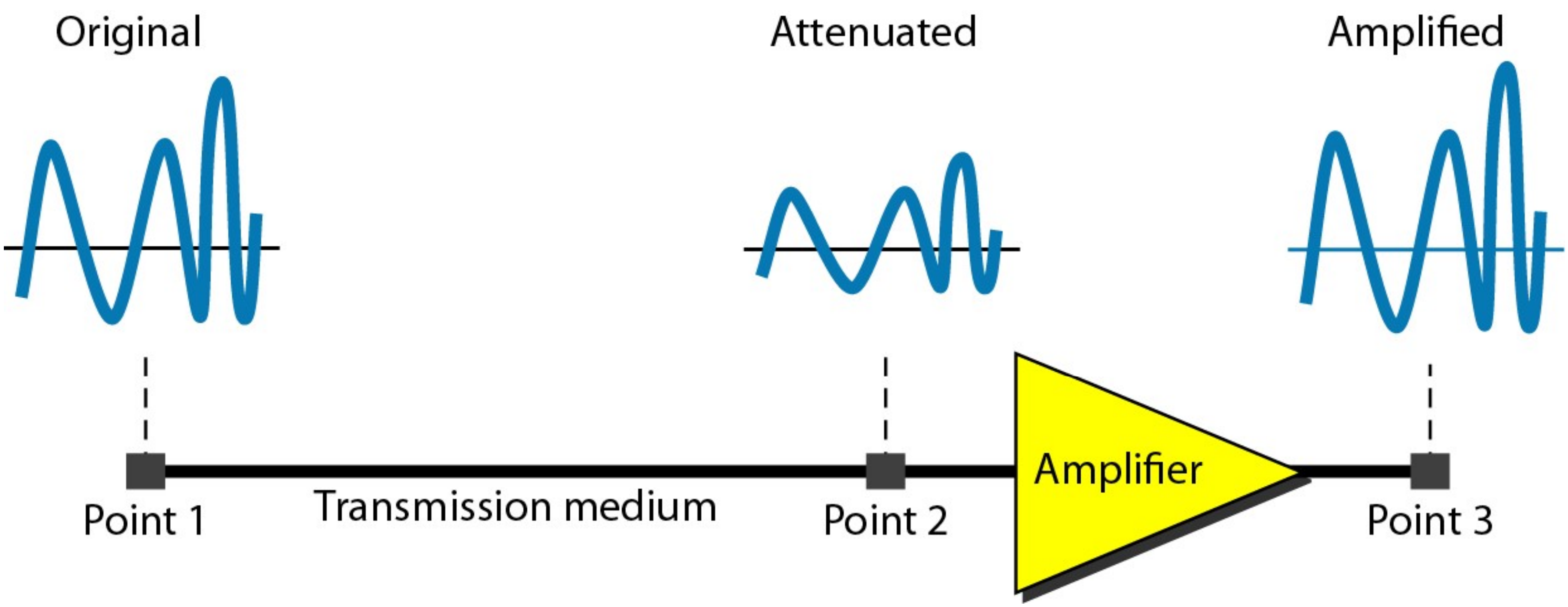


Figure 3.26 *Attenuation*

Attenuation (Conti…)

Example 3.26: Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P2 is (1/2)P1. In this case, the attenuation (loss of power) can be calculated as:

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5 P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

A loss of 3 dB (–3 dB) is equivalent to losing one-half the power.

Attenuation (Conti…)

Example 3.27: A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as:

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

$$= 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

Attenuation (Conti…)

Example 3.28: One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In Figure 3.27 a signal travels from point 1 to point 4. In this case, the decibel value can be calculated as:

$$dB = -3 + 7 - 3 = +1$$

Attenuation (Conti…)

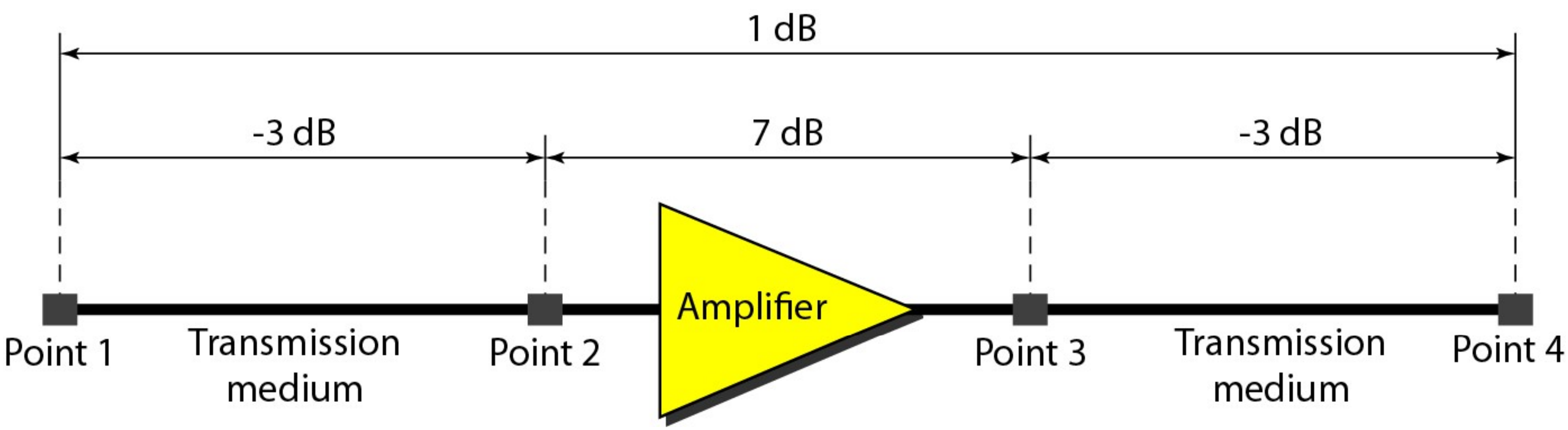


Figure 3.27 *Decibels for Example 3.28*

Attenuation (Conti…)

Example 3.29: Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as $dB_m = 10 \log10 P_m$, where P_m is the power in milliwatts. Calculate the power of a signal with $dB_m = -30$.

Solution

We can calculate the power in the signal as:

$$dB_m = 10 \log_{10} P_m = -30$$

$$\log_{10} P_m = -3 \qquad P_m = 10^{-3} \text{ mW}$$

Attenuation (Conti…)

Example 3.30: The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with −0.3 dB/km has a power of 2 mW, what is the power of the signal at 5 km?

Solution

The loss in the cable in decibels is 5 × (−0.3) = −1.5 dB. We can calculate the power as:

$$dB = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$

$$P_2 = 0.71 P_1 = 0.7 \times 2 = 1.4 \text{ mW}$$

Distortion

- Means that the signal changes its form or shape.
- Distortion occurs in composite signals made of different frequencies.
- Each frequency component has its own propagation speed traveling through a medium.
- The different components therefore arrive with different delays at the receiver.
- That means that the signals have different phases at the receiver than they did at the source.

Distortion (Conti…)

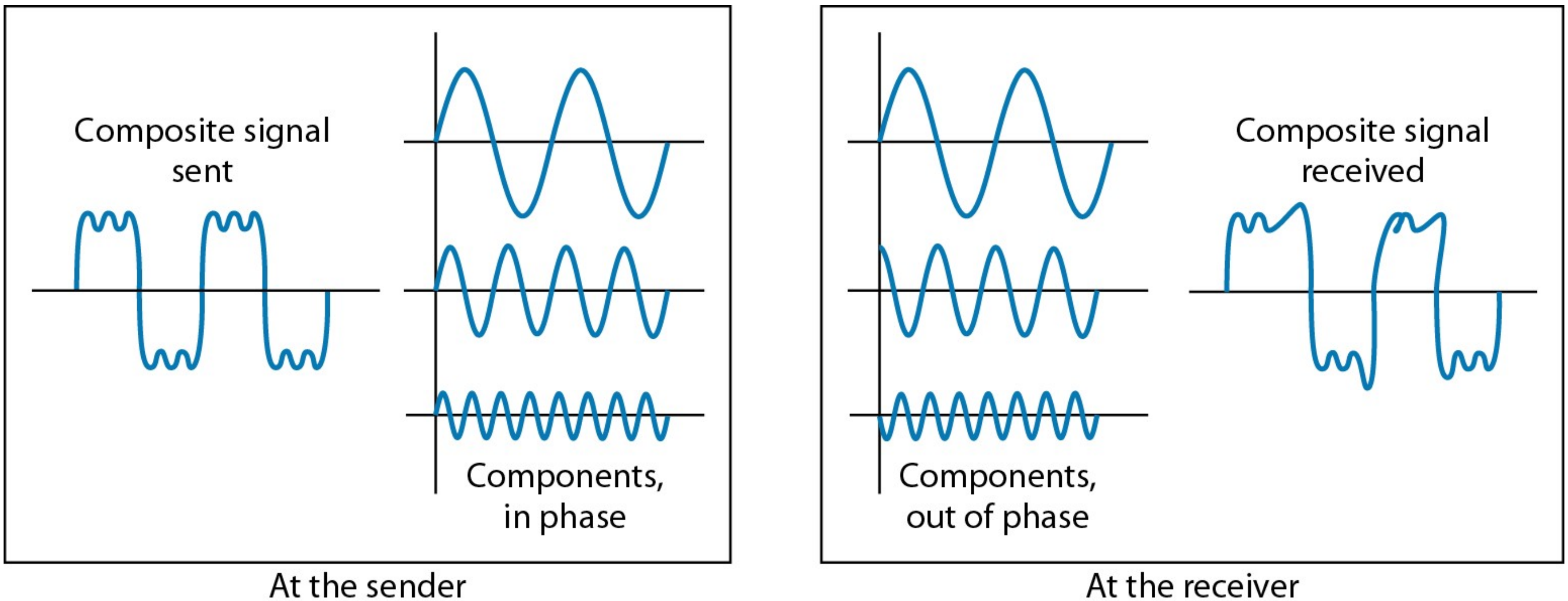


Figure 3.28 *Distortion*

Noise

- There are different types of noise:
  - Thermal - random motion of electrons in the wire creates an extra signal.
  - Induced – comes from sources such as motors and appliances, devices act are transmitter antenna and medium as receiving antenna.
  - Crosstalk – effect of one wire on another.
  - Impulse - Spikes that result from power lines, lighting, etc.

Noise (Conti…)

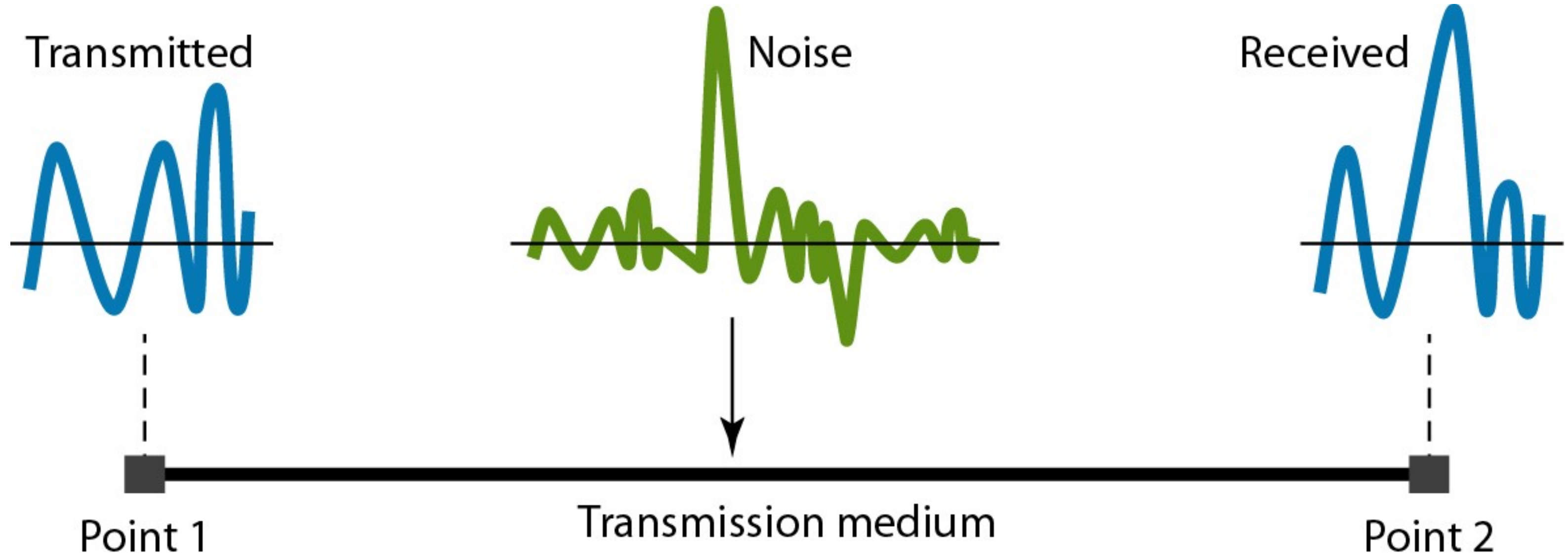


Figure 3.29 *Noise*

Signal to Noise Ratio (SNR)

- Used to measure the quality of a system.
- It indicates the strength of the signal power wrt the noise power in the system
- It is the ratio between two powers and is defined as:

SNR = Average signal power/Average noise power

- Often described in decibels and defined as:

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

Signal to Noise Ratio (Conti…)

Example 3.31: The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and SNR_{dB} ?

Solution:

The values of SNR and SNR_{dB} can be calculated as follows:

Signal to Noise Ratio (Conti…)

Example 3.32: The values of SNR and SNR_{dB} for a noiseless channel are:

$$SNR = \frac{\text{signal power}}{0} = \infty$$

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

We can never achieve this ratio in real life; it is an ideal.

Signal to Noise Ratio (Conti…)

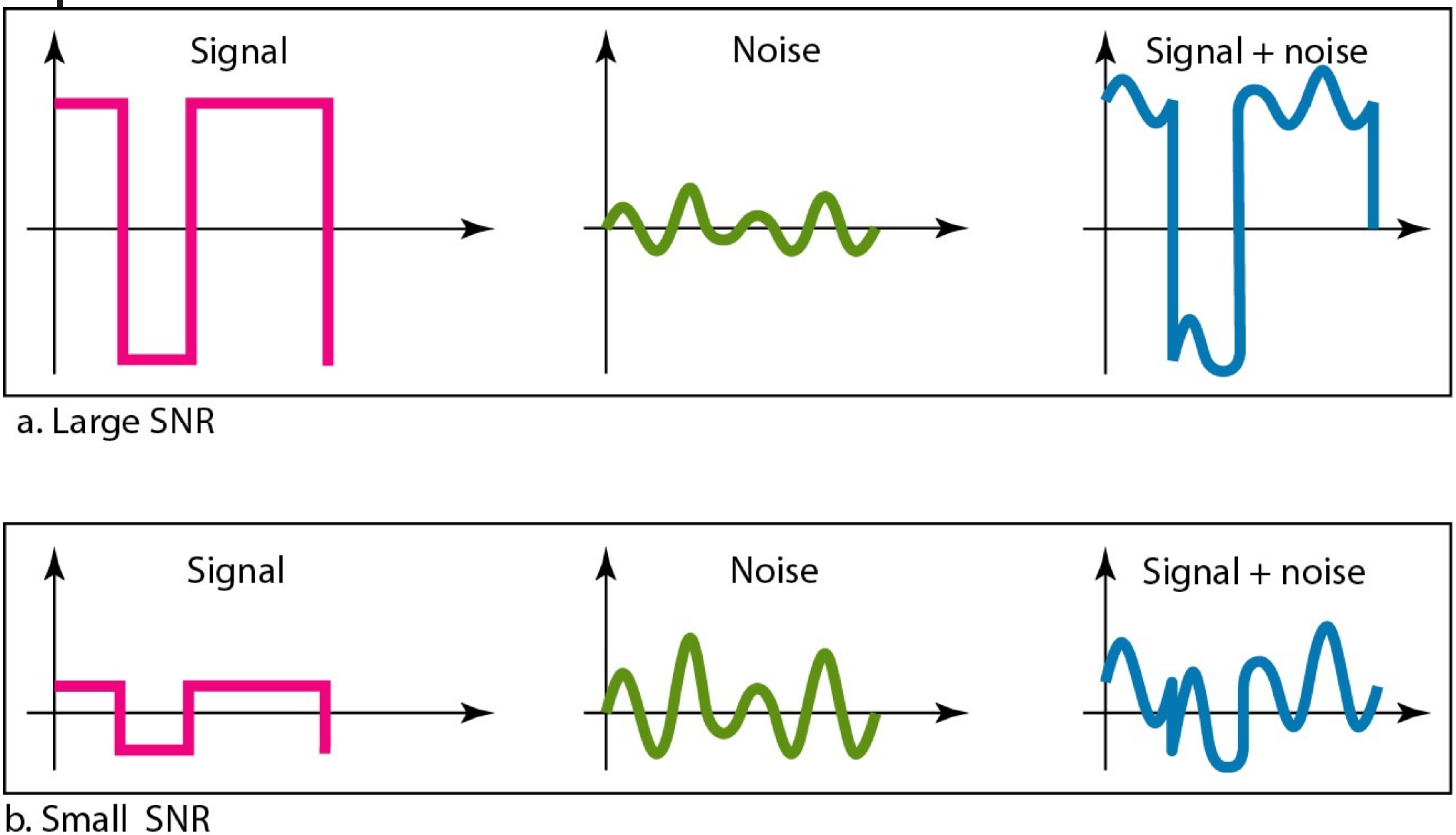


Figure 3.30 *Two cases of SNR: a high SNR and a low SNR*

Data Rate Limits

- A very important consideration in data communications is how fast data can be send, in bits per second, over a channel.
- Data rate depends on three factors:
  - The bandwidth available
  - The level of the signals used
  - The quality of the channel (the level of noise)

Capacity of a System

- The bit rate of a system increases with an increase in the number of signal levels we use to denote a symbol.
- A symbol can consist of a *single* bit or *n* bits.
- The number of signal levels $L = 2^n$.
- As the number of levels goes up, the spacing between level decreases -> increasing the probability of an error occurring in the presence of transmission impairments.

Nyquist Theorem : Noiseless Channel

- For noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate:

$$C = 2\ B \log_2 L$$

C= capacity in bps

B = bandwidth in Hz

L = Levels of signals

- 2 levels of signal can easily understandable at receiver
- Sophisticated receivers are required for 64 levels
- Note: Increasing the levels of signal may reduce the reliability of the system.

Nyquist Theorem (Conti…)

Example 3.34: Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as:

$$\text{BitRate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$

Nyquist Theorem (Conti…)

Example 3.35: Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as:

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000 \text{ bps}$$

Nyquist Theorem (Conti…)

Example 3.36: We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

Solution:

We can use the Nyquist formula as shown :

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate. If we have 128 levels, the bit rate is 280 kbps. If we have 64 levels, the bit rate is 240 kbps.

Shannon Capacity – Noisy Channel

- In reality, the channel is always noisy.
- Shannon capacity (formula) was introduced in 1944 to determine the theoretical highest data rate for noisy channel:

$$C = 2\ B \log_2(1 + SNR)$$

C= capacity in bps

B = bandwidth in Hz

SNR = Signal to Noise Ration

Shannon Capacity (Conti…)

Example 3.37: Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as:

$$C = B \log_2(1 + \text{SNR}) = B \log_2(1 + 0) = B \log_2 1 = B \times 0 = 0$$

This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.

Shannon Capacity (Conti…)

Example 3.39: The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as:

$$SNR_{dB} = 10 \log_{10} SNR \rightarrow SNR = 10^{SNR_{dB}/10} \rightarrow SNR = 10^{3.6} = 3981$$

$$C = B \log_2 (1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$$

Shannon Capacity (Conti…)

Example 3.40: For practical purposes, when the SNR is very high, we can assume that SNR + 1 is almost the same as SNR. In these cases, the theoretical channel capacity can be simplified to:

$$C = B \times \frac{\text{SNR}_{\text{dB}}}{3}$$

For example, we can calculate the theoretical capacity of the previous example as:

$$C = 2\text{ MHz} \times \frac{36}{3} = 24\text{ Mbps}$$

Shannon Capacity (Conti…)

Example 3.41: We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

Solution:

First, we use the Shannon formula to find the upper limit.

$$C = B \log_2 (1 + \text{SNR}) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$

Shannon Capacity (Conti…)

Example 3.41 (Conti…):

The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels.

$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \quad \Rightarrow \quad L = 4$$

Note

The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.

Performance

- One important issue in networking is the performance of the network—how good is it?
- The following terms are used to measure the performance of the network:
  - Bandwidth - capacity of the system
  - Throughput - number of bits that can be pushed through
  - Latency (Delay) - delay incurred by a bit from start to finish
  - Bandwidth-Delay Product

Bandwidth

- In networking the term bandwidth is used in two context:
  - The first, *bandwidth in Hertz*, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.
  - The second, *bandwidth in bits per second*, refers to the speed of bits transmission on a channel or link.
- An increase in bandwidth in Hertz means an increase in bandwidth in bits per second.

Bandwidth (Conti…)

- Example 3.42: The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data transmission can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog.
- Example 3.43: If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology as mentioned in Example 3.42.

Throughput

- Throughput is the actual speed of data movement over the network.
- Seems same as bandwidth in bps but different.
- Bandwidth in bps is the potential measurement but throughput is the actual measurement.
- A link may have a bandwidth of *B* bps and *T* bps throughput with *T* always less than *B*.
- A link may have bandwidth of 1Mbps but the devices connects may handle only 200Kbps.

Throughput (Conti…)

Example 3.44: A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution:

We can calculate the throughput as:

$$\text{Throughput} = \frac{12{,}000 \times 10{,}000}{60} = 2 \text{ Mbps}$$

The throughput is almost one-fifth of the bandwidth in this case.

Latency (Delay)

- Latency (delay) defines how long it takes for entire message to completely arrive at the destination from the time the first bit is sent out from the source.
- Latency is made of four components:
  - Propagation time
  - Transmission time
  - Queuing time
  - Processing time

Latency = Propagation delay + Transmission delay + Queuing time + Processing time

Propagation Time

- Propagation time measures the time required for a bit to travel from source to the destination.
- It is calculated by dividing the distance by the propagation speed, i.e.

Propagation time = Distance / Propagation speed

Propagation Time (Conti…)

Example 3.45: What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^8 m/s in cable.

Solution:

We can calculate the propagation time as:

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.

Transmission Time

- Transmission time is the time between the first bit leaving the sender and the last bit arriving at the receiver.
- The time required for transmission of a message depends on the size of the message and the bandwidth of the channel.

Transmission time = Message Size / Bandwidth

Propagation Time (Conti…)

Example 3.46: What are the propagation time and the transmission time for a 2.5-kbyte message (an e-mail) if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

We can calculate the propagation and transmission time as shown on the next slide:

Propagation Time (Conti…)

Example 3.46 (Conti…):

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

Note that in this case, because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time. The transmission time can be ignored.

Propagation Time (Conti…)

Example 3.47: What are the propagation time and the transmission time for a 5-Mbyte message (an image) if the bandwidth of the network is 1 Mbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

We can calculate the propagation and transmission times as shown on the next slide.

Propagation Time (Conti…)

Example 3.47 (Conti…):

Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Bandwidth-Delay Product

- Bandwidth and Delay are two performance metrics of a channel/link.
- However, the product of the two, the bandwidth-delay product, is also very important.
- The bandwidth-delay product defines the number of bits that can fill the link.
- To elaborate the bandwidth-delay product, consider the two hypothetical cases as examples.

Bandwidth-Delay Product (Conti…)

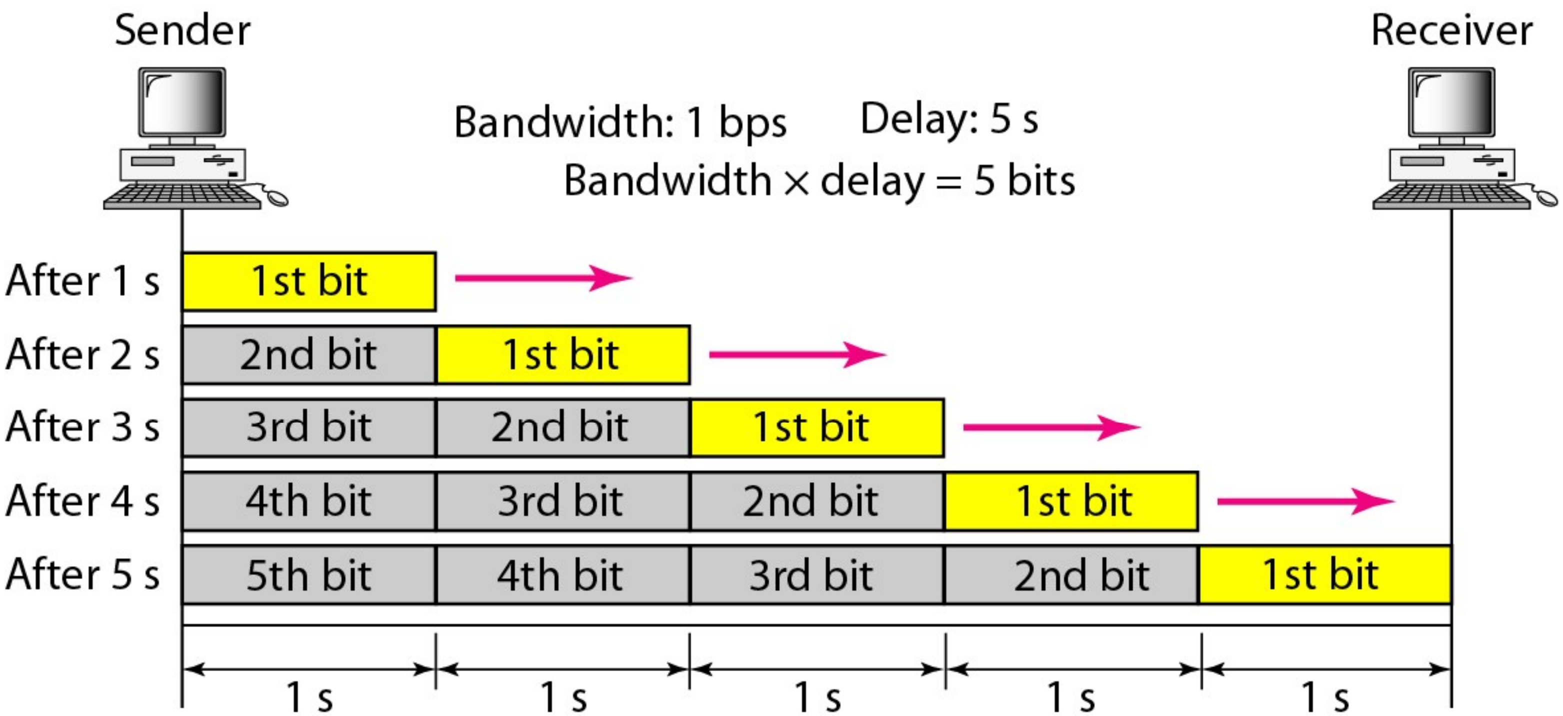


Figure 3.31 *Filling the link with bits for case 1*

Bandwidth-Delay Product (Conti…)

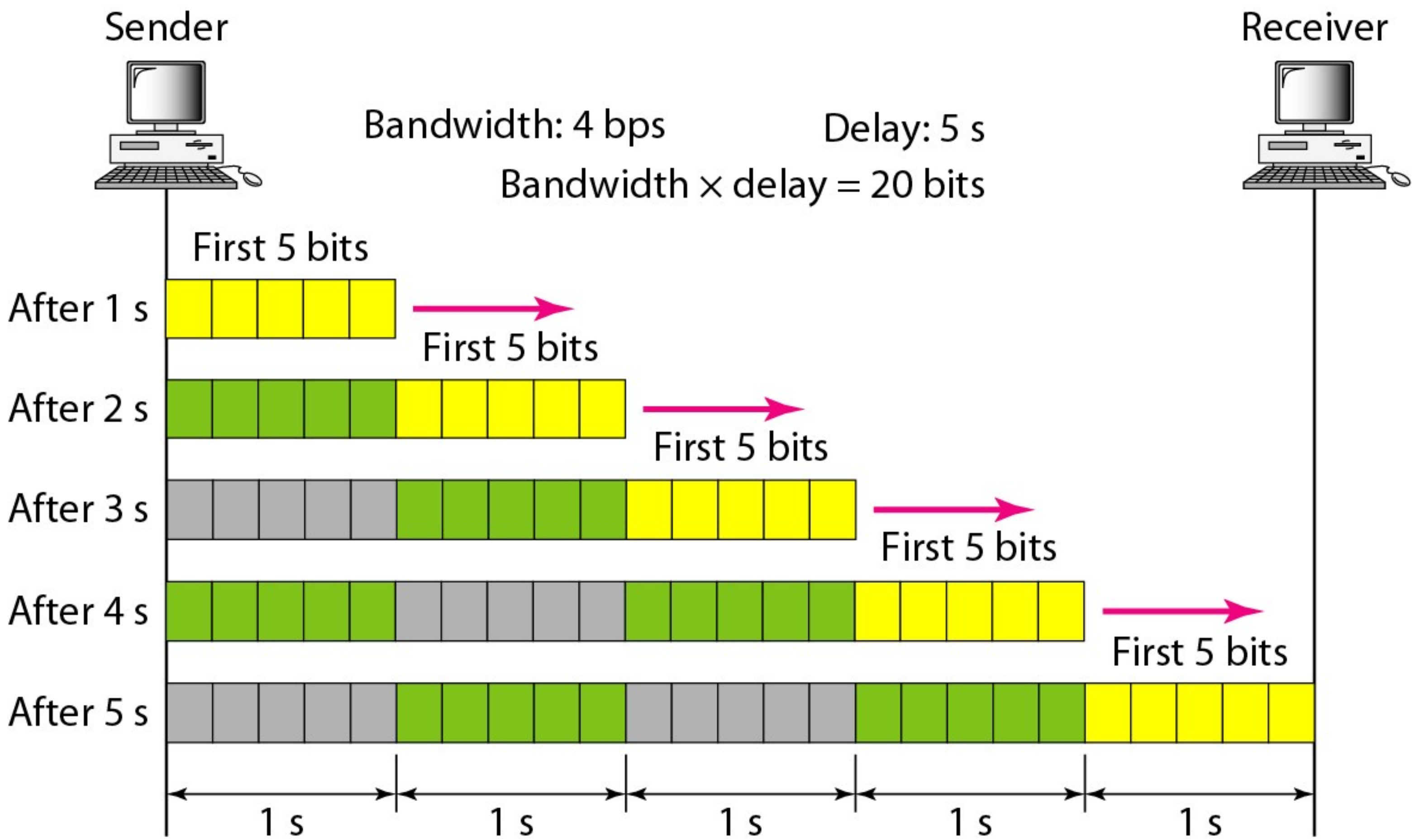


Figure 3.32 *Filling the link with bits in case 2*

Bandwidth-Delay Product (Conti…)

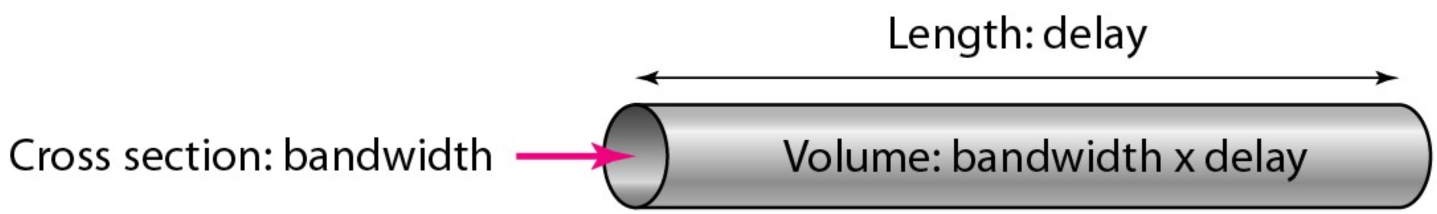


Figure 3.33 *Concept of bandwidth-delay product*