DC is Prerequisite of: Computer network domain, IoT

Data Communication (ITUA21183)

Course Teacher

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Unit I :Fundamentals of Signals

- Agenda
  - Analog and Digital: Analog and Digital Data, Analog and Digital Signals, Periodic and Non-periodic Signal Periodic Analog Signals: Sine Wave, Phase, Wavelength, Time and Frequency Domains, Composite Signals Bandwidth
  - Digital Signals: Bit Rate, bit Length, Digital Signal as a Composite Analog Signal, Transmission of Digital Signals Transmission Impairment: Attenuation, Distortion, Noise Data Rate Limits: Noiseless Channel: Nyquist Bit Rate, Noisy Channel: Shannon Capacity Performance: Bandwidth, Throughput, Latency (delay)

Preview

- Data communications are the transfer of data from one device to another via some form of transmission medium.
- A data communications system must transmit data to the correct destination in an accurate and timely manner.
- The five components that make up a data communications system are the message, sender, receiver, medium, and protocol.
- Text, numbers, images, audio, and video are different forms of information.
- Data flow between two devices can occur in one of three ways: simplex, half-duplex, or full-duplex.
- A network is a set of communication devices connected by media links.
- In a point-to-point connection, two and only two devices are connected by a dedicated link. In a multipoint connection, three or more devices share a link.
- Topology refers to the physical or logical arrangement of a network. Devices may be arranged in a mesh, star, bus, or ring topology. o A network can be categorized as a local area network or a wide area network

Chapter 3

Data and Signals

Data and Signals

- Data are entities that convey meaning (computer file, music on CD, a command on network)
- Signals are the electric or electromagnetic encoding of data (telephone conversation, we page download)
- Computer networks and data/voice communication systems transmit signals
- Data and signals can be analog or digital – this can be misleading – let's talk more about this

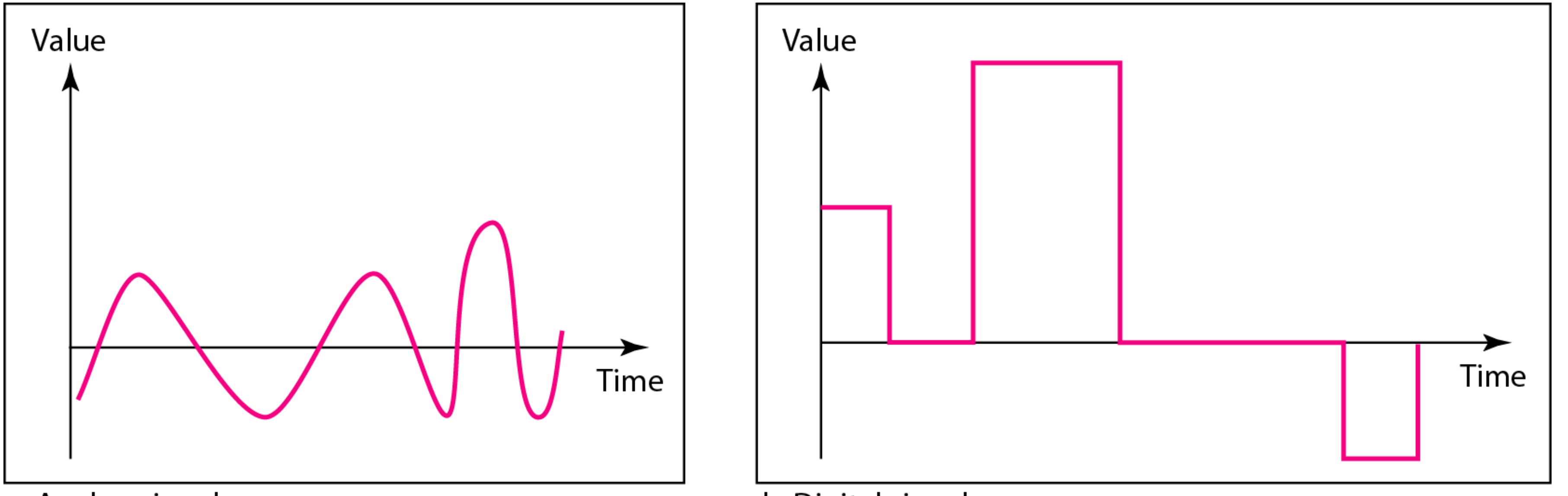
Analog vs. Digital Signals

- Signals can be interpreted as either analog or digital
- In reality, all signals are analog
- Analog signals are continuous, non-discrete
- Digital signals are non-continuous, discrete
- Digital signals lend themselves more nicely to noise reduction techniques

Analog vs. Digital Signals

- There are actually multiple “kinds” of digital signals
- Discrete square waveforms found in digital systems such as LANs (see an example on the next slide)
- Digital logic voltage levels (a binary 0 is 0 to 2 volts; a binary 1 is 4 to 6 volts)
- Analog signals which can only be interpreted in a finite number of ways (modulation techniques)

Figure 3.1 *Comparison of analog and digital signals*



a. Analog signal

b. Digital signal

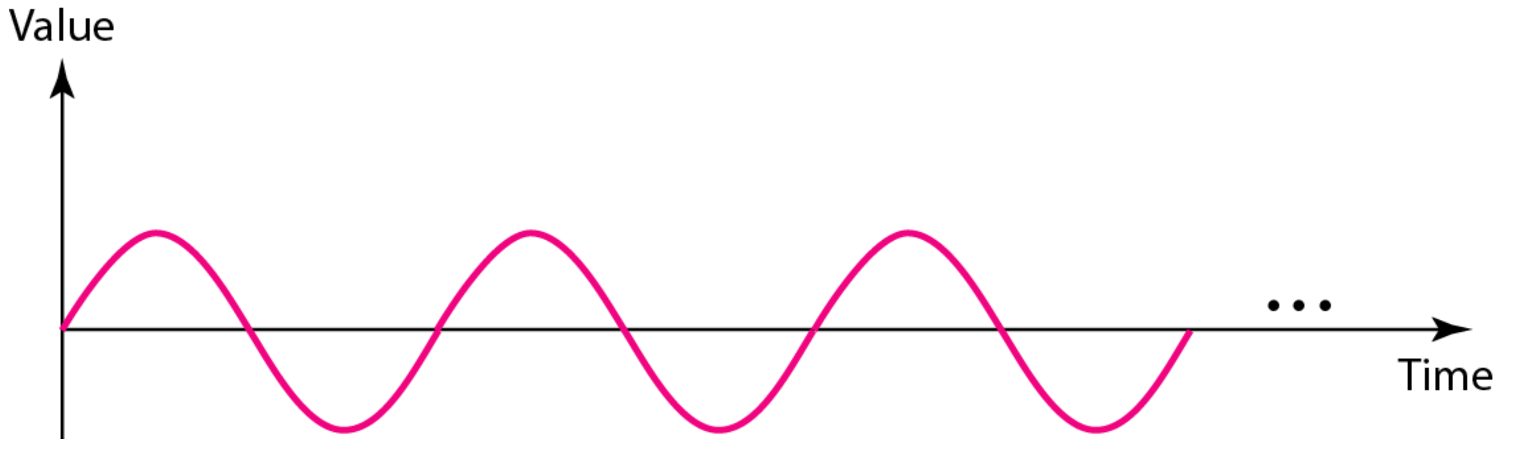
Time domain concepts

- Continuous signal
  - Infinite number of points at any given time
- Discrete signal
  - Finite number of points at any given time; maintains a constant level then changes to another constant level
- Periodic signal
  - Pattern repeated over time
- Aperiodic (non-periodic) signal
  - Pattern not repeated over time

Time domain concepts

- In data communications, we commonly use periodic analog signals and nonperiodic 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.

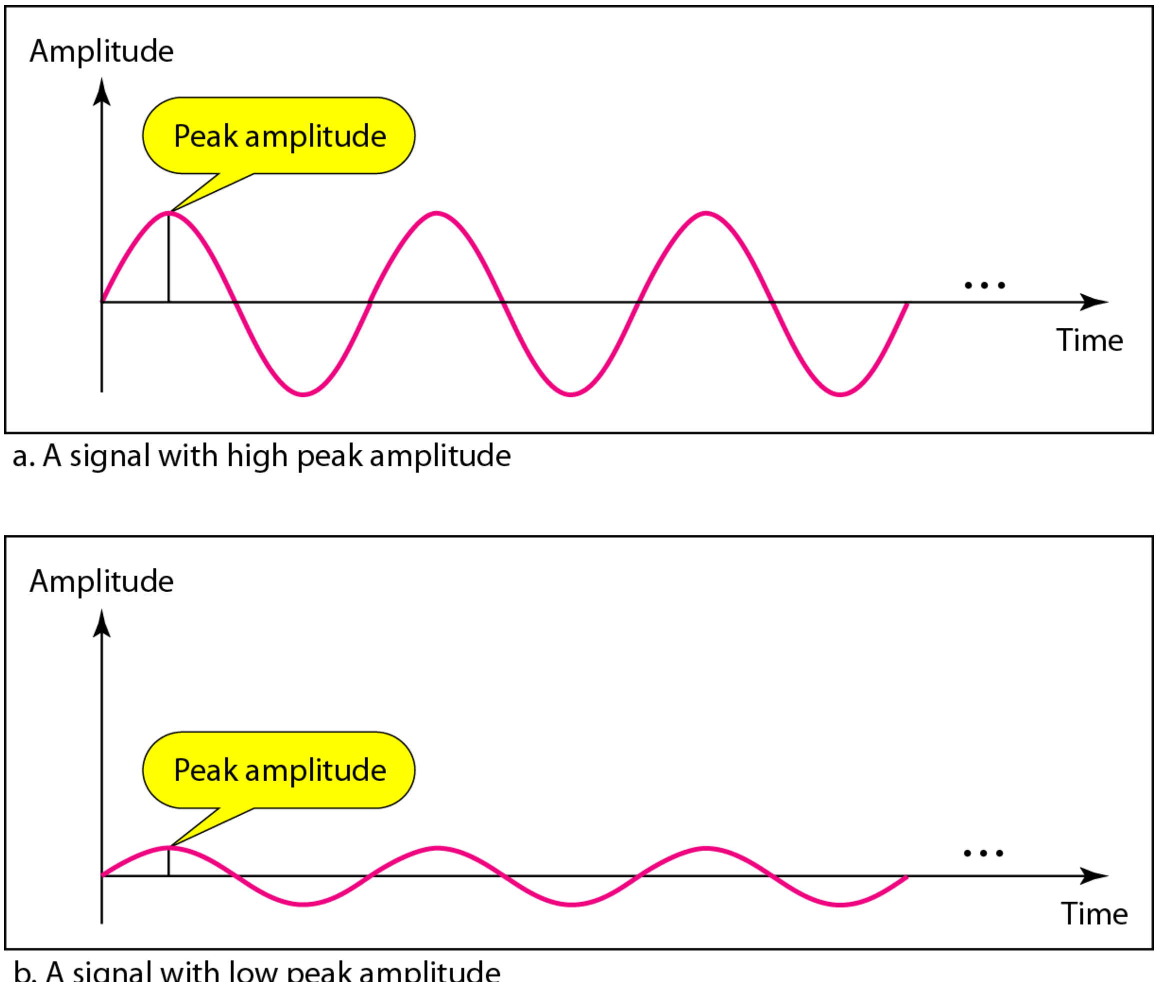
Figure 3.2 *A sine wave*



Signal Properties

- All signals are composed of three properties:
  - Amplitude
  - Frequency
  - Phase

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



Note

Frequency and period are the inverse of each other.

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

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

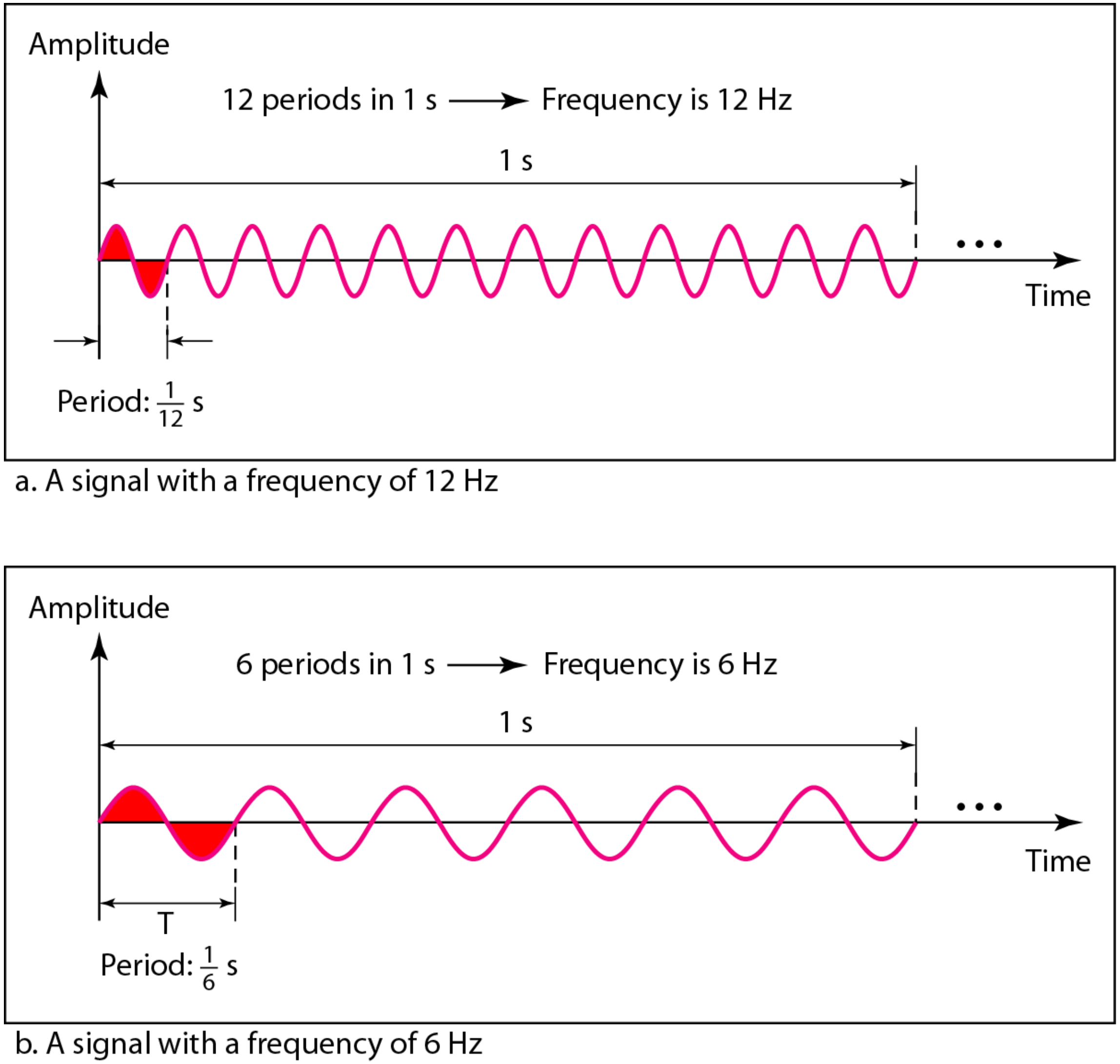


Table 3.1 ***Units of period and frequency***

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

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:

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

Example 3.5

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

Solution:

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).

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

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

Note

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.

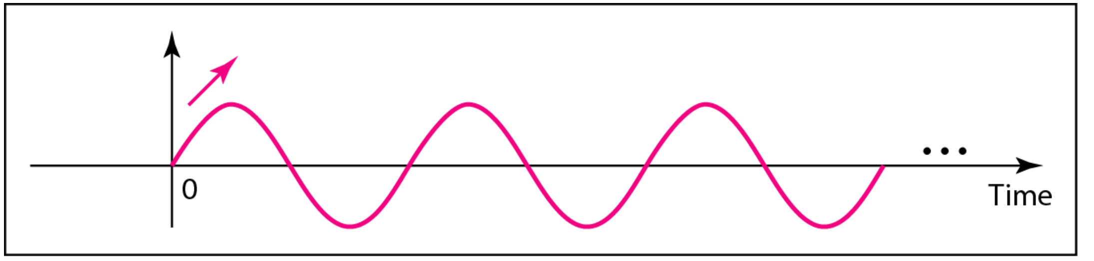
Note

If a signal does not change at all, its frequency is zero.
If a signal changes instantaneously, its frequency is infinite.

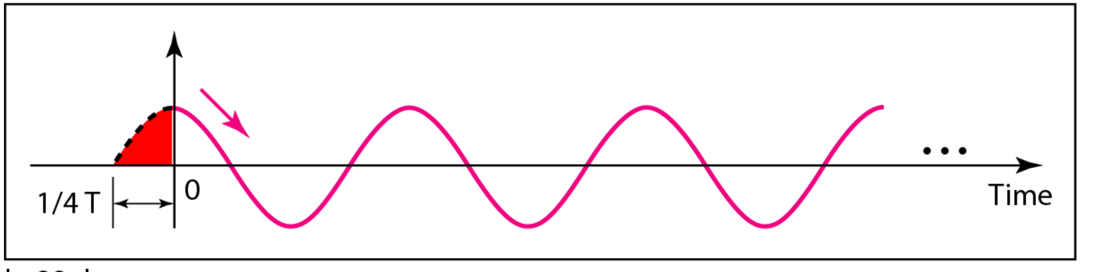
Note

Phase describes the position of the waveform relative to time 0.

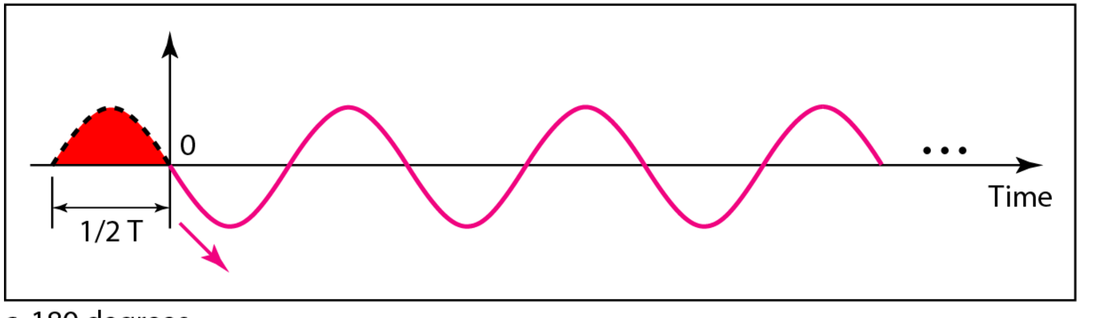
Figure 3.5 *Three sine waves with the same amplitude and frequency, but different phases*



a. 0 degrees



b. 90 degrees

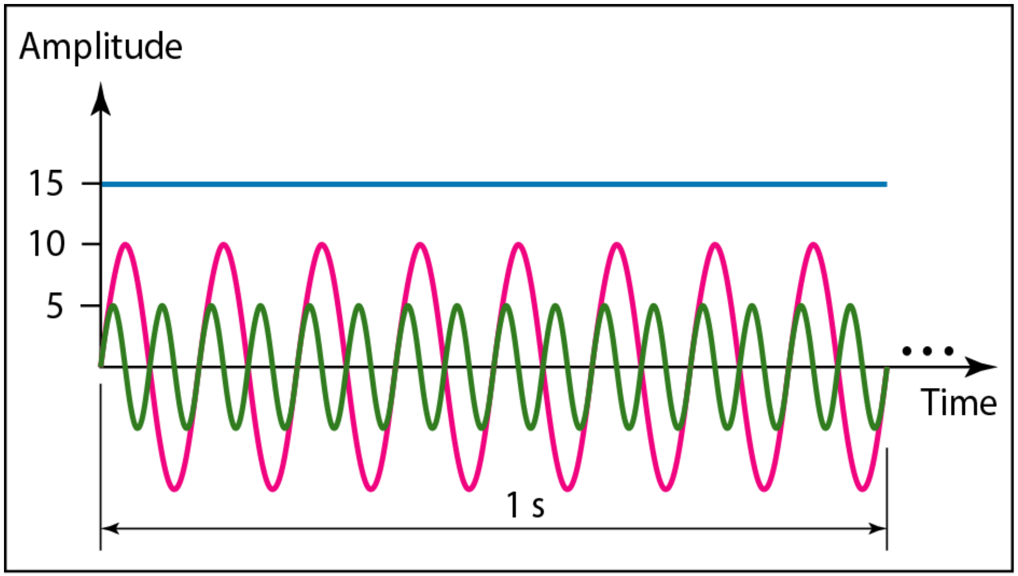


c. 180 degrees

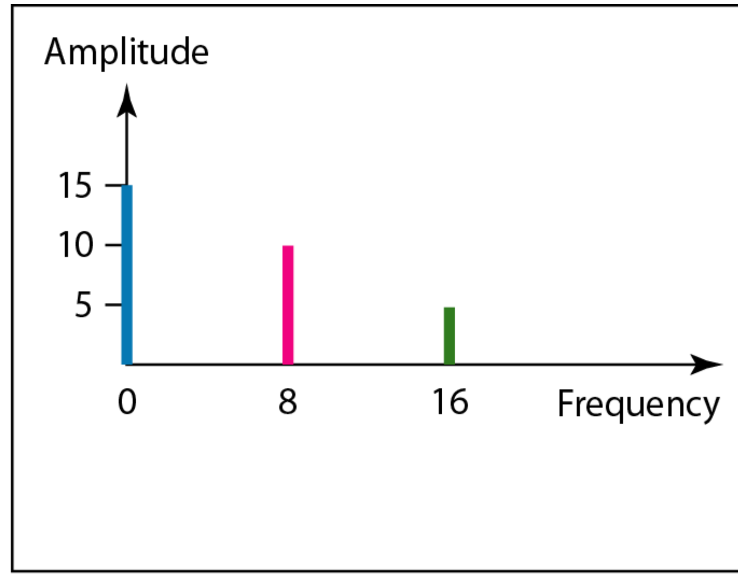
Example 3.7

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.

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

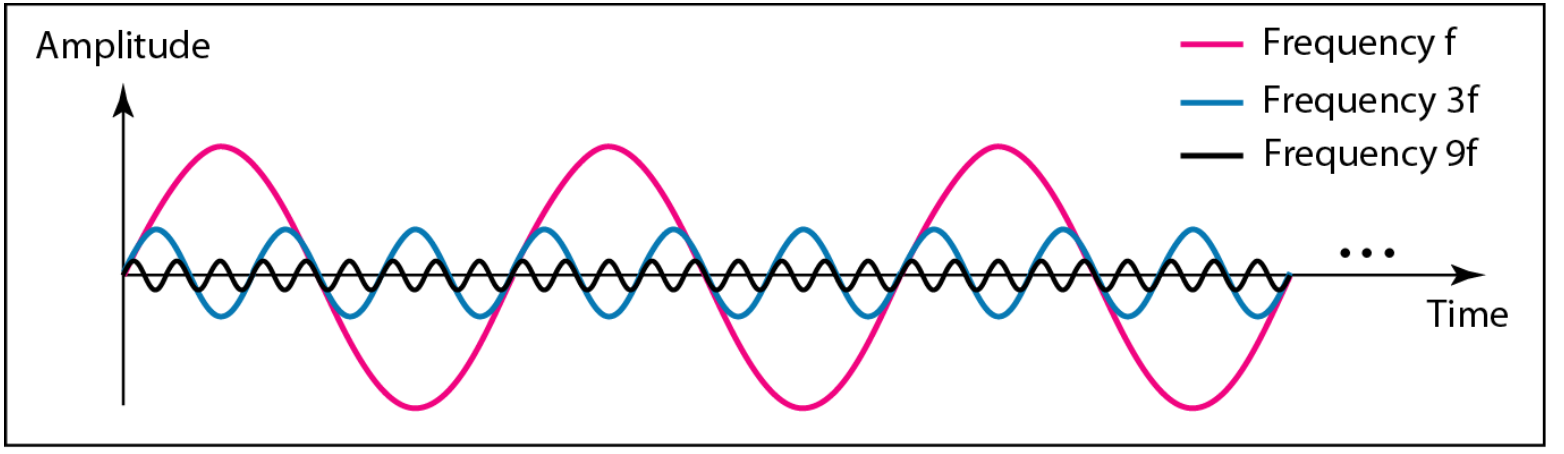


a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

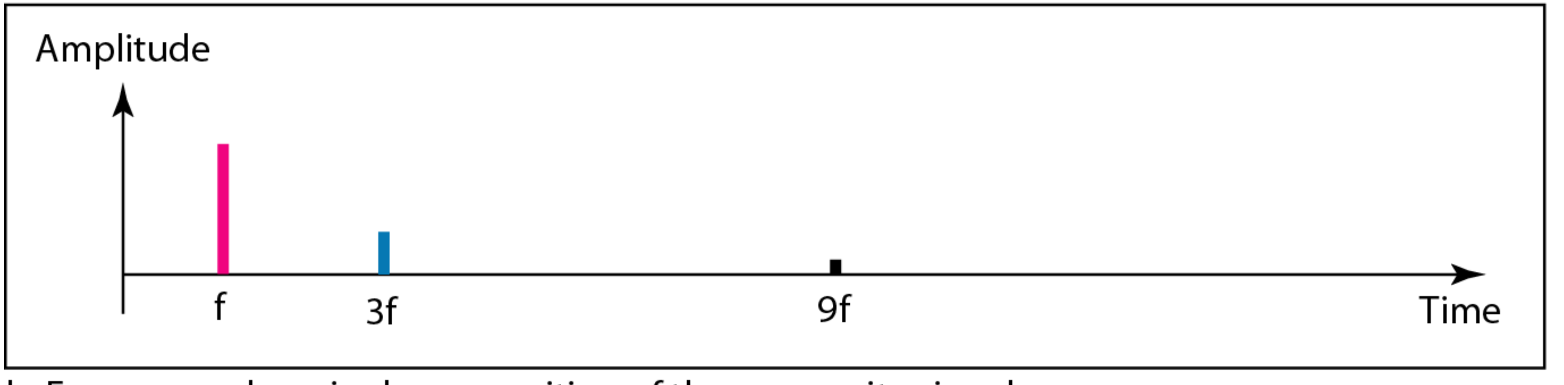


b. Frequency-domain representation of the same three signals

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

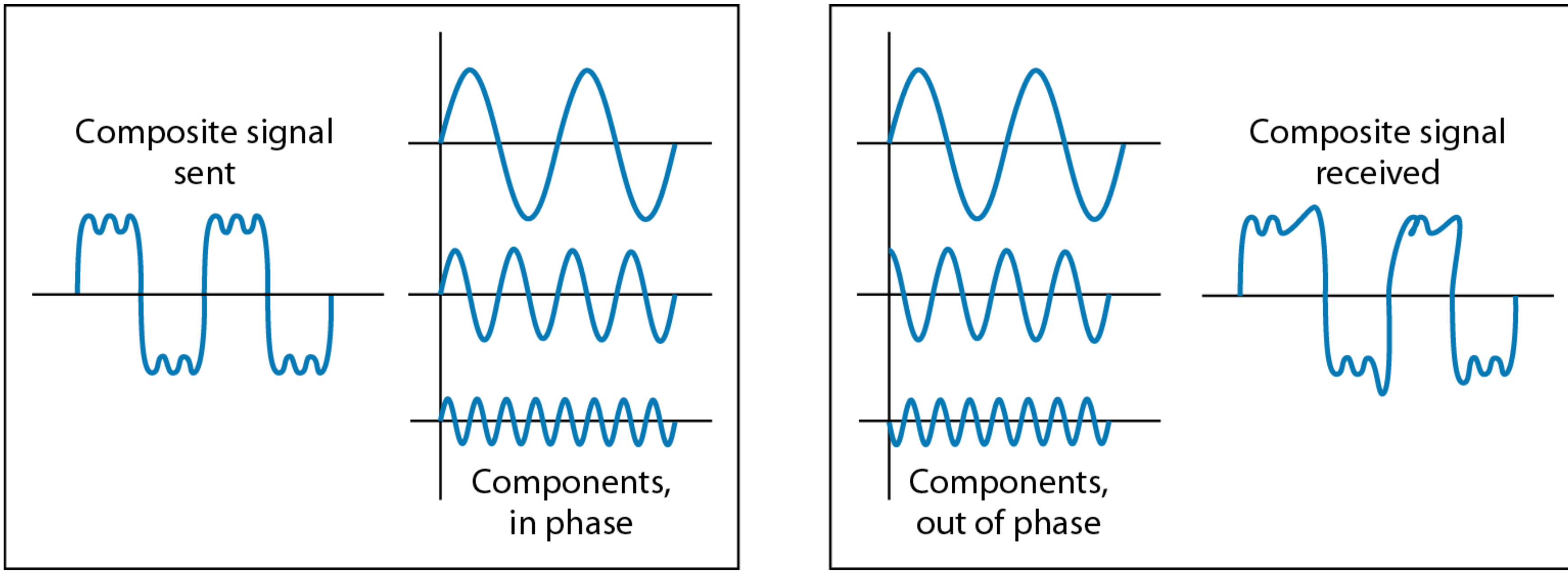


a. Time-domain decomposition of a composite signal



b. Frequency-domain decomposition of the composite signal

Composite signal



At the sender

At the receiver

Note

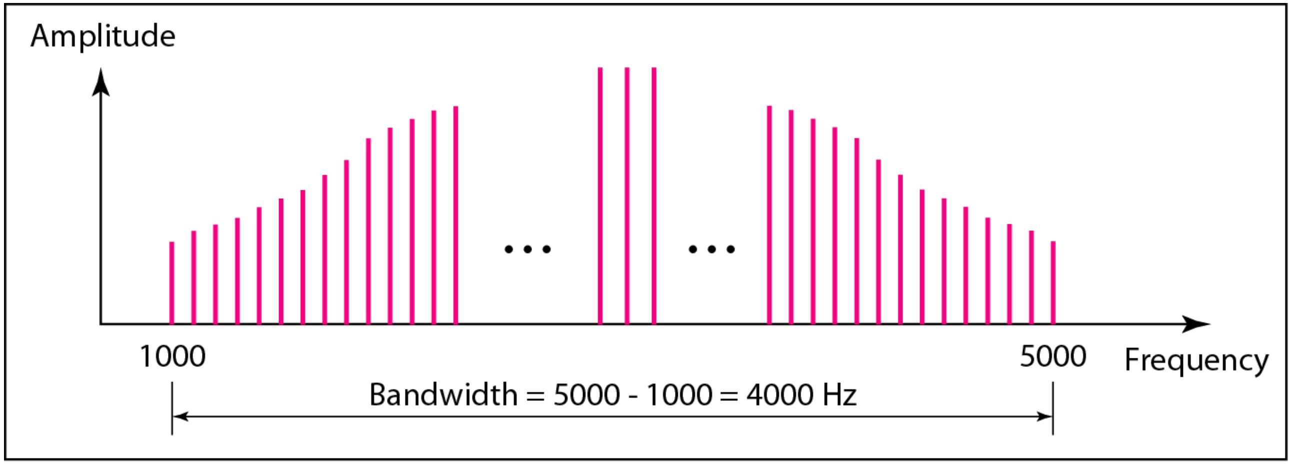
A single-frequency sine wave is not useful in data communications; we need to send a composite signal, a signal made of many simple sine waves.

Note

The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.

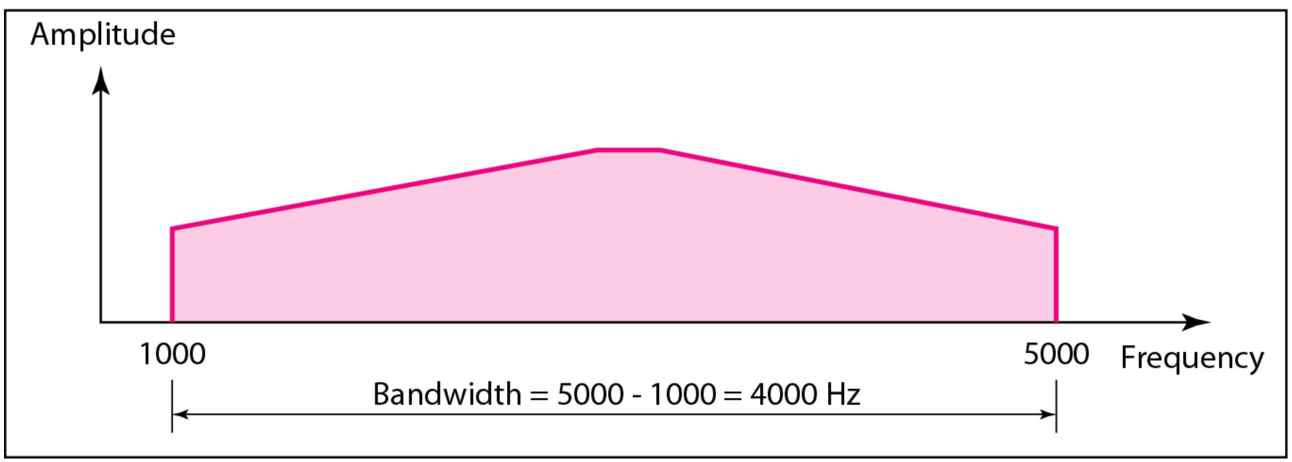
Figure 3.12 *The bandwidth of periodic and nonperiodic composite signals*

Note: each frequency is identifiable



a. Bandwidth of a periodic signal

Note: frequencies are all over the place



b. Bandwidth of a nonperiodic signal

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 (range of frequencies), assuming all components have a maximum amplitude of 10 V.

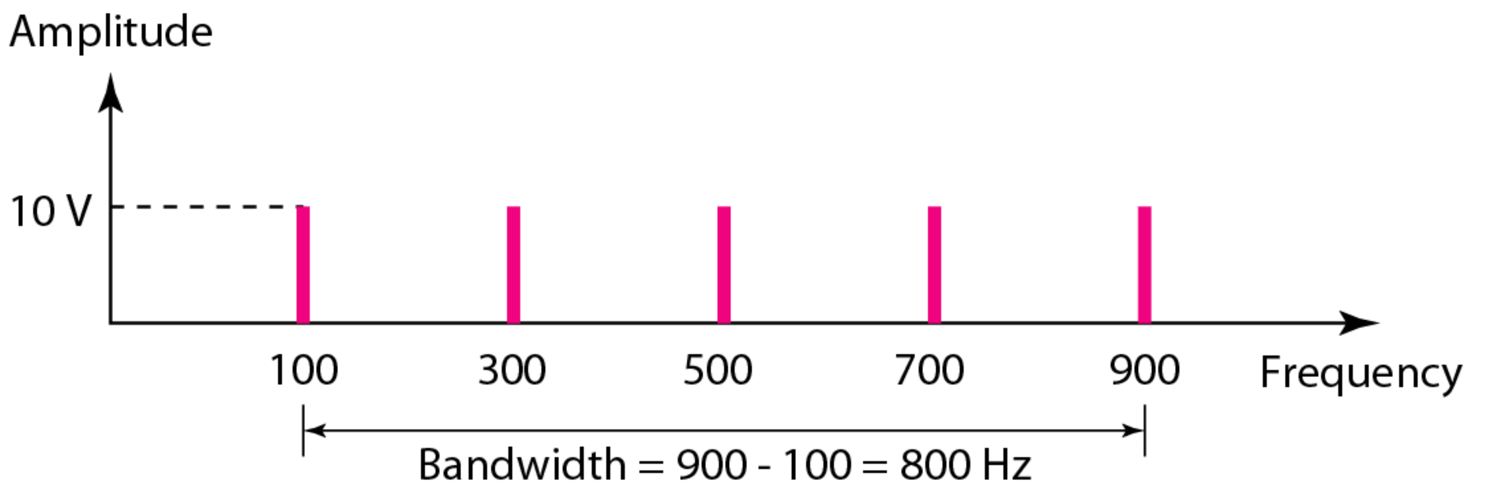
Solution

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

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

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*



Example 3.12

A nonperiodic 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:

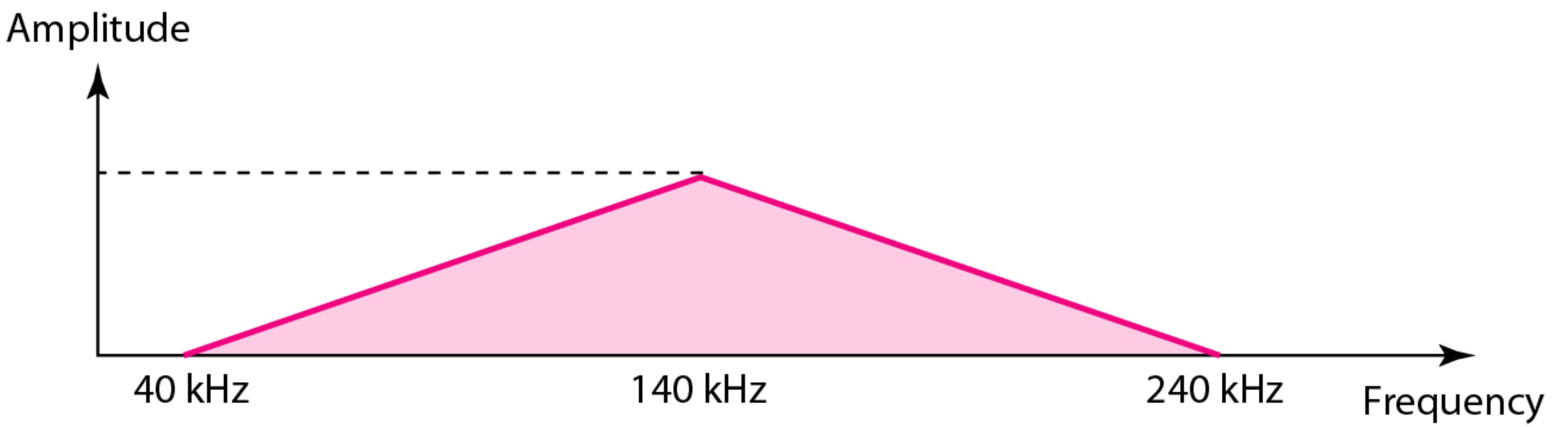
Example 3.12

A nonperiodic 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.

Figure 3.15 *The bandwidth for Example 3.12*



3-3 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. In this case, we can send more than 1 bit for each level.

Topics discussed in this section:

Bit Rate
Bit Length

Definitions

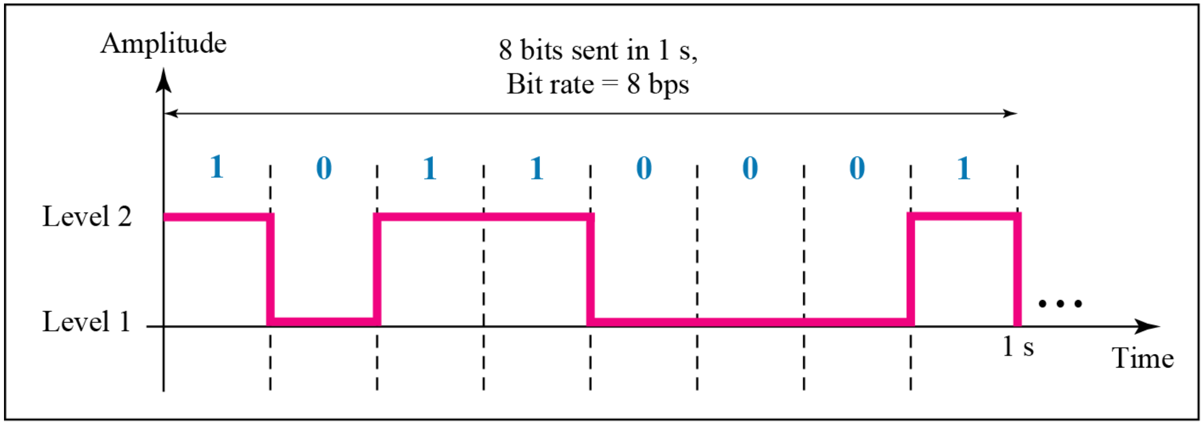
- Bit rate:

  the number of bits per second that can be transmitted along a digital network.

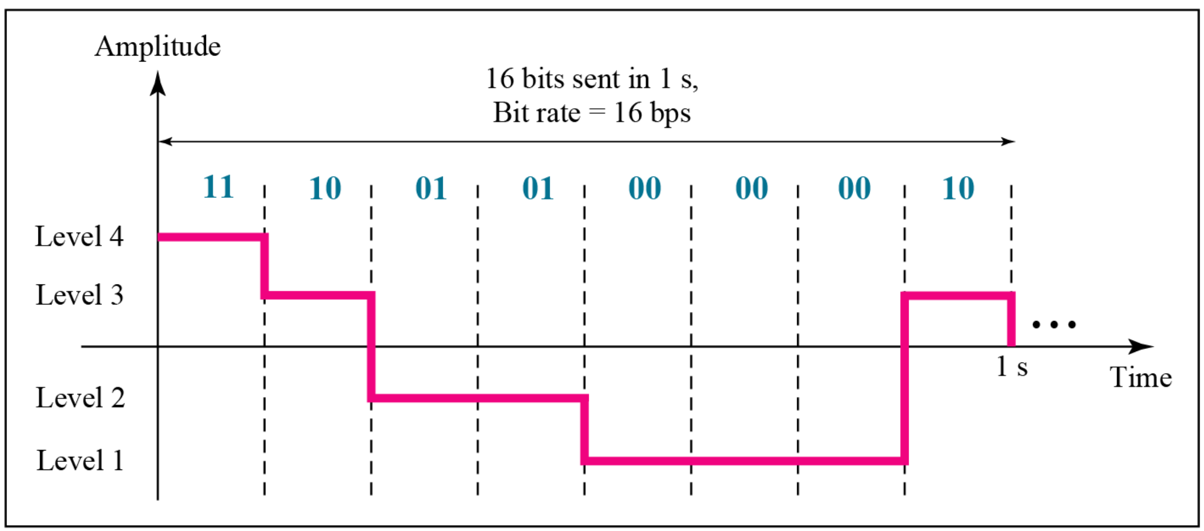
- Bit length:

  the number of binary digits, called bits, necessary to represent an integer (a single level) in the binary number system

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



a. A digital signal with two levels



b. A digital signal with four levels

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

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

Each signal level is represented by 3 bits.

Example 3.17

What about a digital signal with 16 levels?
How many bits are needed per level?

What about 32 levels? 64 levels? 128 levels?

What about 9 levels??
$2^{?} = 9$?
3.17 bits
However, this answer is not realistic.

3-4 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.

Definitions

- Attenuation

  the reduction of the amplitude of a signal, electric current, or other oscillation.

  attenuation is a general term that refers to any reduction in the strength of a signal.

- Distortion

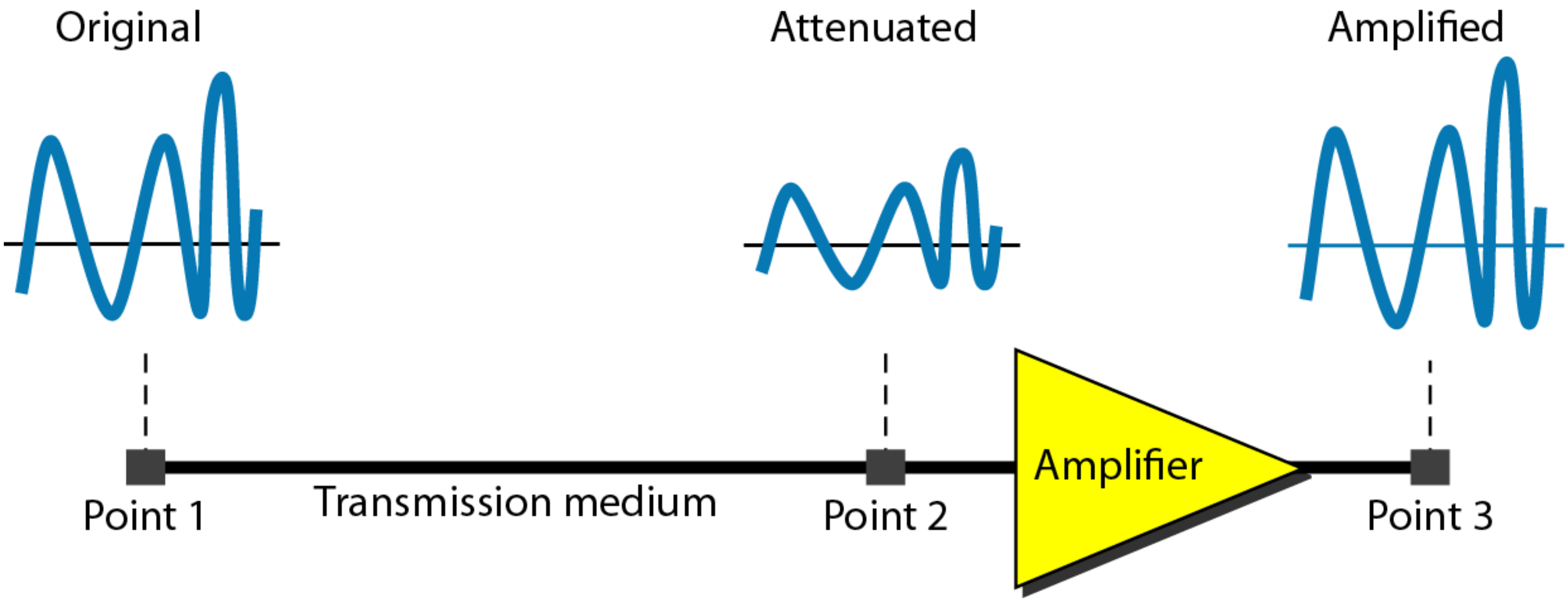
  distortion refers to any kind of deformation of an output waveform compared to its input, usually clipping, harmonic distortion

- Noise

  unwanted (and, in general, unknown) modifications that a signal may suffer during capture, storage, transmission, processing, or conversion.

  any unwanted (electrical) signal within a communication system that interferes with the original signal being communicated.

Figure 3.26 *Attenuation (the first impairment)*



Signal strength :Decibels

- Signal strength is measured in decibels (dB)
- dB is a relative measure of loss (or gain)
- $N_{dB} = 10 \times \log_{10} (P2 / P1)$
  - P2 = ending power level in watts
  - P1 = beginning power level in watts
- Example: P1 = 10 watts, P2 = 5 watts
- Losses and gains are additive

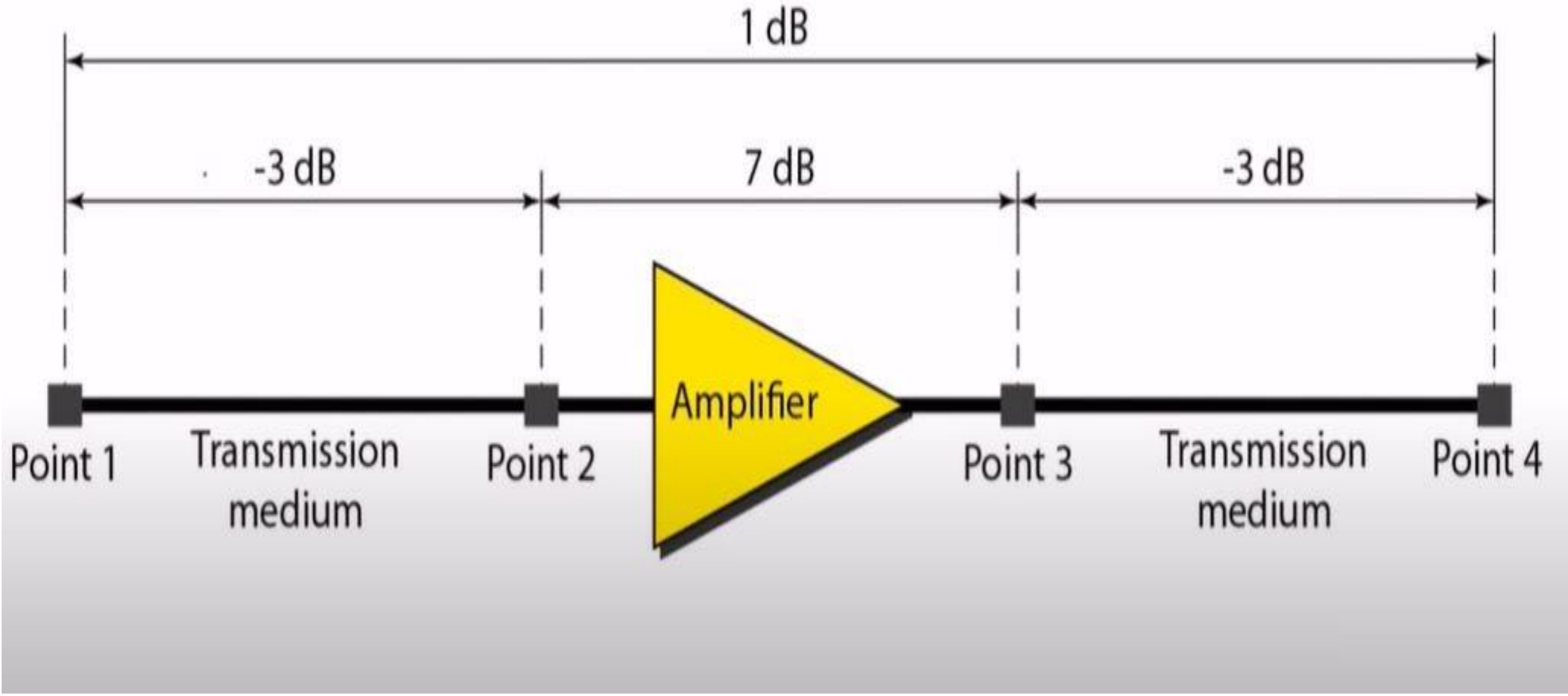
A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as

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

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

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

$$\boxed{\mathrm{dB} = -3 + 7 - 3 = +1}$$


1 dB
-3 dB
7 dB
-3 dB
Amplifier
Point 1
Transmission medium
Point 2
Point 3
Transmission medium
Point 4

Signal to Noise Ratio (SNR or S/N)

- *Signal to noise ratio* shows the ratio of signal power to noise power
- Power often expressed in *watts*
- S/N = signal power/noise power
- Just a simple ratio

Signal to Noise Ratio$_{dB}$: Example for practice (SNR$_{dB}$ or S/N$_{dB}$)

- *Signal to noise ratio$_{dB}$* shows the ratio of signal power to noise power in decibels
- $S/N_{dB} = 10 \log_{10}$ (signal power/noise power)

Figure 3.28 *Distortion (the second impairment)*

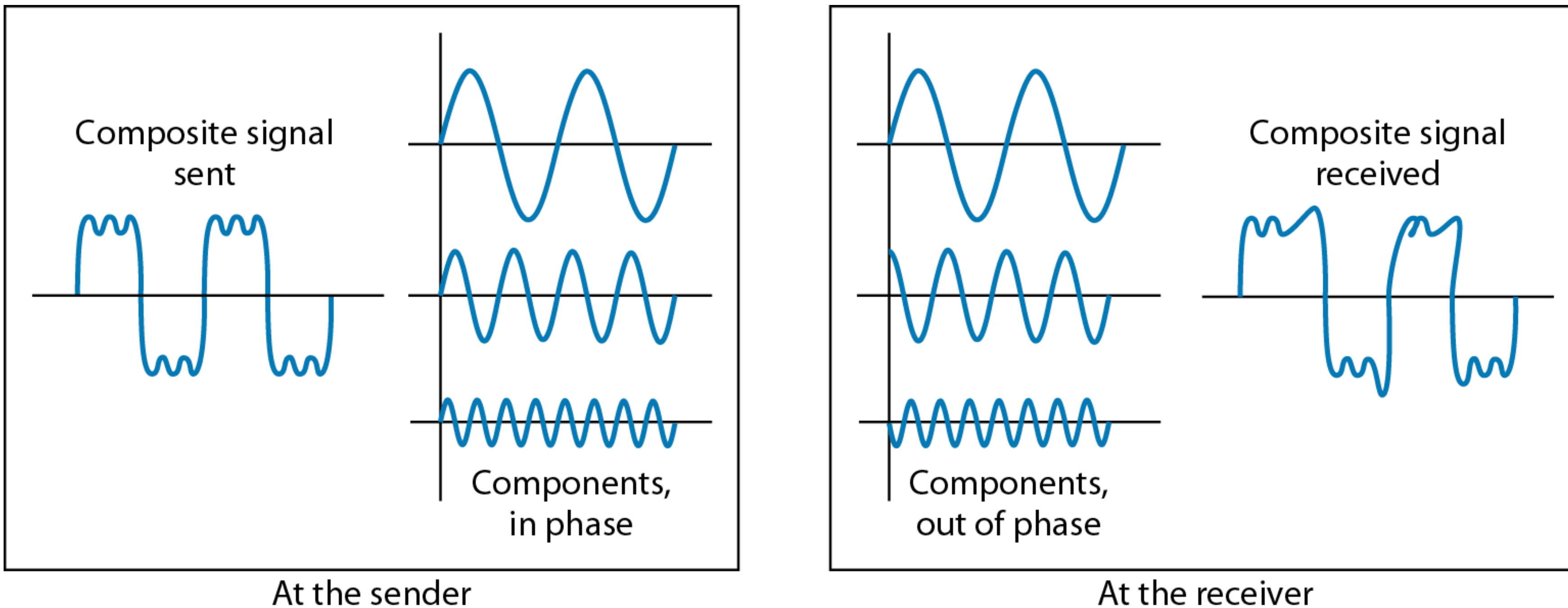
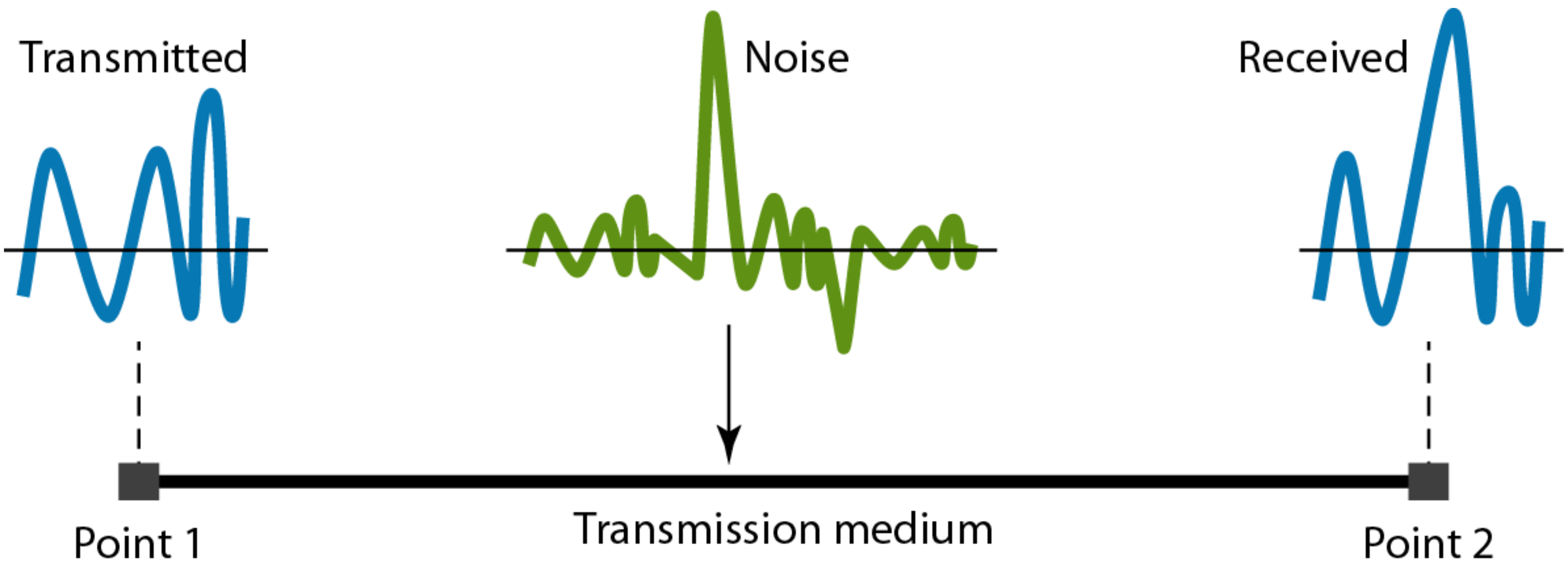


Figure 3.29 *Noise (the third impairment)*



Example 3.32

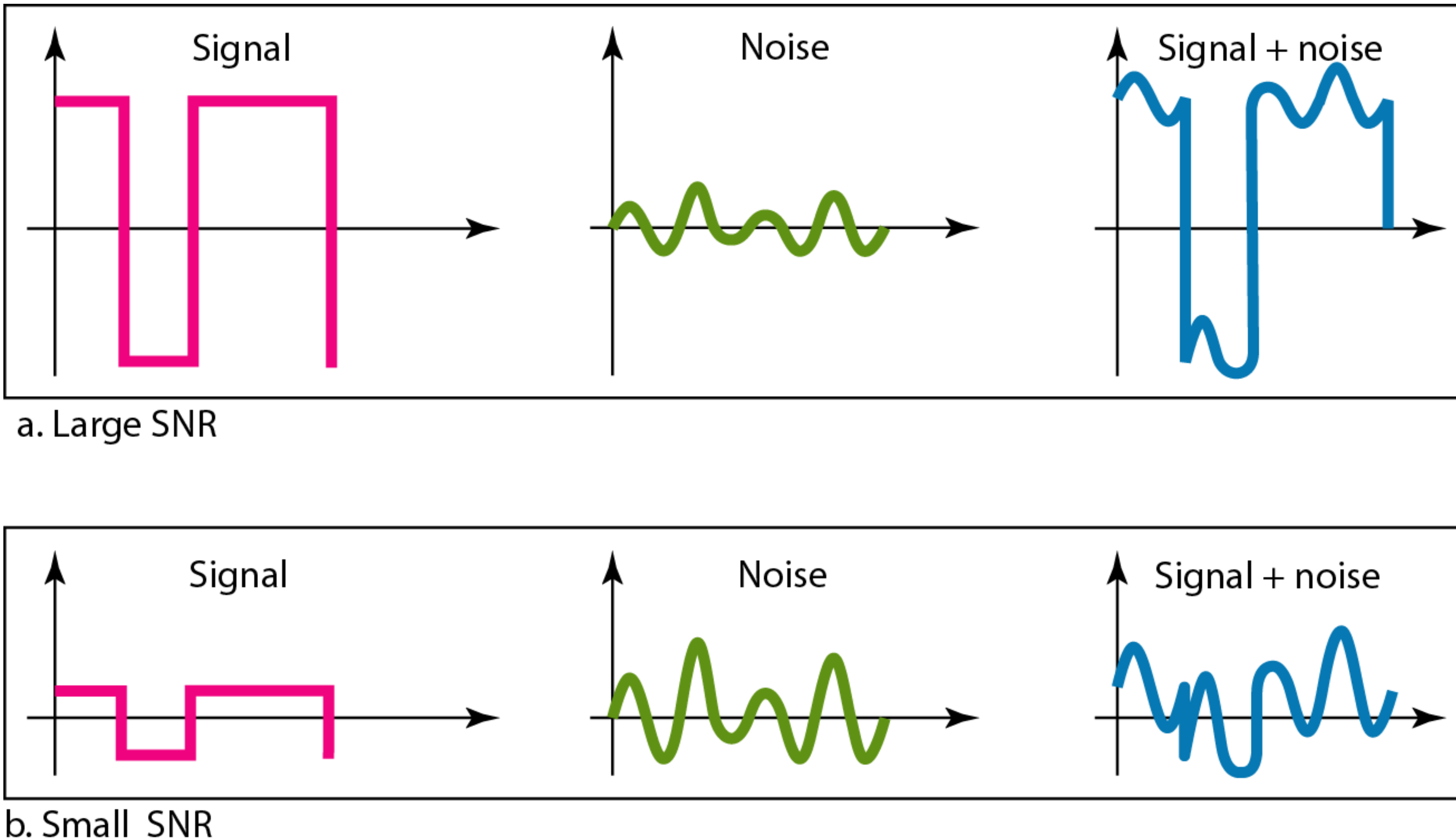
The values of SNR and SNR_{dB} for a noiseless channel are

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

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

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

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



3-5 DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel.

Data rate depends on three factors:

1. ***The bandwidth available***
2. ***The level of the signals we use***
3. ***The quality of the channel (the level of noise)***

<u>Topics discussed in this section:</u>

Noiseless Channel: Nyquist Bit Rate
Noisy Channel: Shannon Capacity
Using Both Limits

Note

Increasing the levels of a signal may reduce the reliability of the system.

Channel Capacity

- Data rate
  - In bits per second
  - Rate at which data can be communicated
- Bandwidth
  - In cycles per second of Hertz
  - Constrained by transmitter and medium
- Baud rate
  - Frequency with which the components change

BPS vs. Baud

- Data rate rarely the same as baud rate

Channel Capacity

- Nyquist
  - Maximum data rate of a <u>noiseless</u> channel = $2 * B * \log_2(L)$ bps
  - Where B = bandwidth
  - L = the number of discrete levels
  - Example: F = 4000 Hz, L = 2

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

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

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

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

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

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

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.

Channel Capacity

- Shannon (which includes noise)
  - Maximum data rate (in bps) = B x $\log_2(1 + S/N)$
  - B = bandwidth, or frequency
  - S = signal power in watts
  - N = noise power in watts (S/N = SNR)
  - Example: B = 3400 Hz, S = 0.2 w, N = 0.0002 w
  - Max data rate = 3400 x $\log_2(1 + 1000)$
  - = 3400 x 9.97
  - = 33898 bps

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:

??

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

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

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.

Example 3.38

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

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

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

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

Note

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

Note

In networking, we use the term bandwidth in two contexts.

- **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 bit transmission in a channel or link.**

Example 3.42

As the bandwidth increases, so too can the data rate.

Stated another way, to transmit a high data rate, we need a wide bandwidth.
OR
We need to use a signaling technique that has a high number of signal levels.

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.

3-6 PERFORMANCE

One important issue in networking is the performance of the network—how good is it? In this section, we introduce terms that we need for future chapters.

Topics discussed in this section:

Bandwidth
Throughput
Latency (Delay)
Bandwidth-Delay Product

Performance- ***BANDWIDTH***

One characteristic that measures network performance is bandwidth. However, the term can be used in two different contexts with two different measuring values: bandwidth in hertz and bandwidth in bits per second.

Note

In networking, we use the term bandwidth in two contexts.

- **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 bit transmission in a channel or link.**

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 a sophisticated modem to change the digital signal to analog.

Performance- THROUGHPUT

The throughput is a measure of how fast we can actually send data through a network.

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

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.

Performance- Latency (Delay)

The latency or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source.

We can say that latency is made of four components:
propagation time,
transmission time,
queuing time and processing delay.
Latency =propagation time +transmission time + queuing time + processing delay

Performance- propagation time

Propagation time measures the time required for a bit to travel from the source to the destination.

The propagation time is calculated by dividing the distance by the propagation speed.

$$\text{Propagation time} = \frac{\text{Distance}}{\text{Propagation speed}}$$

Performance- transmission time

In data communications we don't send just 1 bit, we send a message. The first bit may take a time equal to the propagation time to reach its destination; the last bit also may take the same amount of time.
However, there is a time between the first bit leaving the sender and the last bit arriving at the receiver.

The first bit leaves earlier and arrives earlier; the last bit leaves later and arrives later. The time required for transmission of a message depends on the size of the message and the bandwidth of the channel.

$$\text{Transmission time} = \frac{\text{Message size}}{\text{Bandwidth}}$$

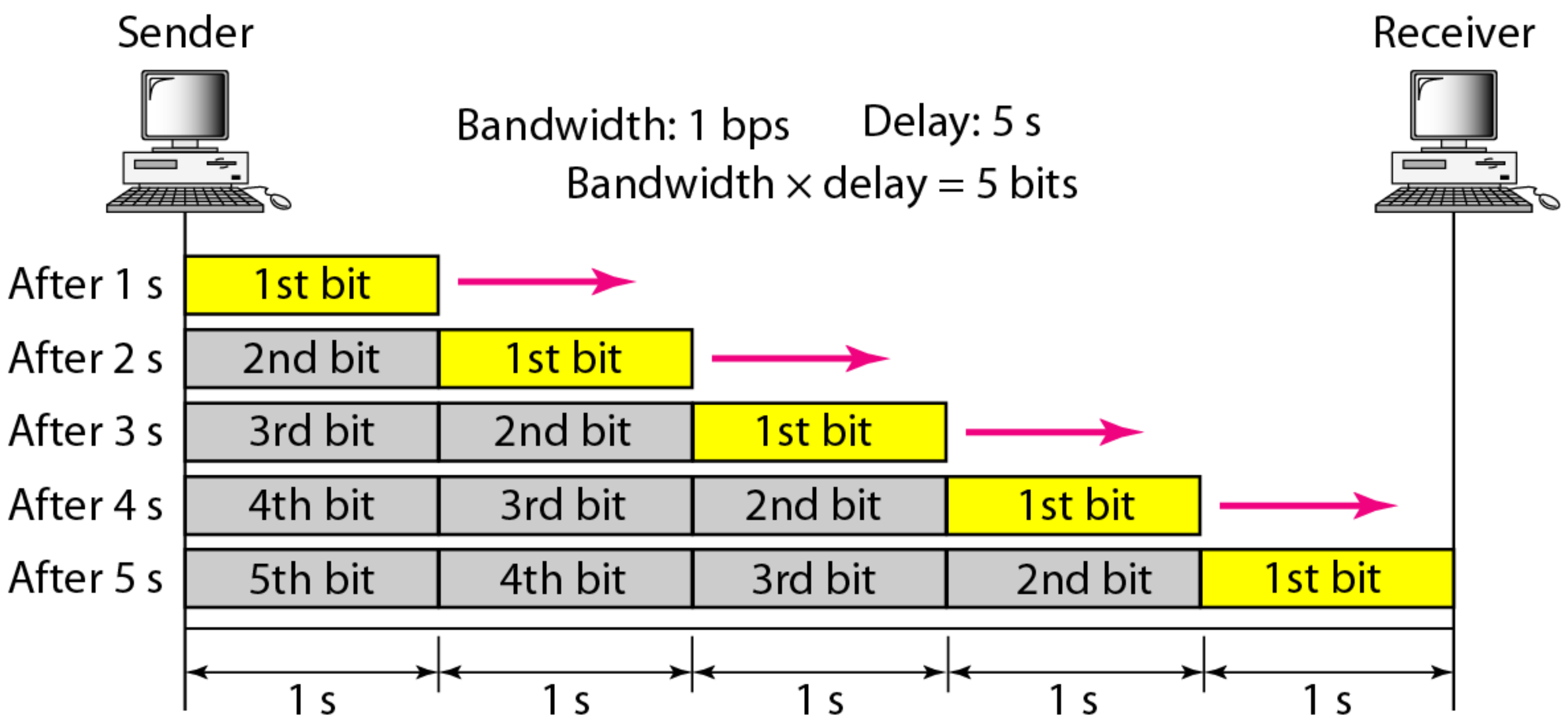
Performance- queuing time

The third component in latency is the queuing time, the time needed for each intermediate or end device to hold the message before it can be processed.

The queuing time is not a fixed factor; it changes with the load imposed on the network. When there is heavy traffic on the network, the queuing time increases.

Performance- Bandwidth-Delay Product

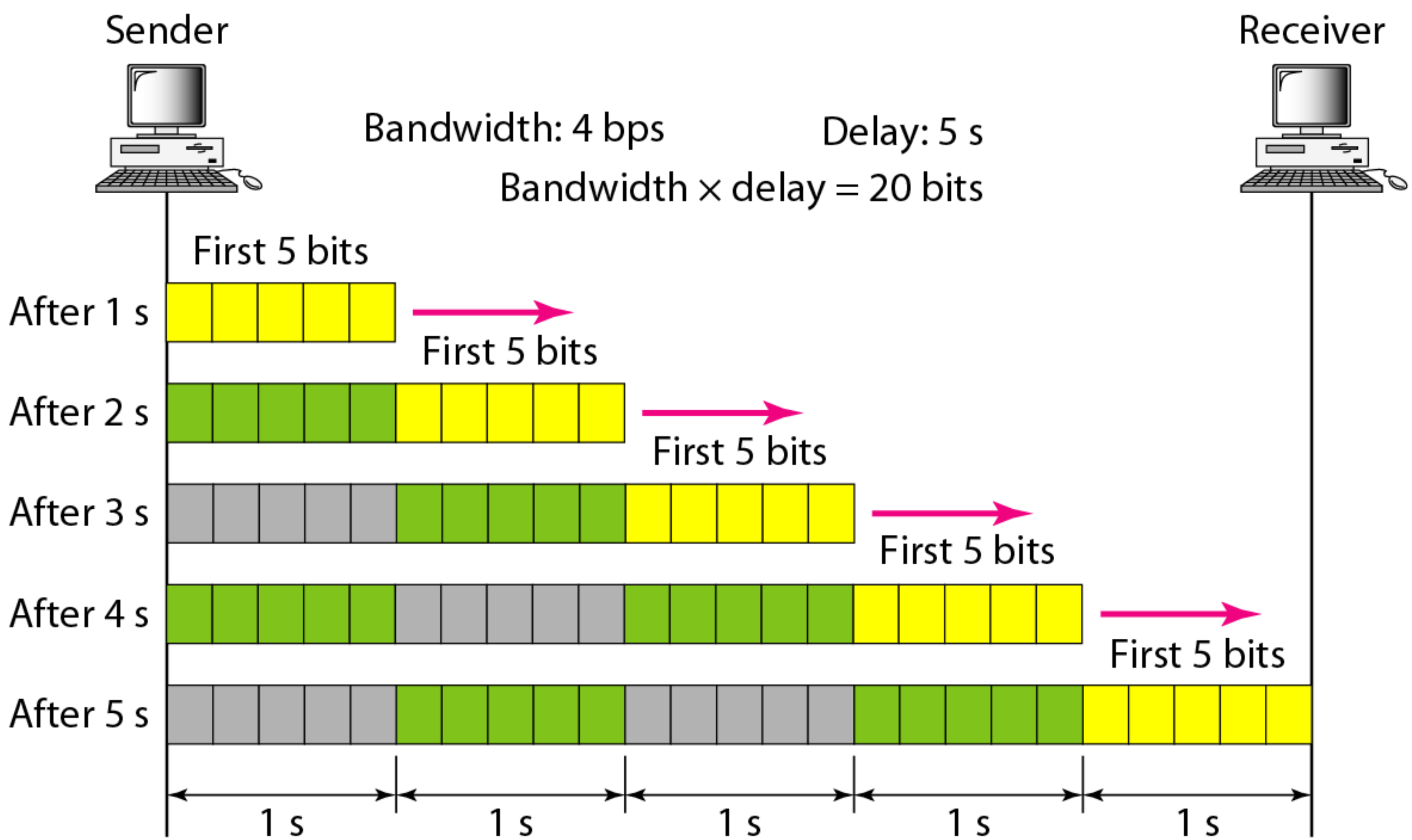
Figure 3.31 *Filling the link with bits for case 1*



Example 3.48

We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product, as shown in Figure 3.33.

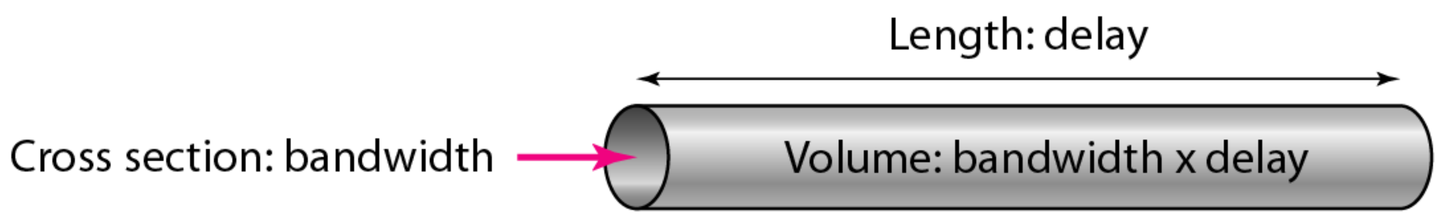
Figure 3.32 *Filling the link with bits in case 2*



Note

The bandwidth-delay product defines the number of bits that can fill the link.

Figure 3.33 *Concept of bandwidth-delay product*



Review Questions

- What is a composite signal?
- How do you calculate a dB?
- How do you calculate signal to noise ratio?
- How do you read/create a frequency domain representation?

Review Questions

- How do you use the Nyquist formula?
  - 4000 Hz, 8 signal levels, data rate?
  - 50,000 bps data rate, 4000 Hz, how many signal levels?
- How do you use the Shannon formula?
  - 8000 Hz, signal power = 20w, noise power = 0.002w, what is the data rate?
  - 5000 Hz, signal power = 50w, data rate = 20000bps, what is the possible noise power?