DATA AND SIGNALS

To be transmitted, data must be transformed to electromagnetic signals.

ANALOG AND DIGITAL

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. Analog data take on continuous values. Digital data take on discrete values.

Analog and Digital Data
Analog and Digital Signals
Periodic and Nonperiodic Signals

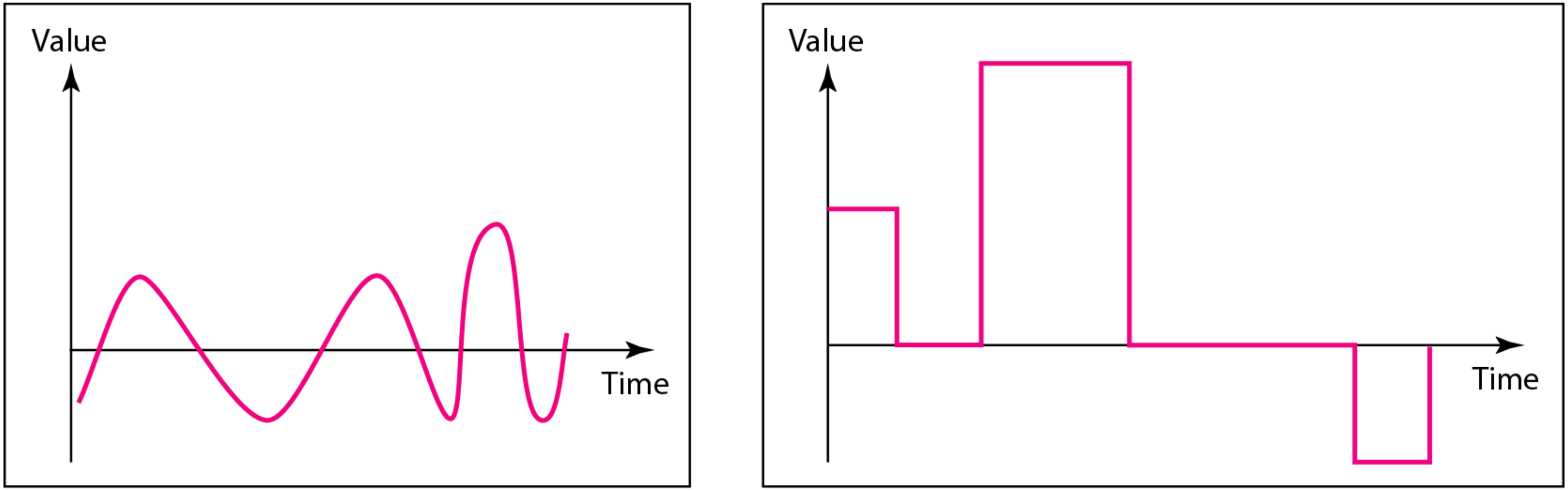
Note

Data can be analog or digital.
Analog data are continuous and take continuous values.
Digital data have discrete states and take discrete values.

Note

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.

Comparison of analog and digital signals



a. Analog signal

b. Digital signal

Periodic and Non Periodic

- **A periodic signal** completes a pattern within a measurable time frame, called a period, and repeats that pattern over subsequent identical periods.

- The completion of one full pattern is called as a **cycle.**

- A **non-periodic signal** changes without exhibiting a pattern or a cycle.

Note

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

Sine wave is _______

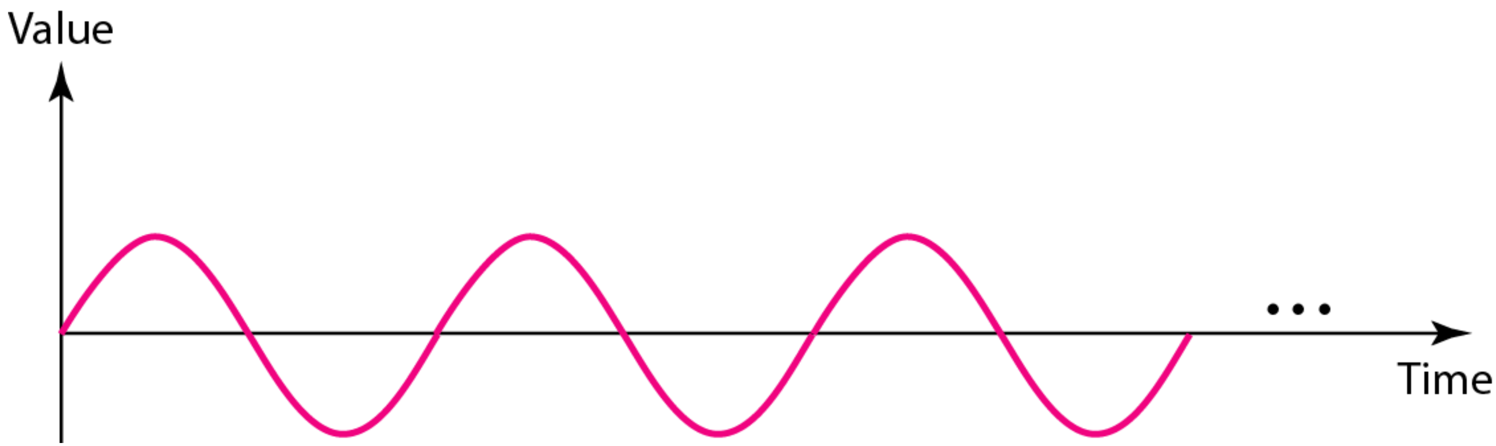
a. Periodic and continuous
b. APeriodic and continuous
c. Periodic and discontinuous
d. APeriodic and discontinuous

- Ans A

PERIODIC ANALOG SIGNALS

Periodic analog signals can be classified as simple or composite.

Figure *A sine wave*



A sine wave is represented by:

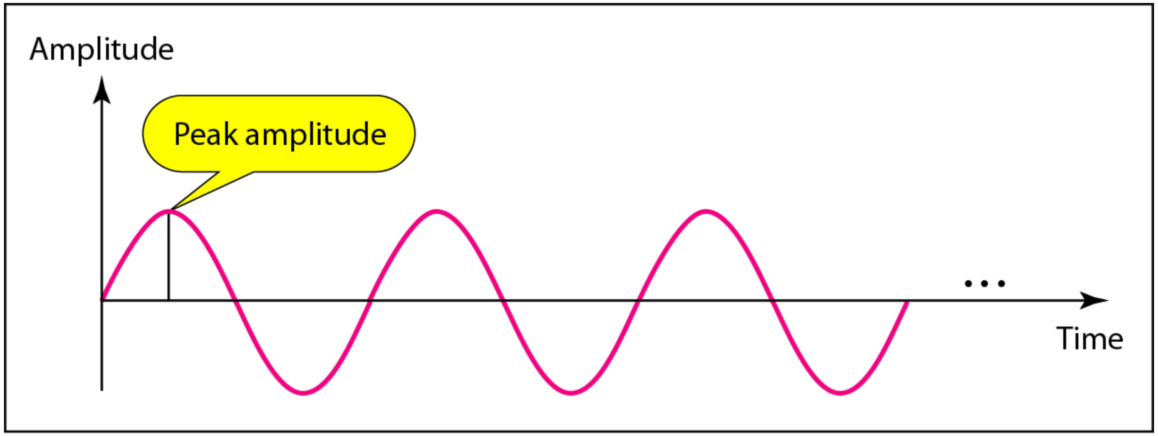
- Peak Amplitude
- Frequency
- Phase
- Wavelength

Peak Amplitude

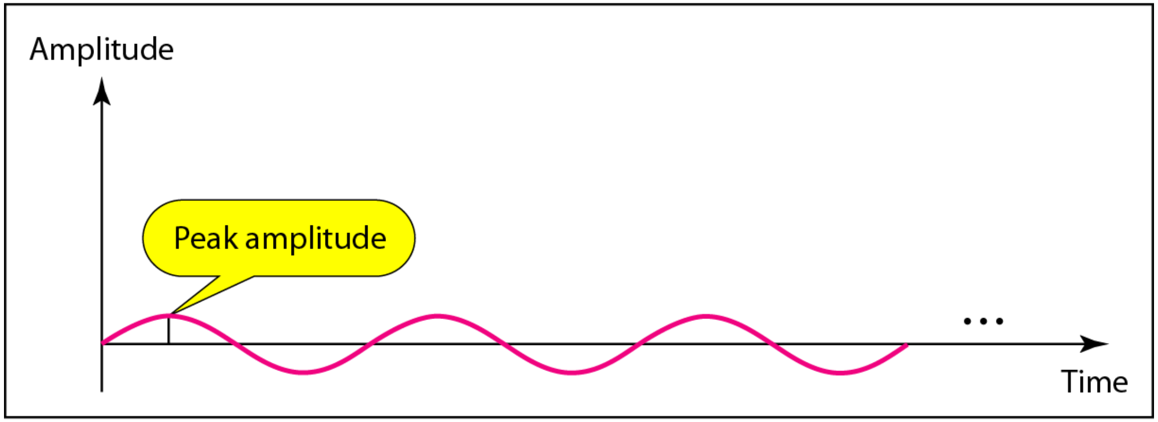
- The peak amplitude of a signal is the absolute value of its highest intensity, proportional to energy it carries.

- Measured in volts.

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



a. A signal with high peak amplitude



b. A signal with low peak amplitude

Period and Frequency

- Period refers to amount of time, in seconds, a signal takes to complete one cycle.

- Frequency refers to the number of periods in 1 second.

- Period is expressed in seconds and frequency is expressed in hertz (Hz)

Note

Frequency and period are the inverse of each other.

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

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.

Time period increases when frequency ________

a. Increases

b. Decreases

c. Remains same

d. Doubles

- Ans B

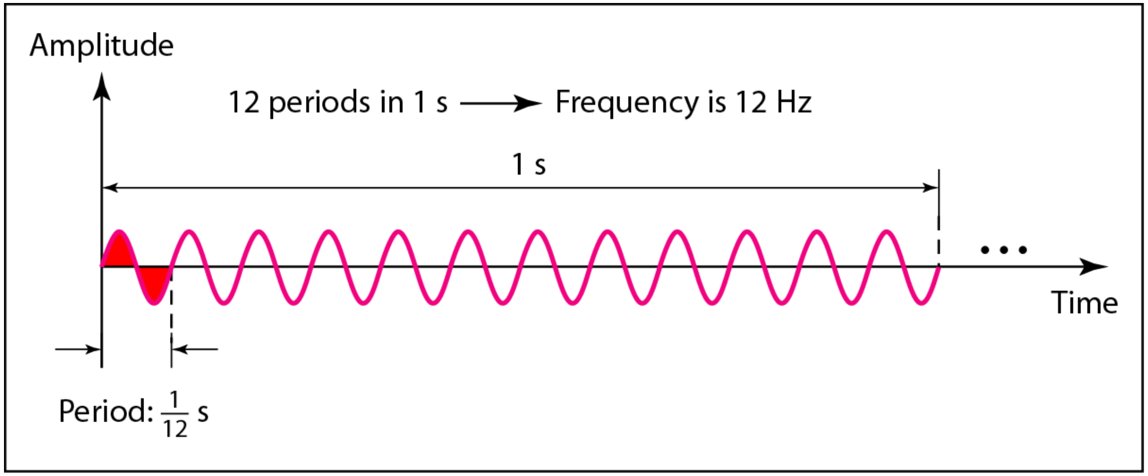
Note

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

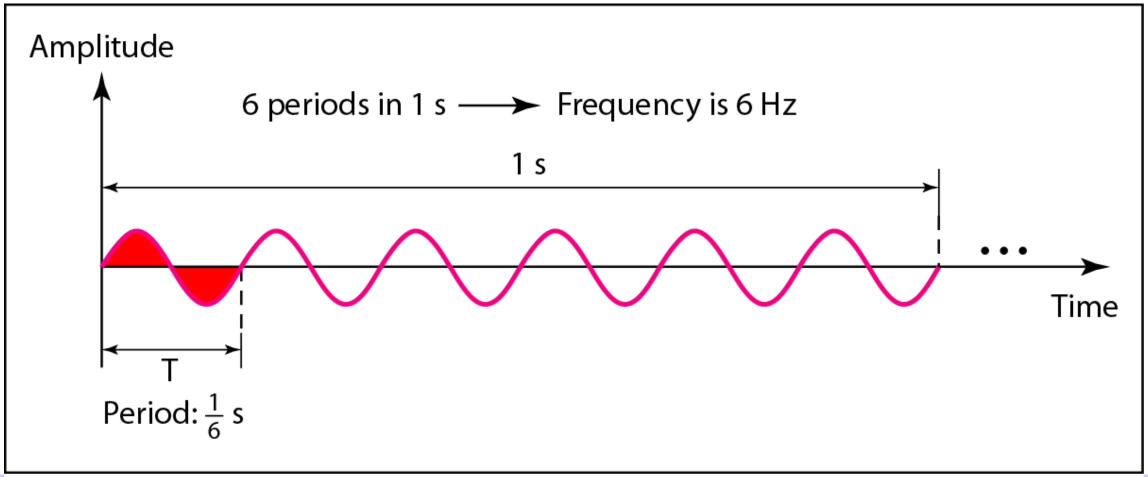
Table ***Units of period and frequency***

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

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



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Example

The power we use at home has a frequency of 60 Hz. Determined the period of this sine wave?

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

Example

Express a period of 100 ms in microseconds.

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

a) 10^{-1}

b) 10^{-2}

c) 10^{-3}

- Ans B

Example

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

Solution

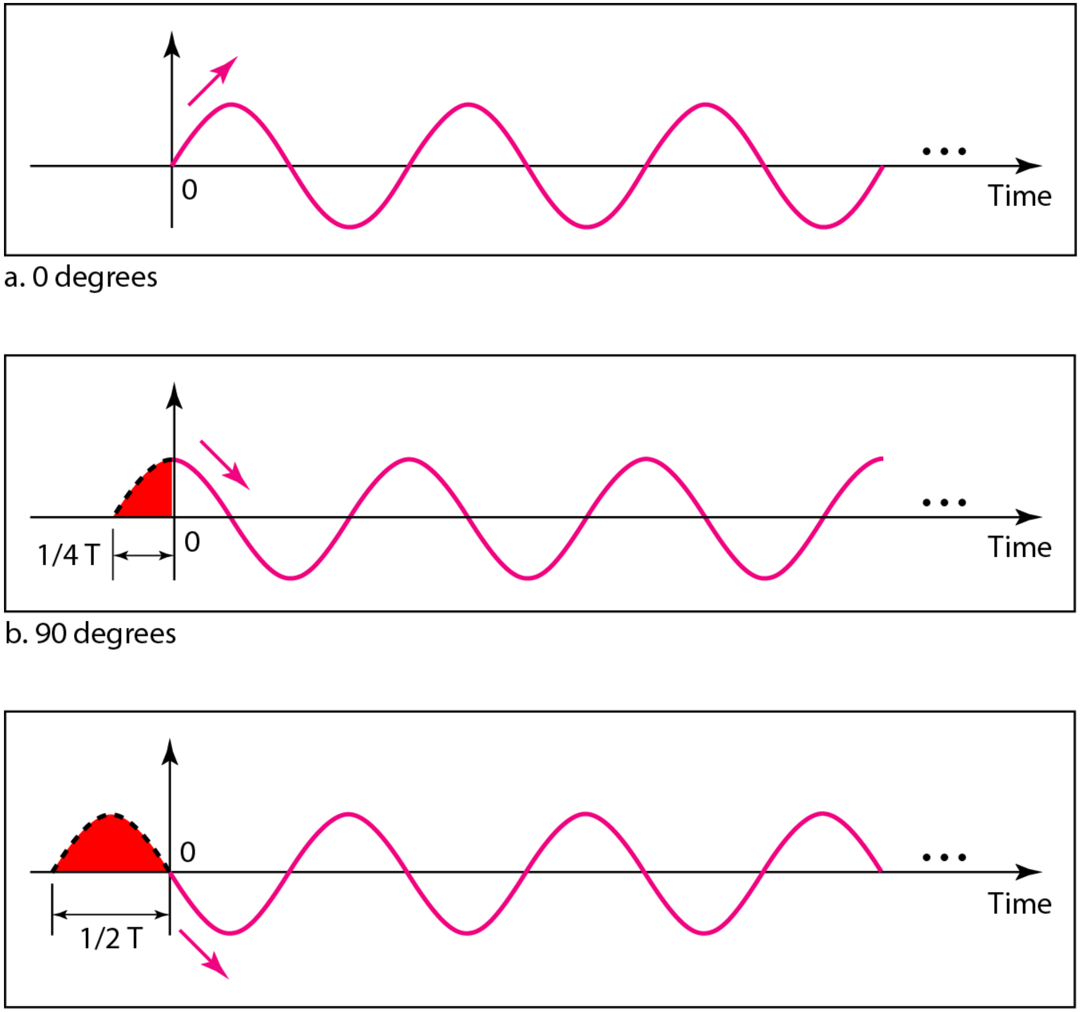
$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 10^{-1} \text{ s}$$

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

Note

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

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



a. 0 degrees

b. 90 degrees

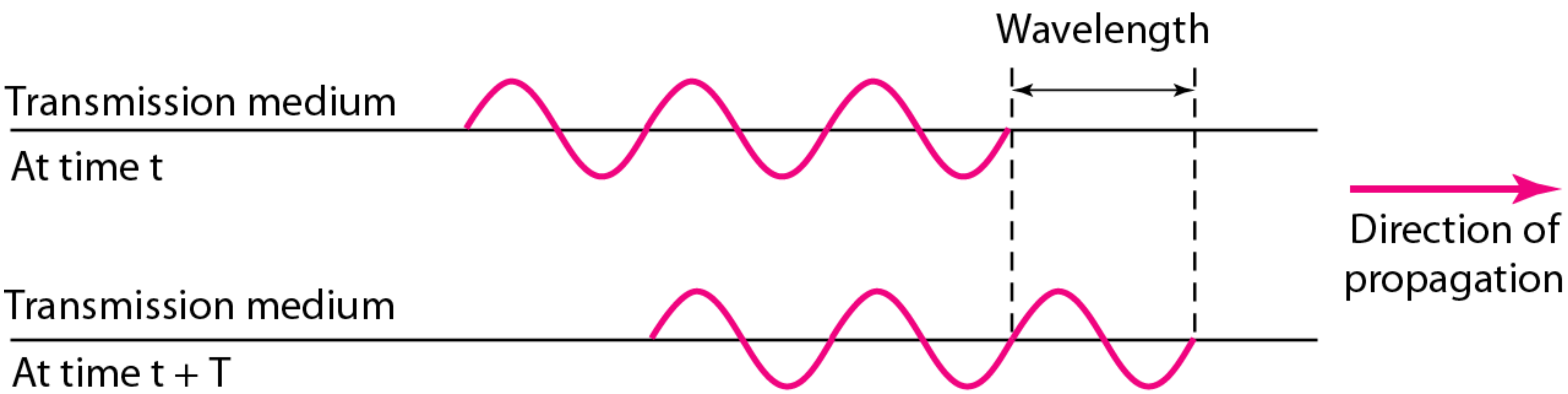
c. 180 degrees

Example

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

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

Figure *Wavelength and period*



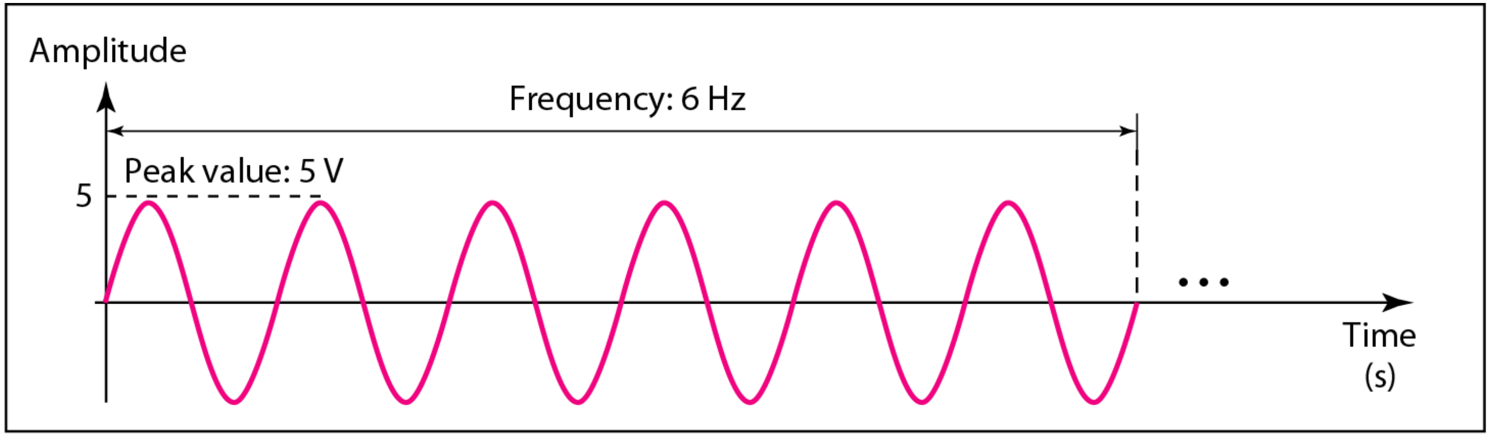
Wavelength

- Wavelength is the distance a signal can travel in one period.
- Wavelength= propagation speed* period

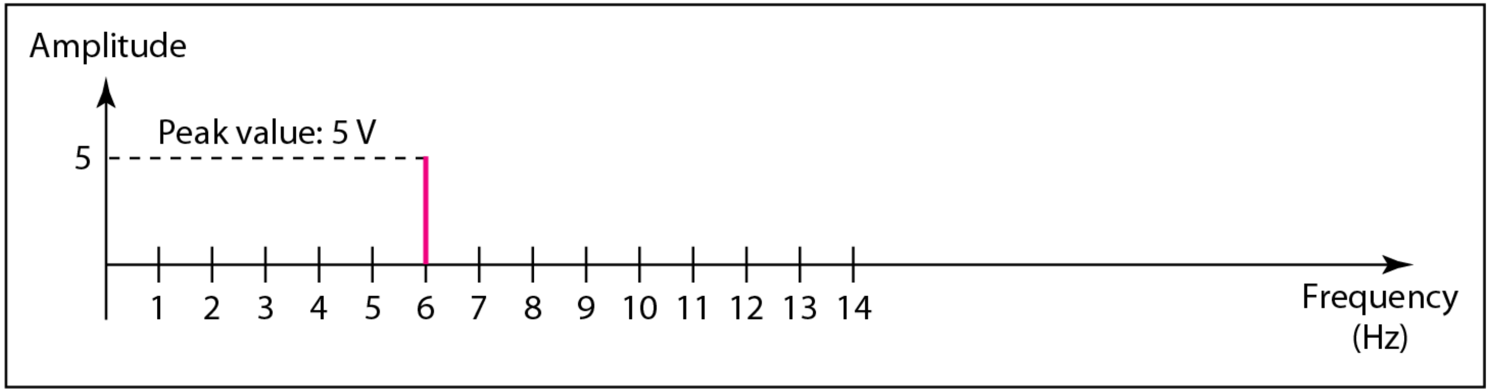
Or

- Wavelength= propagation speed/ frequency

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



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)

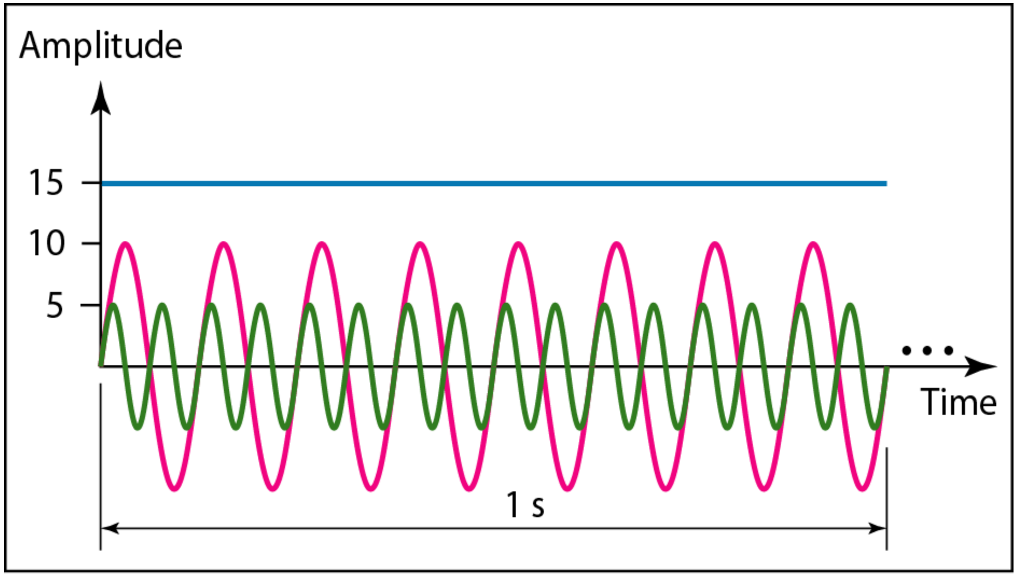
Note

A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

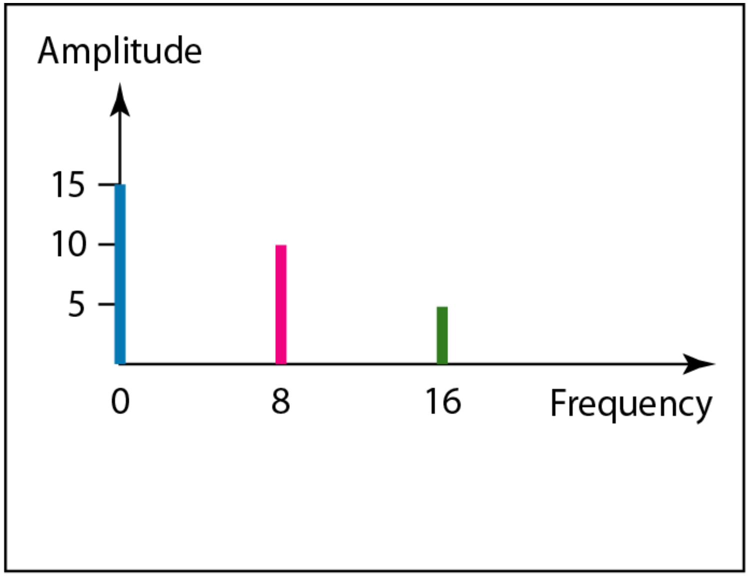
Example

The frequency domain is more compact and useful when we are dealing with more than one sine wave.

Figure ***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

Frequency is the rate of change with respect to _____

a. Time
b. Distance
c. Speed
d. Voltage

- Ans A

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

According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.

Note

**If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies;
if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.**

Example

Figure 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.

Figure *A composite periodic signal*

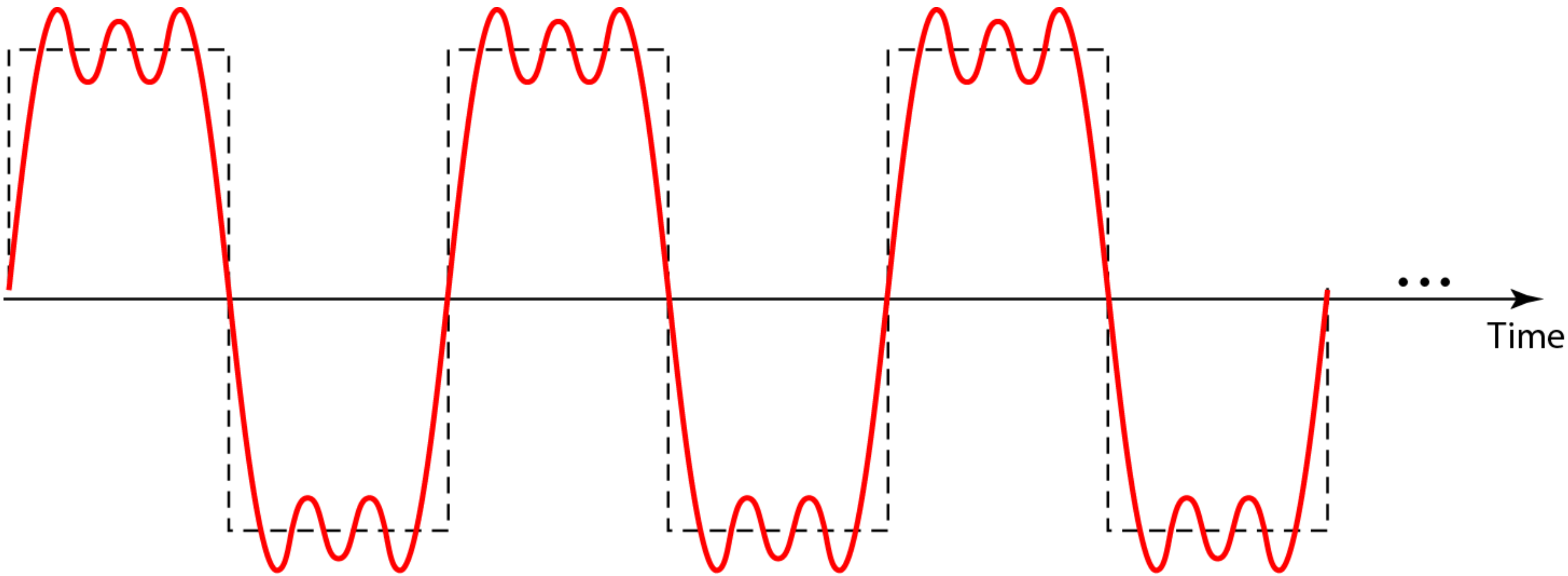
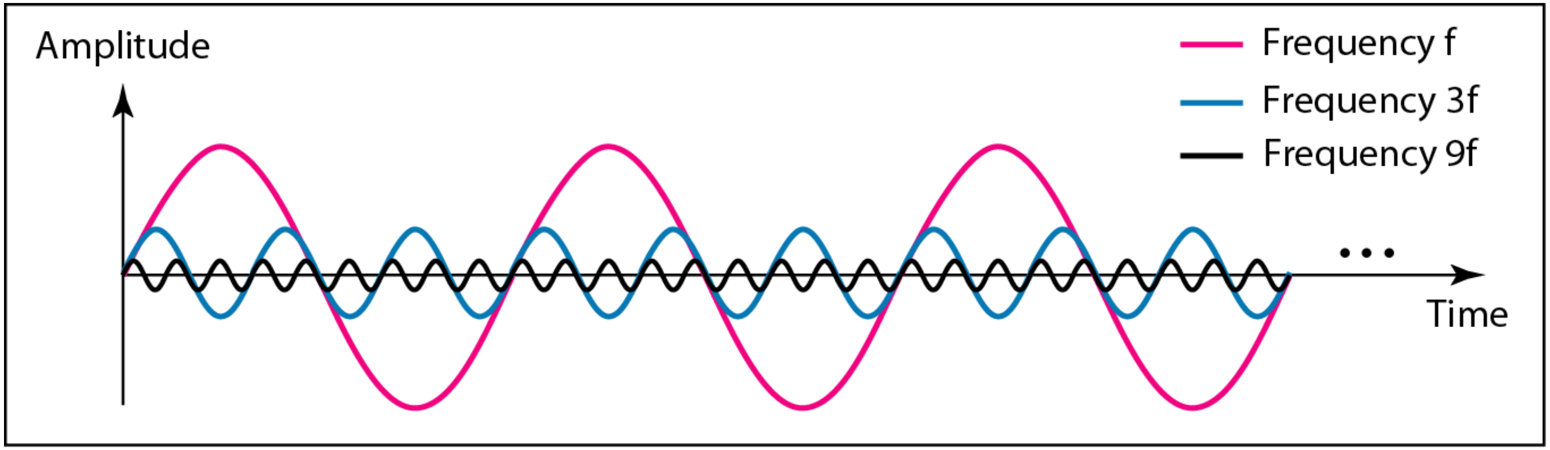
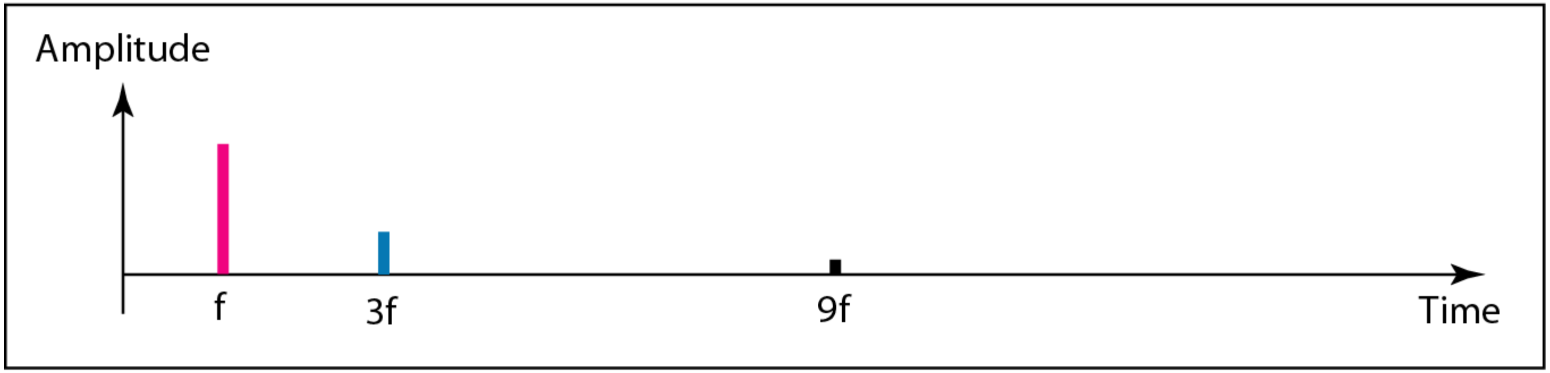


Figure ***Decomposition of a composite periodic signal in the time and frequency domains***



a. Time-domain decomposition of a composite signal

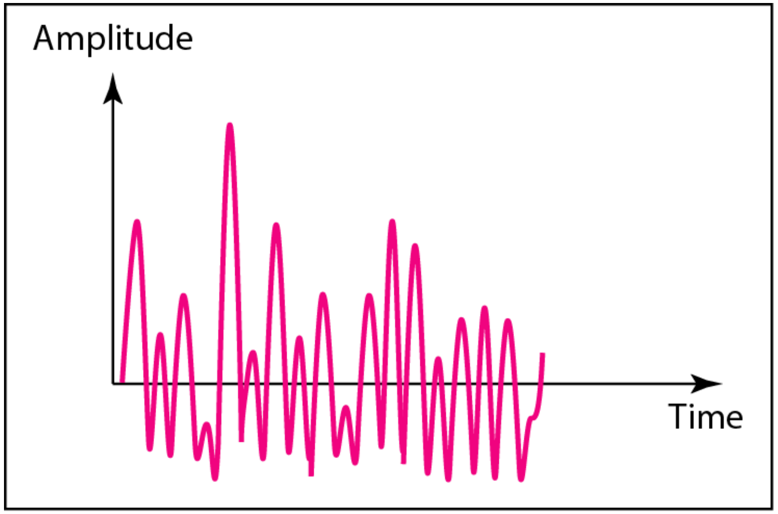


b. Frequency-domain decomposition of the composite signal

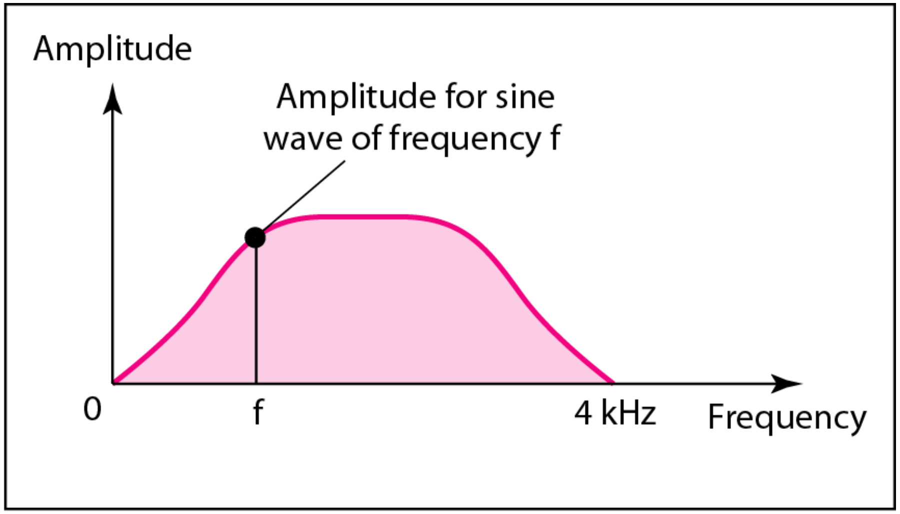
Example

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



a. Time domain

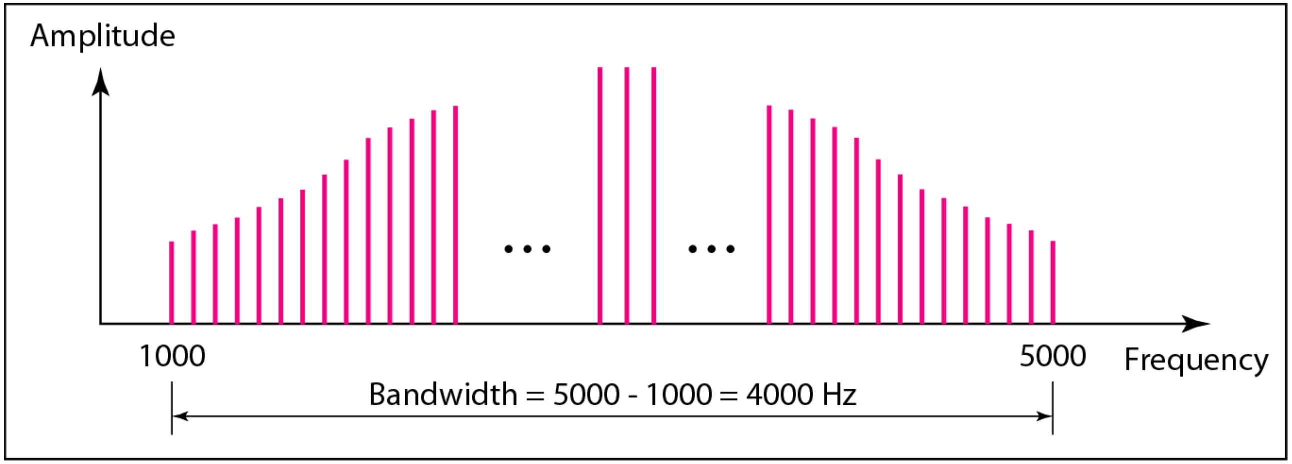


b. Frequency domain

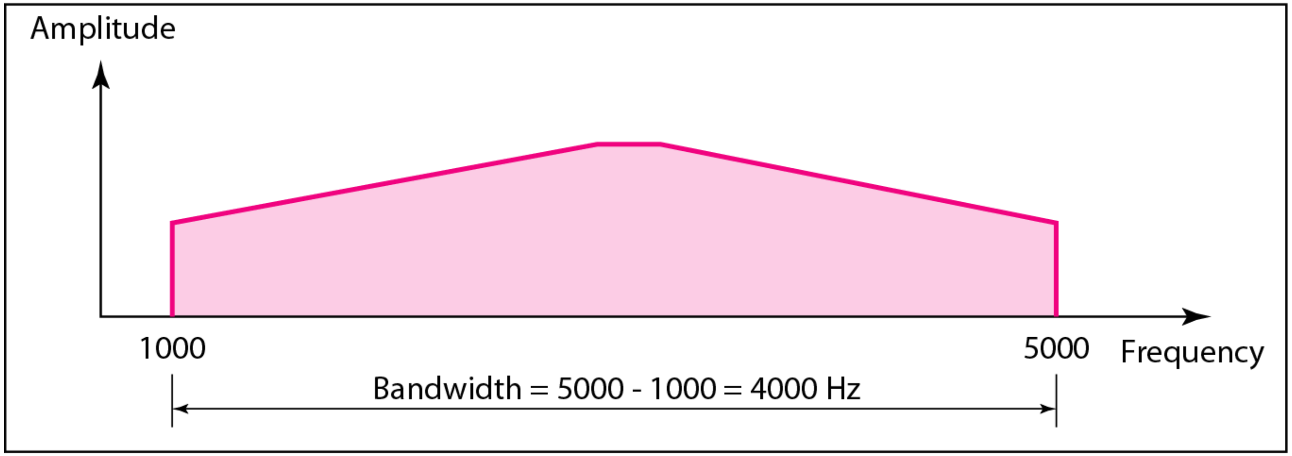
Note

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

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



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Example

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.

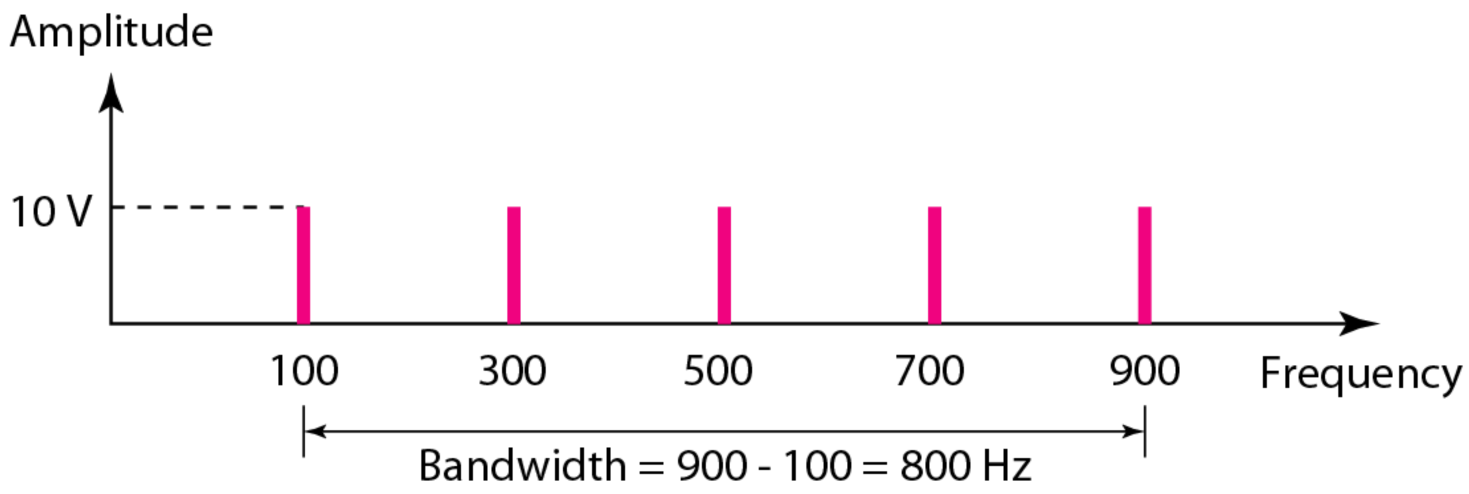
Solution

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

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

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

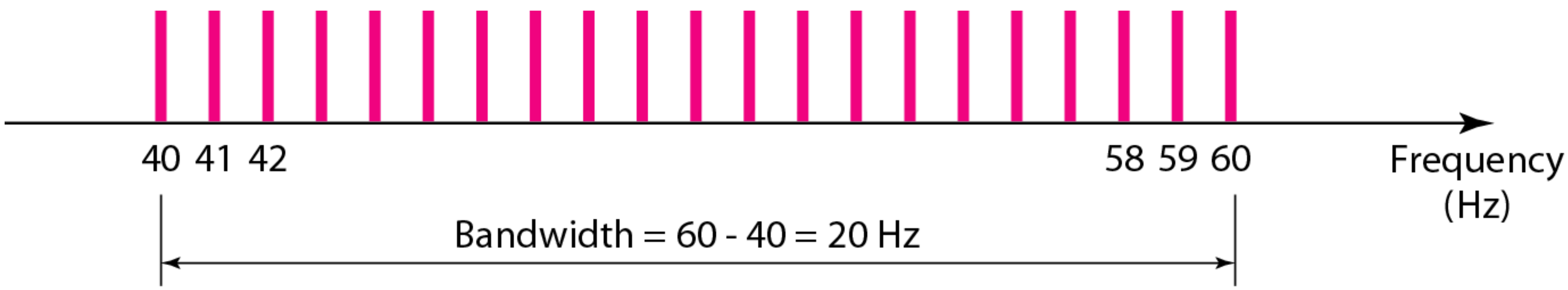
Figure *The bandwidth for Example*



A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency?

a) 60 Hz
b) 20 HZ
c) 40 Hz
d) 80 Hz

Draw the spectrum if the signal contains all frequencies of the same amplitude.



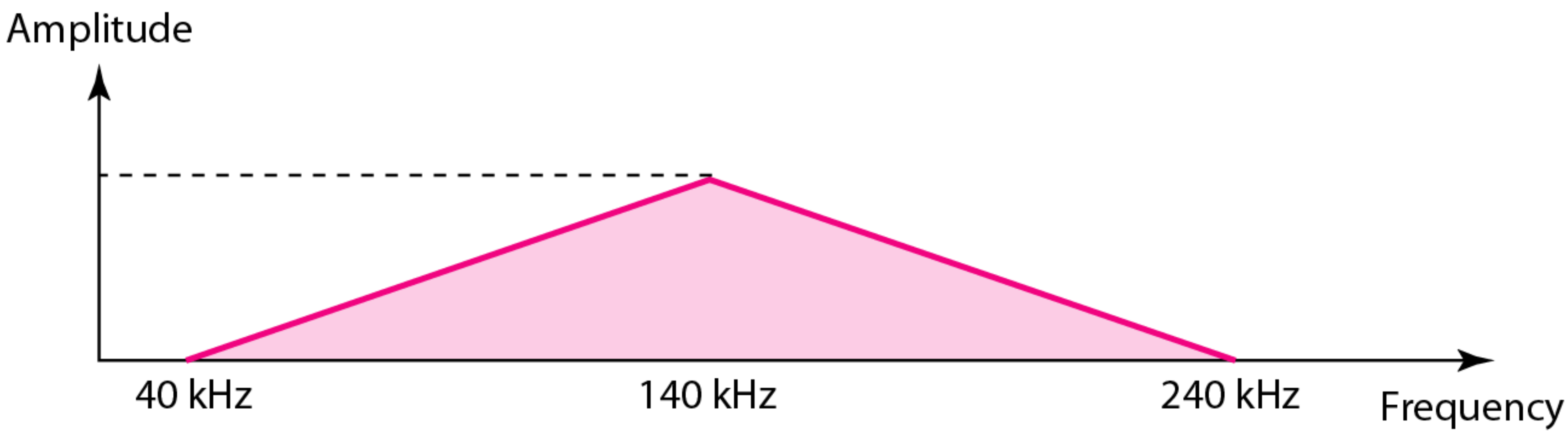
Example

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 shows the frequency domain and the bandwidth.

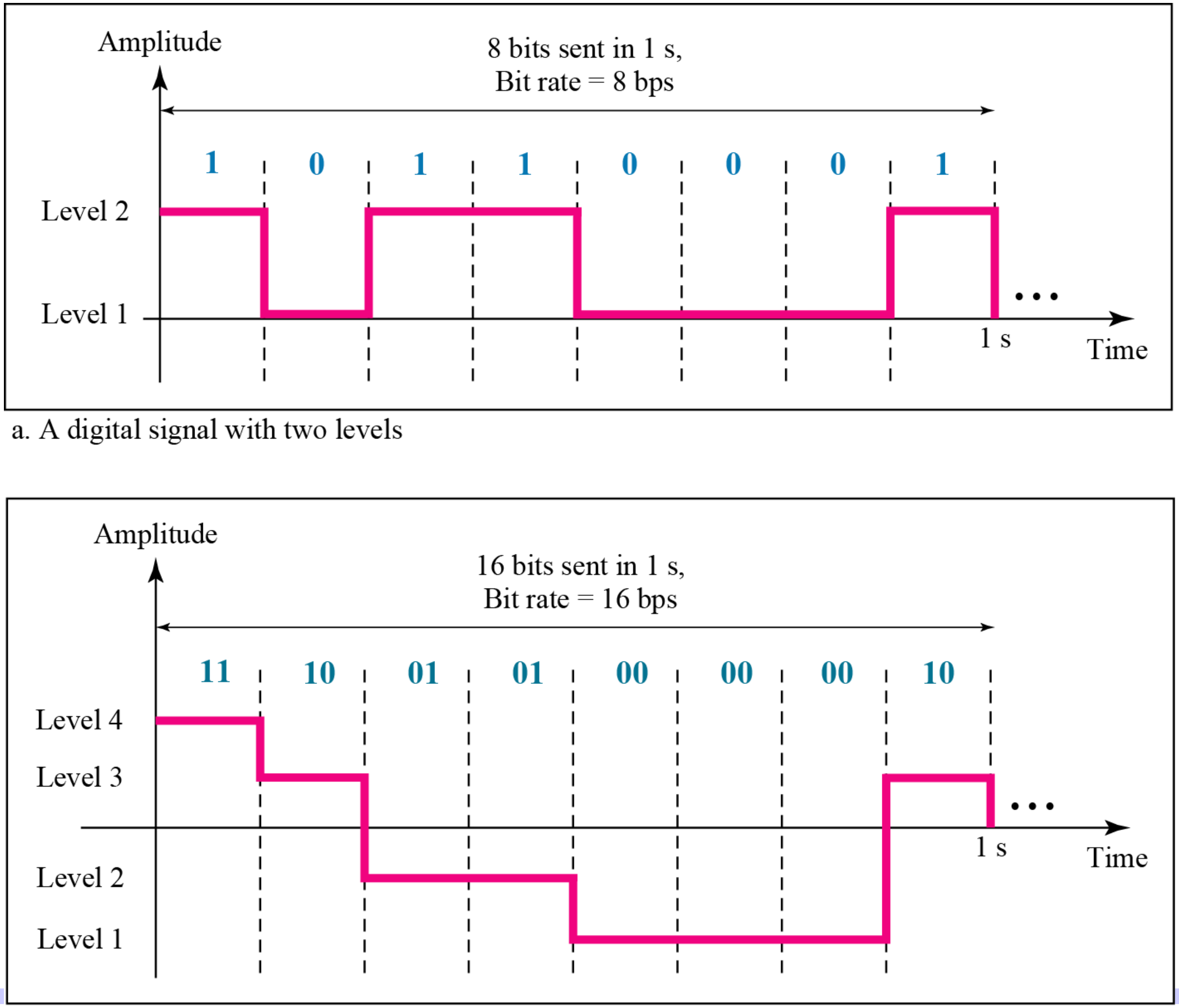
Figure ***The bandwidth for Example***



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.

Figure ***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

A digital signal has eight levels. How many bits are needed per level?

a) ***16***
b) ***3***
c) ***8***
d) ***0***

- Ans B

Example

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

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

Each signal level is represented by 3 bits.

Example

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. Therefore, period and frequency are not appropriate characteristics.
- Bit rate is used.
- Bit rate is number of bits sent in 1s. Expressed in **bps.**

Example

Assume we need to download text documents at the rate of 100 pages per minute. 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, the bit rate is

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

A digitized voice channel 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?

a) 64 kbps
b) 12 kbps
c) 32 kbps

Example

A digitized voice channel 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

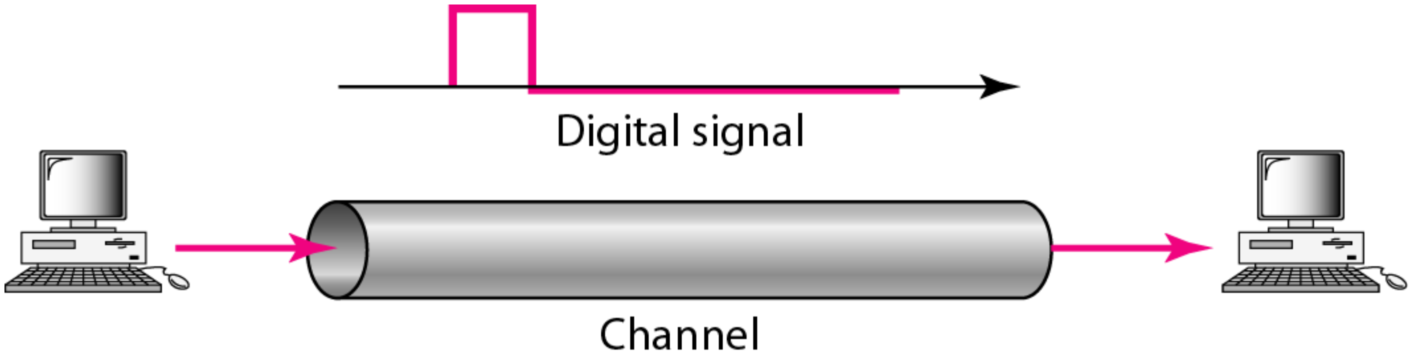
$$2 \times 4000 \times 8 = 64{,}000 \text{ bps} = 64 \text{ kbps}$$

Bit Length

- Bit length is distance one bit occupies on transmission medium.

- Bit length= propagation speed* bit duration

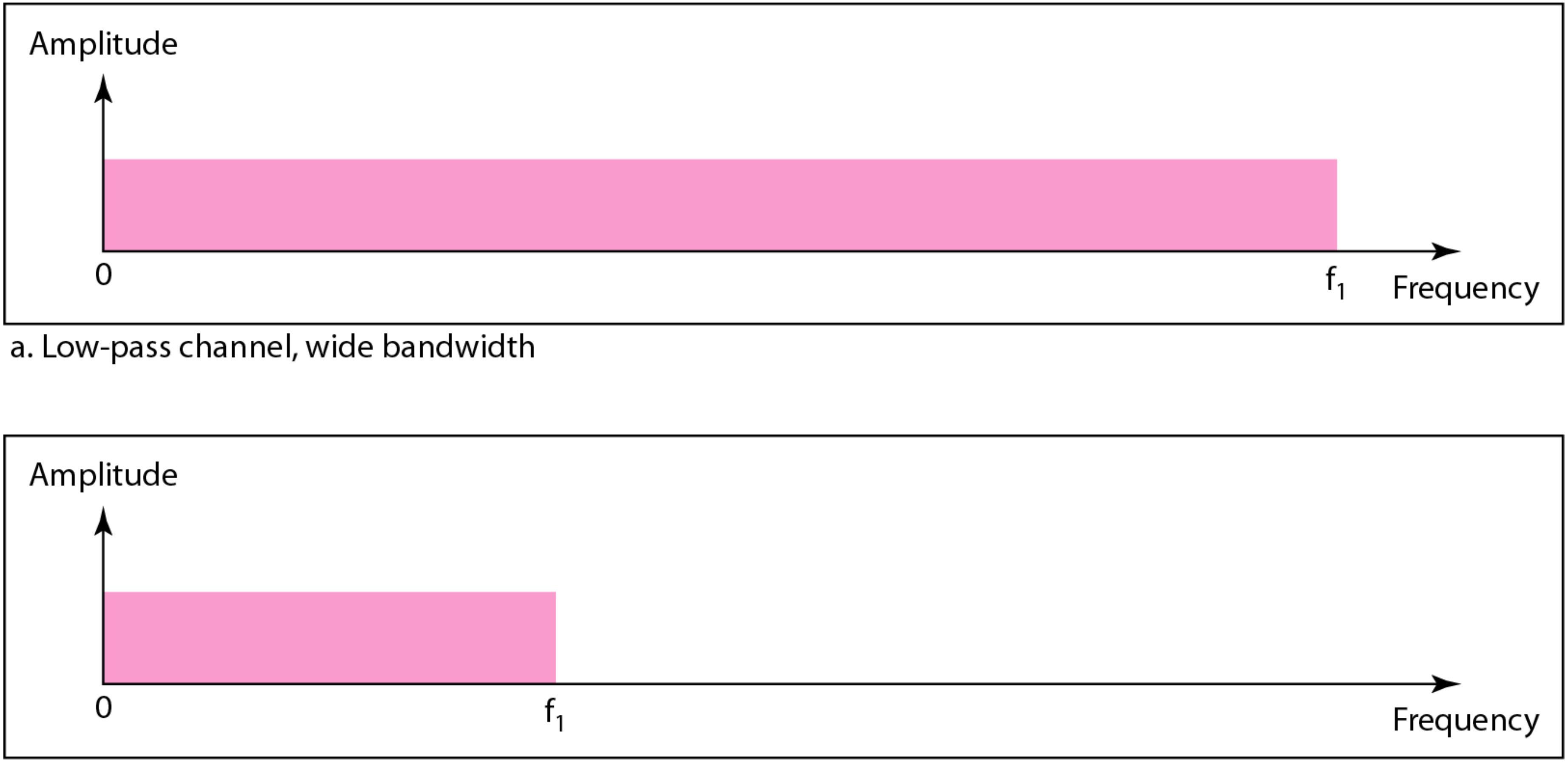
Figure *Baseband transmission*



Note

A digital signal is a composite analog signal with an infinite bandwidth.

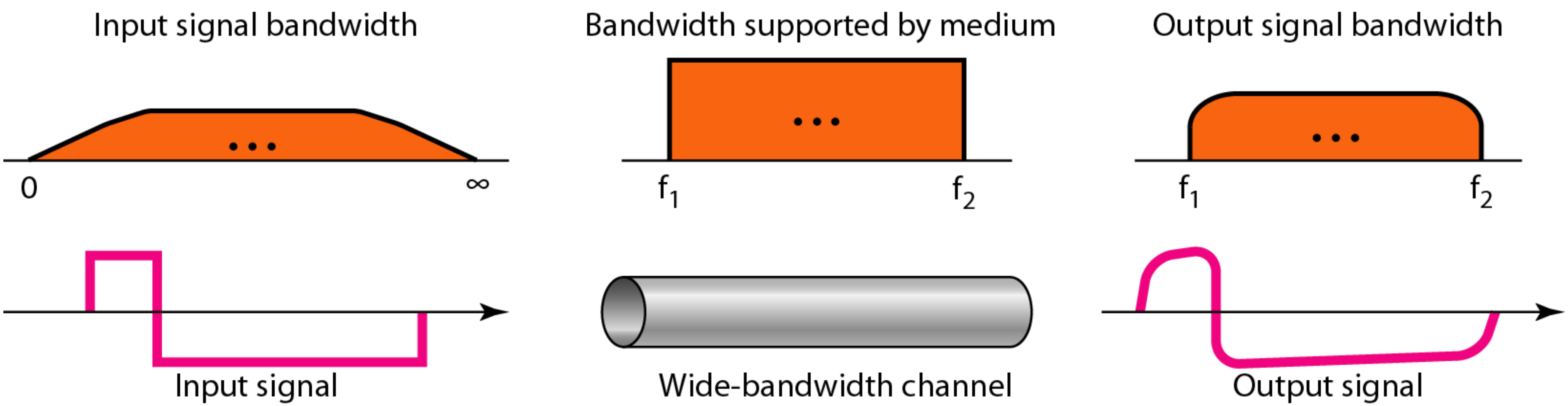
Figure *Bandwidths of two low-pass channels*



a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

Figure *Baseband transmission using a dedicated medium*



Note

Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.

Note

In baseband transmission, the required bandwidth is proportional to the bit rate; if we need to send bits faster, we need more bandwidth. Bit rate is twice the bandwidth required.

Example

What is the required bandwidth of a low-pass channel if we need to send 1 Mbps by using baseband transmission?

Solution

The minimum bandwidth, is B = bit rate /2, or 500 kHz.

Example

We have a low-pass channel with bandwidth 100 kHz. What is the maximum bit rate of this channel?

- ***a) 100 kbps***
- ***b) 200 kbps***
- ***c) 400 kbps***

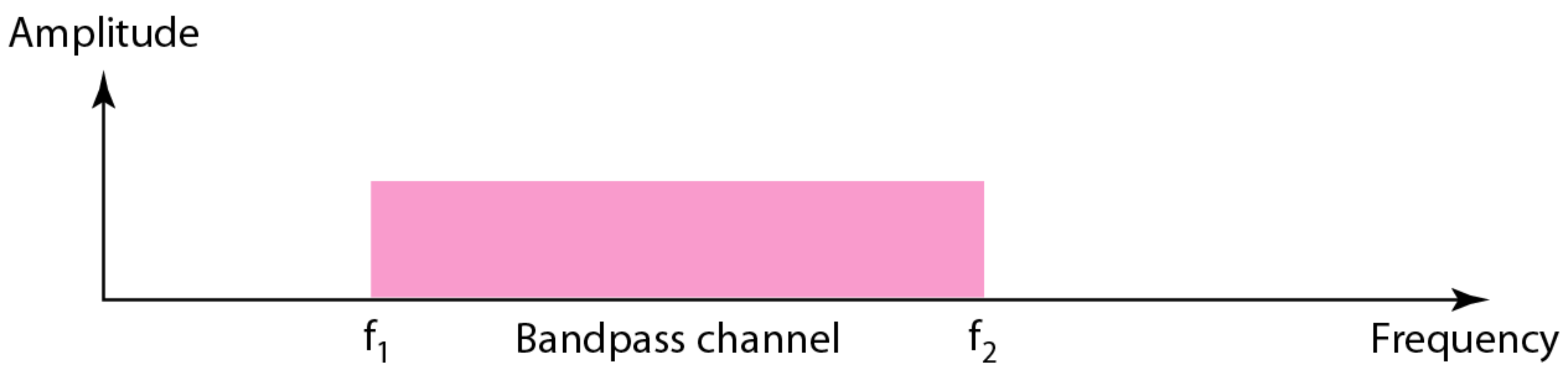
Example

We have a low-pass channel with bandwidth 100 kHz. What is the maximum bit rate of this channel?

Solution

The maximum bit rate can be achieved if we use the first harmonic. The bit rate is 2 times the available bandwidth, or 200 kbps.

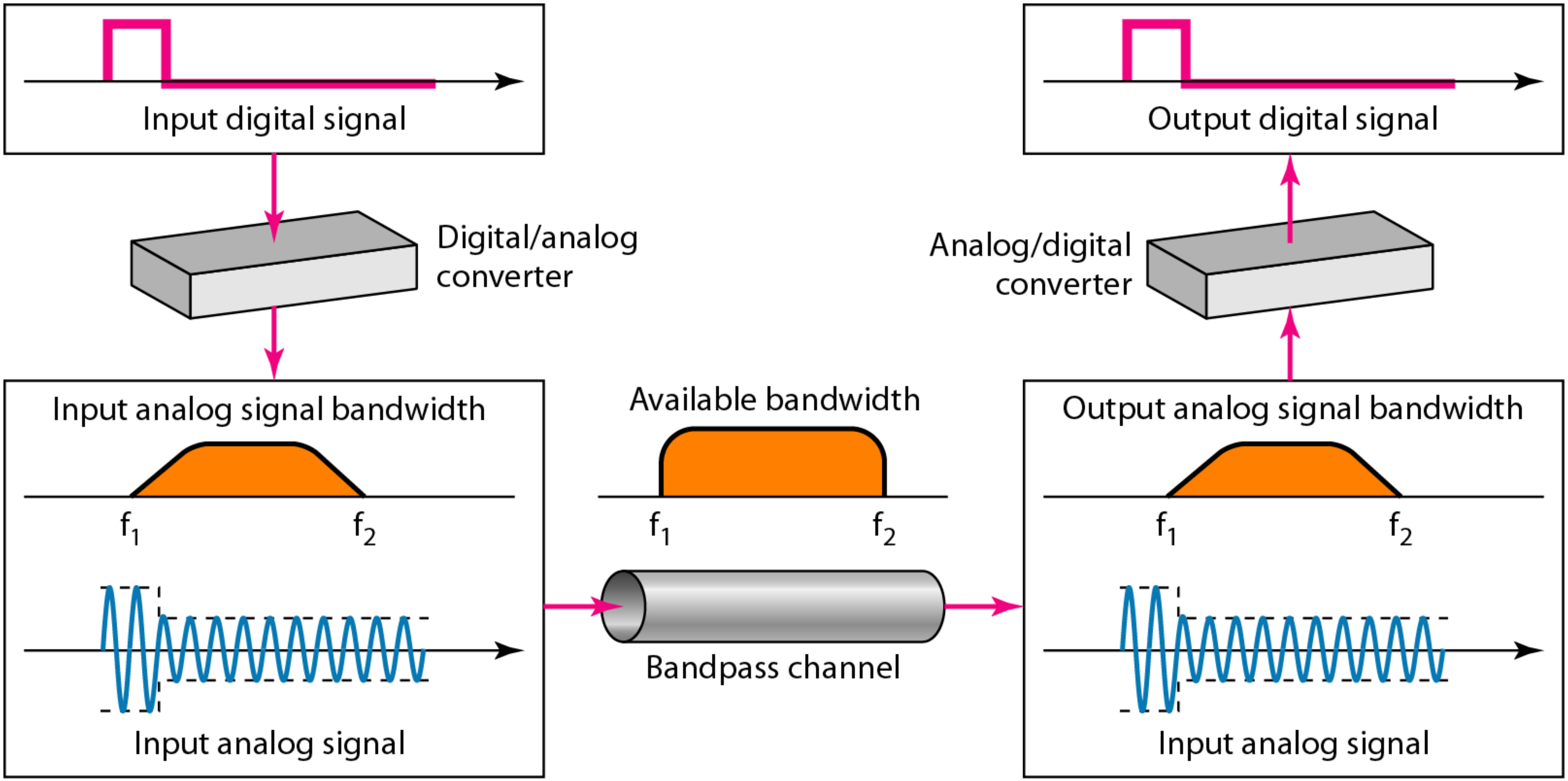
Broadband Transmission: *Bandwidth of a bandpass channel*



Note

**If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel;
we need to convert the digital signal to an analog signal before transmission.**

Figure *Modulation of a digital signal for transmission on a bandpass channel*



Example

An example of broadband transmission using modulation is the sending of computer data through a telephone subscriber line, the line connecting a resident to the central telephone office. These lines are designed to carry voice with a limited bandwidth. The channel is considered a bandpass channel. We convert the digital signal from the computer to an analog signal, and send the analog signal. We can install two converters to change the digital signal to analog and vice versa at the receiving end. The converter, in this case, is called a modem

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)

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.

Noiseless Channel: Nyquist Bit Rate

Bit Rate= 2 * bandwidth * $\log_2 L$

Example

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

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

Example

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate will be

A) 6000 bps
B) 4000 bps
C) 12000 bps

Example

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

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.

Noisy Channel : Shannon Capacity

- Capacity= Bandwidth * $\log_2(1+SNR)$

Example

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.

Example

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

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

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

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