Data Communications and Networking Fourth Edition

Chapter 3

Data and Signals

Data and Signals

- Information can be voice, image, numeric data, characters, code, picture, and so on

- To be transmitted, information must be into electromagnetic signals.

3.1 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.

Topics discussed in this section:

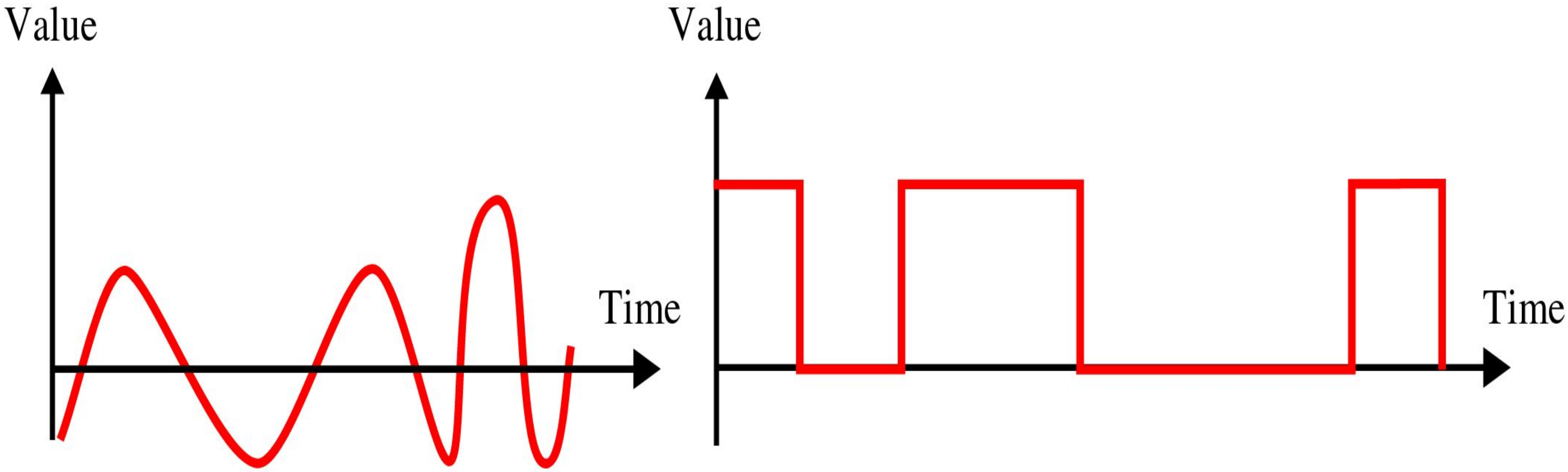
Analog and Digital Data
Analog and Digital Signals
Periodic and Nonperiodic Signals

Analog and Digital Signals

- **Analog signal**
  - Having infinitely many levels of intensity over a period of time
  - As the wave moves from value A to value B, it passes through and includes an infinite number of values along its path.
- **Digital signal**
  - Can have only a limited number of defined values

Analog and Digital Signals (cont'd)

- Comparison of analog and digital signals



a. Analog signal b. Digital signal

Aperiodic and periodic signals

- Periodic signals(주기신호)

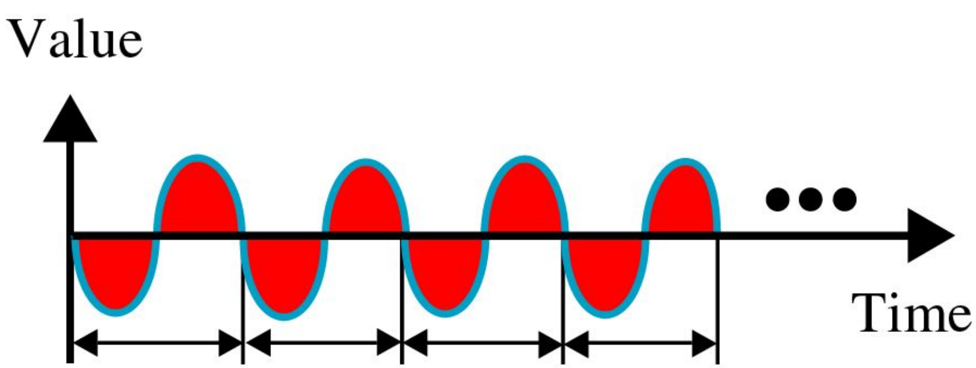
  ~ consists of a continuously repeated pattern.

- The periodic of a signal(T) is expressed in seconds.

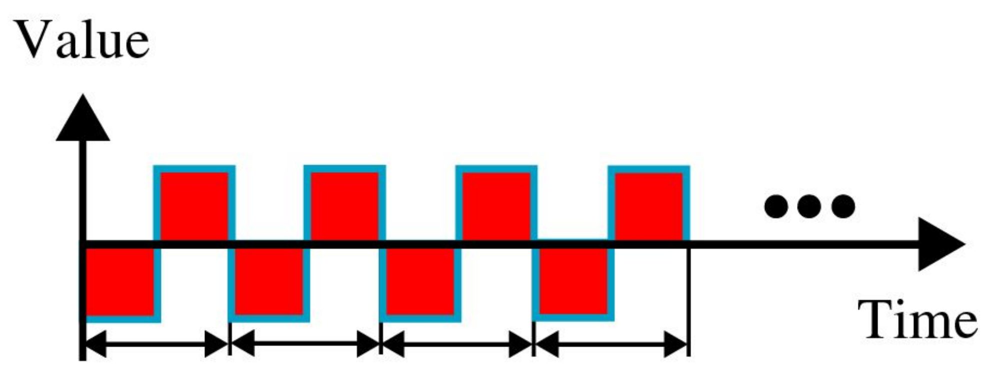
- A cycle :   the completion of one full pattern

Aperiodic and periodic signals (cont'd)

Example of periodic signals



a. Analog



b. Digital

Aperiodic and periodic signals (cont'd)

- **Aperiodic signals(비주기 신호)**

  ~ changes constantly without exhibiting a pattern or cycle that repeat over time.

  ~ signal has no repetitive pattern.

- **In data communication, we commonly use periodic analog signals and aperiodic digital signals**

3.2 PERIODIC ANALOG 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.

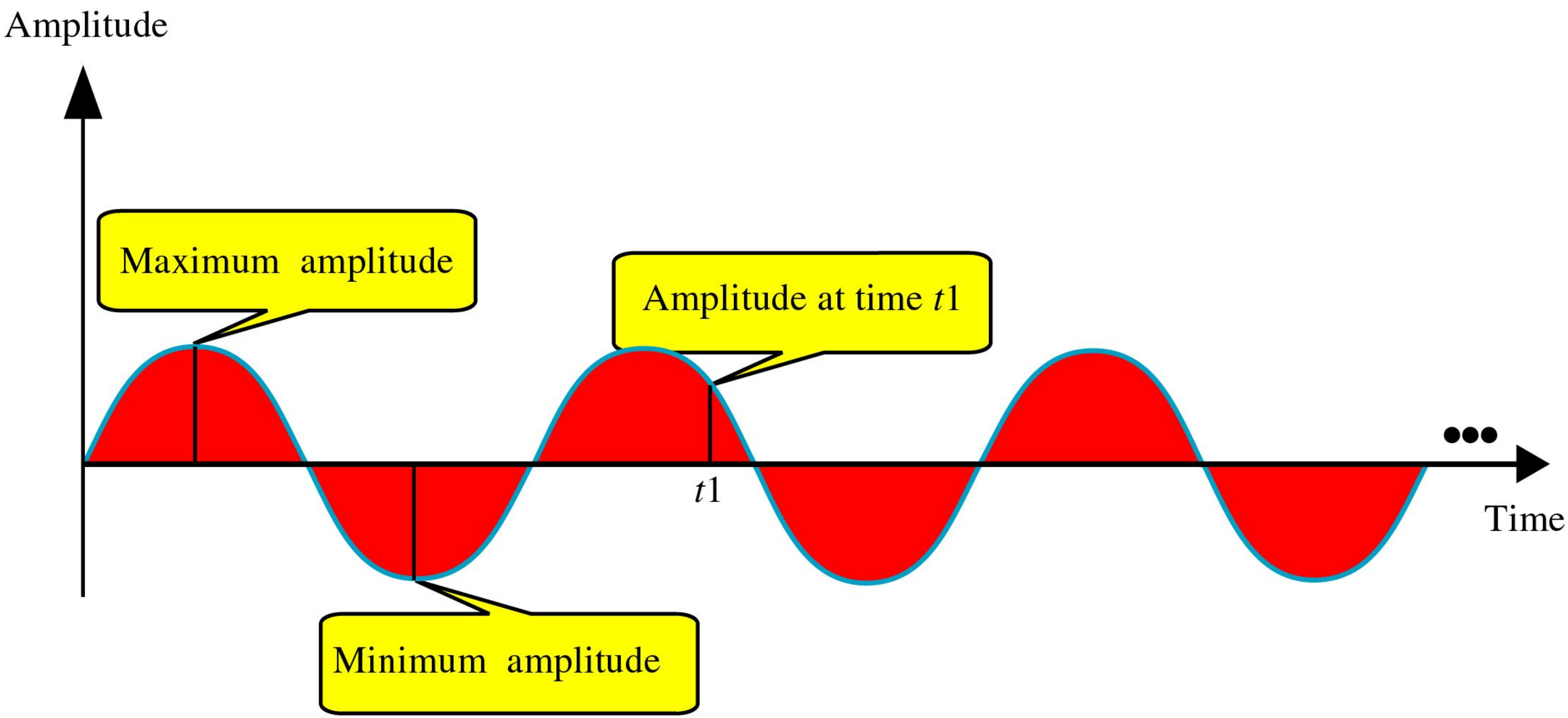
- **the sine wave is the most fundamental form of a periodic analog signal.**

Topics discussed in this section:

Sine Wave
Wavelength
Time and Frequency Domain
Composite Signals
Bandwidth

Analog signals(cont'd)

- **Sine Wave (정현파)**



Analog signals(cont'd)

- Sine wave can be fully described by three characteristics
  - amplitude(진폭)
  - period(주기), frequency(주파수)
  - phase(위상)

Analog signals(cont'd)

- **Amplitude(진폭)**

  ~ refer to the height of the signal.

  특정 순간의 신호 값; voltage(전압), amperes(전류), watts(전력)

- **Period(주기), Frequency(주파수)**
  - **Period**

    ~ refers to the amount of time, in seconds, a signal needs to complete one cycle.
  - **Frequency**

    ~ refers to number of periods a signal makes over the course of one second.(주기의 역수(1/t), 초당 주기의 반복 횟수)

Analog signals(cont'd)

Frequency=1/Period, Period=1/Frequency

$f = 1 / T$, $T = 1 / f$

- Unit of Frequency

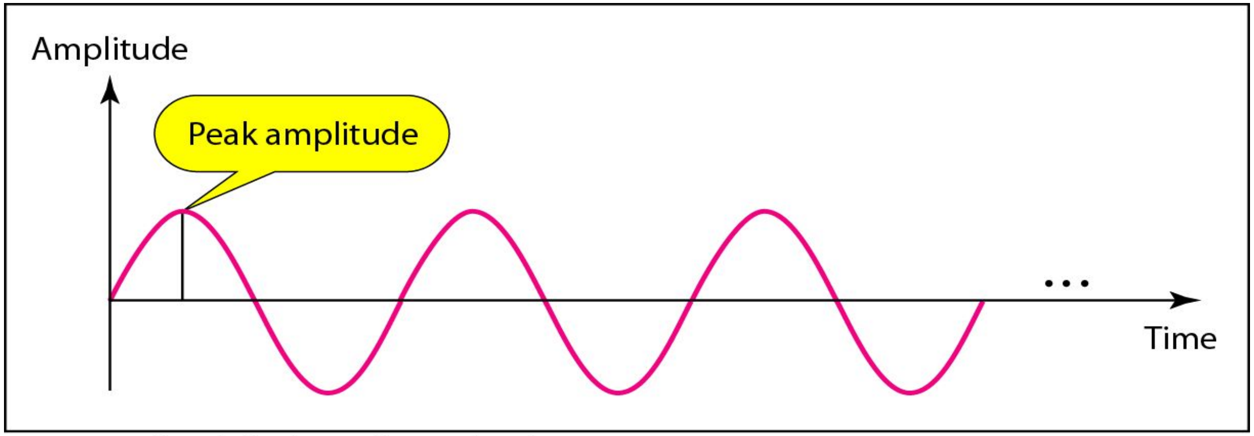
  ~ is expressed in Hertz(Hz).

- Unit of Period

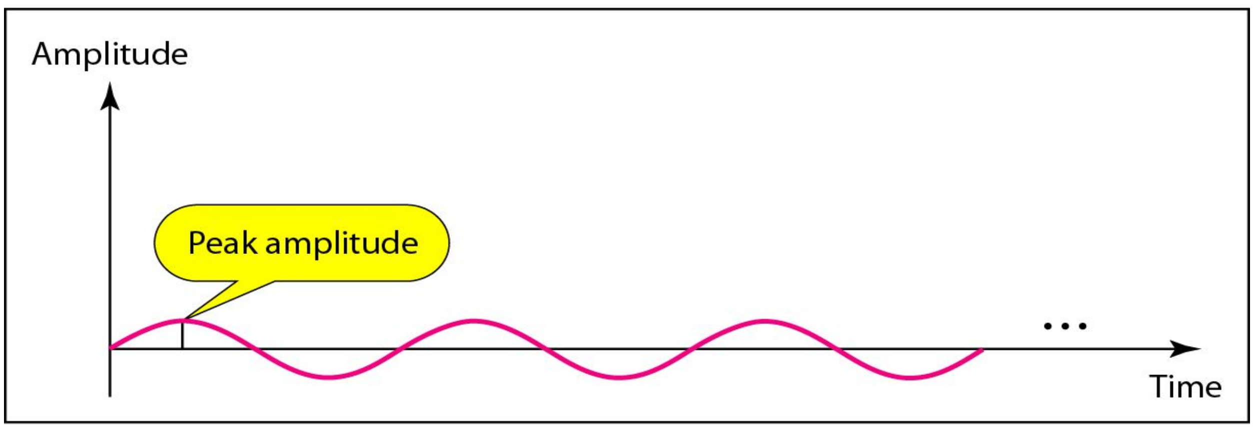
  ~ is expressed in seconds.

Analog signals (cont'd)

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



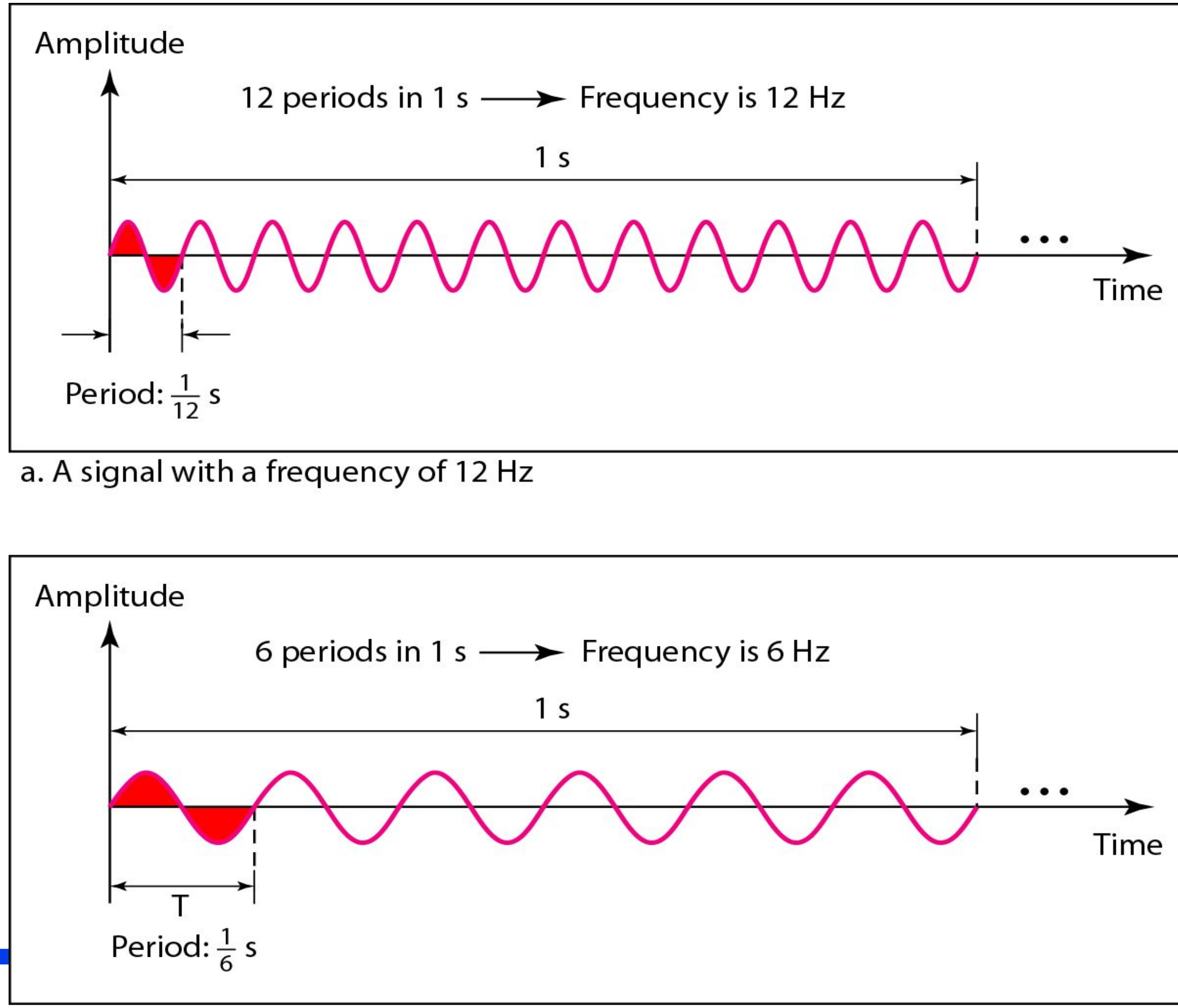
a. A signal with high peak amplitude



b. A signal with low peak amplitude

Analog signals (cont'd)

Figure 3.4 ***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

Analog signals(cont'd)

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

Analog signals(cont'd)

- **More about Frequency**
  - Frequency is rate of change with respect to time
  - Change in a short span of time means high frequency.
  - Change in a long span of time means low frequency.
- **Two Extremes**
  - If a signal does not change at all, its frequency is zero.
  - If a signal changes instantaneously, its frequency is infinity.

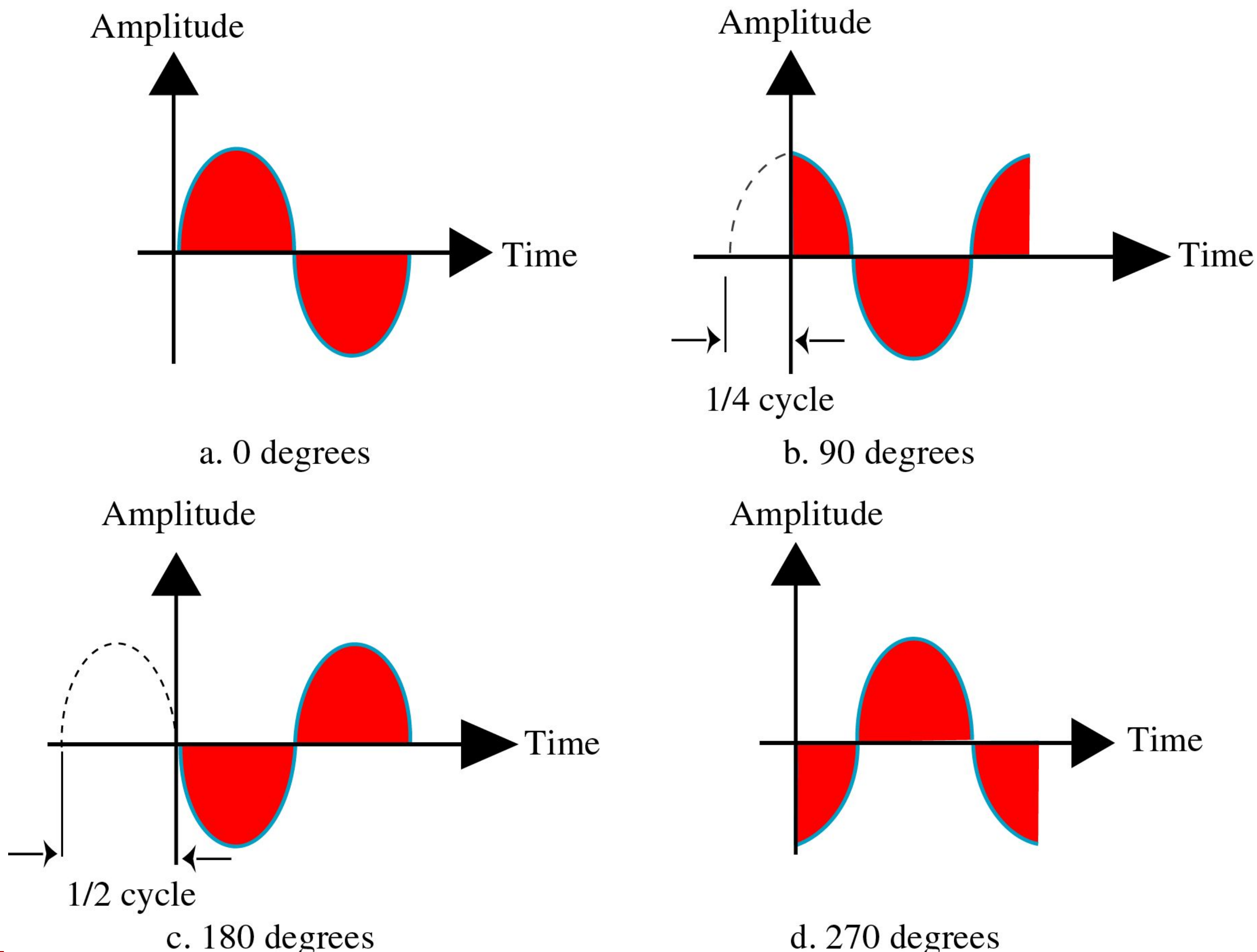
Analog signals(cont'd)

- **Phase(위상)**

  ~ describes the position of the waveform relative to time zero(시간 0에 대한 파형의 상대적인 위치)

Analog signals(cont'd)

- Relationship between different phases



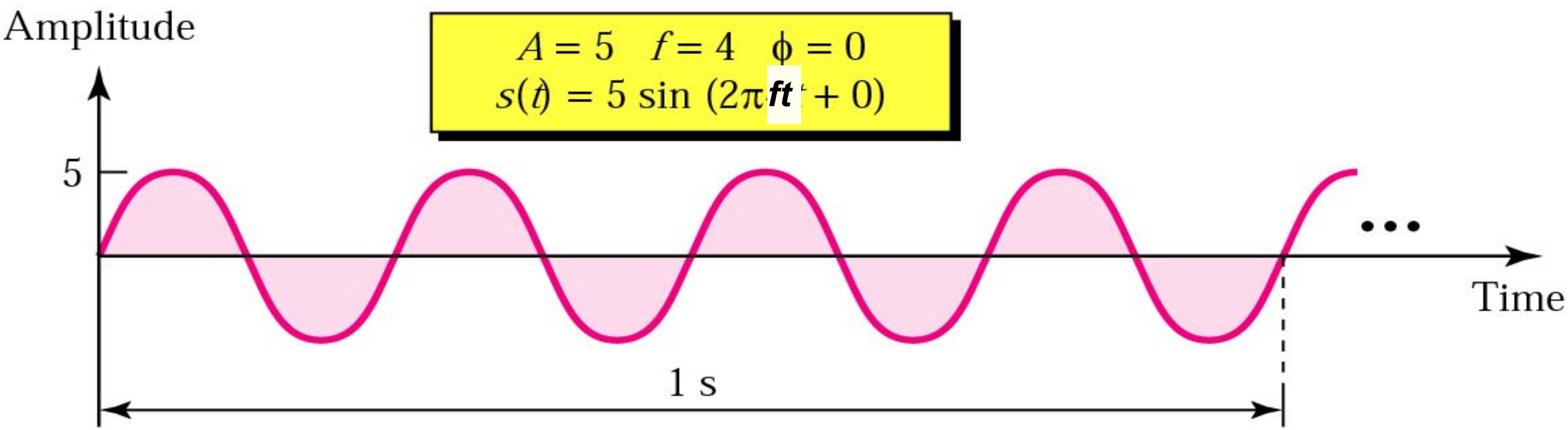
Analog signals (cont'd)

- **Example 3.6 : A sine wave is offset one-sixth of a cycle with respect to time zero. What is its phase in degrees and radians?**

- **Solution**
  - **We know that one complete cycle is 360 degrees.**
  - **Therefore, 1/6 cycle is**
  - **(1/6) 360 = 60 degrees = 60 x ($2\pi/360$) rad = 1.046 rad**

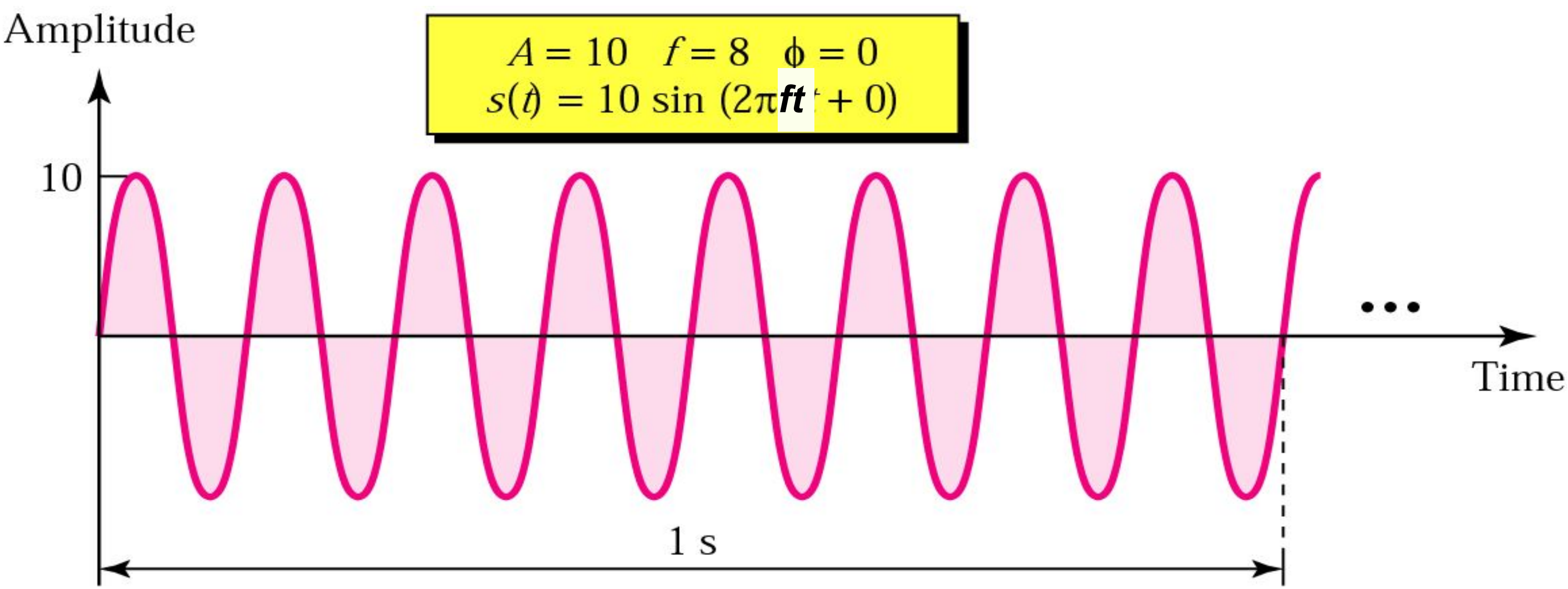
2pi radians equal to 360 degrees, thus 1 radian = 180/pi

- **Sine wave examples**



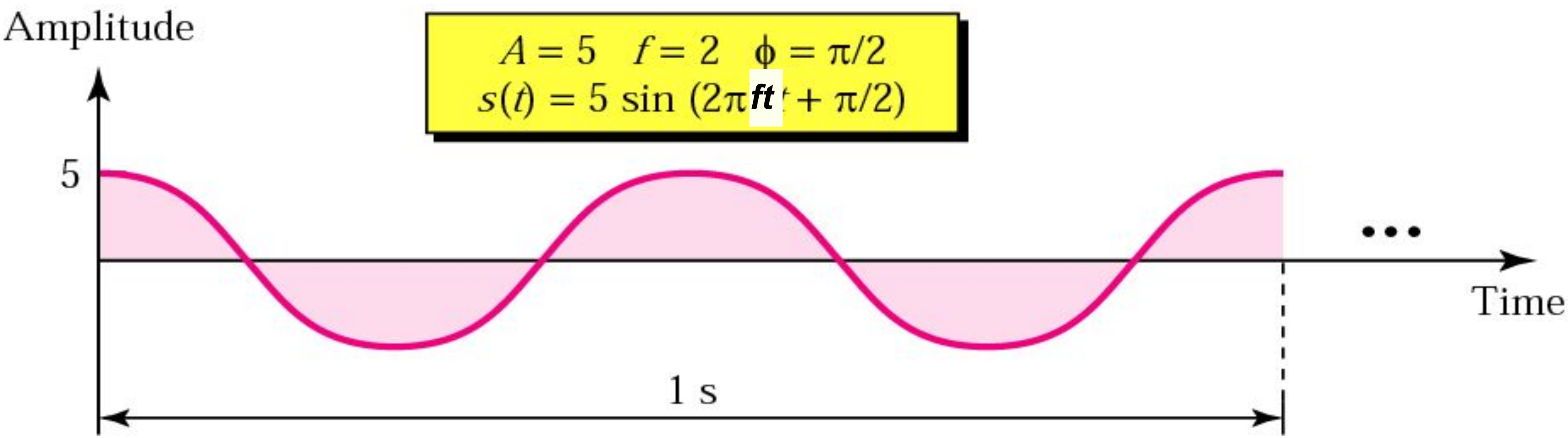
Analog signals(cont'd)

- Sine wave examples



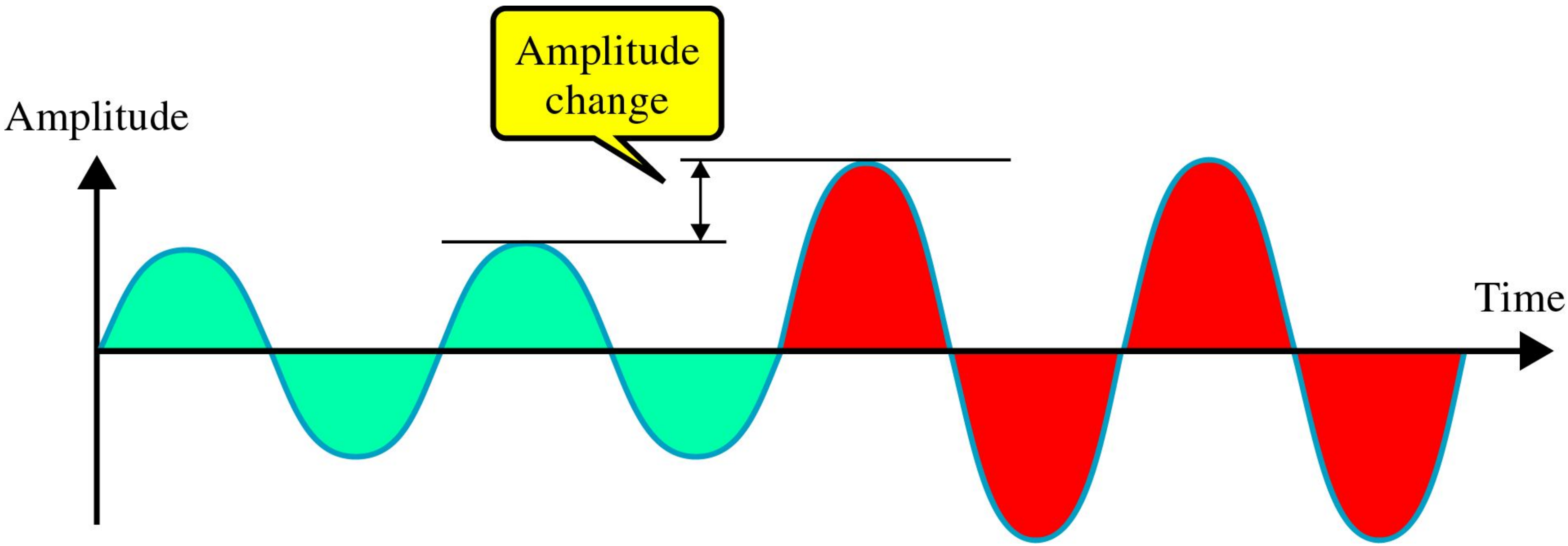
Analog Signals(cont'd)

- Sine wave examples



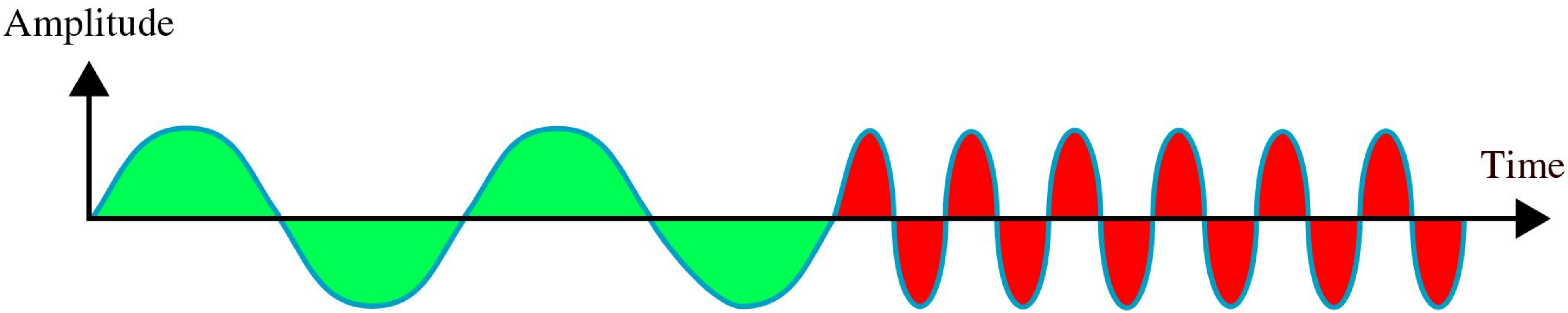
Analog signals(cont'd)

- Amplitude change



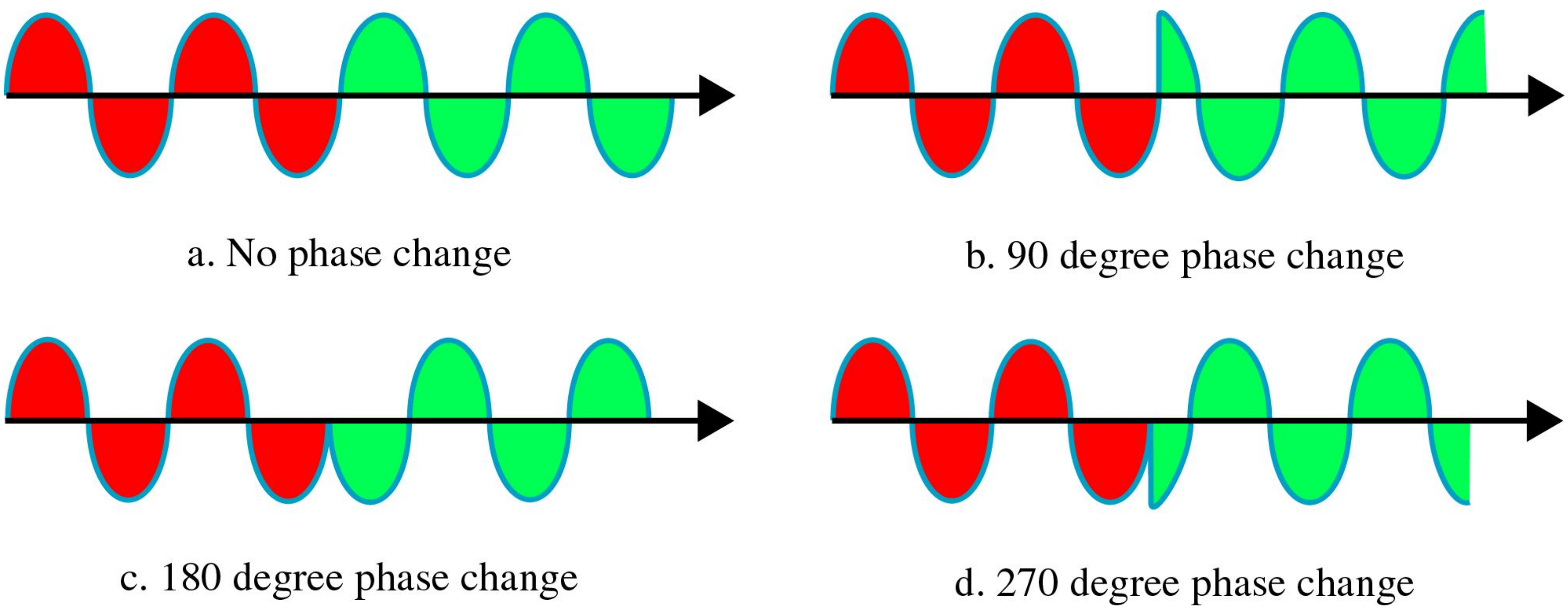
Analog signals(cont'd)

- Frequency change



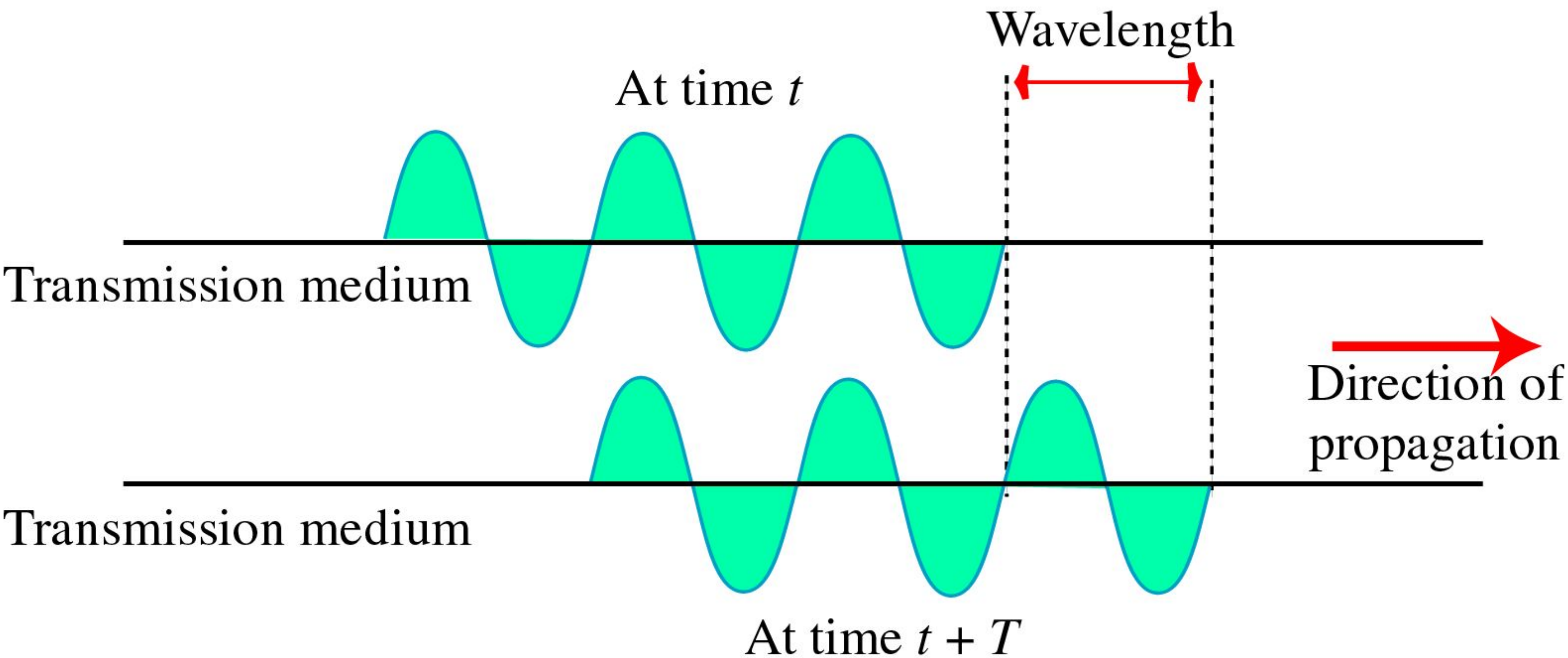
Analog signals(cont'd)

❑ Phase change



Analog signals(cont'd)

- Wavelength = Lamda = c/f (propagation speed/frequency)



Analog signals(cont'd)

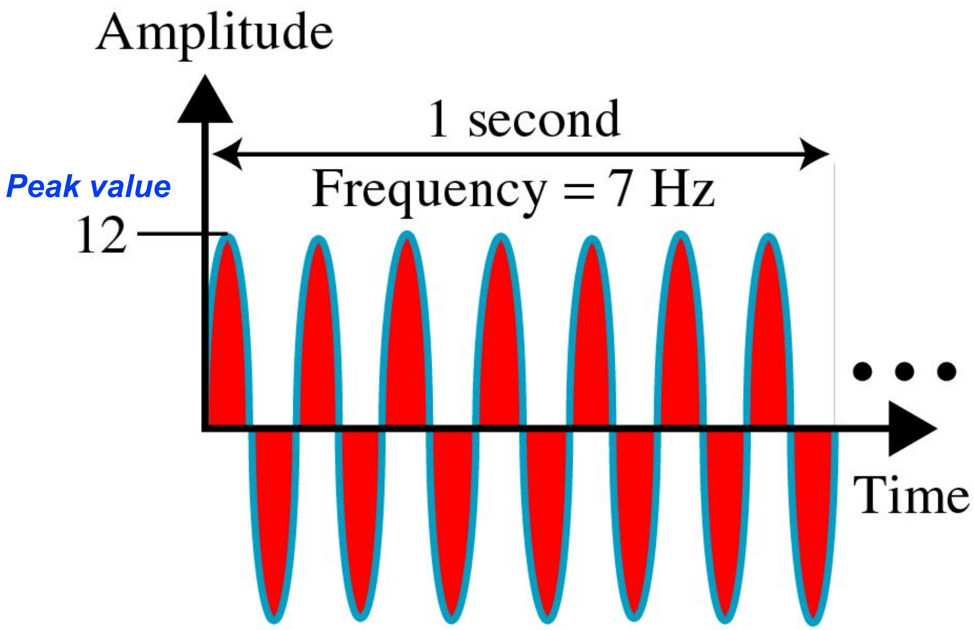
- **Time versus Frequency Domain**
  - **Time Domain : instantaneous amplitude with respect to time.**
  - **Frequency Domain : maximum amplitude with respect to frequency.**

Analog signals(cont'd)

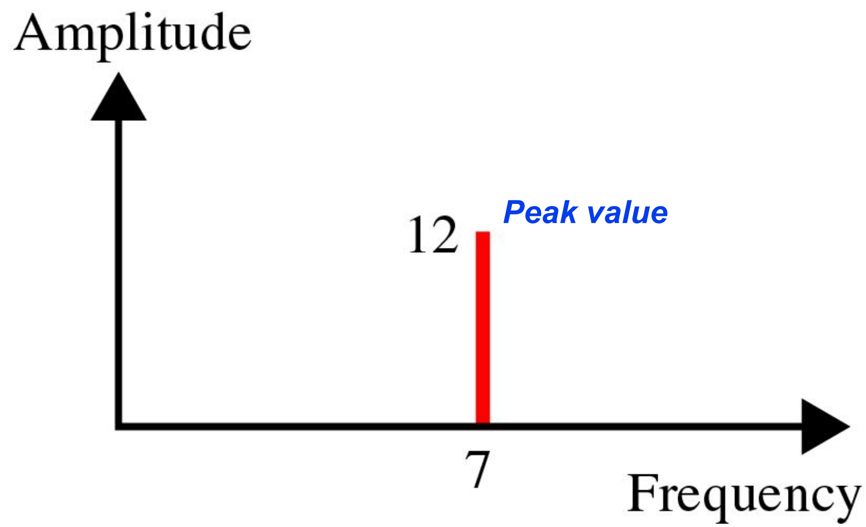
- **Time versus Frequency Domain**
  - **Time Domain : instantaneous amplitude with respect to time.**
  - **Frequency Domain : maximum amplitude with respect to frequency.**

Analog signals(cont'd)

- Time and Frequency domains



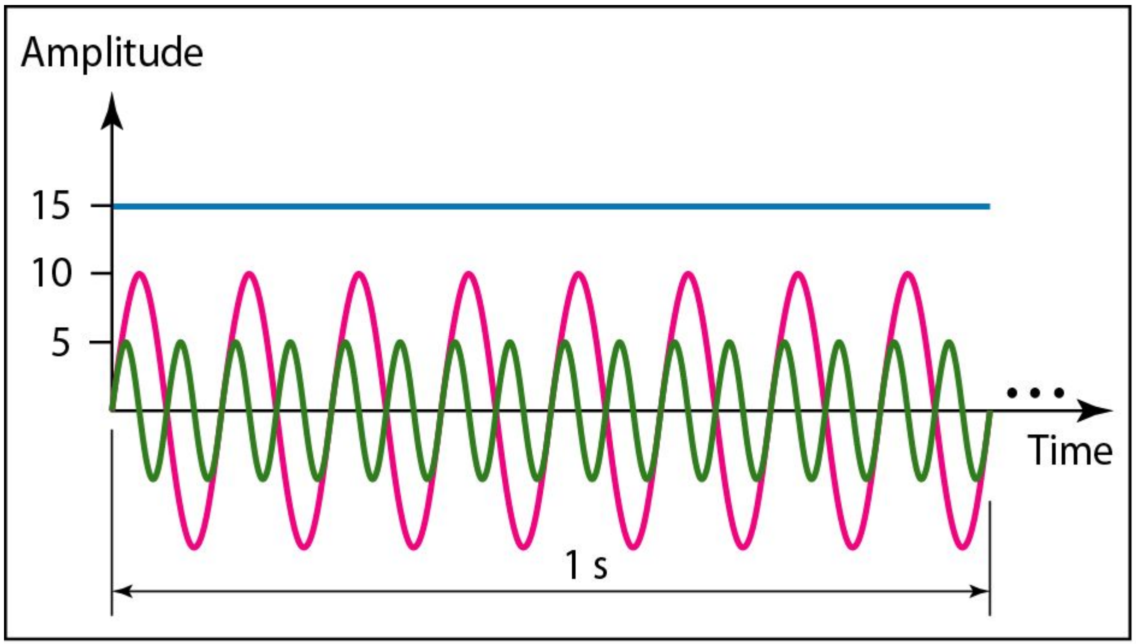
a. Time domain



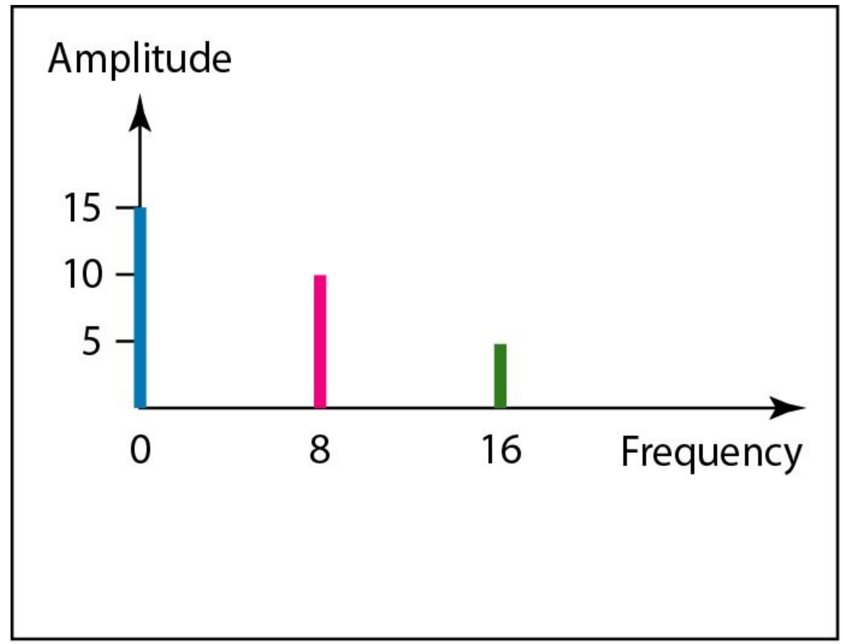
b. Frequency domain

Analog signals(cont'd)

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

Composite Signal

Composite Signal

- **A single-frequency sine wave is not useful in data communications; we need to change one or more of its characteristics to make it useful.**
- **When we change one or more characteristics of a single-frequency signal, it becomes a composite signal made of many frequencies.**

Composite Signal (cont'd)

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

- 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.

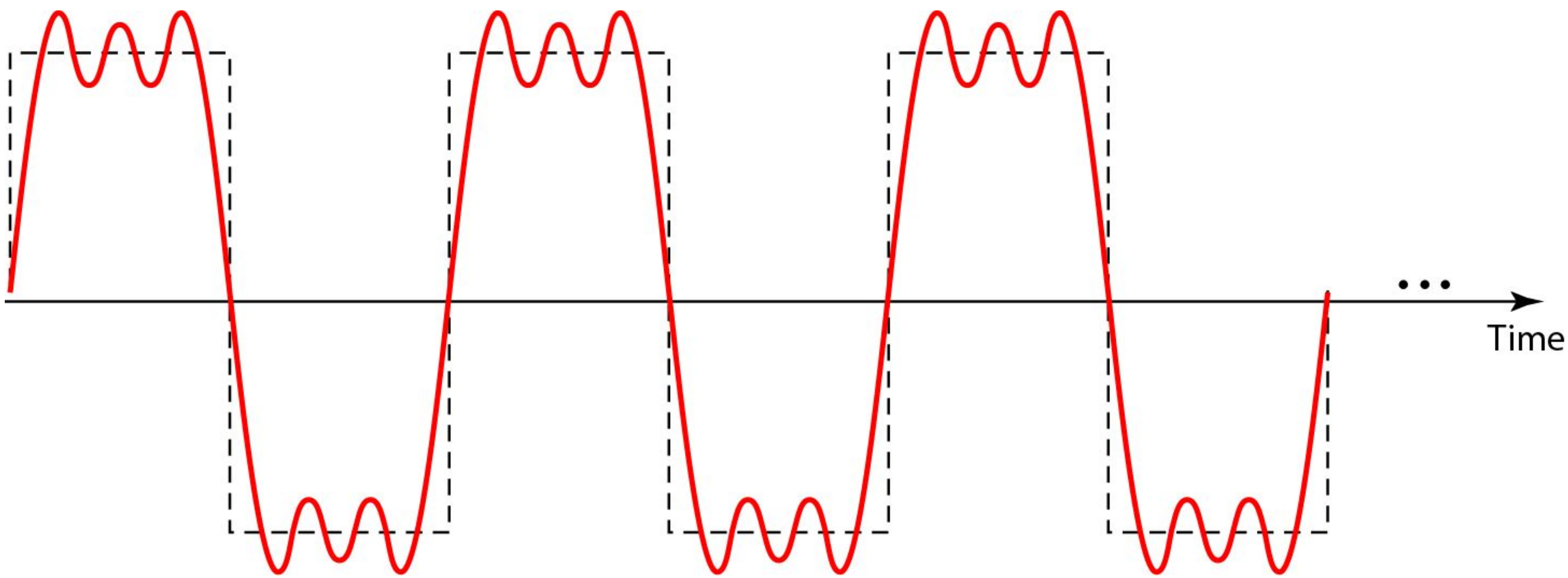
Composite Signal (cont'd)

- ***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.

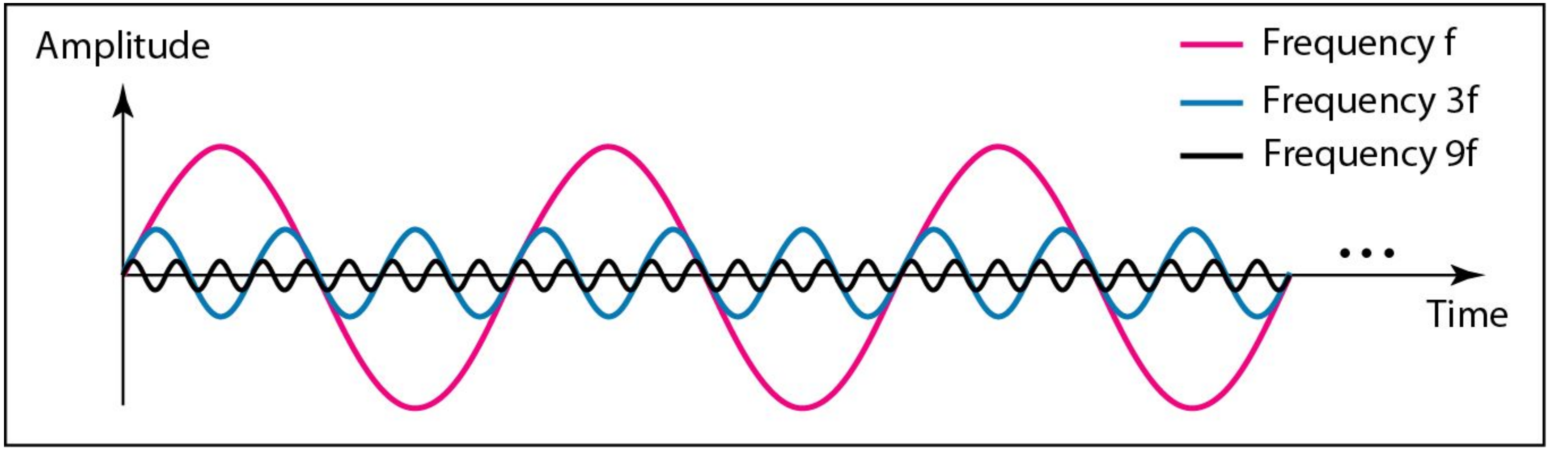
Composite Signal (cont'd)

Figure 3.9 ***A composite periodic signal***

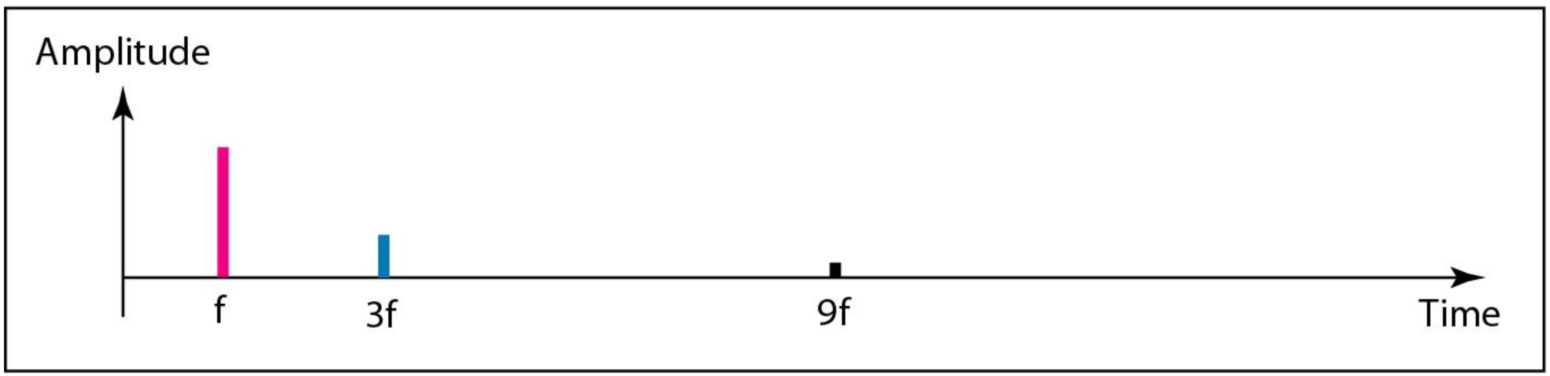


Composite Signal (cont'd)

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



a. Time-domain decomposition of a composite signal



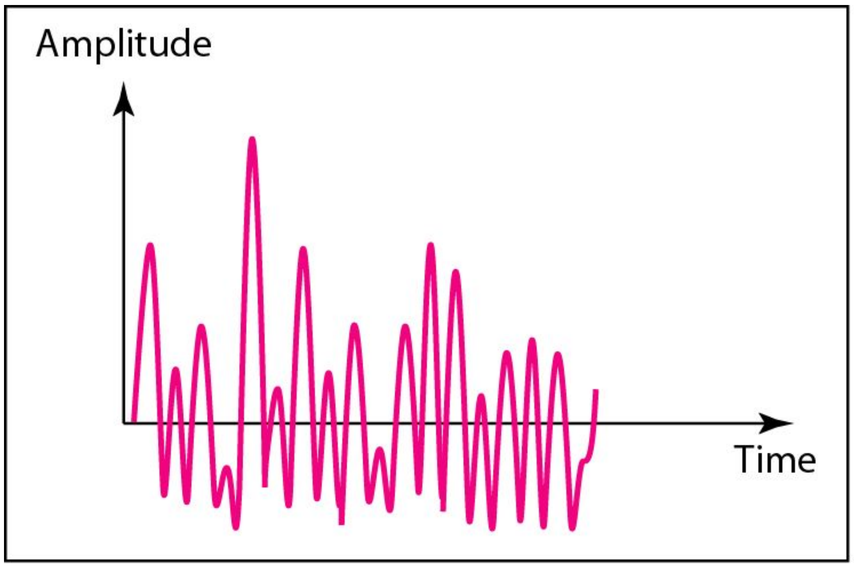
b. Frequency-domain decomposition of the composite signal

Composite Signal (cont'd)

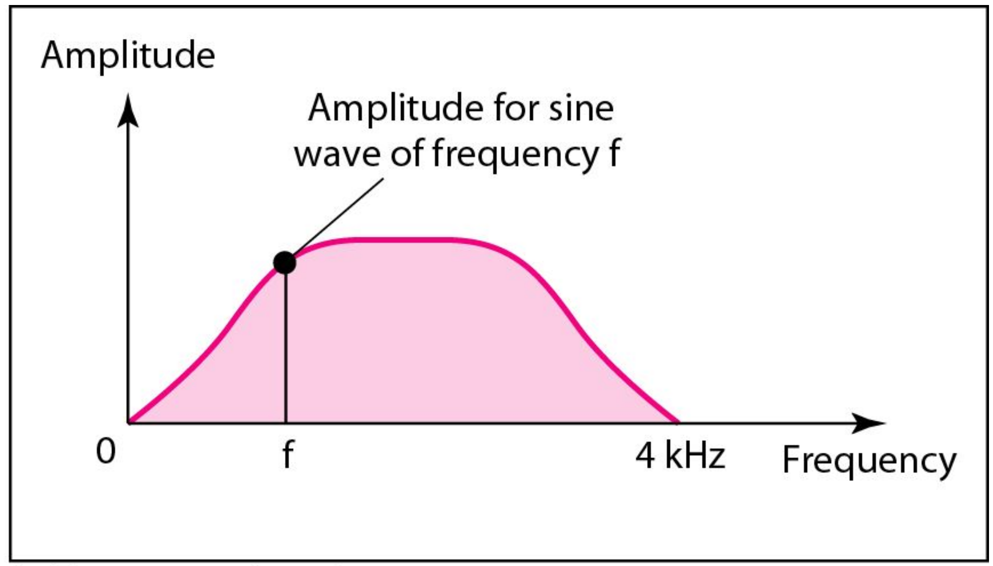
- ## *Example 3.9*

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



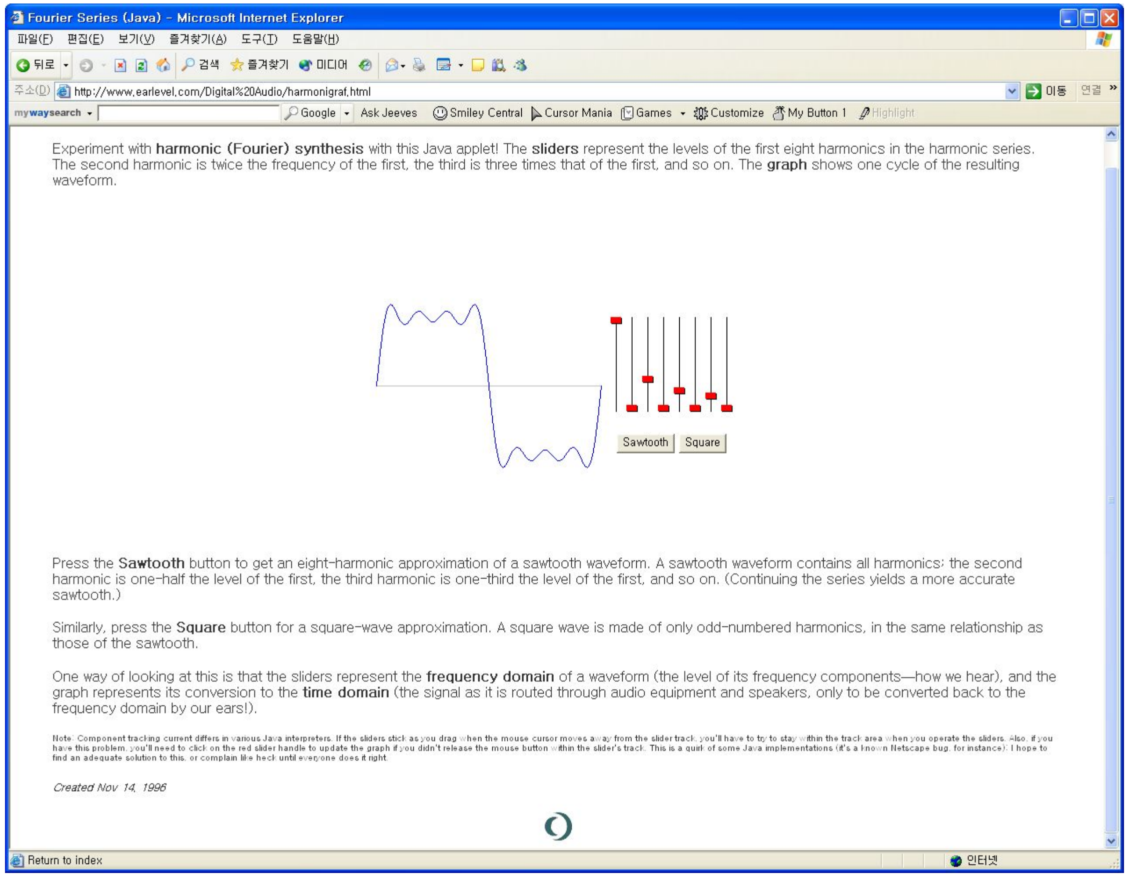
a. Time domain



b. Frequency domain

Composite Signal (cont'd)

- **An demonstration on Fourier**
  - **http://www.earlevel.com/Digital%20Audio/harmonigraf.html**



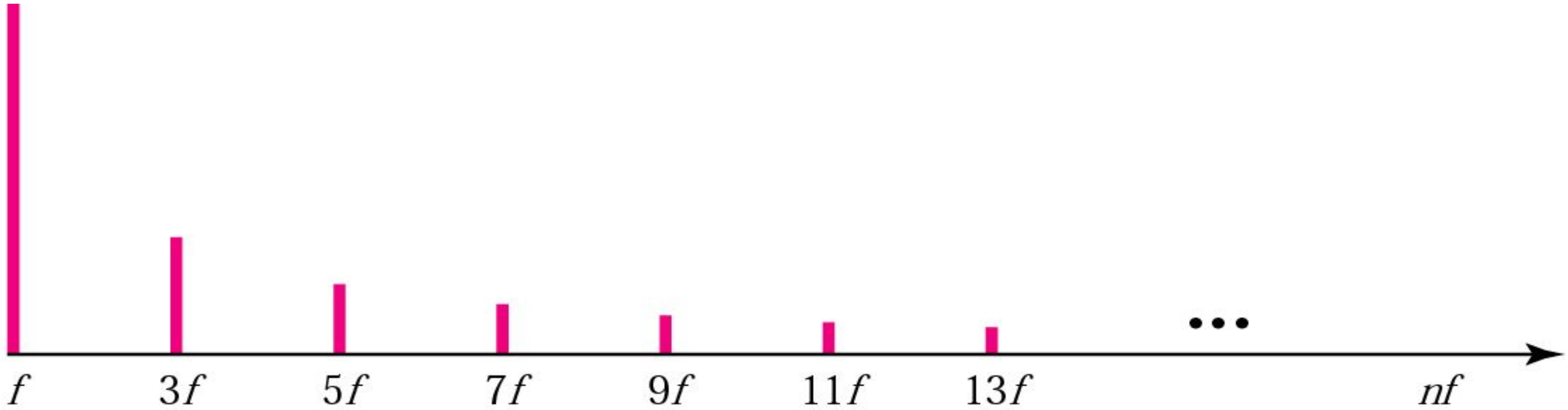
Bandwidth

Frequency Spectrum and Bandwidth

- The frequency spectrum of a signal is the combination of all sine wave signals that make signal.
- The bandwidth of a signal is the width of the frequency spectrum
  - The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.

Bandwidth (cont'd)

- Frequency Spectrum

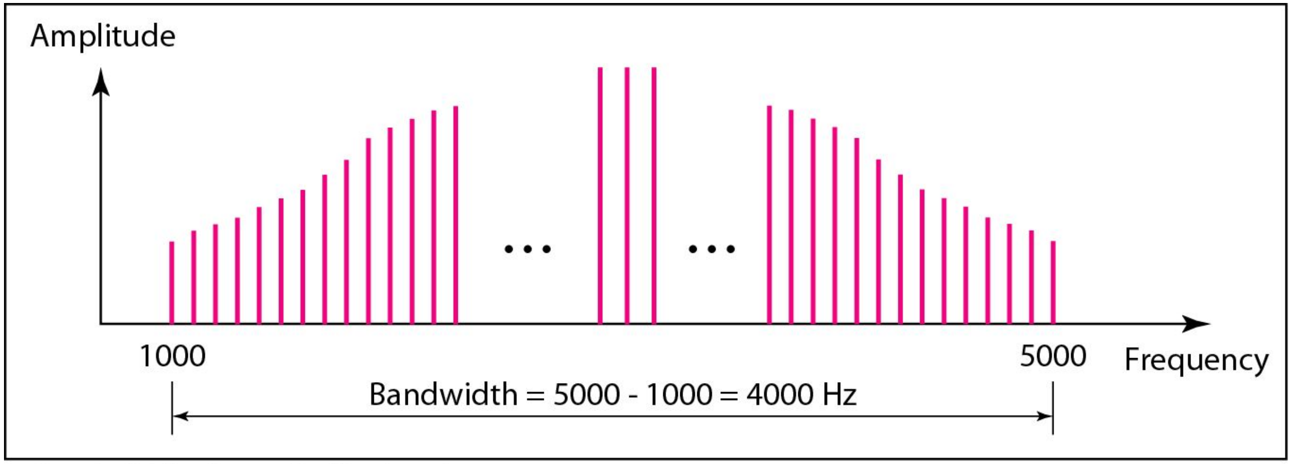


a. Frequency spectrum of a square wave

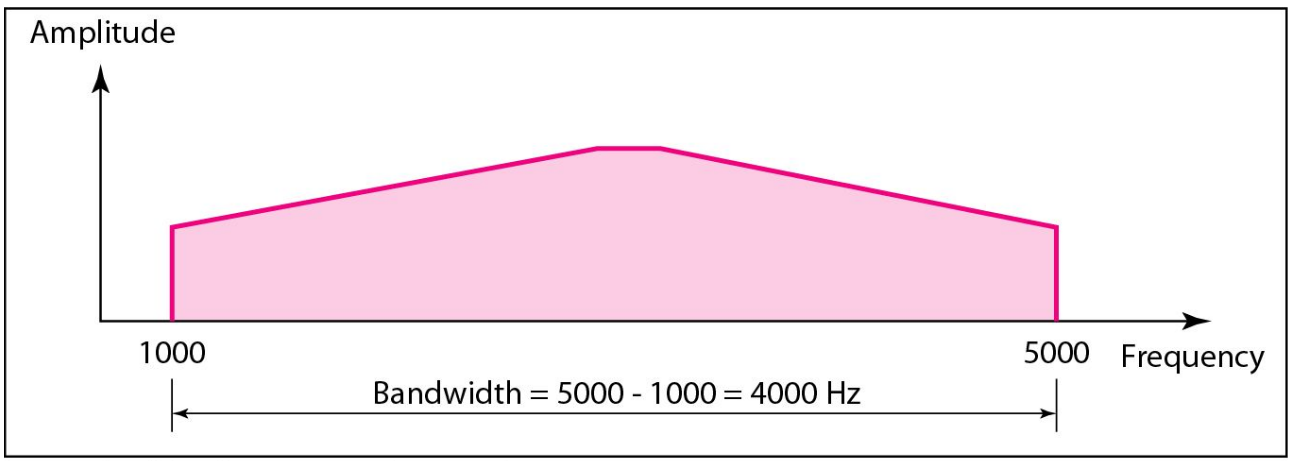
b. Frequency spectrum of an approximation with only three harmonics

Bandwidth (cont'd)

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



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

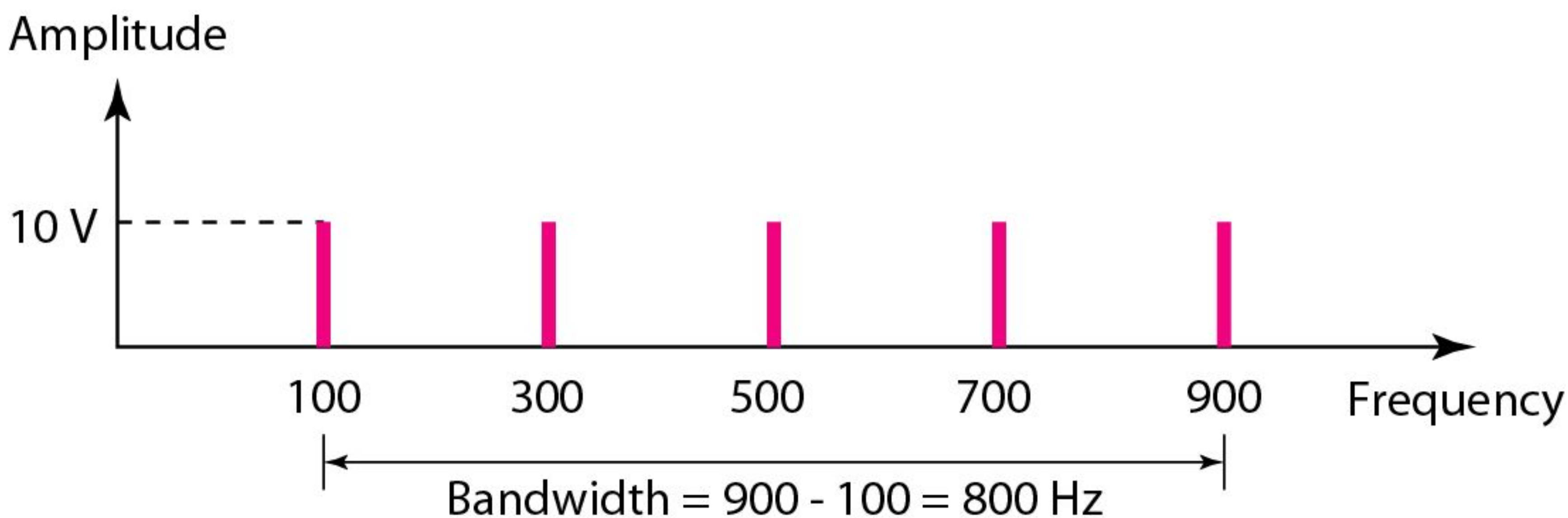
Bandwidth (cont'd)

- ***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.

Bandwidth (cont'd)

Figure 3.13 ***The bandwidth for Example 3.10***

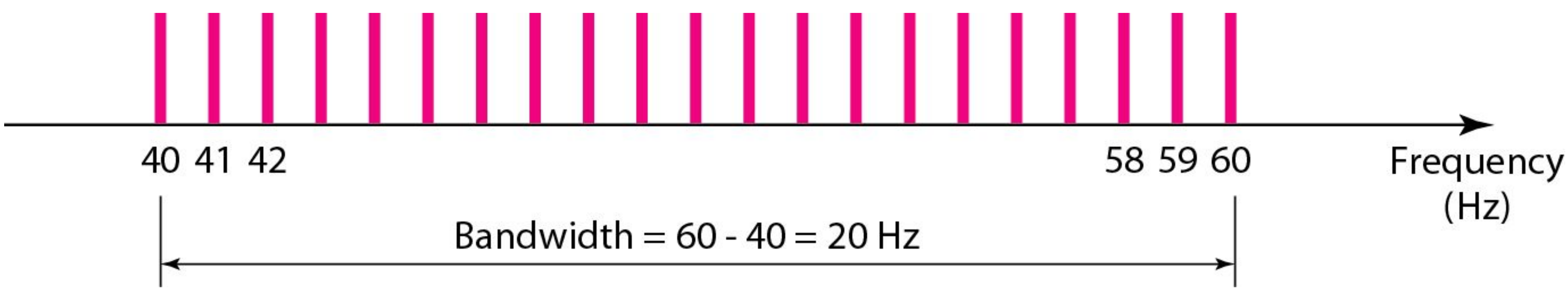


Bandwidth (cont'd)

- ***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.

Figure 3.14 *The bandwidth for Example 3.11*



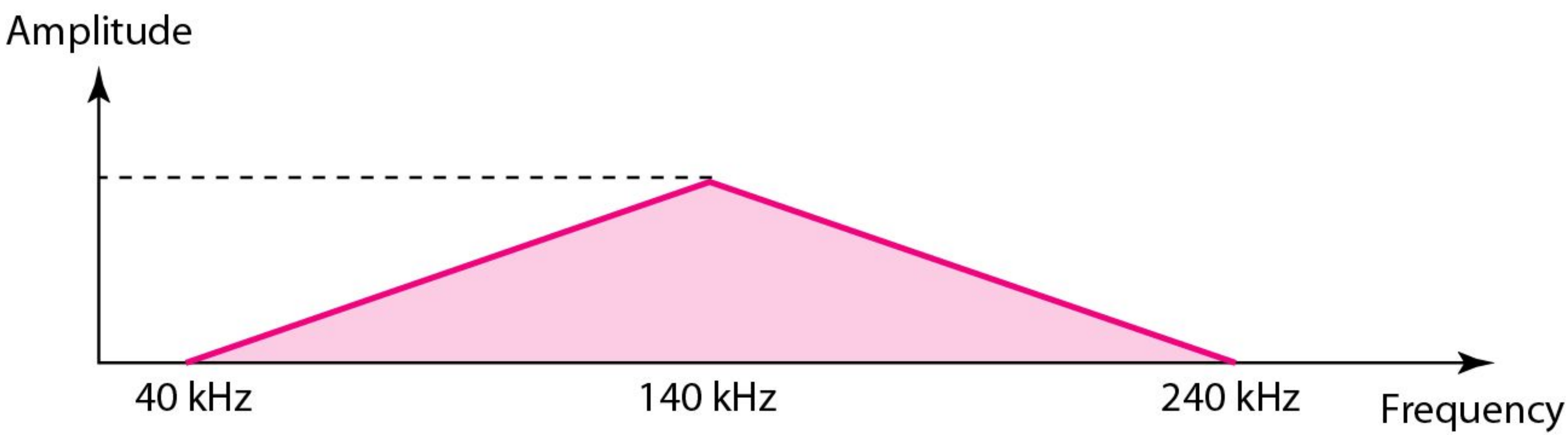
Bandwidth (cont'd)

- ***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.

Bandwidth (cont'd)

Figure 3.15 *The bandwidth for Example 3.12*



3.3 DIGITAL SIGNALS

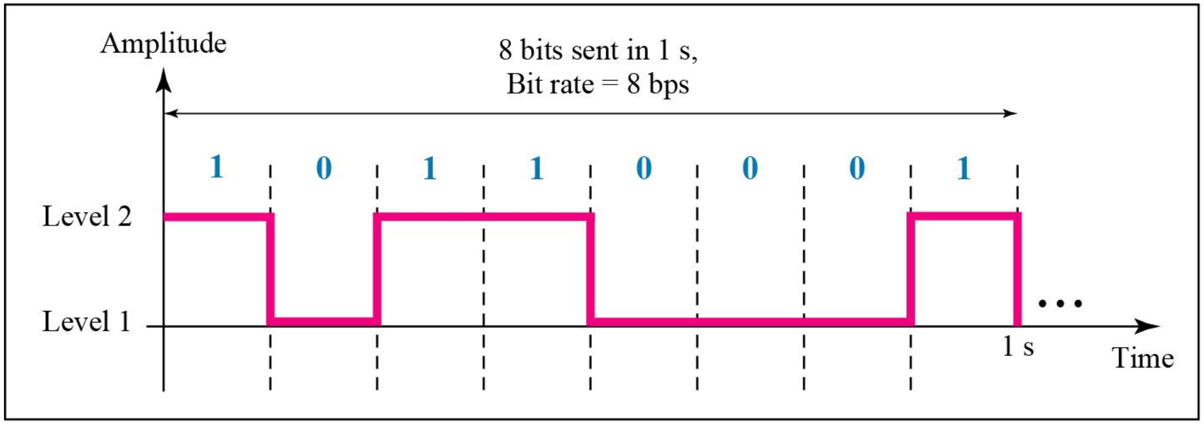
In addition to being represented by an analog signal, information can also be represented by a digital signal. For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level.

Topics discussed in this section:

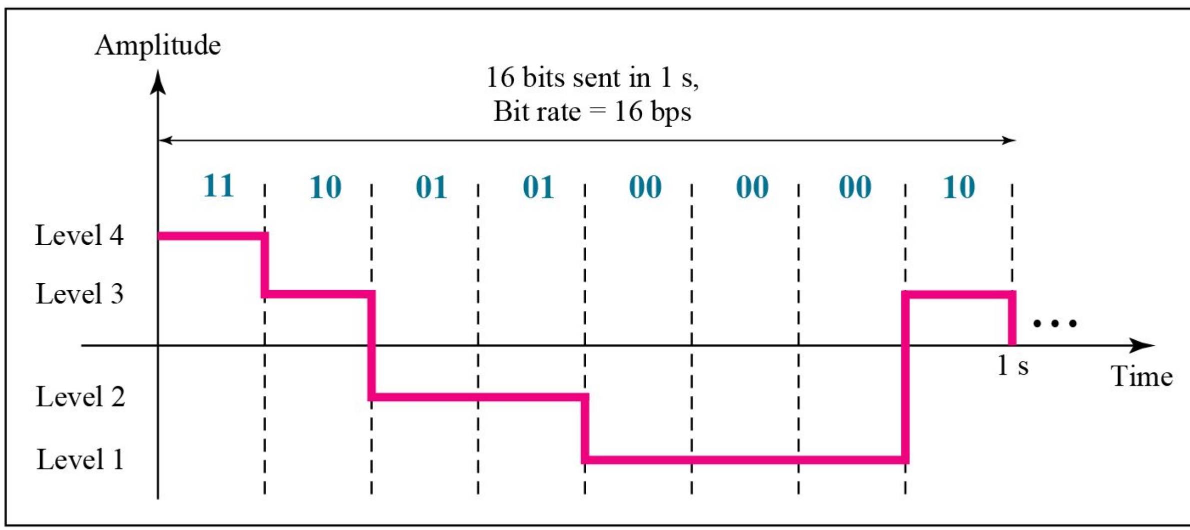
Bit Rate
Bit Length
Digital Signal as a Composite Analog Signal
Application Layer

Digital Signals

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

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

Each signal level is represented by 3 bits.

- ***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

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

Digital Signals (cont'd)

- ***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.

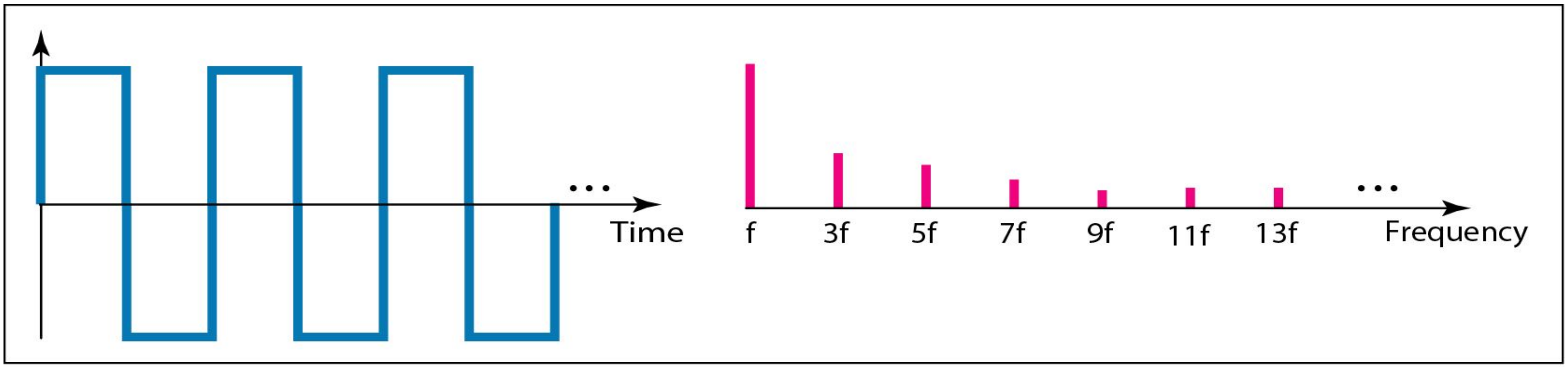
Digital Signals (cont'd)

Bit Length

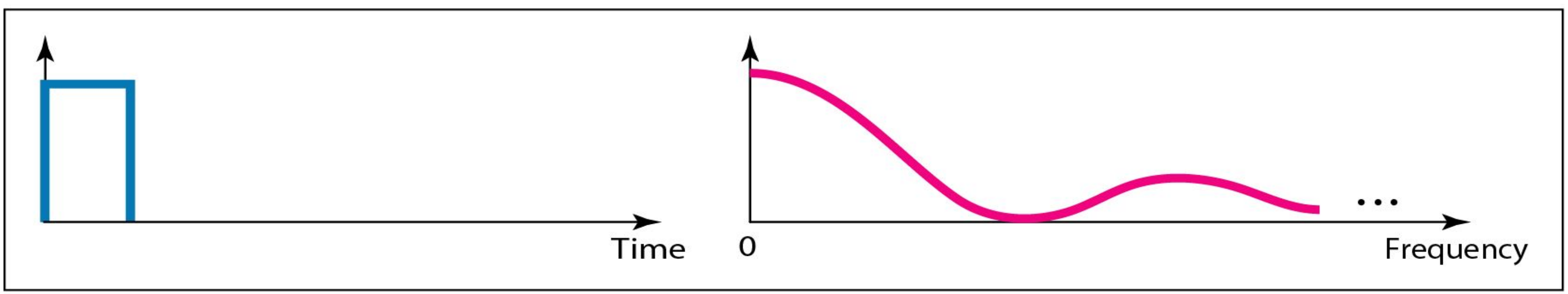
- **Bit Length = propagation speed x bit duration**

Digital Signal as a Composite Analog Signal

Figure 3.17 ***The time and frequency domains of periodic and nonperiodic digital signals***



a. Time and frequency domains of periodic digital signal

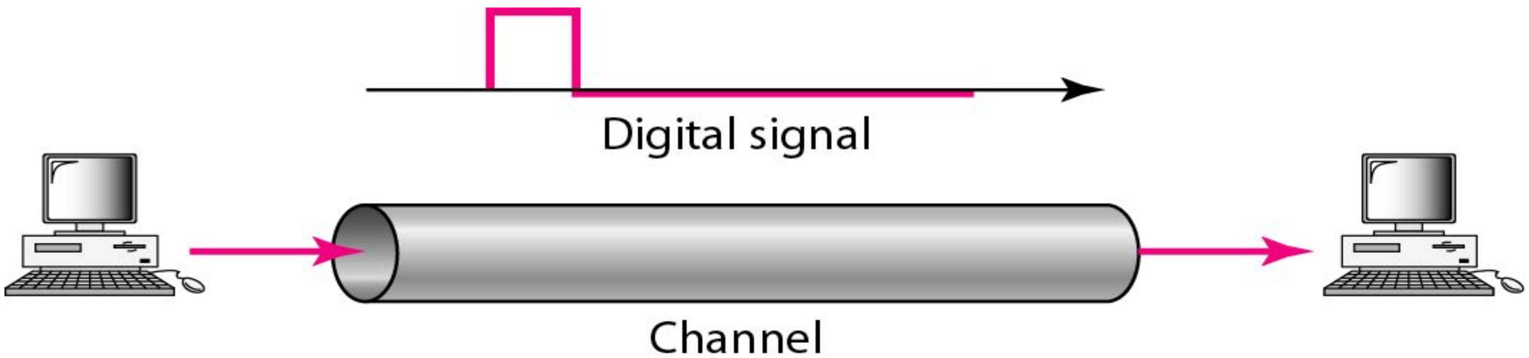


b. Time and frequency domains of nonperiodic digital signal

Transmission of Digital Signals

- Transmission types of digital signals :
  - Baseband and Broad-band transmission

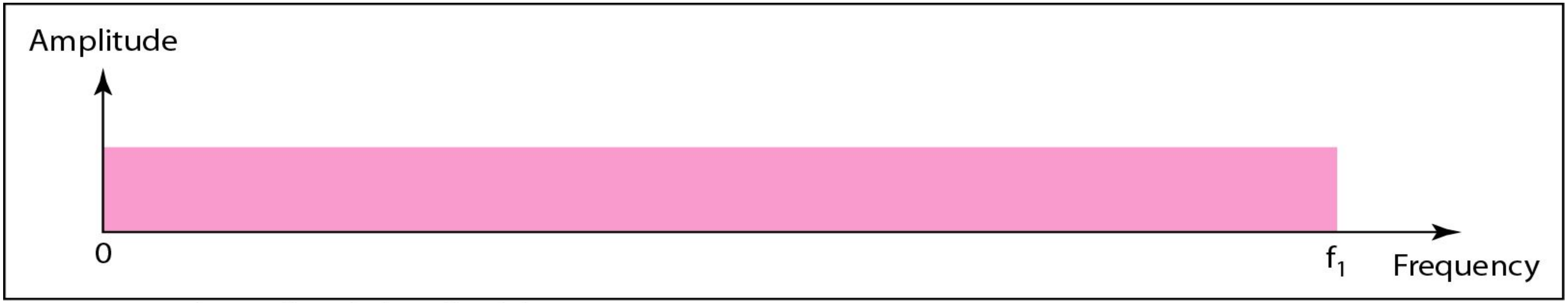
Figure 3.18 ***Baseband transmission***



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

Transmission of Digital Signals (cont'd)

Figure 3.19 ***Bandwidths of two low-pass channels***



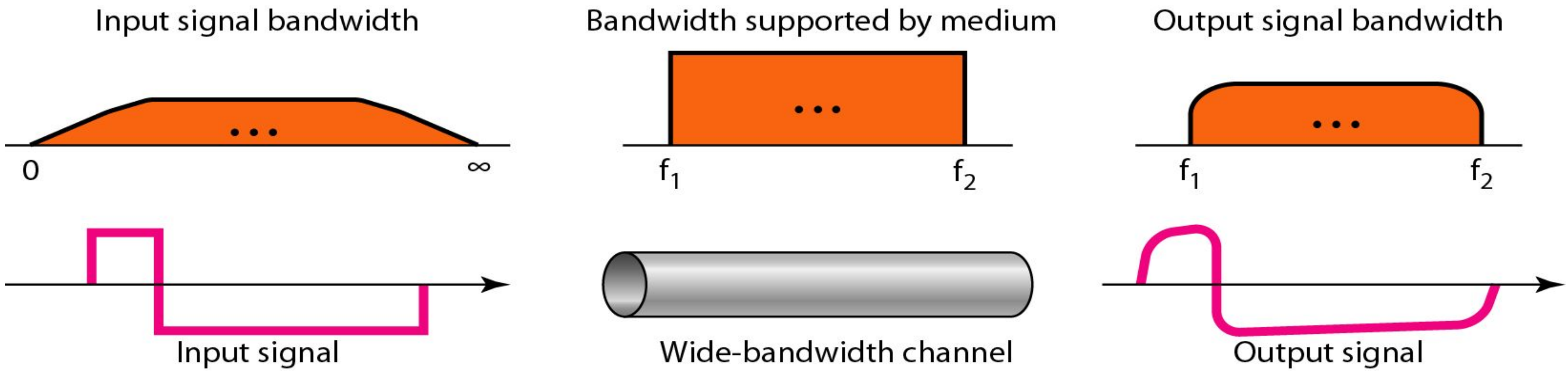
a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

Transmission of Digital Signals (cont'd)

- Low-Pass Channel with Wide Bandwidth

Figure 3.20 ***Baseband transmission using a dedicated medium***

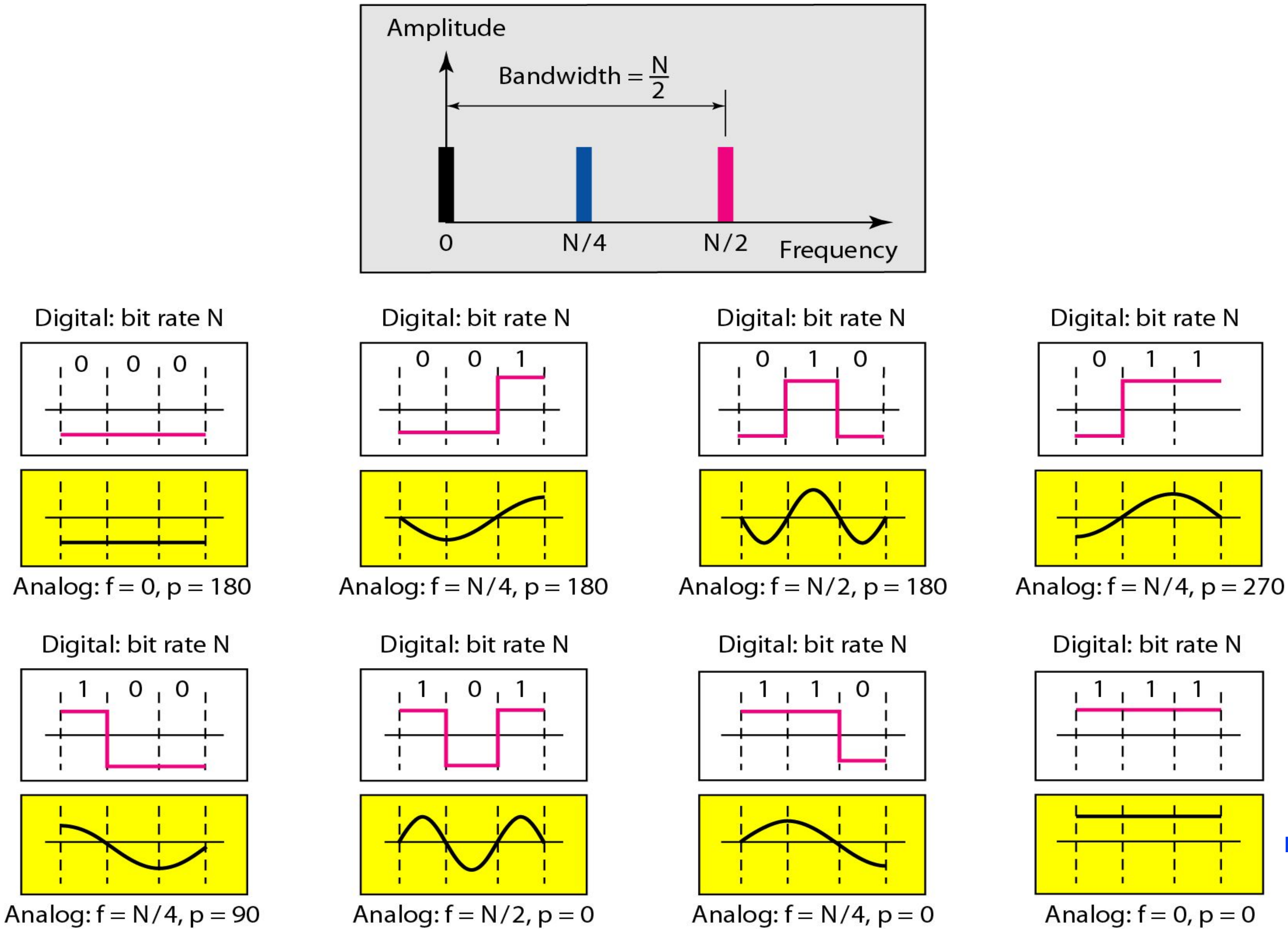


Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.

Transmission of Digital Signals (cont'd)

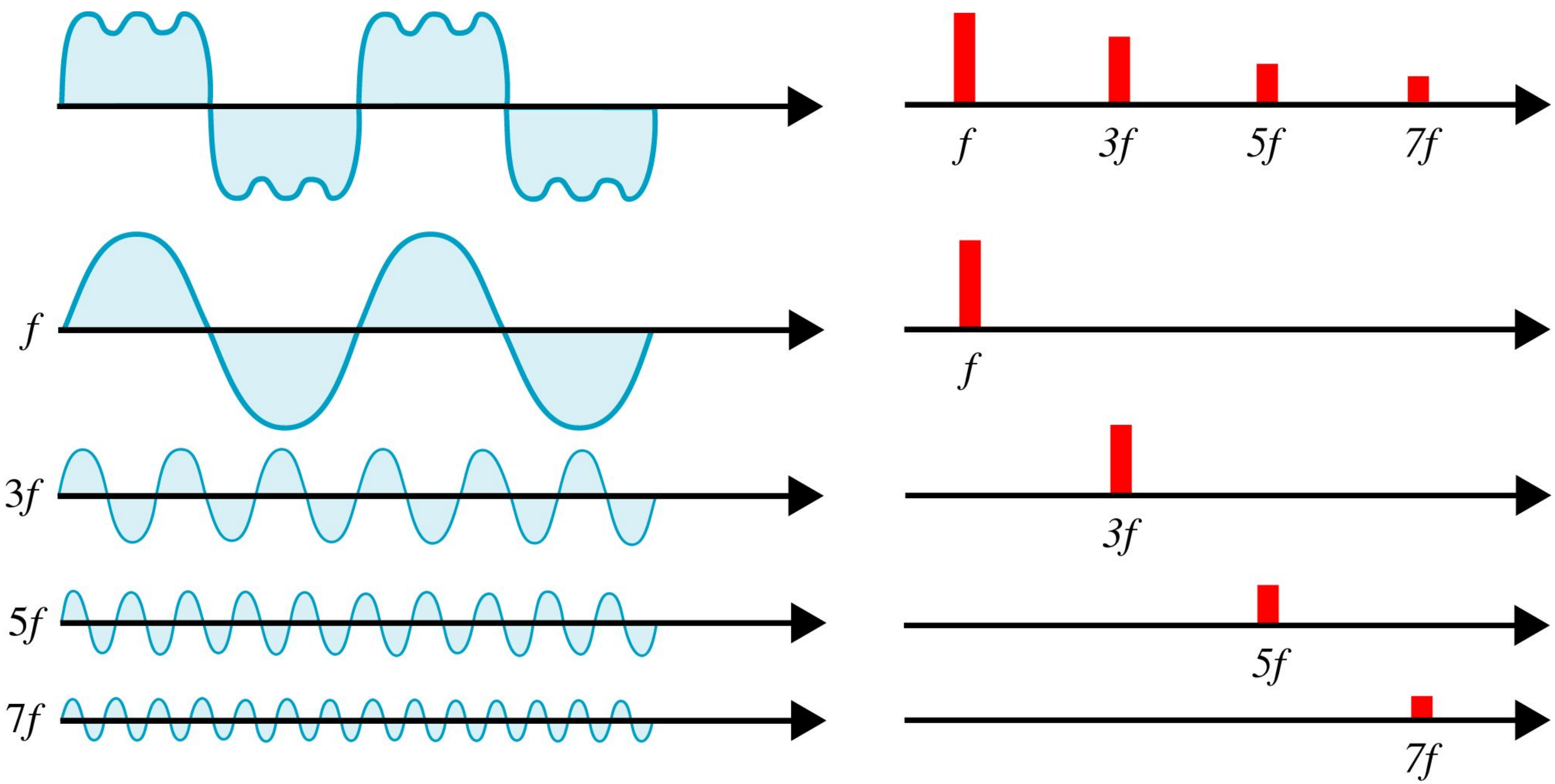
- **Loss-Pass Channel with Limited Bandwidth**

Figure 3.21 *Rough approximation of a digital signal using the first harmonic for worst case*



Transmission of Digital Signals (cont'd)

- Complex waveform

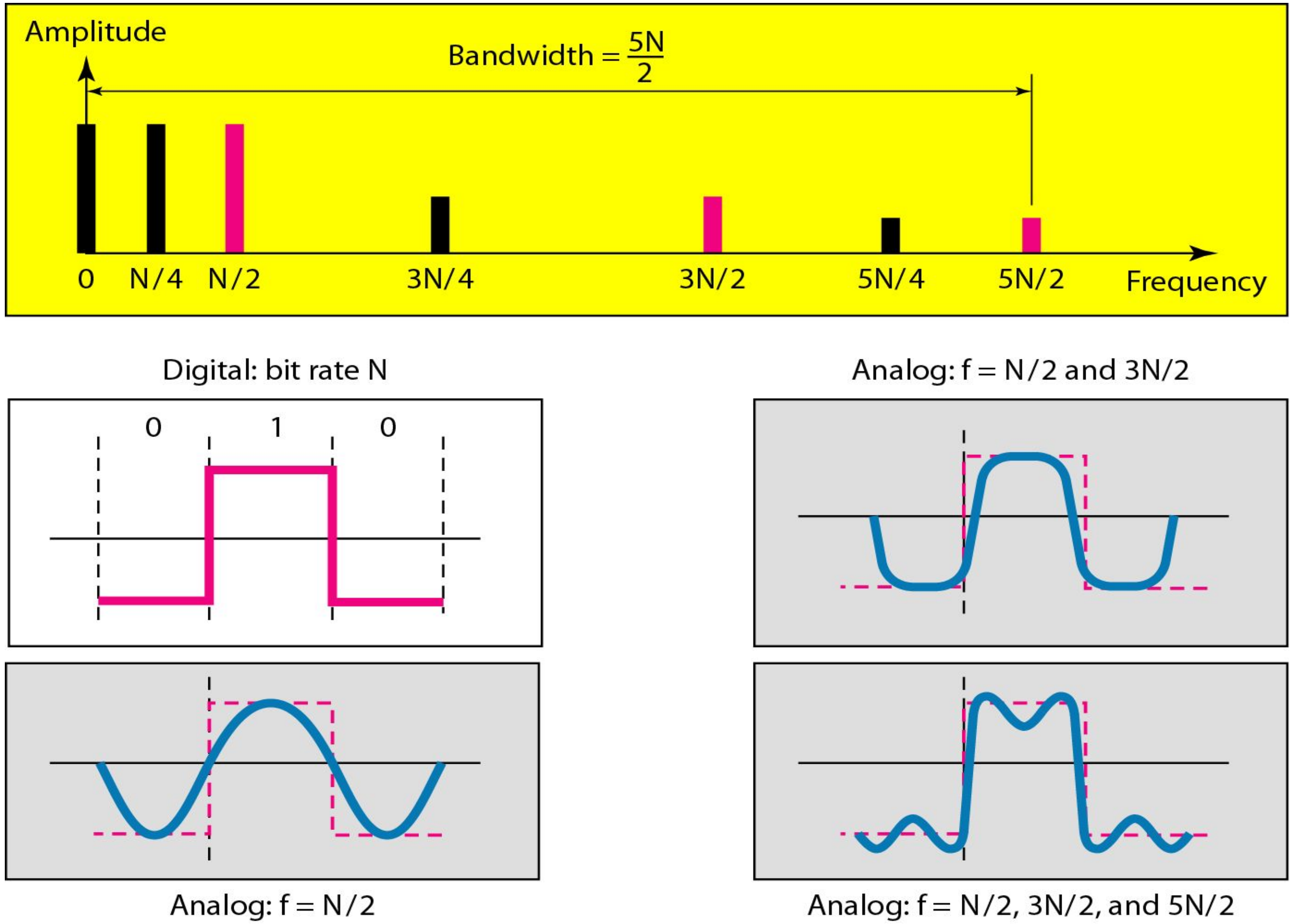


a. Time domain

b. Frequency domain

Transmission of Digital Signals (cont'd)

Figure 3.22 ***Simulating a digital signal with first three harmonics***



Transmission of Digital Signals (cont'd)

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

Transmission of Digital Signals (cont'd)

Table 3.2 ***Bandwidth requirements***

Bit Rate	*Harmonic 1*	*Harmonics 1, 3*	*Harmonics 1, 3, 5*
$n = 1$ kbps	$B = 500$ Hz	$B = 1.5$ kHz	$B = 2.5$ kHz
$n = 10$ kbps	$B = 5$ kHz	$B = 15$ kHz	$B = 25$ kHz
$n = 100$ kbps	$B = 50$ kHz	$B = 150$ kHz	$B = 250$ kHz

B = n/2 **B = 3n/2** **B = 5n/2**

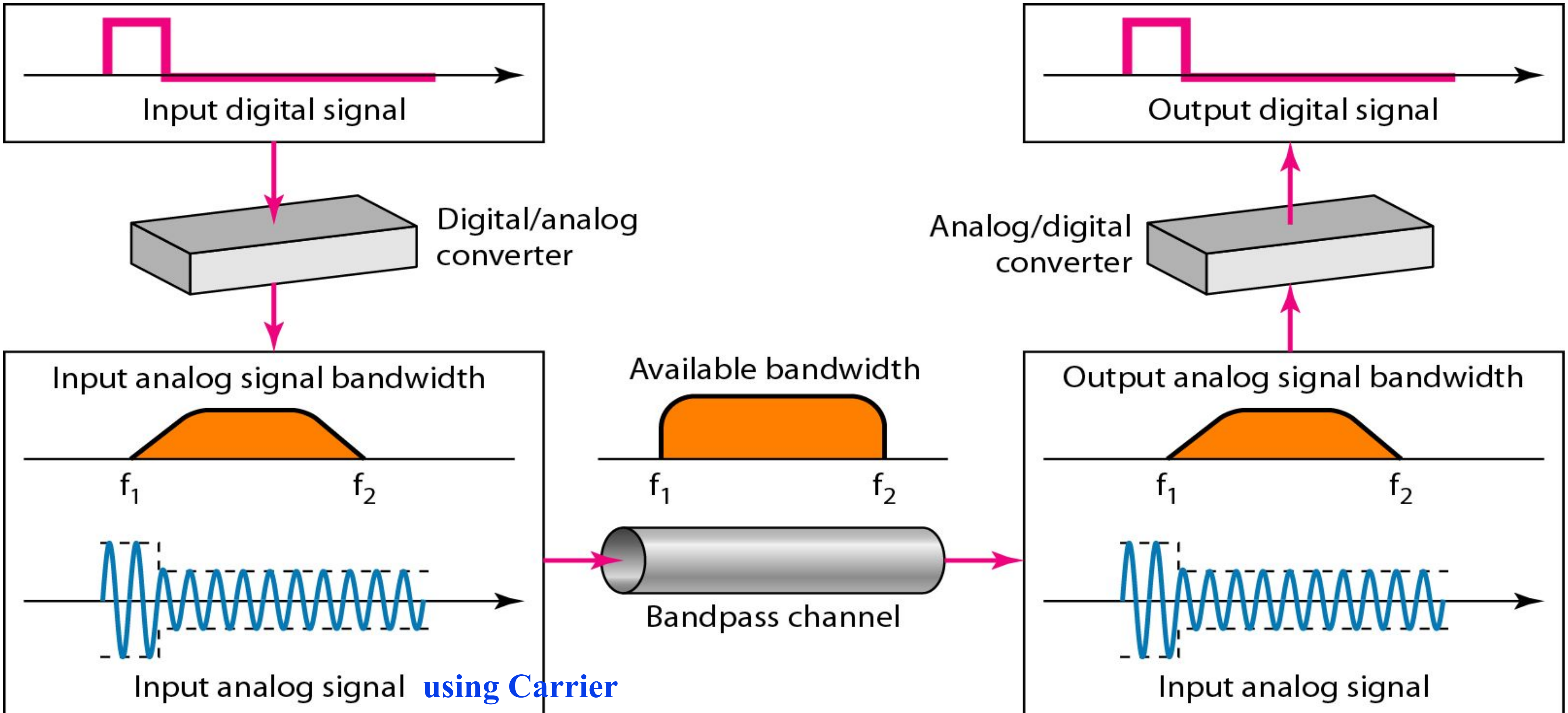
Broadband Transmission (Using Modulation)

Figure 3.23 *Bandwidth of a bandpass channel*

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.

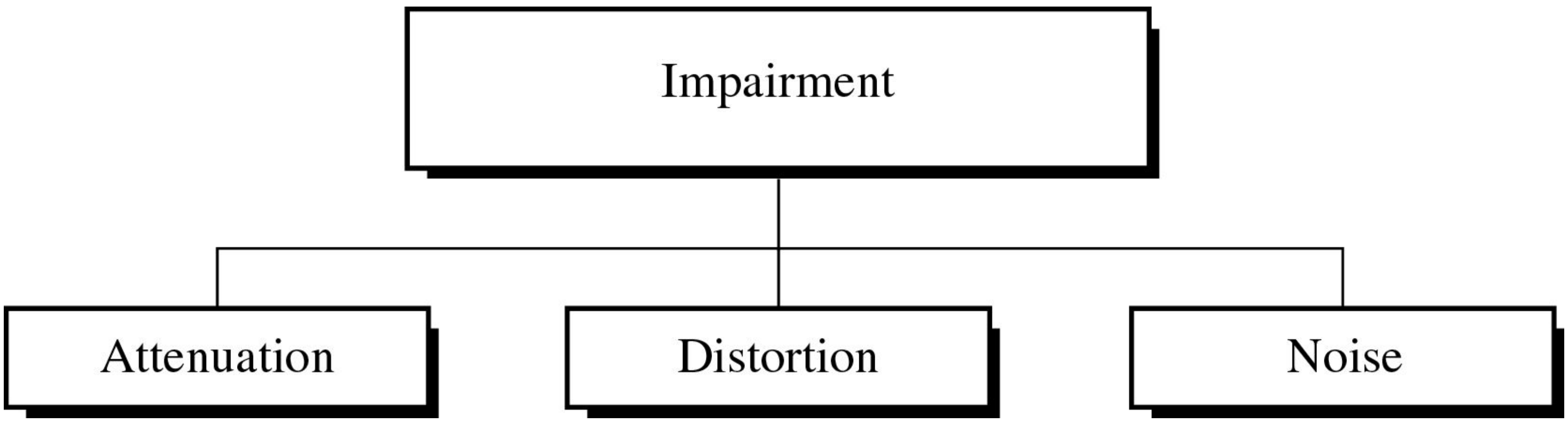
Broadband Transmission (Using Modulation)

Figure 3.24 *Modulation of a digital signal for transmission on a bandpass channel*



3.4 TRNSMISSION IMPAIRMENT

- Transmission media are not perfect because of impairment in the signal sent through the medium
  - Signal at the beginning and end of the medium are not same

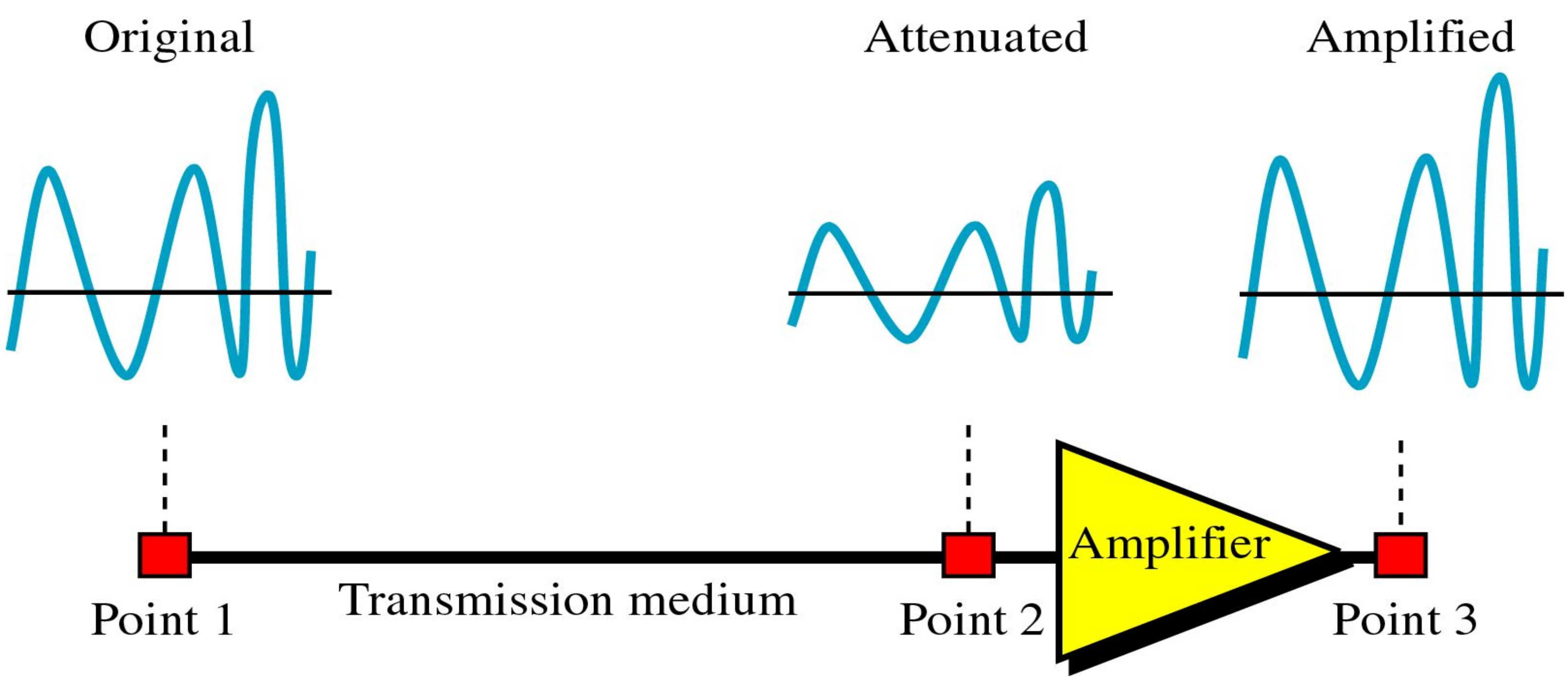


Transmission Impairment

- **Attenuation**
  - means loss of energy
  - When signal travels trough a medium, it losses some of it's energy
  - So, to compensate for this loss, amplifiers are used to amplify the signal
- **Decibel (dB)**
  - $dB = 10 \log_{10} (p_2/p_1)$

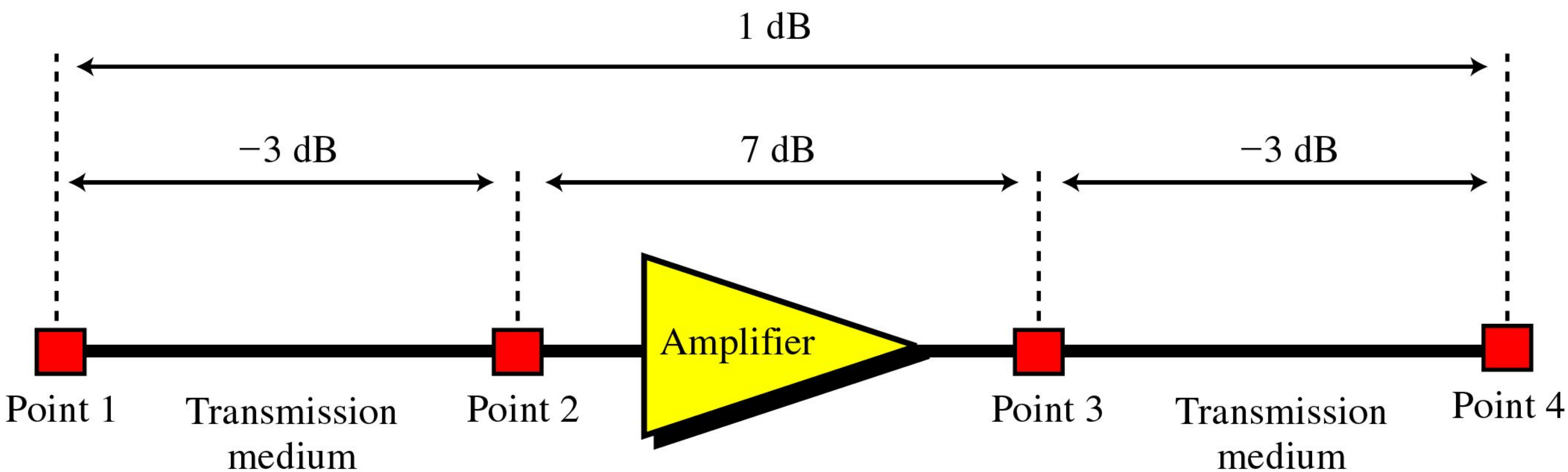
Transmission Impairment

- If signal power is reduced to one-half.
  - $p_2 = (1/2)\ p_1 \rightarrow 10 \log_{10} 0.5P_1 / p_1 = 10 \log_{10} 0.5 = -3$ dB
- If signal power is increased 10 times by AMP
  - $p_2 = (10)\ p_1 \rightarrow 10 \log_{10} 10P_1 / p_1 = 10 \log_{10} 10 = 10$ dB



Transmission Impairment

- dB at point 4 = -3 + 7-3 = +1



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 $dB_m = 10 \log_{10} P_m$, 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

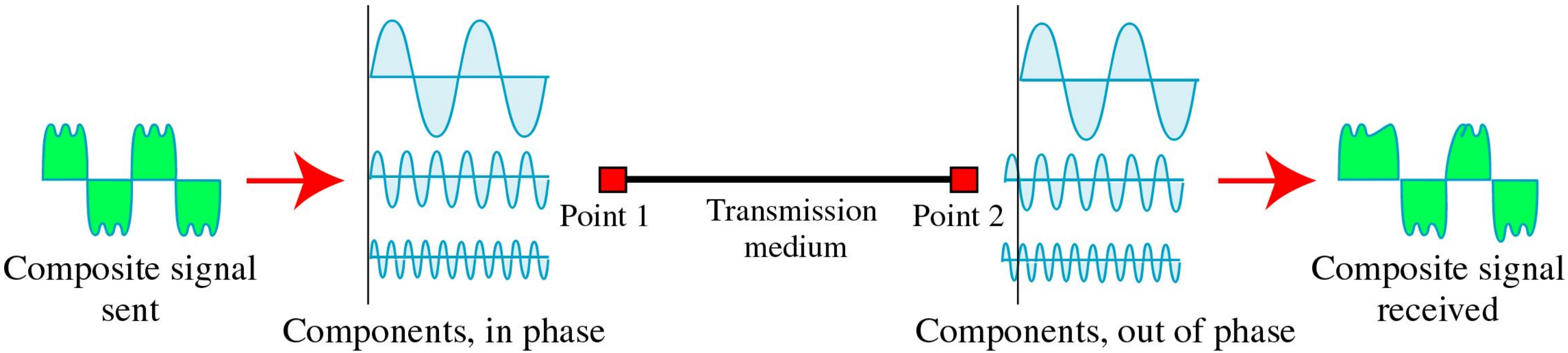
$$\mathrm{dB_m} = 10 \log_{10} P_m = -30$$

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

Transmission Impairment

Distortion

- **Means that signal changes its form or shape**



Transmission Impairment

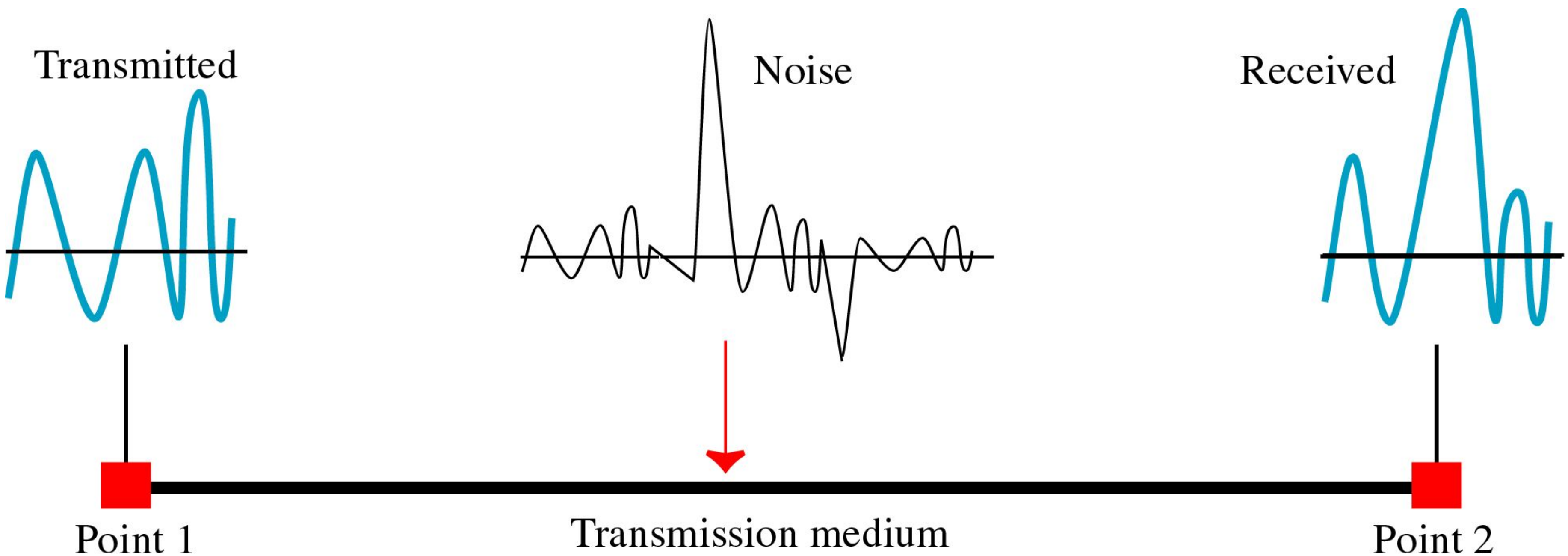
- **Noise**

  - Noise types

  - thermal noise, induced noise, crosstalk and impulse noise
  - Thermal noise : random motion of electrons
  - Induced noise : from sources such as motors, appliances
  - Crosstalk : the effect of one wire on the other
  - Impulse noise : a spike that comes from power lines, lightning, and so on.

Transmission Impairment

- noise



Signal to Noise Ratio

- SNR= average signal power / average noise power
- $SNR_{dB} = 10 \log_{10} SNR$

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:

$$SNR = \frac{10{,}000\ \mu W}{1 uW} = 10{,}000$$

$$SNR_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

Signal to Noise Ratio

Example 3.32

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

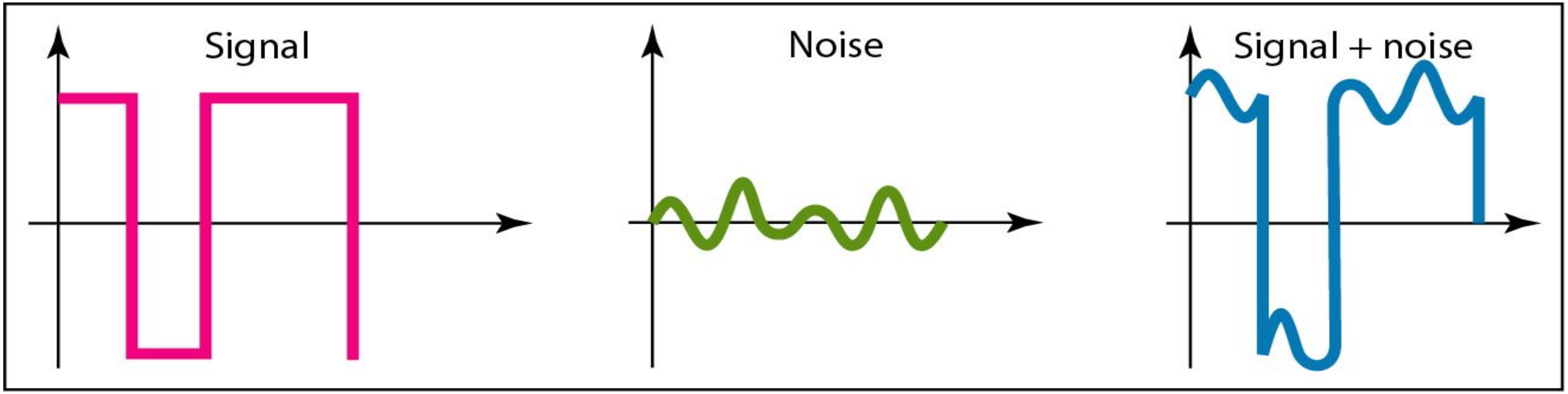
$$SNR = \frac{\text{signal power}}{0} = \infty$$

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

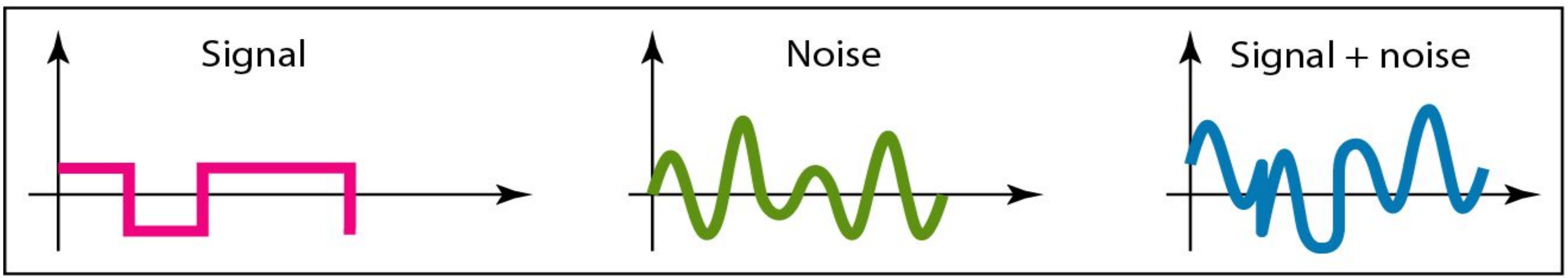
We can never achieve this ratio in real life; it is an ideal.

Signal to Noise Ratio

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



a. Large SNR



b. Small SNR

3.5 DATA RATE LIMITS

- Data rate depends on three factors
  1. The available bandwidth
  2. The levels of signals we can use
  3. The quality of the channel (the level of the noise)

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

- Noiseless channel : Nyquist Bit Rate
  - Bit Rate = 2 x Bandwidth x $\log_2 L$

  L : number of signal levels

- 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

    Bit Rate = $2 \times 3000 \times \log_2 2 = 6000$ bps

Data Rate Limits

- **Noisy channel: Shannon Capacity**
  - **Capacity = Bandwidth x $\log_2$ (1 + SNR)**
- **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 is calculated as

$$C = B \log_2 (1 + SNR) = B \log_2 (1 + 0)$$

$$= B \log_2 (1) = B \times 0 = 0$$

Data Rate Limits

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

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

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

Data Rate Limits

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

If S/N >> 1, then

$$\boxed{C = B \times \frac{\mathrm{SNR_{dB}}}{3}}$$

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

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

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.

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

Data Rate Limits

Example 3.41 (continued)

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.

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

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

3.6 PERFORMANCE

One important issue in networking is the performance of the network—how good is it? We discuss quality of service, an overall measurement of network performance, in greater detail in Chapter 24. In this section, we introduce terms that we need for future chapters.

Topics discussed in this section:

Bandwidth
Throughput
Latency (Delay)
Bandwidth-Delay Product

Definition of Bandwidth

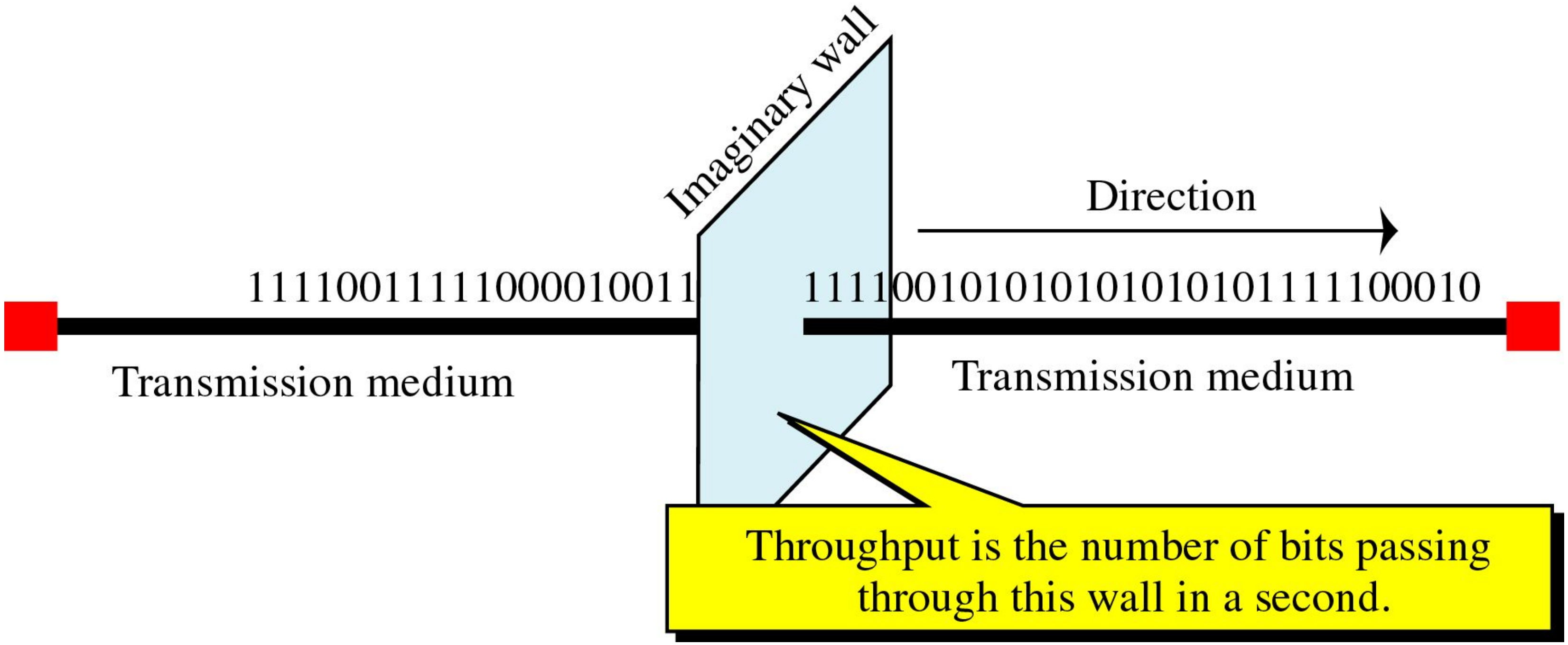
In networking, we use the term bandwidth in two contexts.

- **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.**

3. 6 Performance

❑ Throughput

- is the measurement of how fast data can pass through a point



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.

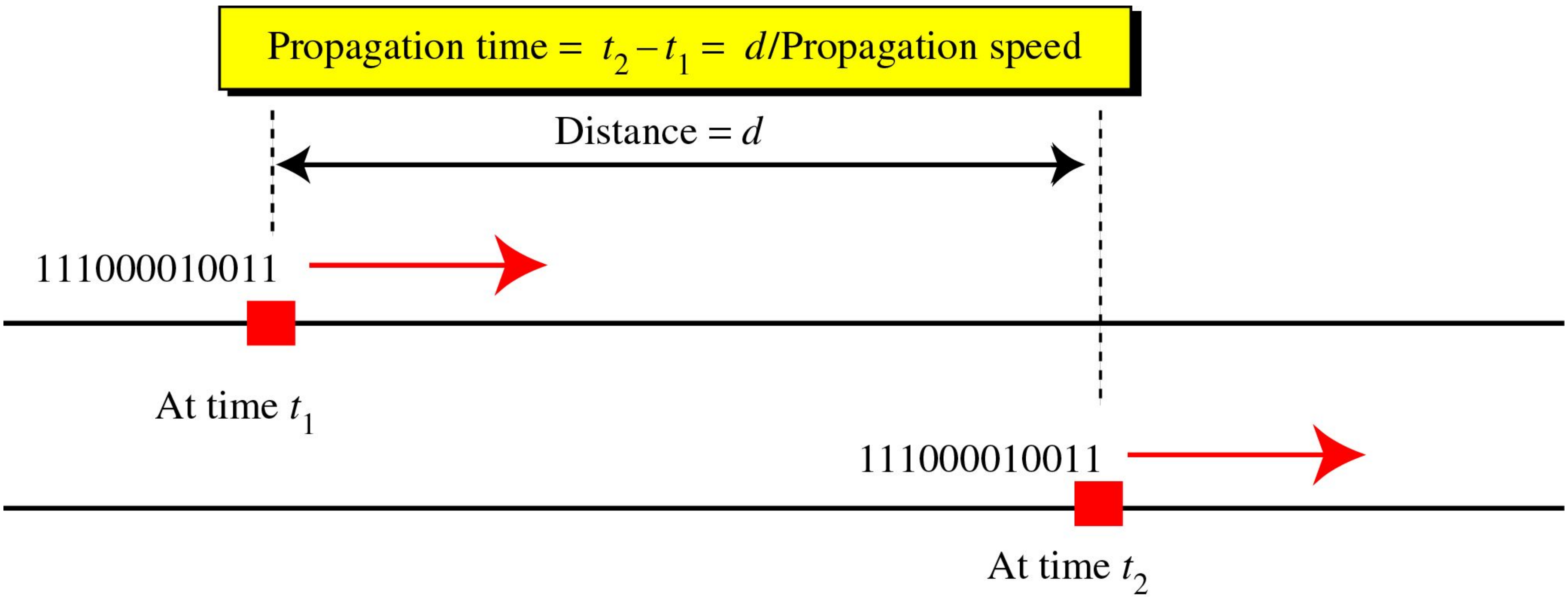
Performance (cont'd)

- 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.
  - Latency (지연) =propagation time(전파시간) + transmission time(전송시간)

    + queuing time(큐시간) +processing delay(처리시간)
  - Propagation time : The time required for a bit to travel from the source to the destination.
    - Propagation time = distance / propagation speed
  - Transmission time : The time between the first bit leaving the sender and the last bit arriving at the receiver.
    - Transmission time = Message size / Bandwidth

Performance (cont'd)

- **Propagation Time**



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.

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:

Example 3.46 (continued)

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

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

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.

Performance (cont'd)

- **Bandwidth-delay Product**

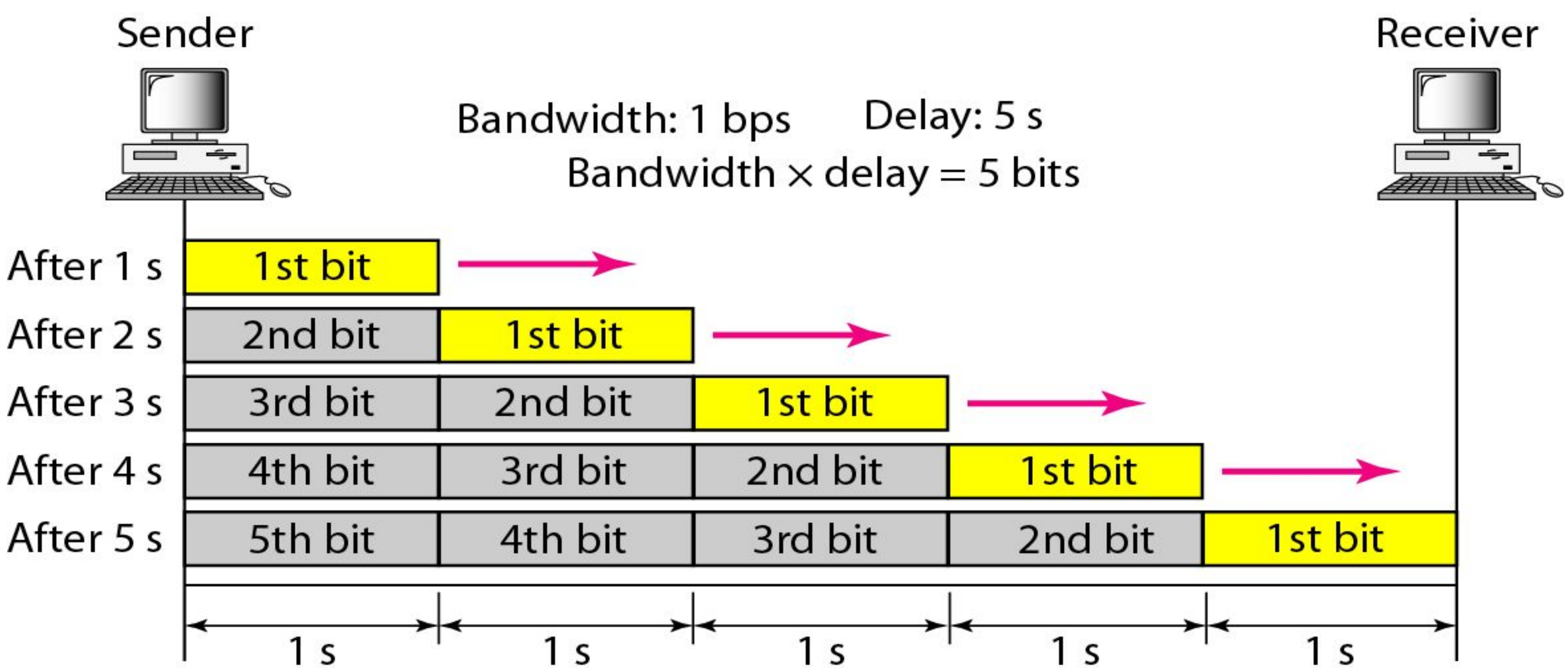


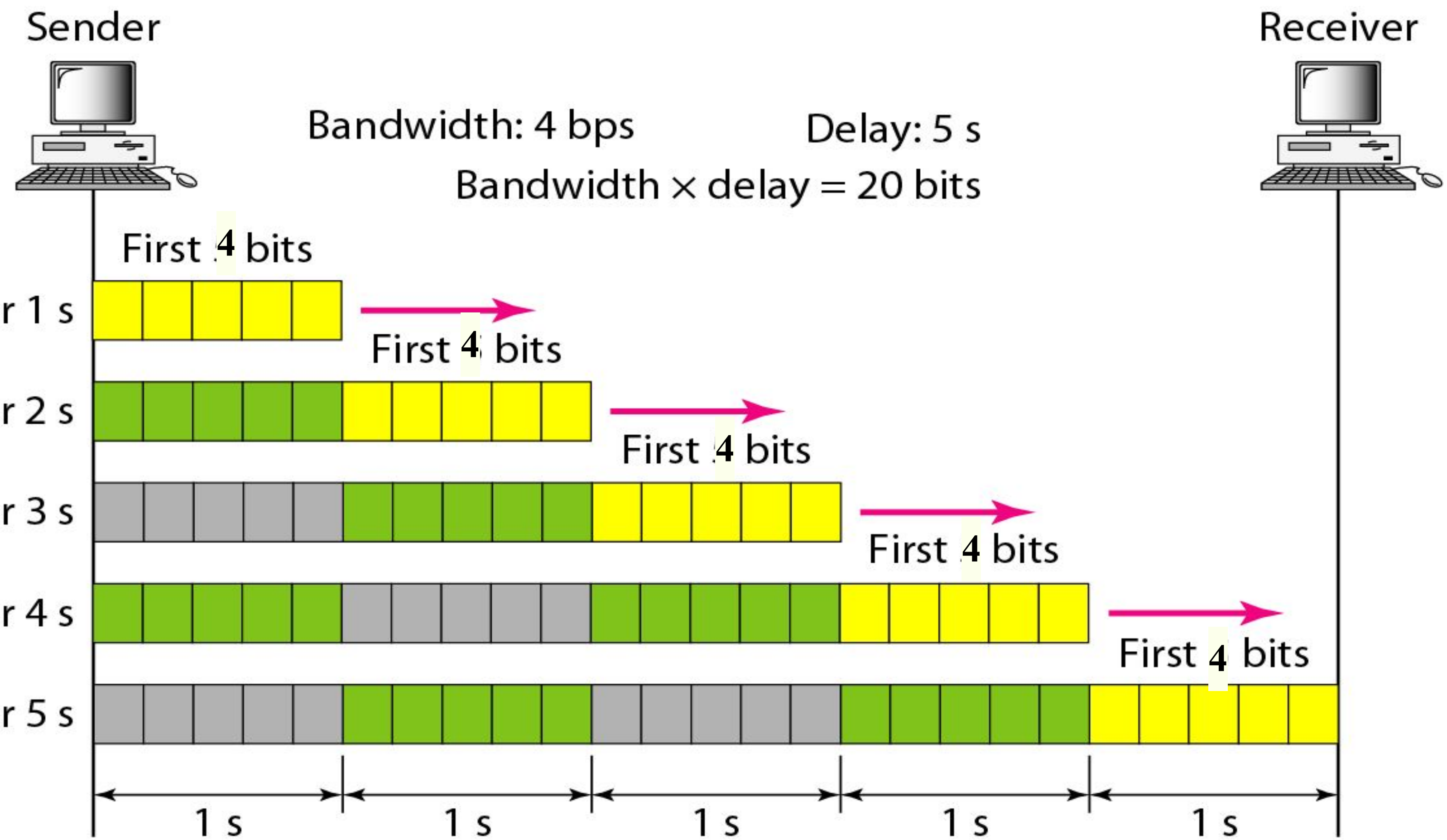
Figure 3.31 *Filling the link with bits for case 1*

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

Performance (cont'd)

- Bandwidth-delay Product

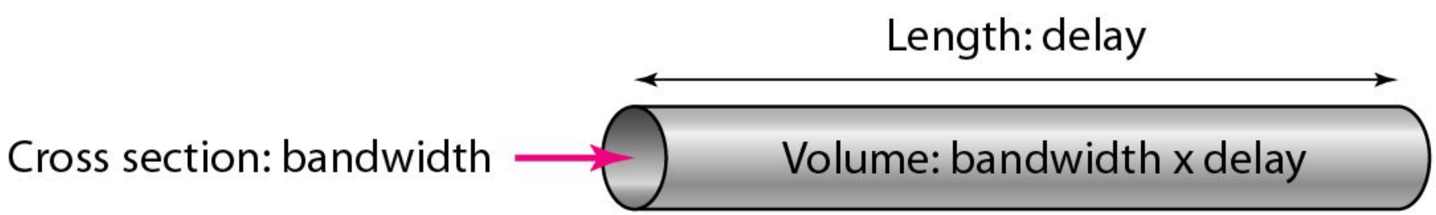
Figure 3.32 *Filling the link with bits in case 2*



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 3.33 ***Concept of bandwidth-delay product***



Summary(1)

- Data must be transformed to electromagnetic signals to be transmitted.
- Data can be analog or digital. Analog data are continuous and take continuous values. Digital data have discrete states and take discrete values.
- 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.
- In data communications, we commonly use periodic analog signals and nonperiodic digital signals.
- Phase describes the position of the waveform relative to time 0.
- A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

Summary(2)

- A single-frequency sine wave in not useful in data communications; we need to send a composite signal, a signal made of many simple sine waves.
- According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.
- The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.
- A digital signal is a composite analog signal with an infinite bandwidth.
- 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 of very wide bandwidth.

Summary(3)

- If the available channel is a bandpass channel, we cannot send a digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.
- For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate. For a noisy channel, we need to use the Shannon capacity to find the maximum bit rate.
- Attenuation, distortion, and noise can impair a signal.
- Attenuation is the loss of a signal's energy due to the resistance of the medium.
- Distortion is the alteration of a signal due to the differing propagation speeds of each of the frequencies that make up a signal.
- Noise is the external energy that corrupts a signal.

Q & A