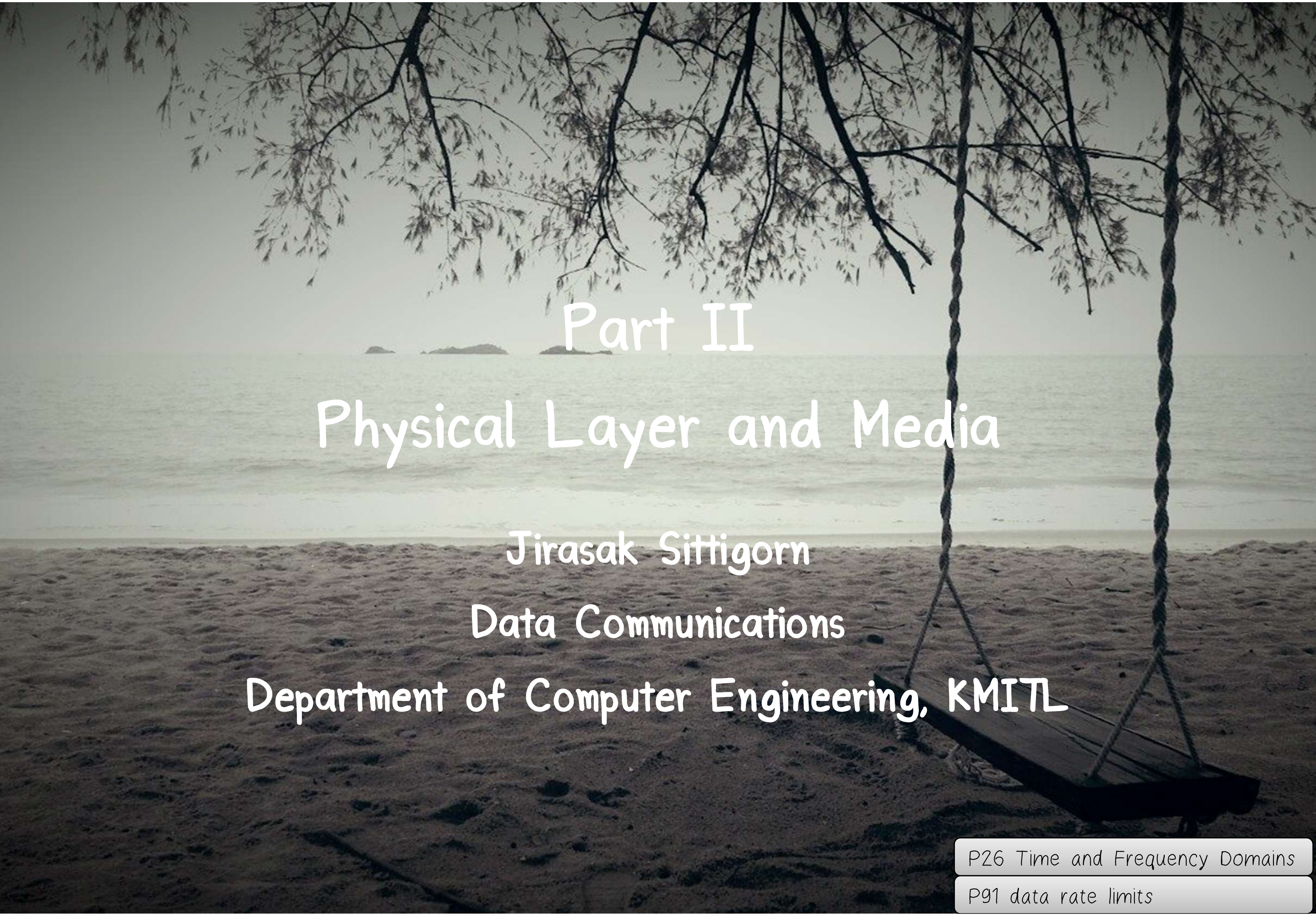
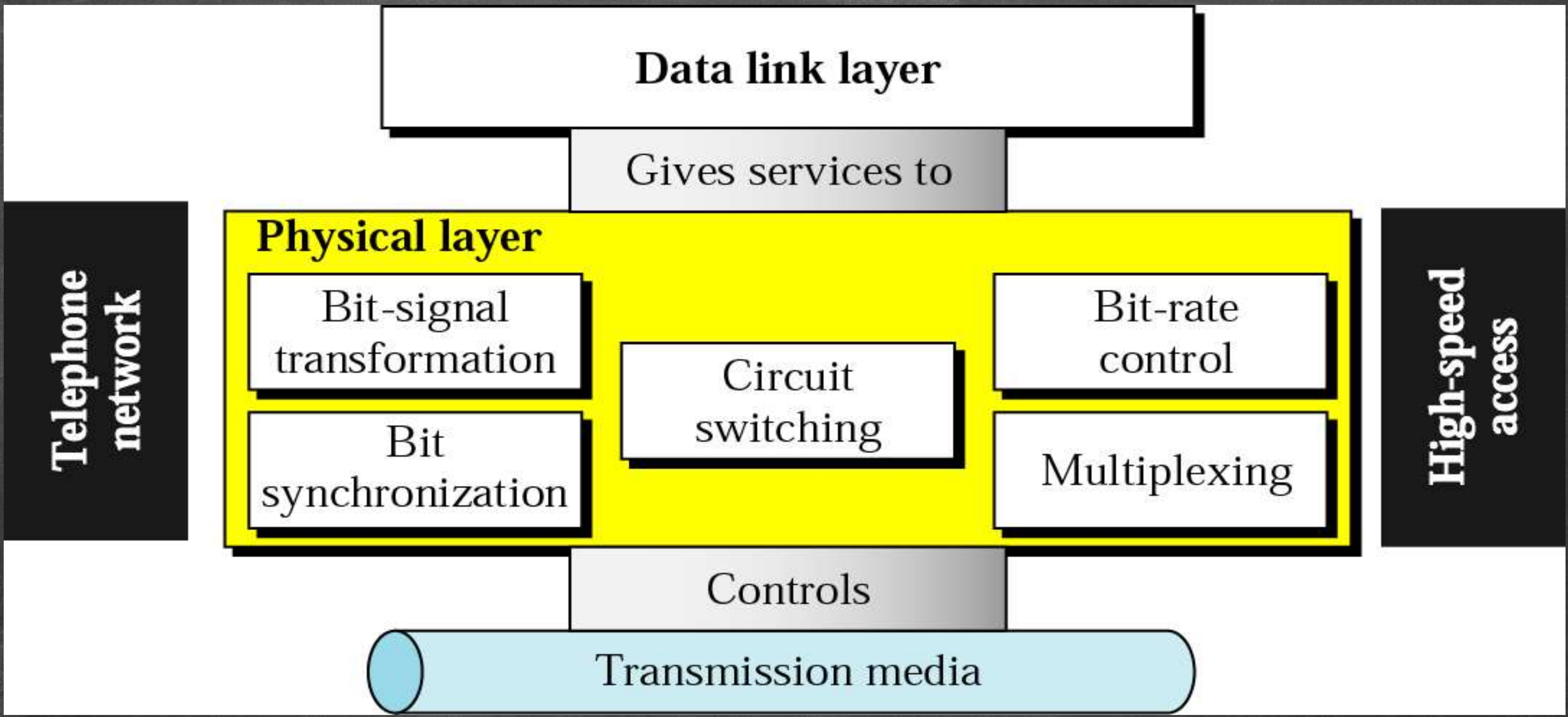


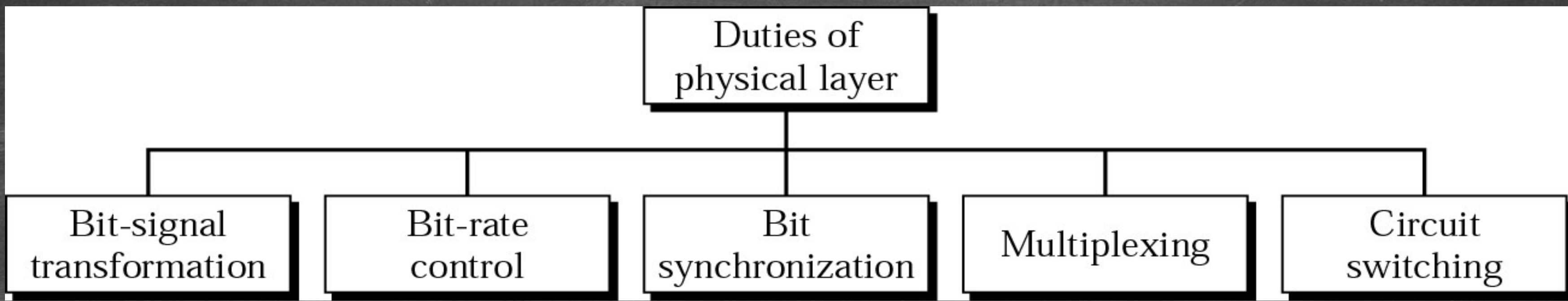
Part II
Physical Layer and Media

Jirasak Sittigorn
Data Communications
Department of Computer Engineering, KMITL

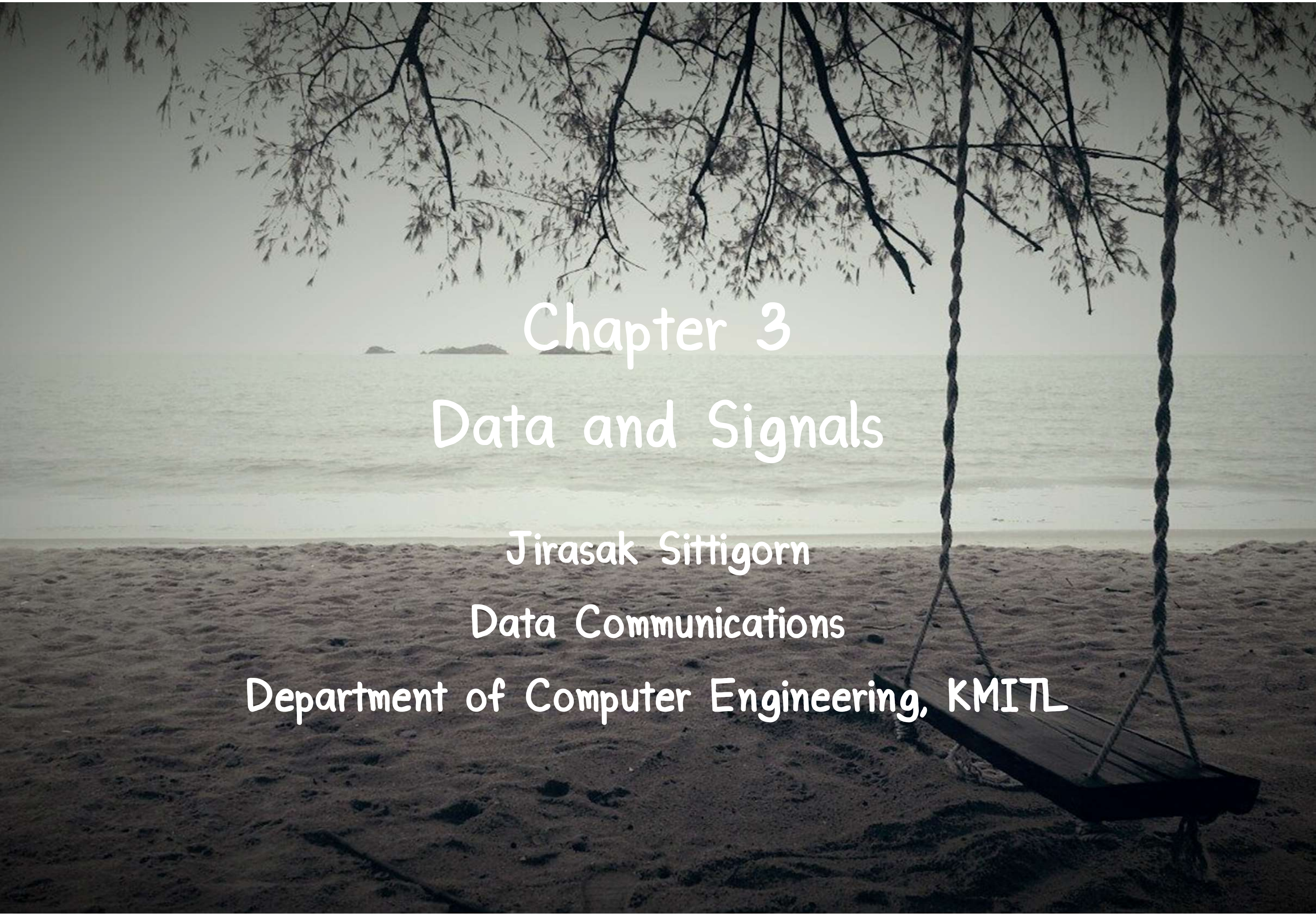
Position of the physical layer



Services



- Chapter 3 Data and Signals
- Chapter 4 Digital Transmission
- Chapter 5 Analog Transmission
- Chapter 6 Multiplexing
- Chapter 7 Transmission Media



Chapter 3
Data and Signals

Jirasak Sittigorn

Data Communications

Department of Computer Engineering, KMITL

Bit-Signal Conversion

- To be transmitted, data must be transformed to electromagnetic signals.
- Conversion (Transformation)

  Data คือสิ่งที่เราจะส่งออกไป

  - Digital Transmission (need digital signals)
    - Digital data to Digital Signal : Line Coding
    - Analog data to Digital Signal : Digital Modulation (PCM)
  - Analog Transmission (need analog signals)
    - Digital data to Analog Signal : Shift Keying
    - Analog data to Analog Signal : Analog Modulation

ANALOG AND DIGITAL

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

Analog and Digital Data

- Data can be analog or digital.
  - Analog data are continuous and take continuous values.
    - Sound from human voice
  - Digital data have discrete states and take discrete values.
    - {0, 1} in memory

Analog and Digital Signals

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

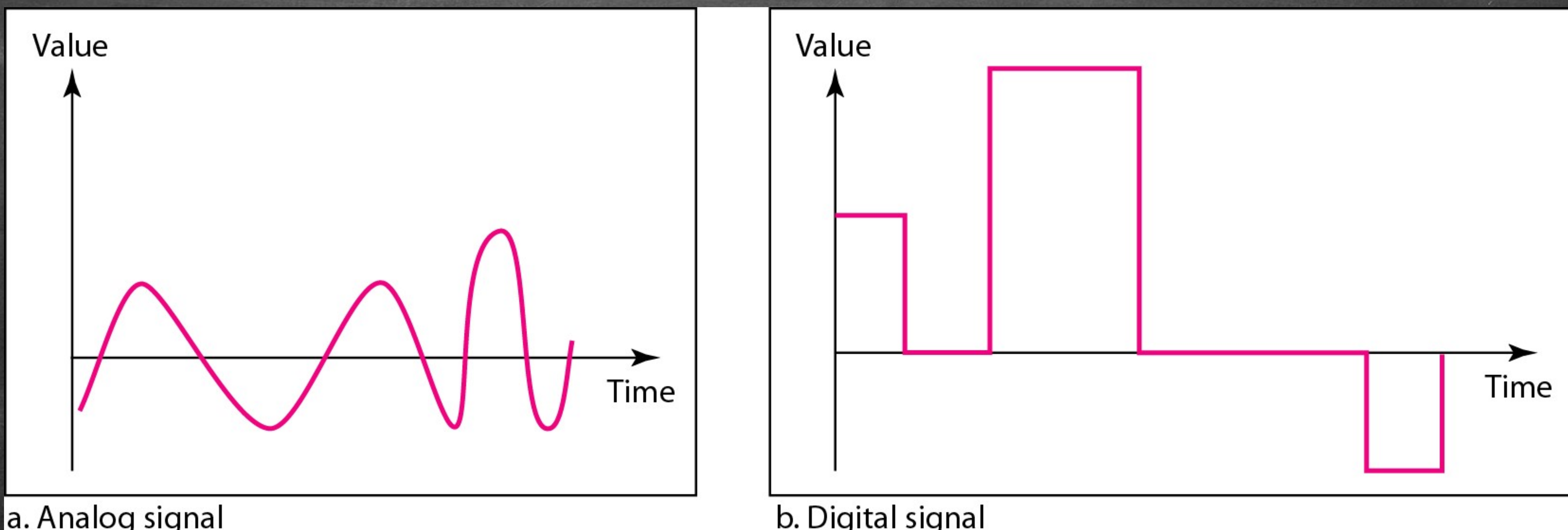


Figure 3.1 Comparison of analog and digital signals

Periodic and Nonperiodic Signals

- analog and digital signals => Periodic Signals
  - completes a pattern within a measurable time frame : period
  - repeats that pattern over subsequent identical periods
- analog and digital signals => Nonperiodic (aperiodic) Signals
  - changes without exhibiting a pattern or cycle that repeats over time
- In data communications, we commonly use
  - periodic analog signals (need less bandwidth)
  - nonperiodic digital signals (represent variation in data)

จะต้องได้

PERIODIC ANALOG SIGNALS

- Sine Wave
- Wavelength
- Time and Frequency Domains
- Composite Signals
- Bandwidth

Sine Wave

$$s(t) = A\sin(\omega t + \varphi) = A\sin(2\pi f t + \varphi) = A\sin(\frac{2\pi}{T}t + \varphi)$$

$\omega = 2\pi f$ $\quad$ $f = \frac{1}{T}$

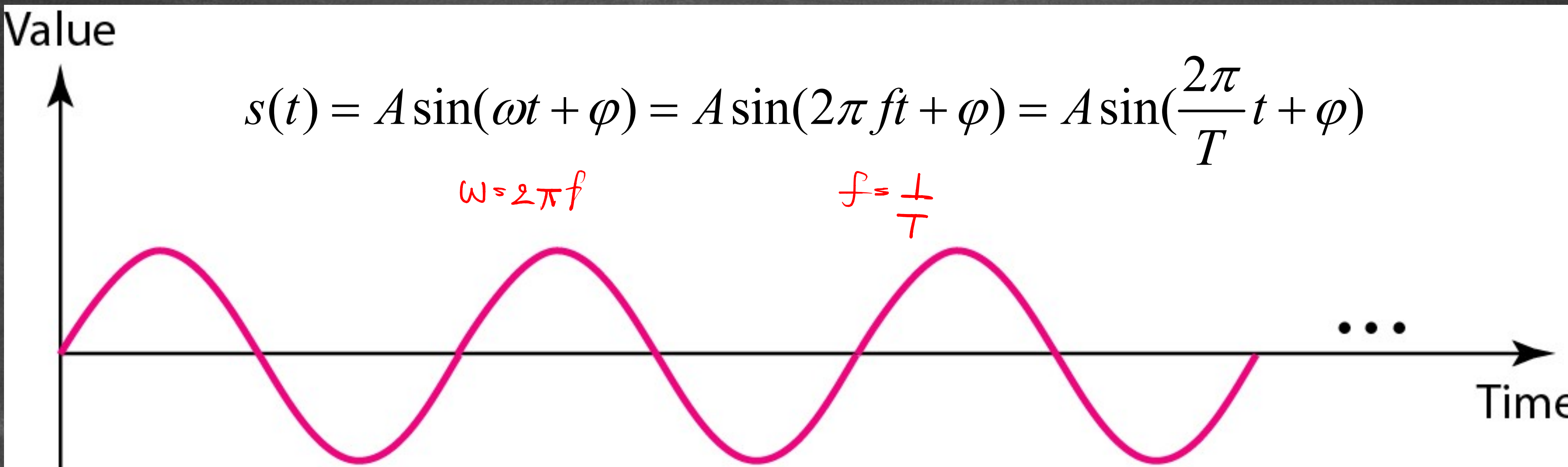
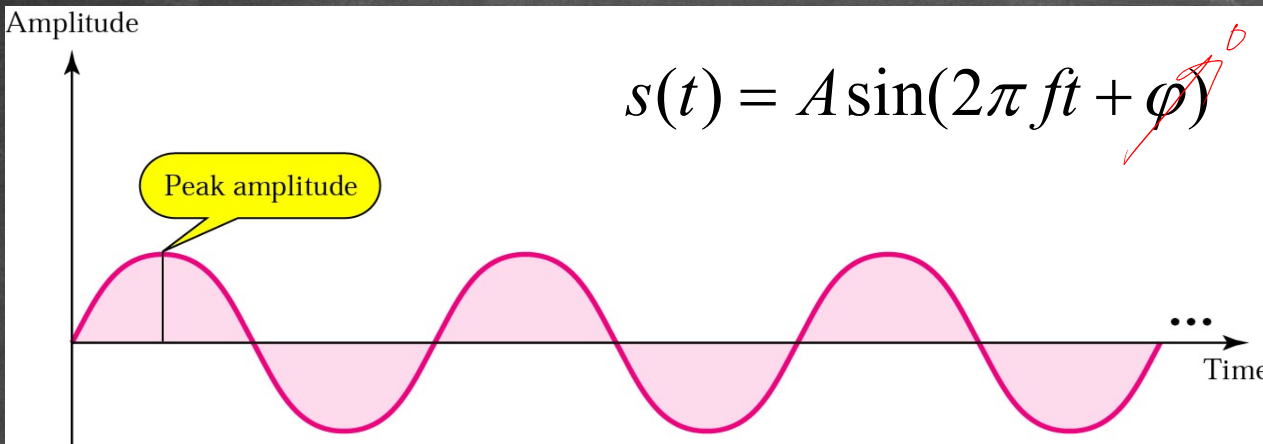


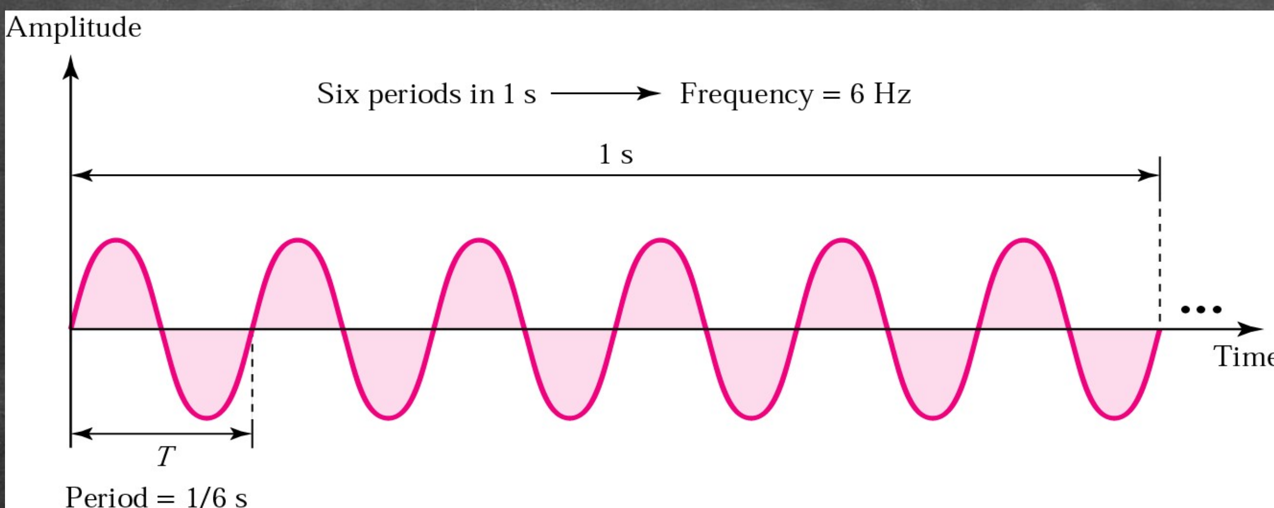
Figure 3.2 A sine wave

- Sinewave Signal Characteristics
  - Peak Amplitude : A (Volt)
    - Peak
    - Peak-to-peak
    - RMS (root mean square)
  - Frequency : f (Hz)
  - Period : T (s)
  - Phase shift : degree

Sine Wave (Peak Amplitude)



1st cycle 2nd cycle 3th cycle



1st cycle 2nd cycle 3th cycle 4th cycle 5th cycle 6th cycle

$T = \frac{1}{6}$

$f = 6 \cdot 5$

Sine Wave (Peak Amplitude)

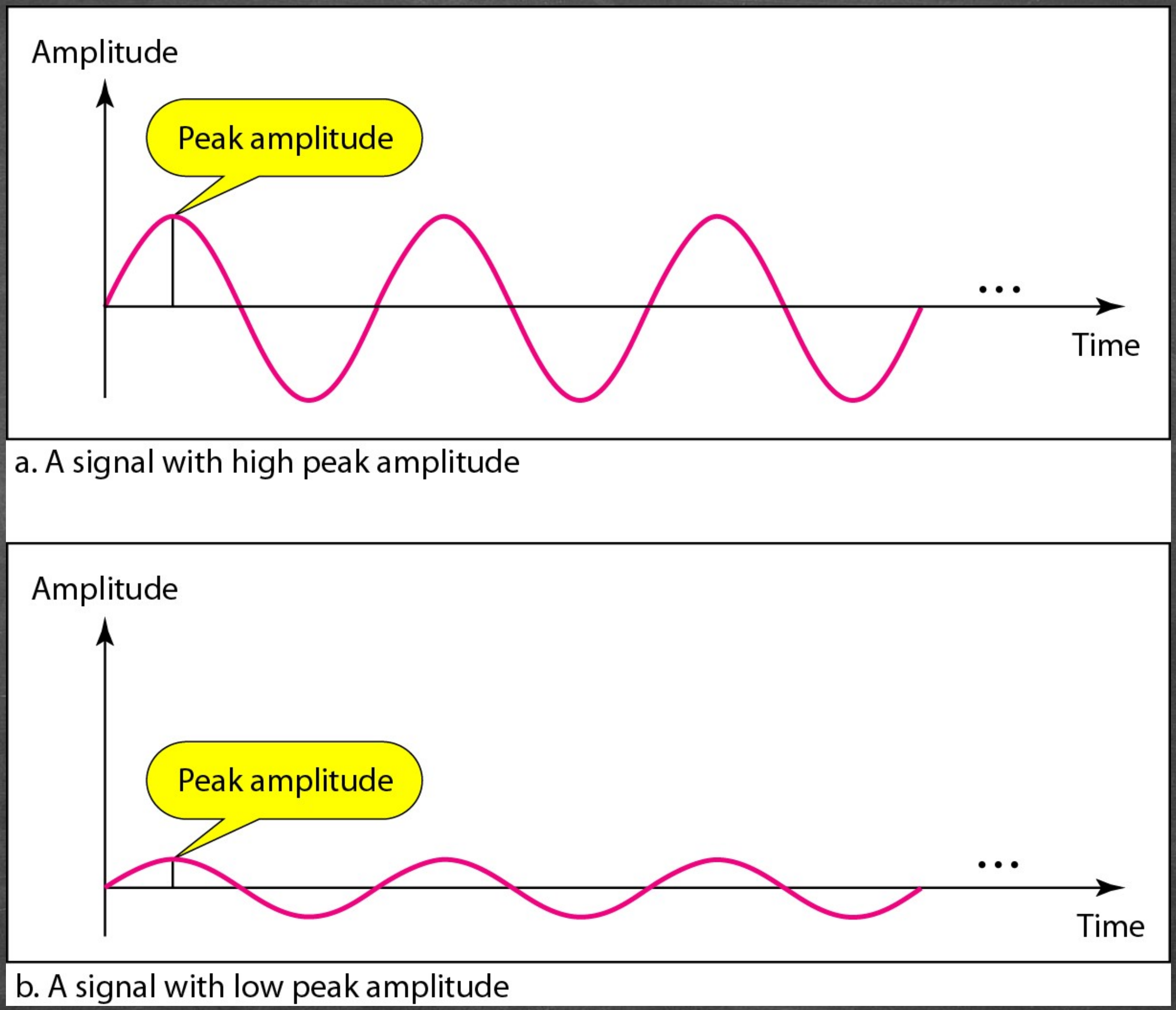


Figure 3.3 Two signals with the same phase and frequency, but different amplitudes

Sine Wave (Frequency/Period)

- Frequency and period are the inverse of each other.

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

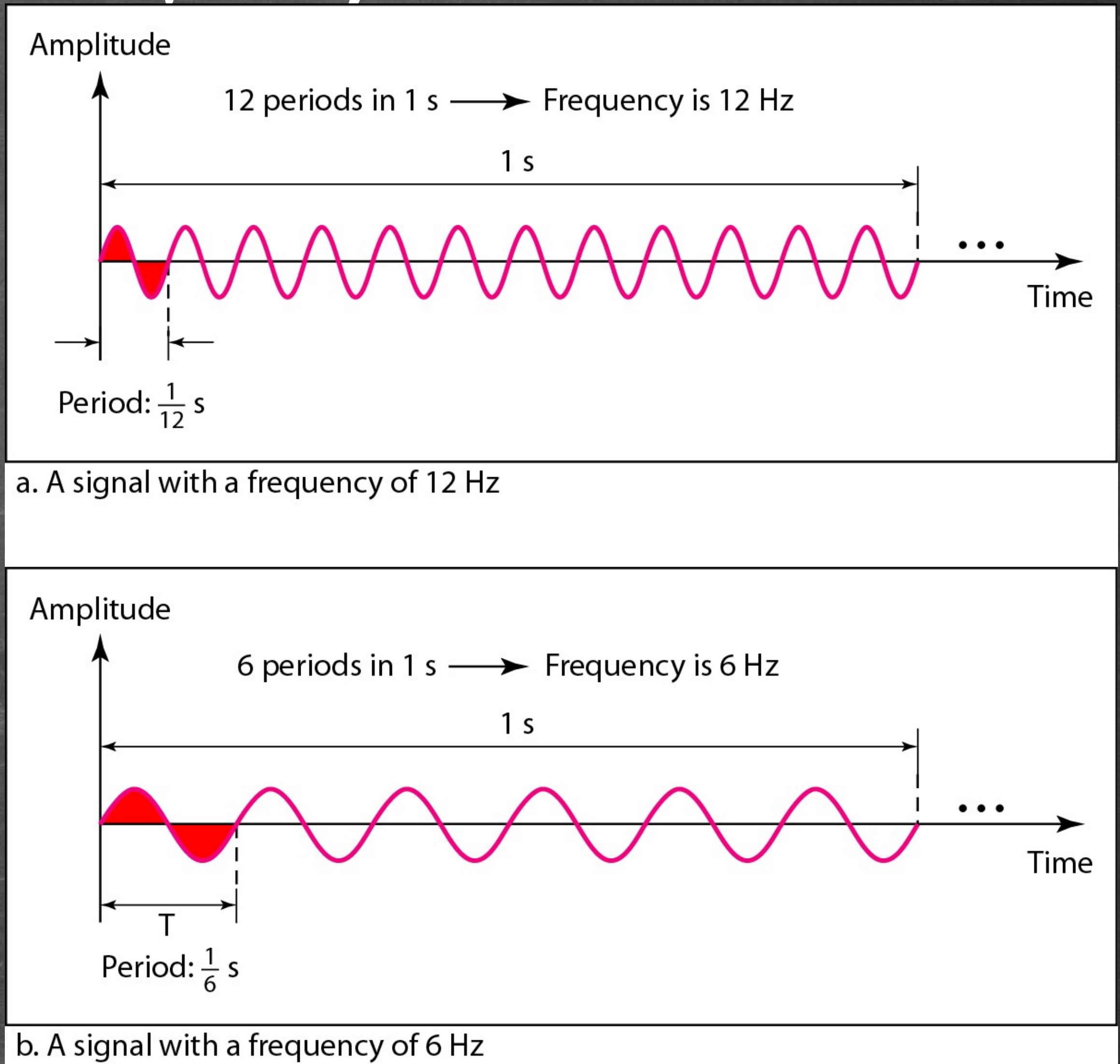


Figure 3.4 Two signals with the same amplitude and phase, but different frequencies

Sine Wave (Frequency/Period)

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:

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

Example 3.4

- Express a period of 100 ms in microseconds.
- Solution
  - From Table 3.1 we find the equivalents of 1 ms (1 ms is 10^{-3} s) and 1 s (1 s is 10^6 μs). We make the following substitutions:.

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

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).

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

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

Sine Wave (Frequency/Period)

- 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.

Sine Wave (Phase)

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

$$s(t) = A\sin(2\pi ft + \varphi)$$

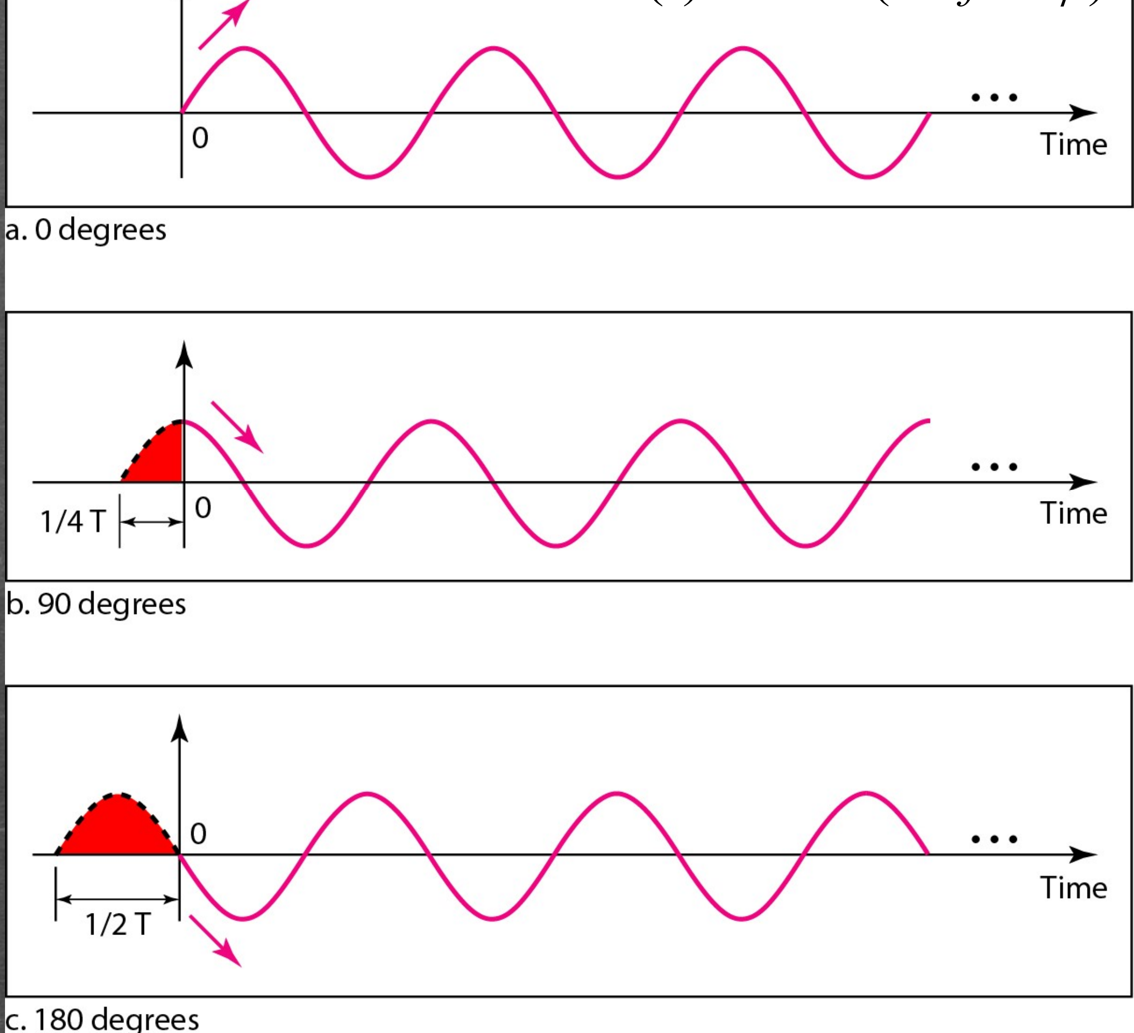


Figure 3.5 Three sine waves with the same amplitude and frequency, but different phases

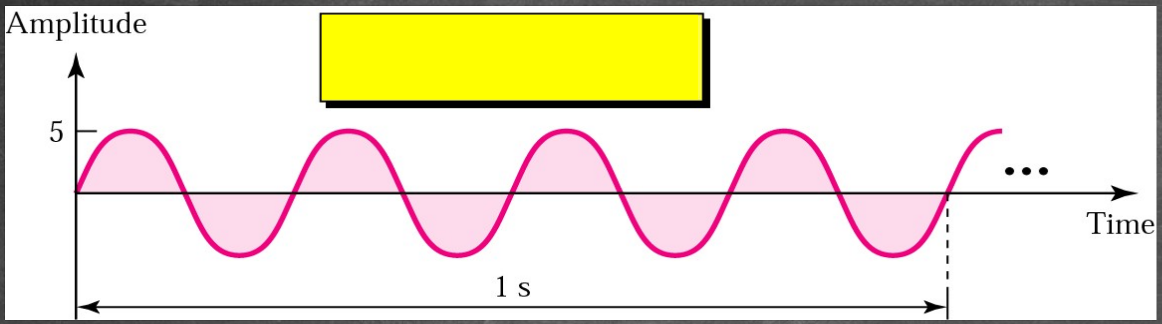
Example 3.6

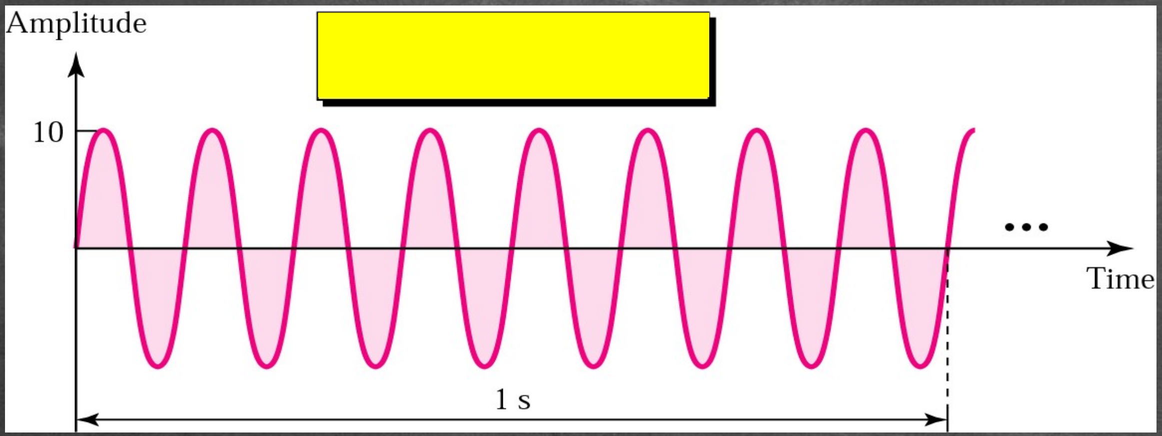
- A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?
- Solution
  - We know that 1 complete cycle is 360 degree. Therefore, 1/6 cycle is

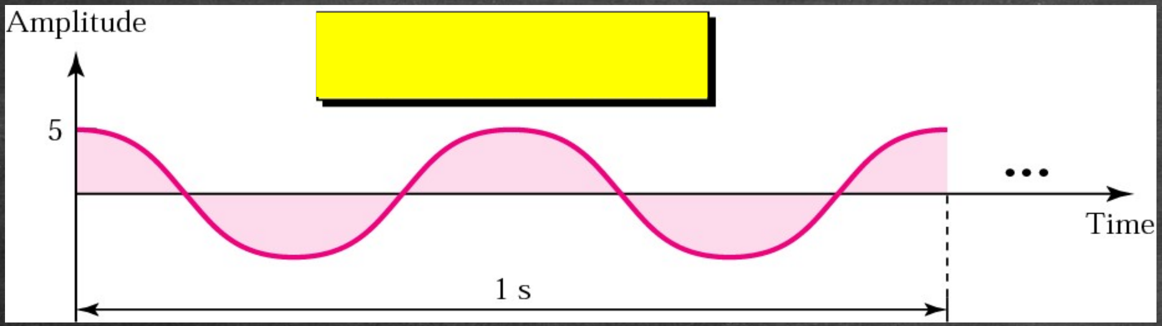
$$\frac{1}{6} \times 360 = 60° = 60 \times \frac{2\pi}{360} \text{ rad} = \frac{\pi}{3} \text{ rad} = 1.046 \text{ rad}$$

Sine Wave

$$s(t) = A\sin(2\pi ft + \varphi)$$







B. A. Forouzan, Data Communications and Networking, 4th edition, McGRAW-HILL

Wavelength

- characteristic of a signal traveling through a transmission medium
- binds the period or the frequency of a simple sine wave to the propagation speed of the medium

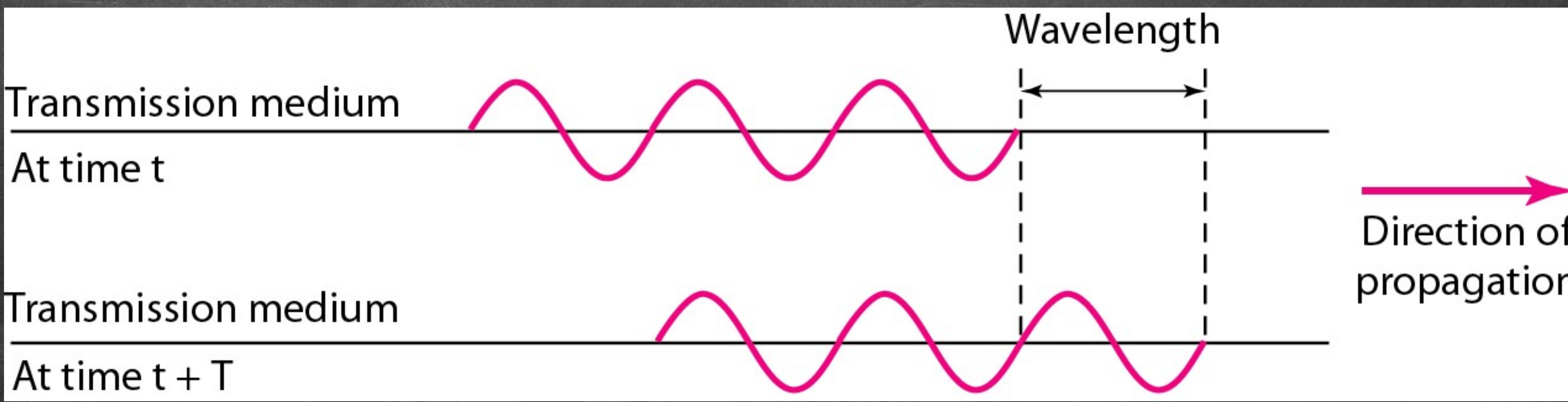
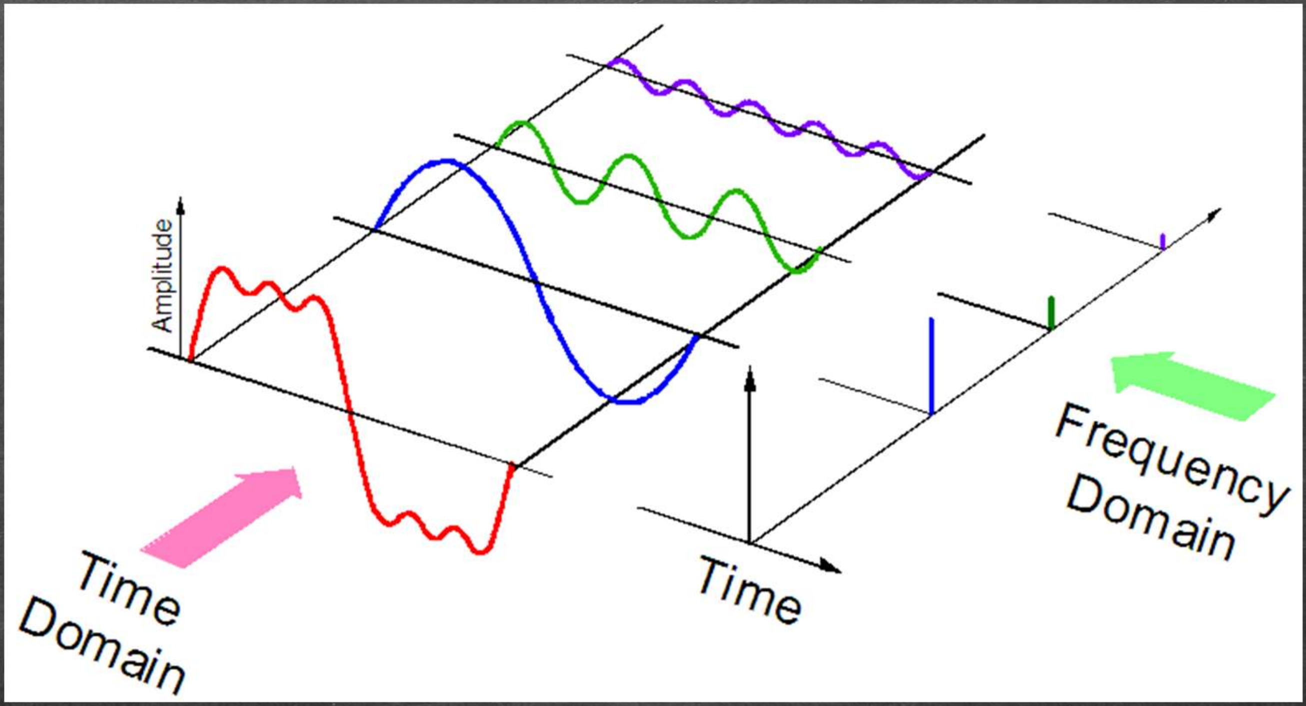


Figure 3.6 Wavelength and period

Time and Frequency Domains

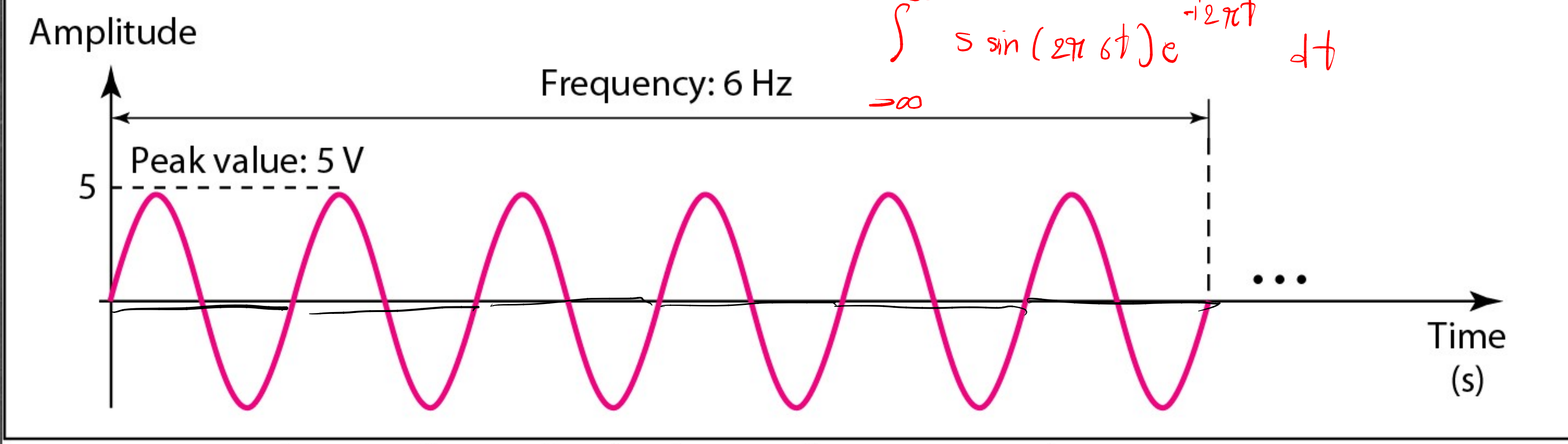
- Sine wave defined by amplitude, frequency, and phase
- A complete sine wave in the time domain can be represented by one single spike in the frequency domain.



http://blog.algoengines.com/2014/08/condition-monitoring-in-time-and.html

Time and Frequency Domains

$\int_{-\infty}^{\infty} 5 \sin(2\pi\, 6t)\, e^{-i2\pi t}\, dt$

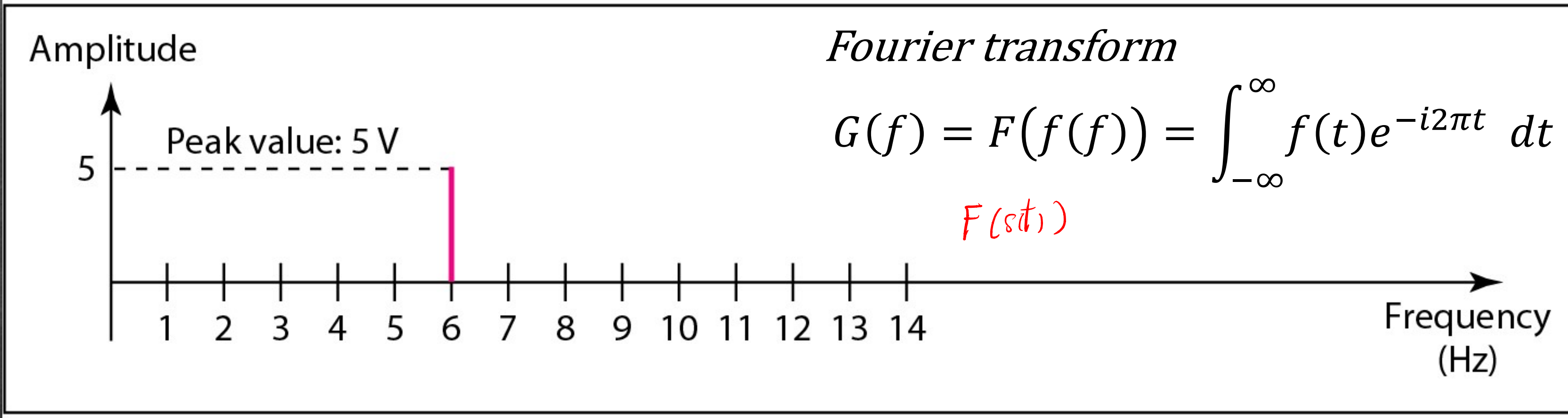


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

Fourier transform

$$G(f) = F\big(f(f)\big) = \int_{-\infty}^{\infty} f(t)e^{-i2\pi t}\ dt$$

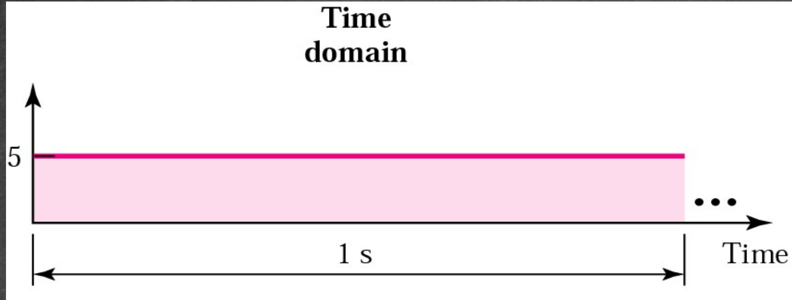
$F(s(t))$



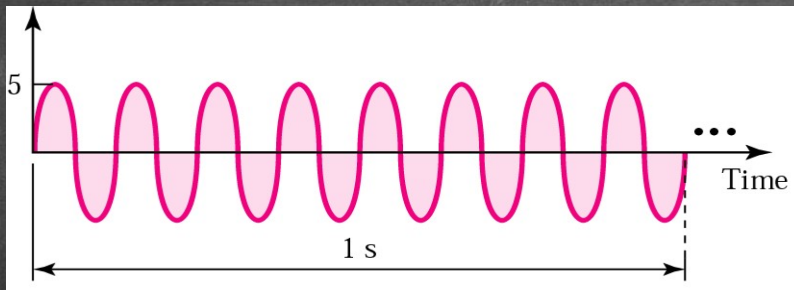
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

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

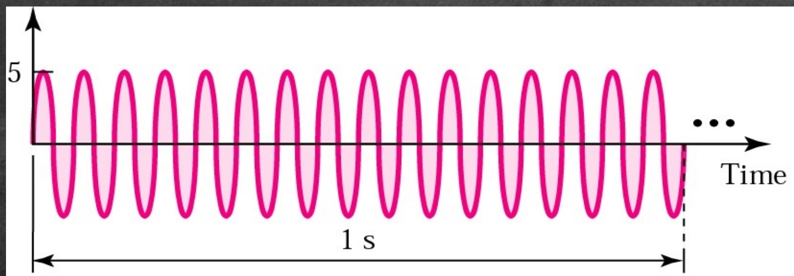
Time and Frequency Domains



a. A signal with frequency 0



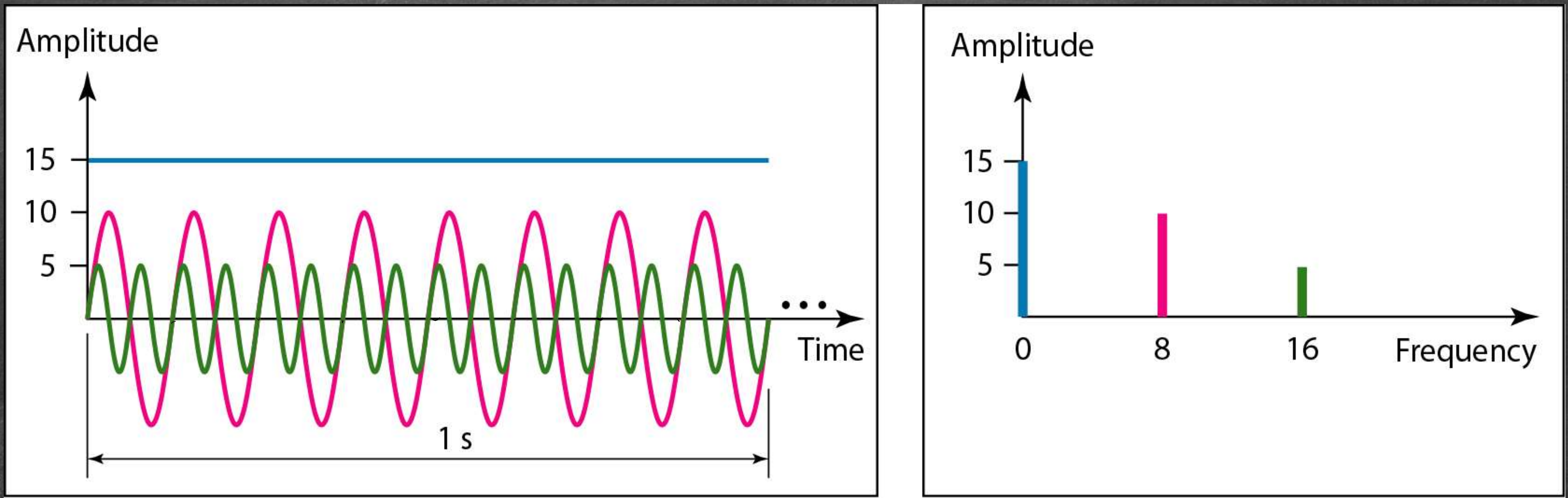
b. A signal with frequency 8



c. A signal with frequency 16

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.



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

b. Frequency-domain representation of the same three signals

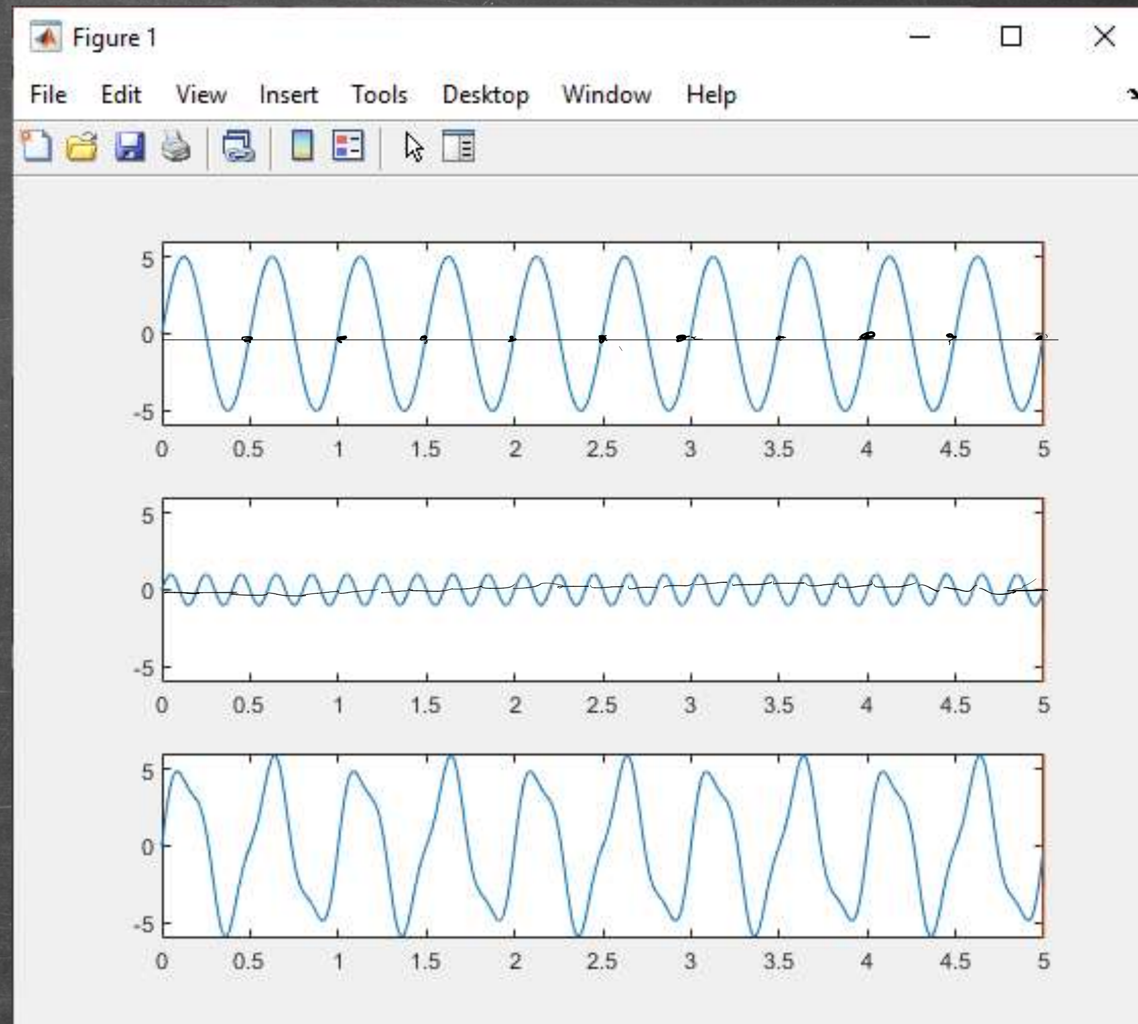
Figure 3.8 The time domain and frequency domain of three sine waves

Composite Signals

$s_1(t) = 5\sin(2\pi(5)t + \varphi)$

$s_2(t) = 1\sin(2\pi(2)t + \varphi)$

$s_3(t) = s_1(t) + s_2(t)$



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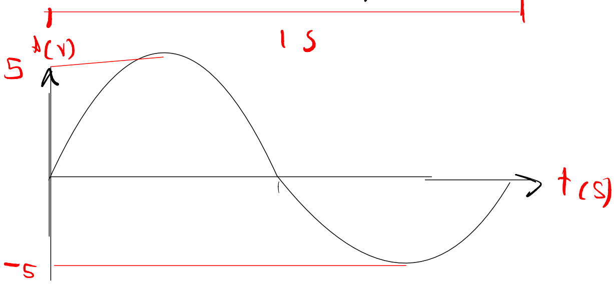
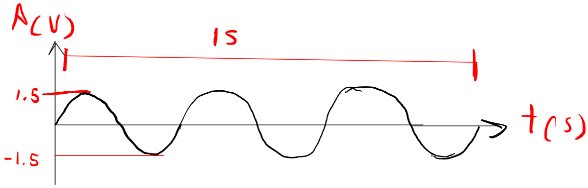
$s_1(t) = 5\sin(2\pi f_0 t + \varphi_1)$



กำหนด $f_0 = 1$ $\varphi_1 = 0$

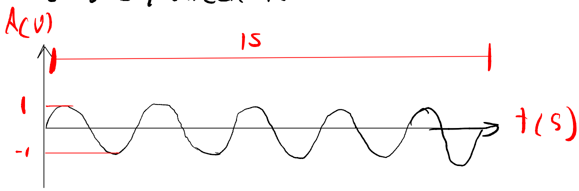
$s_2(t) = 1.5\sin(2\pi 3 f_0 t + \varphi_1)$



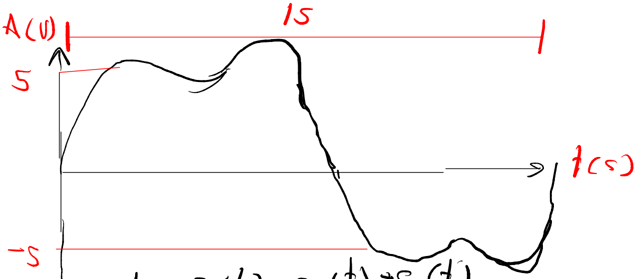
สรุป

เมื่อมีการนำ signal มาบวกกัน ถ้า Amplitute มีค่าบวกลบ เหมือนกัน จะทำให้นำ ค่ามาเสริมกัน

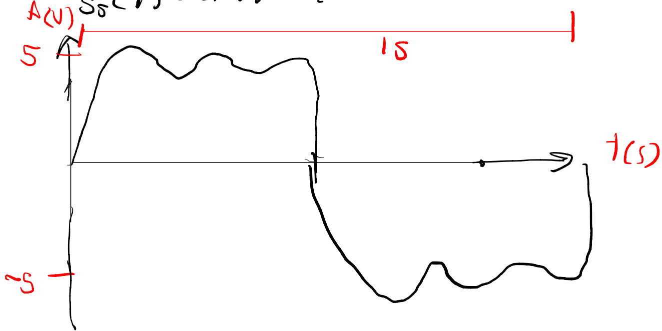
$s_3(t) = 1\sin(2\pi 5 f_0 t + \varphi_1)$



$s_4(t) = s_1(t) + s_2(t)$



$s_5(t) = s_1(t) + s_2(t) + s_3(t)$



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.
- 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 Signals

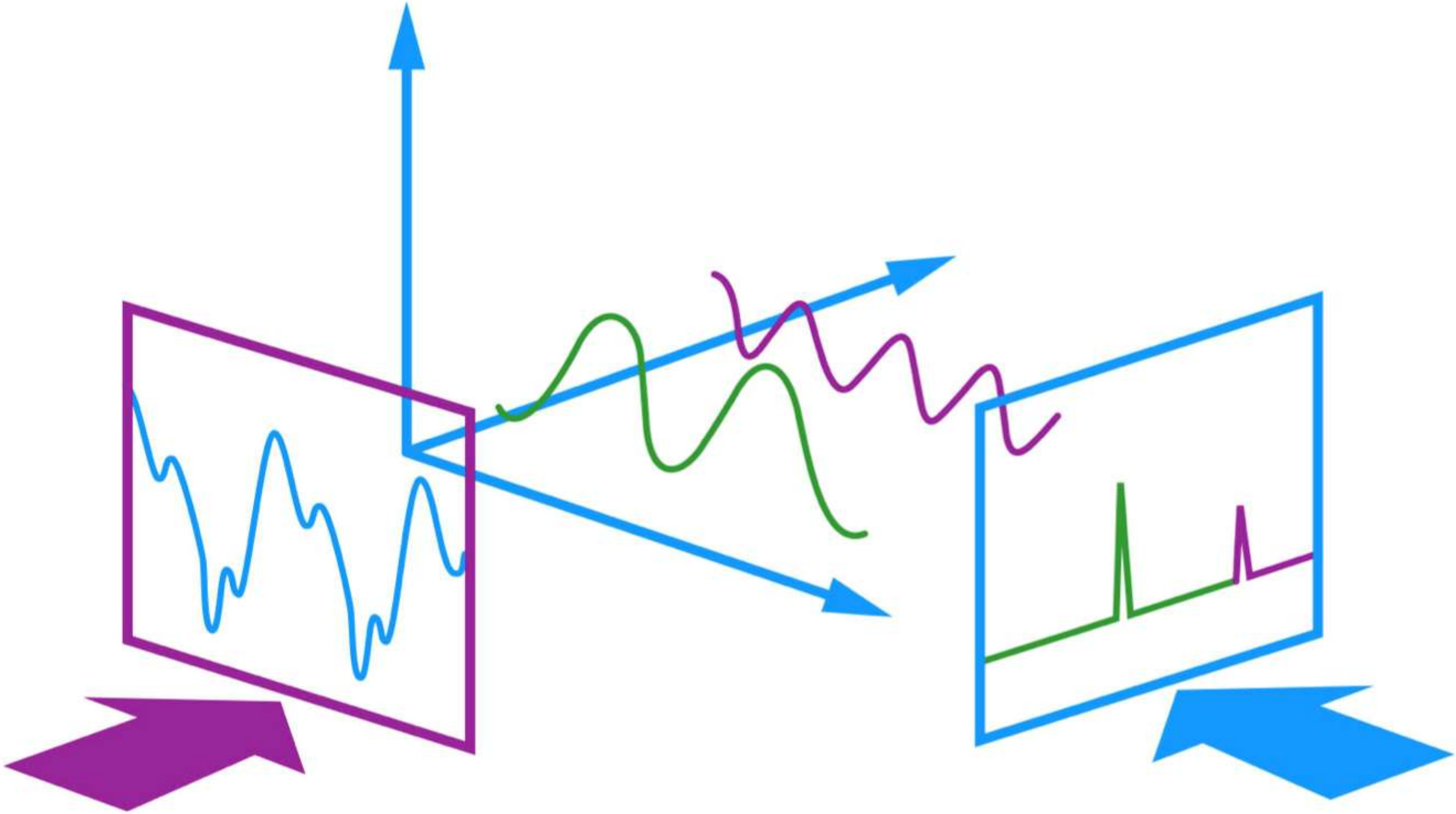
- Using Fourier Analysis
  - any composite signal can be represented as
    - a linear combination of simple sine waves with
      - different frequencies, phases, and amplitudes.

$$s(t) = A_1 \sin(2\pi f_1 t + \varphi_1) + A_2 \sin(2\pi f_2 t + \varphi_2) + A_3 \sin(2\pi f_3 t + \varphi_3) + \cdots$$

- Fourier Equation

$$s(t) = A_0 + \sum_{n=1}^{\infty} \left[A_n \sin\left(2\pi n f_0 t\right) + B_n \cos\left(2\pi n f_0 t\right) \right]$$

$$A_0 = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} s(t)\,dt \qquad A_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} s(t) \sin\left(2\pi n f_0 t\right) dt \qquad B_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} s(t) \cos\left(2\pi n f_0 t\right) dt$$



http://www.wlanpros.com/wlw052-7-rules-accurate-site-surveys/

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.

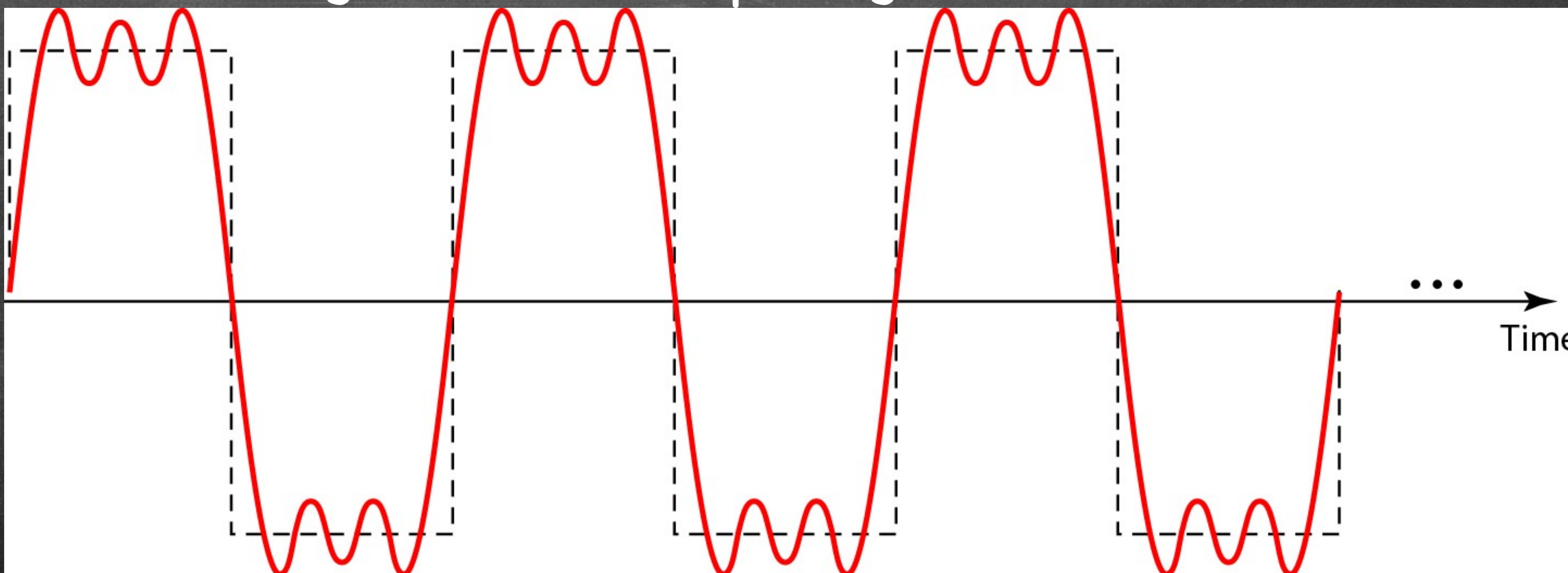


Figure 3.9 A composite periodic signal

Composite Signals

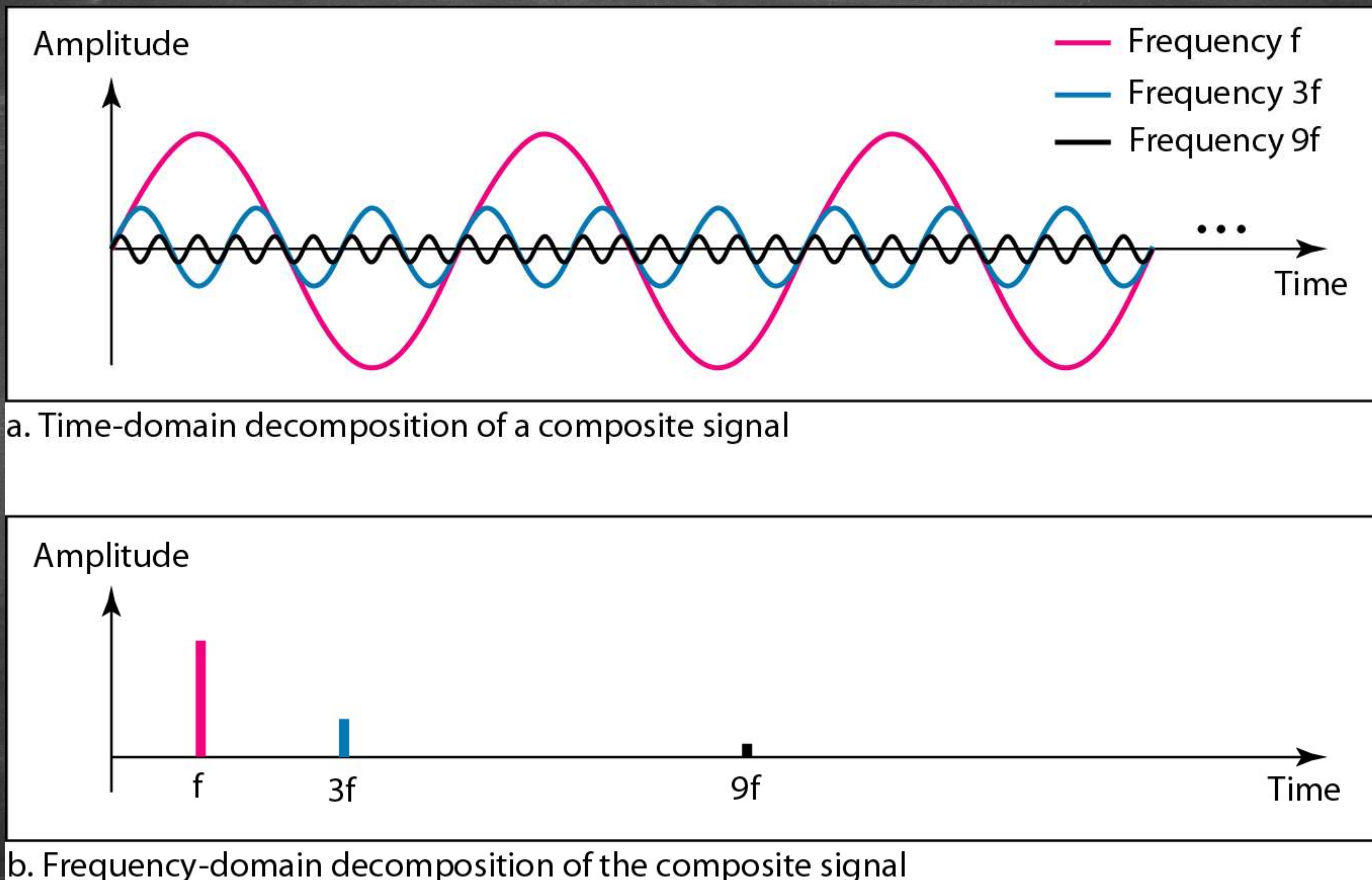


Figure 3.10 Decomposition of a composite periodic signal in the time and frequency domains

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.

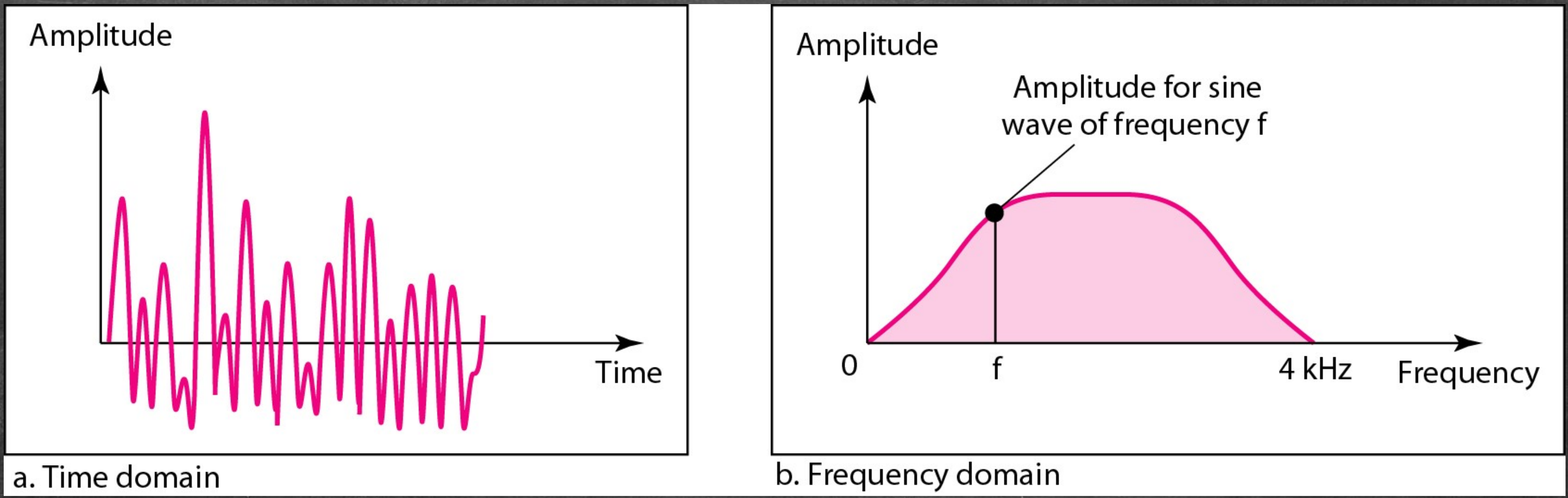


Figure 3.11 The time and frequency domains of a nonperiodic signal

Bandwidth

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

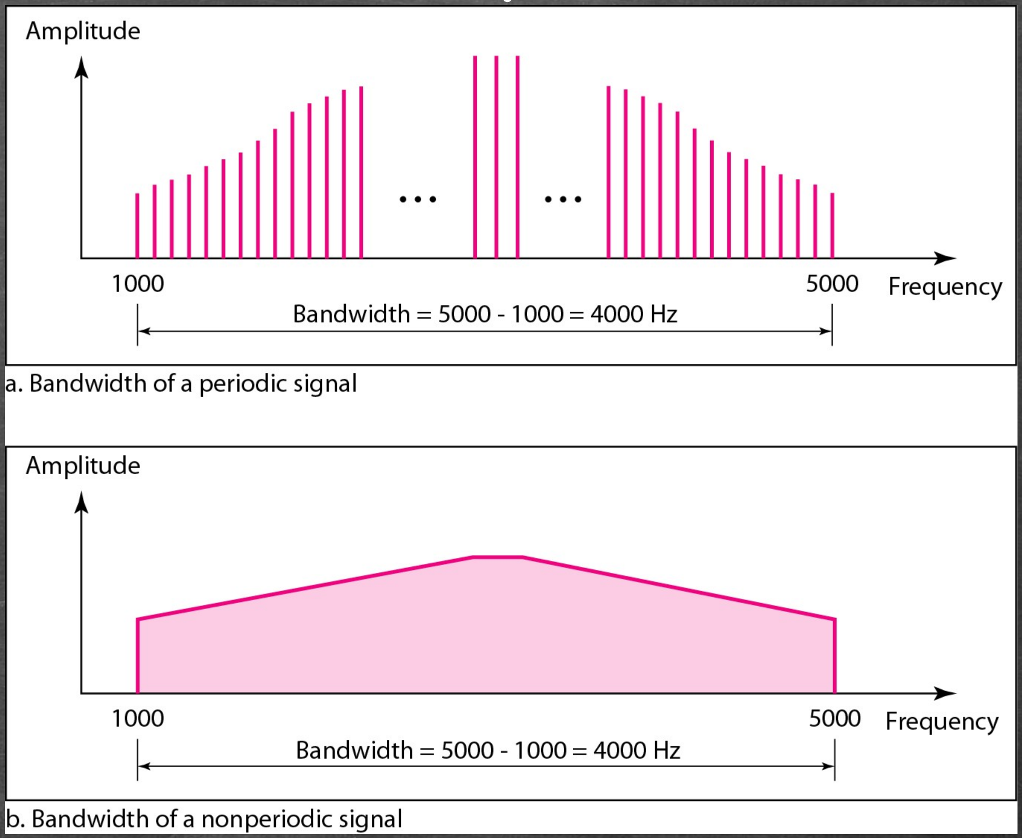


Figure 3.12 The bandwidth of periodic and nonperiodic composite signals

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

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

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

Example 3.10

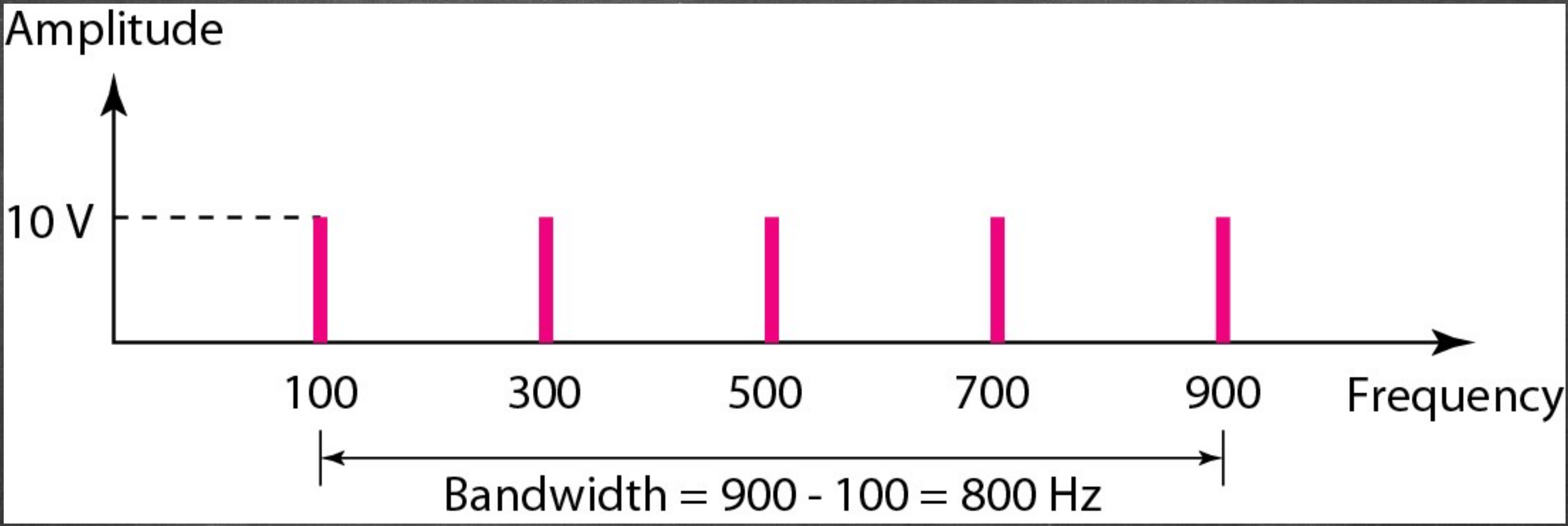


Figure 3.13 The bandwidth for Example 3.10

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

Example 3.12

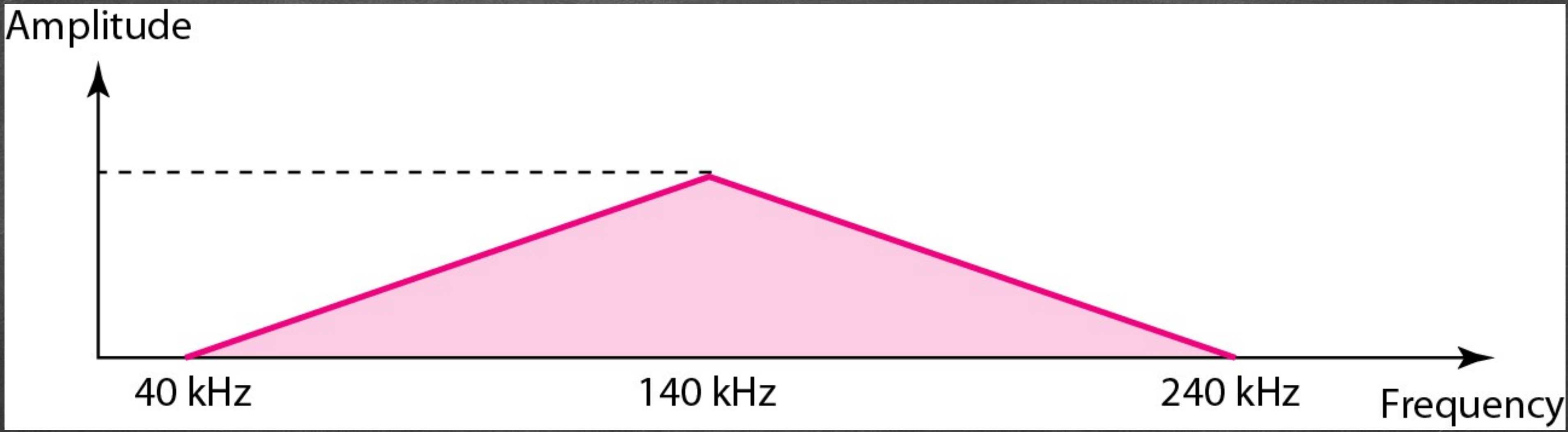
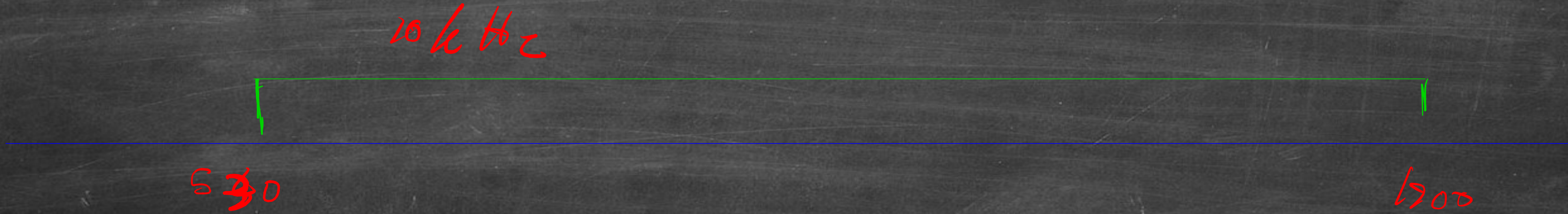


Figure 3.15 The bandwidth for Example 3.12

Example 3.13

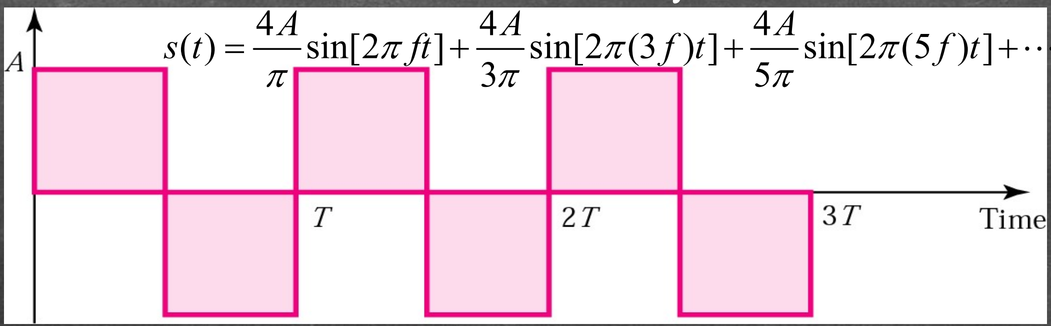
- An example of a nonperiodic composite signal is the signal propagated by an AM radio station. In the United States, each AM radio station is assigned a 10-kHz bandwidth. The total bandwidth dedicated to AM radio ranges from 530 to 1700 kHz. We will show the rationale behind this 10-kHz bandwidth in Chapter 5.

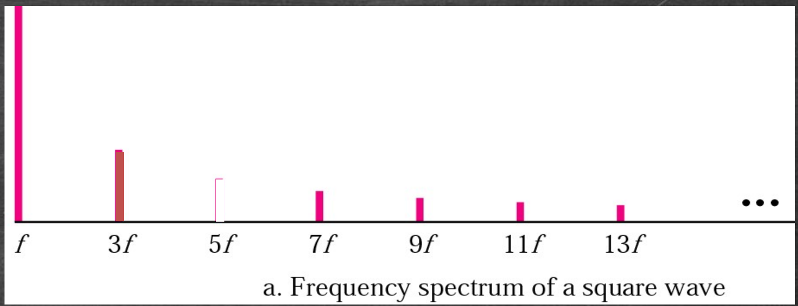


Periodic Digital Signals

- Periodic Digital Signal Characteristics
  - Amplitude (Peak)
  - Frequency (f(Hz)) -> Multiple frequencies
    - Fundamental frequency (f) + Odd-Harmonics (3f, 5f, ..., inf)

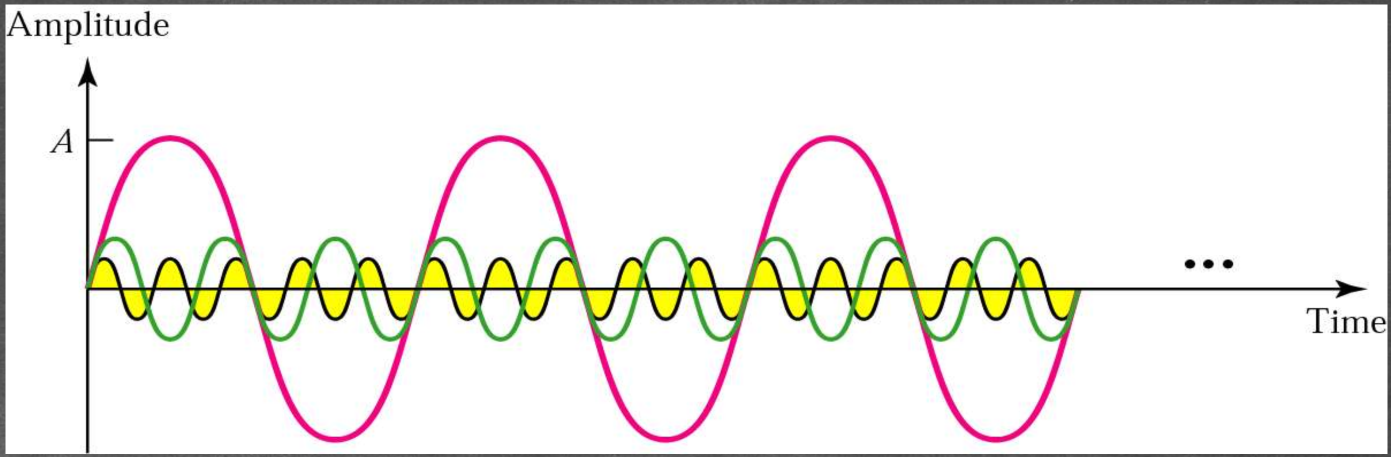
$$s(t) = \frac{4A}{\pi}\sin[2\pi ft] + \frac{4A}{3\pi}\sin[2\pi(3f)t] + \frac{4A}{5\pi}\sin[2\pi(5f)t] + \cdots$$

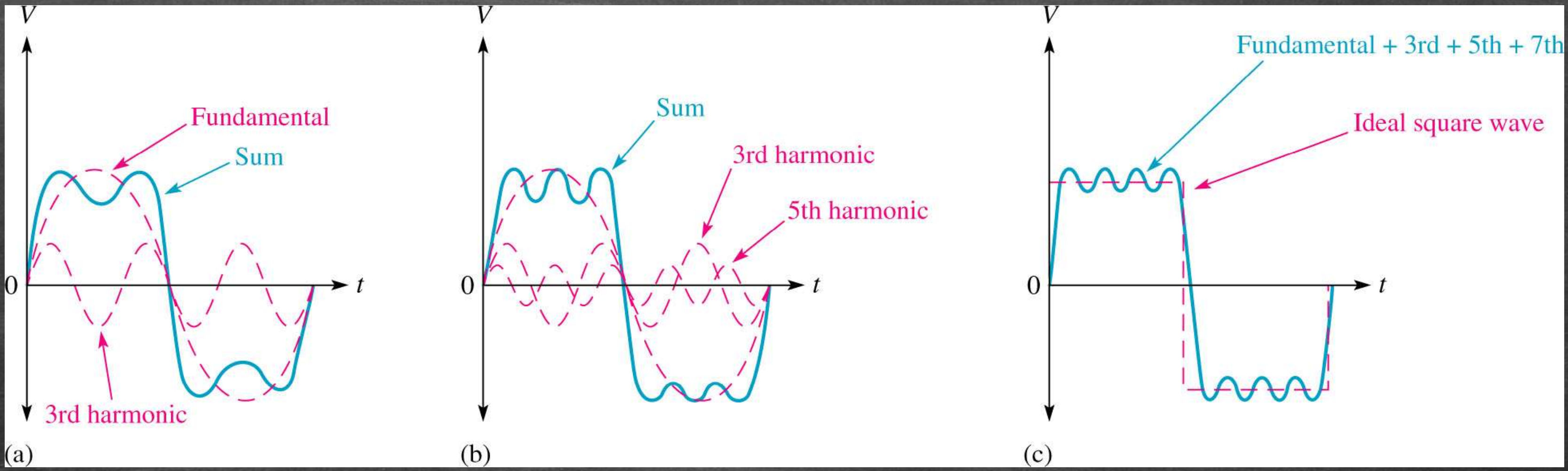




a. Frequency spectrum of a square wave

Periodic Digital Signals

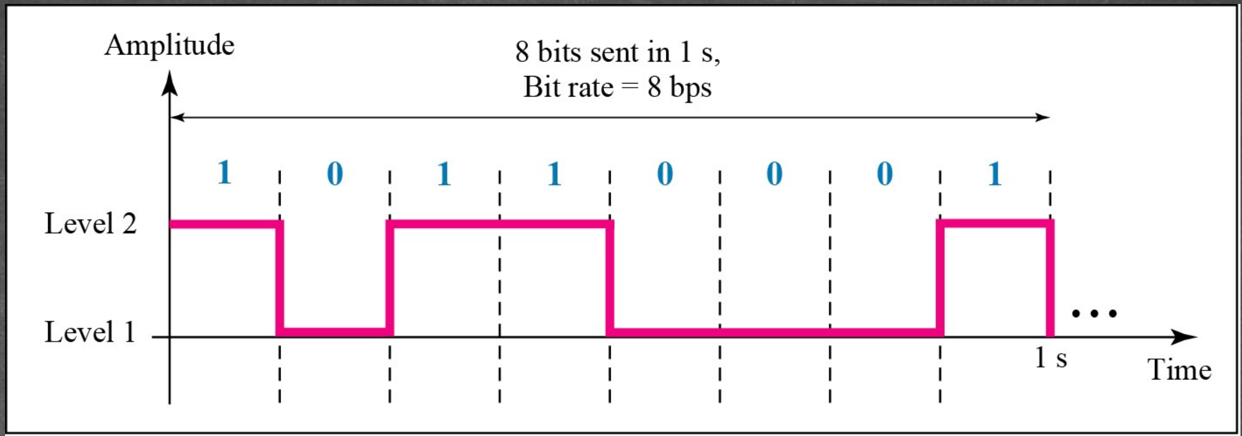




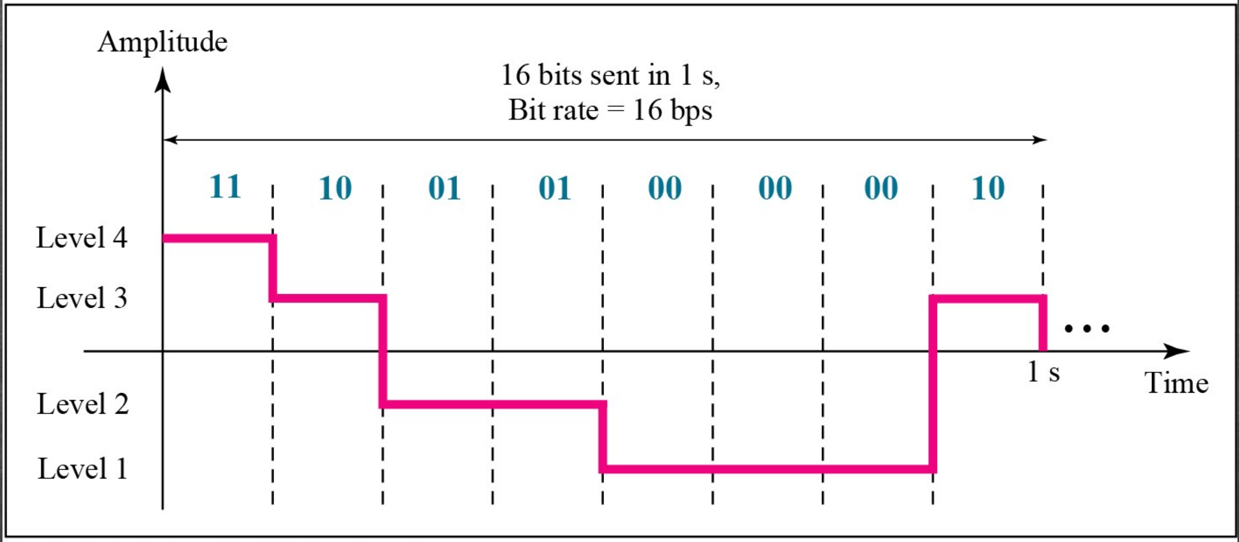
DIGITAL SIGNALS

- Bit Rate
- Bit Length
- Digital Signal as a Composite Analog Signal
- Transmission of Digital Signals

DIGITAL SIGNALS



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

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

จำนวน Level

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

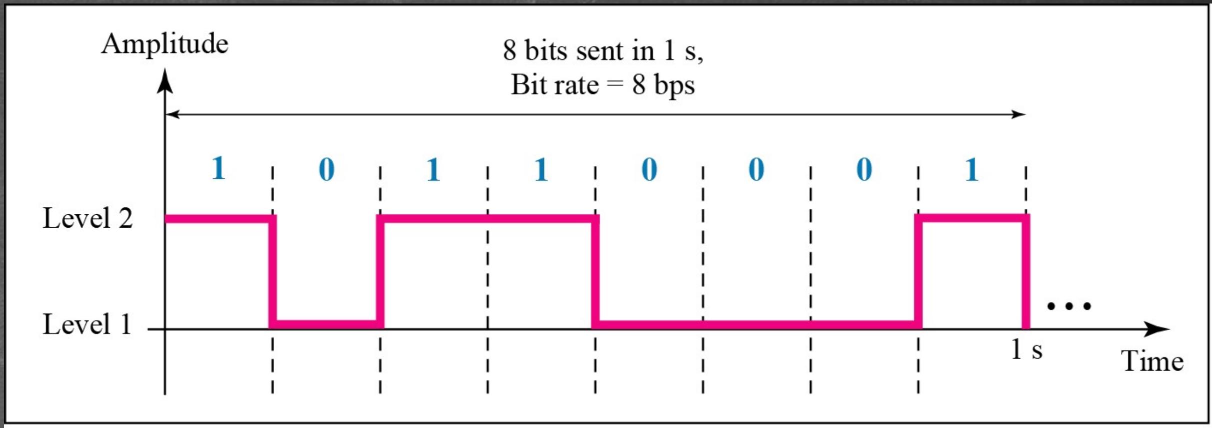
- Each signal level is represented by 3 bits.

Example 3.17

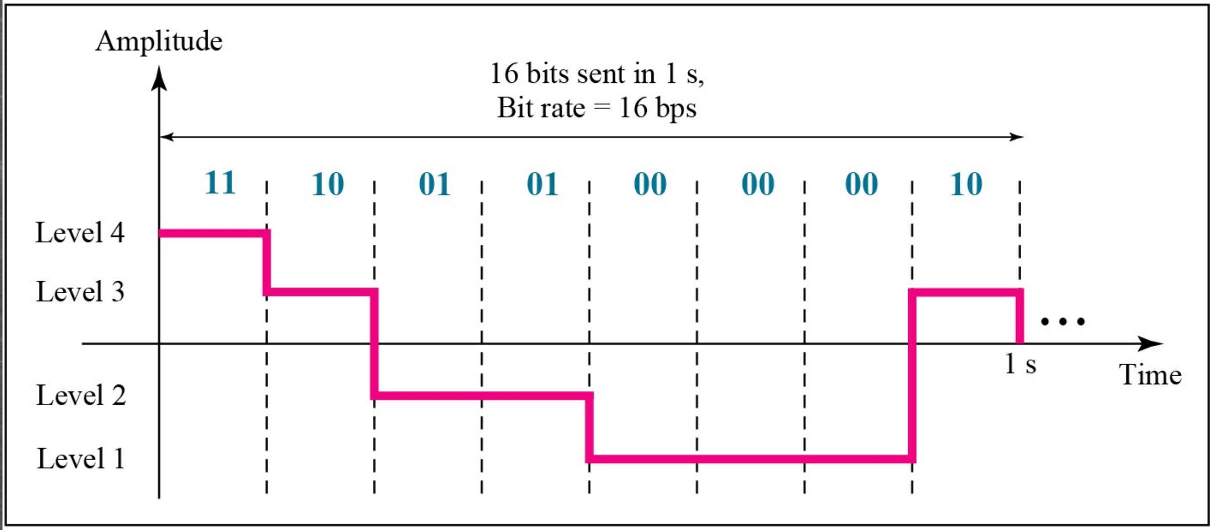
- A digital signal has nine levels.
  - How many bits are needed per level?

Bit Rate

- Most digital signals are nonperiodic and thus period and frequency are not appropriate characteristics.
- The bit rate is the number of bits sent in 1 Sec



a. A digital signal with two levels



b. A digital signal with four levels

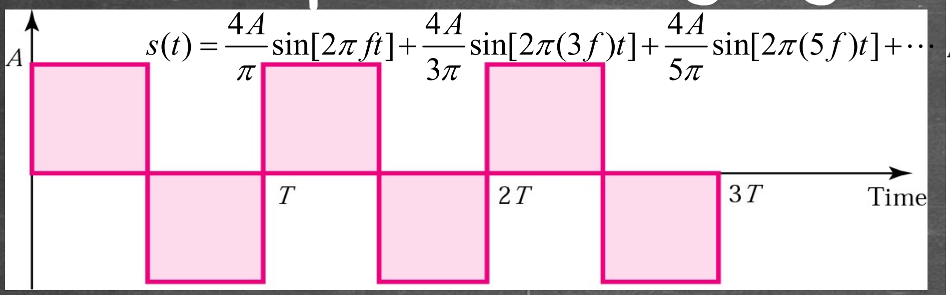
Bit Length

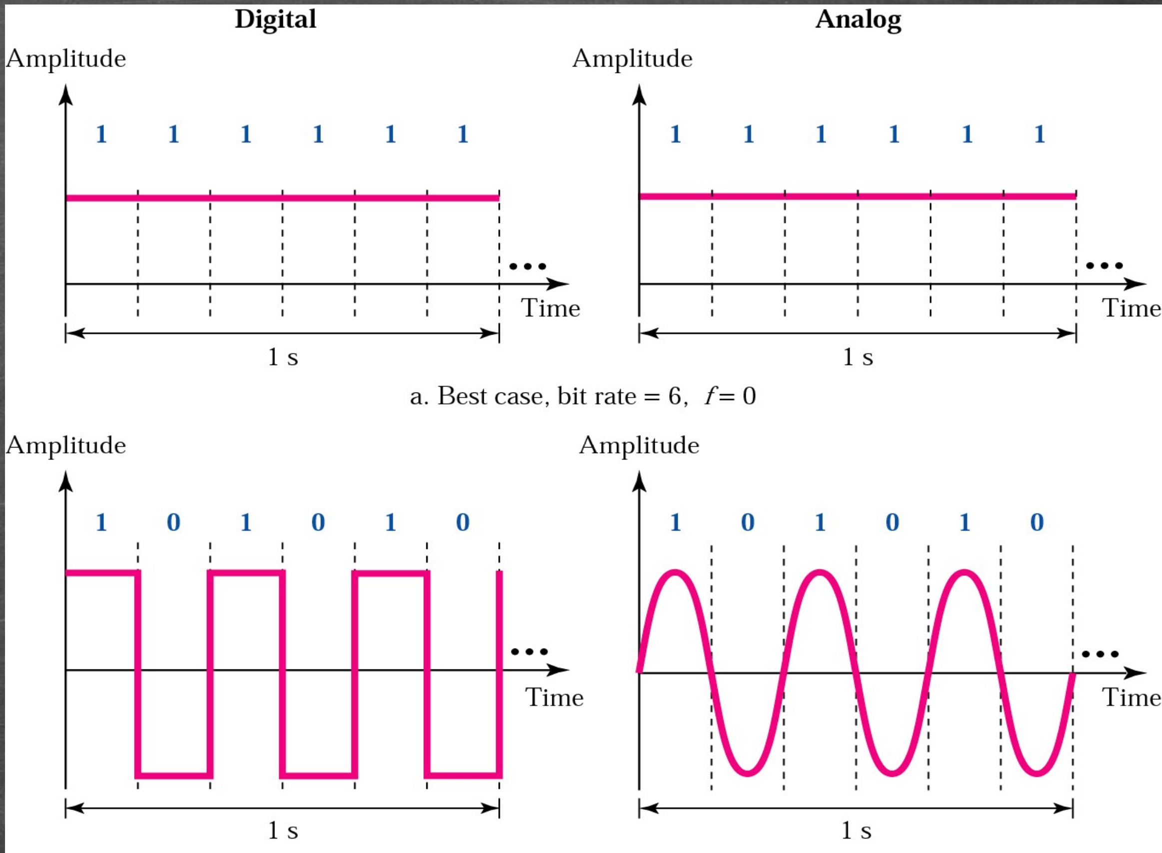
- We discussed the concept of the wavelength for an analog signal: the distance one cycle occupies on the transmission medium.
- We can define something similar for a digital signal: the bit length. The bit length is the distance one bit occupies on the transmission medium.

$$\text{Bit length} = \text{propagation speed} \times \text{bit duration}$$

Digital Signal as a Composite Analog Signal

- Based on Fourier analysis, a digital signal is a composite analog signal. The bandwidth is infinite.

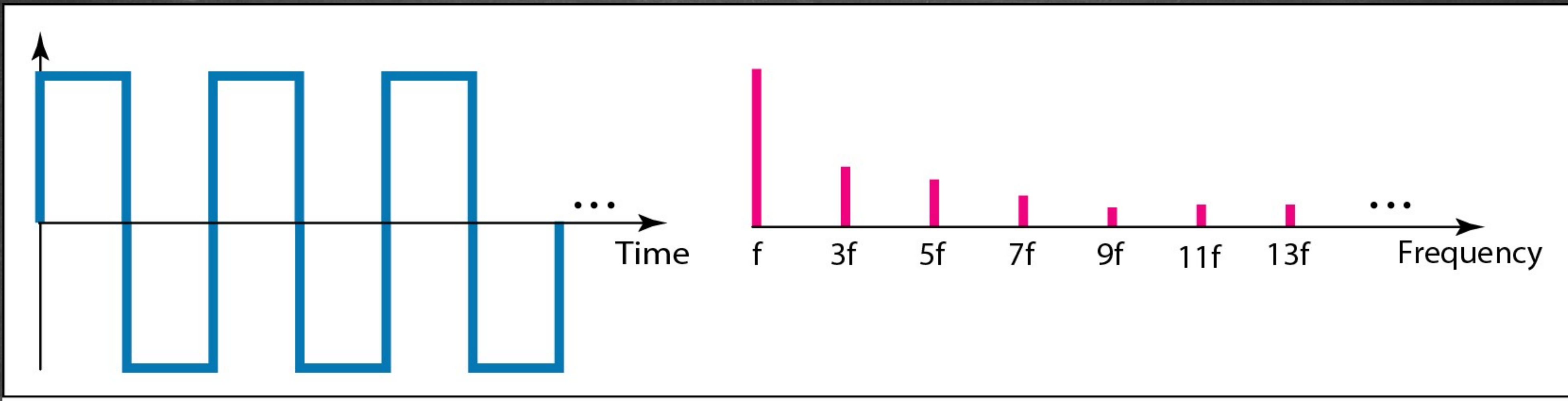




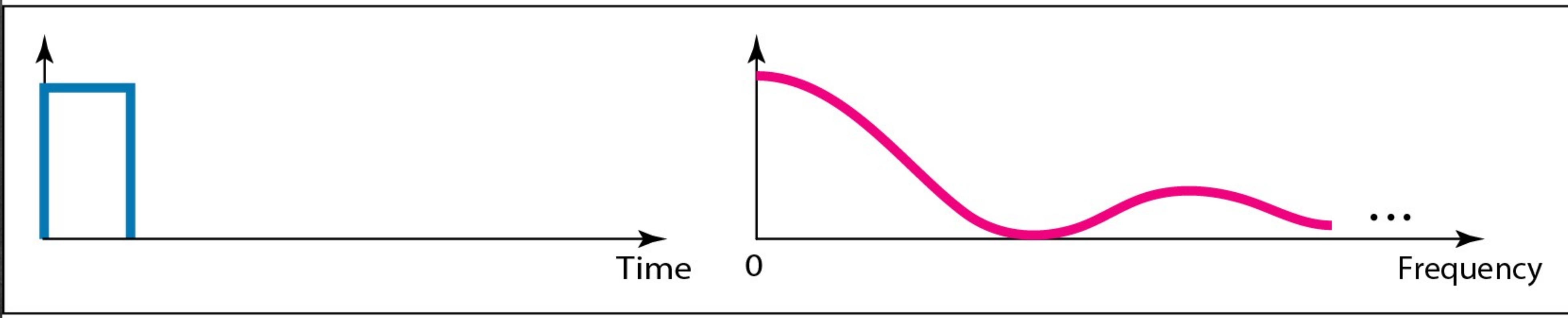
a. Best case, bit rate = 6, $f = 0$

b. Worst case, bit rate = 6, $f = 3$

Digital Signal as a Composite Analog Signal



a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

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

Transmission of Digital Signals

- A digital signal is a composite analog signal with an infinite bandwidth.
- Transmission of Digital Signals
  - Baseband Transmission
  - Broadband transmission

Baseband Transmission

มี Digital ก็ส่ง Digital ออกไป

- Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal.

ไม่ต้องจาก

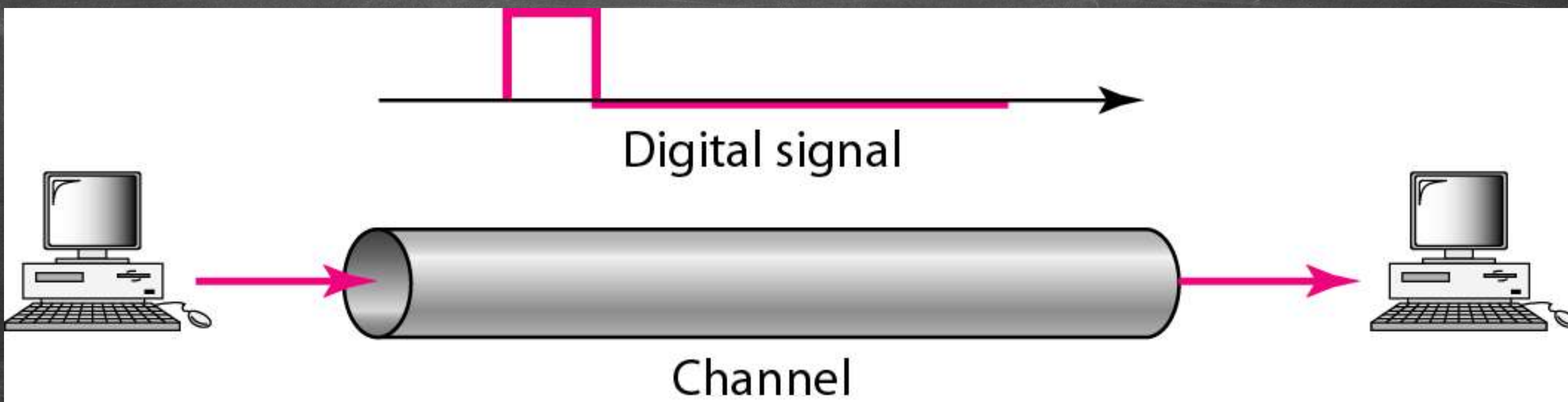


Figure 3.18 Baseband transmission

Baseband Transmission

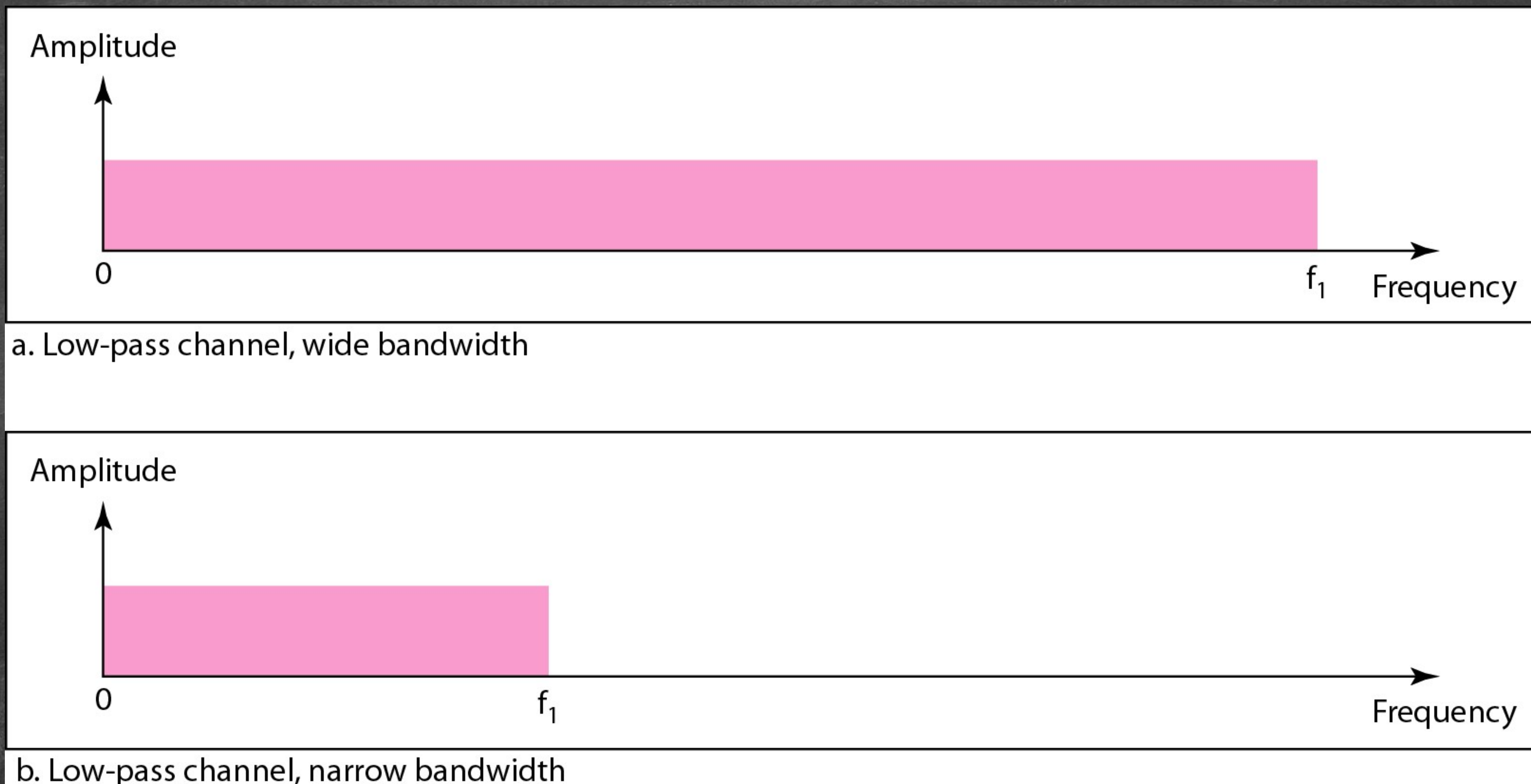


Figure 3.19 Bandwidths of two low-pass channels

Baseband Transmission

- Case 1: Low-Pass Channel with Wide Bandwidth

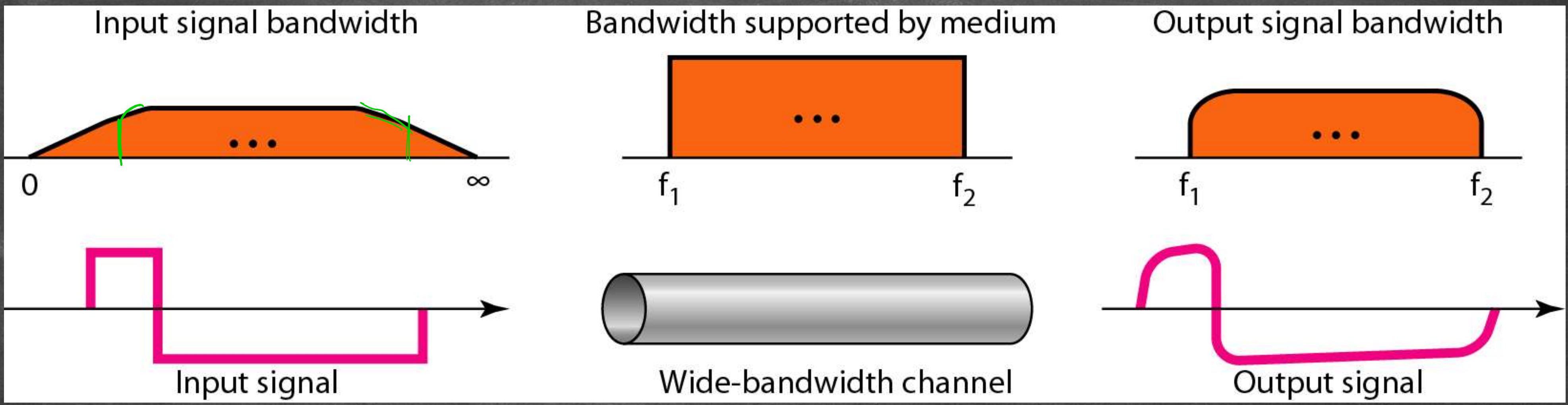


Figure 3.20 Baseband transmission using a dedicated medium

- 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.

Baseband Transmission

- Case 2: Low-Pass Channel with Limited Bandwidth

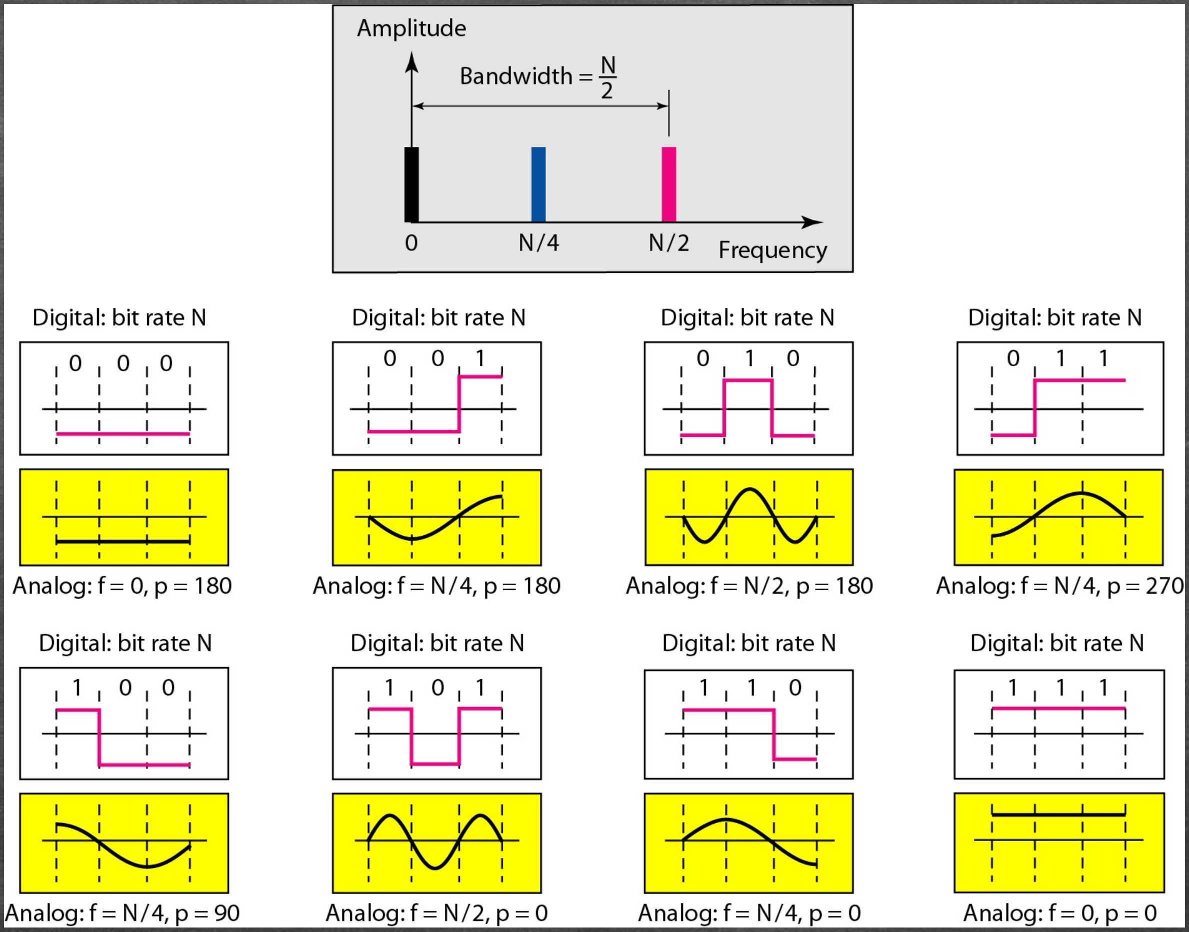


Figure 3.21 Rough approximation of a digital signal using the first for worst case

Baseband Transmission

- Better Approximation

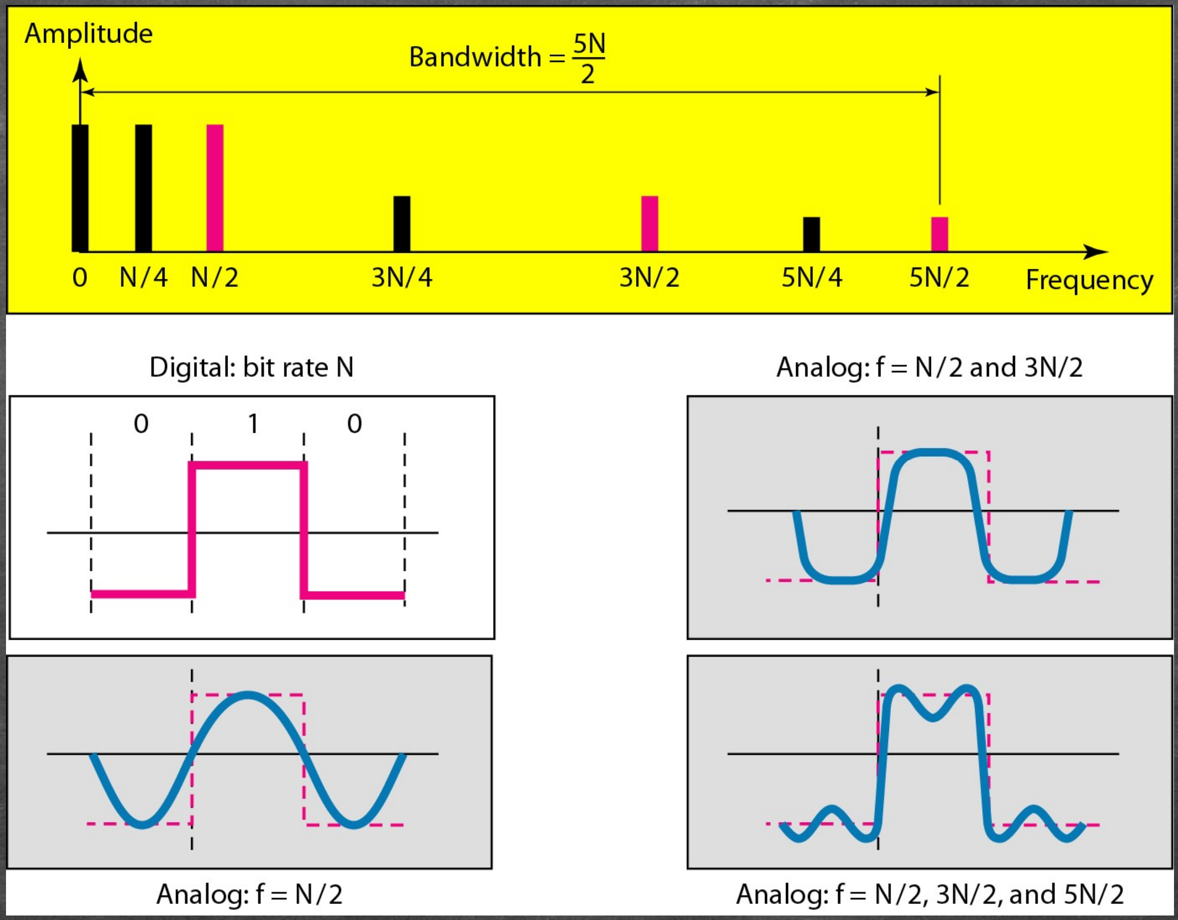


Figure 3.22 Simulating a digital signal with first three harmonics

Baseband Transmission

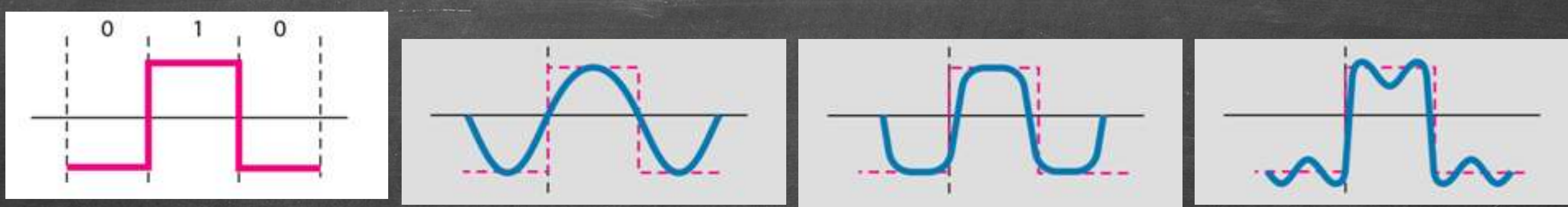
- In baseband transmission, the required bandwidth is proportional to the bit rate; if we need to send bits faster, we need more bandwidth.

$f_0 = \frac{N}{2}$

$\frac{1k}{2} = 500$

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



Broadband Transmission (Using Modulation)

- Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.
- Modulation allows us to use a bandpass channel-a channel with a bandwidth that does not start from zero.

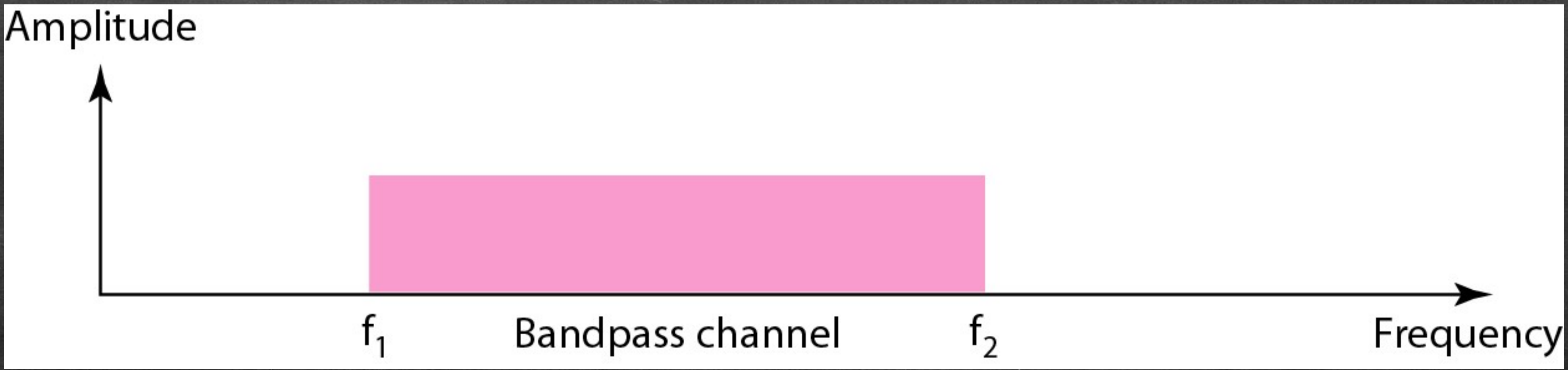


Figure 3.23 Bandwidth of a bandpass channel

Broadband Transmission (Using Modulation)

- 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

TRANSMISSION IMPAIRMENT

- Attenuation
- Distortion
- Noise

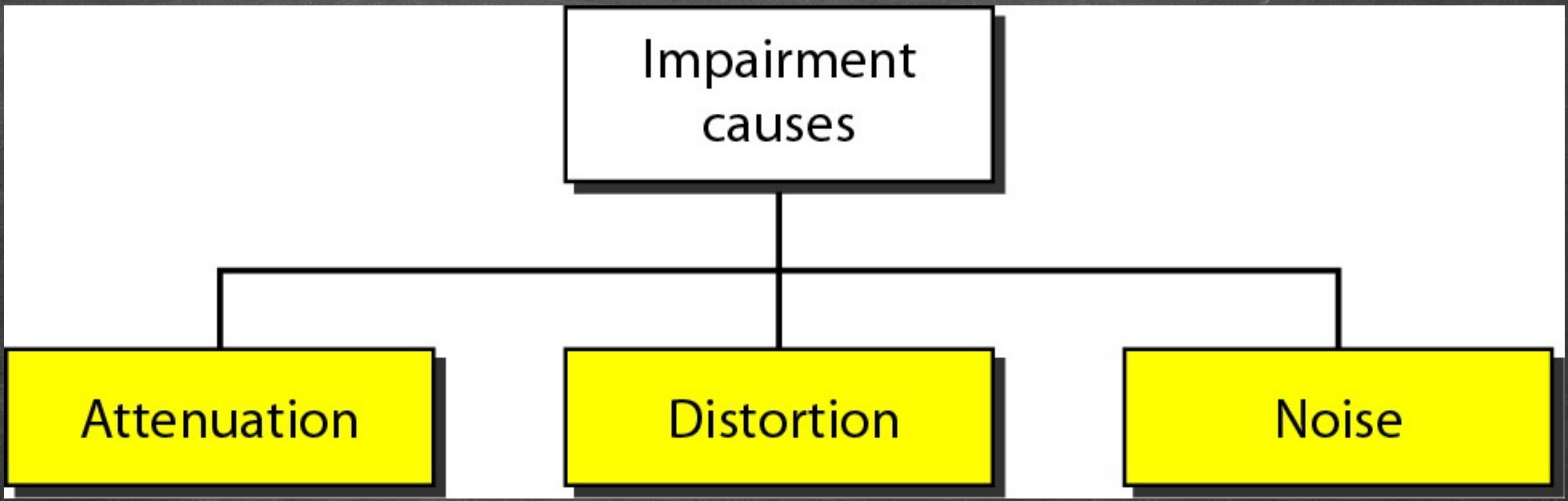


Figure 3.25 Causes of impairment

Attenuation

- Means a loss of energy
  - the resistance of the medium
  - converted to heat

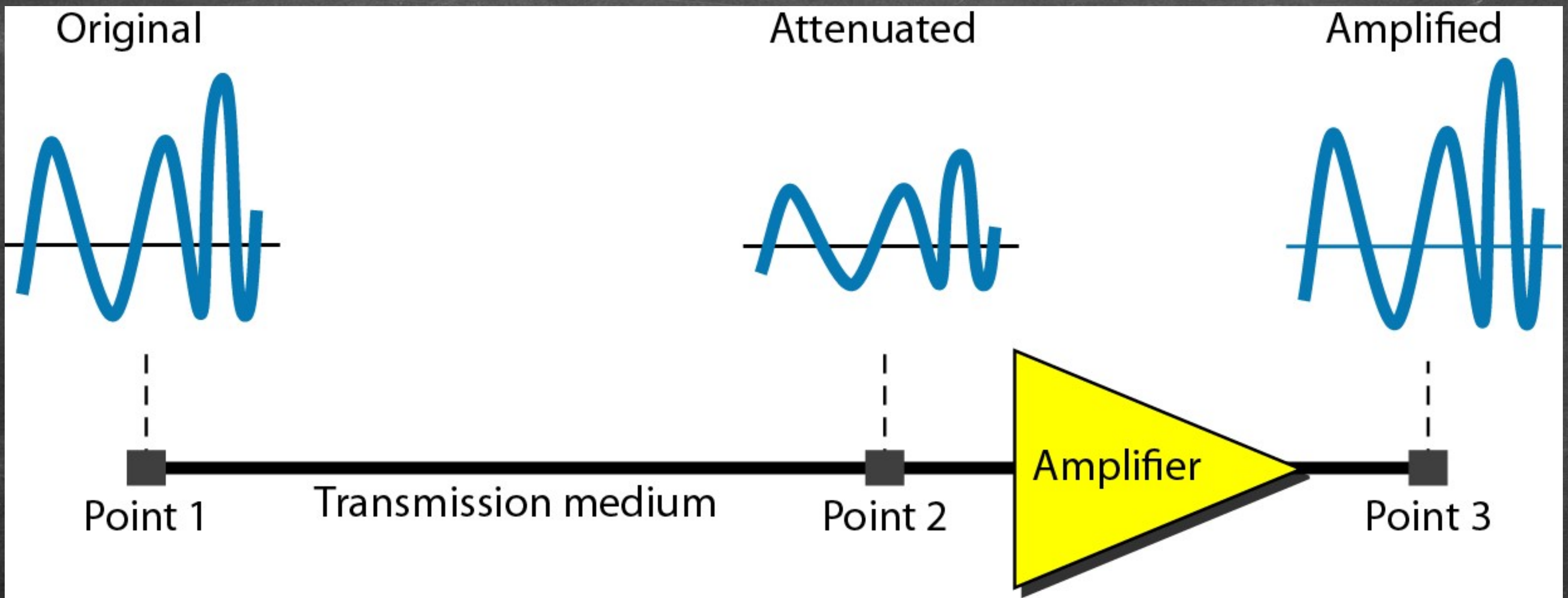


Figure 3.26 Attenuation

Attenuation

- Decibel (dB)
  - a signal has lost or gained strength
  - measures the relative strengths of two signals or one signal at two different points

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

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

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.

Distortion

- means that the signal changes its form or shape
  - can occur in a composite signal made of different frequencies
  - Each signal component has its own propagation speed (delay => phase)

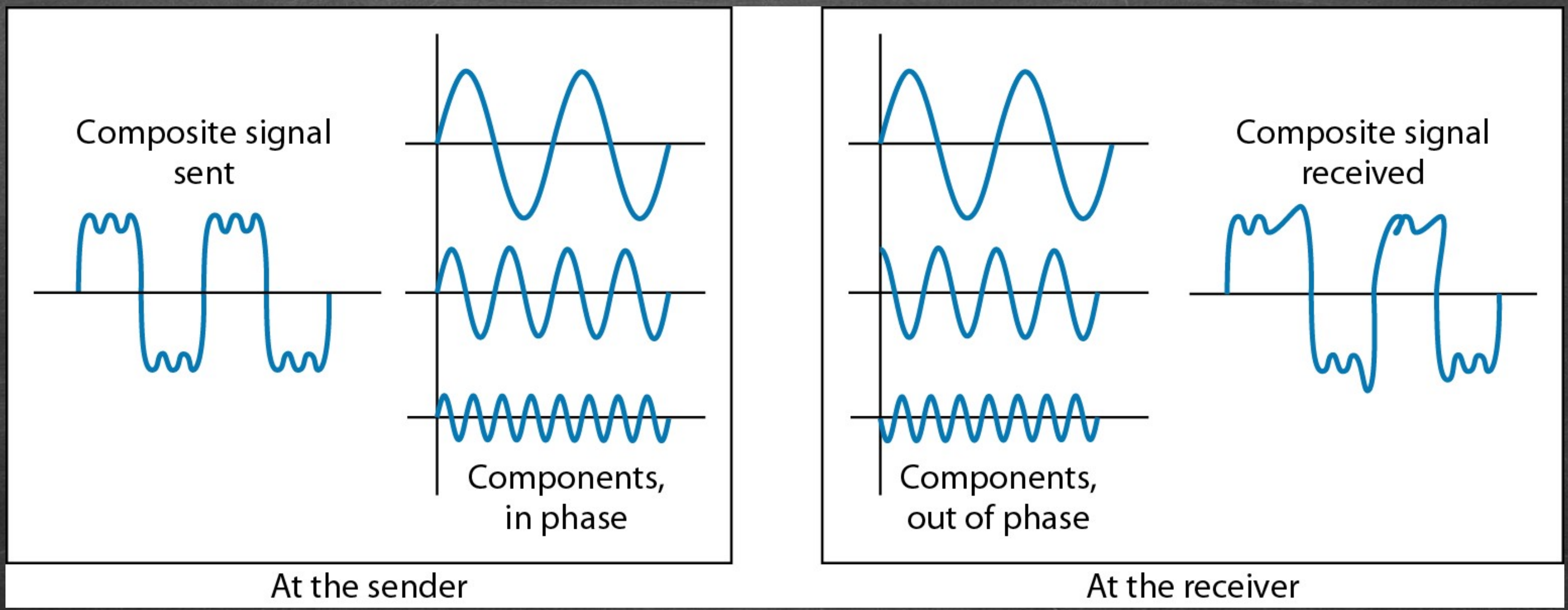


Figure 3.28 Distortion

Noise

- another cause of impairment
  - Several types of noise : thermal noise, induced noise (motors and appliances), crosstalk (effect of one wire), and impulse noise (power lines, lightning), may corrupt the signal

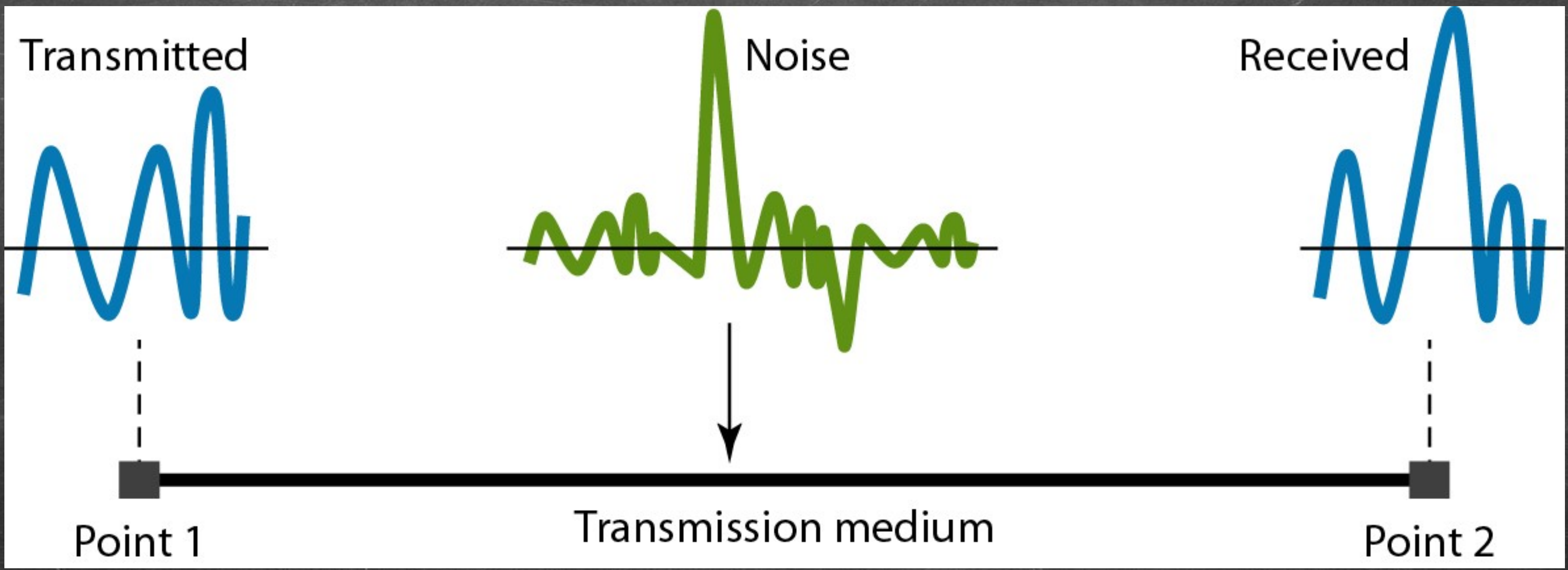


Figure 3.29 Noise

Signal-to-Noise Ratio (SNR)

- the ratio of the signal power to the noise power

$$SNR = \frac{\text{average signal power}}{\text{average noise power}}$$

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

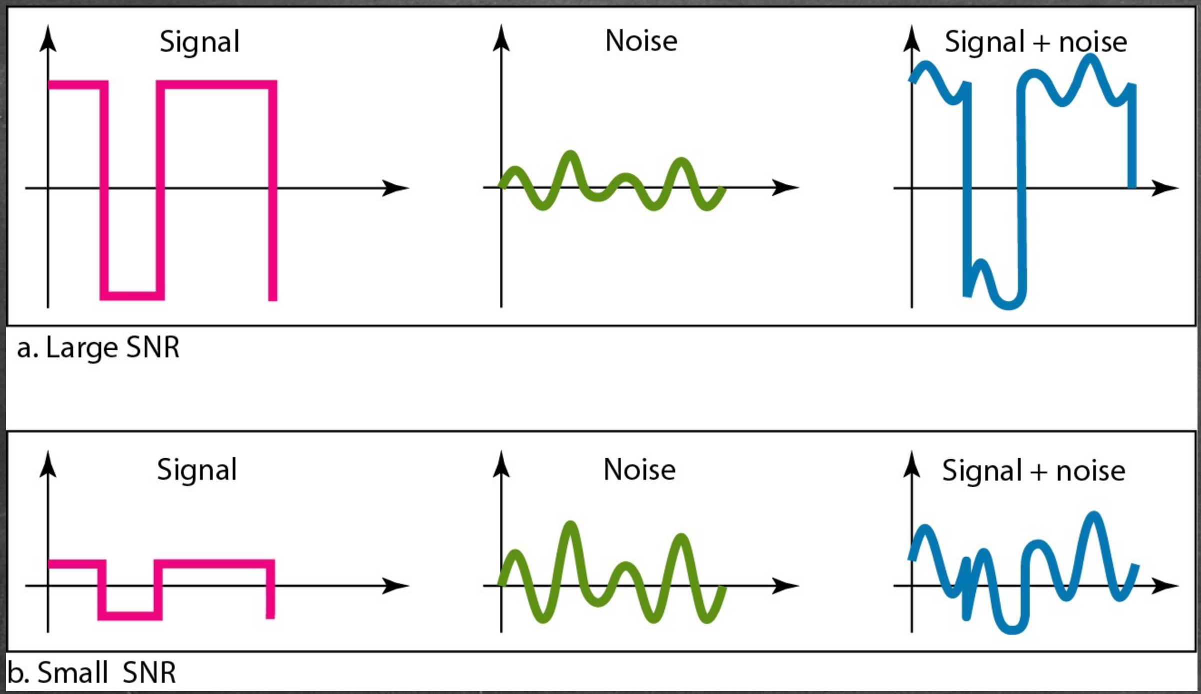


Figure 3.30 Two cases of SNR: a high SNR and a low SNR

DATA RATE LIMITS

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

Harry Nyquist

https://en.wikipedia.org/wiki/Harry_Nyquist

Claude Shannon

https://en.wikipedia.org/wiki/Claude_Shannon

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:
  - The bandwidth available
  - The level of the signals we use
  - The quality of the channel (the level of noise)
- Two theoretical formulas were developed to calculate the data rate
  - Nyquist for a <u>noiseless channel</u>
  - Shannon for a <u>noisy channel</u>

Noiseless Channel: Nyquist Bit Rate

- Nyquist bit rate formula defines the theoretical maximum bit rate

$$\text{BitRate} = 2 \times \text{bandwidth} \times \log_2 L$$

  - bandwidth is the bandwidth of the channel
  - L is the number of signal levels used to represent data
  - BitRate is the bit rate in bits per second
- Increasing the levels of a signal may reduce the reliability of the system.

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

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

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.

Noisy Channel: Shannon Capacity

- Shannon capacity, to determine the theoretical highest data rate for a noisy channel

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

  - bandwidth is the bandwidth of the channel
  - SNR is the signal-to-noise ratio
  - capacity is the capacity of the channel in bits per second

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.

Using Both Limits

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

- In practice, we need to use both methods to find the limits and signal levels. Let us show this with an example.

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.

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

Example 3.41

- 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.

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

PERFORMANCE

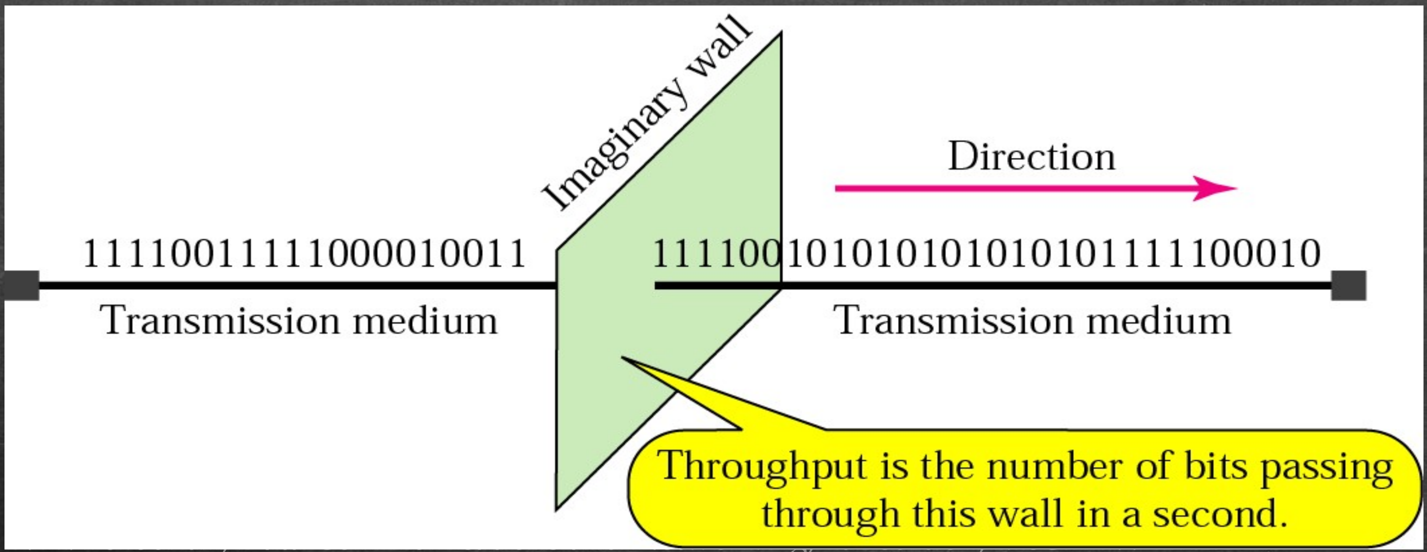
- Bandwidth
- Throughput
- Latency (Delay)
- Bandwidth-Delay Product

Bandwidth

- Bandwidth in Hertz
  - the range of frequencies contained in a composite signal or the range of frequencies a channel can pass : bandwidth of a subscriber telephone line is 4 kHz
- Bandwidth in Bits per Seconds
  - refer to the number of bits per second that a channel, a link, or even a network can transmit : Max of Fast Ethernet network 100 Mbps
- Relationship
  - bandwidth in hertz
  - bandwidth in bits per seconds

Throughput

- a measure of how fast we can actually send data through a network
  - A link may have a bandwidth of *B bps, but we can only send T bps* through this link with *T always less than B.*
  - the bandwidth is a potential measurement of a link; the throughput is an actual measurement of how fast we can send data



Latency (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 = propagation time + transmission time + queuing time + processing delay

- propagation time = distance / propagation speed
- transmission time = message size / bandwidth
- queuing time = the time needed for each intermediate or end device to hold the message before it can be processed
- processing delay

Bandwidth-Delay Product

- The bandwidth-delay product defines the number of bits that can fill the link.
  - Link Bandwidth (bps)
  - Delay from Sender to Receiver (sec)
- two performance metrics of a link
  - Case 1. Figure 3.31 shows case 1.
  - Case 2. Now assume we have a bandwidth of 4 bps. Figure 3.32

Case 1.

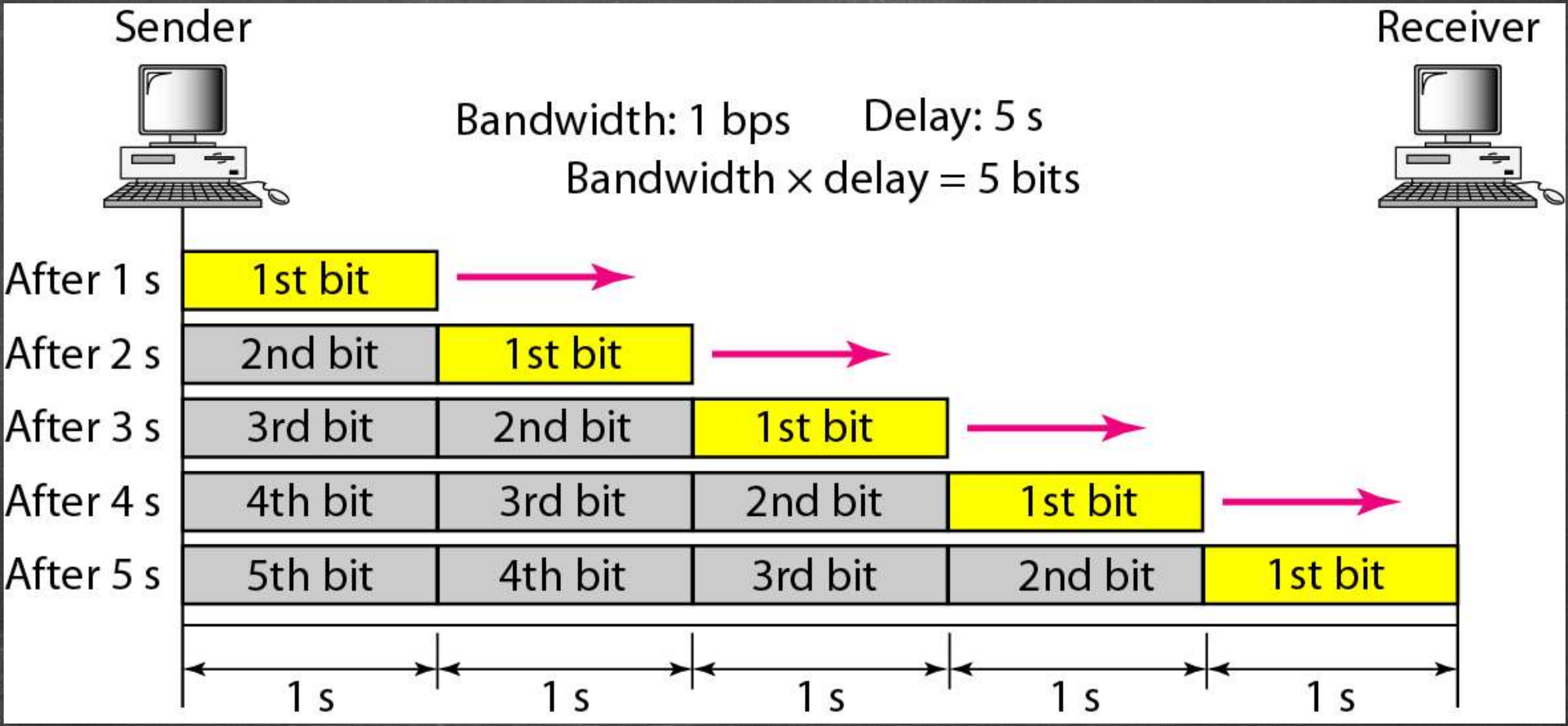


Figure 3.31 Filling the link with bits for case 1

Case 2.

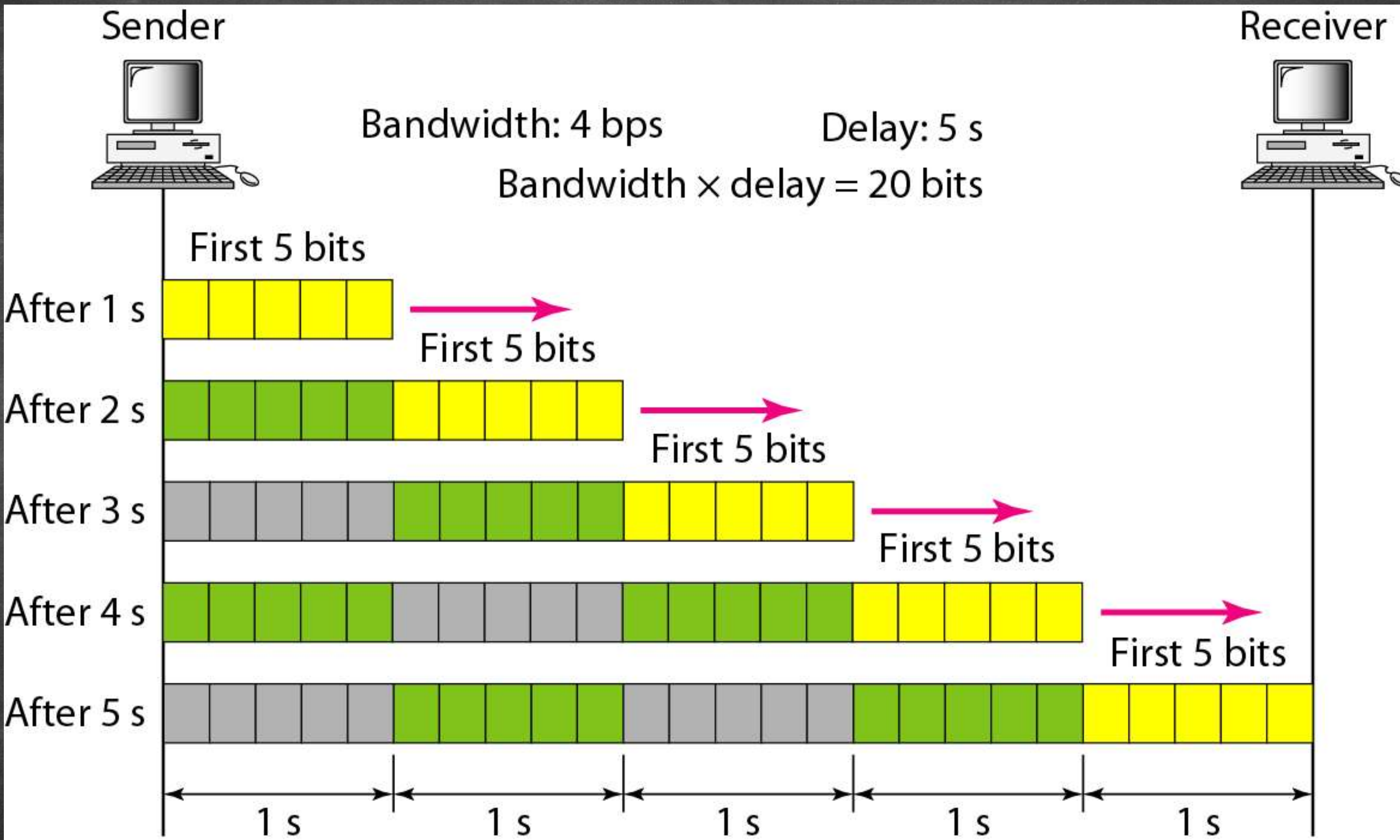


Figure 3.32 Filling the link with bits in case 2