Lecture 03
Introduction to Physical Layer

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Course Schedule (Tentative)

- FL: Flipped learning
- **Rec: Recorded video for makeup class**

No	Topics	Date-M		Date-Th	
1	Introduction to course and data communications (Ch1)	09/05	FL (**Zoom**)	09/08	FL
2	Intro. to data communications (Ch1) & Network models (Ch2)	09/12	**Rec**	09/15	FL
3	Intro. to physical layer (Ch3)	09/19	FL	09/22	FL
4	Digital transmission (Ch4)	09/26	FL	09/29	FL
5	Analog transmission (Ch5) & Bandwidth utilization: multiplexing (Ch6.1)	10/03	**Rec**	10/06	**Rec**
6	Bandwidth utilization: spread spectrum (Ch6.2) Transmission Media (Ch7)	10/10	**Rec**	10/13	FL
7	Switching (Ch8) Introduction to Data-Link Layer (Ch9)	10/17	FL	10/20	FL
8	**Midterm exam**	**10/24**	**Evening**	**10/24**	**Evening**
9	Error detection and correction (Ch10)	10/31	FL	11/03	FL
10	Data link control (Ch11)	11/07	FL	11/10	FL
11	Media Access Control (Ch12)	11/14	FL	11/17	**Rec**
12	Wired LAN (Ethernet) (Ch13) & Other wired network (Ch14)	11/21	**Rec**	11/24	FL
13	Wireless LAN (Ch15)	11/28	FL	12/01	FL
14	Other wireless networks (Ch16) Connecting devices and virtual LANs (Ch17)	12/05	FL	12/08	FL
15	**Final exam**	**12/12**	**Evening**	**12/12**	**Evening**

OUTLINES

- Chapter 3
  - Data and signals
  - Periodic analog signals
  - Digital signals
  - Transmission impairment
  - Data rate limits
  - Performance
- Summary & Next class

Ch 3. Intro. Physical Layer

: Data and signals, Periodic analog signals, Digital signals, Transmission impairment, Data rate limits, Performance

- ❑ <u>Ch 3. Introduction to physical layer</u>
- ❑ Summary & Next Class

Ch 3 Objective

- The first section shows how data and signals can be either analog or digital.
  - Analog refers to an entity that is continuous
  - Digital refers to an entity that is discrete.
- The second section shows that only periodic analog signals can be used in data communication.
  - It discusses simple and composite signals.
  - The attributes of analog signals such as period, frequency, and phase are also explained.
- The third section shows that only non-periodic digital signals can be used in data communication.
  - The attributes of a digital signal such as bit rate and bit length are discussed.
  - We also show how digital data can be sent using analog signals. Baseband and broadband transmission are also discussed in this section.

Ch 3 Objective

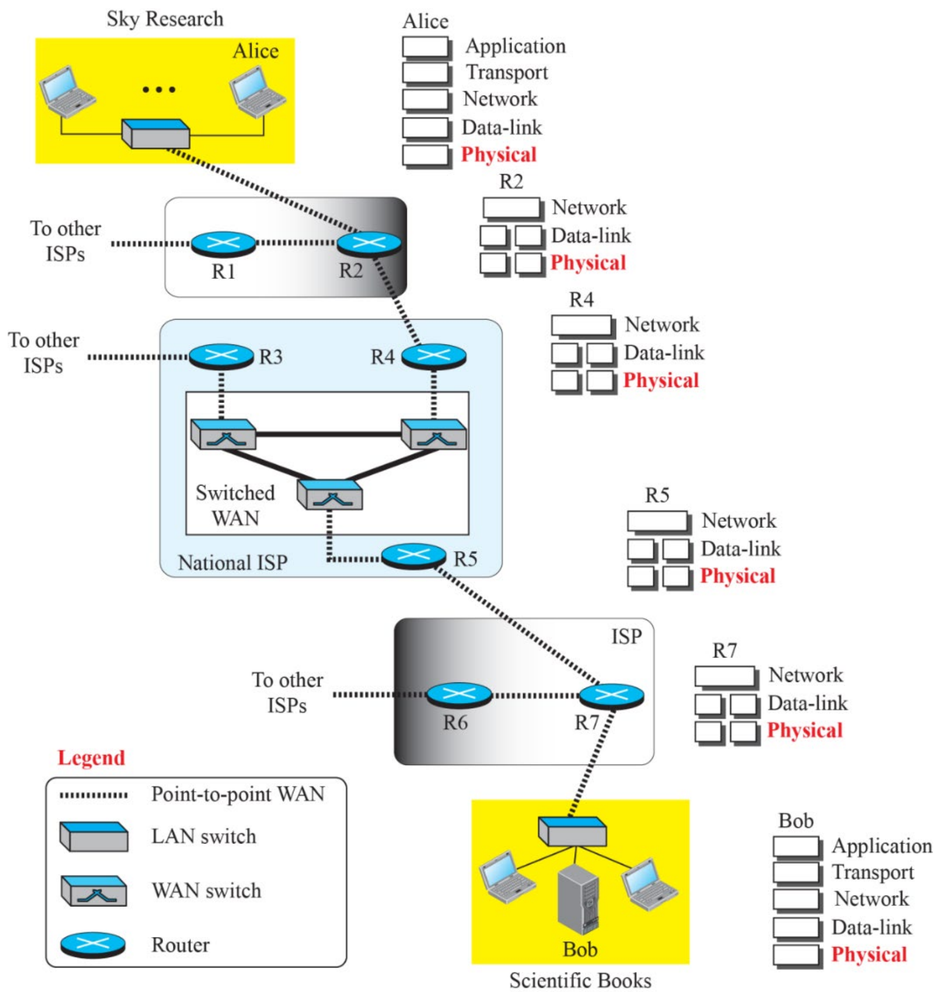
- The fourth section is devoted to transmission impairment.
  - The section shows how attenuation, distortion, and noise can impair a signal.
  - The fifth section discusses the data rate limit
    - How many bits per second we can send with the available channel.
  - The data rates of noiseless and noisy channels are examined and compared.
- The sixth section discusses the performance of data transmission.
  - Several channel measurements are examined including bandwidth, throughput, latency, and jitter.
  - Performance is an issue that is revisited in several future chapters.

3-1 DATA AND SIGNALS

- Figure 3.1 shows a scenario in which a scientist working in a research company, Sky Research, needs to order a book related to her research from an online bookseller, Scientific Books.
  - Alice and Bob need to exchange data
  - Communication at the PHY layer means exchanging signals
  - Both data and signals: analog or digital

3-1 DATA AND SIGNALS

- Figure 3.1: Communication at the physical layer



3.1.1 Analog and Digital Data

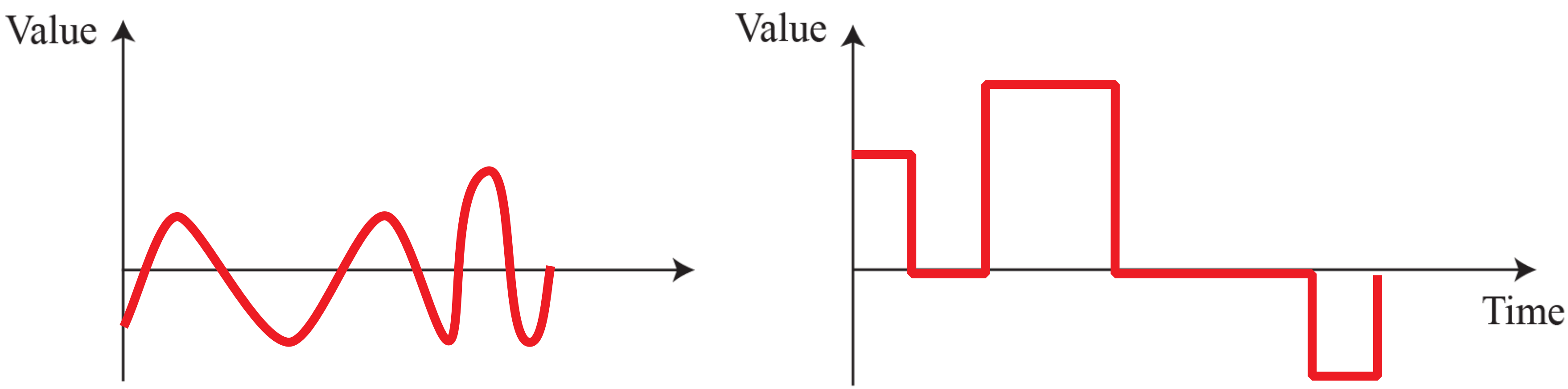
- Data can be analog or digital.
  - The term analog data refers to information that is continuous;
  - Digital data refers to information that has discrete states.
  - For example,
    - An analog clock that has hour, minute, and second hands gives information in a continuous form; the movements of the hands are continuous.
    - On the other hand, a digital clock that reports the hours and the minutes will change suddenly from 8:05 to 8:06.

3.1.2 Analog and Digital Signals

- Like the data they represent, signals can be either analog or digital.
  - An analog signal has 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.
  - A digital signal, on the other hand, can have only a limited number of defined values.
    - Although each value can be any number, it is often as simple as 1 and 0.

3.1.2 Analog and Digital Signals

- Figure 3.2: Comparison of analog and digital signals



a. Analog signal

b. Digital signal

3.1.3 Periodic and Nonperiodic

- 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 a cycle.
- A nonperiodic signal changes without exhibiting a pattern or cycle that repeats over time.
- Both analog and digital signals.

3-2 PERIODIC ANALOG SIGNALS

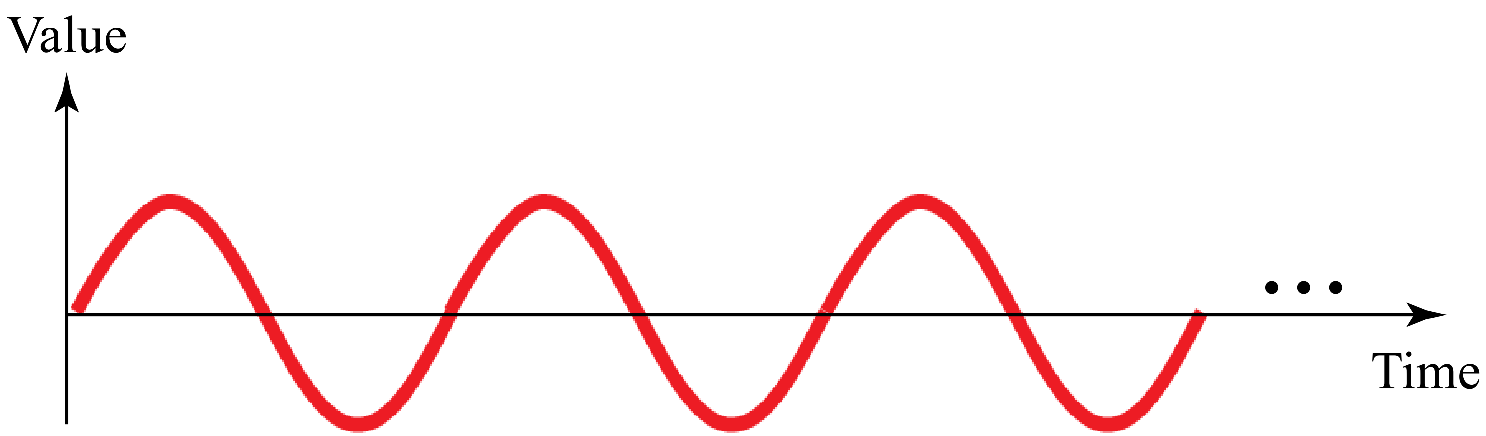
- Periodic analog signals can be classified as simple or composite.
  - A simple periodic analog signal, a sine wave, cannot be decomposed into simpler signals.
  - A composite periodic analog signal is composed of multiple sine waves.

3.2.1 Sine Wave

- The sine wave is the most fundamental form of a periodic analog signal.
  - When we visualize it as a simple oscillating curve, its change over the course of a cycle is smooth and consistent, a continuous, rolling flow.
  - Figure 3.3 shows a sine wave.
    - Each cycle consists of a single arc above the time axis followed by a single arc below it.

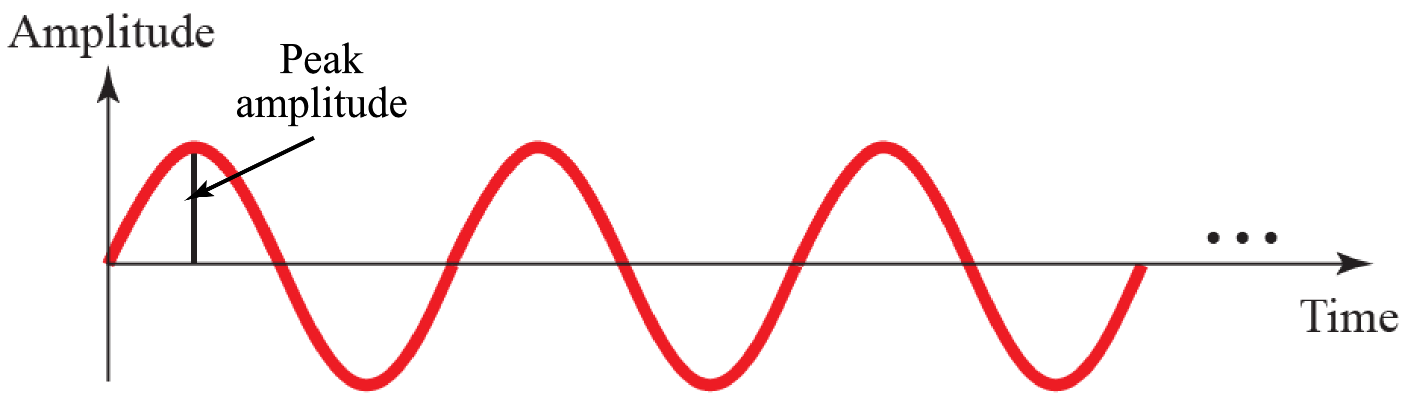
3.2.1 Sine Wave

- Figure 3.3: A sine wave

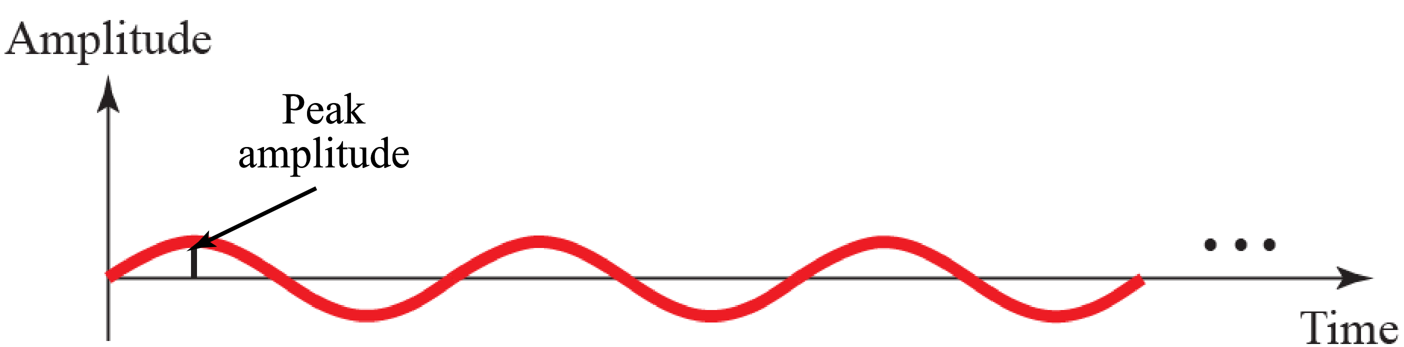


3.2.1 Sine Wave

- Figure 3.4: Two signals with two different amplitudes



a. A signal with high peak amplitude



b. A signal with low peak amplitude

3.2.1 Sine Wave

- Example 3.1
  - The power in your house can be represented by a sine wave with a peak amplitude of 155 to 170 V. However, it is common knowledge that the voltage of the power in U.S. homes is 110 to 120 V. This discrepancy is due to the fact that these are root mean square (rms) values. The signal is squared and then the average amplitude is calculated. The peak value is equal to $2^{1/2} \times$ rms value.

- Example 3.2
  - The voltage of a battery is a constant; this constant value can be considered a sine wave, as we will see later. For example, the peak value of an AA battery is normally 1.5 V.

3.2.1 Sine Wave

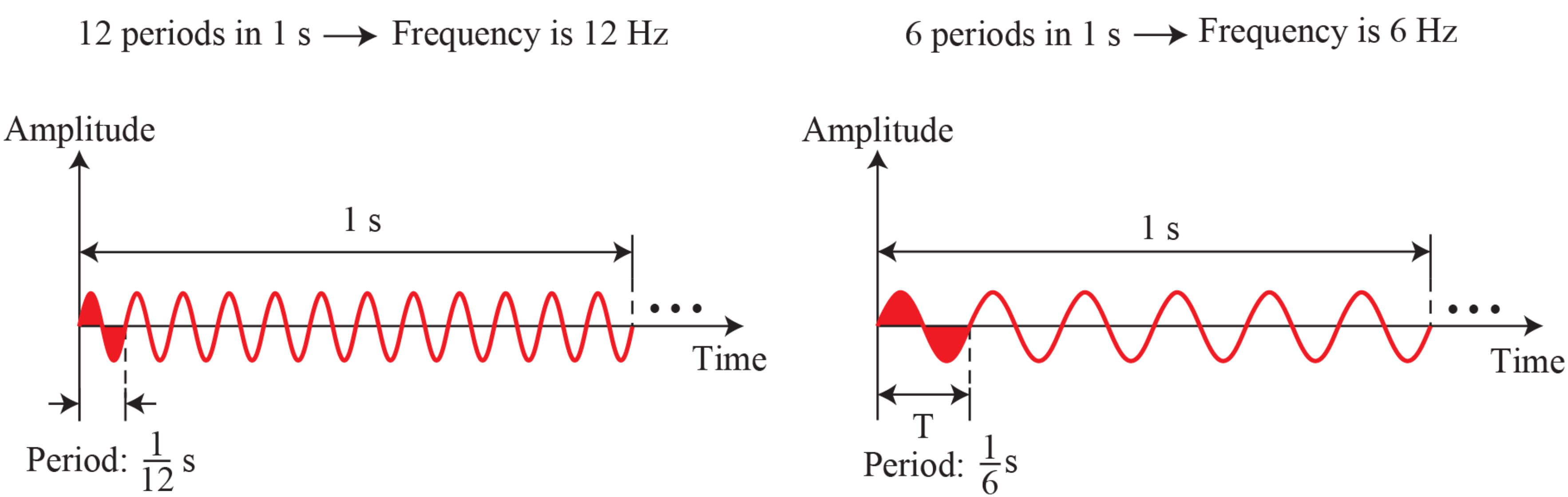
- Period: T
  - The amount of time, in seconds, a signal needs to complete 1 cycle
- Frequency: f
  - The number of periods in 1 sec
- Frequency and period are the inverse of each other

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

- Hertz (Hz)
  - Cycle per second

3.2.1 Sine Wave

- Figure 3.5: Two signals with the same phase and frequency, but different amplitudes



a. A signal with a frequency of 12 Hz

b. A signal with a frequency of 6 Hz

3.2.1 Sine Wave

- Table 3.1: Units of period and frequency

Period		*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

3.2.1 Sine Wave

- Example 3.3
  - The power we use at home has a frequency of 60 Hz (50 Hz in Europe). The period of this sine wave can be determined as follows:

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

  - This means that the period of the power for our lights at home is 0.0116 s, or 16.6 ms. Our eyes are not sensitive enough to distinguish these rapid changes in amplitude.

3.2.1 Sine Wave

- 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 106 μs). We make the following substitutions:

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

3.2.1 Sine Wave

- 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).

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

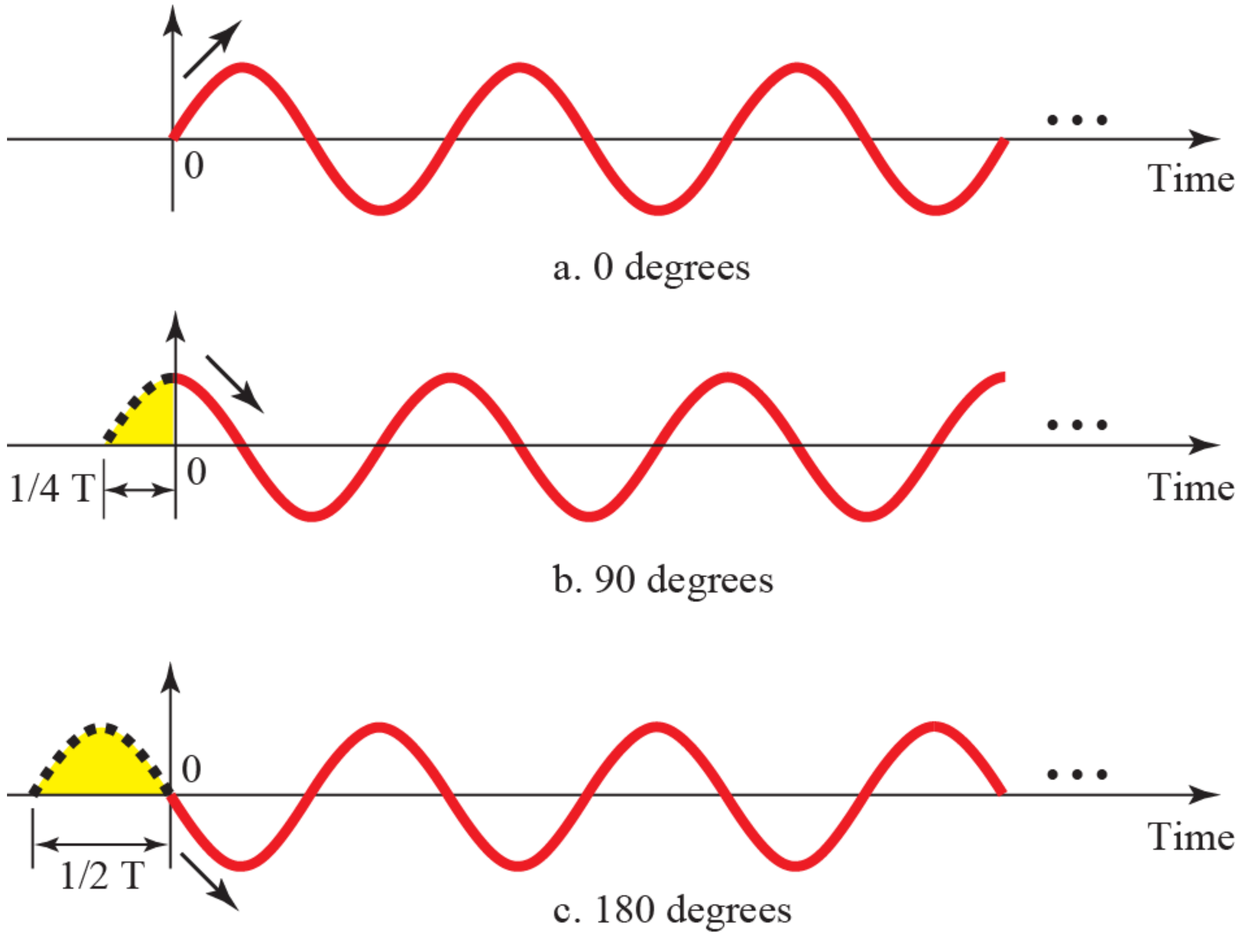
$$f = \frac{1}{T} = \frac{1}{10^{-1}} \text{Hz} = 10 \text{ Hz} = 10 \times 10^{-3} \text{ kHz} = 10^{-2} \text{ kHz}$$

3.2.2 Phase

- The term phase, or phase shift, describes the position of the waveform relative to time 0.
  - If we think of the wave as something that can be shifted backward or forward along the time axis, phase describes the amount of that shift.
  - It indicates the status of the first cycle.
- Phase is measured in degrees or radians
  - 360° is 2π rad
  - 1° is $2\pi/360$ rad
  - 1 rad is $360/(2\pi)^\circ$

3.2.2 Phase

- Figure 3.6: Three sine waves with different phases



3.2.2 Phase

- Example 3.6
  - A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?
  - Solution
    - We know that 1 complete cycle is 360°. Therefore, 1/6 cycle is

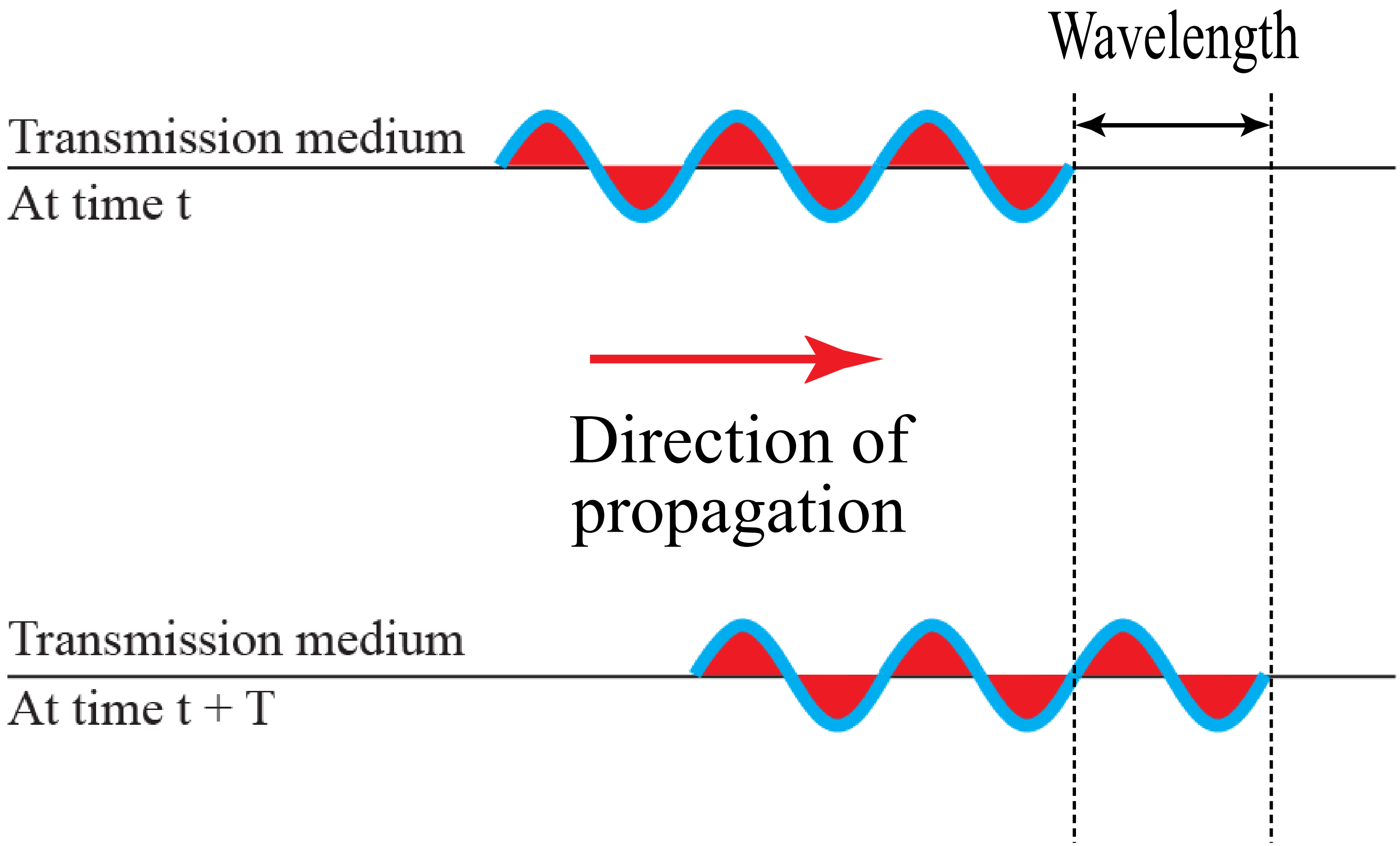
$$\frac{1}{6} \times 360 = 60^\circ = 60 \times \frac{2\pi}{360} \text{ rad} = \frac{\pi}{3} \text{ rad} = 1.046 \text{ rad}$$

3.2.3 Wavelength

- Wavelength is another characteristic of a signal traveling through a transmission medium.
- Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium (see Figure 3.7).

3.2.3 Wavelength

- Figure 3.7: Wavelength and period



3.2.3 Wavelength

- The frequency of a signal is independent of the medium
- The wavelength depends on both the frequency and medium
- For wavelength λ, propagation speed c (3×10^8), and frequency f,

$$\text{Wavelength} = (\text{propagation speed}) \times \text{period} = \frac{\text{propagation speed}}{\text{frequency}}$$

$$\lambda = \frac{c}{f}$$

- For example

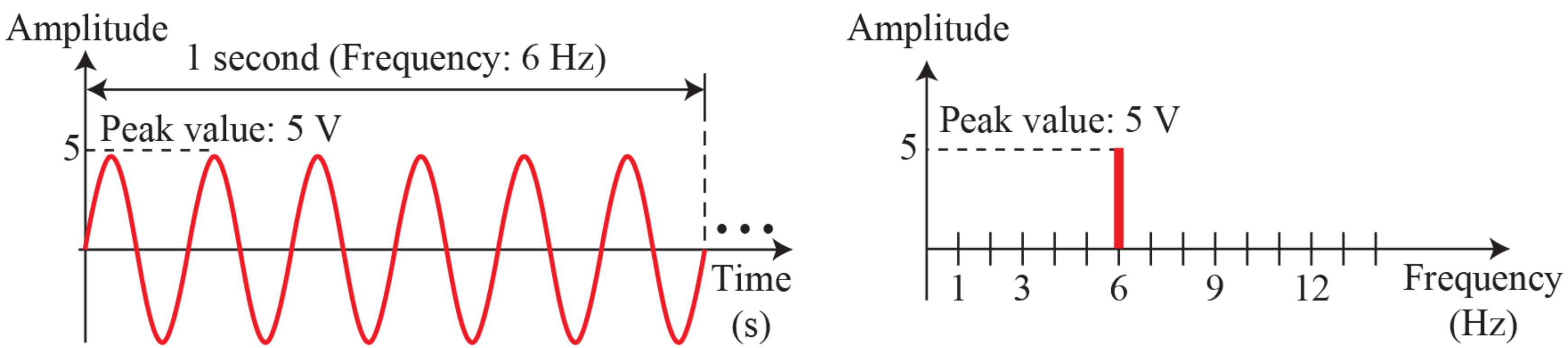
$$\lambda = \frac{c}{f} = \frac{3\times10^8}{4\times10^{14}} = 0.75 \times 10^{-6}\ \text{m} = 0.75\ \mu\text{m}$$

3.2.4 Time and Frequency Domains

- A sine wave is comprehensively defined by its amplitude, frequency, and phase.
- We have been showing a sine wave by using what is called a time domain plot.
- The time-domain plot shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot).
- Phase is not explicitly shown on a time-domain plot.

3.2.4 Time and Frequency Domains

- Figure 3.8: The time-domain and frequency-domain plots of a sine wave

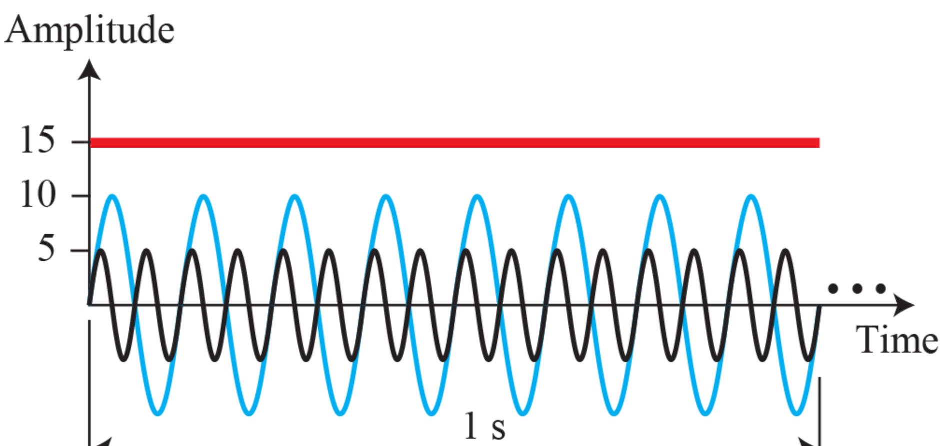


a. A sine wave in the time domain

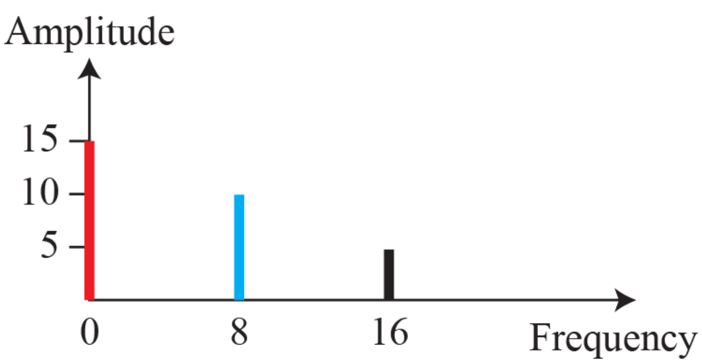
b. The same sine wave in the frequency domain

3.2.4 Time and Frequency Domains

- Example 3.7
  - The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.9 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.
  - Figure 3.9: The time domain and frequency domain of three sine waves



a. Time-domain representation



b. Frequency-domain representation

3.2.5 Composite Signals

- Simple sine waves have many applications in daily life.
- We can send a single sine wave to carry electric energy from one place to another.
- For example,
  - The power company sends a single sine wave with a frequency of 60 Hz to distribute electric energy to houses and businesses.
  - The sine wave is carrying energy
- As another example,
  - we can use a single sine wave to send an alarm to a security center when a burglar opens a door or window in the house.
  - The sine wave is a signal of danger.

3.2.5 Composite Signals

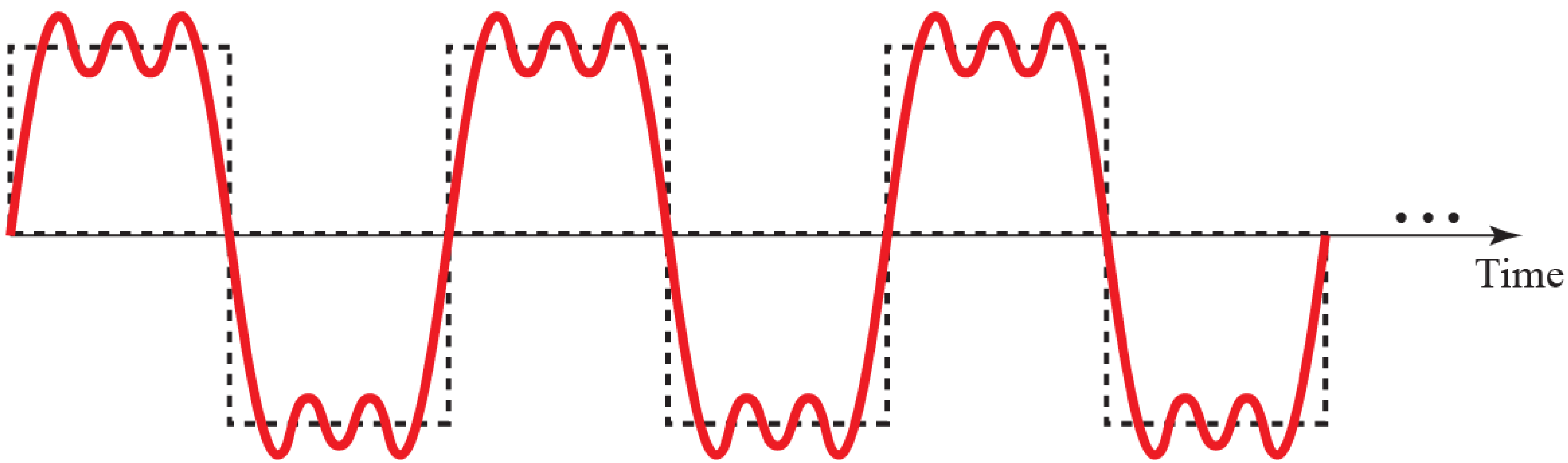
- A single-frequency sine wave is not useful in data communications
  - We need to send a composite signal, a signal made of many simple sine waves
- According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases
- If the composite 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.

3.2.5 Composite Signals

- Example 3.8
  - Figure 3.10 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.
  - It is very difficult to manually decompose this signal into a series of simple sine waves. However, there are tools, both hardware and software, that can help us do the job. We are not concerned about how it is done; we are only interested in the result.
  - Figure 3.11 shows the result of decomposing the above signal in both the time and frequency domains.

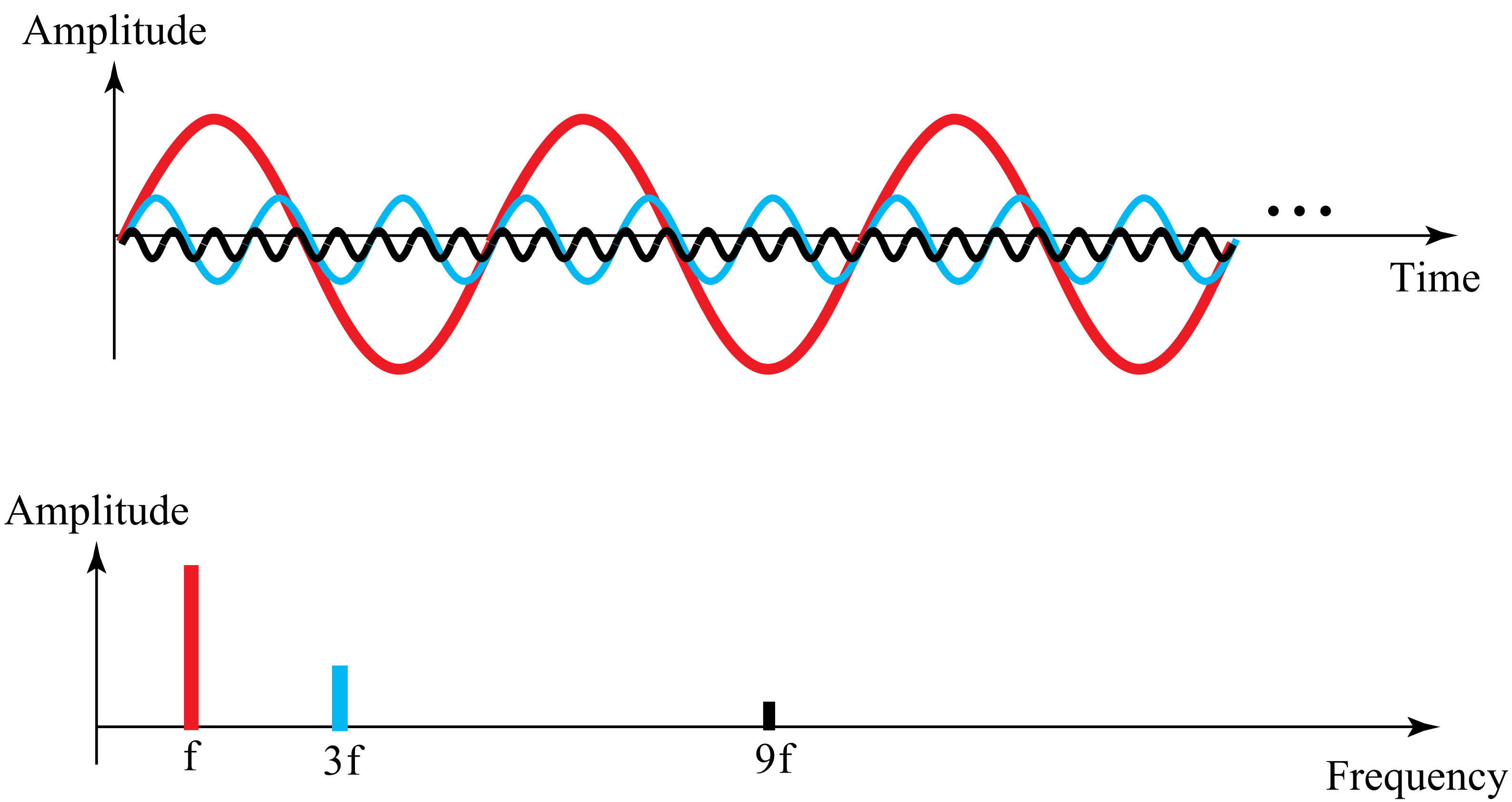
3.2.5 Composite Signals

- Figure 3.10: A composite periodic signal



3.2.5 Composite Signals

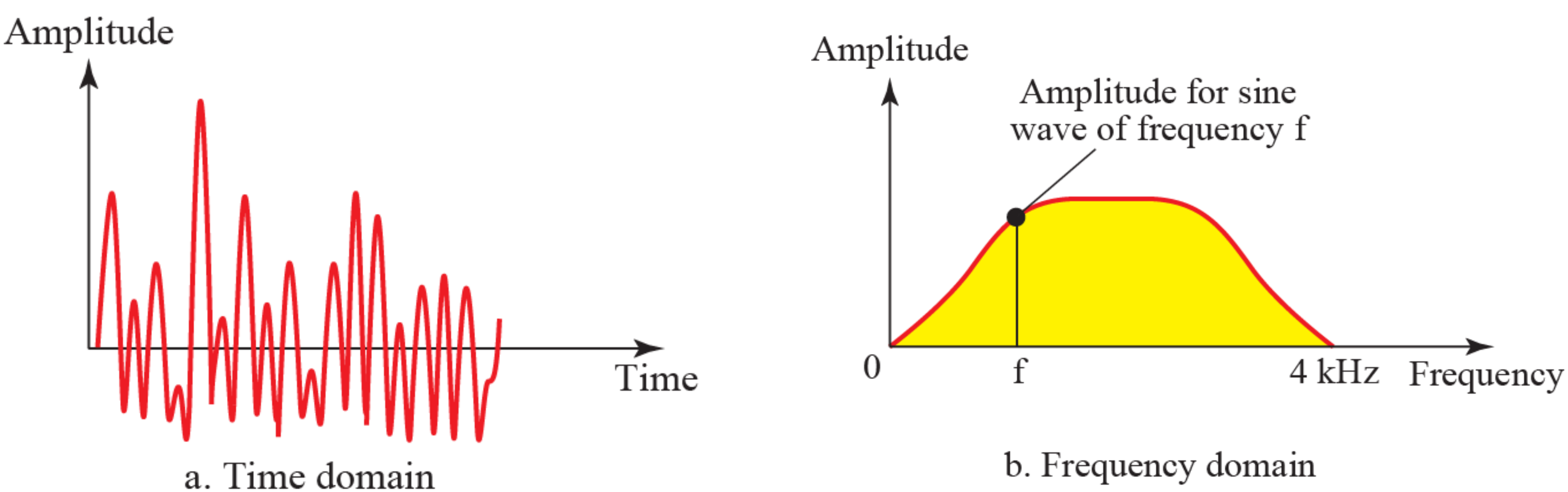
- Figure 3.11: Decomposition of a composite periodic signal



b. Frequency-domain decomposition of the composite signal

3.2.5 Composite Signals

- Example 3.9
  - Figure 3.12 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 3.12: Time and frequency domain of a non-periodic signal

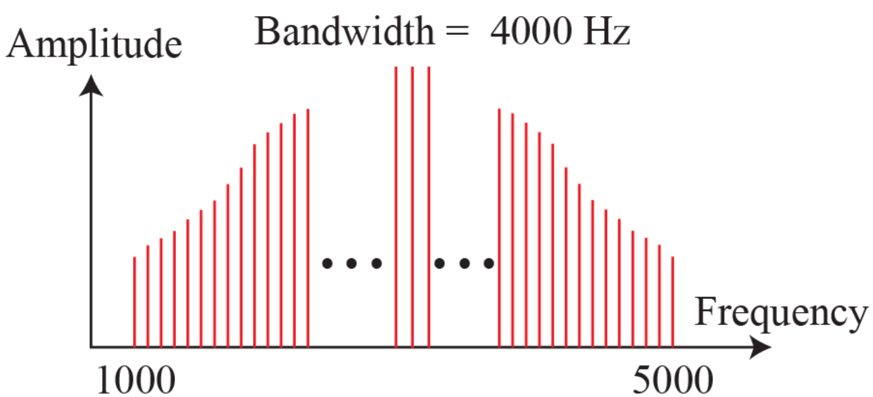


3.2.6 Bandwidth

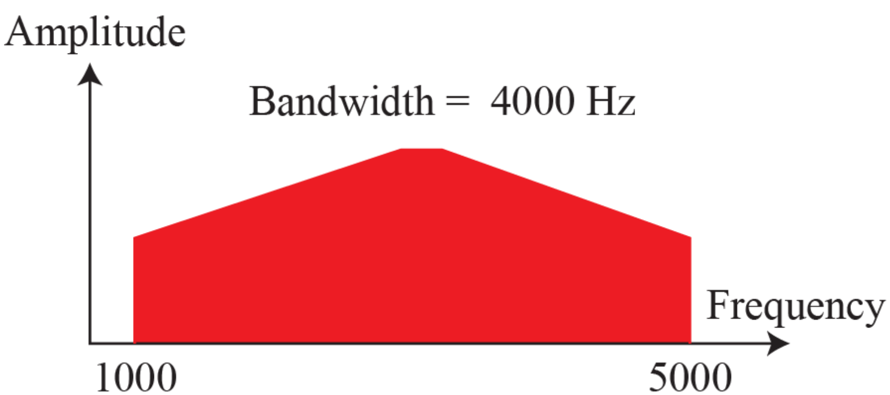
- The range of frequencies contained in a composite signal is its bandwidth.
- The bandwidth is normally a difference between two numbers.
- For example,
  - If a composite signal contains frequencies between 1000 and 5000, its bandwidth is 5000 − 1000, or 4000.

3.2.6 Bandwidth

- Figure 3.13: The bandwidth of periodic and nonperiodic composite signals



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

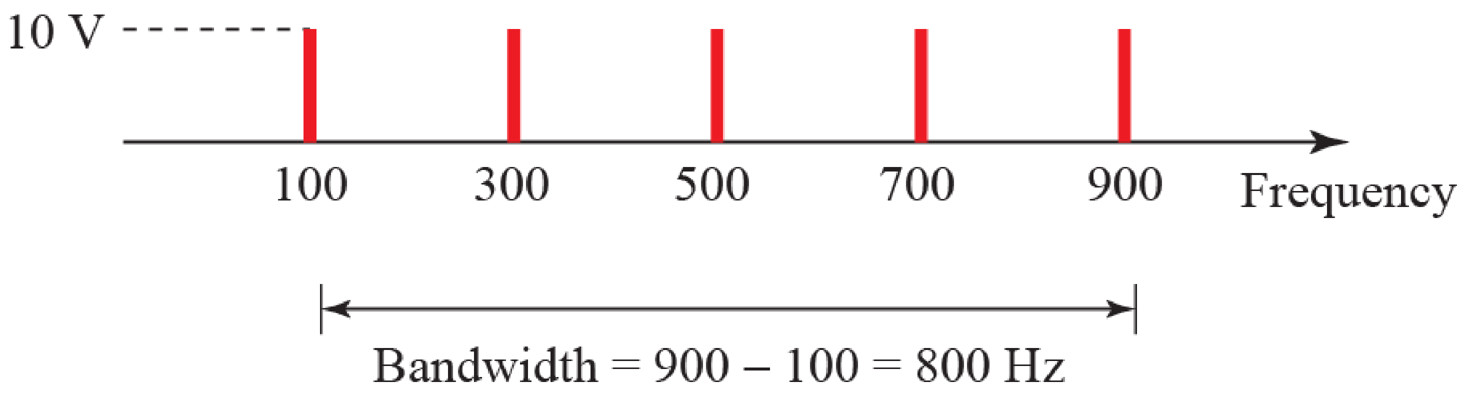
3.2.6 Bandwidth

- Example 3.10
  - If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.
  - Solution
  - Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

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

3.2.6 Bandwidth

- Figure 3.14: The bandwidth for example 3.10



3.2.6 Bandwidth

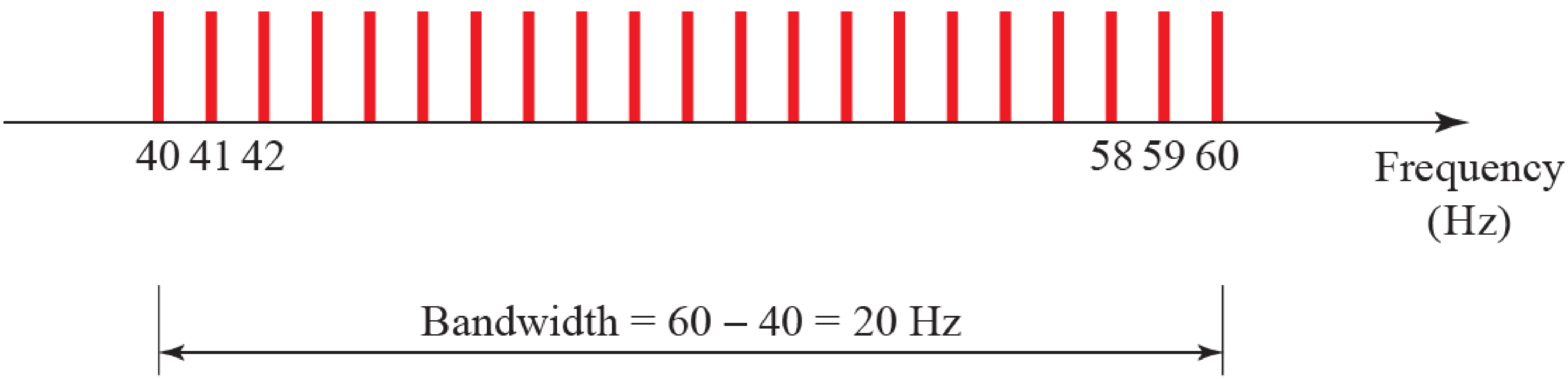
- Example 3.11
  - A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all frequencies of the same amplitude.
  - Solution
    - Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

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

    - The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.15).

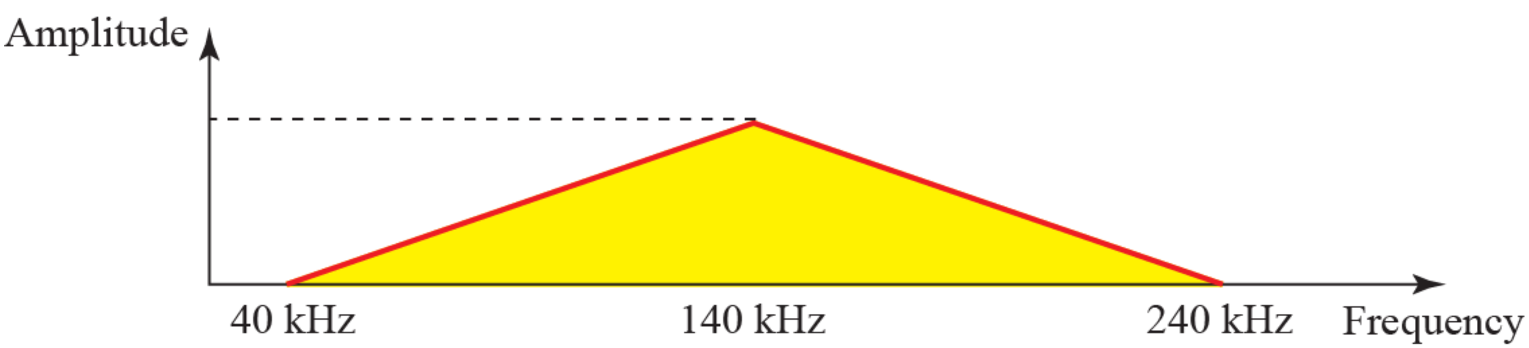
3.2.6 Bandwidth

- Figure 3.15: The bandwidth for example 3.11



3.2.6 Bandwidth

- 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 3.16 shows the frequency domain and the bandwidth.
  - Figure 3.16: The bandwidth for example 3.12



3.2.6 Bandwidth

- 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.

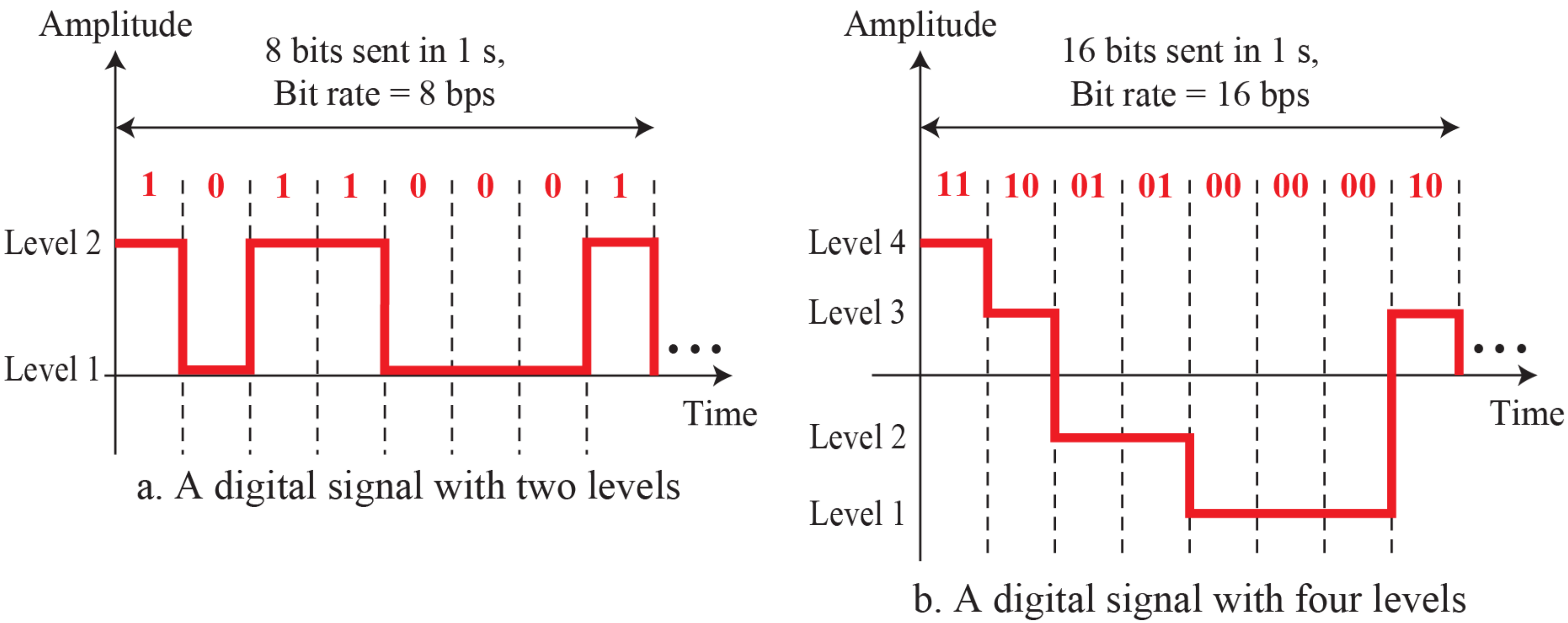
- Example 3.14
  - Another example of a nonperiodic composite signal is the signal propagated by an FM radio station. In the United States, each FM radio station is assigned a 200-kHz bandwidth. The total bandwidth dedicated to FM radio ranges from 88 to 108 MHz. We will show the rationale behind this 200-kHz bandwidth in Chapter 5.

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.
  - Figure 3.17 shows two signals, one with two levels and the other with four.

3-3 DIGITAL SIGNALS

- Figure 3.17: Two digital signals: one with two signal levels and the other with four signal levels



3-3 DIGITAL SIGNALS

- Example 3.16
  - A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the following formula. Each signal level is represented by 3 bits.

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

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

3.3.1 Bit Rate

- Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics.
- Another term—bit rate (instead of frequency)—is used to describe digital signals.
- The bit rate is the number of bits sent in 1s, expressed in bits per second (bps). Figure 3.17 shows the bit rate for two signals.

3.3.1 Bit Rate

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

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

3.3.1 Bit Rate

- 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 (in contrast to 4 : 3 for regular TV), which means the screen is wider. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel. We can calculate the bit rate as

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

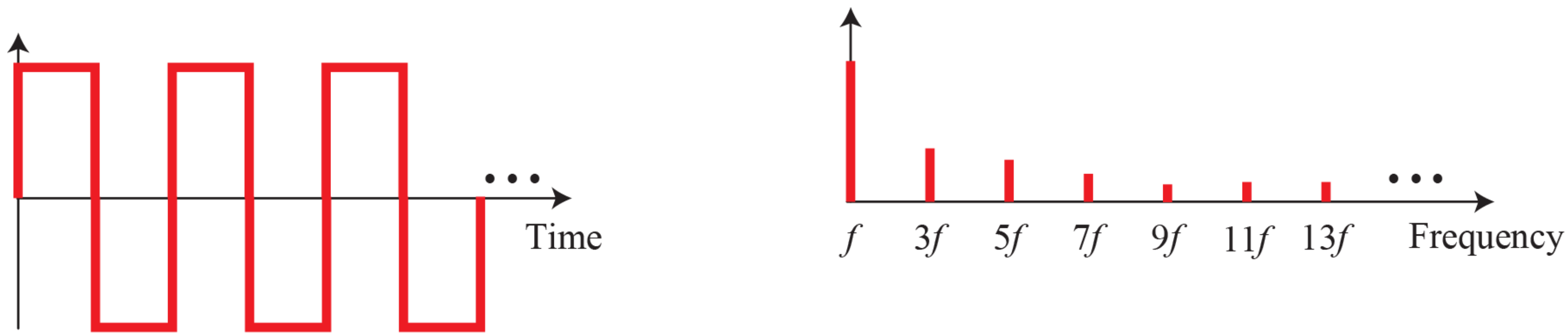
  - The TV stations reduce this rate to 20 to 40 Mbps through compression.

3.3.3 Digital As Composite Analog

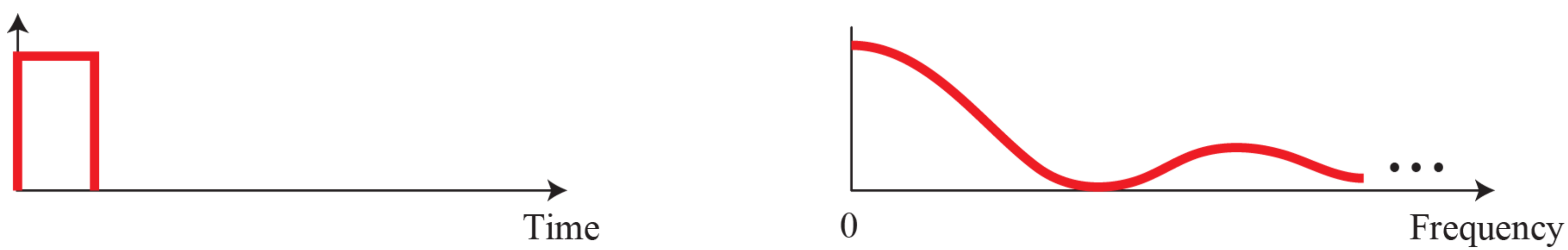
- Based on Fourier analysis, a digital signal is a composite analog signal.
- The bandwidth is infinite, as you may have guessed. We can intuitively come up with this concept when we consider a digital signal.
- A digital signal, in the time domain, comprises connected vertical and horizontal line segments.
  - A vertical line in the time domain means a frequency of infinity
  - A horizontal line in the time domain means a frequency of zero.
- Going from a frequency of zero to a frequency of infinity implies all frequencies in between are part of the domain.

3.3.3 Digital As Composite Analog

- Figure 3.18: The time and frequency domains of periodic and nonperiodic digital signals



a. Time and frequency domains of periodic digital signal



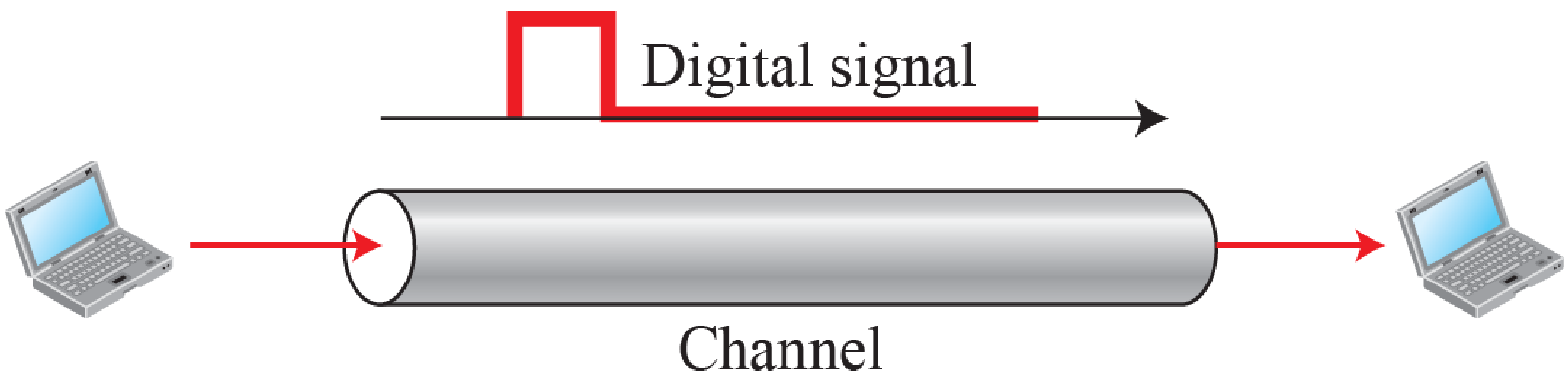
b. Time and frequency domains of nonperiodic digital signal

3.3.4 Transmission of Digital Signals

- The previous discussion asserts that a digital signal, periodic or nonperiodic, is a composite analog signal with frequencies between zero and infinity.
  - A digital signal is a composite analog signal with an infinite bandwidth
- The fundamental question is,
  - How can we send a digital signal from point A to point B?
- We can transmit a digital signal by using one of two different approaches: baseband transmission or broadband transmission (using modulation).

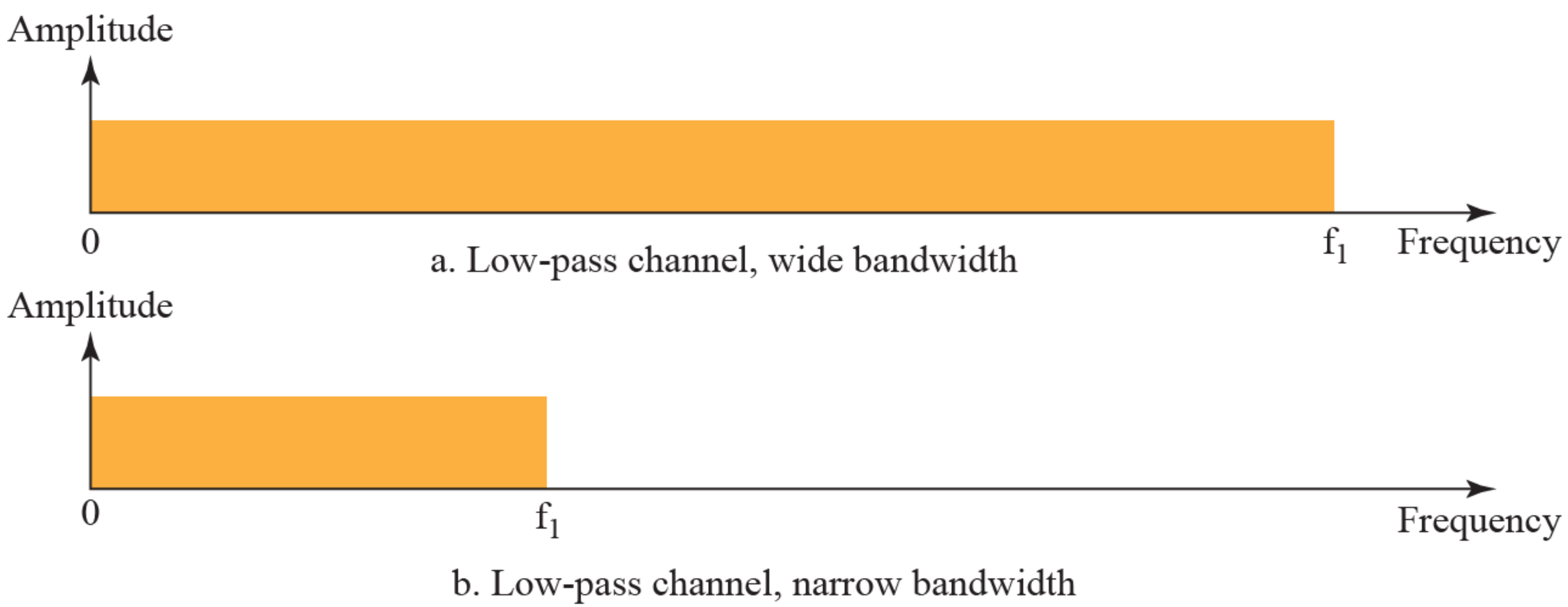
3.3.4 Transmission of Digital Signals

- Baseband transmission
  - Sending digital signal over a channel without changing the digital signal to an analog signal
- Figure 3.19: Baseband transmission



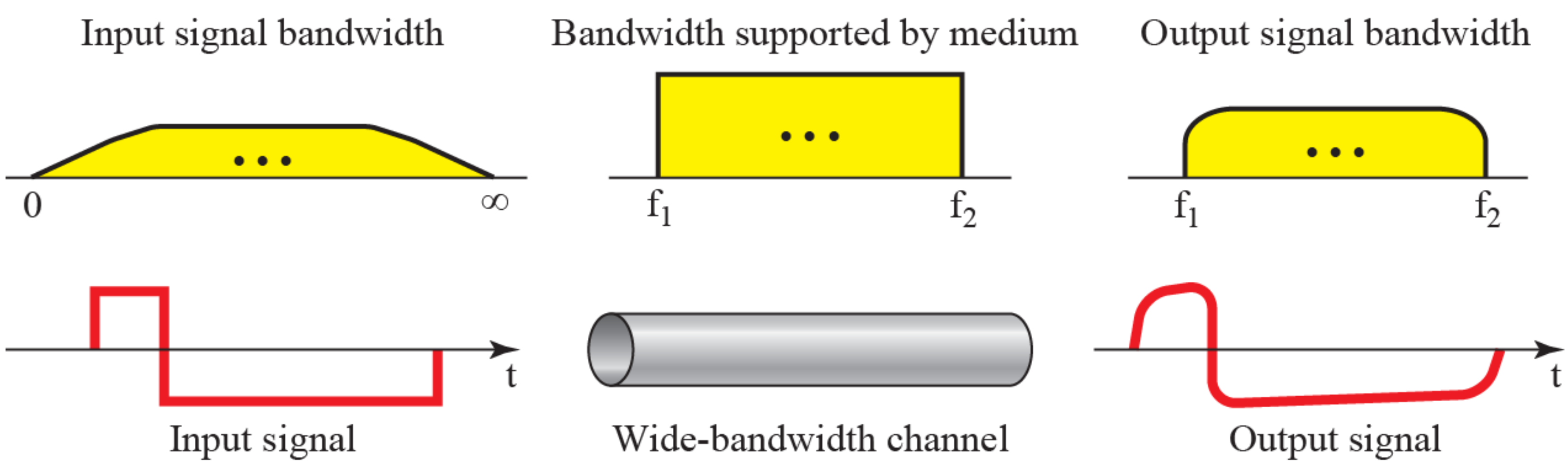
3.3.4 Transmission of Digital Signals

- Low-pass channel
  - A channel with an bandwidth that starts from zero
  - It can ben used for baseband communication
  - In real life, impossible to have a low-pass channel with infinite bandwidth
- Figure 3.20: Bandwidth of two low-pass channels



3.3.4 Transmission of Digital Signals

- Case 1: Low-Pass Channel with Wide Bandwidth
  - Continuous range of frequencies between zero and infinity
  - Not possible between two devices
  - Only very good accuracy
- Figure 3.21: Baseband transmission using a dedicated medium

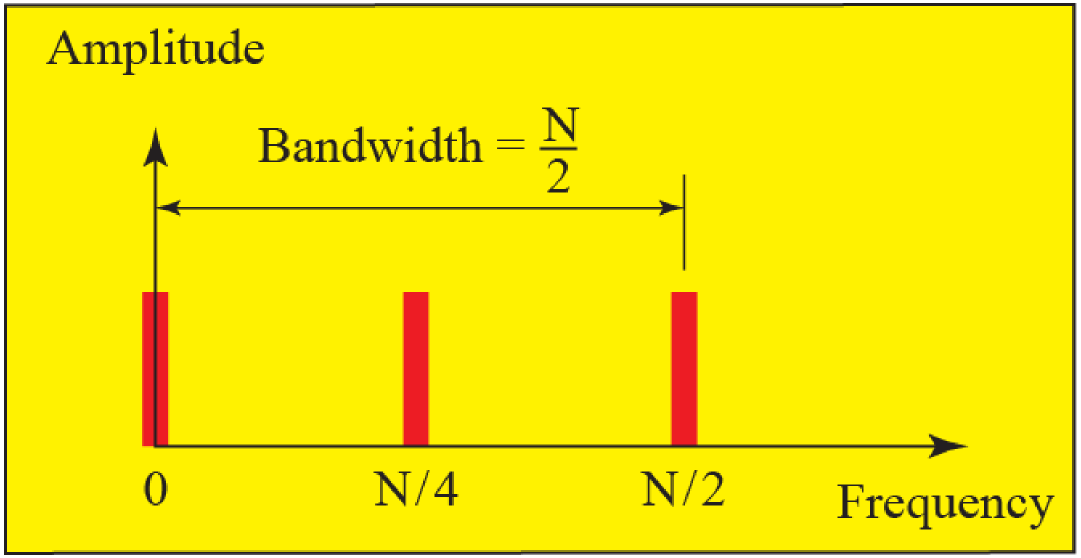


3.3.4 Transmission of Digital Signals

- 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.

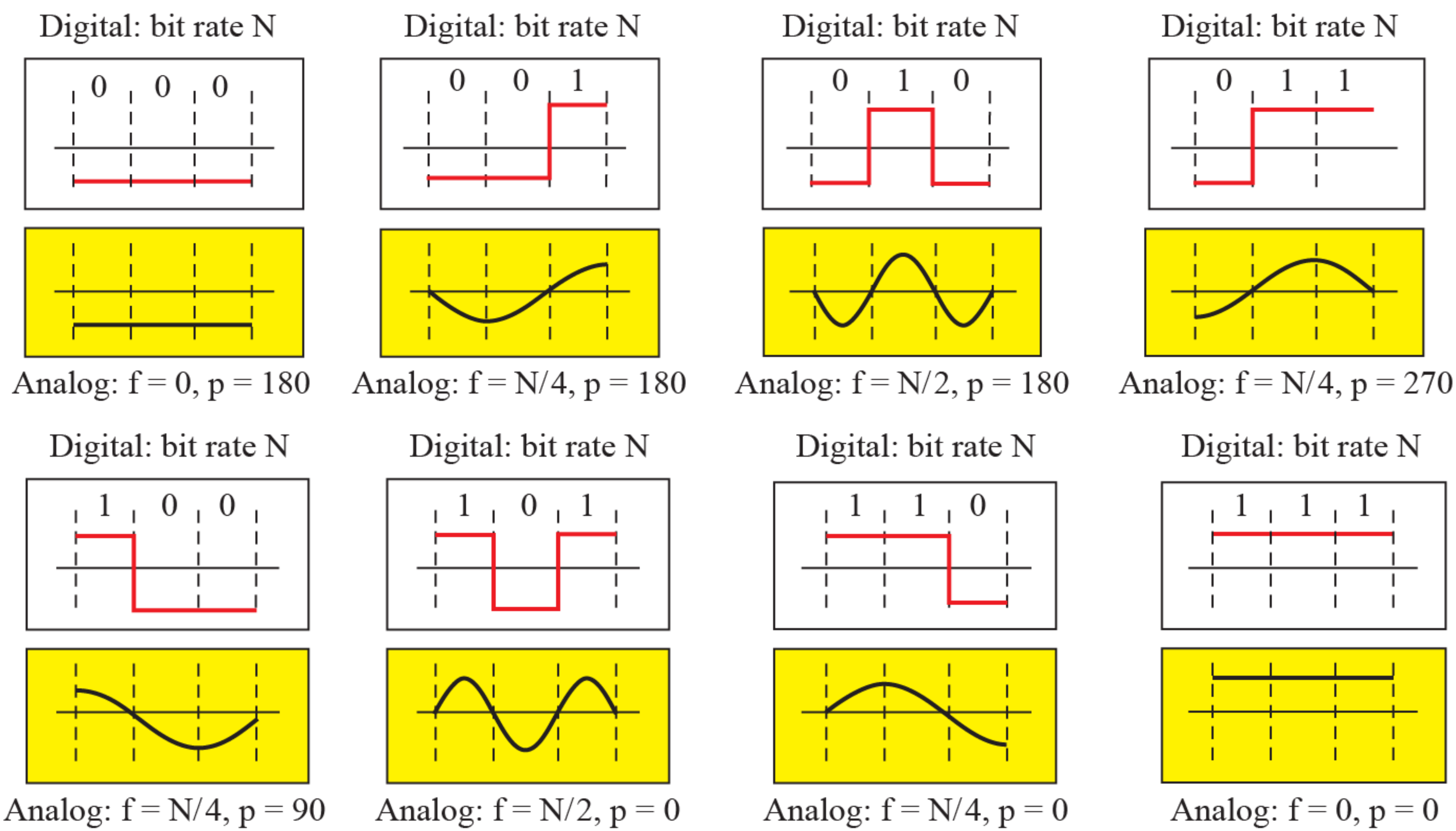
3.3.4 Transmission of Digital Signals

- Case 2: Low-Pass Channel with Limited Bandwidth
  - In a low-pass channel with limited bandwidth, we approximate the digital signal with an analog signal.
    - The level of approximation depends on the bandwidth available.
- Figure 3.22: Rough approximation of a digital signal (part 1)



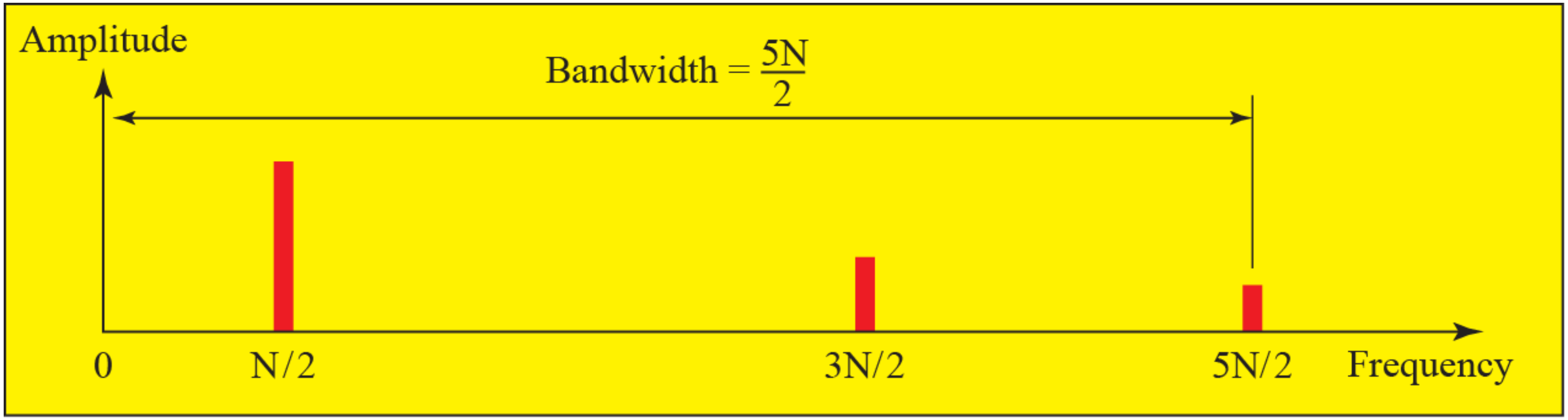
3.3.4 Transmission of Digital Signals

- Figure 3.22: Rough approximation of a digital signal (part 2)



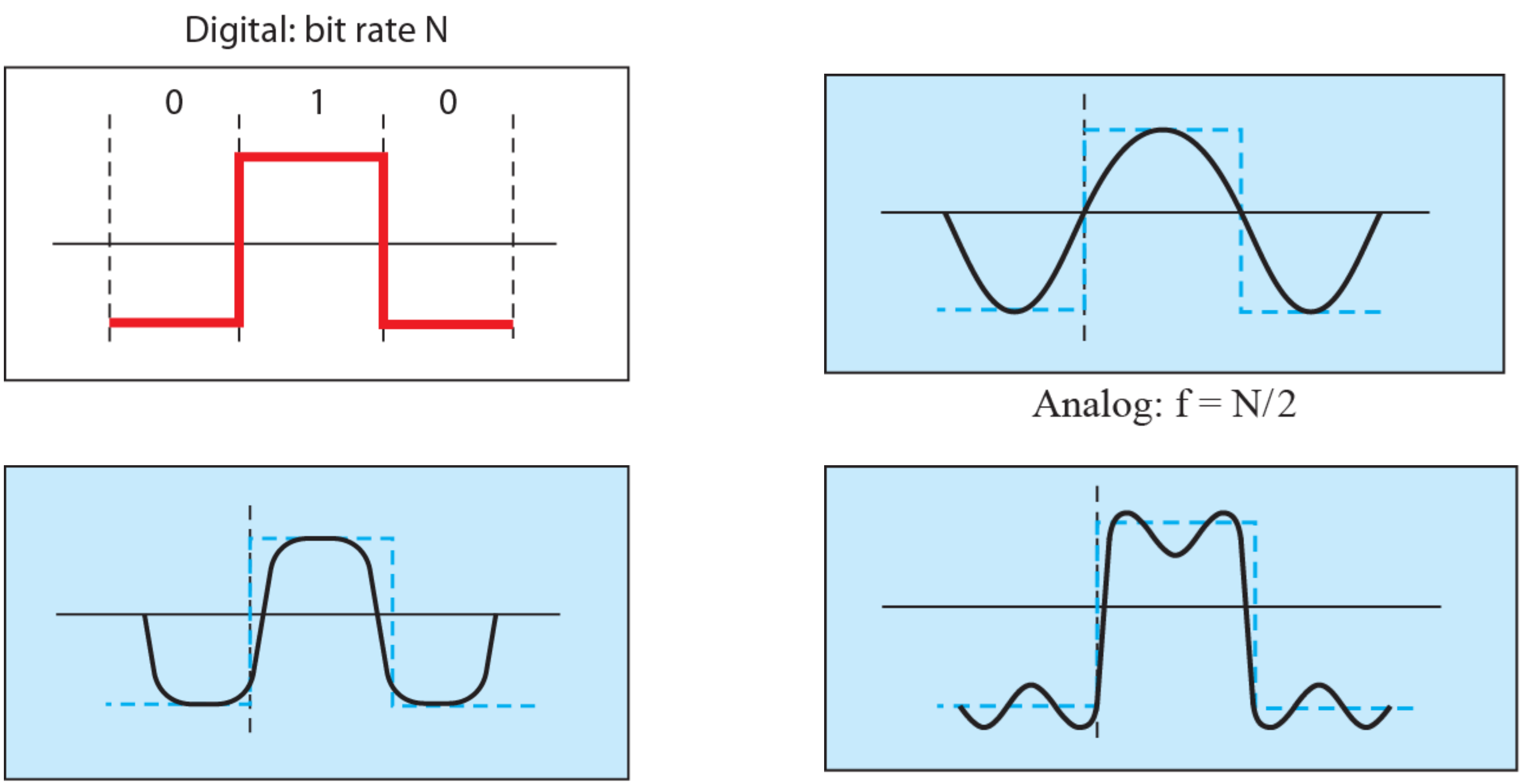
3.3.4 Transmission of Digital Signals

- Better approximation
  - By adding more harmonics of the frequencies
  - In baseband transmission, the required bandwidth is proportional to the bit rate;
    - if we need to send bits faster, we need more bandwidth.
- Figure 3.23: Simulating a digital signal with first three harmonics (part I)



3.3.4 Transmission of Digital Signals

- Figure 3.23: Simulating a digital signal with first three harmonics (part II)



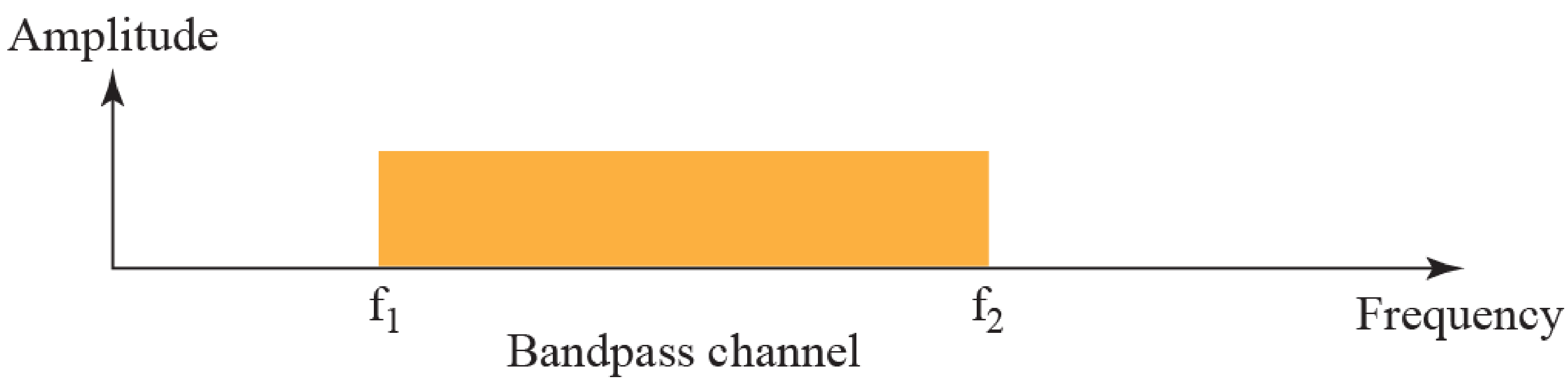
Analog: f = N/2

Analog: f = N/2 and 3N/2

Analog: f = N/2, 3N/2, and 5N/2

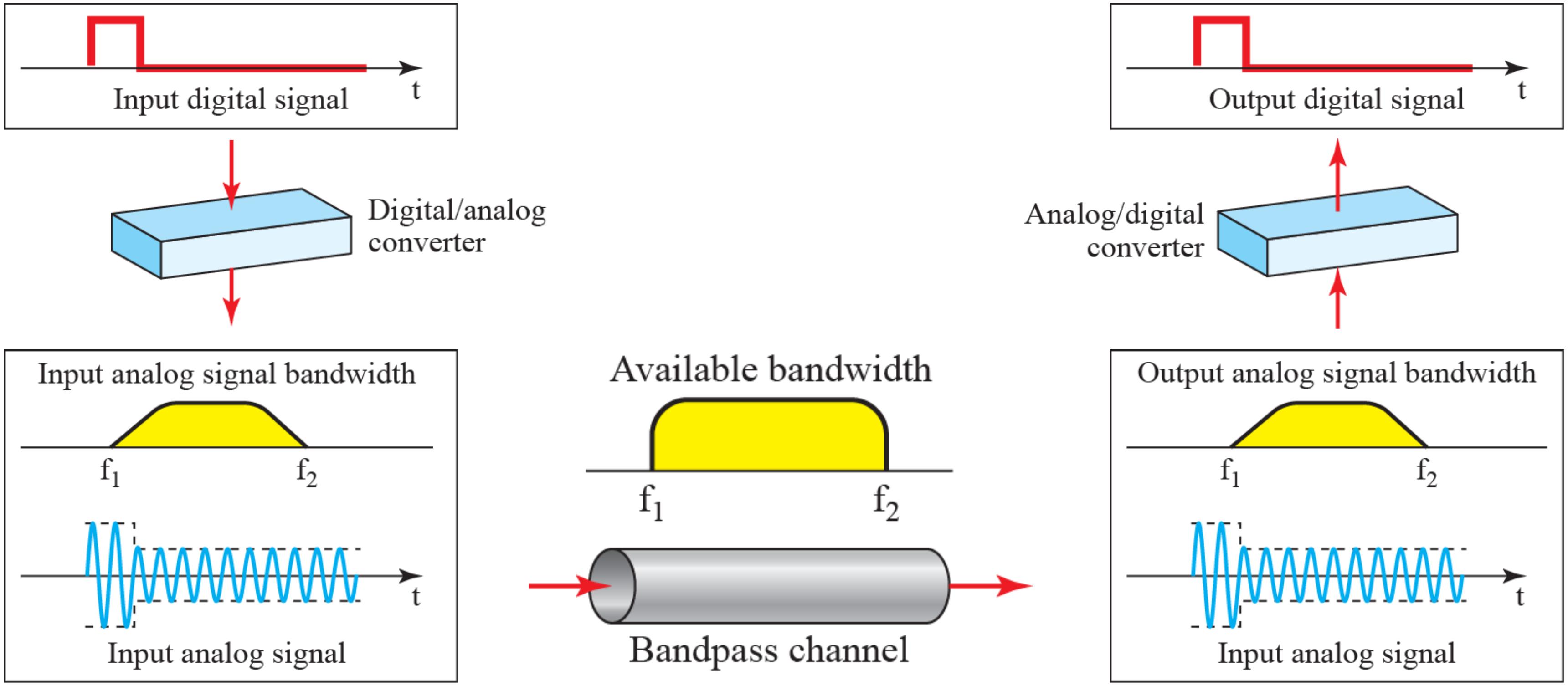
3.3.4 Transmission of Digital Signals

- Baseband transmission (using modulation)
  - 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
  - Note that a low-pass channel can be considered a bandpass channel with the lower frequency starting at zero.
- Figure 3.24: Bandwidth of a band-pass channel



3.3.4 Transmission of Digital Signals

- 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 3.25: Modulation of a digital signal for transmission on band-pass channel

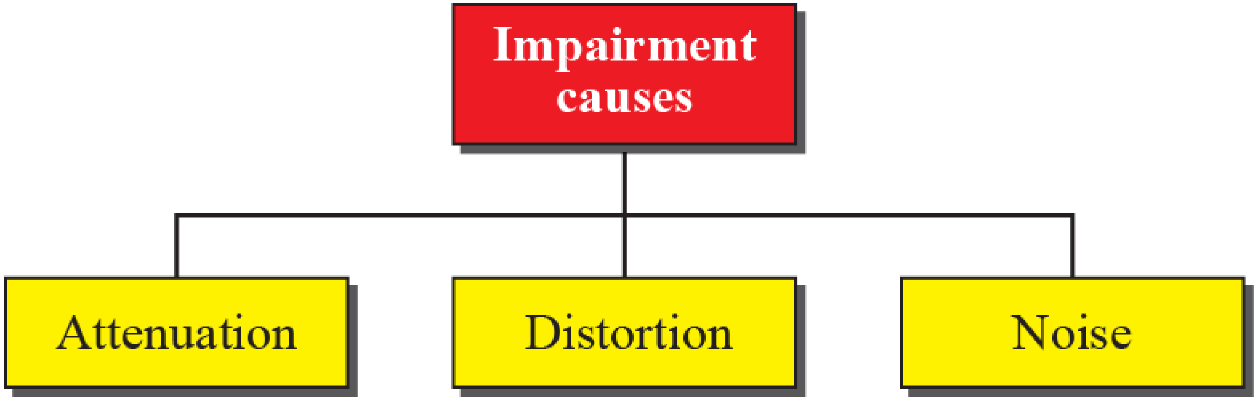


3.3.4 Transmission of Digital Signals

- Example 3.25
  - A second example is the digital cellular telephone. For better reception, digital cellular phones digitize analog voice. Although the bandwidth allocated to a company providing digital cellular phone service is very wide, we still cannot send the digitized signal without conversion. The reason is that we have only a band-pass channel available between caller and callee. For example, if the available bandwidth is W and we allow 1000 couples to talk simultaneously, this means the available channel is W/1000, just part of the entire bandwidth. We need to convert the digitized voice to a composite analog signal before transmission.

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.
- Figure 3.26: Causes of impairment

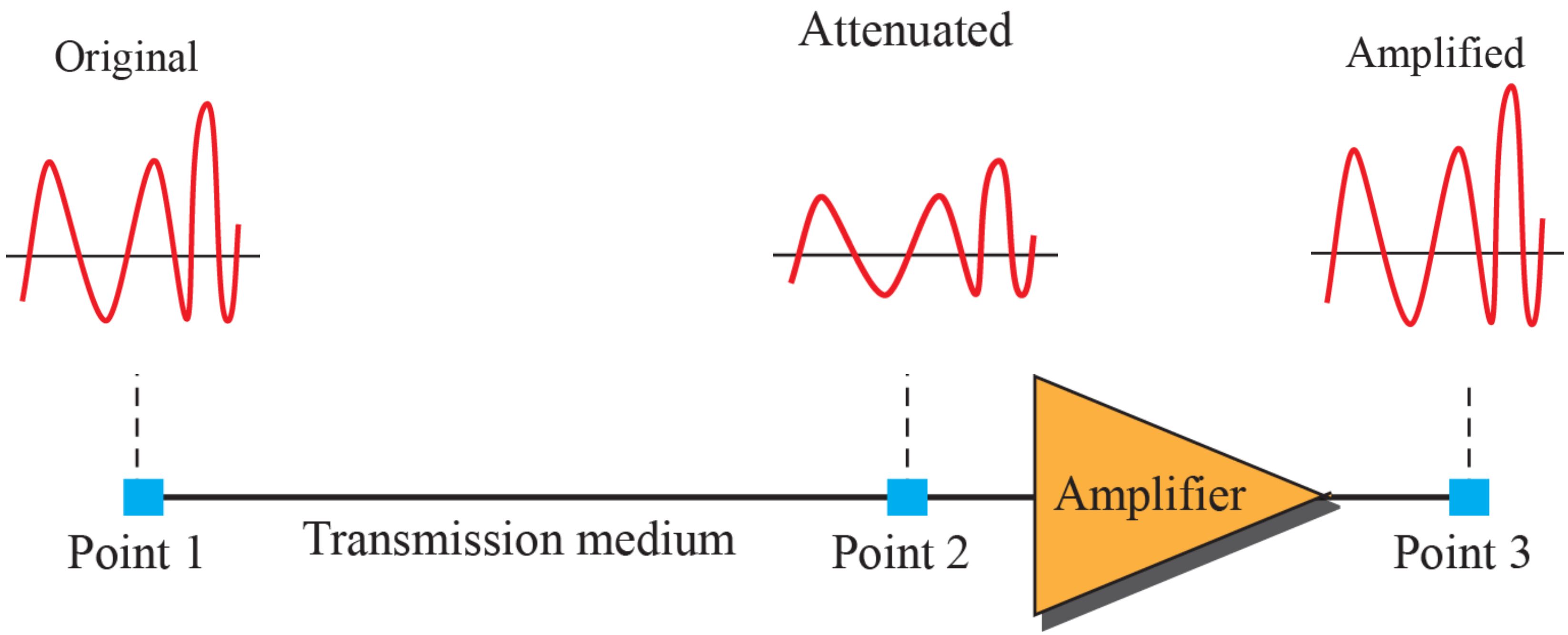


3.4.1 Attenuation

- Attenuation means a loss of energy.
  - When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium.
  - That is why a wire carrying electric signals gets warm, if not hot, after a while.
  - Some of the electrical energy in the signal is converted to heat. To compensate for this loss, amplifiers are used to amplify the signal. Figure 3.27 shows the effect of attenuation and amplification.

3.4.1 Attenuation

- Figure 3.27: Attenuation and amplification



3.4.1 Attenuation

Decibel

- The decibel (dB) measures the relative strengths of two signals or one signal at two different points.
- The decibel is negative if a signal is attenuated and positive if a signal is amplified.

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

- Variables P_1 and P_2 are the powers of a signal at points 1 and 2, respectively.
  - Note that some engineering books define the decibel in terms of voltage instead of power

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

3.4.1 Attenuation

- Example 3.26
  - Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that $P_2 = 0.5\ P_1$. In this case, the attenuation (loss of power) can be calculated as

$$\mathbf{10 \log_{10} P_2/P_1 = 10 \log_{10} (0.5\ P_1)/P_1 = 10 \log_{10} 0.5 = 10 \times (-0.3) = -3\ dB.}$$

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

3.4.1 Attenuation

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

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1} = 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

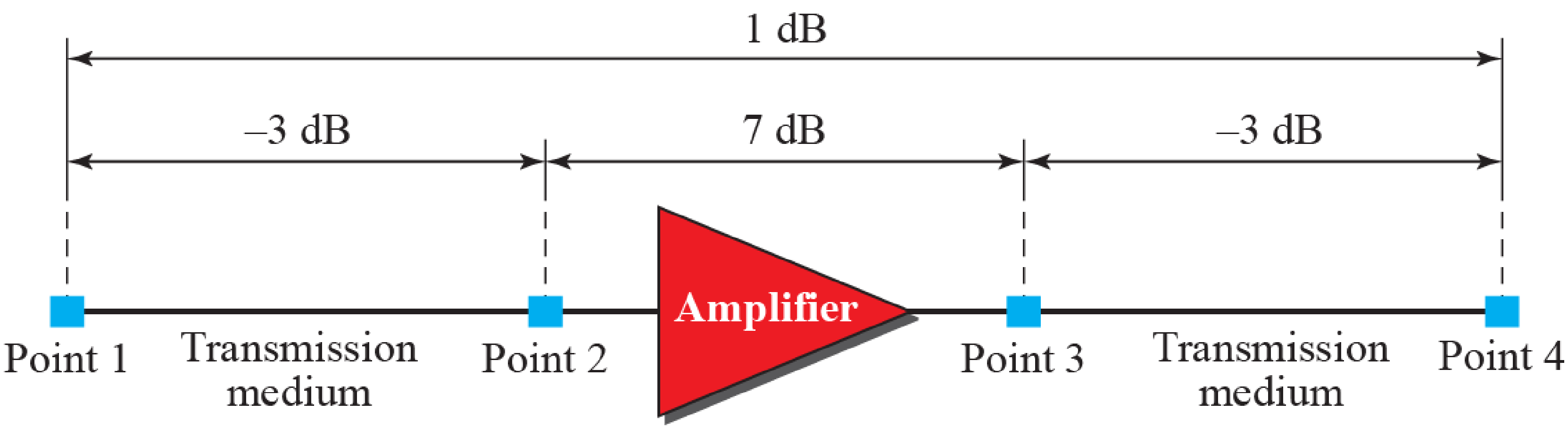
3.4.1 Attenuation

- Example 3.28
  - One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In Figure 3.28 a signal travels from point 1 to point 4. The signal is attenuated by the time it reaches point 2. Between points 2 and 3, the signal is amplified. Again, between points 3 and 4, the signal is attenuated. We can find the resultant decibel value for the signal just by adding the decibel measurements between each set of points. In this case, the decibel value can be calculated as

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

3.4.1 Attenuation

- Figure 3.28: Decibels for Example 3.28



3.4.1 Attenuation

- Example 3.29
  - Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dBm and is calculated as dBm = 10 $\log_{10} P_m$, where P_m is the power in milliwatts. Calculate the power of a signal if its dBm = −30.
  - Solution
    - We can calculate the power in the signal as

$$\mathrm{dB_m} = 10\log_{10} \longrightarrow dB_m = -30 \longrightarrow \log_{10}P_m = -3 \longrightarrow P_m = 10^{-3}\,\mathrm{mW}$$

3.4.1 Attenuation

- Example 3.30
  - The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with −0.3 dB/km has a power of 2 mW, what is the power of the signal at 5 km?
  - Solution
    - The loss in the cable in decibels is $5 \times (-0.3) = -1.5$ dB. We can calculate the power as

$$\mathrm{dB} = 10 \log_{10} (P_2 / P_1) = -1.5 \quad \longrightarrow \quad (P_2 / P_1) = 10^{-0.15} = 0.71$$

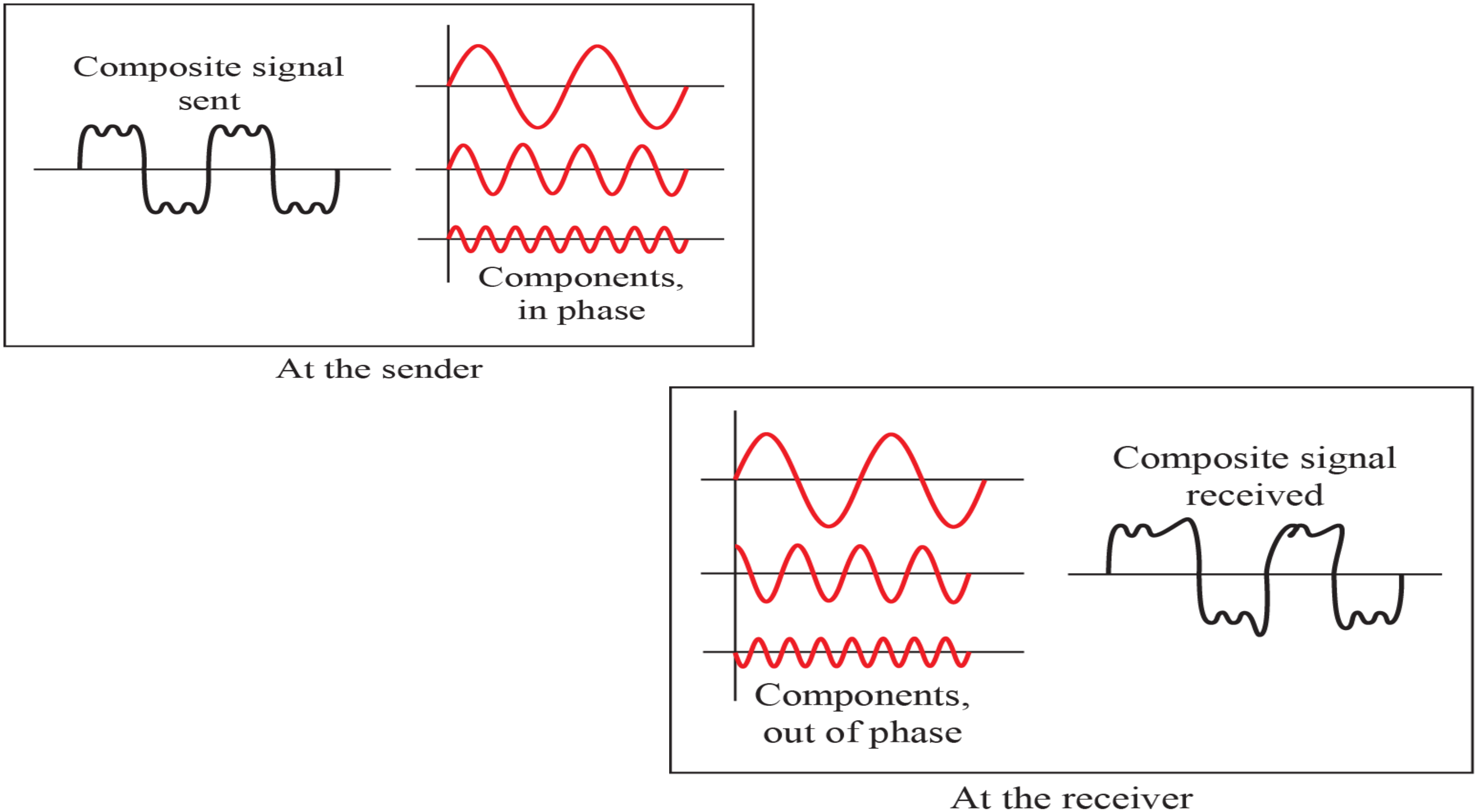
$$P_2 = 0.71 P_1 = 0.7 \times 2 \text{ mW} = 1.4 \text{ mW}$$

3.4.2 Distortion

- Distortion means that the signal changes its form or shape.
- Distortion can occur in a composite signal made of different frequencies.
- Each signal component has its own propagation speed (see the next section) through a medium and, therefore, its own delay in arriving at the final destination.
- Differences in delay may create a difference in phase if the delay is not exactly the same as the period duration.

3.4.2 Distortion

- Figure 3.29: Distortion

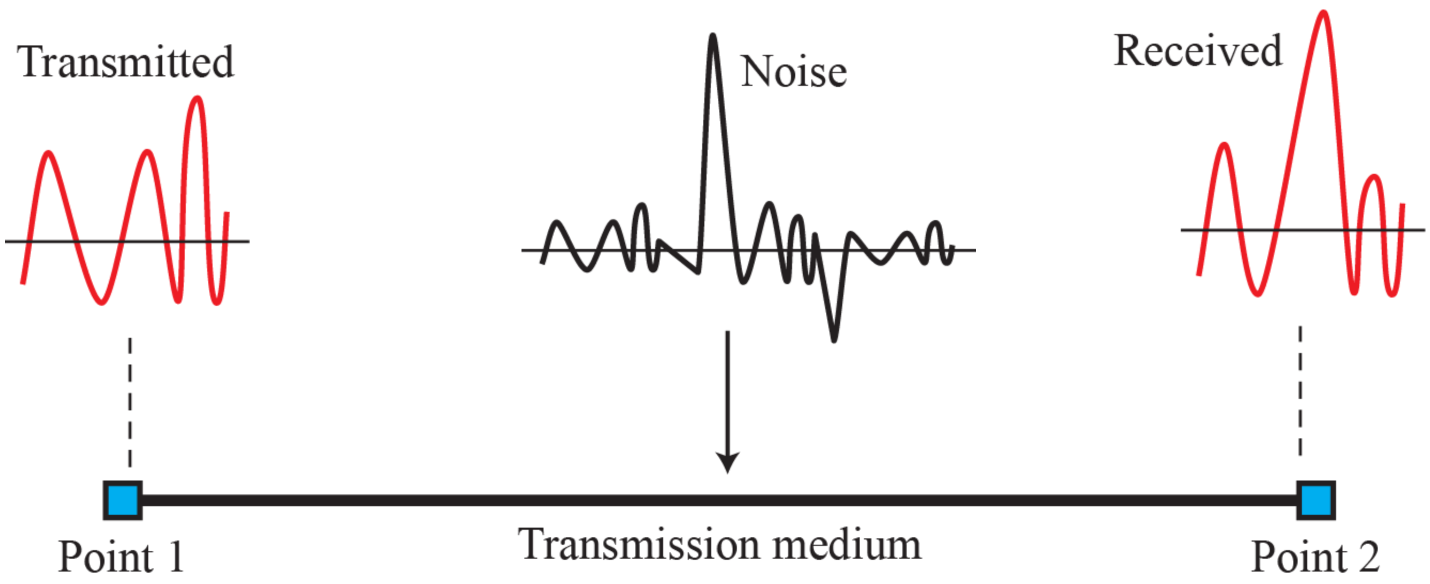


3.4.3 Noise

- Noise is another cause of impairment.
- Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.
  - Thermal noise is the random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter.
  - Induced noise comes from sources such as motors.
  - Crosstalk (or interference) is the effect of one wire on the other.

3.4.3 Noise

- Figure 3.30: Noise



3.4.3 Noise

Signal-to-Noise Ratio (SNR)

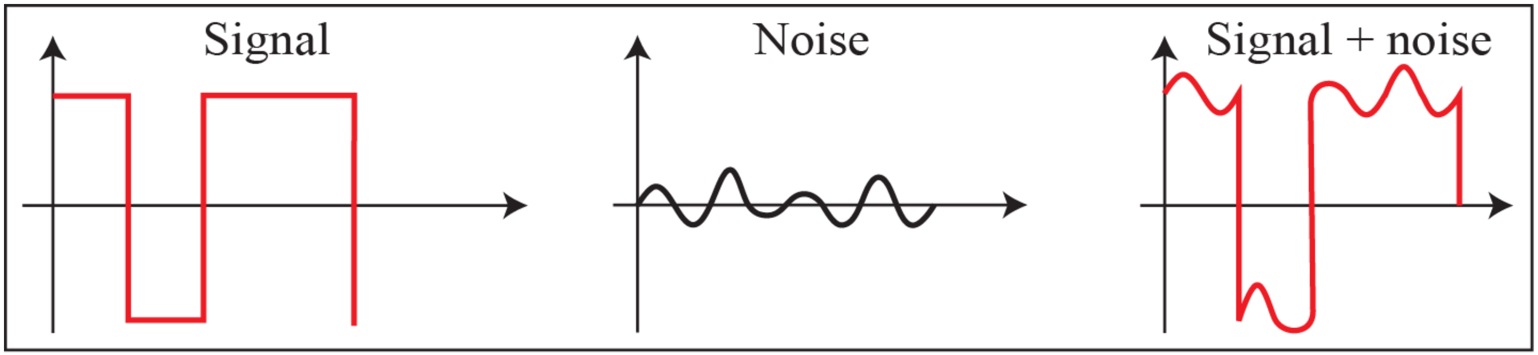
$$\text{SNR} = \frac{\text{average signal power}}{\text{average noise power}}$$

- Used to find the theoretical bit rate limit
- Need to consider the average signal power and the average noise power because these may change with time
- Because SNR is the ratio of two powers, it is often described in decibel units, SNR_{dB}, defined as

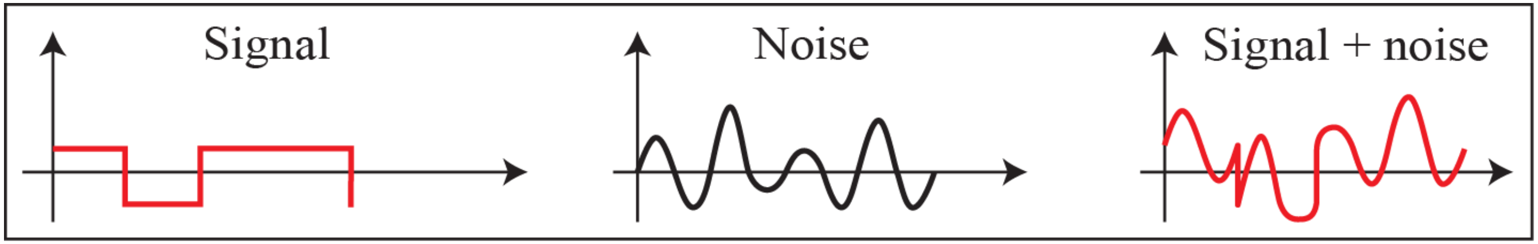
$$\text{SNR}_{\text{dB}} = 10 \log_{10} \text{SNR}$$

3.4.3 Noise

- Figure 3.31: Two cases of SNR: a high SNR and a low SNR



a. High SNR



b. Low SNR

3.4.3 Noise

- 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:

$$\text{SNR} = (10{,}000\ \mu\text{w}) / (1\ \mu\text{w}) = 10{,}000 \qquad \text{SNR}_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

3.4.3 Noise

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

$$\mathbf{SNR = (signal\ power) / 0 = \infty \quad \longrightarrow \quad SNR_{dB} = 10 \log_{10} \infty = \infty}$$

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

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)
- Two theoretical formulas were developed to calculate the data rate:
  - One by Nyquist for a noiseless channel
  - Another by Shannon for a noisy channel

3.5.2 Noisy Channel: Shannon Capacity

- In reality, we cannot have a noiseless channel; the channel is always noisy.
- In 1944, Claude Shannon introduced a formula, called the Shannon capacity, to determine the theoretical highest data rate for a noisy channel:

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

  - SNR: the signal-to-noise ratio
  - Capacity: the capacity of the channel in bits per second
  - No indication of the signal level
  - It defines a characteristic of the channel, not the method of transmission

3.5.2 Noisy Channel: Shannon Capacity

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

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

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

3.5.2 Noisy Channel: Shannon Capacity

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 Hz (300 to 3300 Hz) assigned for data communications. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

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

- 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.

3.5.2 Noisy Channel: Shannon Capacity

- 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

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

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

3-6 PERFORMANCE

- Up to now, we have discussed the tools of transmitting data (signals) over a network and how the data behave.
- 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.

3.6.1 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
    - The range of frequencies in a composite signal or the range of frequencies that a channel can pass.
  - Bandwidth in bits per second.
    - The number of bits per second that a channel, a link, or even a network can transmit.
    - The speed of bit transmission in a channel or link.

3.6.2 Throughput

- The throughput is a measure of how fast we can actually send data through a network.
- Although, at first glance, bandwidth in bits per second and throughput seem the same, they are different.
- 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.

3.6.2 Throughput

- 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

$$\text{Throughput} = (12{,}000 \times 10{,}000) / 60 = 2 \text{ Mbps}$$

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

3.6.3 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.

$$\text{Latency} = \text{propagation time} + \text{transmission time} + \text{queuing time} + \text{processing delay}$$

3.6.3 Latency (Delay)

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

$$\textbf{Propagation time} = \textbf{Distance} / (\textbf{Propagation Speed})$$

3.6.3 Latency (Delay)

- 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

$$\text{Propagation time} = \frac{12,000 \times 1,000}{2.4 \times 10^8} = 50 \text{ msec}$$

    - 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.

3.6.3 Latency (Delay)

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

$$\textbf{Transmission time} = \textbf{(Message size) / Bandwidth}$$

3.6.3 Latency (Delay)

- Example 3.46
  - What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message 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

$$\textbf{Propagation time} = (12{,}000 \times 1000) / (2.4 \times 10^8) = 50 \text{ ms}$$

$$\textbf{Transmission time} = (2500 \times 8) / 10^9 = 0.020 \text{ ms}$$

    - 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.

3.6.3 Latency (Delay)

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

$$\textbf{Propagation time} = (12{,}000 \times 1000) / (2.4 \times 10^8) = 50 \text{ ms}$$

$$\textbf{Transmission time} = (5{,}000{,}000 \times 8) / 10^6 = 40 \text{ s}$$

3.6.5 Jitter

- Another performance issue that is related to delay is jitter.
- We can roughly say that jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive (audio and video data, for example).
- If the delay for the first packet is 20 ms, for the second is 45 ms, and for the third is 40 ms, then the real-time application that uses the packets endures jitter.
- The jitter will be discussed in greater detail in Chapter 28.

Summary & Next Class

- ❑ Ch 3. Introduction to physical layer
- ❑ Summary & Next Class

Summary: Ch 3

- Data must be transformed to electromagnetic signals to be transmitted
- Periodic analog signals and nonperiodic digital signals
  - Frequency and period are the inverse of each other
  - 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
  - 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
- Low-pass & band pass channel
  - Need to convert the digital signal to an analog signal before transmission.
- Shannon capacity
  - Attenuation, distortion, and noise
  - The bandwidth delay product defines the number of bits that can fill the link

Assignment

- **Solve Assignment # posted on eClass website exercise**
  - eClass → Data Communication → Assignment
  - Textbook problems
  - **Upload your answer sheet** on eClass **until the dealine**
  - **Firm deadline!!**: **late** submission is **not accepted**
  - Only **docx, hwp, pdf** format allowed (**NOT any figure format including jpg, bmp, png** etc.)
  - eClass → Data Communciaton → Assignment
  - Don't forget to write your **name**, **student ID number**.
  - It is not important whether or not your answers are correct. That is, if you **just try to write an answer**, you can **get the perfect scores**.
  - Exams will rigorously check your efforts on solving the assignment and practice problems by yourself.
- In order to inquire about the assignment (problem or scoring), please contact to the teaching assistant

Course Schedule (Tentative)

- FL: Flipped learning
- **Rec: Recorded video for makeup class**

No	Topics	Date-M		Date-Th	
1	Introduction to course and data communications (Ch1)	09/05	FL (**Zoom**)	09/08	FL
2	Intro. to data communications (Ch1) & Network models (Ch2)	09/12	**Rec**	09/15	FL
3	Intro. to physical layer (Ch3)	09/19	FL	09/22	FL
4	Digital transmission (Ch4)	09/26	FL	09/29	FL
5	Analog transmission (Ch5) & Bandwidth utilization: multiplexing (Ch6.1)	10/03	**Rec**	10/06	**Rec**
6	Bandwidth utilization: spread spectrum (Ch6.2) Transmission Media (Ch7)	10/10	**Rec**	10/13	FL
7	Switching (Ch8) Introduction to Data-Link Layer (Ch9)	10/17	FL	10/20	FL
8	**Midterm exam**	**10/24**	**Evening**	**10/24**	**Evening**
9	Error detection and correction (Ch10)	10/31	FL	11/03	FL
10	Data link control (Ch11)	11/07	FL	11/10	FL
11	Media Access Control (Ch12)	11/14	FL	11/17	**Rec**
12	Wired LAN (Ethernet) (Ch13) & Other wired network (Ch14)	11/21	**Rec**	11/24	FL
13	Wireless LAN (Ch15)	11/28	FL	12/01	FL
14	Other wireless networks (Ch16) Connecting devices and virtual LANs (Ch17)	12/05	FL	12/08	FL
15	**Final exam**	**12/12**	**Evening**	**12/12**	**Evening**