UNIVERSITY OF TOMORROW

Data communication and Networks

Course Code: ECEG3074

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Aug – Dec, 2024

Course overview

Course Code	Course name	L	T	P	C
ECEG3074	**Data communication and Networks**	3	0	0	**3**
Total Units to be Covered: 6		**Total Contact Hours:34**			
Prerequisite(s):	Basic knowledge of computer systems and data structures				

Course Objectives

- To help in understanding the concepts of communications and computer networks.

Recommendations

Textbooks

1. Youlu Zheng and Shakil Akhtar, Networks for Computer Scientist and Engineers, Oxford University Press,2006
2. **Behrouz A. Fourouzan, Data Communications and Networking, 2/e Tat McGrawhill,2000**
3. James F. Kurose and Keith W. Ross, Computer Networking – A Top-Down Approach Featuring the Internet, 2/e Pearson Education, 2003

Reference Books

1. S. Keshav, An Engineering Approach to Computer Networking, Pearson education ,2002
2. F. Halsall, Data Communication, Computer Networks and Open Systems, Addison Wesley, 1996
3. **Andrew S. Tanenbaum, Computer Networks , 4/e, Pearson education, 2003**
4. Leon-Garcia and I. Widjaja, Communication Networks, Tata McGraw Hill, 2000
5. Bertsekas and Gallagar , Data Networks, 2/e, PHI, 1992
6. Douglas E Comer ,Computer Networks and Internet’s, 2/e Pearson Education,2004
7. Gallo, Computer Communication and Networking Technologies, Thomson Learning

Modes of Evaluation

✓ **Quiz/Assignment/ presentation/ extempore/ Written Examination**

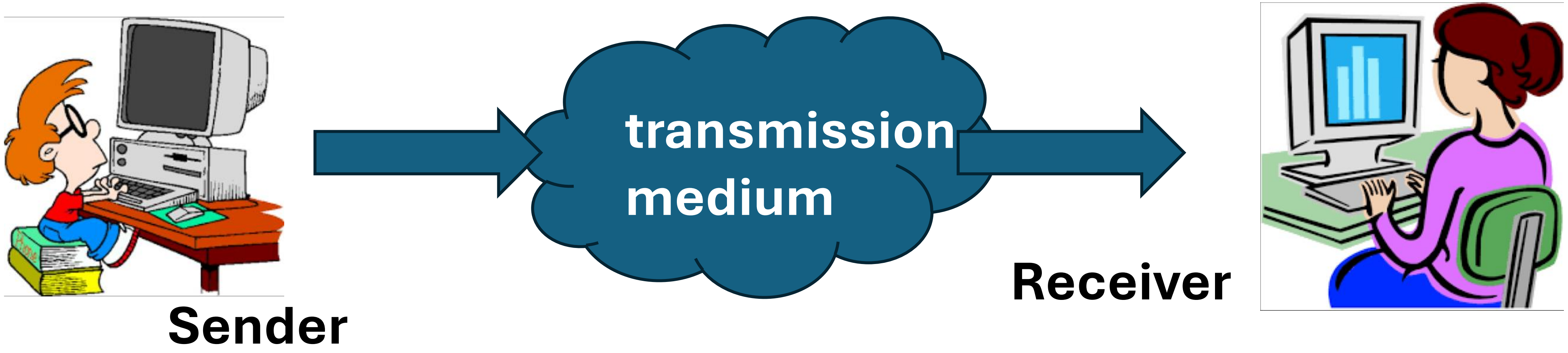
- **Examination Scheme**

Components	IA	MID SEM	End Sem	Total
Weightage (%)	30	20	50	100

- Internal Assessment

Data Communication

- Data communication refers to the process of transferring data **between two or more devices** through any **transmission medium**, such as **cables** or **wireless signals**.
- It involves the **exchange of data using various techniques and protocols to ensure accurate and efficient transmission**.



Data communication and **Networks**

- A **network** is a **collection of interconnected devices**, such as computers, servers, and networking hardware, **that communicate** with each other **to share resources and information**.

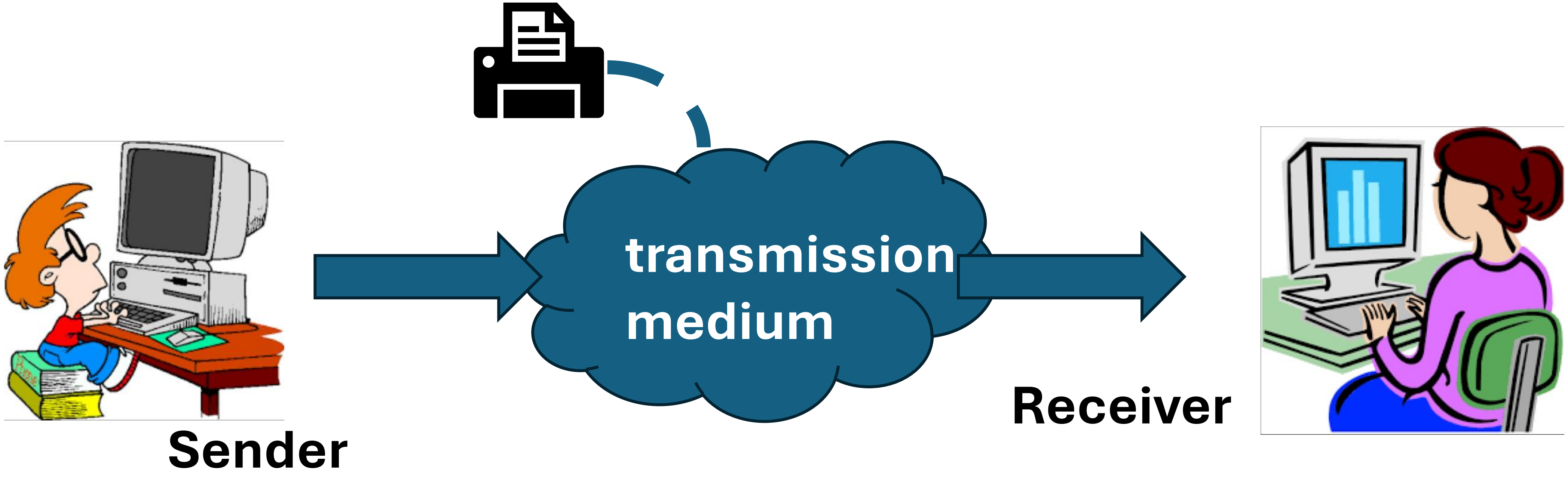
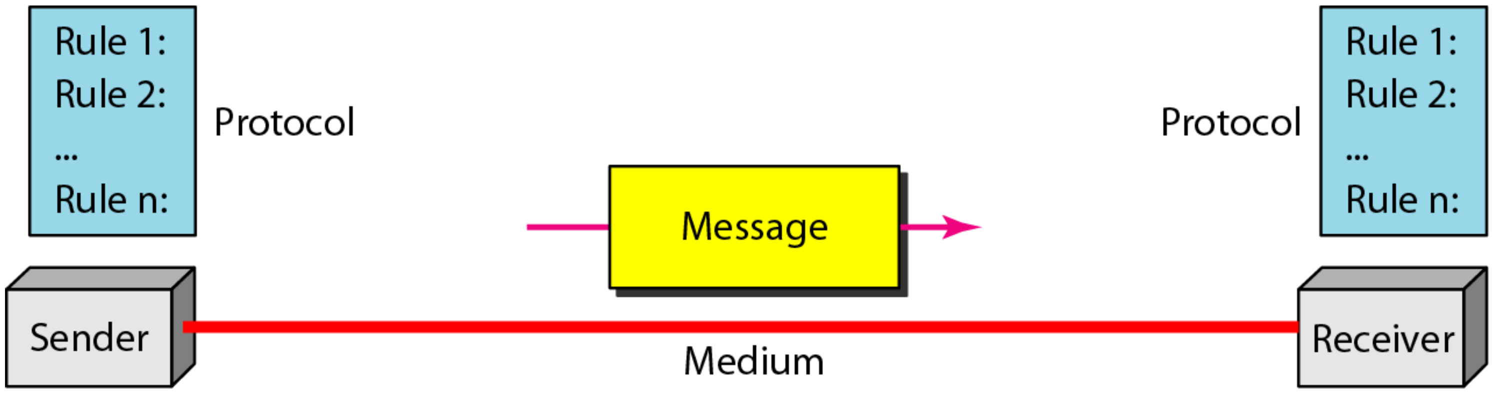


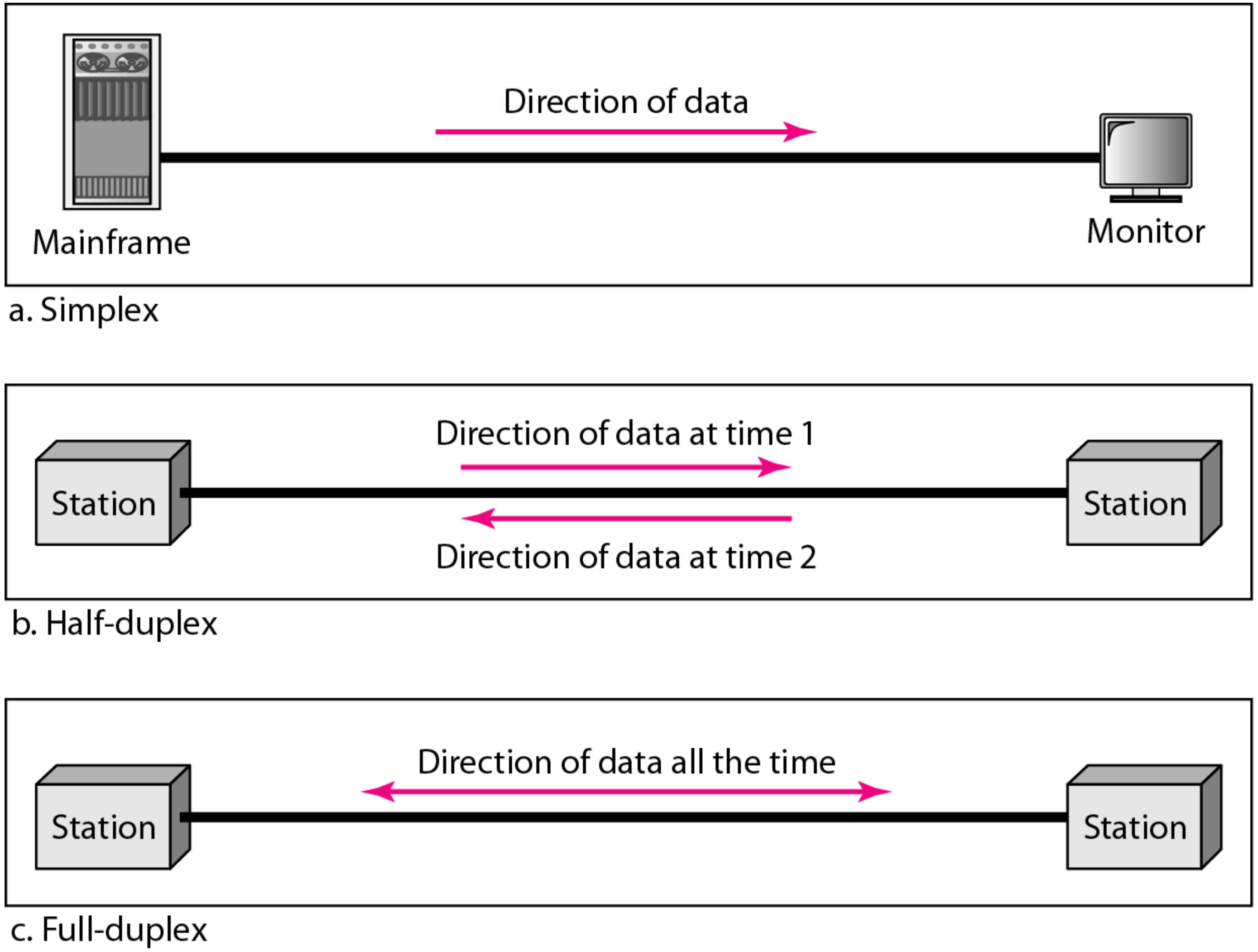
Figure *Five components of data communication*



*A **protocol** is synonymous with rule. It consists **of a set of rules** that **govern data communications**. It determines what is communicated, how it is communicated and when it is communicated. The **key elements of a protocol** are **syntax, semantics and timing***

Figure *Data flow (simplex, half-duplex, and full-duplex)*

Can use the entire capacity of the channel to send data in one direction. E.g. **Keyboards** and traditional **monitors**.



Can both transmit and receive, but not at the same time.
E.g. **Walkie-talkies**

Both stations can transmit and receive simultaneously.
E.g. **Telephone line**

Network Applications

Computer network is popular due to its applications:

- – World Wide Web
- – Email
- – Online social network
- – Streaming audio/video
- – Videoconferencing (e.g. Skype, Google Meet)
- – File sharing
- – Instant messaging
- – … and many more

Types of Networks

1. **Local Area Network (LAN)**
2. **Wide Area Network (WAN)**
3. **Metropolitan Area Network (MAN)**
4. **Personal Area Network (PAN)**

Types of Networks

- **Local Area Network (LAN):** *privately owned network that connects devices within a* ***limited geographic area****, such as a* ***home****,* ***school****, or* ***office*** *building. (**Wireless LAN:** WiFi/Wireless Fidelity)*

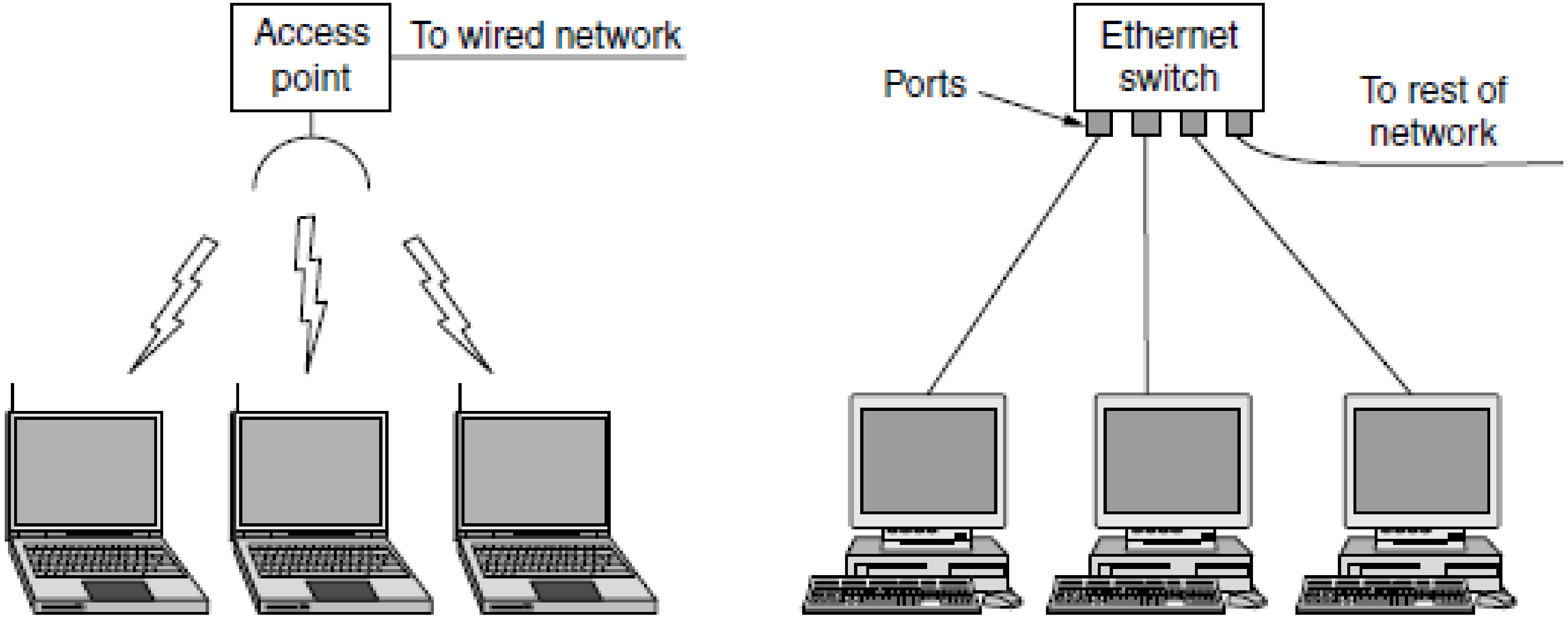


Figure 1-8. Wireless and wired LANs. (a) 802.11. (b) Switched Ethernet.

Virtual LAN
or
VLAN

Types of Networks

- **Metropolitan Area Network (MAN):** *A network that **spans a city** or a **large campus**, **connecting multiple LANs** within the area.*
- *Example:* cable TV networks

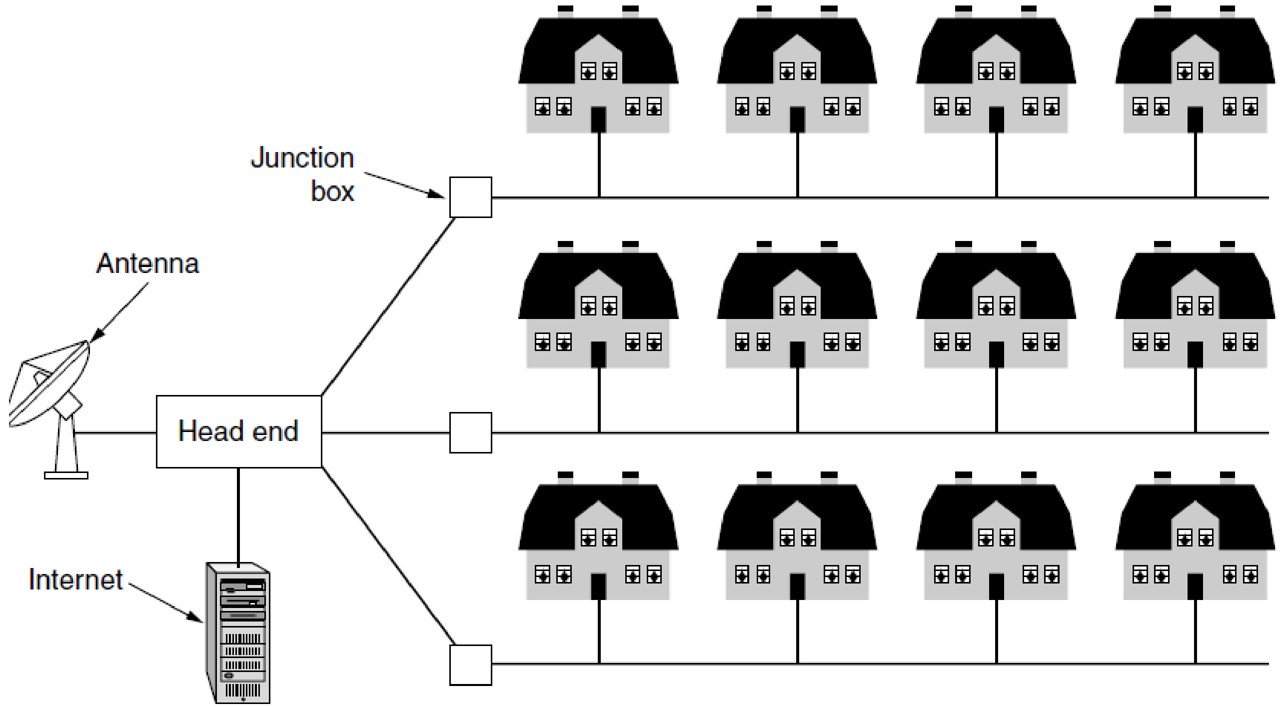


Figure 1-9. A metropolitan area network based on cable TV.

Types of Networks

- **Wide Area Network (WAN):** *A network* ***that covers a broad geographic area****, often using leased telecommunication lines to connect multiple LANs.*

A Virtual Private Network *(VPN) is a technology that creates a secure, encrypted connection over a less secure network, typically the internet. This allows users to send and receive data as if their computing devices were directly connected to a private network, ensuring privacy and security.*

Cellular telephone network is another example of a WAN.

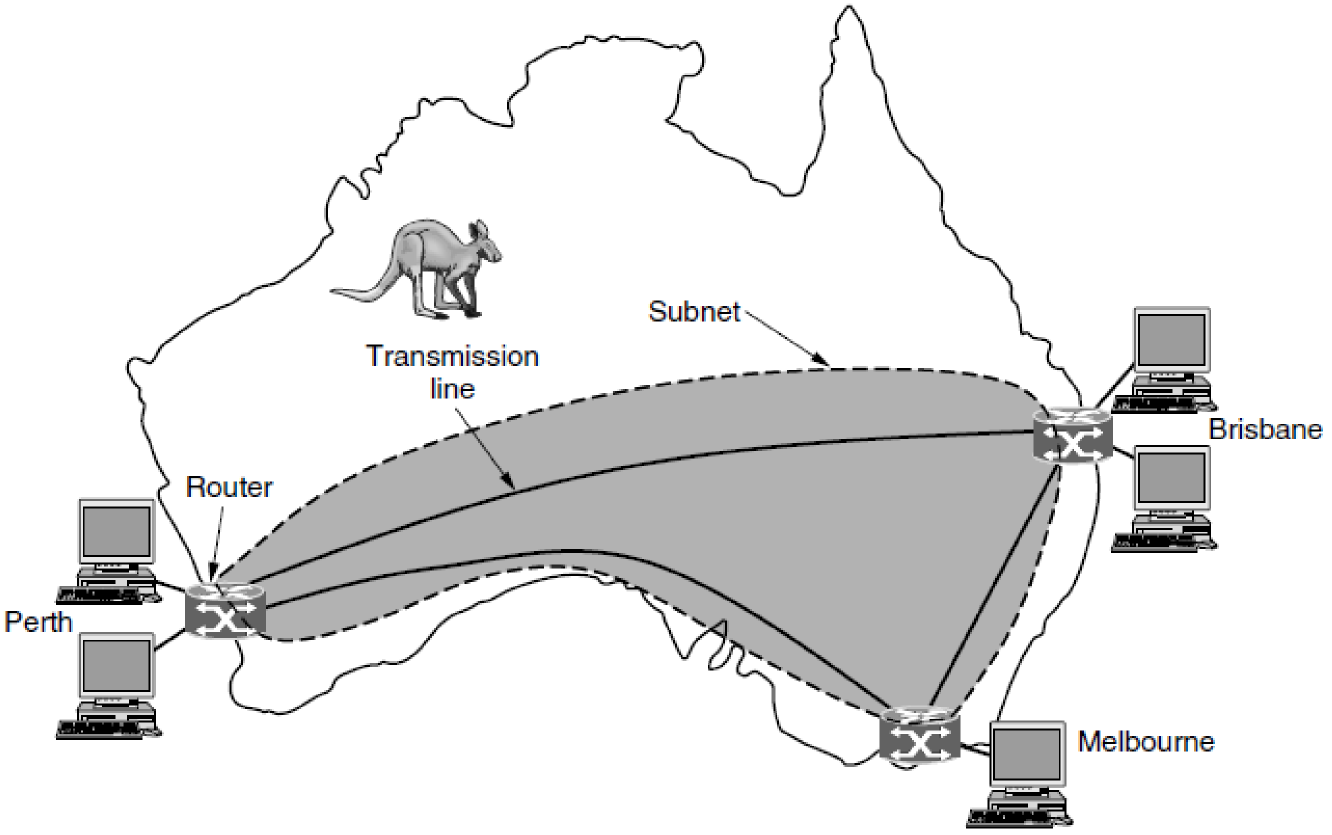
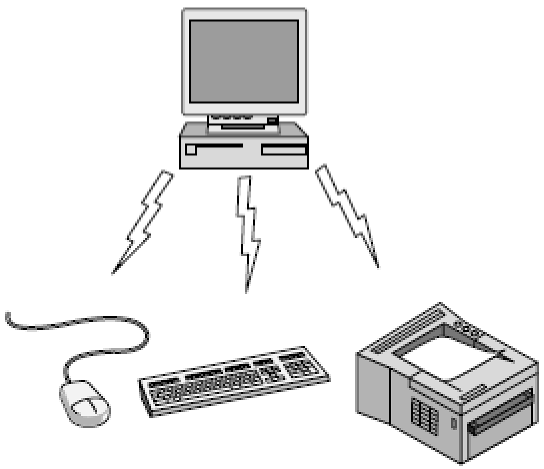
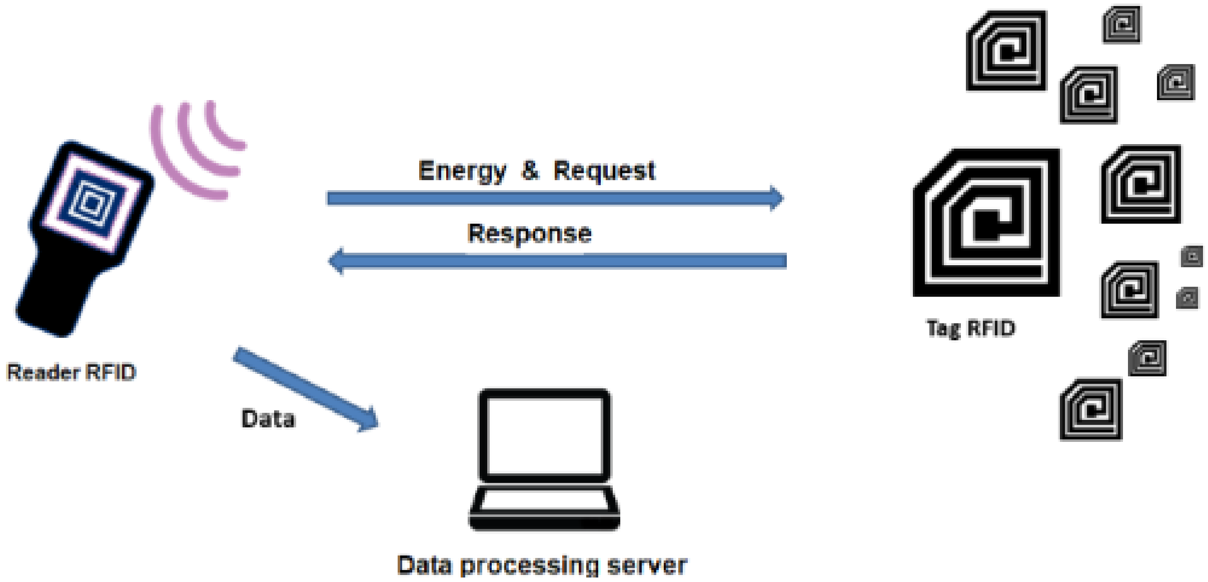


Figure 1-10. WAN that connects three branch offices in Australia.

Types of Networks

- **Personal Area Network (PAN)**: *A network that connects devices within an individual's workspace, typically within a* ***range of a few meters****, such as* ***Bluetooth****-connected devices*, RFID (radio frequency identification) on smartcards and library books.





Classification of interconnected processors by scale

Interprocessor distance	Processors located in same	Example
1 m	Square meter	Personal area network
10 m	Room	
100 m	Building	Local area network
1 km	Campus	
10 km	City	Metropolitan area network
100 km	Country	
1000 km	Continent	Wide area network
10,000 km	Planet	The Internet

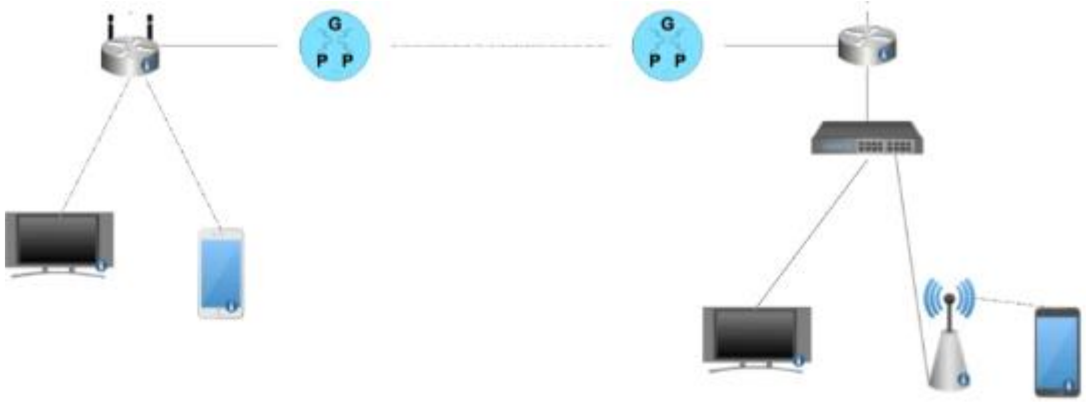
Types of transmission technology

- **Point-to-point** links and
- **Broadcast** links

Point-to-Point Connection

- A **source** and a **destination on a network share the medium** to establish a point-to-point links.
- Short messages, called **packets**, may have to first visit **one or more** intermediate machines.
- Often **multiple routes**, of **different lengths**, are possible, **so finding good ones is important** in point-to-point networks.

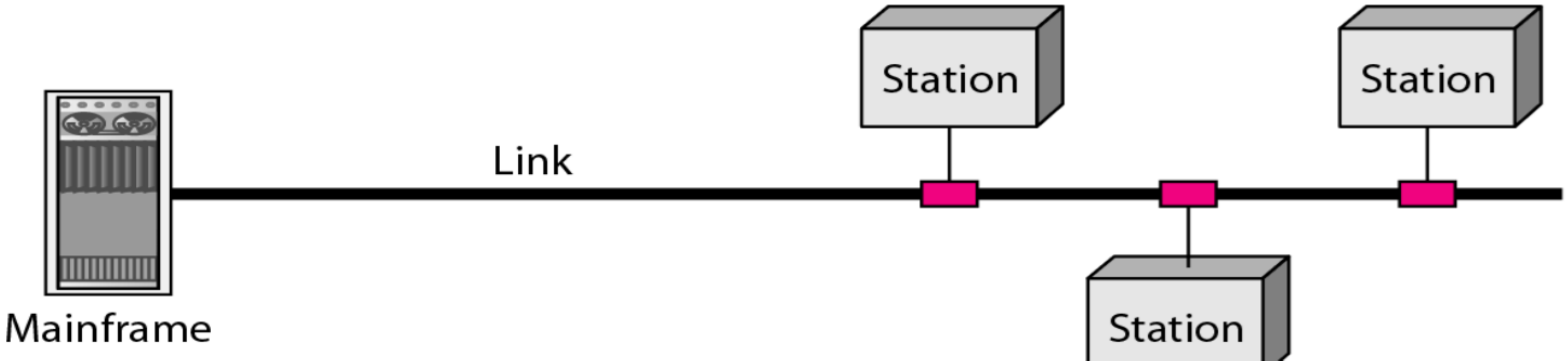
Exactly one sender and one receiver is sometimes called **unicasting**



Point-to-point connection

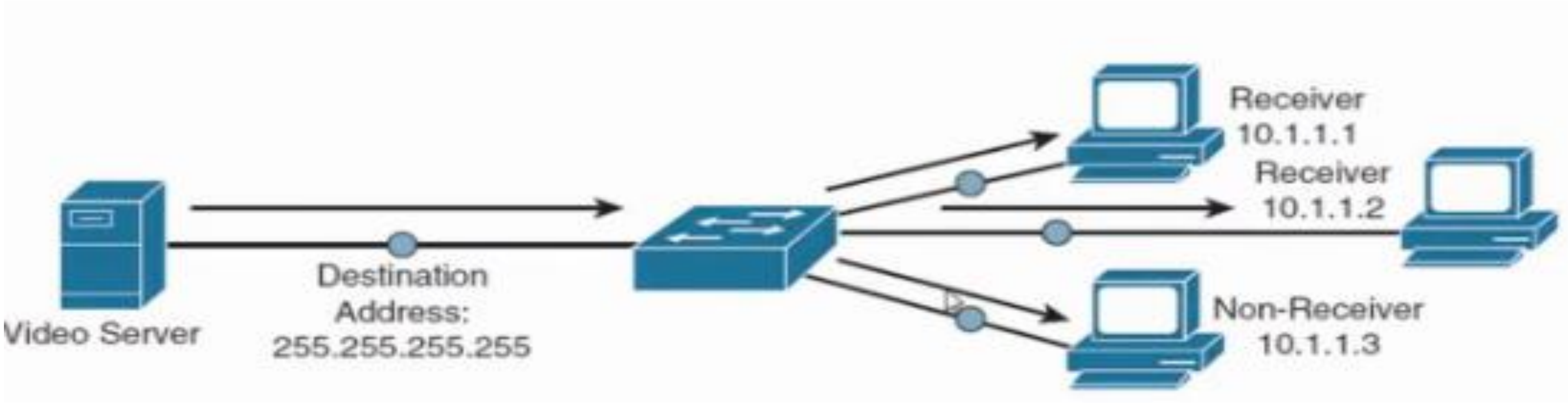
Broadcast Connection

- The communication channel **is shared by all the machines** on the network
- Packets sent by any machine are **received by all** the others



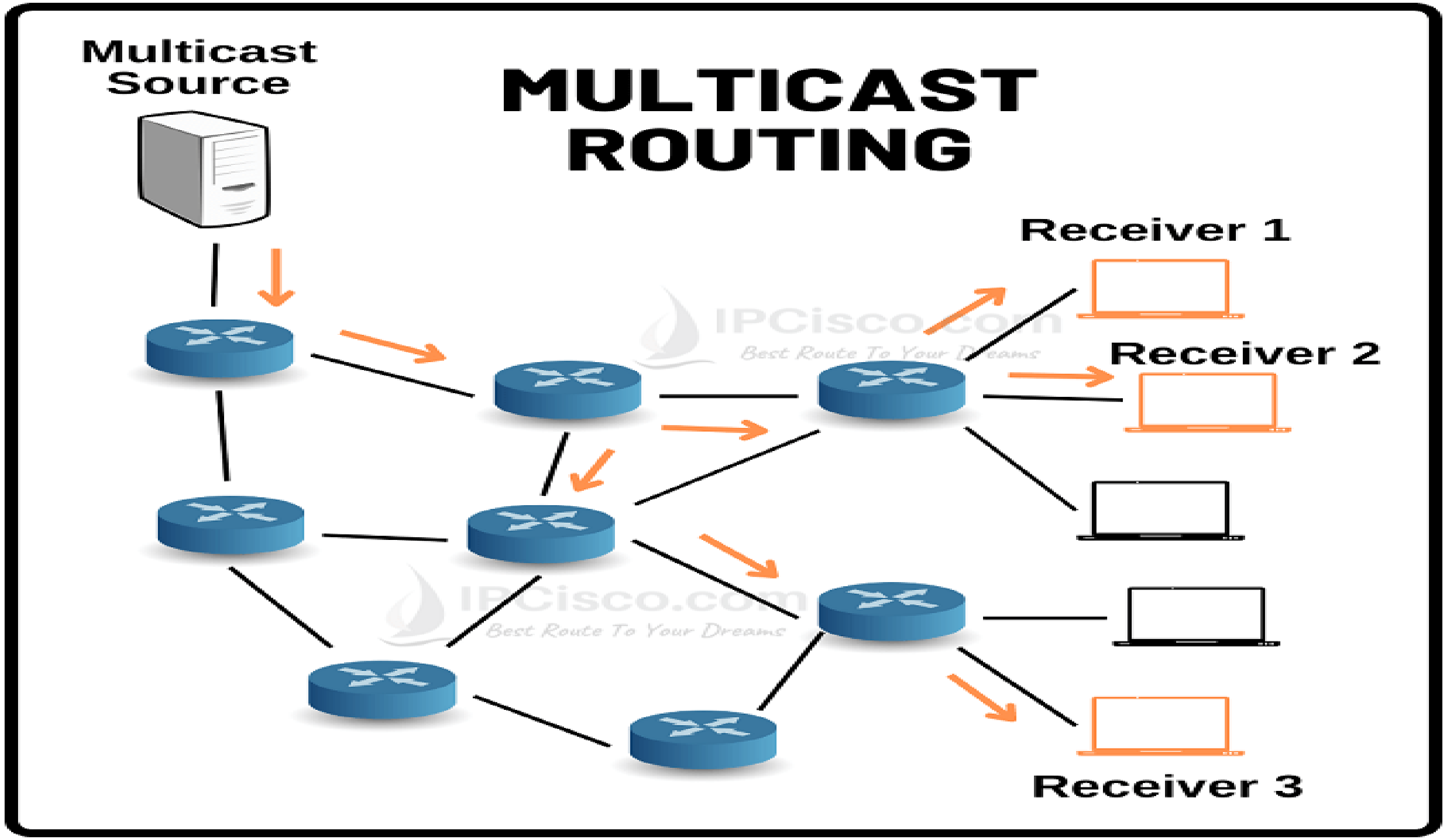
Broadcast Connection

- Addressing a packet to ***all*** **destinations** by **using a special code** in the address field.
- When a packet with **this code is transmitted**, it is received and processed by every machine on the network. This mode of operation is called **broadcasting**.



Broadcast Connection

- Some broadcast systems also support transmission to a **subset of the machines**, which is known as **multicasting**.

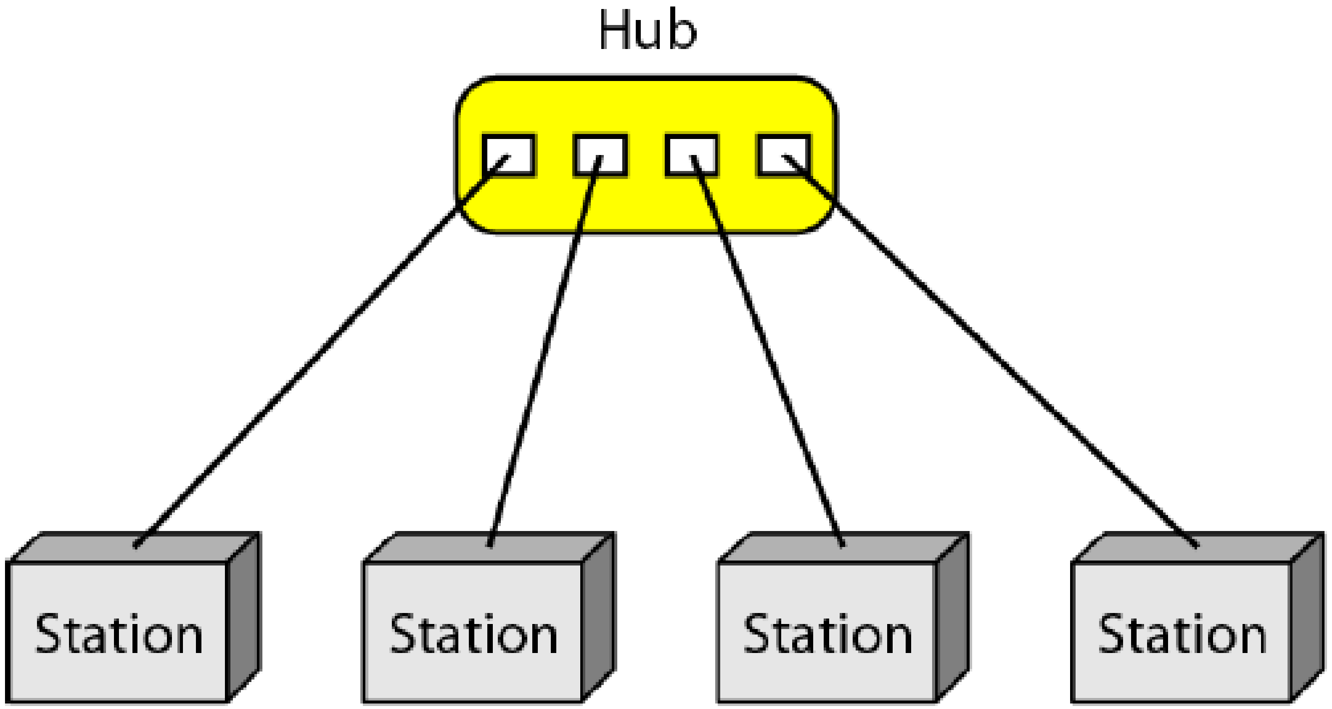


LAN Topologies

- The term *physical topology* refers to the way in which a network is laid out physically.
- It is the geometric representation of the relationship of all the links and linking devices (usually called nodes) to one another
  1. Star
  2. Bus
  3. Ring
  4. Mesh

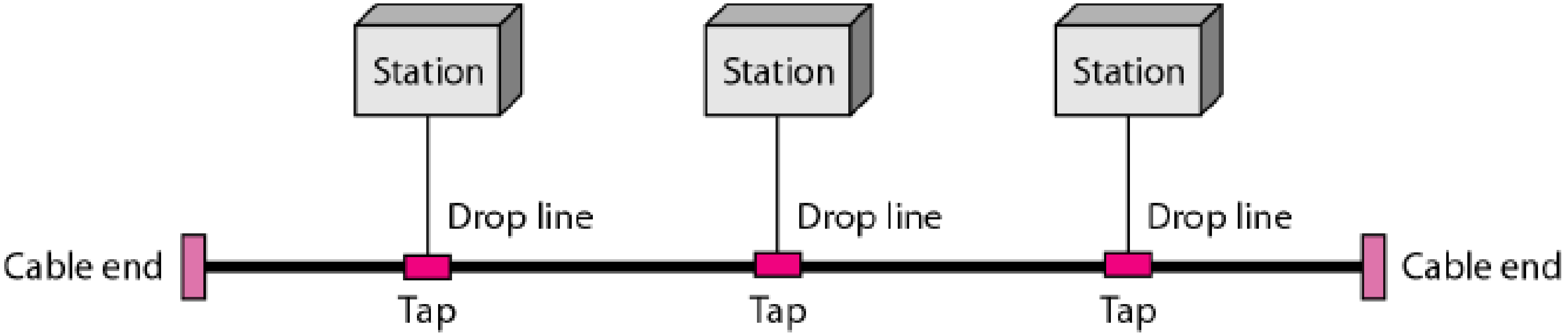
Star Topologies

1. **Star**
2. Bus
3. Ring
4. Mesh



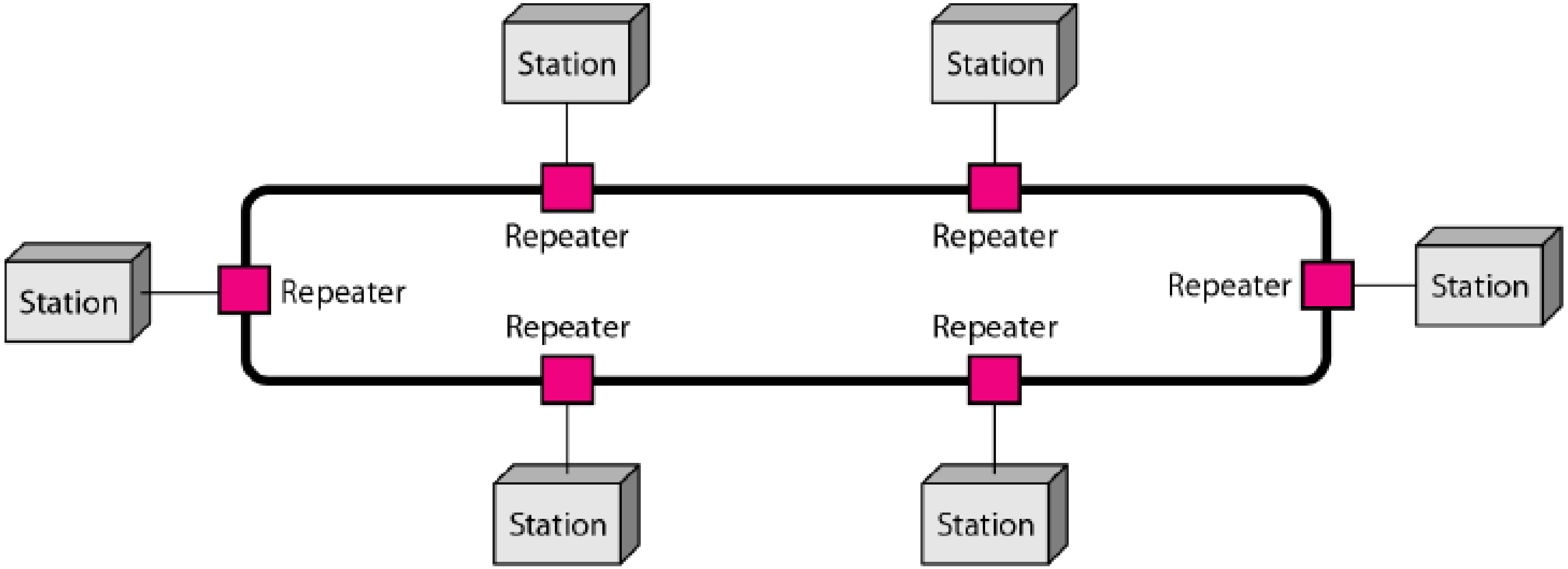
Bus Topologies

1. Star
2. **Bus**
3. Ring
4. Mesh



Bus Topologies

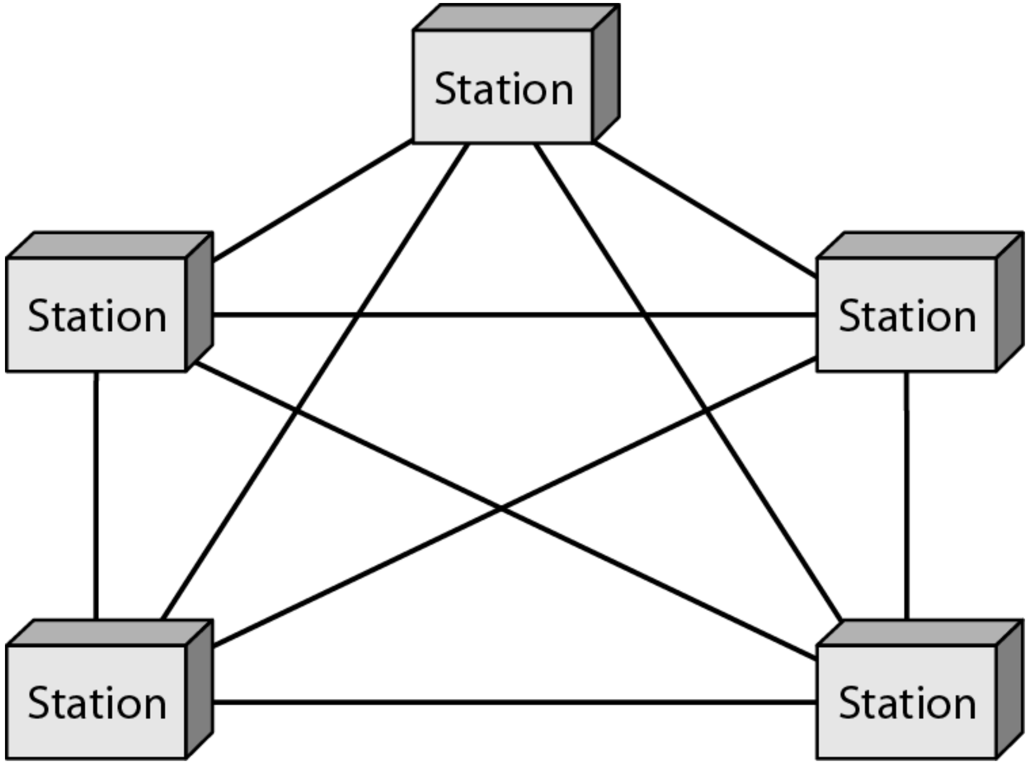
1. Star
2. Bus
3. **Ring**
4. Mesh



Bus Topologies

1. Star
2. Bus
3. Ring
4. **Mesh**

A fully connected ***mesh*** *topology*



n(n-1) physical simplex links
Or **(n(n-1)/2** full-duplex links.

LAN Topologies

Topology	Description	Advantages	Disadvantages	Example Standards
Bus	All devices share a single central cable (bus).	Easy to implement and extend; requires less cable.	Difficult to troubleshoot; a central cable failure affects the whole network.	Early Ethernet (10BASE2, 10BASE5)
Ring	Devices are connected in a circular path.	High-speed data travel; equal access to the network.	Single device or connection failure can disrupt the network.	Token Ring (IEEE 802.5)
Star	All devices are connected to a central hub.	Easy to install and manage; failure of one device does not affect the network.	Central hub failure can bring down the entire network.	Ethernet (IEEE 802.3)
Mesh	Every device is connected to every other device.	Highly reliable; easy to troubleshoot.	Expensive and complex to install; difficult to manage.	Zigbee, some Wi-Fi implementations

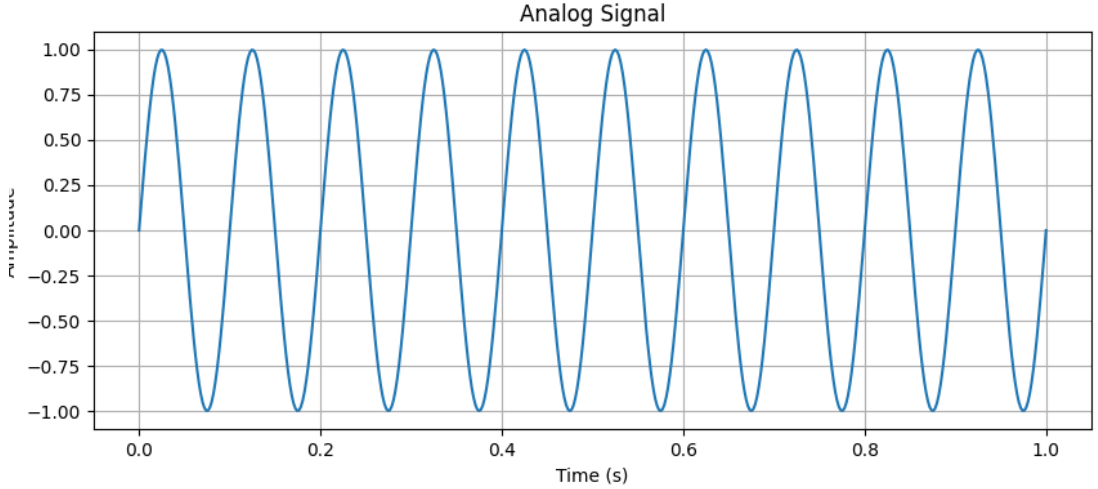
ANALOG and **DIGITAL** Data Transmission

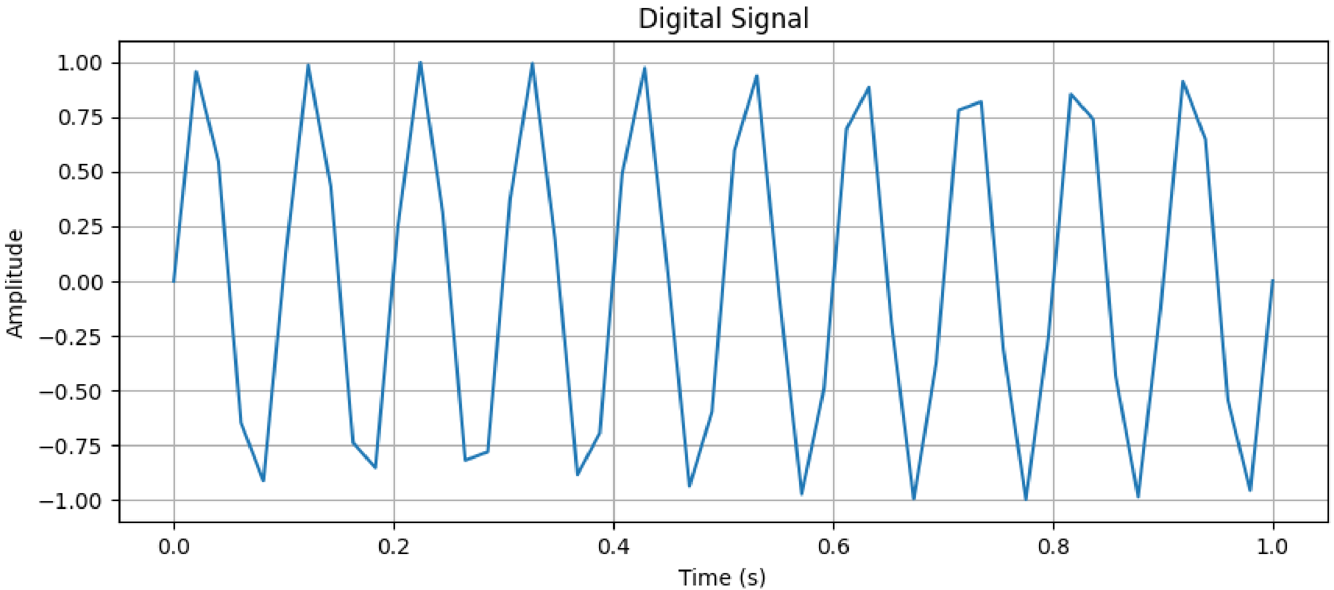
- The term **Analog data** refers to information that is **continuous**
- Analog data take on continuous values
- Eg wave signal (sound data)
- Have an infinite number of values in a range

- **Digital data** refers to information that has discrete states
- Digital data take on discrete values
- Eg wave signal sampled at discrete state to convert to a digital signal
- Can have only a limited number of values

ANALOG and **DIGITAL** Data Transmission

Figure Comparison of analog and digital signals





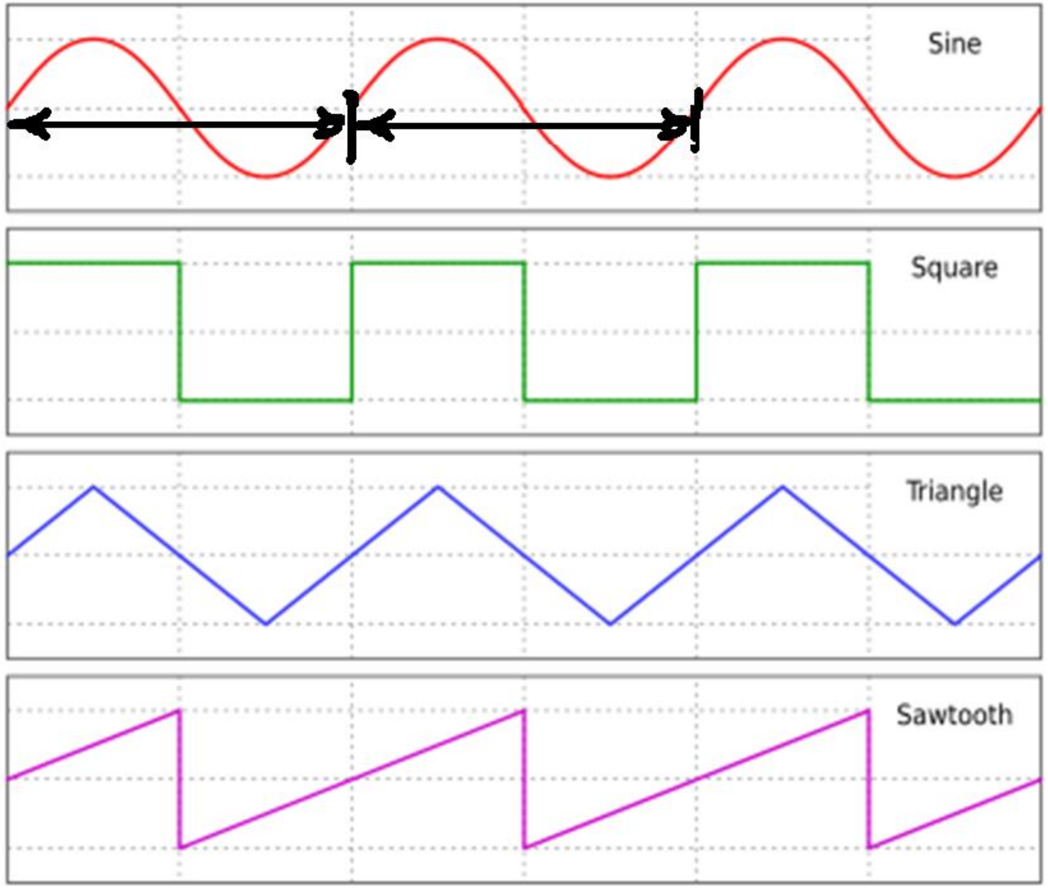
ANALOG and **DIGITAL** Data Transmission

- Both analog and digital signals can take one of two forms:
  - ***periodic*** or
  - ***nonperiodic*** (also refer to as *aperiodic*, the prefix ***a* in Greek means "non"**).

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

ANALOG and **DIGITAL** Data Transmission

- ***Periodic signal:*** A signal is a periodic signal if it completes a ***pattern within a measurable time frame**, **called a period*** and ***repeats that pattern over identical subsequent periods.***
- The completion of a full pattern is called a **cycle**
- The **frequency of a periodic function** is the number of complete cycles that can occur per second, denoted as:
- Frequency = Number of cycles / Time (in seconds)



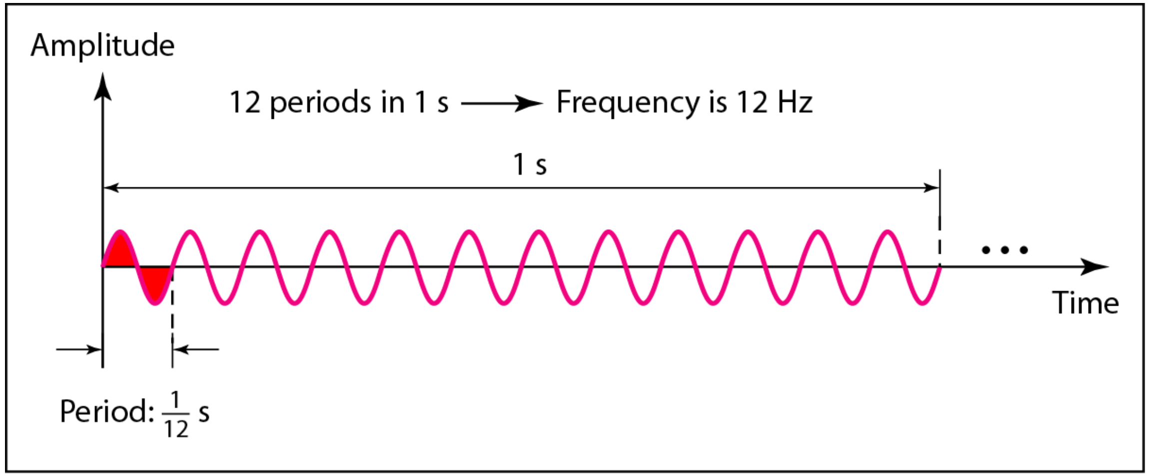
Frequency and period are the inverse of each other.

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

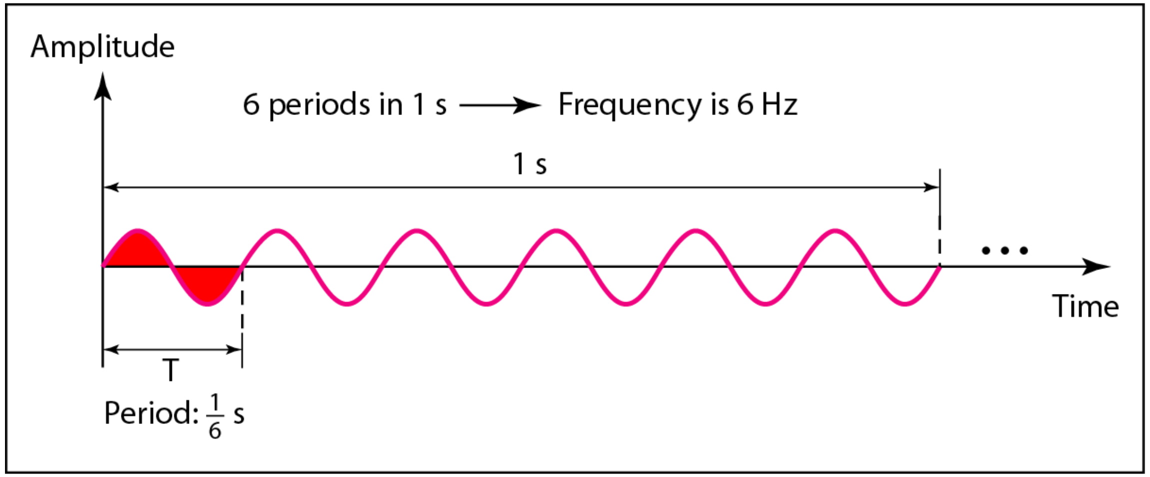
Table Units of period and frequency

Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	10^{-6} s	Megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	Gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz

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



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Example

The 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).

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

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

Frequency is the rate of change with respect to time.

Change in a short span of time means high frequency.

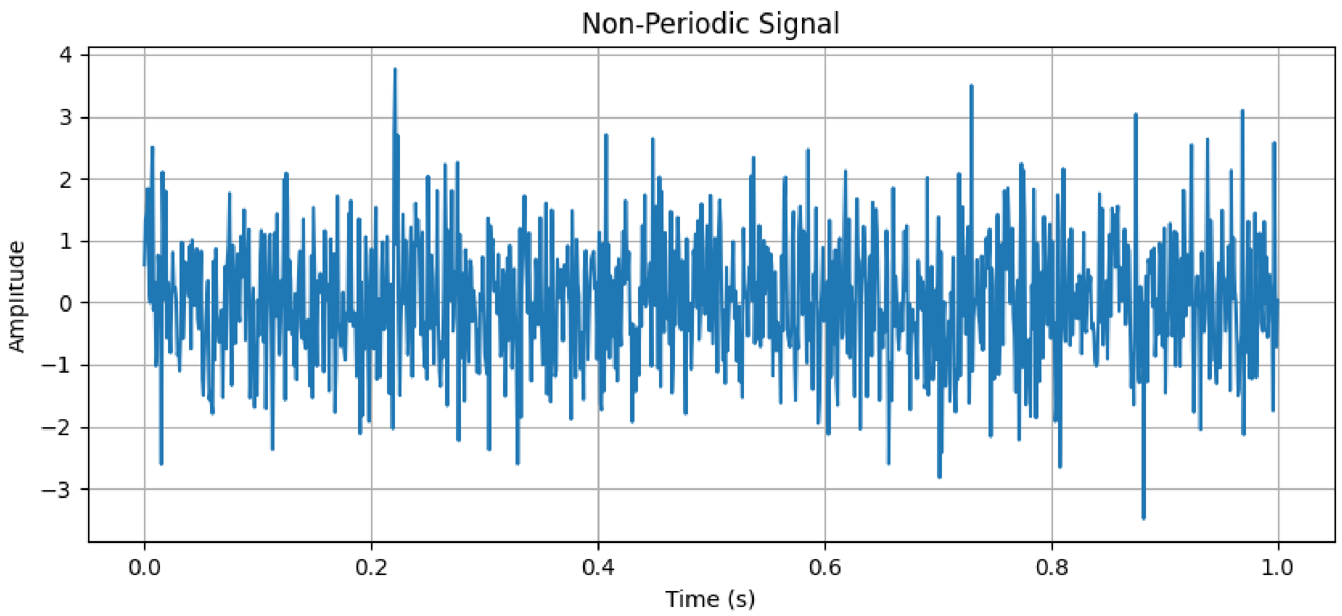
Change over a long span of time means low frequency.

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

If a signal changes instantaneously, its frequency is infinite.

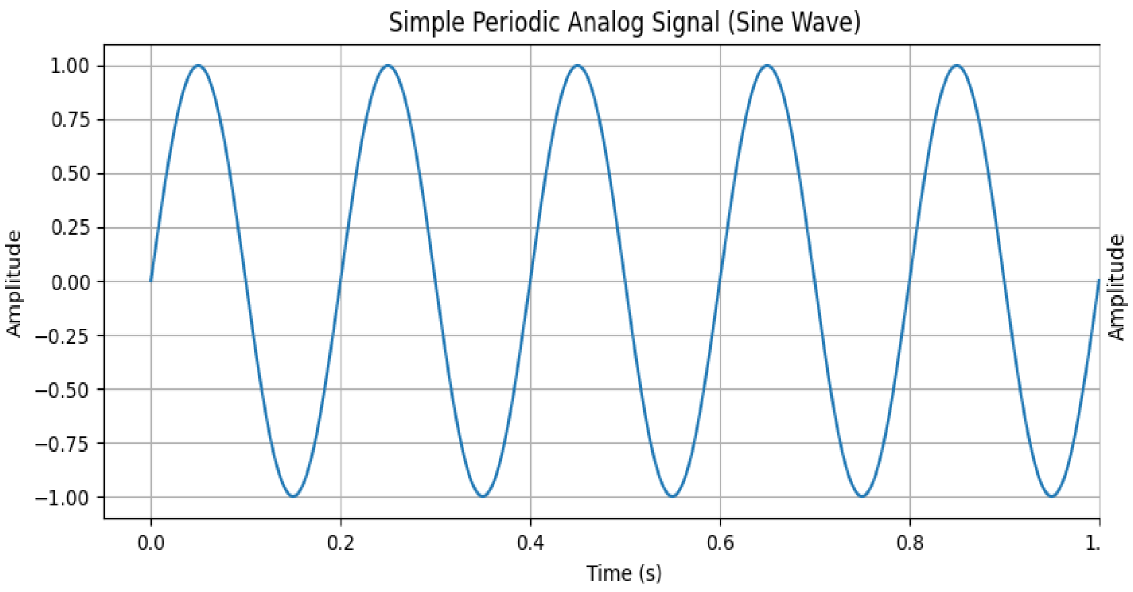
ANALOG and **DIGITAL** Data Transmission

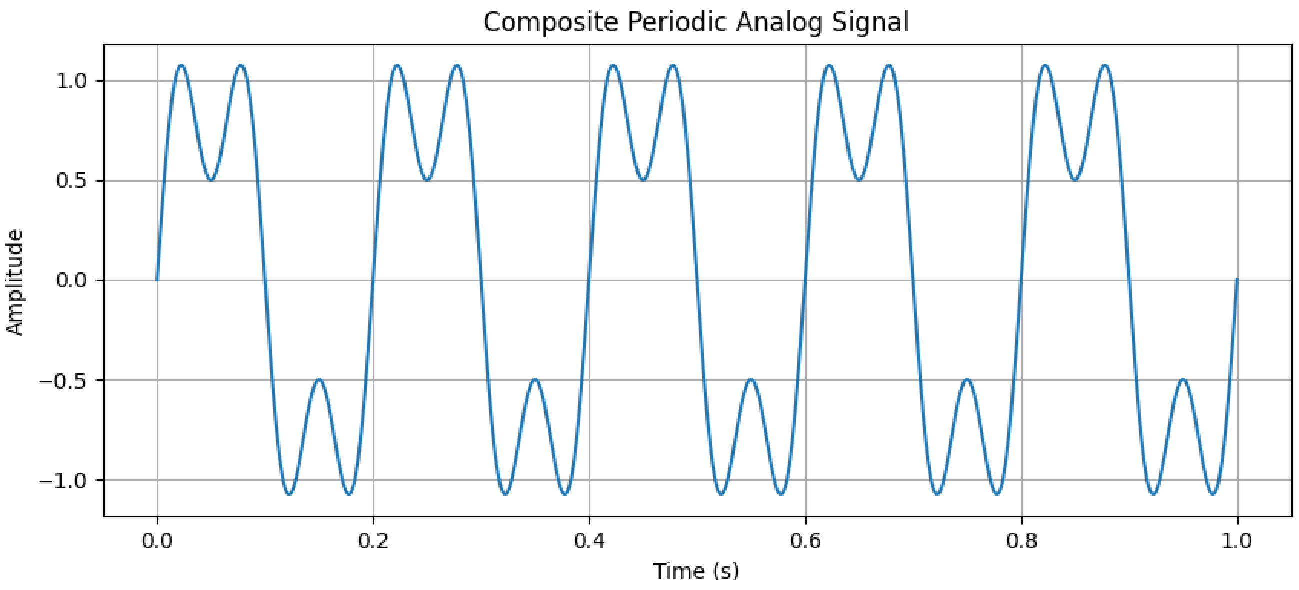
- ***Non-Periodic signal*** **do not exhibit regular** or repeating **patterns** over time.
- Unlike periodic signals, which repeat at regular intervals, non-periodic signals have no discernible cycle or pattern
- Signals that carry real information, such as **speech**, **music** or **video**, **do not repeat endlessly**.
- In other words, non-periodic signals, **do not have just one particular frequency**.



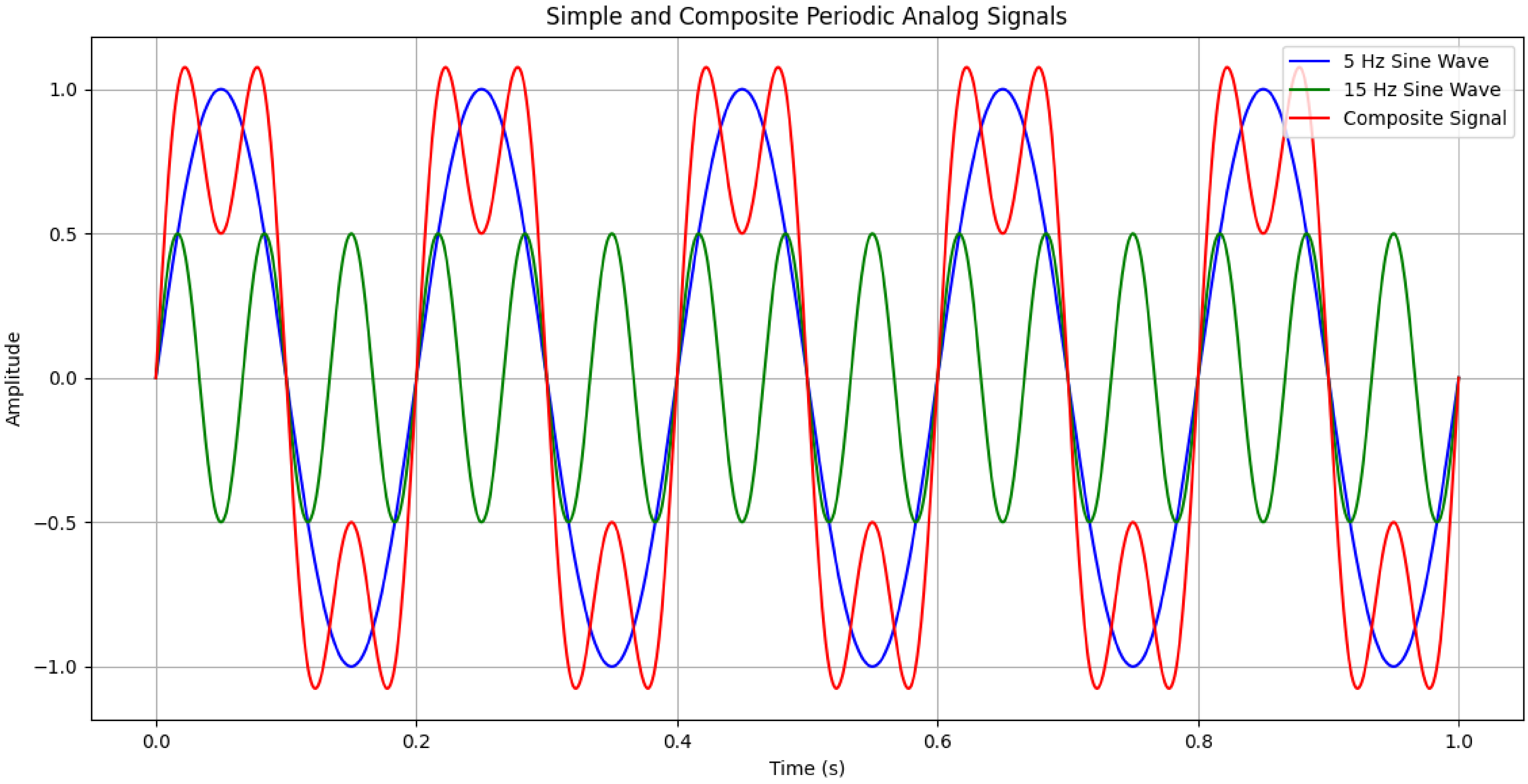
ANALOG and **DIGITAL** Data Transmission

- 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**.





ANALOG and **DIGITAL** Data Transmission



Sine Wave

- Sine wave is **the most fundamental form** of a periodic analog signal.
- According to **Fourier analysis**, **any periodic signal** can be decomposed into a sum of sine and cosine waves.
- The sine wave is the building block for **all more complex periodic signals**
- Mathematically,

$$y(t)=\mathbf{A}\,sin(2\pi\,\mathbf{f}\,\mathbf{t} + \boldsymbol{\phi})$$

where **A** is amplitude, ***f*** is frequency, ***t*** is time, and **ϕ** is phase

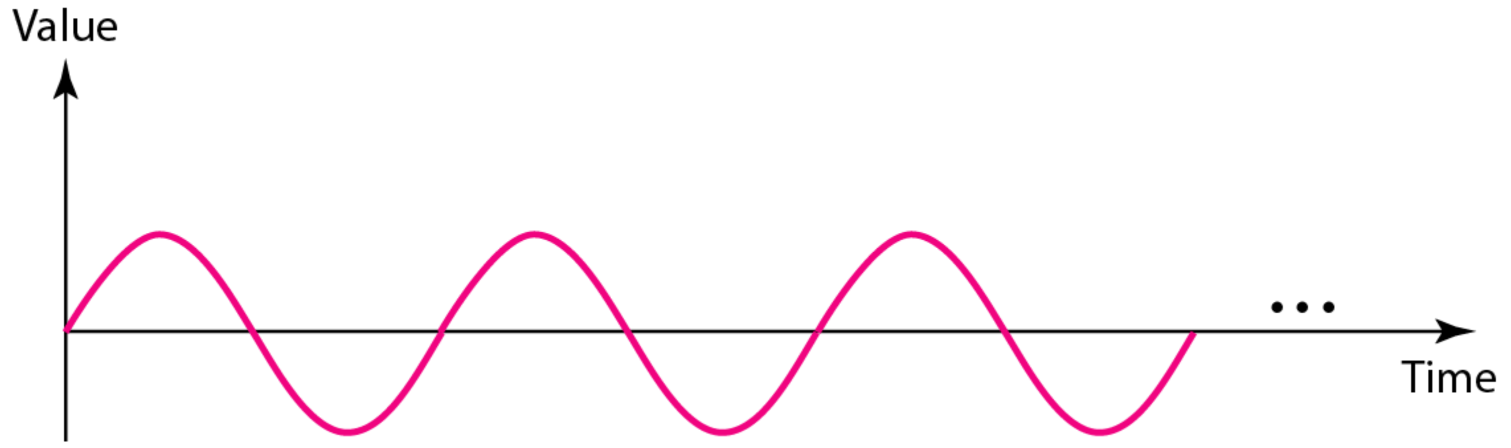
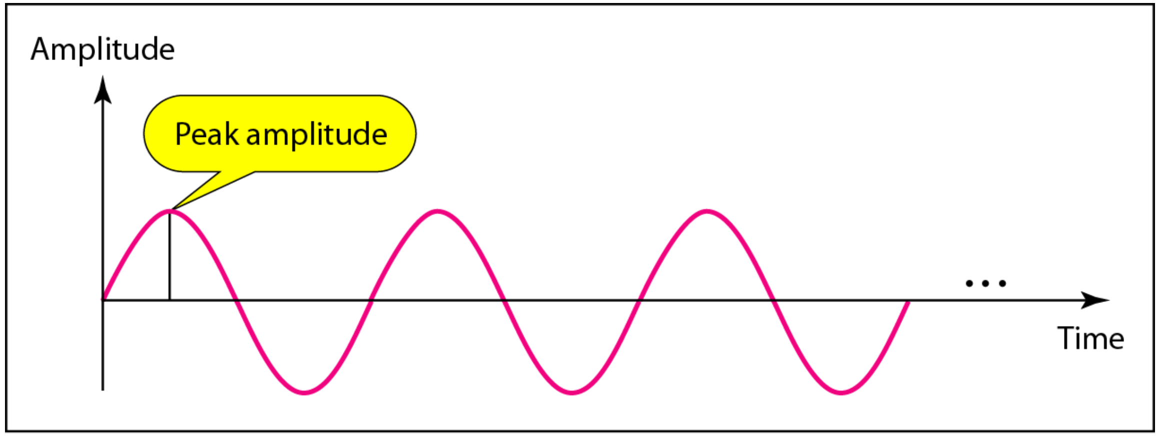


Figure A sine wave

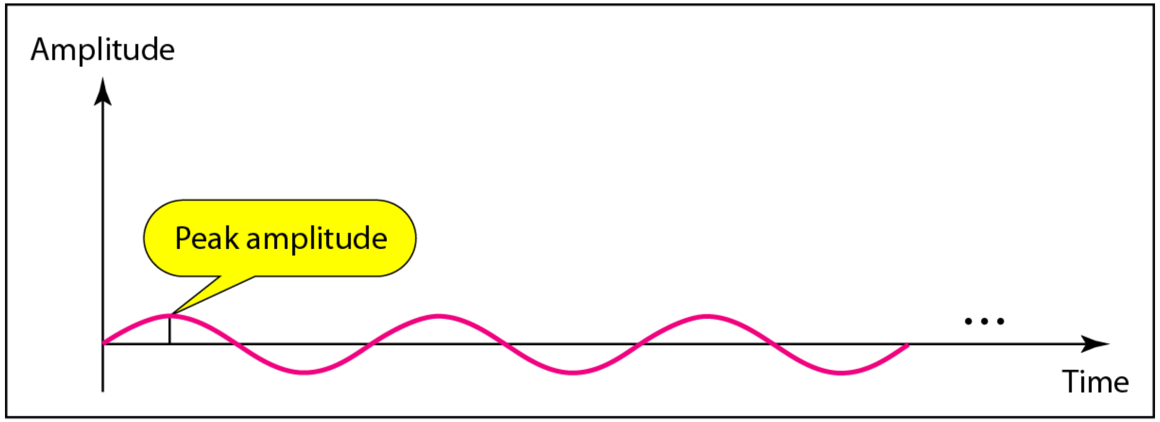
ANALOG and DIGITAL Data Transmission

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

- The peak amplitude of a signal is the **absolute value of its highest intensity**, proportional to the energy it carries.
- For electric signals, peak amplitude is normally measured in ***volts***.



a. A signal with high peak amplitude



b. A signal with low peak amplitude

Example

- 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 (110 to 120V) are root mean square (rms) values.

Peak and RMS Relationship

The relationship between the **rms** voltage and the **peak** voltage is given by:

$$V_{peak} = V_{rms} \times \sqrt{2}$$

- **India**: 230V (rms), 50 Hz
- **Europe**: 230V (rms), 50 Hz
- **United States**: 110-120V (rms), 60 Hz

Phase 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.

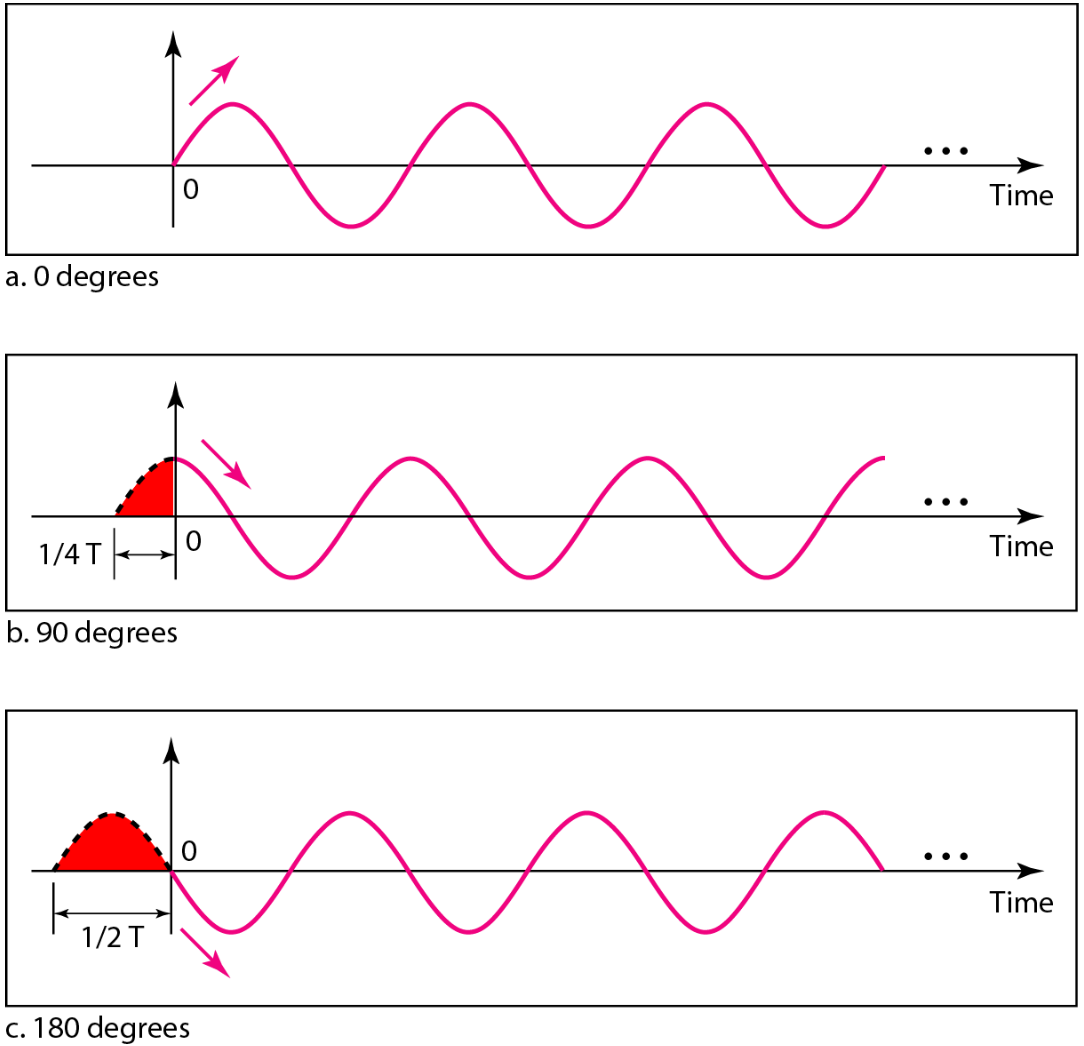
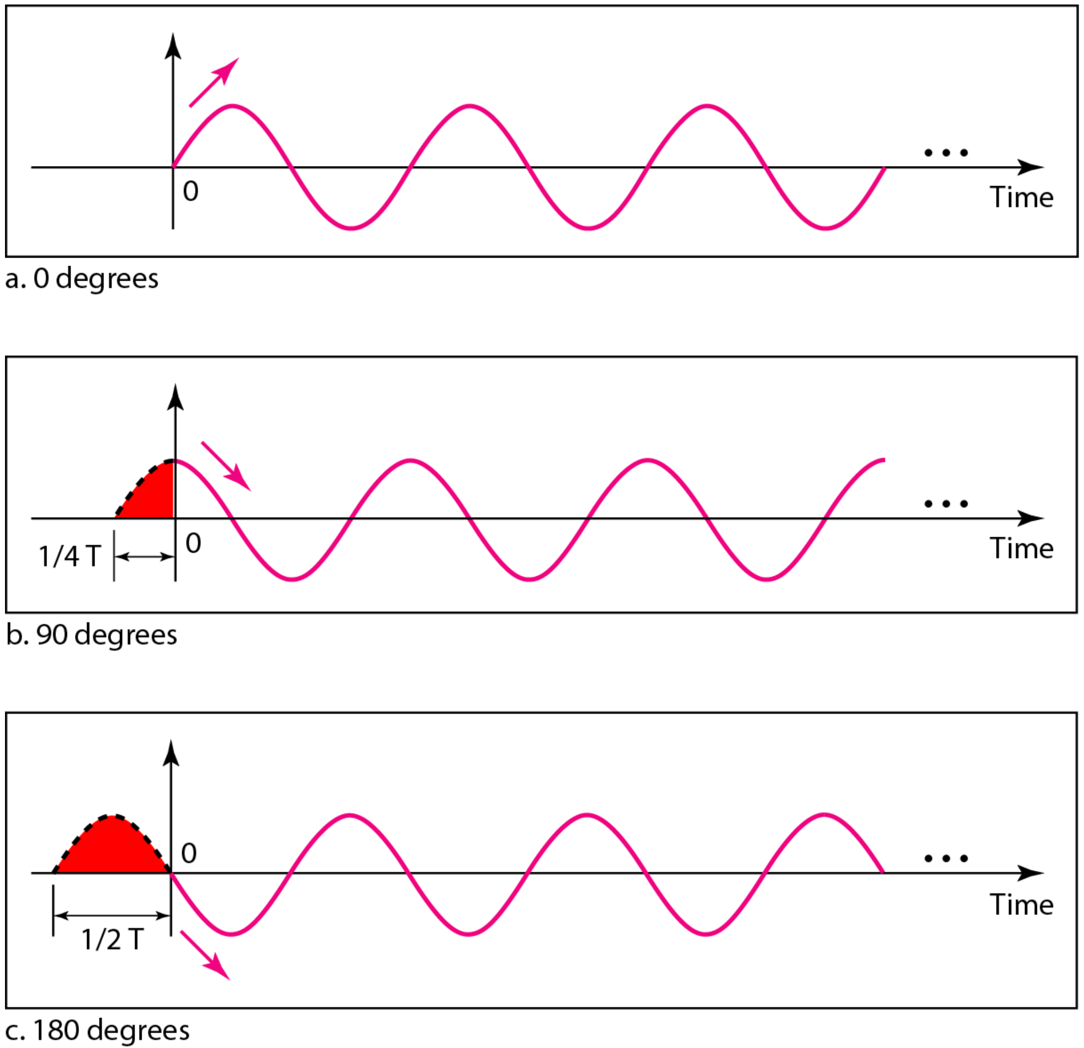


Figure Three sine waves with the same amplitude and frequency, but different phases

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

- Phase is measured in degrees or radians
  - A phase shift of **360° corresponds to a shift of a complete period**;
  - a phase shift of 180° corresponds to a shift of one-half of a period; and
  - a phase shift of 90° corresponds to a shift of one-quarter of a period



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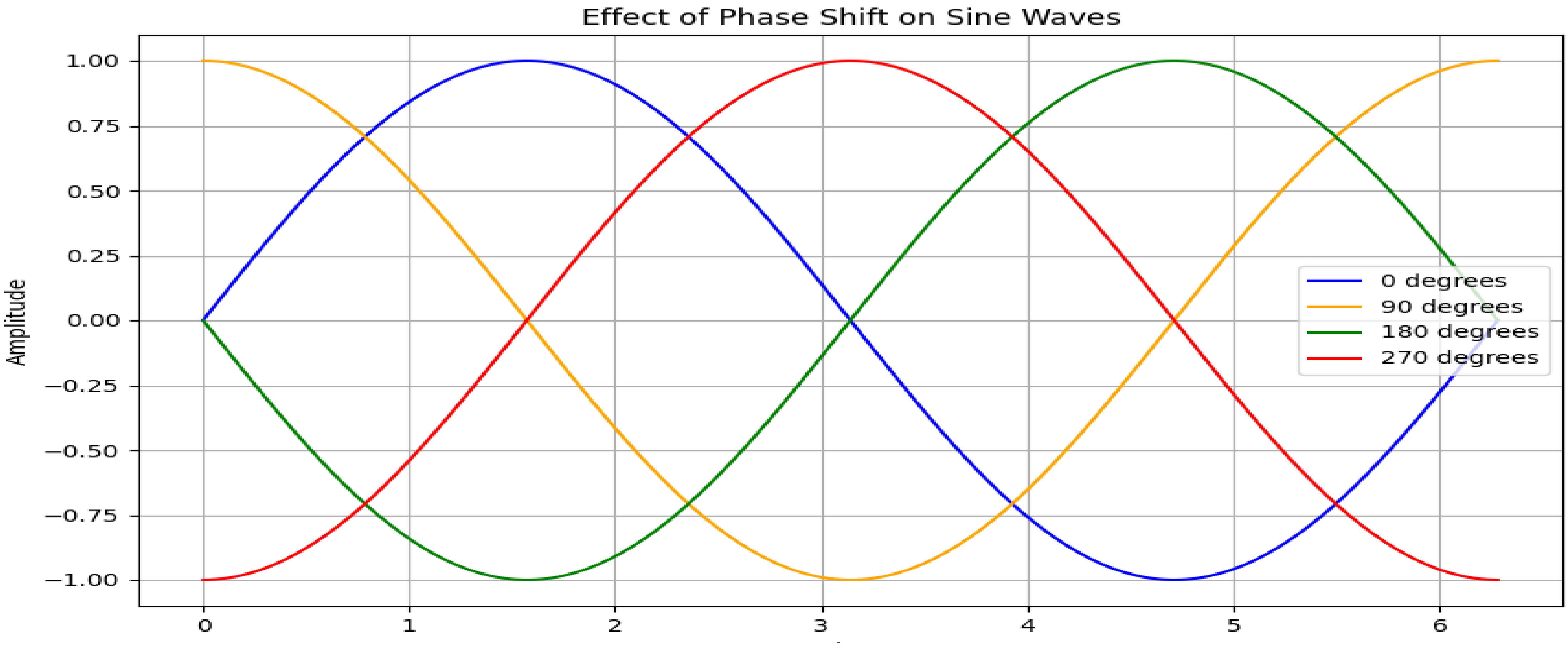
Phase describes the position of the waveform relative to time 0.

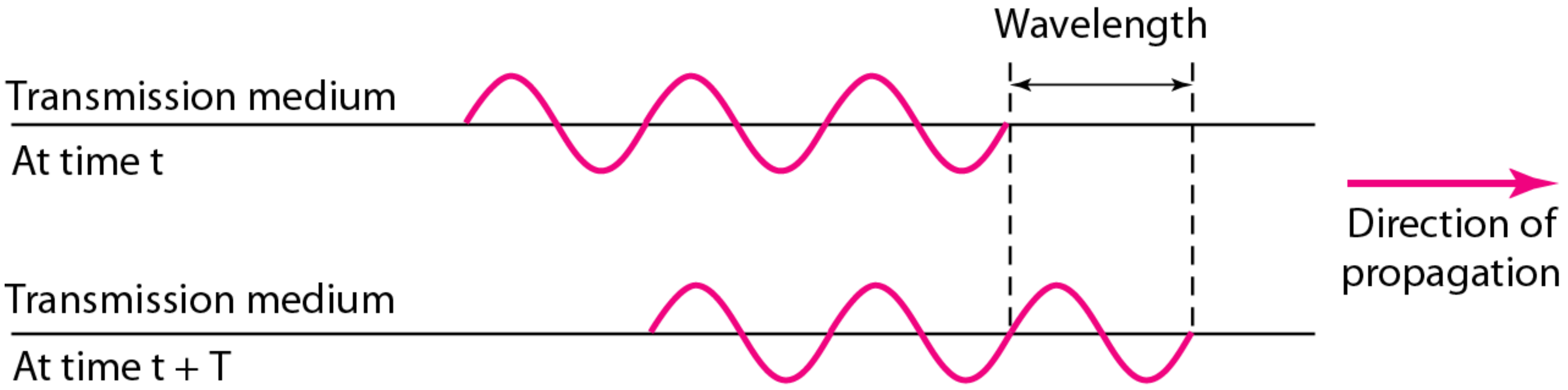


Wavelength

- Wavelength is a 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:

$$\boldsymbol{\lambda} = \frac{v}{f}$$

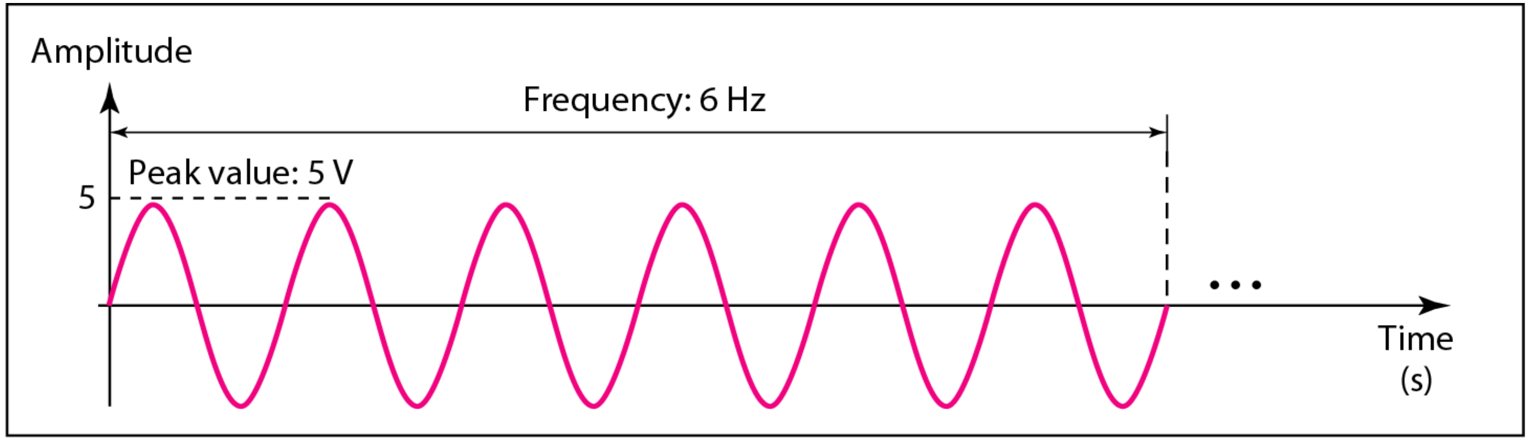
Where **λ** is the wavelength; f is the frequency of the wave and v is the propagation speed of the wave in the medium



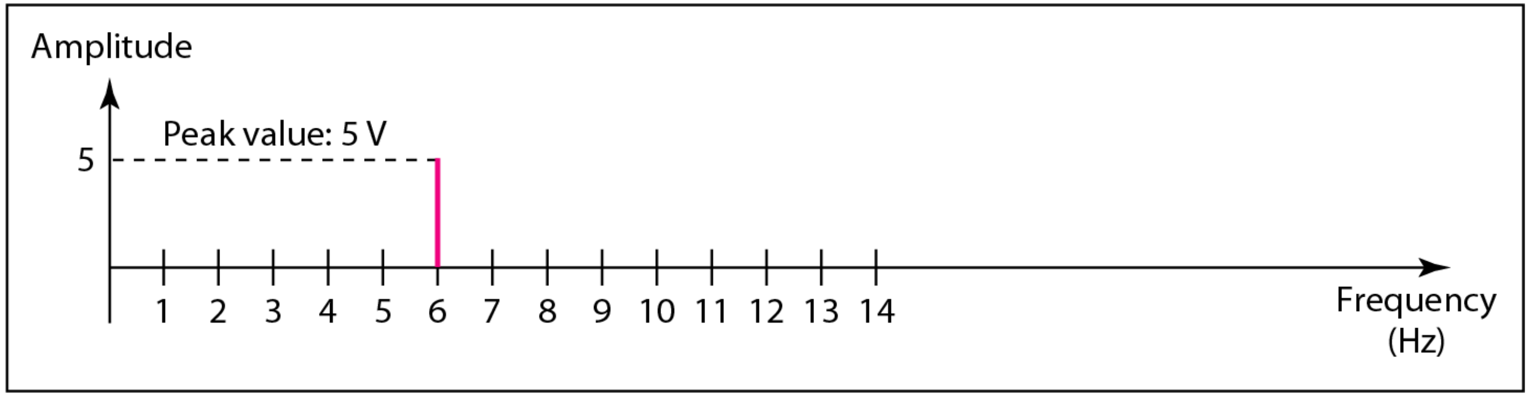
The time-domain and frequency-domain

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

- The advantage of the frequency domain:
  - Can immediately see the values of the **frequency** and **peak amplitude**.
  - A complete sine wave is represented by one spike.

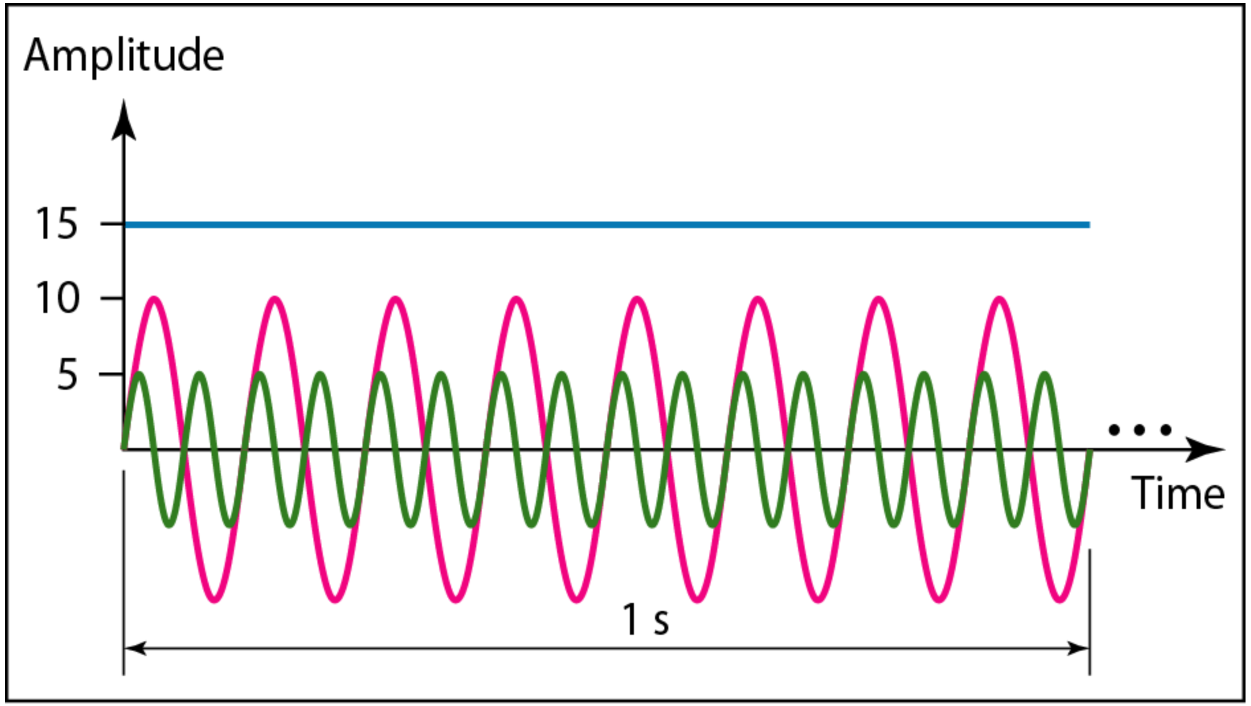


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

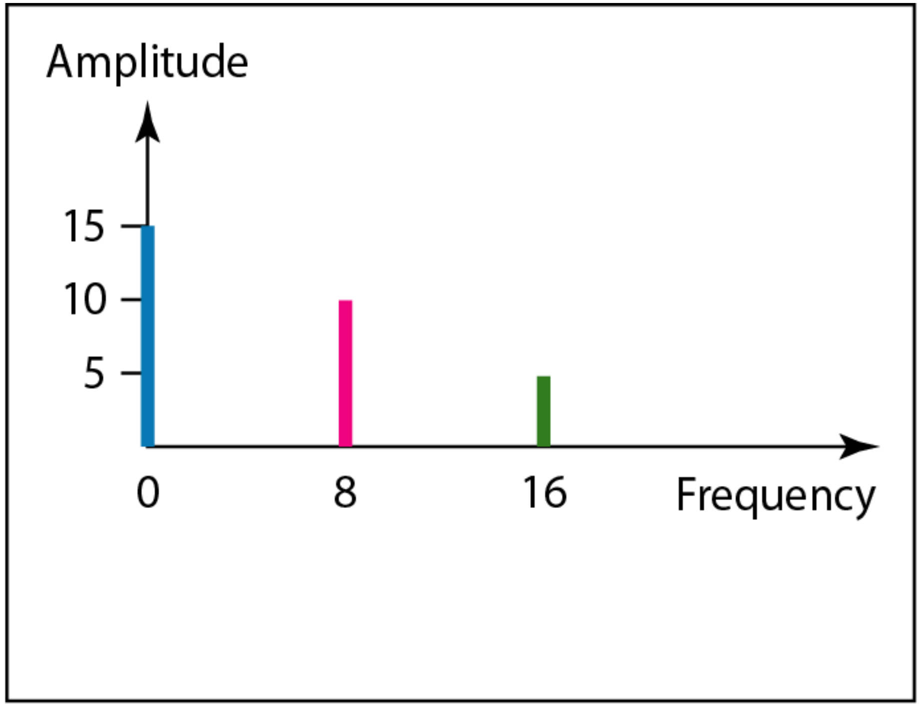


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Figure The time domain and frequency domain of three sine waves



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



b. Frequency-domain representation of the same three signals

Example

- Figure shows a **nonperiodic composite signal**.
- It can be the **signal created by a microphone or a telephone set when a word or two is pronounced**.

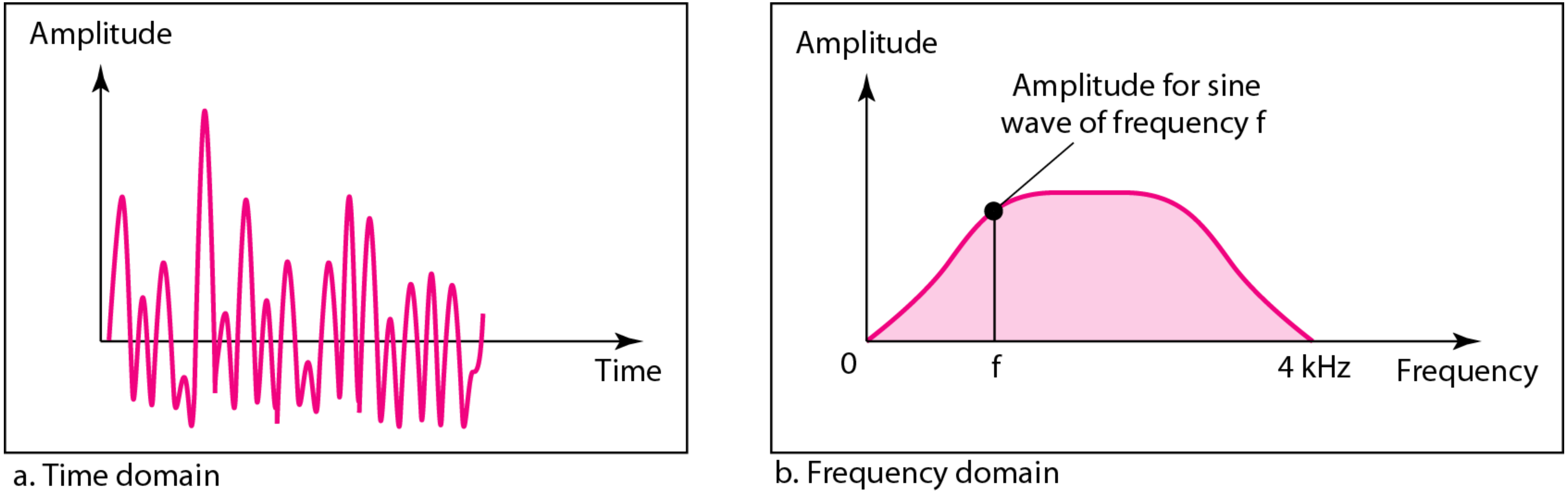
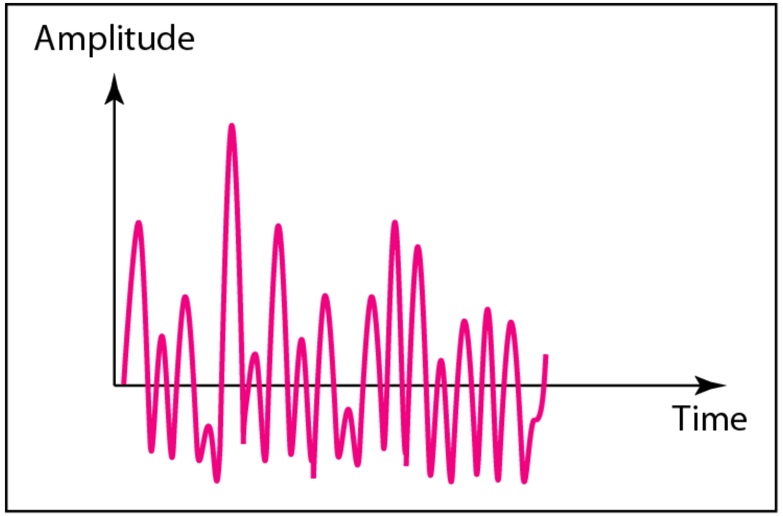


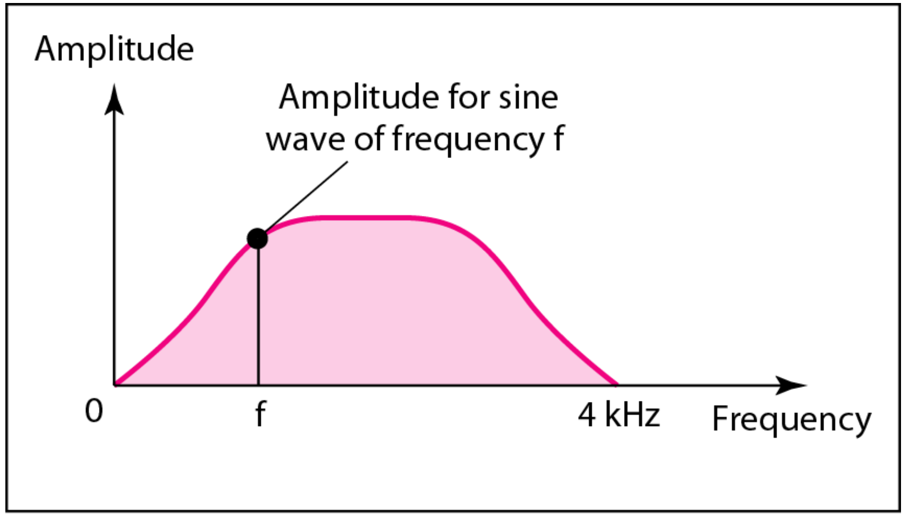
Figure The time and frequency domains of a nonperiodic signal

Example

- There are an infinite number of simple sine frequencies.
- Although the number of frequencies in a human voice is infinite, the range is limited.
- A normal human being can create a continuous range of frequencies between 0 and 4 kHz.



a. Time domain



b. Frequency domain

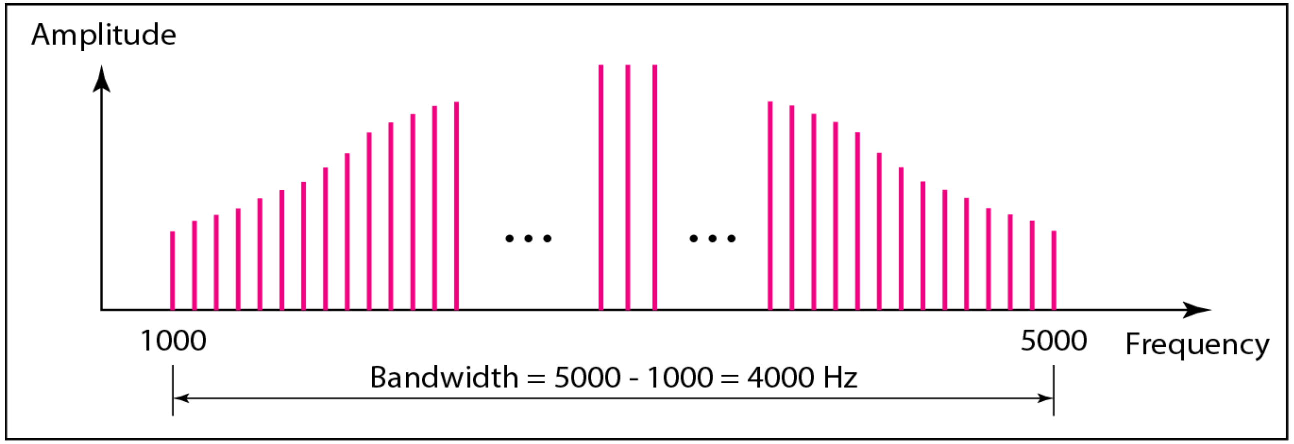
Figure The time and frequency domains of a nonperiodic signal

Bandwidth

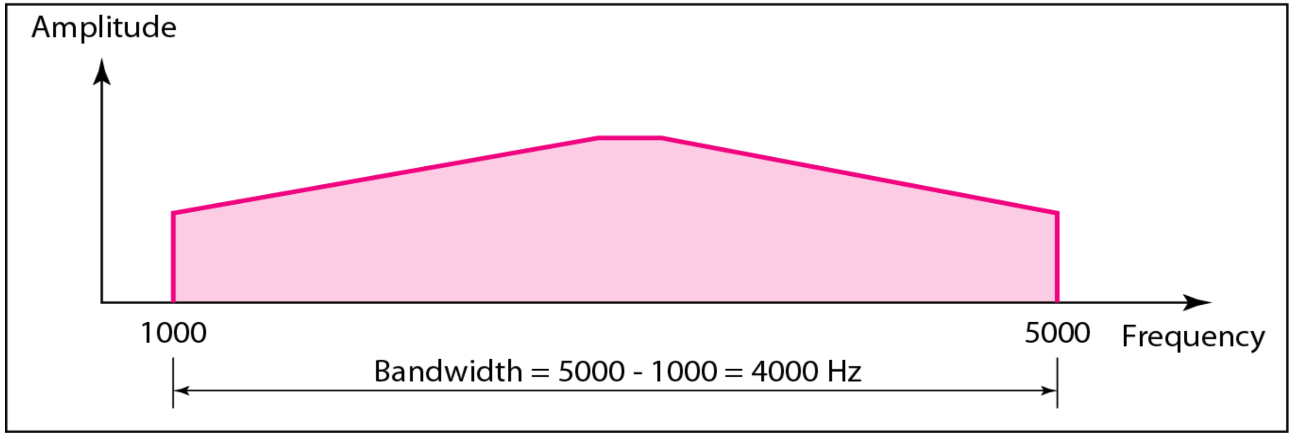
The bandwidth of a composite signal is the **difference between the highest and the lowest frequencies** contained in that signal.

Bandwidth

Figure The bandwidth of periodic and nonperiodic composite signals



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Example

If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

Solution

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

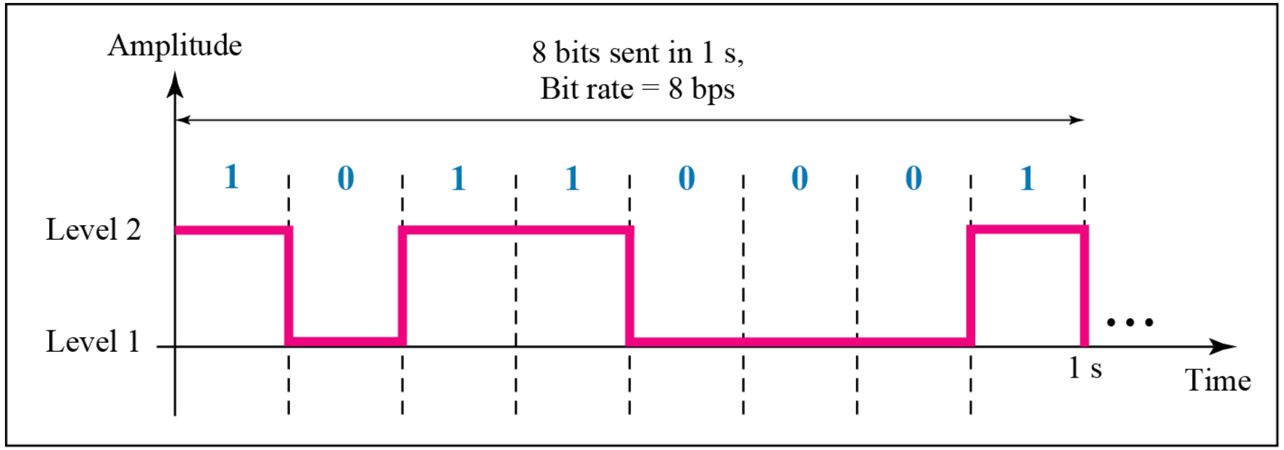
$$\boxed{B = f_h - f_l = 900 - 100 = 800 \text{ Hz}}$$

The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz.

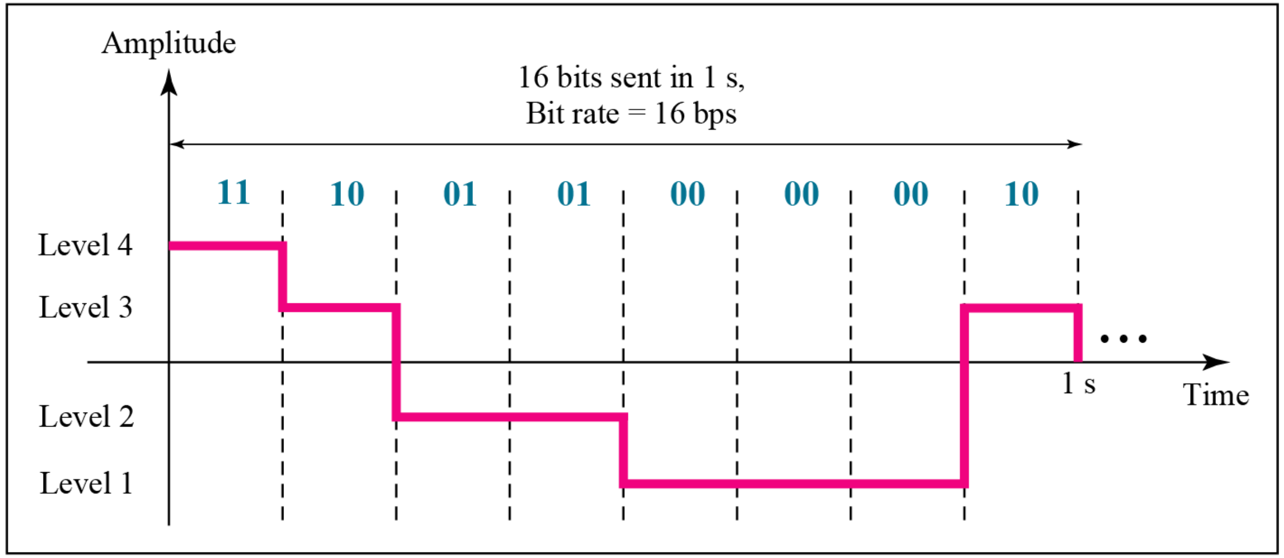
DIGITAL SIGNALS

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**.

DIGITAL SIGNALS



a. A digital signal with two levels



b. A digital signal with four levels

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

Example

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

Solution: We calculate the number of bits using the formula

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

Each signal level is represented by 3 bits.

Example

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

Solution: We calculate the number of bits by using the same formula.
Each signal level is represented by **3.17** bits ($\log_2 9$).
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**.
Therefore, we will **use 4 bits** to represent each level.

Bit Rate

Bit rate is a measure of the number of bits that are transmitted or processed per unit of time in a digital communication system, expressed in bits per second (bps)

Example

Assume we need to download text documents at the rate of **100 pages per minute**. What is the required bit rate of the channel?

Solution

A page is an **average of 24 lines** with **80 characters** in each line.

If we assume that one character requires **8 bits**, the **bit rate** is

$$\boxed{100 \times 24 \times 80 \times 8 = 1{,}536{,}000 \text{ bps} = 1.536 \text{ Mbps}}$$

Bit Rate

Example

A digitized voice channel, is made by digitizing a **4-kHz** bandwidth analog voice signal. We need to sample the **signal at twice the highest frequency** (two samples per hertz). We assume that **each sample requires 8 bits**.
What is the required bit rate?

Solution

The bit rate can be calculated as

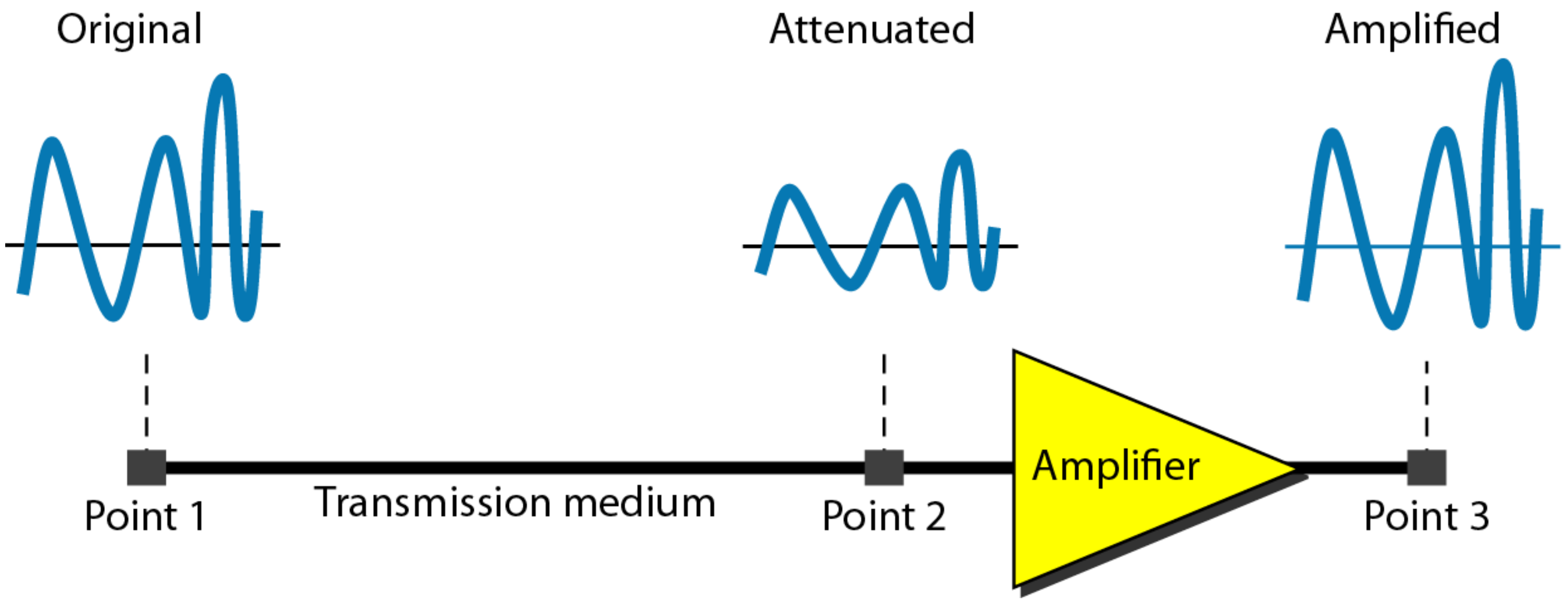
$$\boxed{2\text{x } 4000 \text{ x } 8 = 64{,}000 \text{ bps} = 64 \text{ kbps}}$$

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.

- Three **causes of impairment** are:
  - **attenuation**,
  - **distortion**, and
  - **noise**.

Attenuation



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**.

Decibel

- To show that **a signal has lost or gained strength**, engineers **use the unit of the decibel**.
- **The decibel (dB) measures the relative strengths** of **two signals** or one signal at two different points.
- Note that the **decibel is negative if a signal is attenuated and positive if a signal is amplified**

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

Where, P_1 and P_2 are the powers of a signal at points 1 and 2

Note that some engineering books define the decibel in terms of **voltage instead of power. Power is proportional to the square of the voltage**, the formula is

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

Example

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**.

Example

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

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

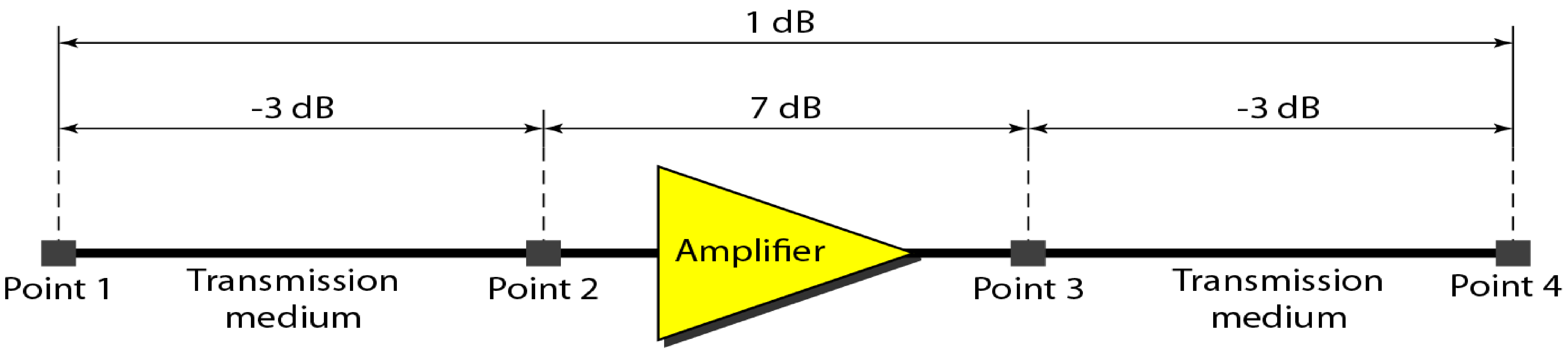
$$= 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

Example

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 a signal travels from **point 1 to point 4**. In this case, the decibel value can be calculated as

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



Example

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

$$\boxed{\begin{array}{c} \mathrm{dB_m} = 10 \log_{10} P_m = -30 \\ \log_{10} P_m = -3 \qquad P_m = 10^{-3}\ \mathrm{mW} \end{array}}$$

Example

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 × (−0.3) = −1.5 dB**. We can calculate the power as

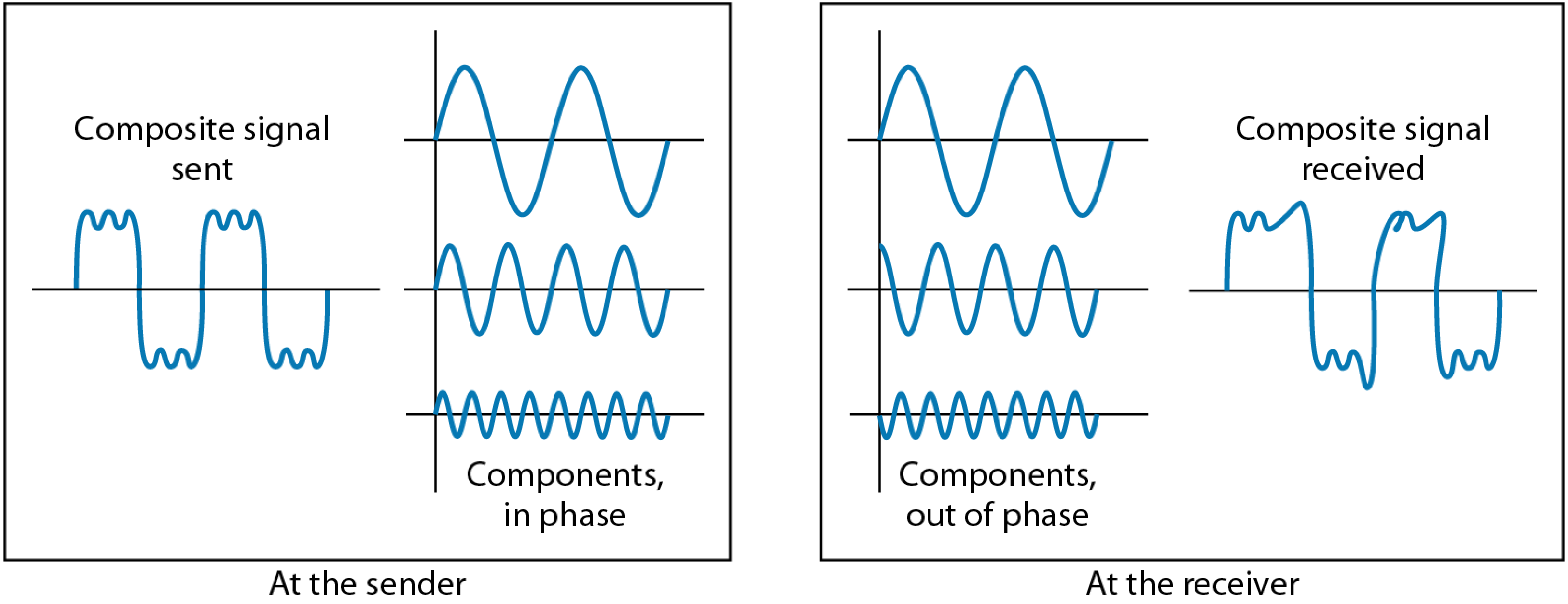
Rate of loss = -0.3 dB/km
P_1 = 2 mW
P_2 = ?

$$\text{dB} = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$

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

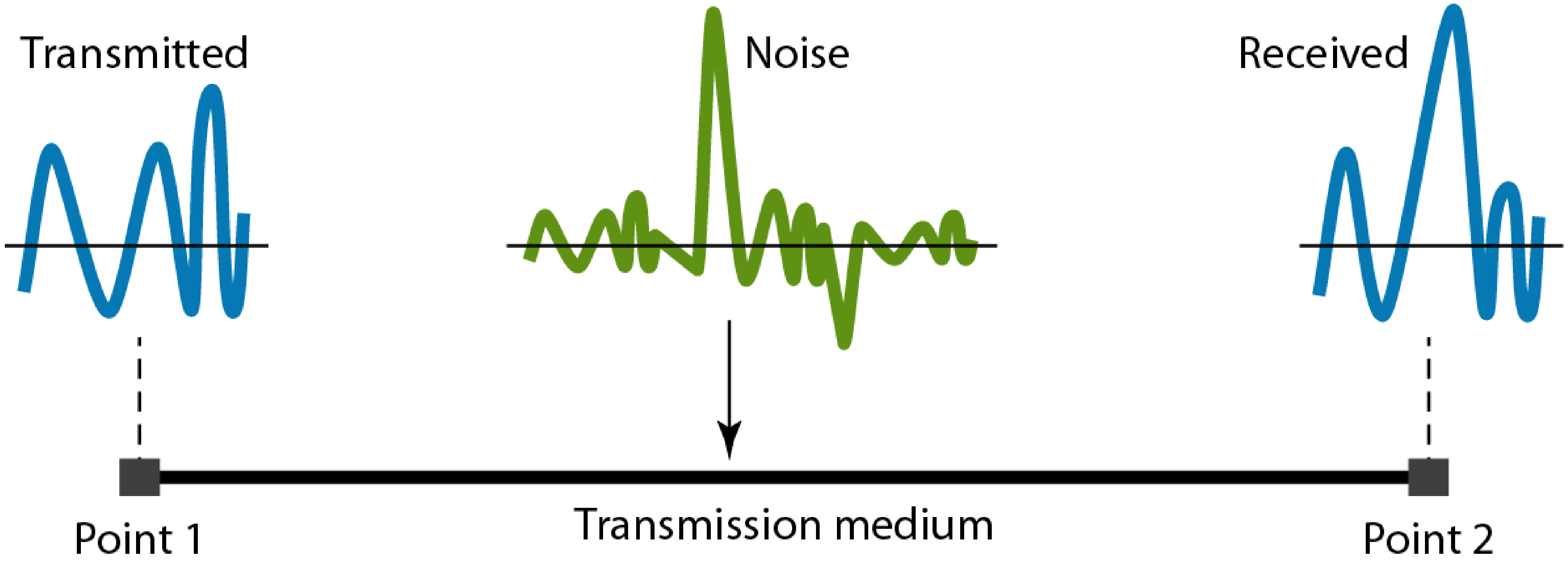
Distortion


Composite signal
sent
Components,
in phase
At the sender
Components,
out of phase
Composite signal
received
At the receiver

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 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.
- In other words, signal components at the **receiver have phases different** from what they had at the sender. The shape of the composite signal is therefore not the same.

Noise


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

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 and appliances. These devices act as a sending antenna, and the transmission medium acts as the receiving antenna.
- ✓ **Crosstalk** is the effect of one wire on the other. One wire acts as a sending antenna and the other as the receiving antenna.
- ✓ **Impulse** noise is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on.

Signal-to-Noise Ratio (SNR)

- To find the **theoretical bit rate limit, we need to know the ratio of the signal power to the noise power**.
- The signal-to-noise ratio is defined as

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

Example

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:

1 W = 10^3 mW
1 W = 10^6 μW

1 mW = 10^3 μW

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

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

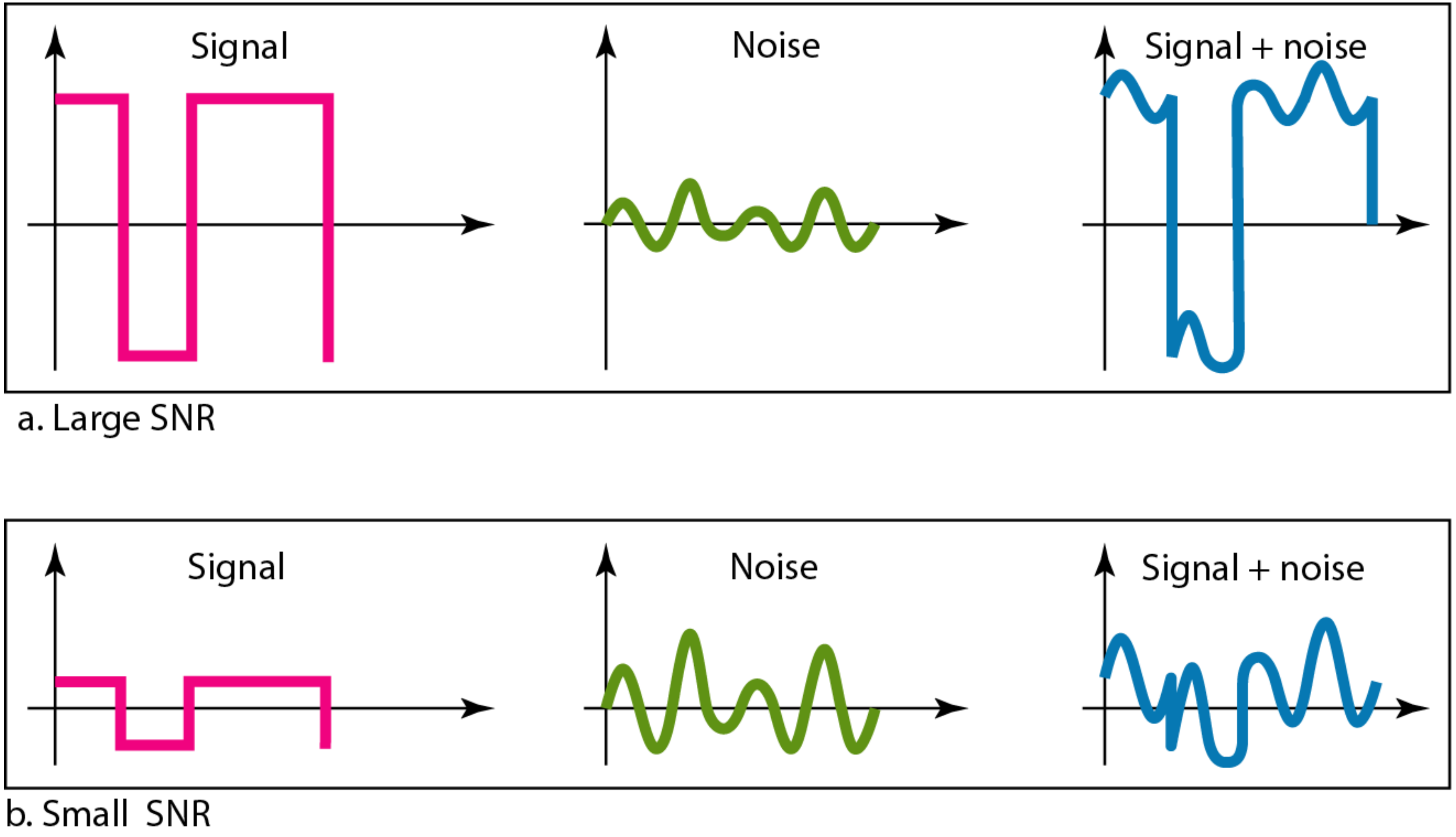
Example

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

$$\boxed{\begin{aligned} SNR &= \frac{\text{signal power}}{0} = \infty \\ SNR_{dB} &= 10 \log_{10} \infty = \infty \end{aligned}}$$

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

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



Quiz 1:

Date: 20/08/2024

A digital signal has 16 levels. How many bits are needed to represent each signal level? What is the formula required to determine the number of bits per level?

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)

DATA RATE LIMITS

- Two theoretical formulas were developed to calculate the **data rate**:
    1. one by **Nyquist** for a **noiseless channel**.
    2. another by **Shannon** for a **noisy channel**.

Noiseless Channel: Nyquist Bit Rate

For a noiseless channel, the **Nyquist bit rate formula** defines the theoretical **maximum** bit rate.

$$\text{BitRate} = \mathbf{2 * bandwidth} * \log_2 (L)$$

Where L is the **number of distinct signal levels**, and BitRate is the bit rate in bits per second **(bps)**

Example

Consider a **noiseless** channel with a bandwidth of 3000 Hz transmitting a **signal with two signal levels**.

The maximum bit rate can be calculated as:

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

Example

Consider the same **noiseless** channel transmitting a signal with **four signal levels** (for each level, we send 2 bits).

The maximum bit rate can be calculated as:

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

Example

We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many **signal levels** do we need?

Solution

We can use the Nyquist formula as shown:

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate.

If we have 128 levels, the bit rate is 280 kbps.

If we have 64 levels, the bit rate is 240 kbps.

Noisy Channel: Shannon Capacity

- ✓ 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**:

Capacity = **bandwidth** x $\mathbf{\log_2 (1 + SNR)}$

Where bandwidth is bandwidth of the channel, SNR is the signal-to-noise ratio, and capacity is the capacity of the channel in bits per second **(bps)**

Example

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

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

- ✓ This means that the capacity of this does not depend on the bandwidth. If the signal-to-noise ratio is zero.

Example

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

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

$\log_2 3163 = 11.62$ approx.

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

Example

- The signal-to-noise ratio is often given in decibels.
- Assume that SNR_{dB} = 36 and the channel bandwidth is 2 MHz.
- The theoretical channel capacity can be calculated as

The SNR in decibels is given by, $\boldsymbol{SNR_{dB} = 10\ \log_{10}(SNR)}$

Given that

$$SNR_{dB} = 36:$$

$$36 = 10\ \log_{10}(SNR) \quad => \quad \frac{36}{10} = \log_{10}(SNR)$$

We can solve for SNR:

$$SNR = 10^{\frac{36}{10}} \quad => 10^{3.6} = 3981$$

$\log_2 3982 = 11.96$ approx.

Now applying Shannon's formula:

$C = B \log_2 (1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 2 \times 10^6 \times 11.96 = 24$ Mbps

Example

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.

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

Bandwidth

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

Bandwidth in Hertz

- Bandwidth in hertz is the **range of frequencies contained in a composite signal** or the range of **frequencies a channel can pass**.
- For example, we can say the bandwidth of a subscriber telephone line is 4 kHz.

Bandwidth in Bits per Seconds

- Bandwidth can also refer to the number of bits per second that a channel, a link, or even a network can transmit.
- For example, one can say the bandwidth of a Fast Ethernet network (or the links in this network) is a maximum of 100 Mbps. This means that this network can send 100 Mbps

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*.**
- In other words, the bandwidth is a **potential measurement of a link**; **the throughput is an actual measurement of how fast we can send data**.
- For example, we may have a link with a bandwidth of 1 Mbps, but the devices connected to the end of the link may handle only **200 kbps**.
- This means that we cannot send more than 200 kbps through this link.

Example

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

$$\boxed{\text{Throughput} = \frac{12{,}000 \times 10{,}000}{60} = 2\ \text{Mbps}}$$

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