Data and Signals

Dr. Md. Fazlul Kader
Professor
Dept. of EEE, University of Chittagong

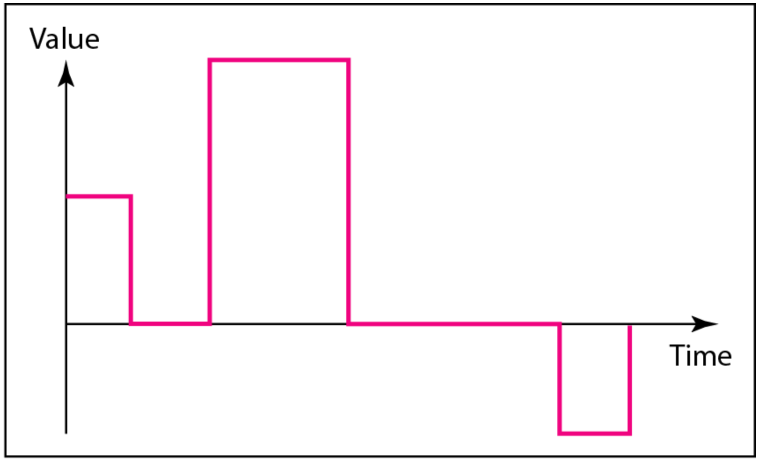
Data and Signals

- Data are entities that convey meaning
  - computer file, music on CD,
  - results from a blood gas analysis machine
- Signals are the electric or electromagnetic encoding of data
  - telephone conversation
- Computer networks and data/voice communication systems transmit signals
- Data and signals can be analog or digital

Analog vs. Digital Signals

- Signals can be interpreted as either analog or digital
- In reality, all signals are analog
- Analog signals are continuous, non-discrete
- Digital signals are non-continuous, discrete
- Digital signals lend themselves more nicely to noise reduction techniques

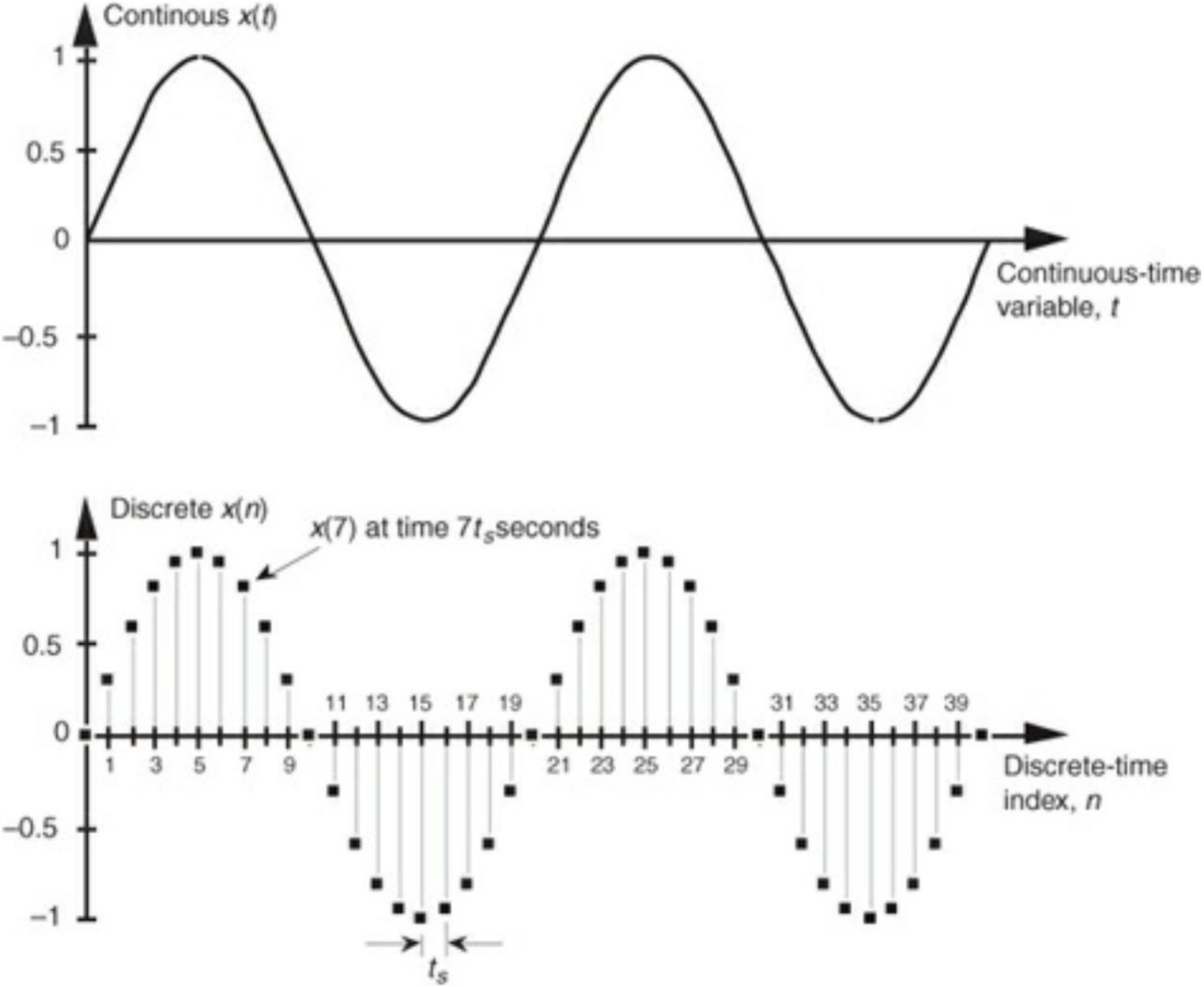
a. Analog signal

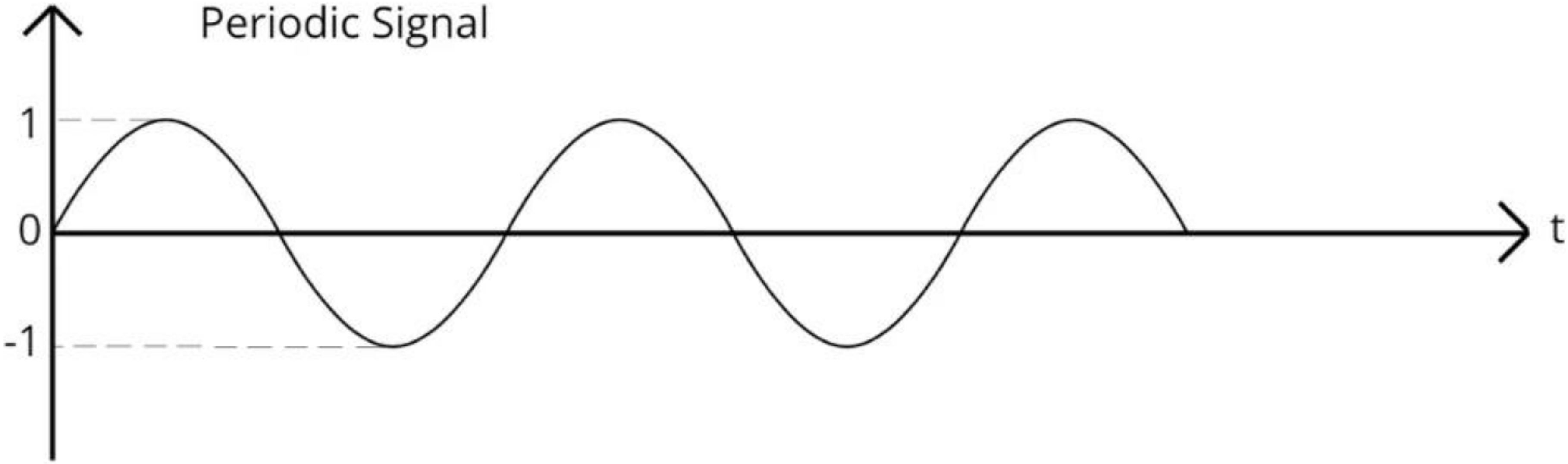


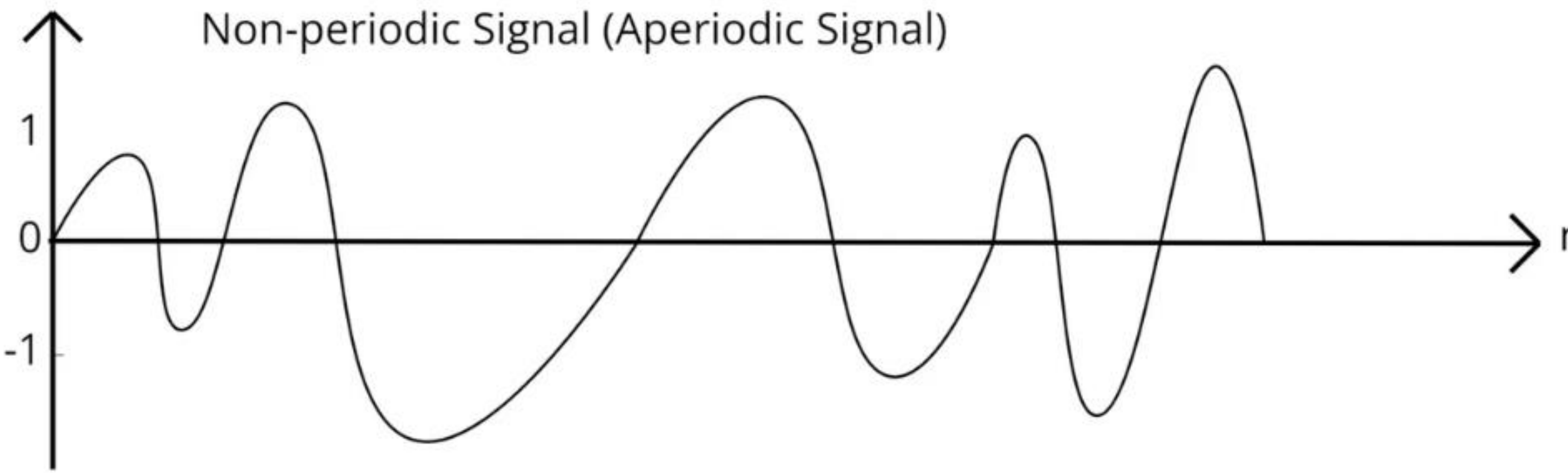
b. Digital signal

Time domain concepts

- Continuous signal
  - Infinite number of points at any given time
- Discrete signal
  - Finite number of points at any given time; maintains a constant level then changes to another constant level
- Periodic signal
  - Pattern repeated over time
- Aperiodic (non-periodic) signal
  - Pattern not repeated over time

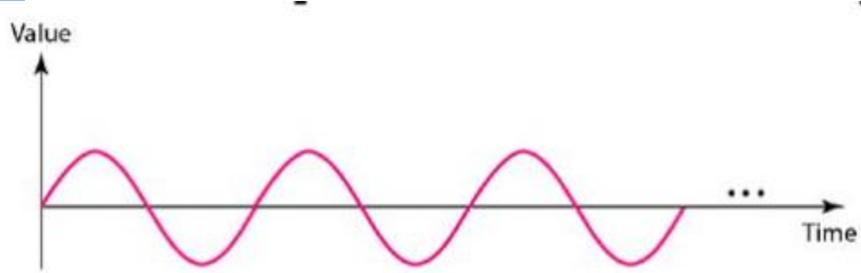

Continous x(t)
1
0.5
0
–0.5
–1
Continuous-time variable, t
Discrete x(n)
x(7) at time 7t_s seconds
11 13 15 17 19
31 33 35 37 39
1 3 5 7 9
21 23 25 27 29
Discrete-time index, n
t_s


Periodic Signal
1
0
-1
t

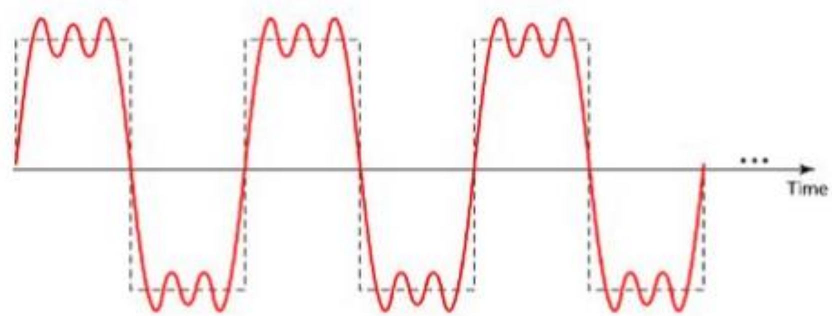

Non-periodic Signal (Aperiodic Signal)
1
0
-1
n

Time domain concepts

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



Simple periodic analog signal



composite periodic analog signal

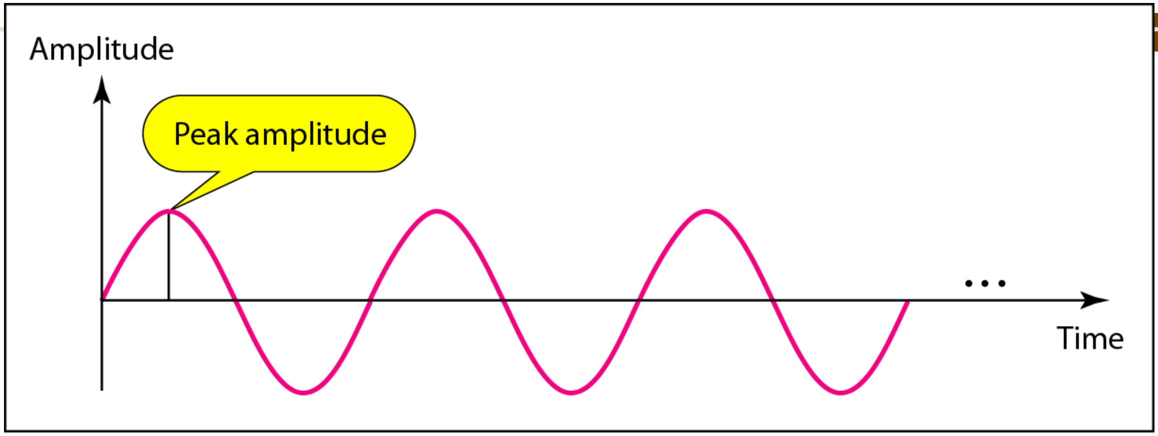
Signal Properties

- All signals are composed of three properties:
  - **Amplitude:** The amplitude of a signal refers to its magnitude or strength, often represented by the height of a waveform from its baseline or equilibrium point.
  - **Frequency:** The frequency of a signal refers to how often a repeating event occurs per unit of time.
  - **Phase:** Phase describes the position of the waveform relative to time 0.

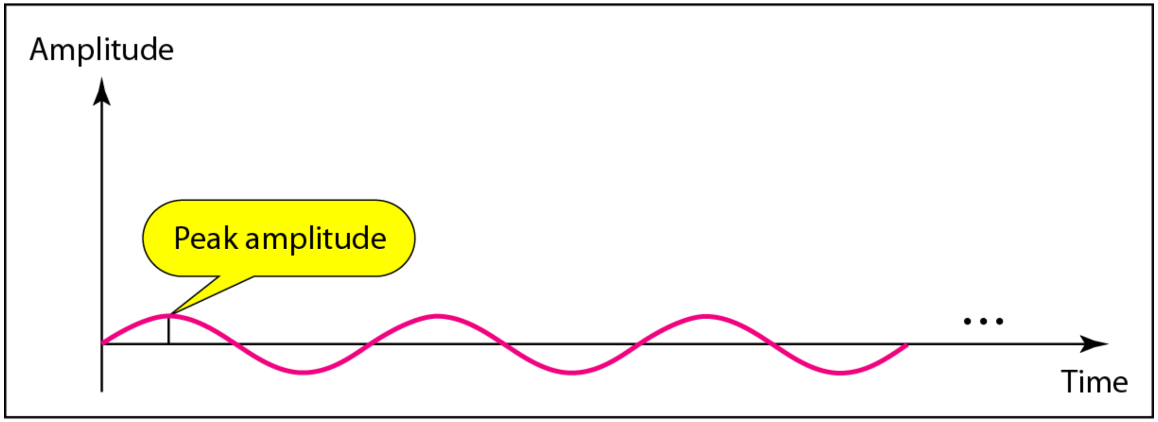
Frequency and period are the inverse of each other.

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

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

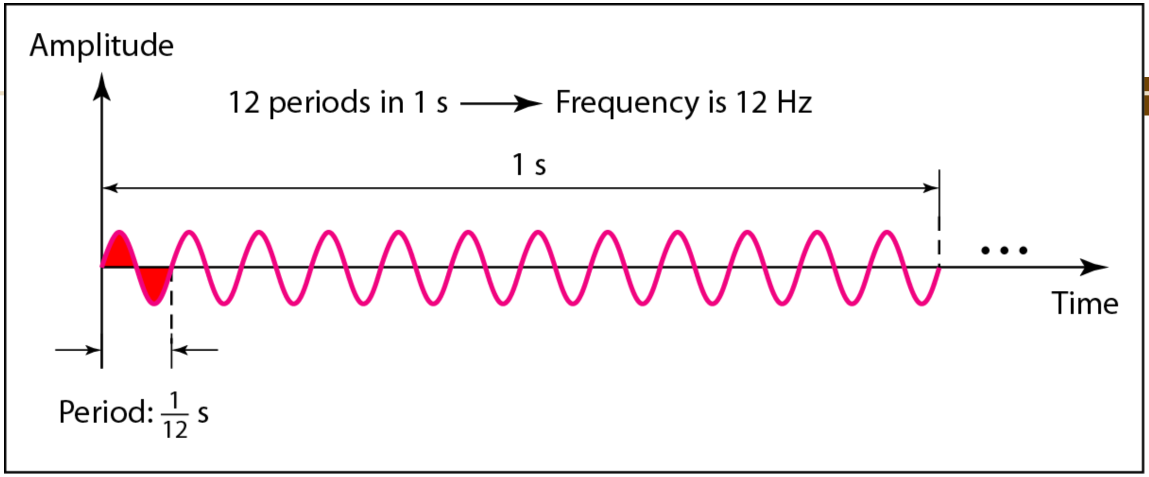


a. A signal with high peak amplitude

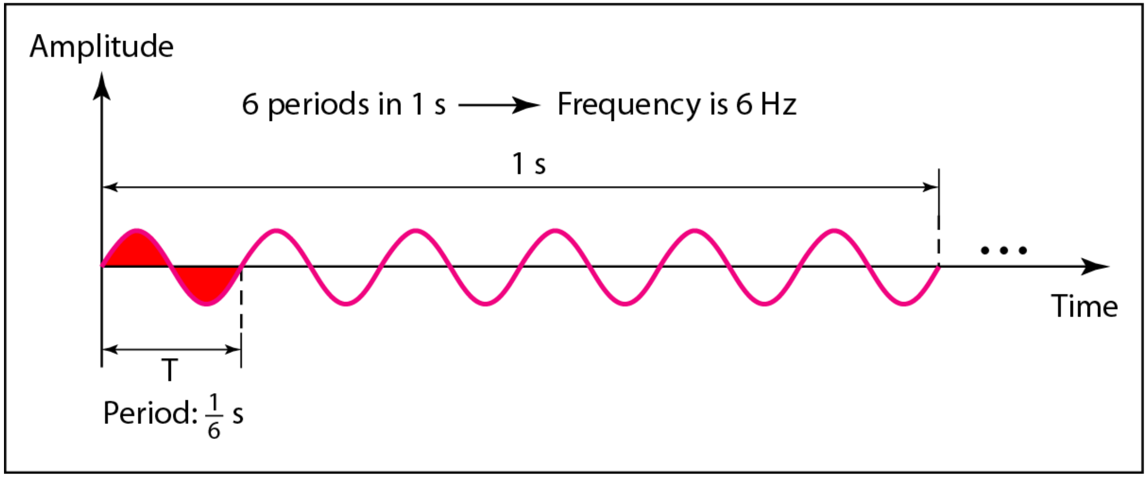


b. A signal with low peak amplitude

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



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

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

The power we use at home has a frequency of 60 Hz. The period of this sine wave can be determined as follows:

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

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:

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

Example 3.5

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

Solution

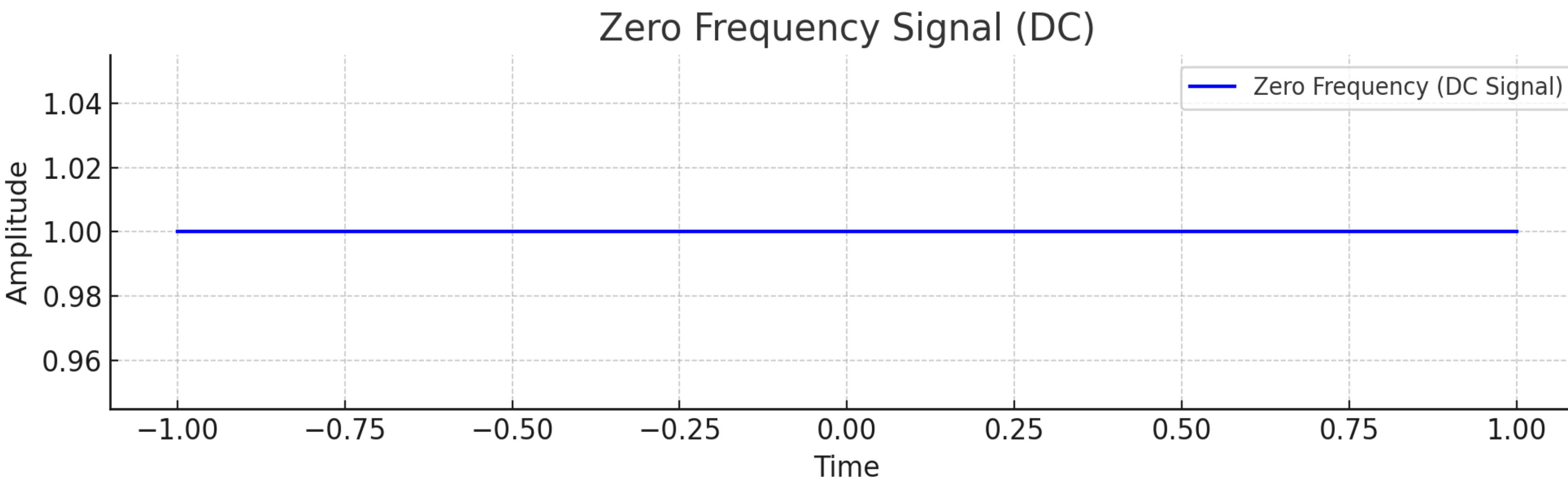
First we change 100 ms to seconds, and then we calculate the frequency from the period (1 Hz = 10^{-3} kHz).

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

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

Note

- Frequency is the rate of change with respect to time.
- Change in a short span of time means high frequency.
- Change over a long span of time means low frequency.
- If a signal does not change at all, its frequency is zero.
- If a signal changes instantaneously, its frequency is infinite.


Zero Frequency Signal (DC)
Zero Frequency (DC Signal)
Amplitude
1.04
1.02
1.00
0.98
0.96
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
Time

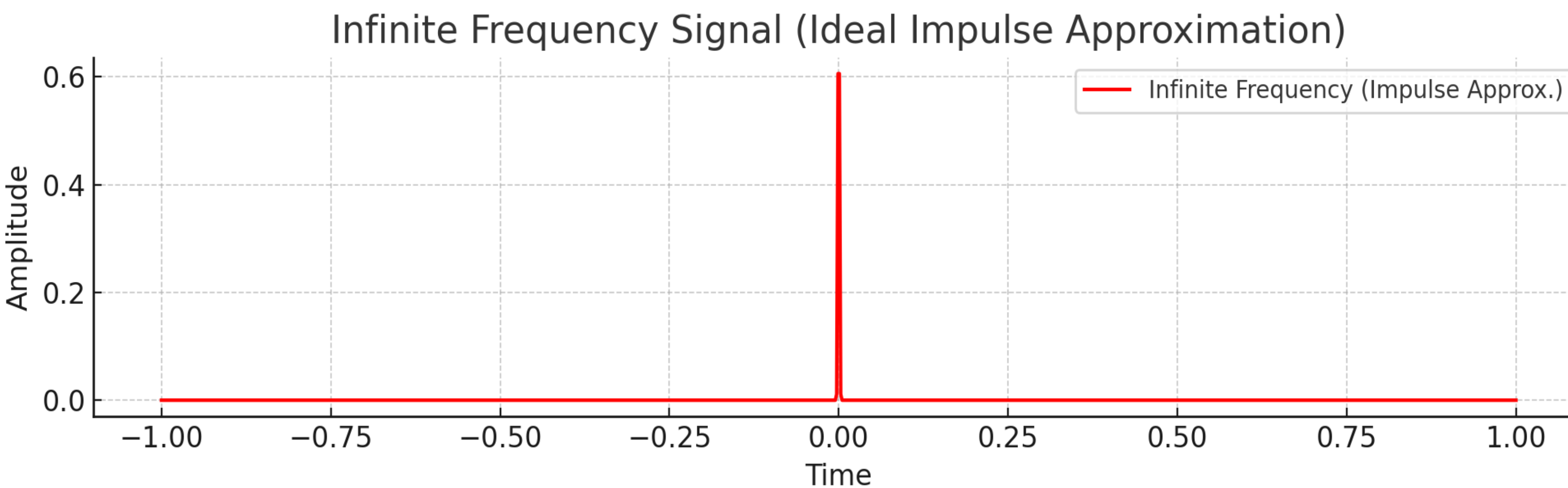
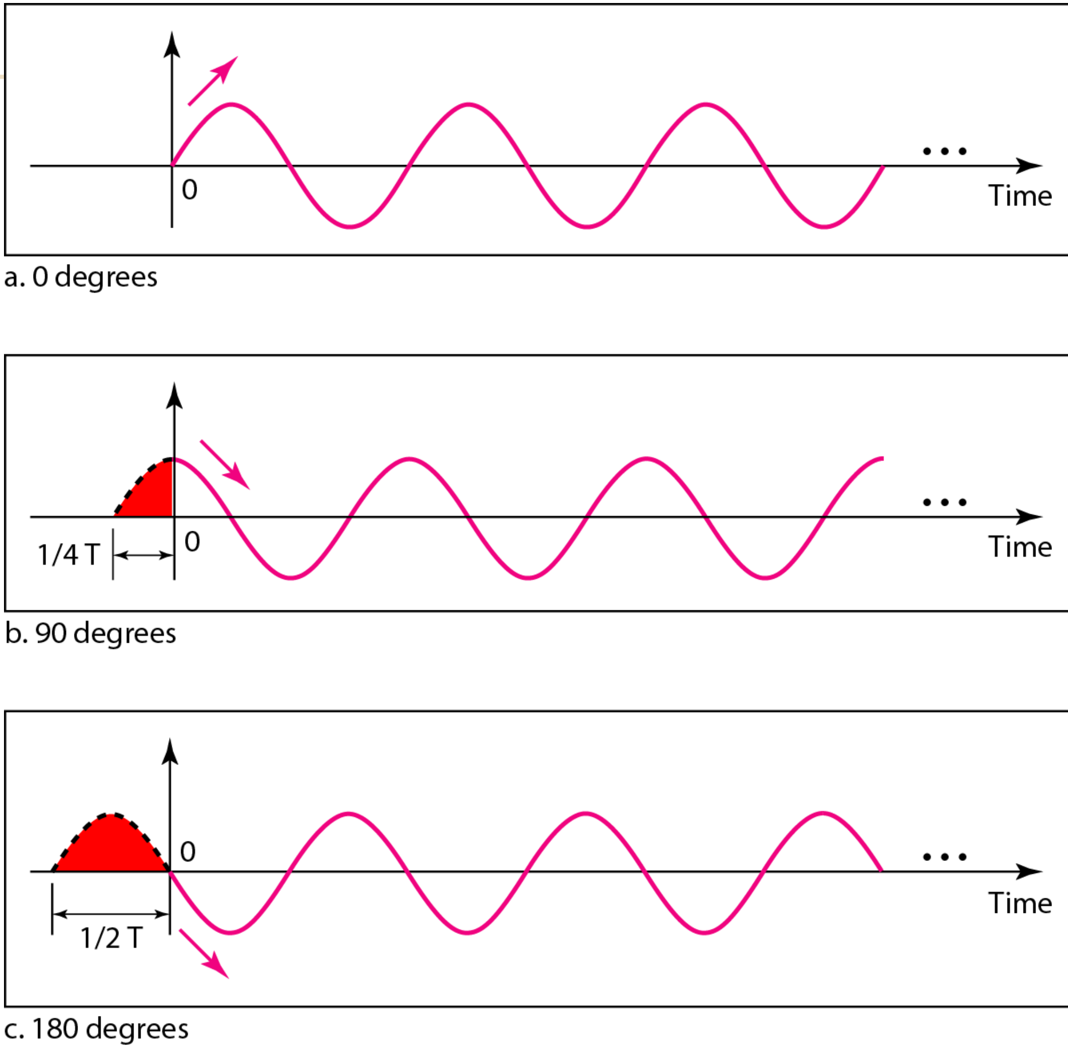

Infinite Frequency Signal (Ideal Impulse Approximation)
Infinite Frequency (Impulse Approx.)
Amplitude
0.6
0.4
0.2
0.0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
Time

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



Example 3.6

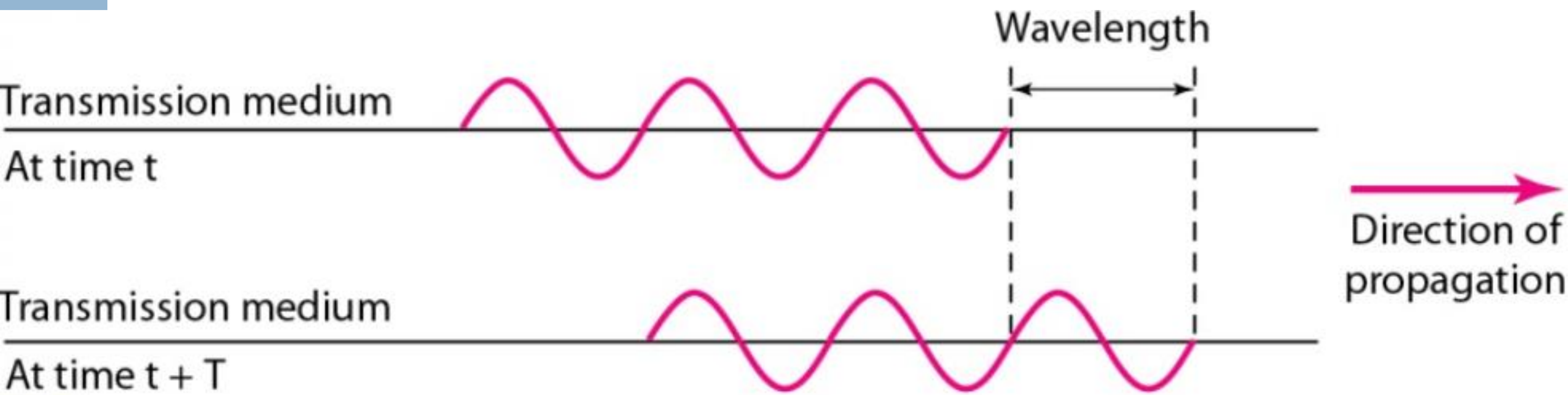
A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

Solution

We know that 1 complete cycle is 360°. Therefore, 1/6 cycle is

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

Wavelength and Period



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

Wavelength λ = propagation speed (v) * period (T)

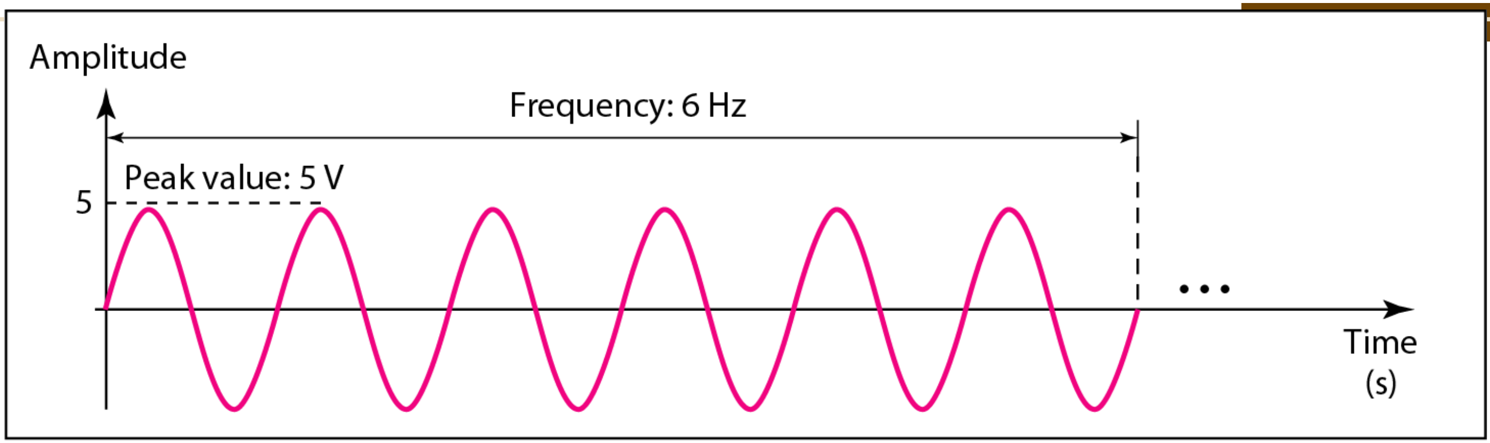
$$T = \frac{1}{f}$$

Where,

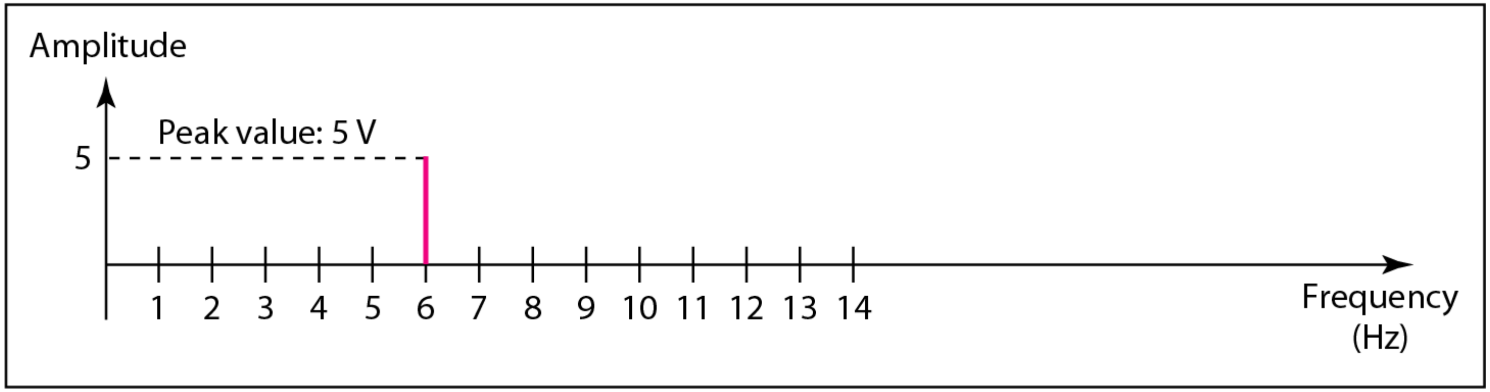
$T = Time\ Period(Seconds)$

$f = Frequency\ (Cycles/sec\ or\ Hz)$

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



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



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

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.

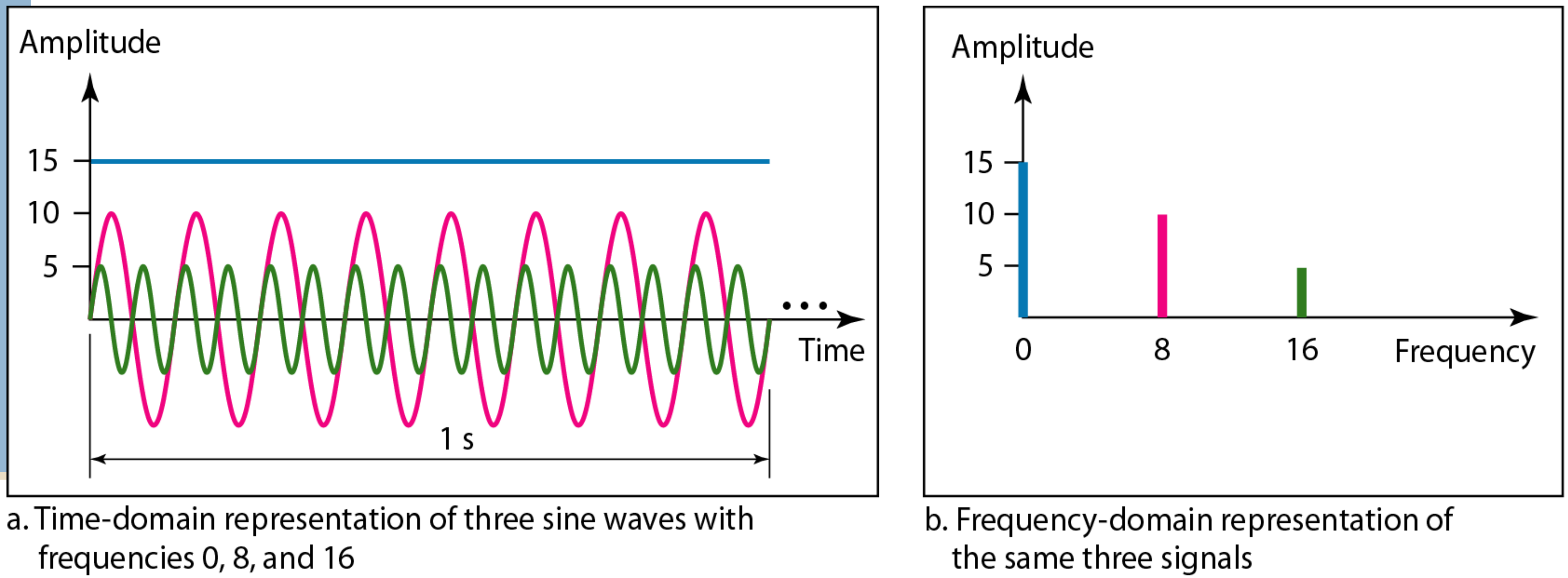


Figure 3.8 *The time domain and frequency domain of three sine waves*

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.

Figure 3.9 *A composite periodic signal*

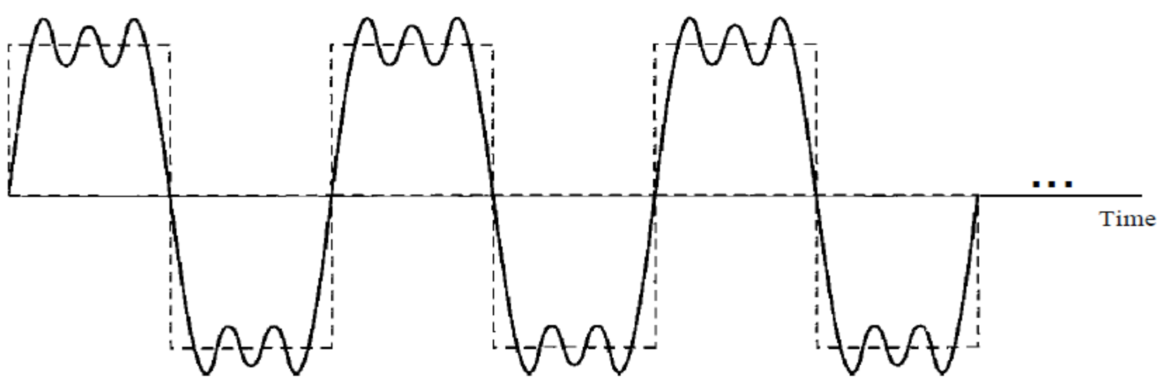
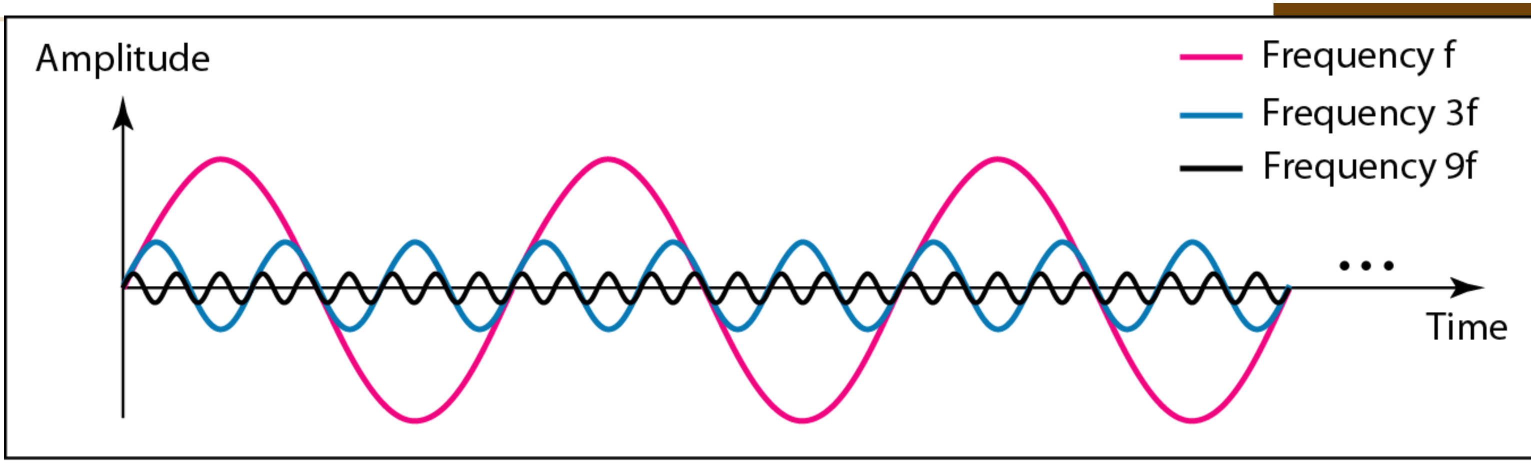
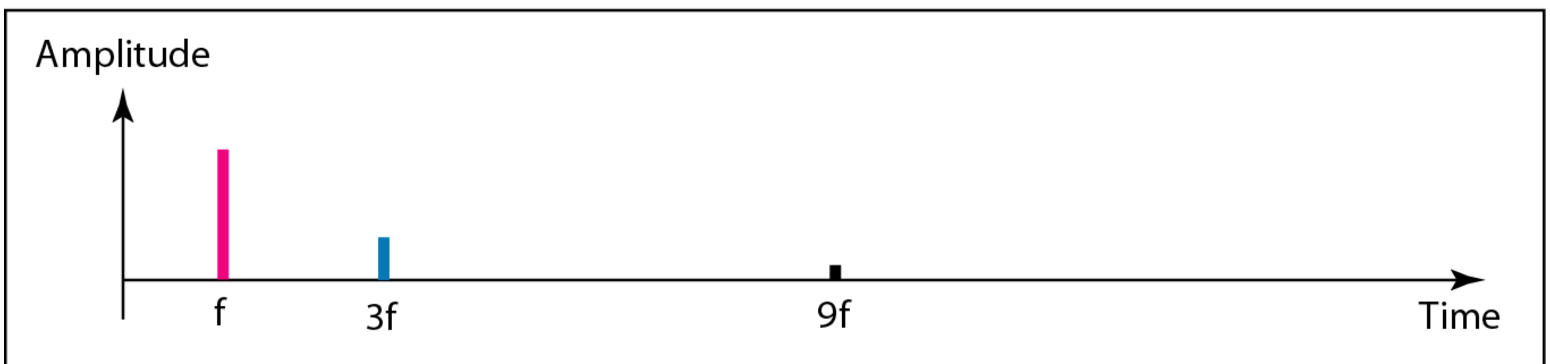


Figure 3.10 *Decomposition of a composite periodic signal in the time and frequency domains*

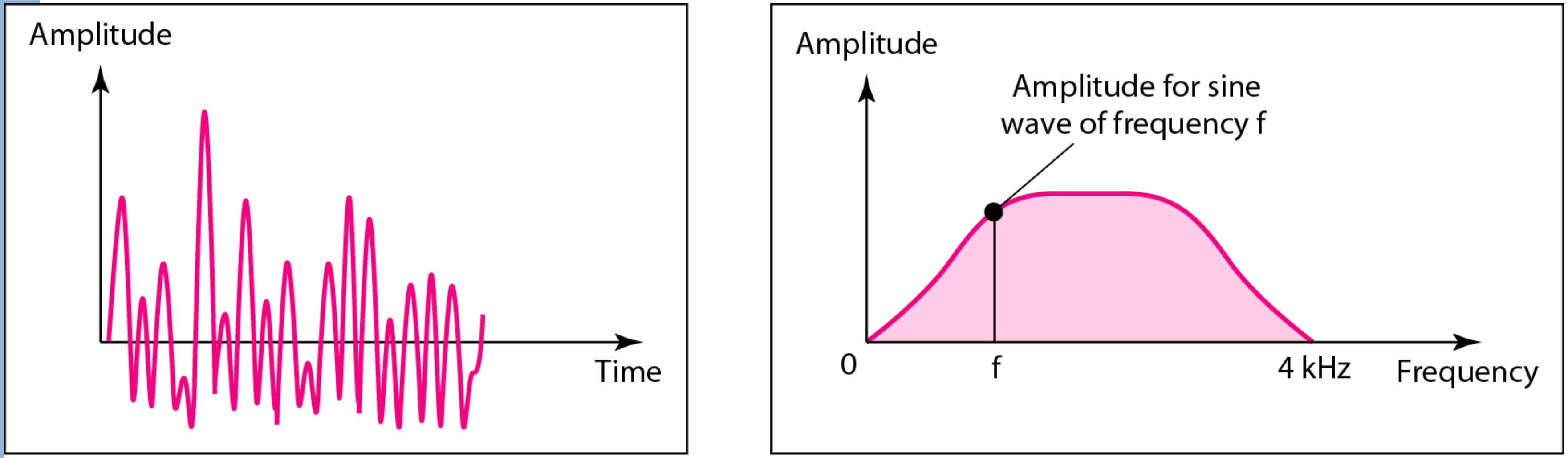


a. Time-domain decomposition of a composite signal



b. Frequency-domain decomposition of the composite signal

Figure 3.11 *The time and frequency domains of a nonperiodic signal, such someone speaking into a microphone*



a. Time domain

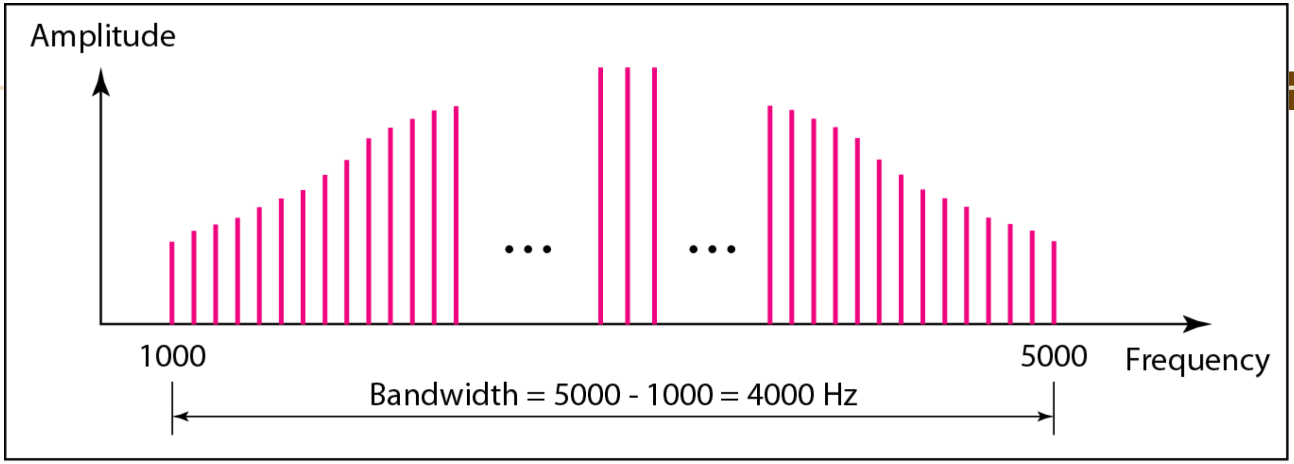
b. Frequency domain

Note

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

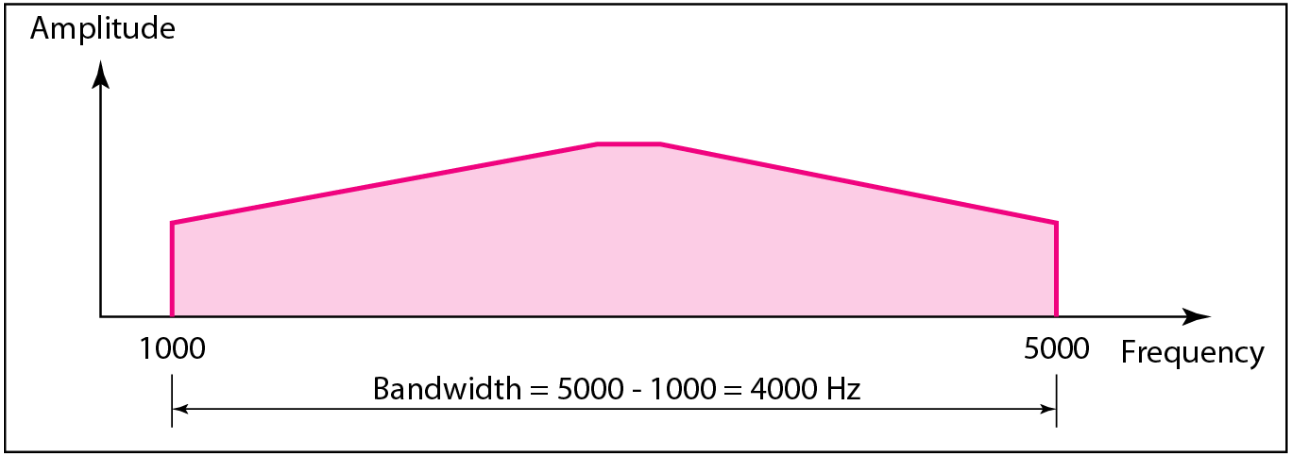
Figure 3.12 *The bandwidth of periodic and nonperiodic composite signals*

Note: each frequency is identifiable



a. Bandwidth of a periodic signal

Note: frequencies are all over the place



b. Bandwidth of a nonperiodic signal

Example 3.10

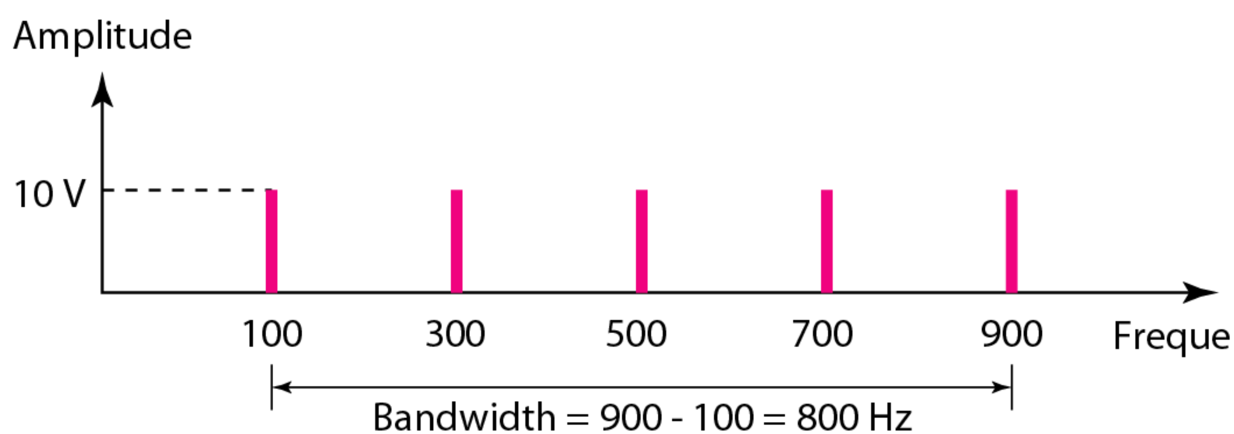
If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum *(range of frequencies), assuming all components have a maximum amplitude of 10 V.*

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 3.12

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.

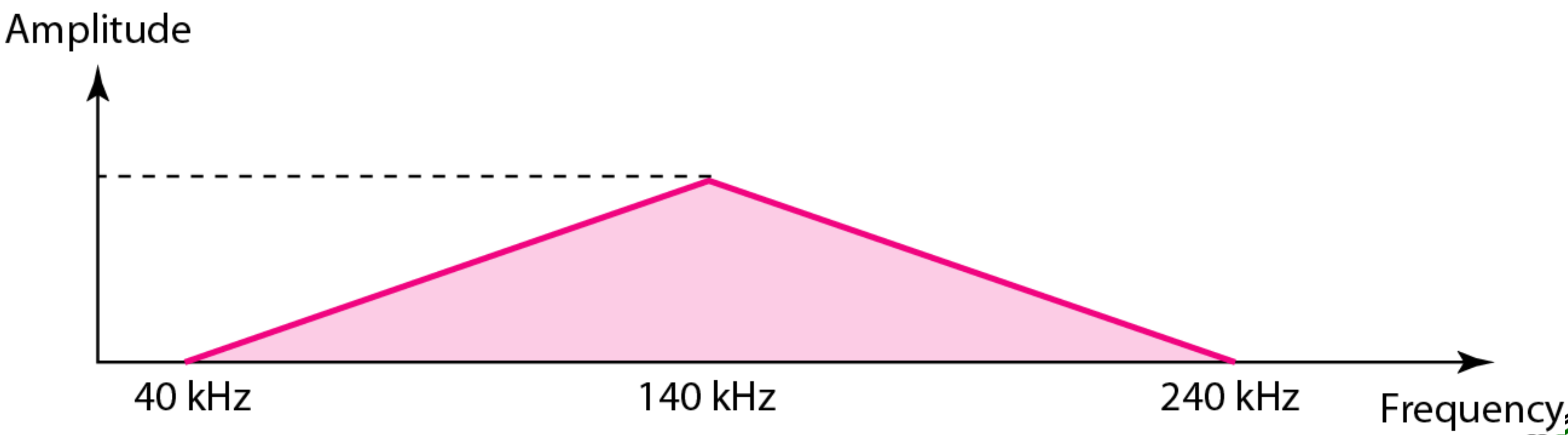


Figure 3.15 ***The bandwidth for Example 3.12***

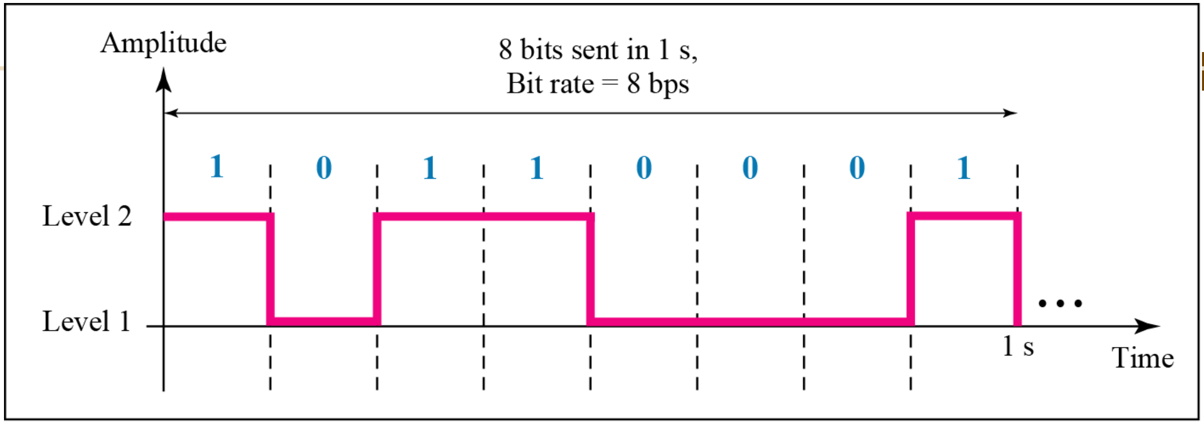
DIGITAL SIGNALS

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

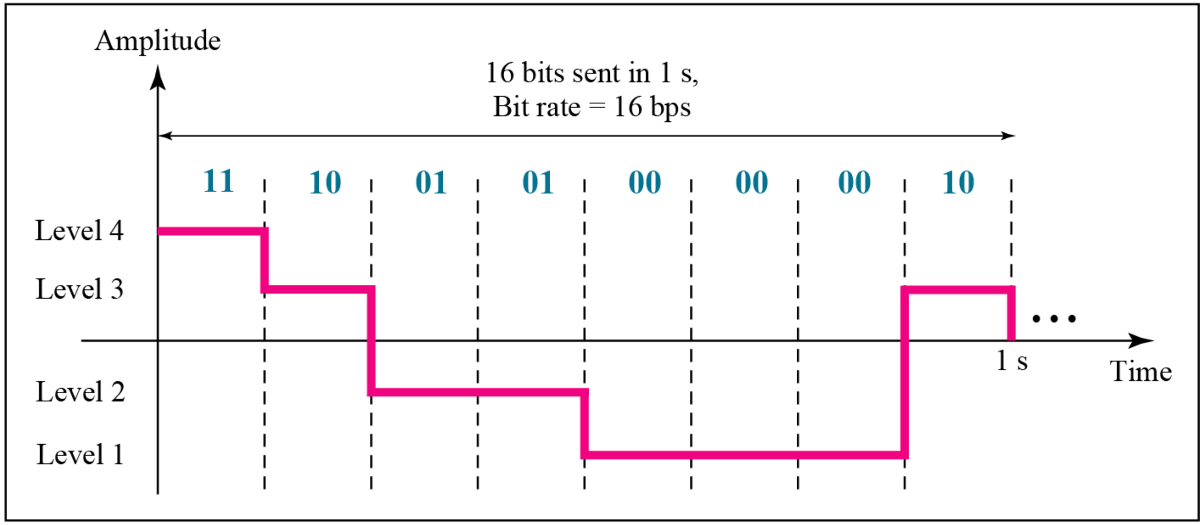
Topics discussed in this section:

- **Bit Rate**
- **Bit Length**
- **Transmission of Digital Signals**

Figure 3.16 *Two digital signals: one with two signal levels and the other with four signal levels*



a. A digital signal with two levels



b. A digital signal with four levels

Example 3.16

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

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

- ***Each signal level is represented by 3 bits.***

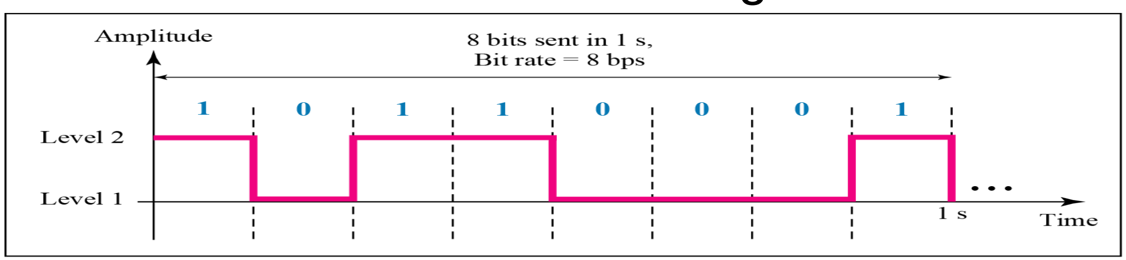
Example 3.17

What about a digital signal with 16 levels?
How many bits are needed per level?
What about 32 levels? 64 levels? 128 levels?
What about 9 levels??
$2^? = 9$?
3.17 bits
However, this answer is not realistic.

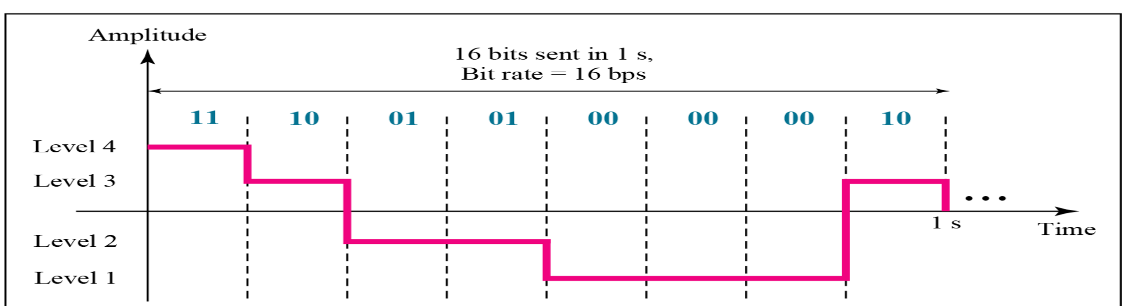
The number of bits sent per level needs to be an integer as well as a power of 2. For this example, 4 bits can represent one level.

Bit Rate

- Most digital signals are 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 Is, expressed in bits per second (bps).
- Figure 3.16 shows the bit rate for two signals.



a. A digital signal with two levels



Example 3.18

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

Solution

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is

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

Example 3.19

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

Solution

The bit rate can be calculated as

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

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

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

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

Bit Length

Wavelength for an analog signal: the distance one cycle occupies on the transmission medium.

The bit length of a digital signal. The bit length is the distance one bit occupies on the transmission medium.

$$\text{Bit length (in meters)} = \text{Propagation speed} \times \text{Bit duration}$$

Where:

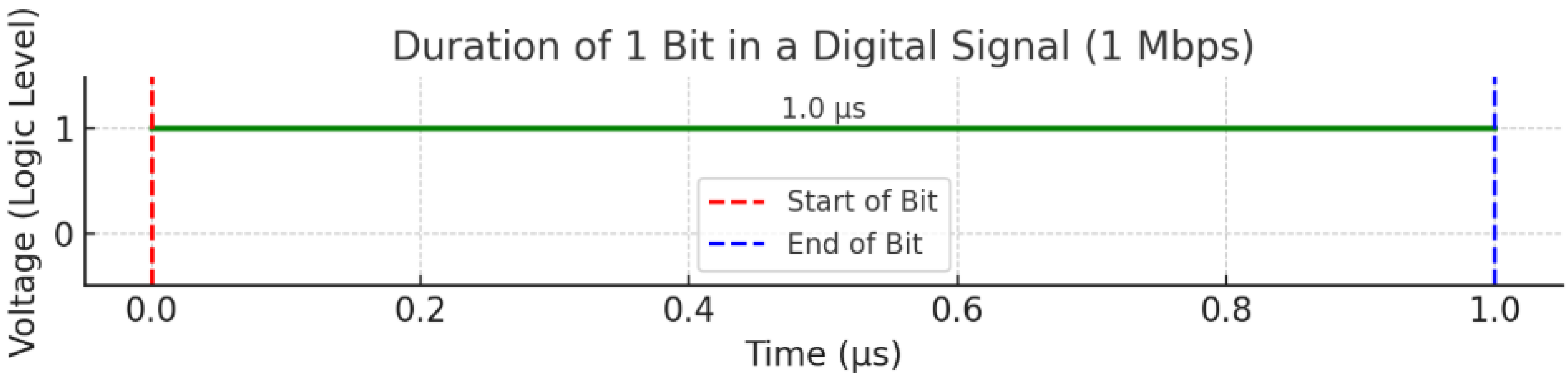
- **Propagation speed** is the speed at which the signal travels through the medium (e.g., in a cable or air), usually in **meters per second (m/s)**
- **Bit duration** is the time to transmit one bit, $\text{Bit duration} = \frac{1}{\text{Bit rate}}$

Suppose:

- Bit rate = 1 Mbps (1,000,000 bits per second)
- Propagation speed = 2×10^8 m/s (approximate speed in copper/fiber)

Then:

1. **Bit duration** = $\frac{1}{10^6} = 1\,\mu s$
2. **Bit length** = $2 \times 10^8\,\text{m/s} \times 1 \times 10^{-6}\,\text{s} = 200\,\text{meters}$

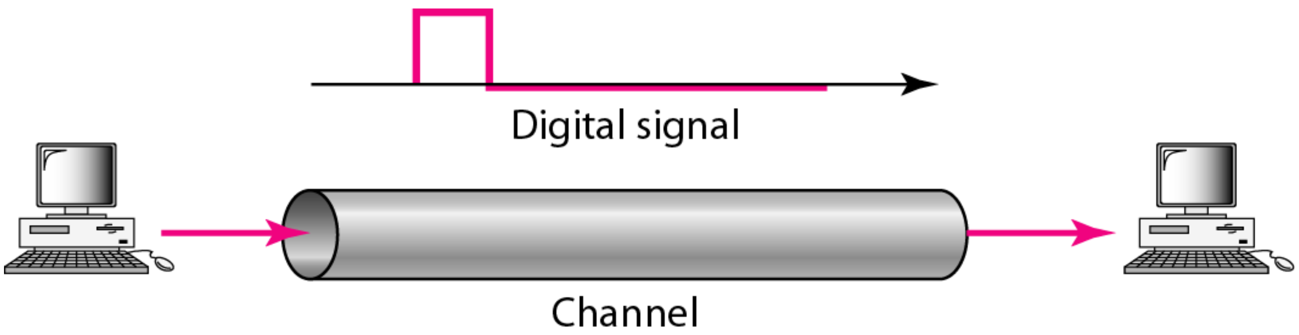


This plot illustrates the **duration of a single bit** in a digital signal at **1 Mbps**:

- The signal is high (logic level 1) for **1 microsecond (µs)**.
- Vertical dashed lines show the **start** and **end** of the bit.
- The flat, constant voltage during this interval represents a single bit being transmitted.

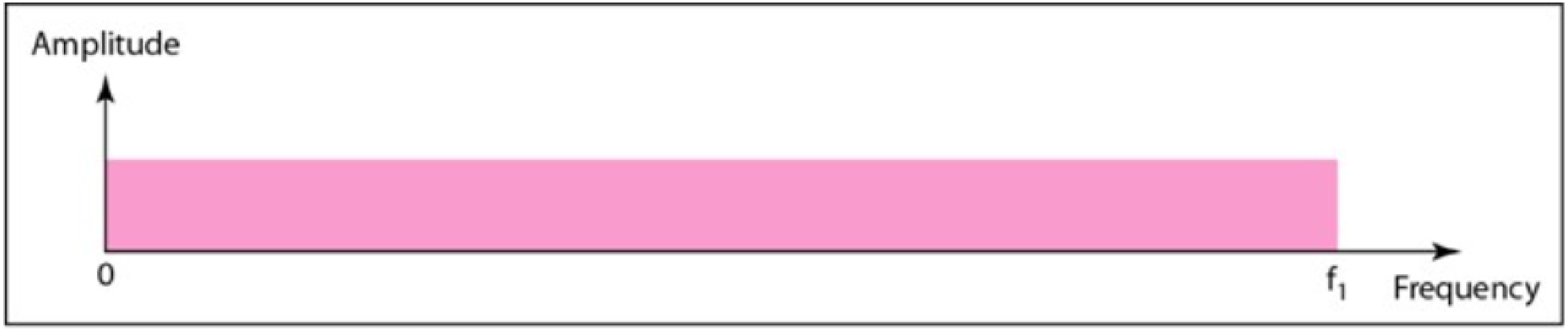
Transmission of Digital Signals

- We can transmit a digital signal by using one of two different approaches:
  - baseband transmission or
  - broadband transmission (using modulation)
- **Baseband transmission** means sending a digital signal over a channel without changing the digital signal to an analog signal.



- Digital transmission on a wire typically "consumes" the entire channel and is labeled baseband signaling.
- The LAN is a common example of baseband signaling.
- Baseband transmission requires that we have a low-pass channel.
- **Low-pass channel:** a channel with a bandwidth that starts from zero.

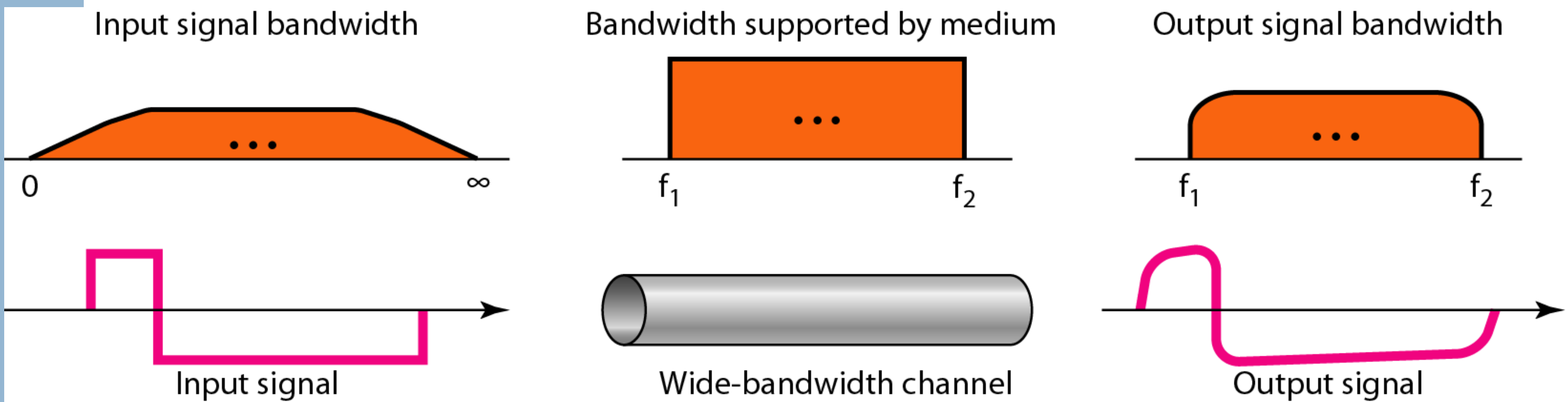
Figure 3.19 *Bandwidths of two low-pass channels*



a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

Figure 3.20 *Baseband transmission using a dedicated medium*



This is ideal.

This is what we get.
Still readable however.

Note

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

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.
  - This type of channel is more available than a low-pass channel.
- Note that a low-pass channel can be considered a bandpass channel with the lower frequency starting at zero

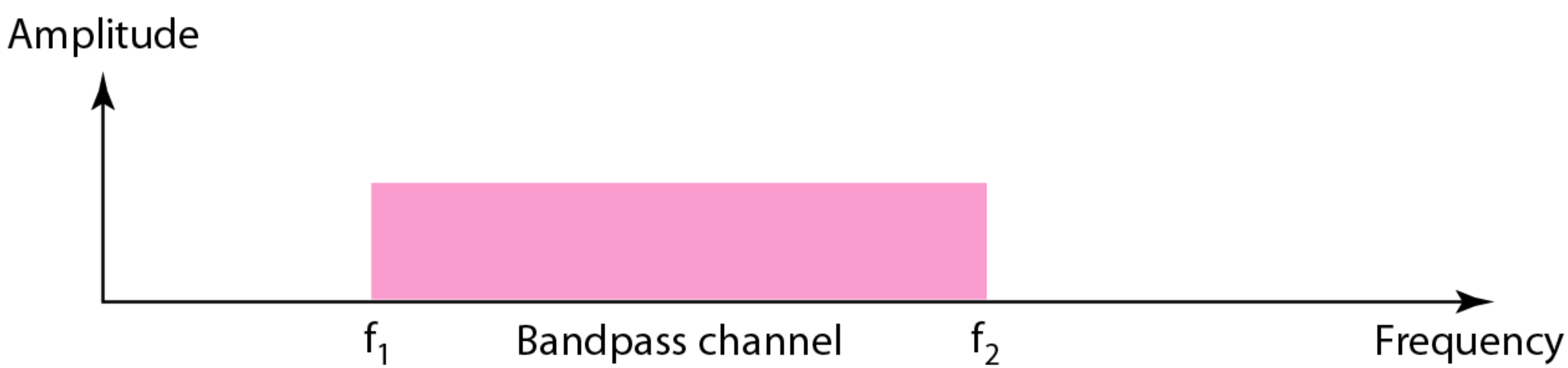
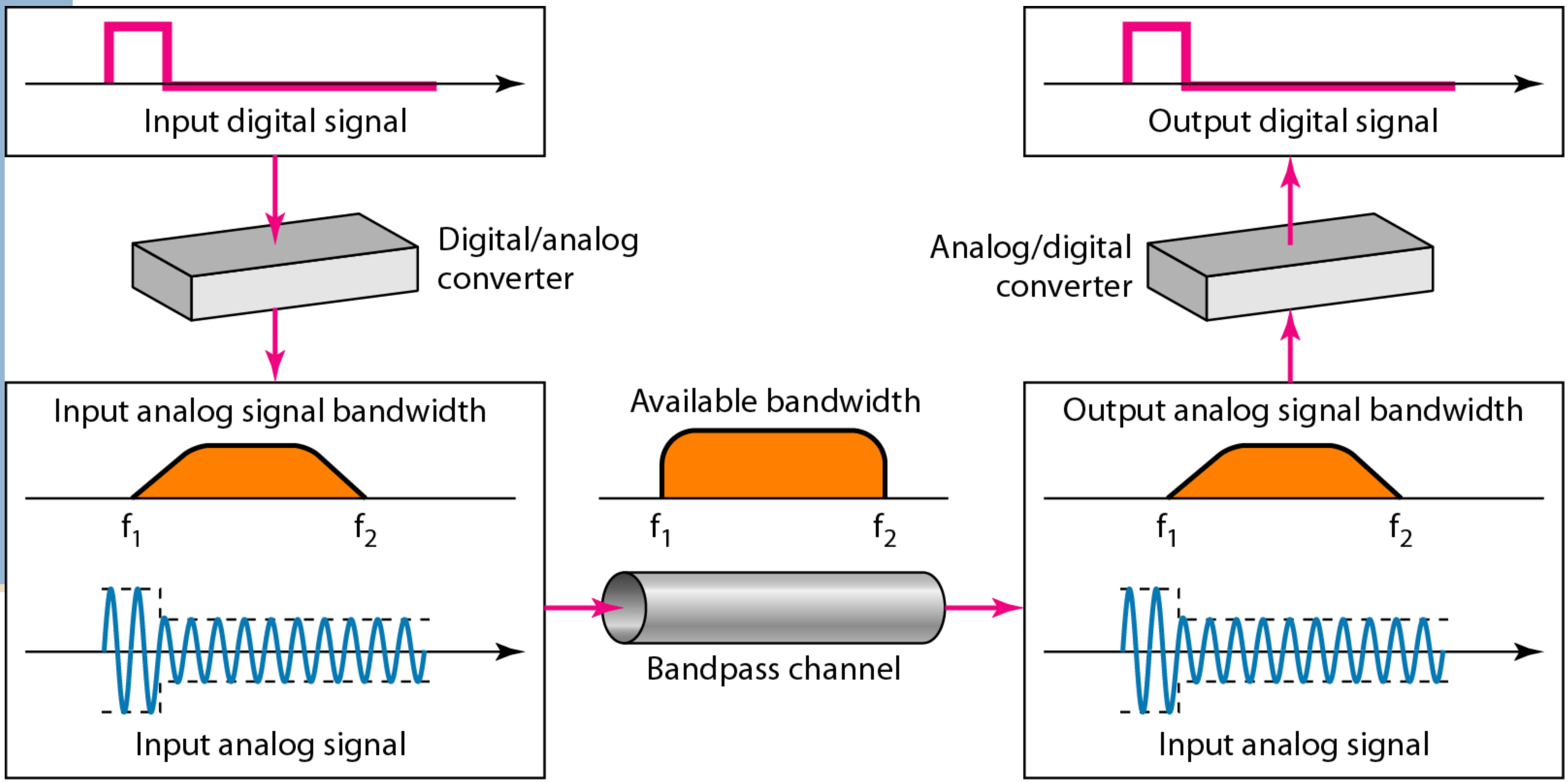


Figure 3.23 ***Bandwidth of a bandpass channel***

Note

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

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



Channel Capacity

Dr. Md. Fazlul Kader
Professor
Dept. of EEE, University of Chittagong

Channel Capacity

- **Channel capacity** is the **tight upper bound** on the rate at which information can be reliably transmitted over a communications channel.
- By the noisy-channel coding theorem, the channel capacity of a given channel is the limiting information rate (in units of information per unit time) that can be achieved with arbitrarily small error probability.
- The **Shannon–Hartley theorem** tells the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth in the presence of noise.

Channel Capacity

Claude Shannon
1916-2001
Bell Labs, MIT

Ralph Hartley
1888-1970
Bell Labs

Shannon Capacity (C)

- $C = B^*Log_2(1 + SNR)$ bps
  - B = channel bandwidth (Hz)
  - SNR = channel signal-to-noise ratio, $\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}$,
- Maximum bit rate that can be reliably achieved via a connection
- EX) Analog Modem (30 dB SNR)
  $C = 3500\ {}^*Log_2(1 + 1000) = 34{,}885$ bps
- EX) 6 MHz TV RF Channel (42 dB SNR)
  $C = 6{,}000{,}000\ {}^*Log_2(1 + 15{,}849) = 83.71$ Mbps

- SNR: **from linear to decibel**: 10Log10(SNRLinear)
- SNR: **from decibel to linear**: 10^(SNRdB/10)

Decibel (dB)

- The **decibel** (**dB**) is a logarithmic unit used to express the ratio between two values of a physical quantity, often power or intensity.

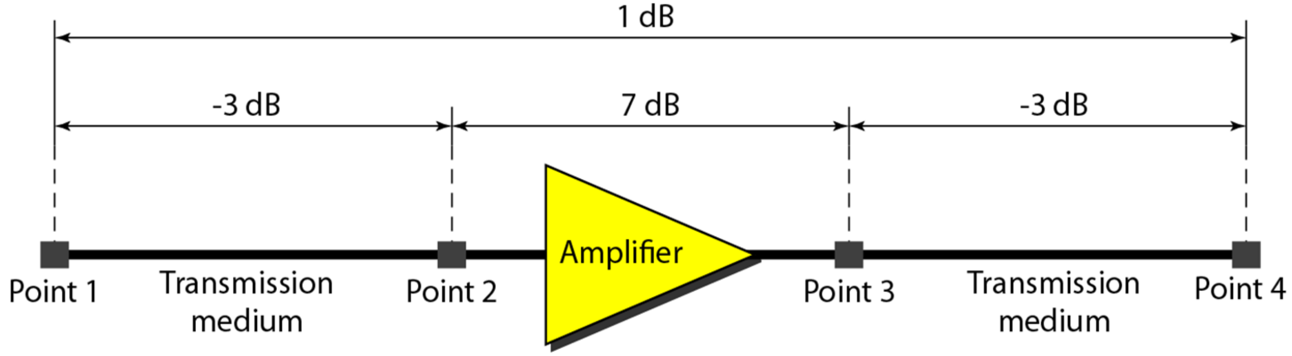
$$L_{\mathrm{dB}} = 10\log_{10}\left(\frac{P_1}{P_0}\right)$$

- The decibel scale is used because it can represent a wide range of values more conveniently than using a linear scale.

dB	Power ratio	Amplitude ratio
10	10	3.162
6	$3.981 \approx 4$	$1.995 \approx 2$
3	$1.995 \approx 2$	$1.413 \approx \sqrt{2}$
1	1.259	1.122
0	1	1
−1	0.794	0.891
−3	$0.501 \approx \frac{1}{2}$	$0.708 \approx \sqrt{\frac{1}{2}}$
−6	$0.251 \approx \frac{1}{4}$	$0.501 \approx \frac{1}{2}$
−10	0.1	0.316 2

Decibel (dB)

- 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.



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 mill watts. In this case, it is referred to as ***dB$_m$*** *and is calculated as $dB_m = 10 \log 10\, P_m$, where P_m is the power in mill watts. 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

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

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

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

Shannon Capacity (C)

$$C = B\log_2\left(1+\frac{P_s}{N_o B}\right)$$

- C is the capacity in bits per second,
- B is the bandwidth in Hertz,
- P_s is the signal power and
- N_o is the noise spectral density.

Capacity vs Throughput

- **Channel Capacity**: Physical data rate
- **Throughput** or network throughput is the rate of *successful* message delivery over a communication channel.
- Throughput is usually measured in bits per second (bit/s or bps), and sometimes in data packets per second (p/s or pps) or data packets per time slot.
- For example, if the throughput is 70 Mbit/s in a 100 Mbit/s Ethernet connection, the channel efficiency is 70%. In this example, effective 70Mbits of data are transmitted every second.

Capacity with increasing signal power

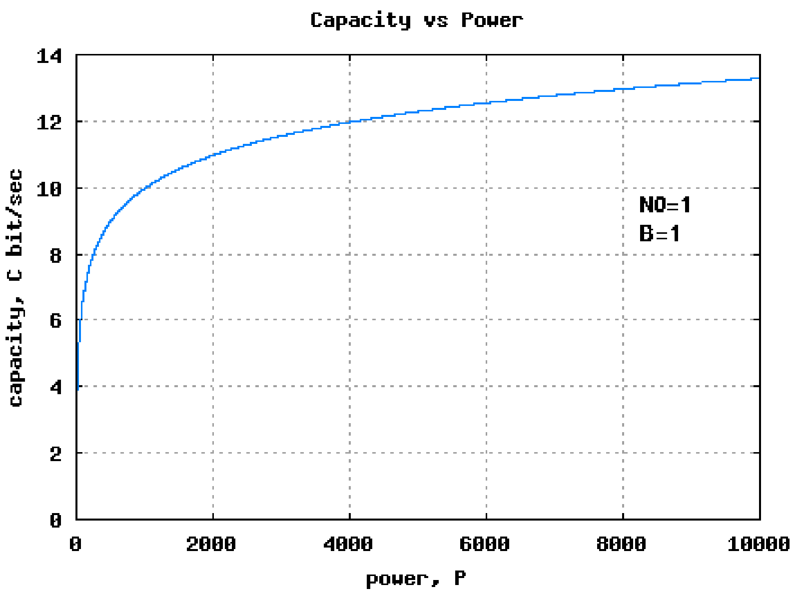


Figure: Capacity vs Power, keeping Noise and Bandwidth to unity

```
%Matlab/Octave script for plotting
%capacity vs power
B=1;
N0=1;
P= [0:10^4];
C = B.*log2(1+P./(N0*B));
plot(P,C);
xlabel('power, P');
ylabel('capacity, C bit/sec');
title('Capacity vs Power')
```

Capacity with increasing bandwidth

- 1. More bandwidth means we can have more transmissions per second, hence higher the capacity.
- 2. However, more bandwidth also means that there is more noise power at the receiver.

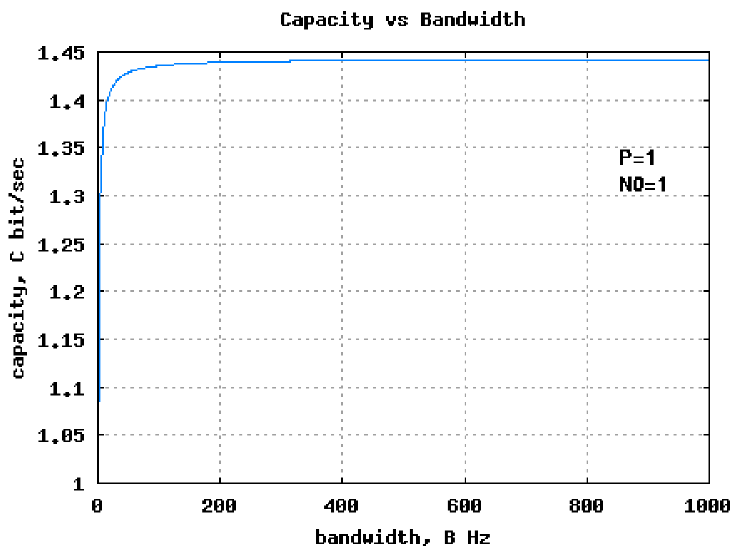


Figure: Capacity vs Bandwidth, keeping signal power and noise power to unity

```
%Matlab/Octave script for plotting capacity
%vs bandwidth
P = 1;
N0 = 1;
B = [1:10^3];
C = B.*log2(1+P./(N0*B));
plot(B,C)
xlabel('bandwidth, B Hz');
ylabel('capacity, C bit/sec');
title('Capacity vs Bandwidth')
```

Fading

- An environmental factor in wireless communications.
- **Fading** is variation or the attenuation of a signal with various variables.
  - Time, geographical position, and radio frequency
- Fading is often modeled as a **random process**.
- A **fading channel** is a communication channel that experiences fading.
- **Reasons for fading:**
  - Due to multipath propagation, referred to as multipath-induced fading,
  - Weather (particularly rain), or
  - Shadowing from obstacles affecting the wave propagation, sometimes referred to as **shadow fading**.
- Reliable **achievable data rate over a fading channel**

$$C = B.*\log_2(1+|h|^2 P./(N0*B));$$

Channel gain

- Reliable **achievable data rate over a AWGN channel**

$$\boxed{C = B\log_2\left(1+\frac{P_s}{N_o B}\right)}$$

SINR and SIR

- SIR: signal-to-interference ratio
  - SIR=S/I
    - the average received modulated carrier power *S* or *C* and
    - the average received co-channel interference power *I*, i.e. crosstalk, from other transmitters than the useful signal.
  - also known as the **carrier-to-interference ratio** (**CIR** or ***C/I***)
  - interference limited systems
  - *I* dominates over *N*
  - In cellular radio systems and broadcasting systems
    - frequency channels are reused in view to achieve high level of area coverage.

SINR and SIR

- SINR: Signal-to-interference-plus-noise ratio
  - SINR=S/(I+N)
  - Both noise and interference occurs
  - Mathematically, SINR for a fading channel

Received signal power

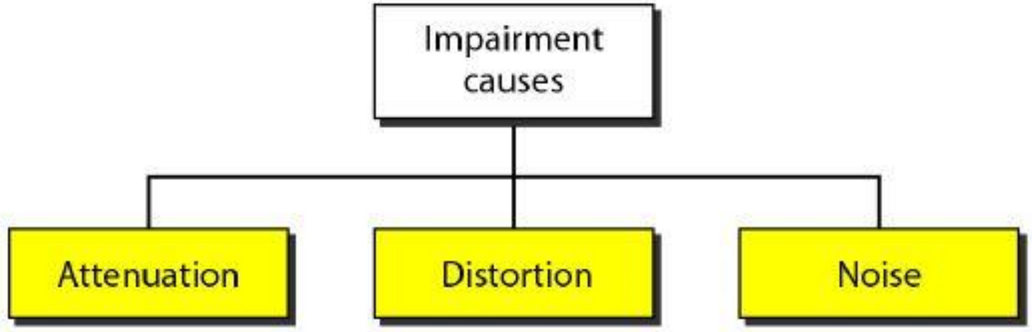
$$\gamma_{SR} = \frac{P_S|h|^2}{\sigma_R^2 + \sum_{i=1}^{M} P_i|\beta_i|^2}$$

Noise

Received interference power

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



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.
- To compensate for this loss, amplifiers are used to amplify the signal.

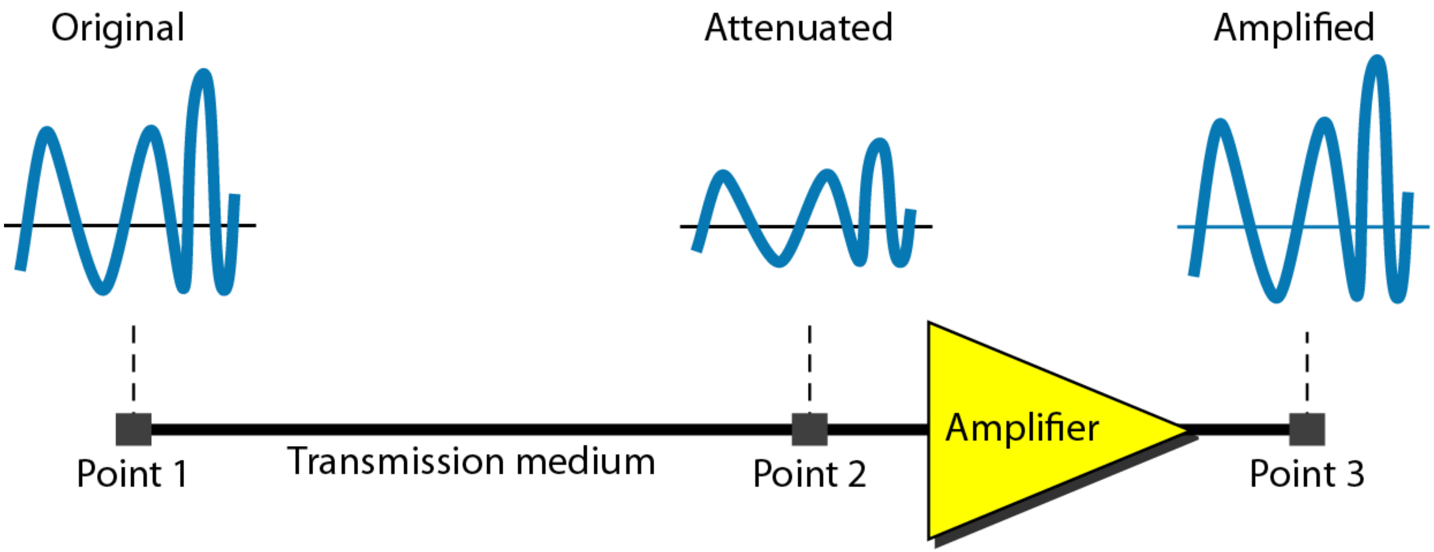


Figure 3.26 ***Attenuation (the first impairment)***

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.
- The shape of the composite signal is therefore not the same.

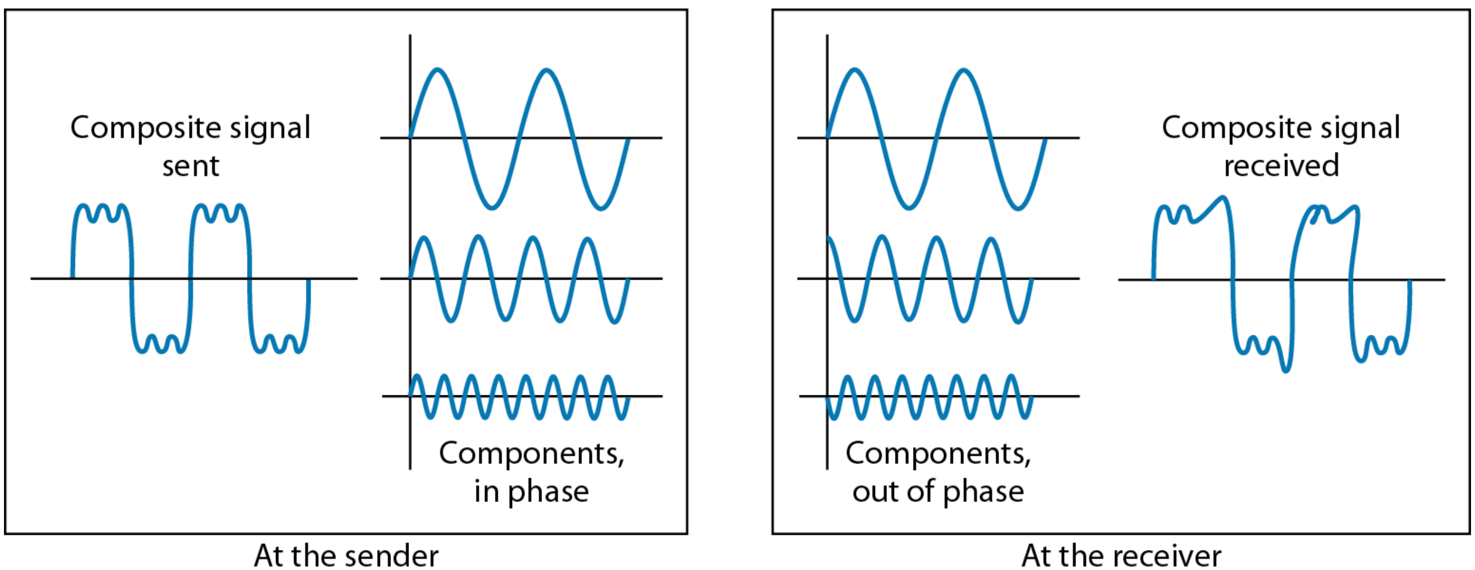


Figure 3.28 ***Distortion (the second impairment)***

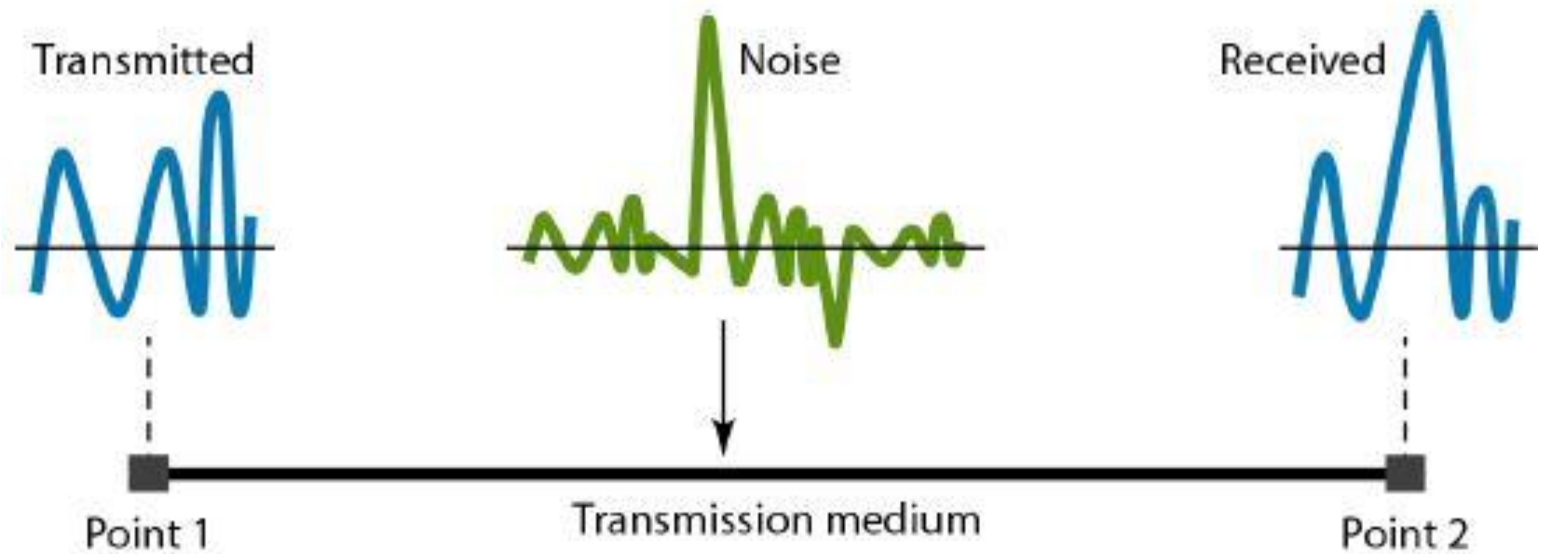
Noise (the third impairment)

- Noise is unwanted electrical or electromagnetic energy that degrades the quality of signals and data.
- Noise occurs in digital and analog systems, and can affect files and communications of all types, including
  - text,
  - programs,
  - images,
  - audio, and
  - telemetry.
- Noise can come from a variety of sources, including
  - radio waves,
  - nearby electrical wires,
  - lightning, and
  - bad connections.

What is Noise?

- Noise is random energy that interfere with the information signal.
- Noise may be defined as any **unwanted introduction of energy** tending to interfere with the proper reception and reproduction of transmitted signal.
- The noise is a summation of unwanted or disturbing energy from **natural** and sometimes **man-made sources**.
- **Noise** is, however, typically **distinguished from interference.**
- **An interference** is that which modifies a signal in a disruptive manner, as it travels along a channel between its source and receiver.

Noise



Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

What is Noise?

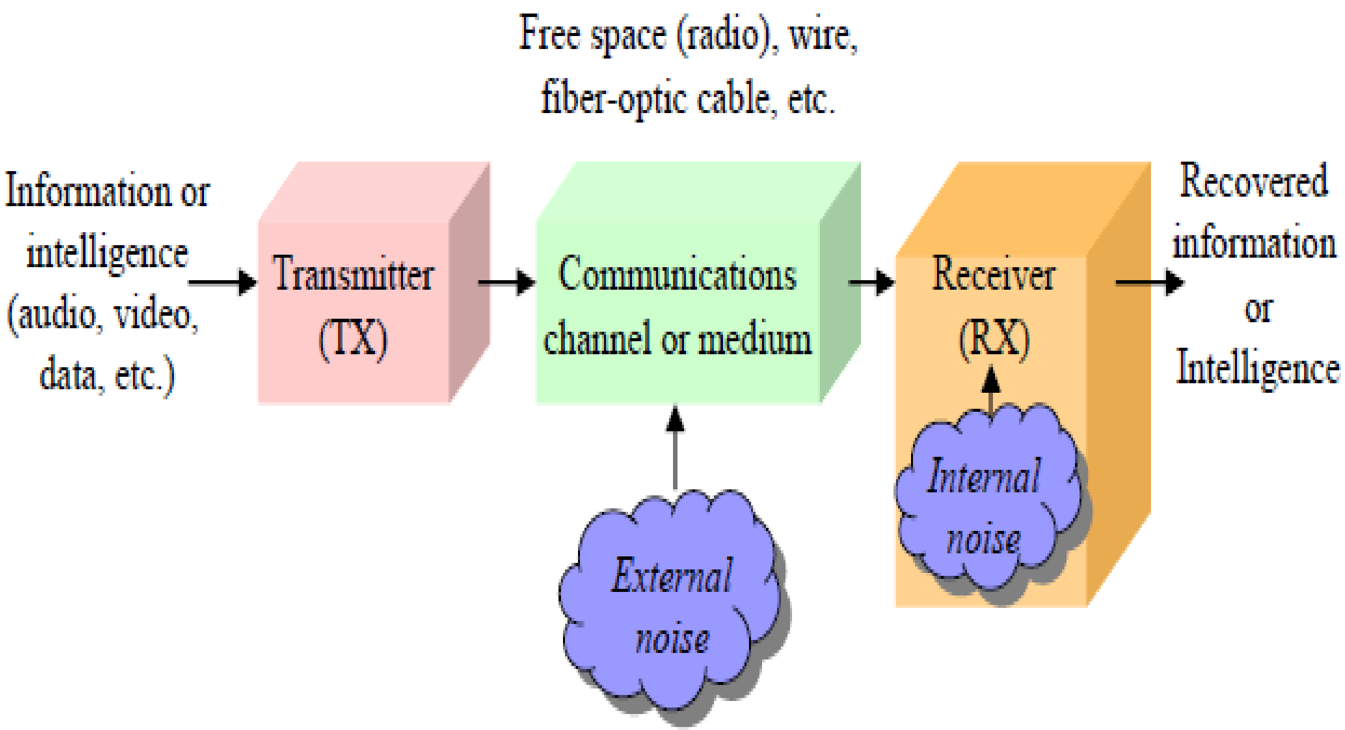
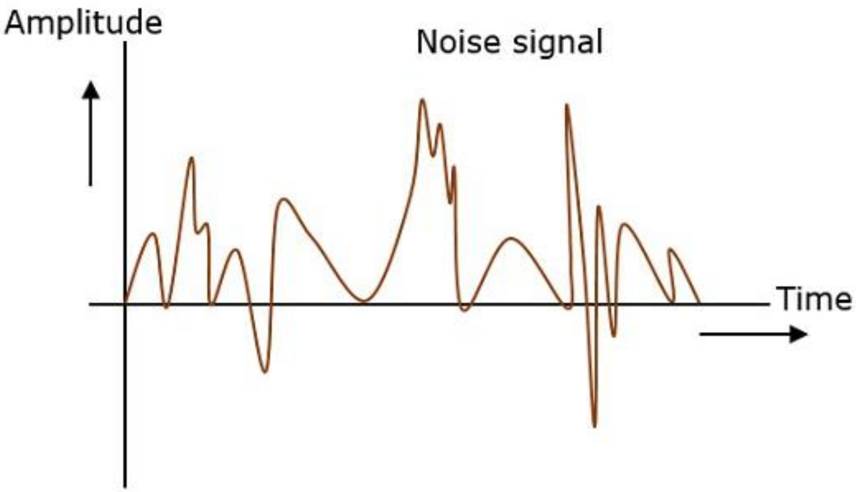


FIG: Simplified block diagram of a two-station data communications circuit.

What is Noise?

- Noise in communication originates both in the **channel** and **communication equipment's**.
- Noise is a random signal that exists in a communication.
- Unfortunately, **noise is unavoidable.**
- **Most common examples of noise** are −
  - Hiss sound in radio receivers
  - Buzz sound amidst of telephone conversations
  - Flicker in television receivers, etc.



Effects of Noise?

- Noise is an inconvenient feature which affects the system performance.
- **Effects of noise:**
  - Degrade system performance for both analog and digital system.
  - In analog system noise deteriorates the quality of the received signal
  - In digital system noise degrades the throughput because it requires retransmission of data packet or extra coding to recover the data in the presence of errors
  - The receiver cannot understand the original signal.
  - Reduce the efficiency of the communication system.
- Noise **cannot be avoided** completely,
- But its **effect can be reduced by filtering or by reducing the signal bandwidth.**

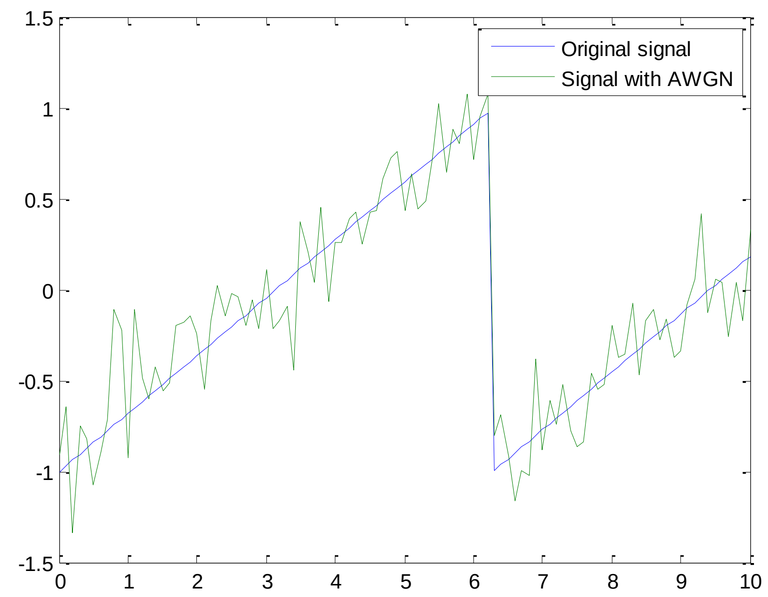
Additive white Gaussian noise (AWGN)

- **Additive white Gaussian noise** (**AWGN**) is a basic noise model used in Information theory **to mimic the effect of many random processes that occur in nature.**
- The modifiers denote specific characteristics:
  - **'Additive'** because it is added to any noise that might be intrinsic to the information system.
  - **'White'** refers to idea that it has uniform power across the frequency band for the information system. It is an analogy to the color white which has uniform emissions at all frequencies in the visible spectrum.
  - **'Gaussian'** because it has a normal distribution in the time domain with an average time domain value of zero.

Additive white Gaussian noise (AWGN)

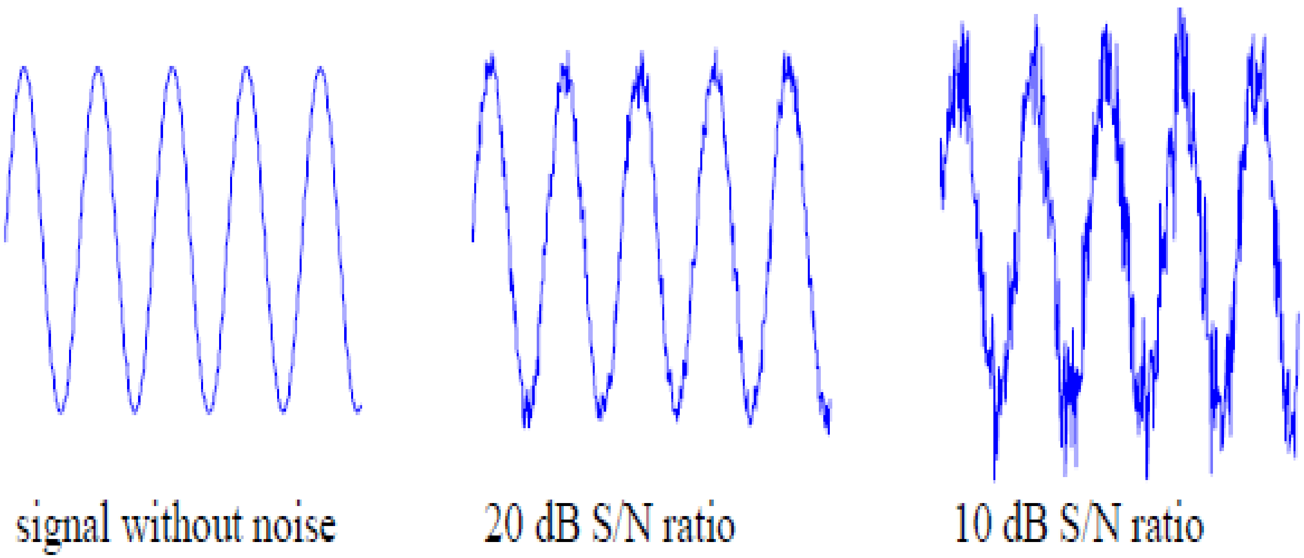
%The commands below add white Gaussian noise to a sawtooth signal. It then plots the original and noisy signals.

```
t = 0:.1:10;
x = sawtooth(t); % Create sawtooth signal.
y = awgn(x,10,'measured'); % Add white Gaussian noise.
plot(t,x,t,y) % Plot both signals.
legend('Original signal','Signal with AWGN');
```



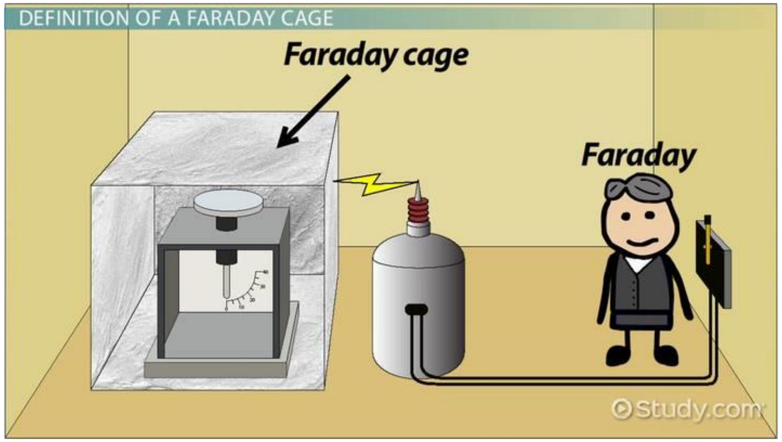
Signal-to-Noise Ratio (SNR)

- A strong signal and weak noise results in a High SNR
- A weak signal and high noise results in Low SNR



Noise Mitigation

- In many cases noise found on a signal in a circuit is unwanted.
- There are many **different noise reduction techniques** that can reduce the noise picked up by a circuit.
  - **Faraday cage –**
    - A Faraday cage enclosing a circuit can be used to isolate the circuit from external noise sources.
    - A Faraday cage or Faraday shield is an enclosure used to block electromagnetic fields.
    - A faraday cage cannot address noise sources that originate in the circuit itself or those carried in on its inputs, including the power supply.



Noise Mitigation

- **Ground loops**
  - When grounding a circuit, it is important to avoid ground loops.
  - Ground loops occur when there is a voltage difference between two ground connections.
  - A good way to fix this is to bring all the ground wires to the same potential in a ground bus.
- **Shielding cables**
  - A shielded cable can be thought of as a Faraday cage for wiring and can protect the wires from unwanted noise in a sensitive circuit.
  - The shield must be grounded to be effective.
  - Grounding the shield at only one end can avoid a ground loop on the shield.

Noise Mitigation

- **Twisted pair wiring**
  - Twisting wires in a circuit will reduce electromagnetic noise.
- **Notch filters**
  - Notch filters or band-rejection filters are useful for eliminating a specific noise frequency.
  - For example, power lines within a building run at 50 or 60 Hz line frequency.
  - A sensitive circuit will pick up this frequency as noise.
  - A notch filter tuned to the line frequency can remove the noise.
- **Noise Cancellation techniques**

Examples

- **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:***

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

$$\text{SNR}_{\text{dB}} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

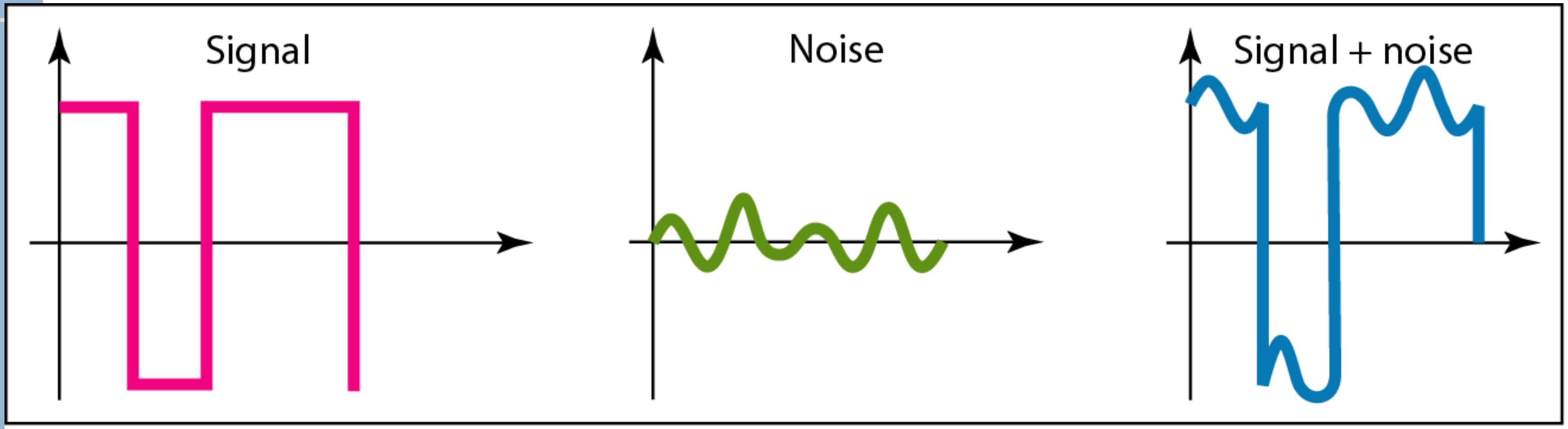
- **Example:** ***The values of SNR and SNR_{dB} for a noiseless channel are***

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

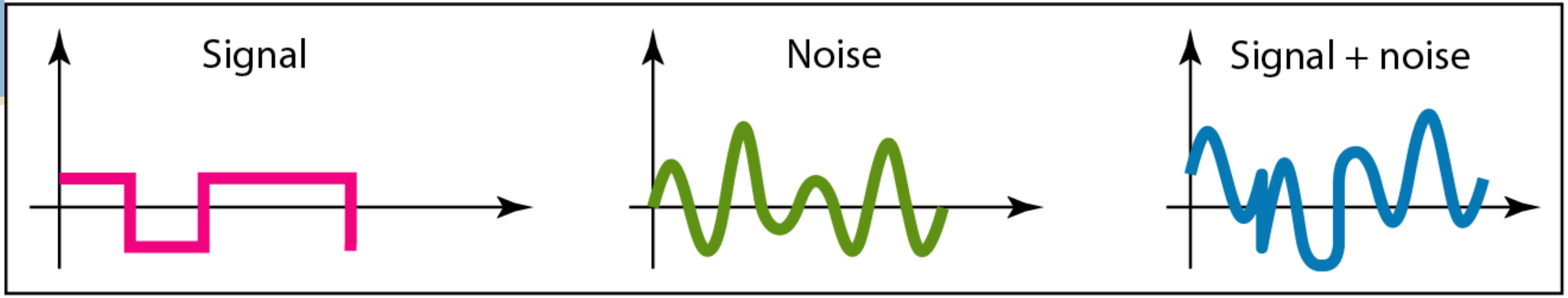
$$\text{SNR}_{\text{dB}} = 10 \log_{10} \infty = \infty$$

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

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



a. Large SNR



b. Small SNR

3-5 DATA RATE LIMITS

- 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 (**As discussed before**)

Noiseless Channel: Nyquist Bit Rate

- For a noiseless channel, the 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, and
  - BitRate is the bit rate in bits per second

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

Examples

- ***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***

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

- ***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.

Example: Shannon Capacity Formula

- ***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***

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

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

Example

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

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

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

Example

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

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

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

- ***For practical purposes, when the SNR is very high, we can assume that SNR + I is almost the same as SNR.***

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.

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

- *The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels.*

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

Note

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

Performance

- One important issue in networking is the performance of the network-how good is it?
- **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 and
    - bandwidth in bits per second.

Cont.

- For example, we can say the bandwidth of a subscriber telephone line is 4 kHz.
- 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.

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

- The first, *bandwidth in hertz,* refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.
- The second, *bandwidth in bits per second,* refers to the speed of bit transmission in a channel or link.

Note

- ***As the bandwidth increases, so too can the data rate.***
- ***Stated another way, to transmit a high data rate, we need a wide bandwidth.***
- ***OR***
- ***We need to use a signaling technique that has a high number of signal levels.***
- ***The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data transmission can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog.***
- ***If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology***

Performance

- **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.
  - 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.
  - Imagine a highway designed to transmit 1000 cars per minute from one point to another. However, if there is congestion on the road, this figure may be reduced to 100 cars per minute. The bandwidth is 1000 cars per minute; the throughput is 100 cars per minute.

Example 3.44

A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution

We can calculate the throughput as

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

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

Cont.

- **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.

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

Cont.

- **Propagation Time:**
  - Propagation time measures the **time required for a bit** to travel from the source to the destination.
  - The propagation time is calculated by dividing the distance by the propagation speed.
  - **Equation:**
    - Propagation time = distance / propagation speed
  - The propagation speed of electromagnetic signals depends on the medium and on the frequency of the signal.
  - For example, in a vacuum, light is propagated with a speed of 3×10^8 m/s.
  - It is much lower in air; it is much lower in cable.

What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^8 m/s in cable.

Solution

We can calculate the propagation time as

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

The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.

Cont.

- **Transmission Time:**
  - In data communication, **transmission time** refers to the time it takes to send all bits of a message onto a link.

```
Time Axis →

+-------------+--------------------+---------------------------------------

|             |                    |

| Start       | End of Transmission| End of Propagation (all bits received)     |

| of sending  | (last bit sent)    |

+-------------+--------------------+---------------------------------------

     ←---- Transmission Time ----→ ←------------ Propagation Time ------------→


Explanation:

- Transmission Time: When sender is *sending* bits

- Propagation Time: When bits are *traveling* to receiver
```

Cont.

Aspect	Transmission Time	Propagation Time
Definition	Time to push all bits into the medium	Time for a bit to travel from sender to receiver
Formula	$T_{tx} = \frac{\text{Data Size (bits)}}{\text{Bandwidth (bps)}}$	$T_{prop} = \frac{\text{Distance}}{\text{Propagation Speed}}$
Depends on	Message length and bandwidth	Distance and propagation speed of the medium
Unit	Seconds	Seconds
Example	Uploading a file	Speed of light delay over fiber
Influenced by	Data rate (e.g., Mbps)	Physical distance and medium (e.g., fiber, copper)
Scenario Example	1 MB file on 1 Mbps link = 8 sec	1000 km fiber at 2×10^8 m/s = 0.005 sec

Example

What are the propagation time and the transmission time for a 2.5-kbyte message (an e-mail) if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

We can calculate the propagation and transmission time as

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

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

Note that in this case, because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time. The transmission time can be ignored.

Example:

What are the propagation time and the transmission time for a 5-Mbyte 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

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

$$\text{Transmission time} = \frac{5{,}000{,}000 \times 8}{10^6} = 40 \text{ s}$$

Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Cont.

- **Queuing Time**
  - The time a packet **waits in the queue** before it can be transmitted on the outbound link.
- **Processing Delay**
  - The time a router or switch takes to **process the packet header**, check for bit-level errors, and determine where to forward the packet.

```
Packet arrives →

    ┌───────────────┐   ┌─────────────┐   ┌─────────────────┐   ┌─────────────────┐
    │ Processing    │ + │ Queuing     │ + │ Transmission    │ + │ Propagation     │
    │ Delay         │   │ Delay       │   │ Delay           │   │ Delay           │
    └───────────────┘   └─────────────┘   └─────────────────┘   └─────────────────┘
```

Example:

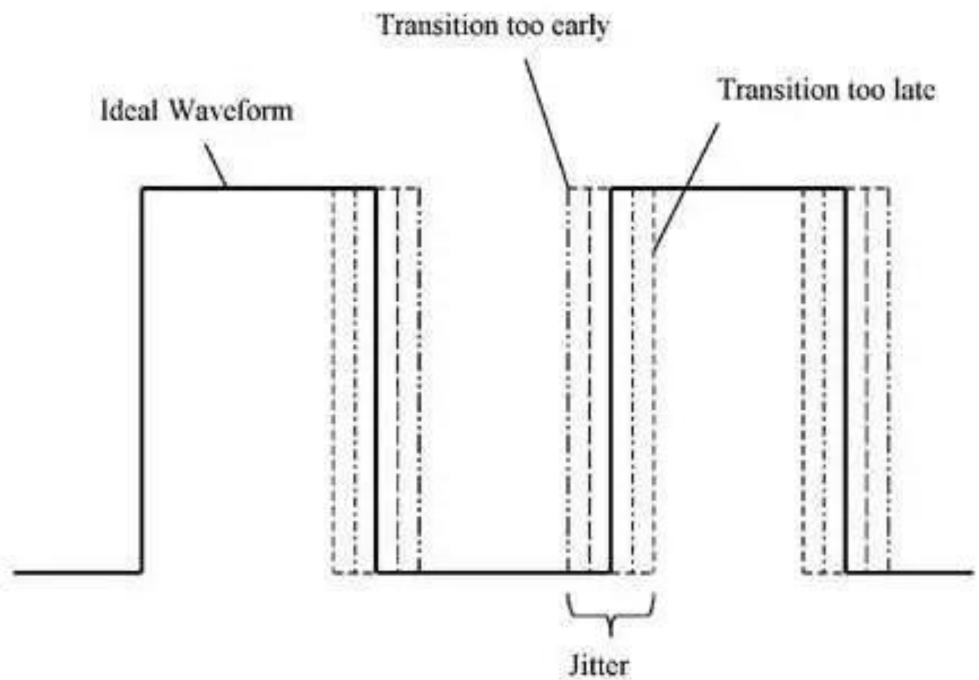
A packet arriving at a router might experience:

- **Processing delay**: 10 microseconds
- **Queuing delay**: varies from 0 to 100 ms (depending on congestion)
- **Transmission delay**: 1 ms (if packet size = 1000 bits and link = 1 Mbps)
- **Propagation delay**: 5 ms (over 1000 km fiber)

> In a busy router, **queuing delay** can dominate the total delay.

Jitter

- **Jitter** is the **variation in packet delay** — that is, the difference in time between when packets are expected to arrive and when they actually arrive.



References

- Chapter-3: Data and Signals
  - Behrouz A. Forouzan: Data Communications and Networking, 4th Edition
  - Online sources