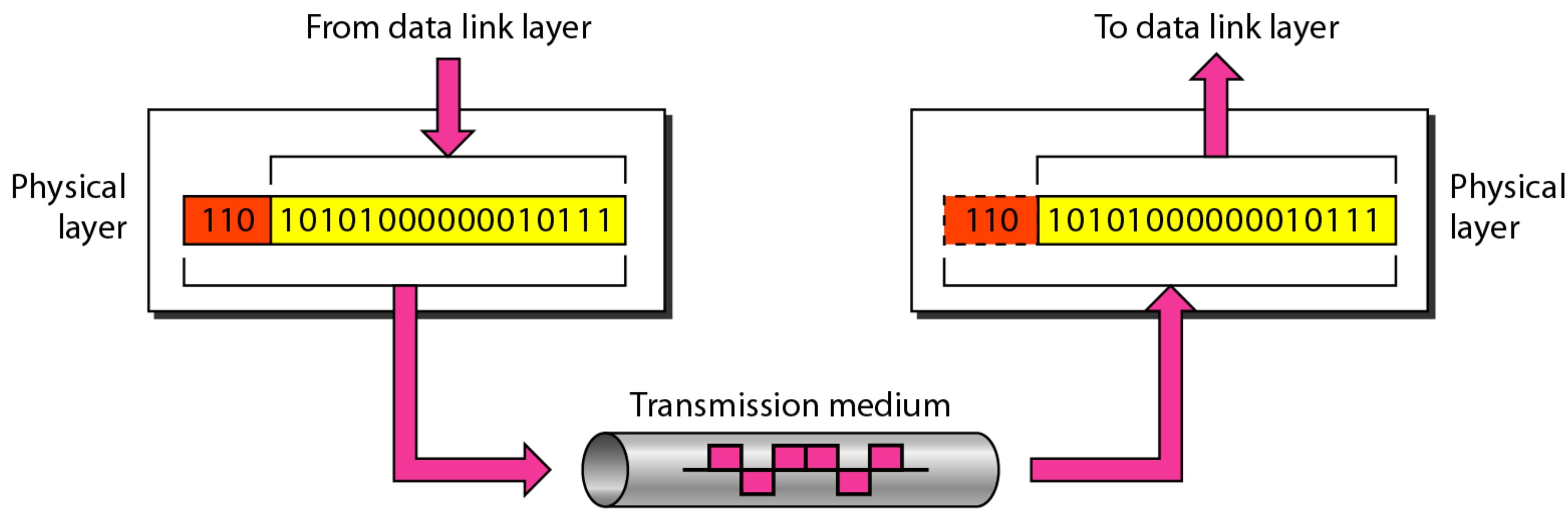
Data and Signals

- Analog and Digital
- Analog-to-Analog Conversion
- Digital Signals
- Transmission Impairment
- Data-rate Limits
- Performance



To be transmitted, data must be transformed to electromagnetic signals.

ANALOG AND DIGITAL

GLA UNIVERSITY MATHURA
Recognised by UGC Under Section 2(f)
Accredited with A Grade by NAAC
12-B Status from UGC

Data can be analog or digital

Analog data refers to information that is continuous

Analog data take on continuous values

Analog signals can have an infinite number of values in a range

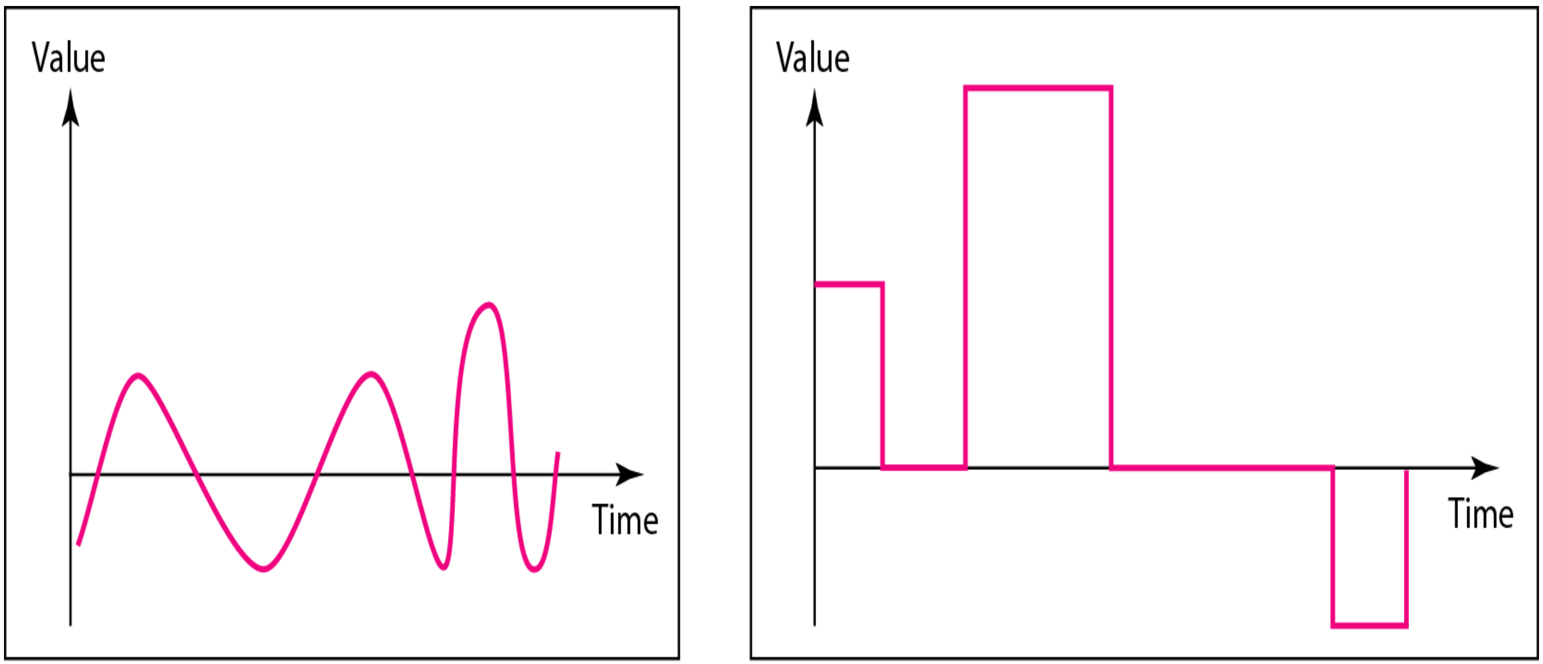
Digital Data

GLA UNIVERSITY MATHURA
Recognised by UGC Under Section 2(f)
Accredited with A Grade by NAAC
12-B Status from UGC

Digital data refers to information that has discrete states

Digital data take on discrete values

Digital signals can have only a limited number of values



a. Analog signal

b. Digital signal

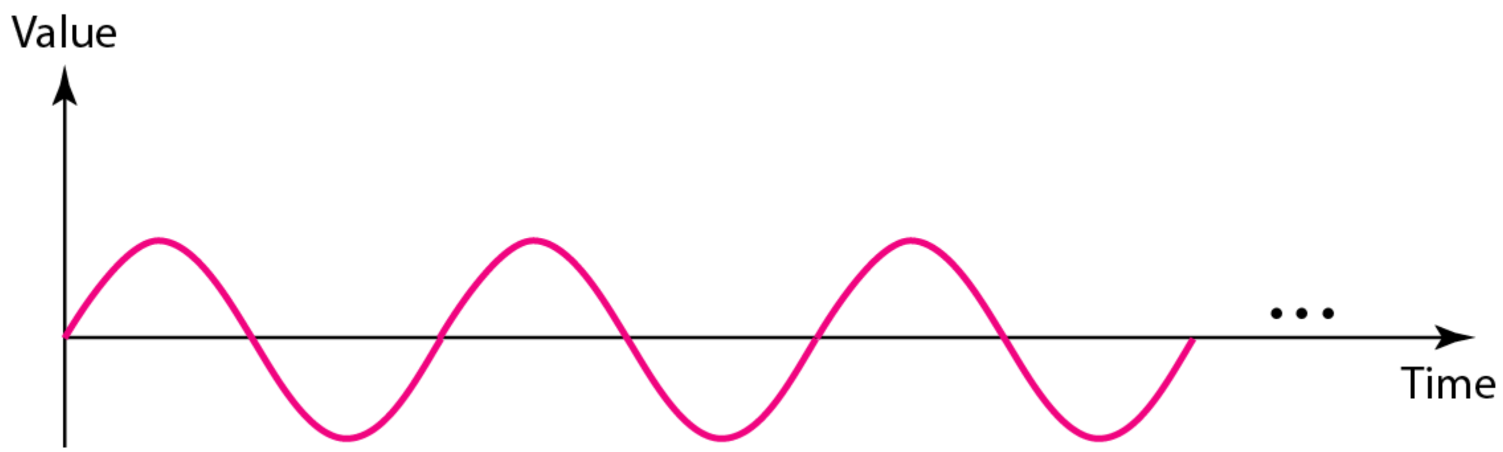
In data communications, we commonly use periodic analog signals and nonperiodic digital signals.

PERIODIC ANALOG SIGNALS

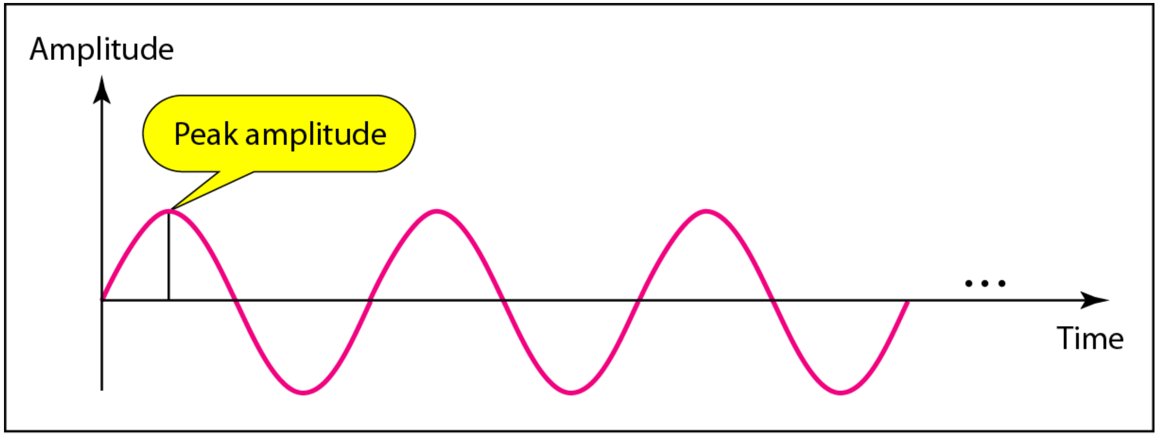
Periodic analog signals can be classified as simple or composite.

A simple periodic analog signal, a sine wave, cannot be decomposed into simpler signals.

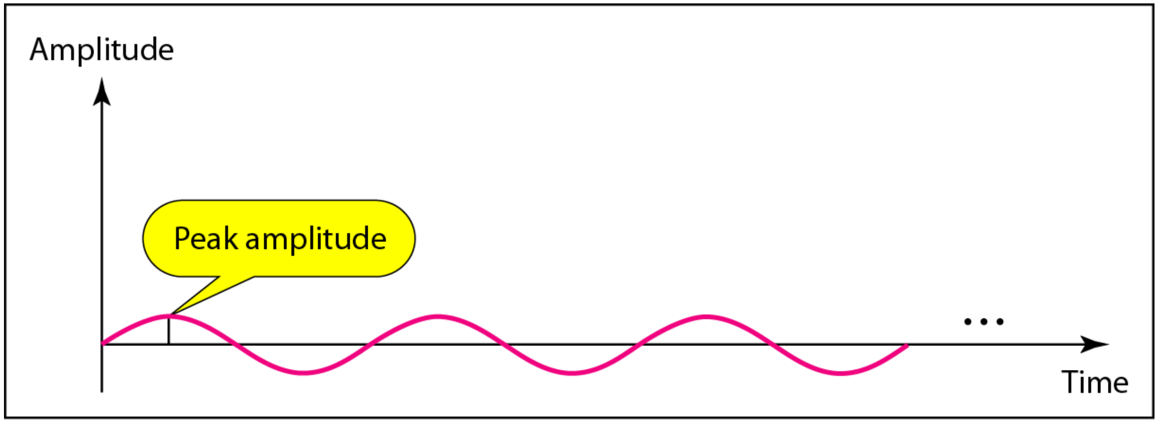
A composite periodic analog signal is composed of multiple sine waves.



Signal amplitude



a. A signal with high peak amplitude



b. A signal with low peak amplitude

Frequency

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.

Frequency and Period

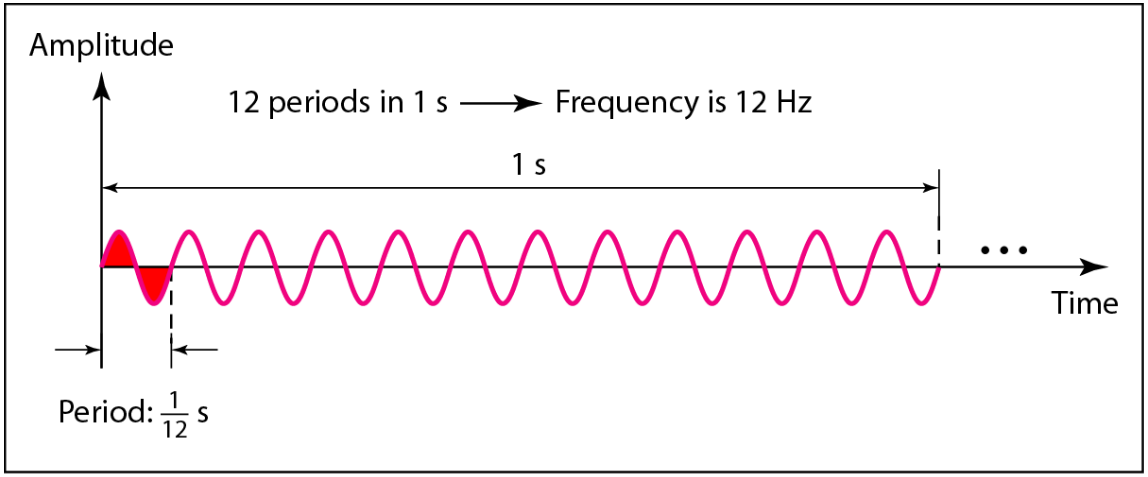
Frequency and period are the inverse of each other.

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

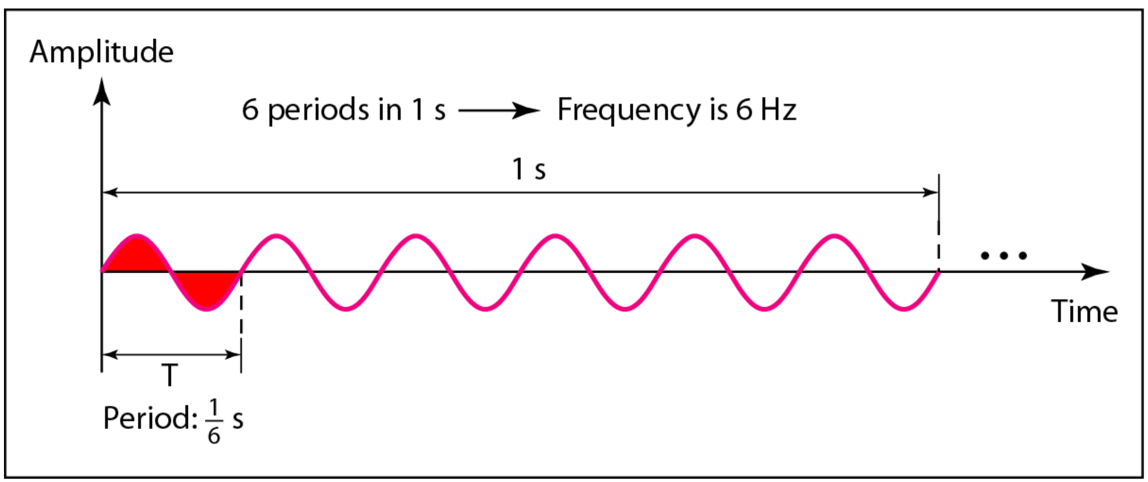
Units of period and frequency

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

Two signals with the same amplitude, but different frequencies



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

Examples

The power we use at home has a frequency of 60 Hz. What is the period of this sine wave ?

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

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

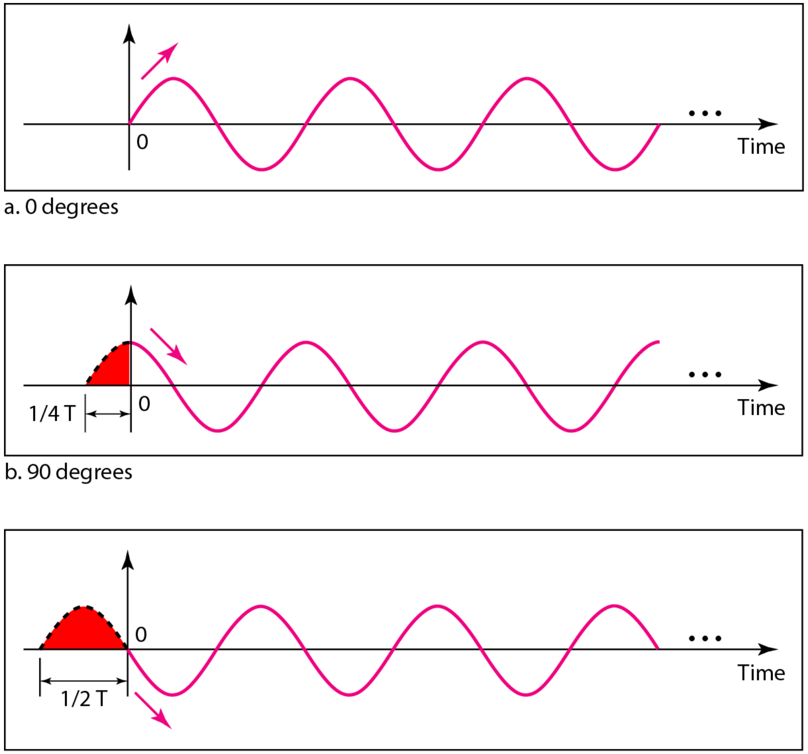
$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 10^{-1} \text{ s}$$

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

Phase

Phase describes the position of the waveform relative to time 0

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



a. 0 degrees

b. 90 degrees

c. 180 degrees

Example

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

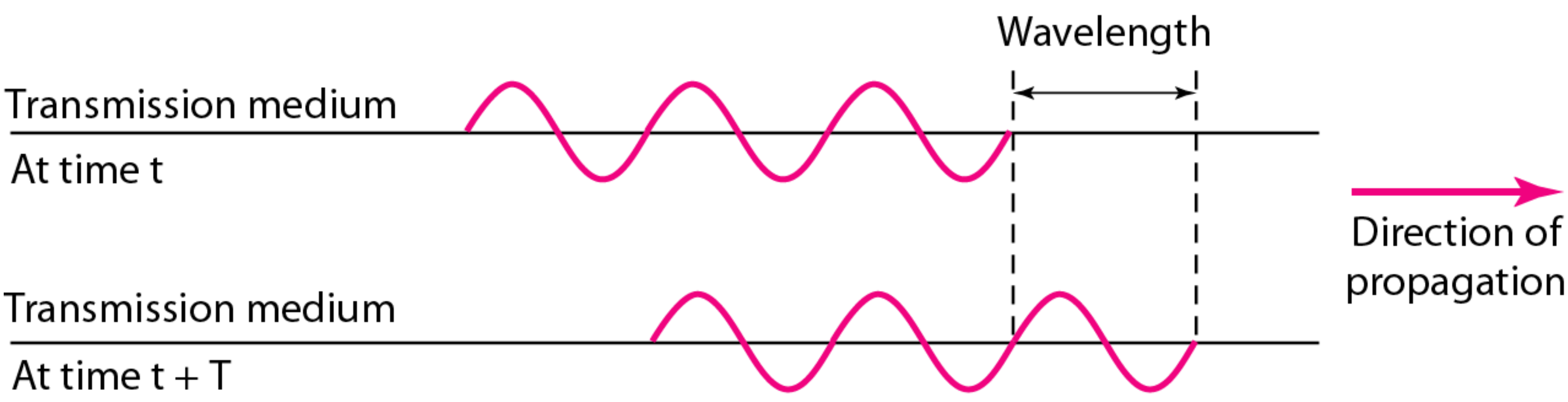
Solution

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

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

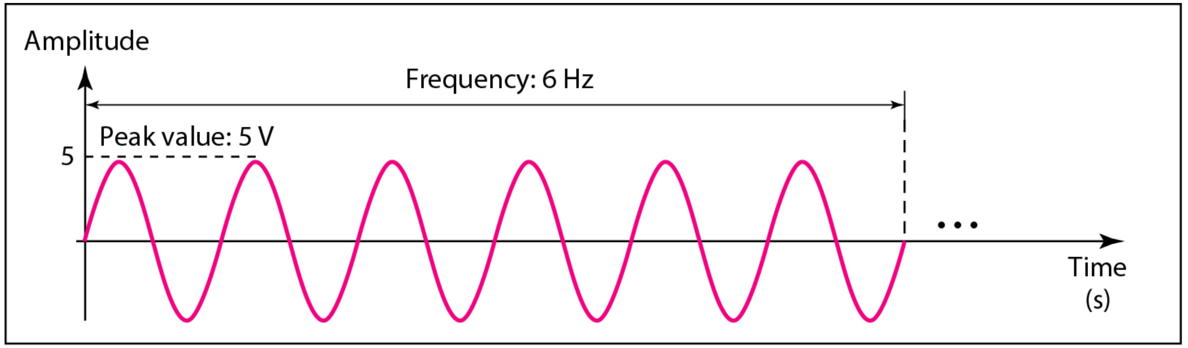
Wavelength and period

Wavelength = Propagation speed x Period
= Propagation speed / Frequency

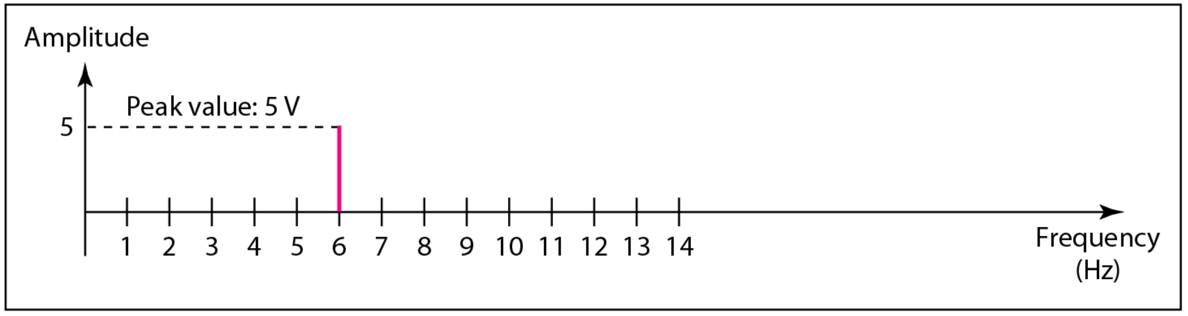


Time-domain and frequency-domain plots of a sine wave

A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

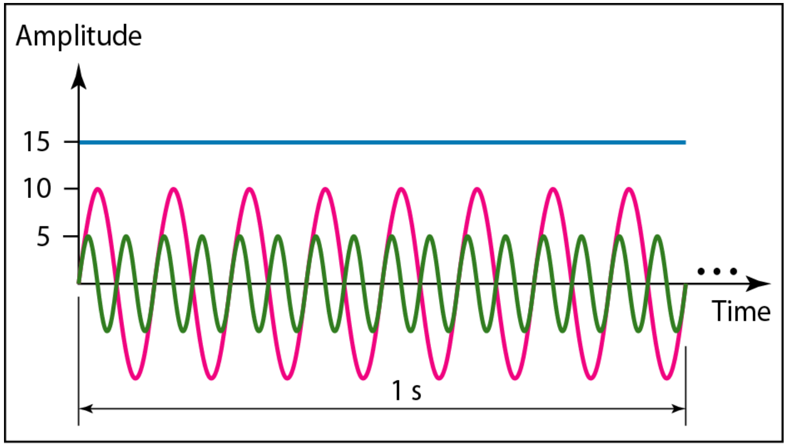


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

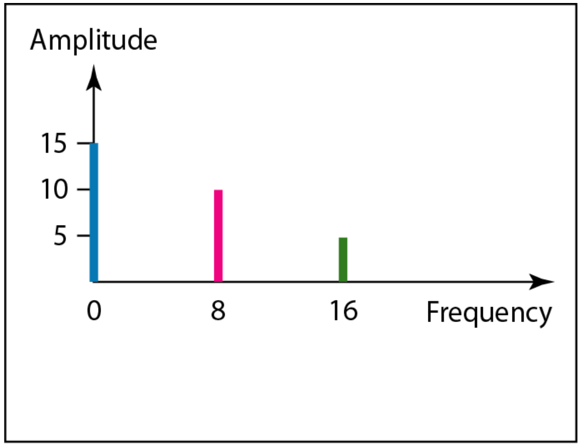


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Frequency Domain



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



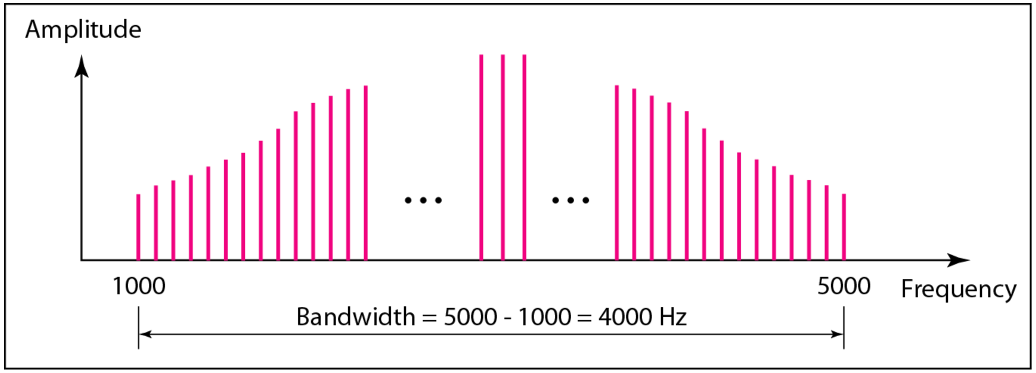
b. Frequency-domain representation of the same three signals

- The frequency domain is more compact and useful when we are dealing with more than one sine wave.

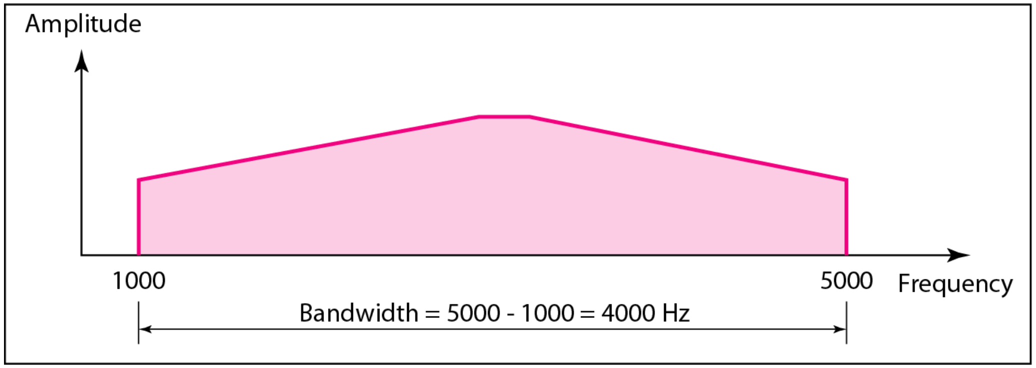
- A single-frequency sine wave is not useful in data communication
  - We need to send a composite signal, a signal made of many simple sine waves.

Bandwidth

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



a. Bandwidth of a periodic signal



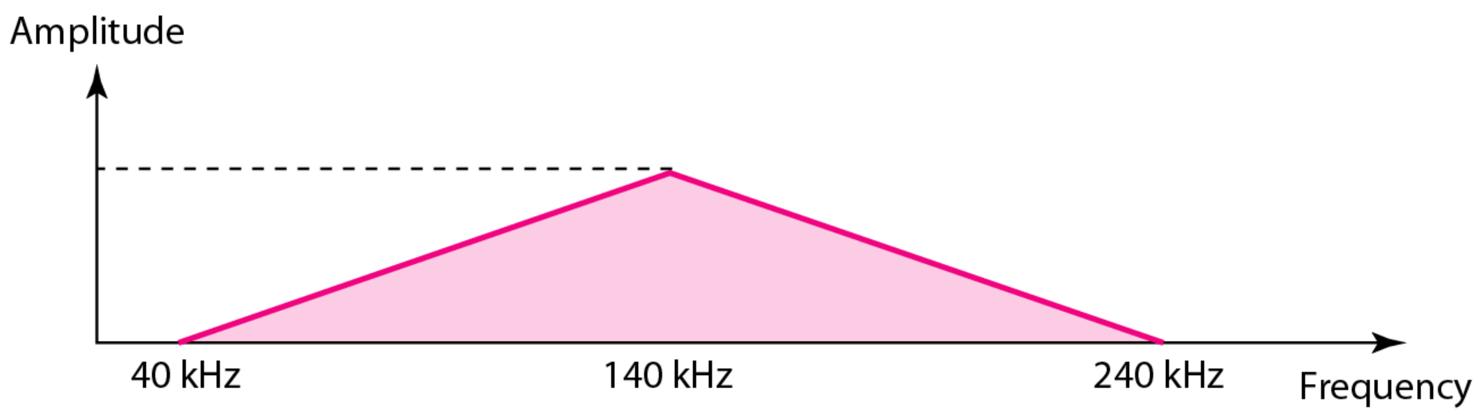
b. Bandwidth of a nonperiodic signal

Example

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

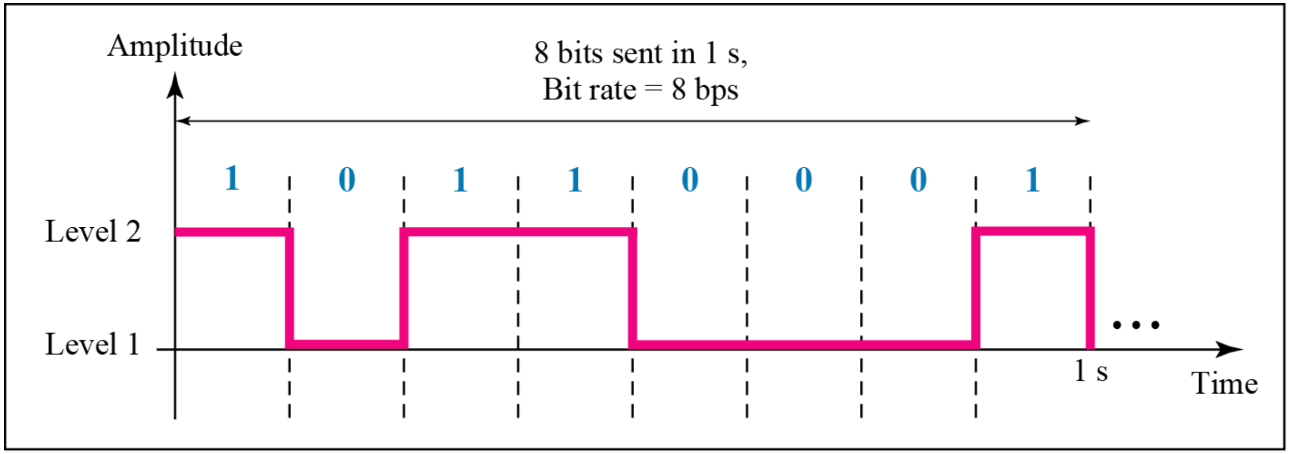
The lowest frequency must be at 40 kHz and the highest at 240 kHz.



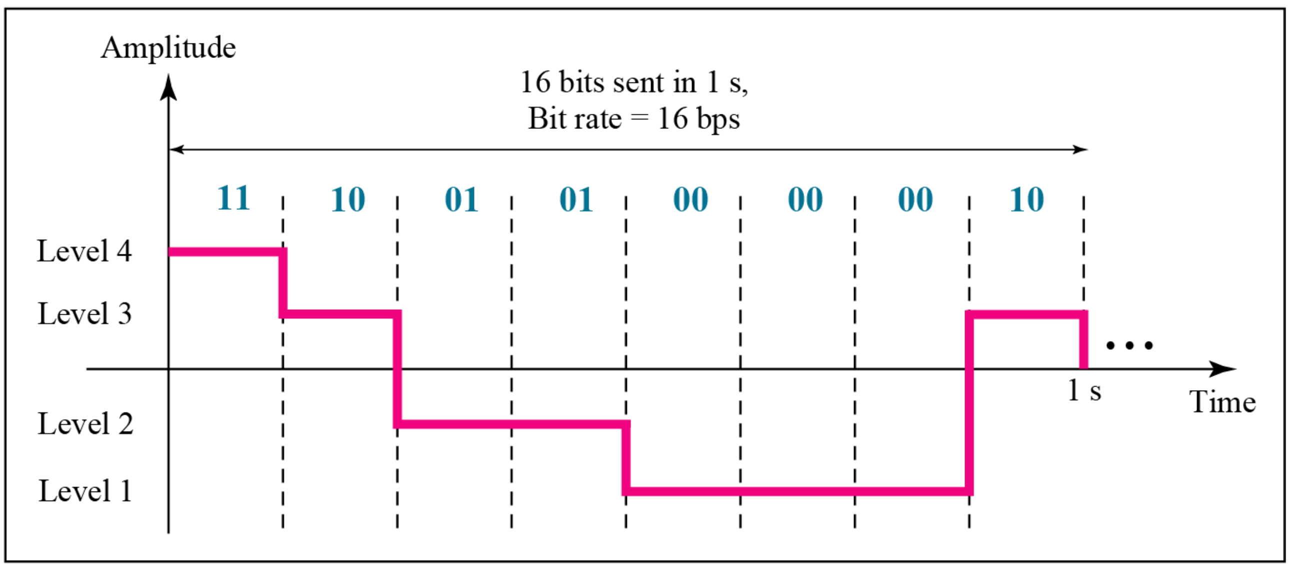
3-3 DIGITAL SIGNALS

- 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.

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

Examples

A digital signal has 8 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.

A digital signal has 9 levels. How many bits are needed per level?

Each signal level is represented by 3.17 bits.
The number of bits sent per level needs to be an integer as well as a power of 2.
Hence, 4 bits can represent one level.

Examples

Assume we need to download files at a rate of 100 pages per minute. A page is an average of 24 lines with 80 characters in each line where one character requires 8 bits. What is the required bit rate of the channel?

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

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). Assume that each sample requires 8 bits. What is the required bit rate?

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

Example

HDTV uses digital signals to broadcast high quality video signals. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Also, 24 bits represents one color pixel.

What is the bit rate for high-definition TV (HDTV)?

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

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

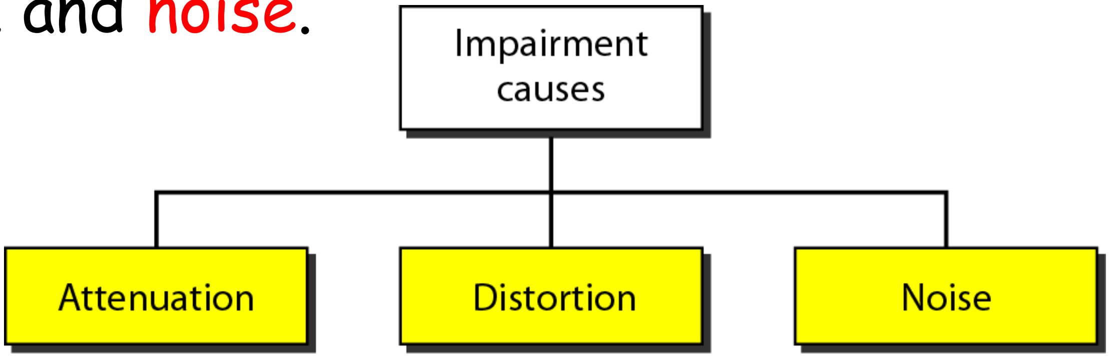
Lecture 25: Outline

Chapter 3: Data and Signals

- 3.1 Analog and Digital
- 3.2 Analog-to-Analog Conversion
- 3.3 Digital Signals
- 3.4 Transmission Impairment
- 3.5 Data-rate Limits
- 3.6 Performance

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

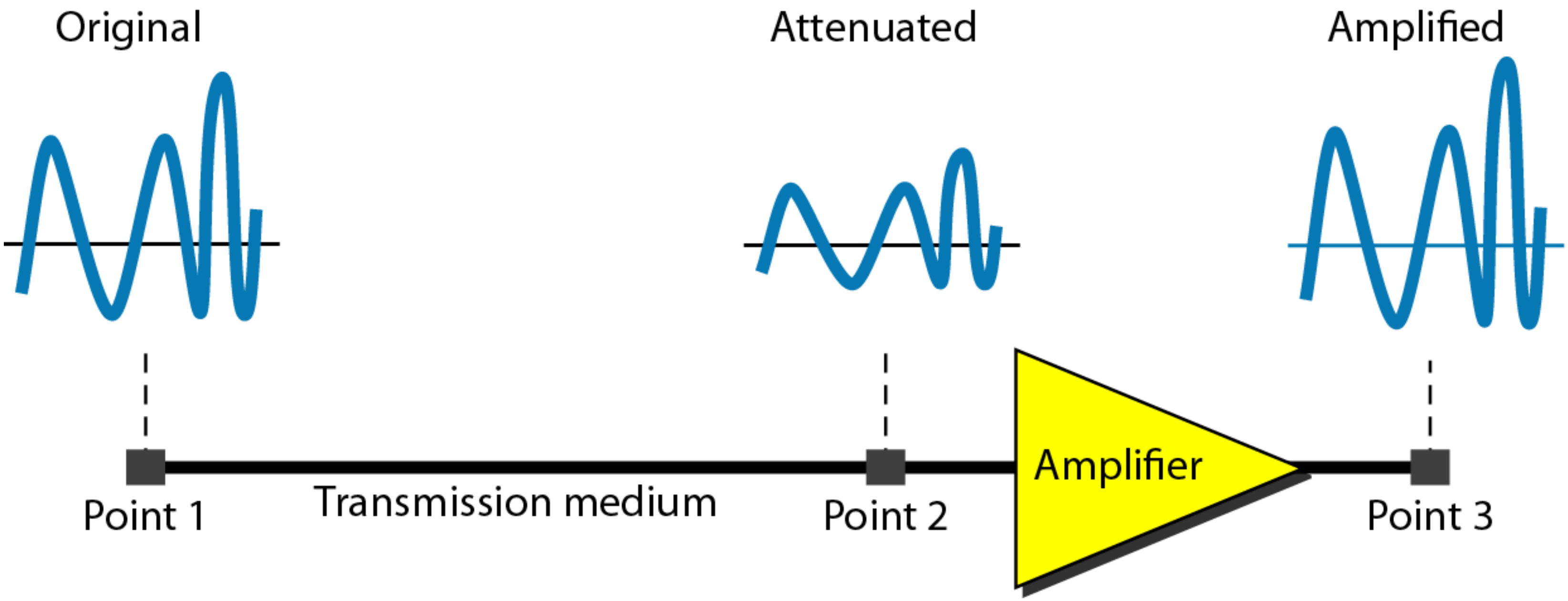


Attenuation

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,

Attenuation



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.

the decibel is negative if a signal is attenuated and positive if a signal is amplified.

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

Suppose a signal travels through a transmission medium and its power is reduced to one-half.

Example

Suppose a signal travels through a transmission medium and its power is reduced to one-half.

This means that P_2 is $(1/2)P_1$.

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 $P_2 = 10P_1$.

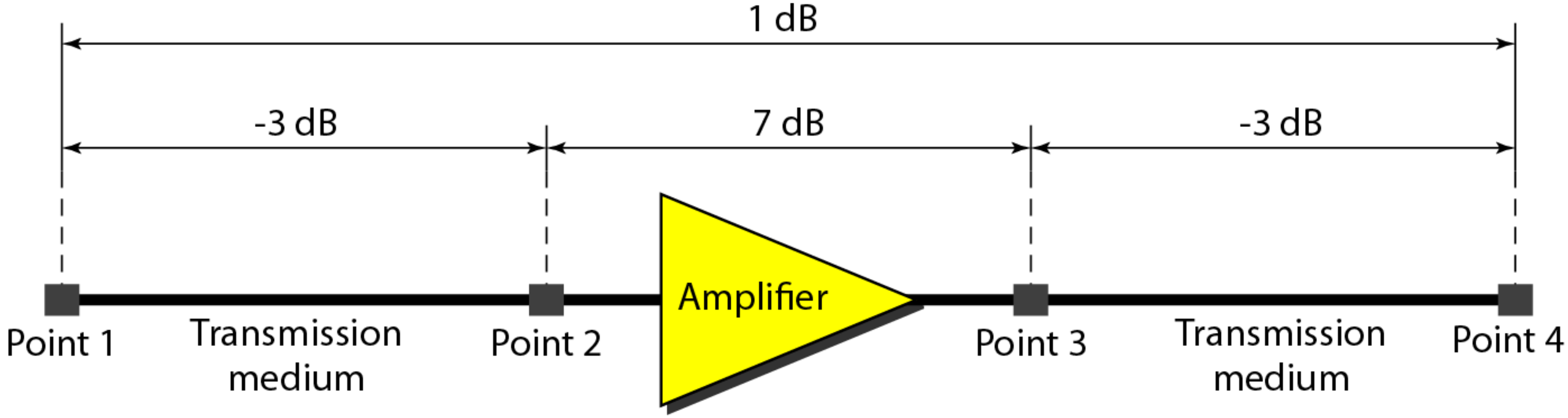
What is the amplification (gain of power)?

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

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

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.
A signal travels from point 1 to point 4.



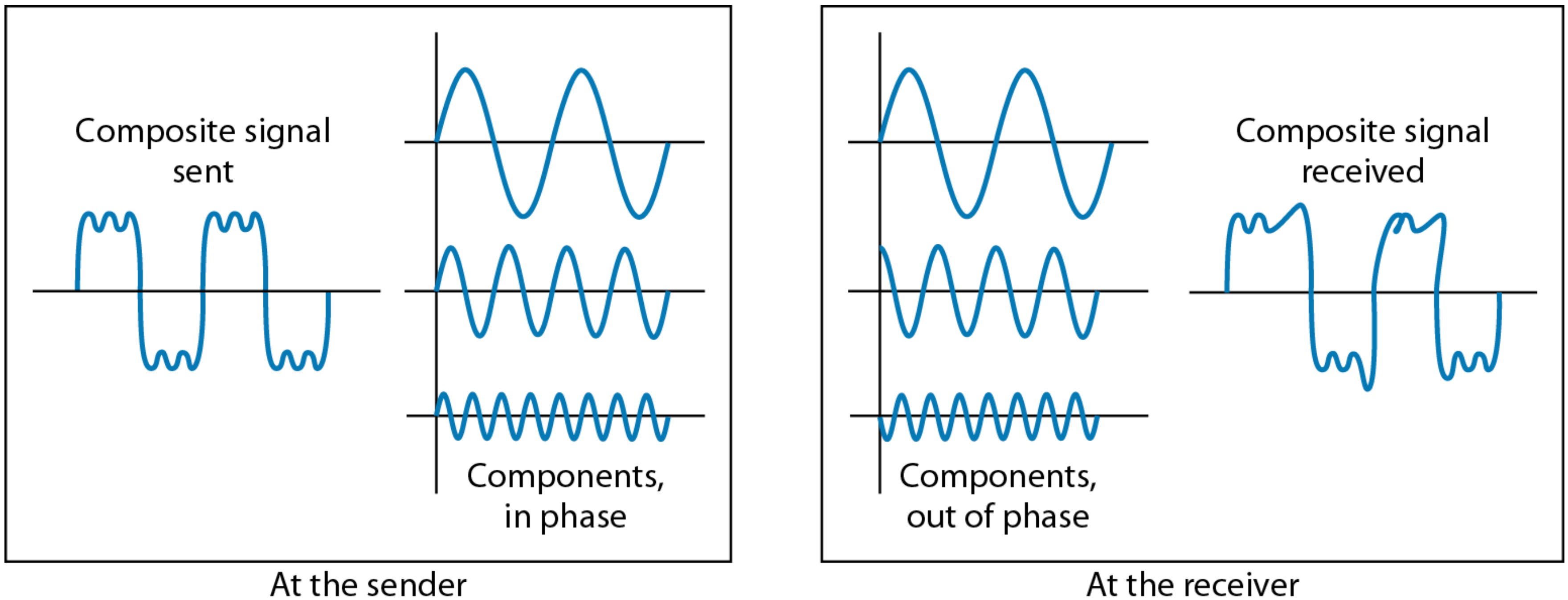
In this case, the decibel value can be calculated as

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

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.*

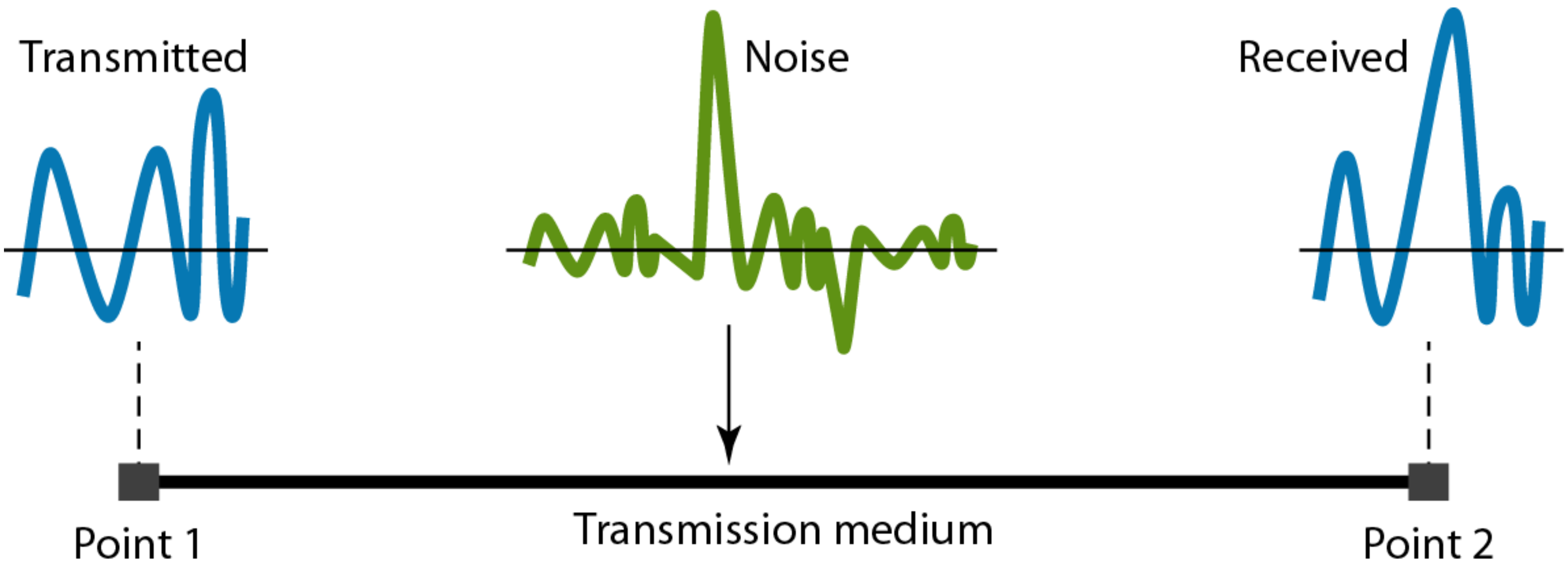
Distortion


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

Noise

Noise is another cause of impairment. Several types of noise, such as thermal noise, induced noise, crosstalk may corrupt the signal.

Noise


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Signal-to-Noise Ratio (SNR)

The signal-to-noise ratio is defined as

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

Because SNR is the ratio of two powers, it is often described in decibel units, SNRdB, defined as

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

The values of SNR and SNRdB for a noiseless channel are

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 SNRdB can be calculated as follows:

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

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

Example

The values of SNR and SNRdB 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.

Lecture 25: Outline

Chapter 3: Data and Signals

- 3.1 Analog and Digital
- 3.2 Analog-to-Analog Conversion
- 3.3 Digital Signals
- 3.4 Transmission Impairment
- 3.5 Data-rate Limits
- 3.6 Performance

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)

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

Nyquist Theorem

For noiseless channel,

$$BitRate = 2 \times Bandwith \times \log_2 Levels$$

it can be applied to baseband transmission and modulation.

Also, it can be applied when we have two or more levels of signals.

Examples

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. What is the maximum bit rate?

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

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). What is the maximum bit rate?

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

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

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

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

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.

Shannon Capacity

In reality, we can not have a noisless channel

For noisy channel,

Capacity = Bandwith x $\log_2(1+SNR)$

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

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. What is the channel capacity?

Solution

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

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.

Example

Let's 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.

What is the channel capacity?

Solution

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

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

For practical purposes, when the SNR is very high, we can assume that SNR + 1 is almost the same as SNR.
 In these cases, the theoretical channel capacity can be simplifiedto

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

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

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

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.

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

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.

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

Example

What are the propagation time and the transmission time for a 2.5-kbyte message if the bandwidth of the network is 1 Gbps? Assume that the distance is 12,000 km and that light travels at 2.4 × 108 m/s.

Solution

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

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

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 if the bandwidth of the network is 1 Mbps? Assume that the distance is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

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

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

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.