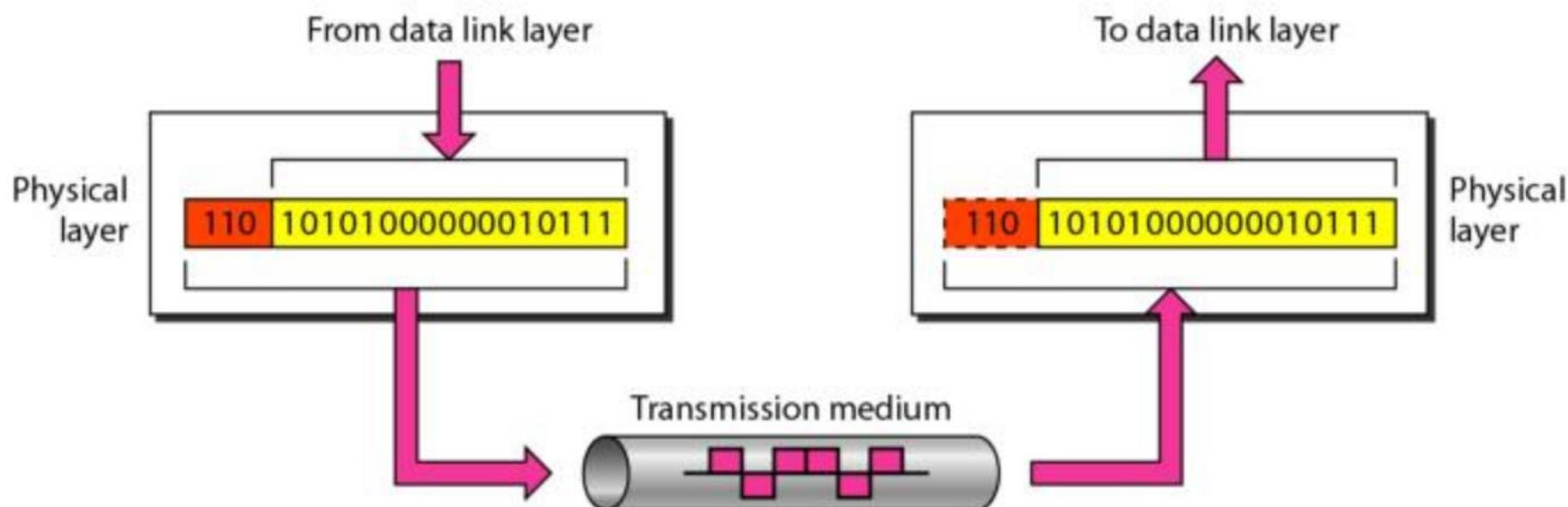


Physical layer



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

3-1 ANALOG AND DIGITAL

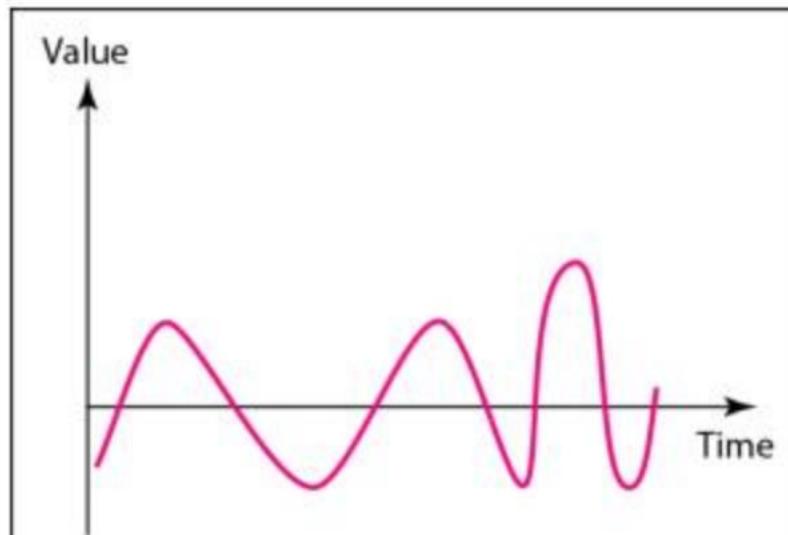
Data can be *analog* or *digital*

- 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

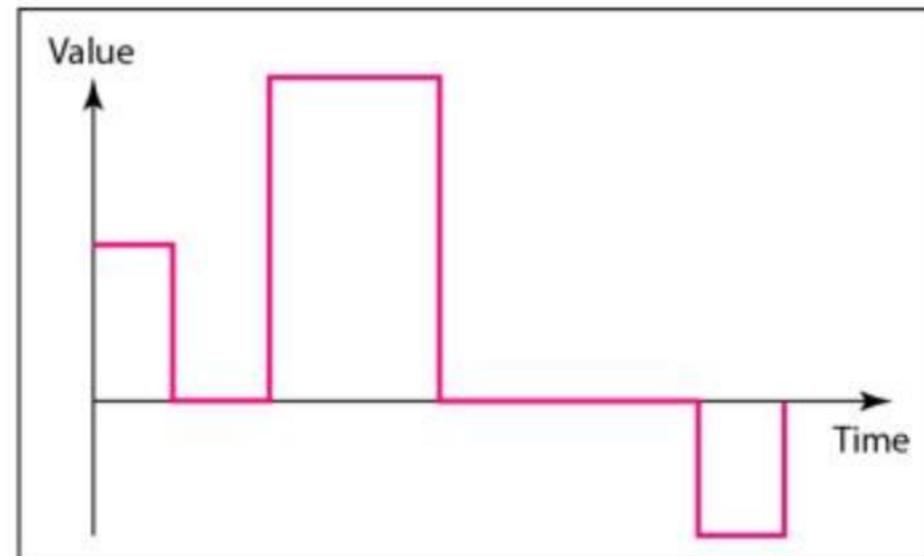
- Digital data refers to information that has discrete states
- Digital data take on discrete values
- Digital signals can have only a limited number of values

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

Comparison of analog and digital signals



a. Analog signal

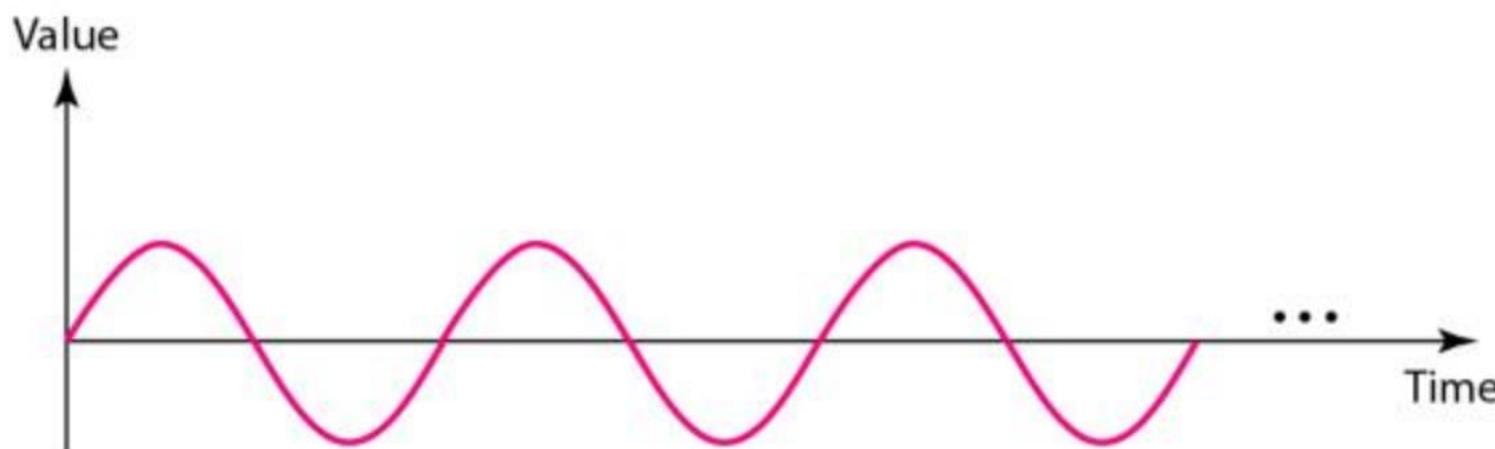


b. Digital signal

3-2 PERIODIC ANALOG SIGNALS

*Periodic analog signals can be classified as **simple** or **composite**.*

- A simple periodic analog signal, a **sine wave**, cannot be decomposed into simpler signals.
- A composite periodic analog signal is composed of multiple sine waves.

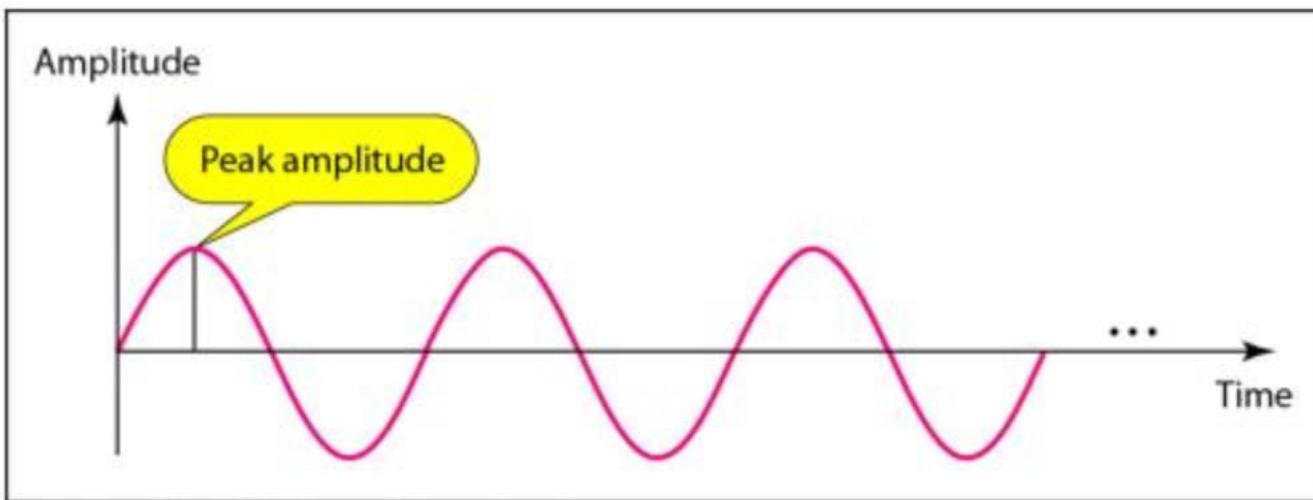


Fundamentals of Signals

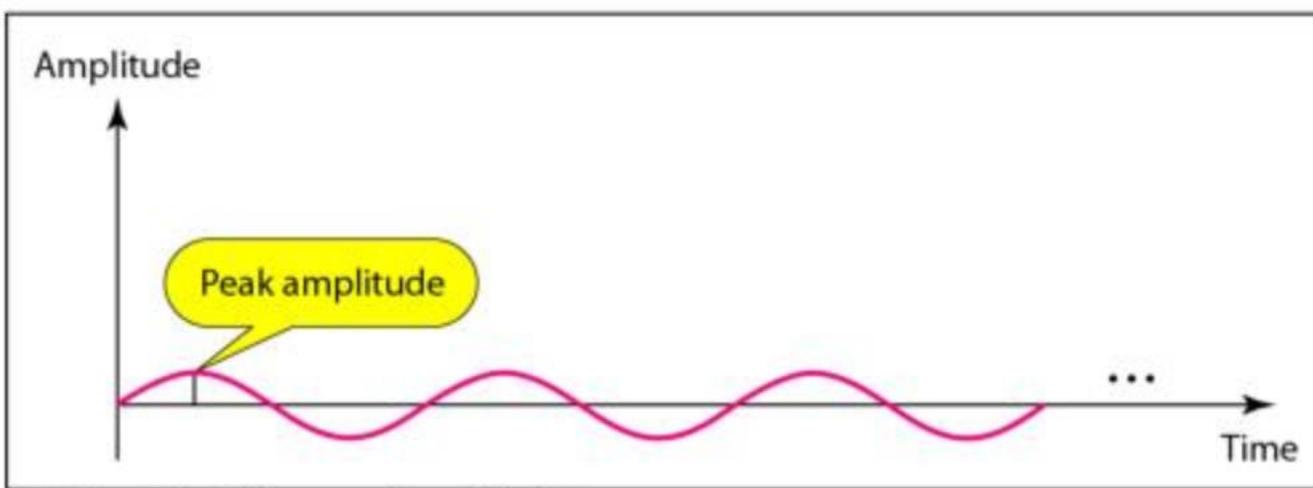
- All signals have three components:
 - Amplitude
 - Frequency
 - Phase

- Amplitude
 - The height of the wave above or below a given reference point
 - Amplitude is usually measured in volts

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

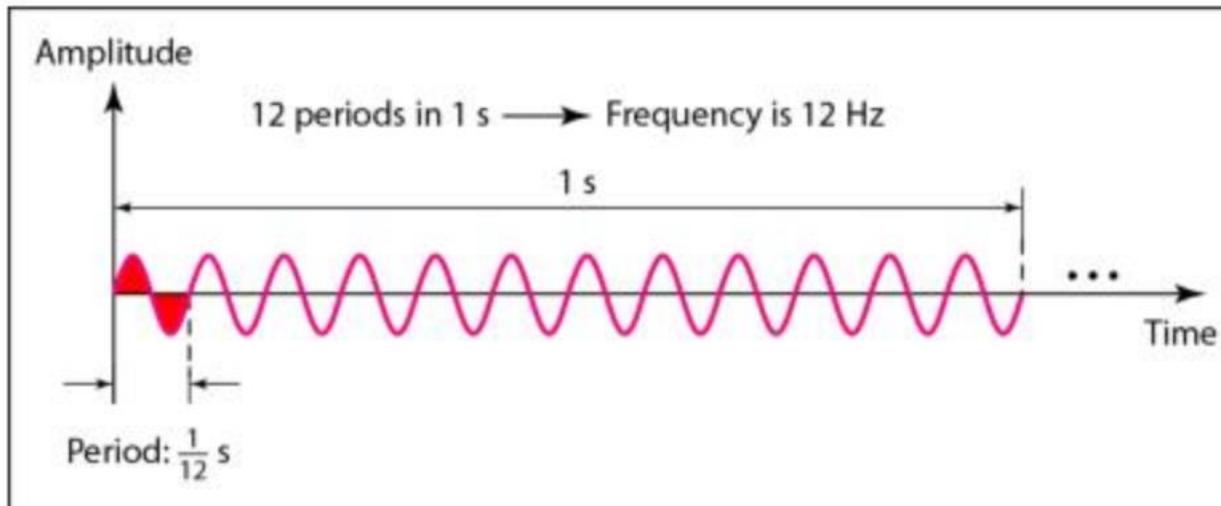
Frequency and period are the inverse of each other.

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

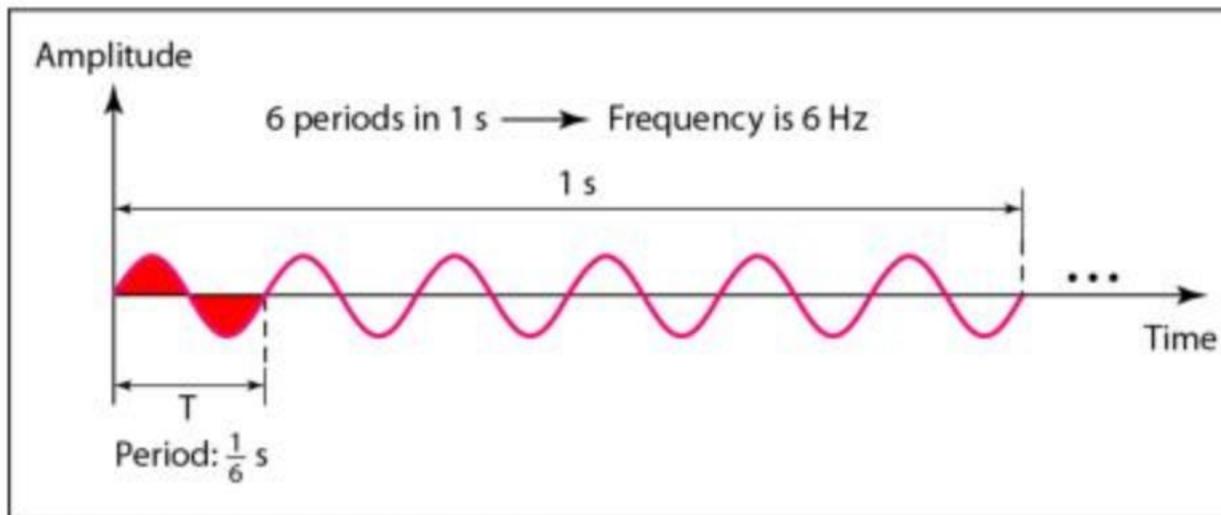
Units of period and frequency

<i>Unit</i>	<i>Equivalent</i>	<i>Unit</i>	<i>Equivalent</i>
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^3 Hz
Microseconds (μ s)	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?

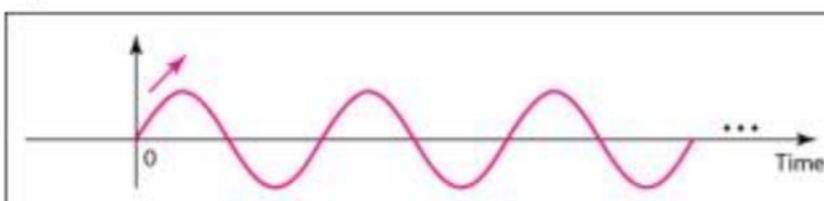
$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 10^{-1} \text{ s}$$

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

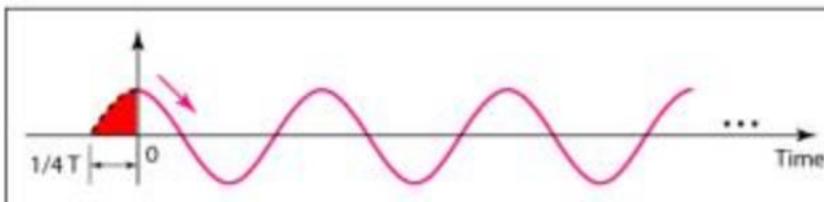
Phase

Phase describes the position of the waveform relative to time 0

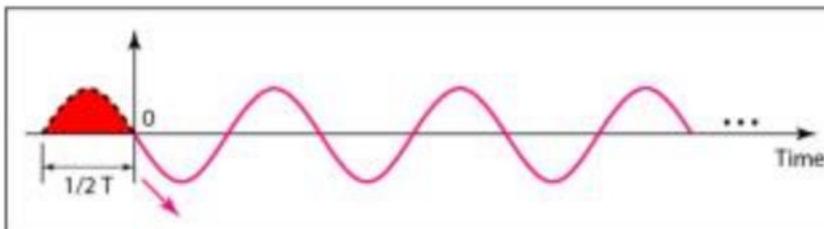
Three sine waves with the same amplitude and frequency, but different phases



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° .

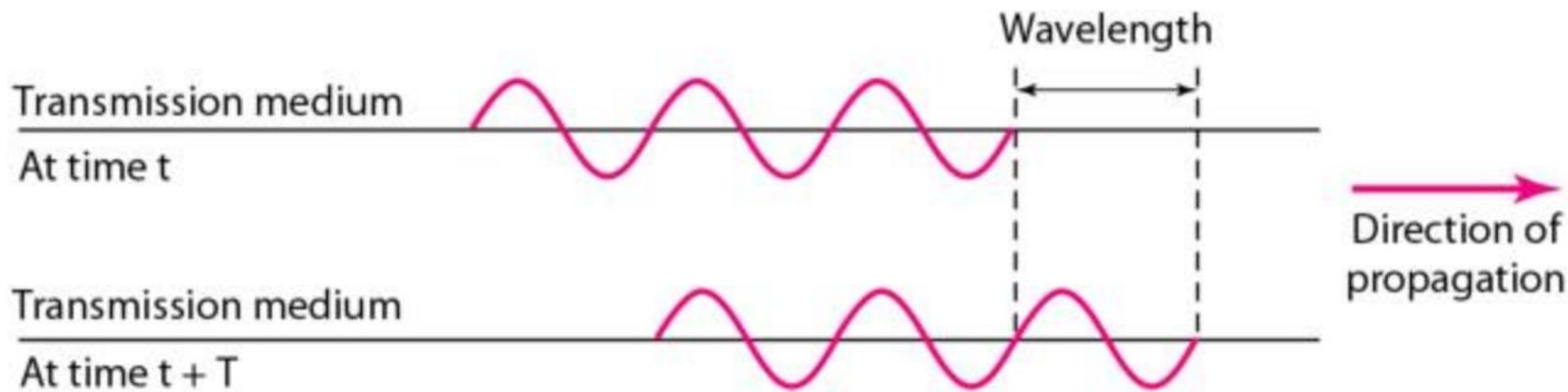
Therefore, 1/6 cycle is

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

Angle in degree	Angle in radian
0°	0
30°	$\pi/6$
45°	$\pi/4$
60°	$\pi/3$
90°	$\pi/2$
180°	π
270°	$(3\pi)/2$
360°	2π

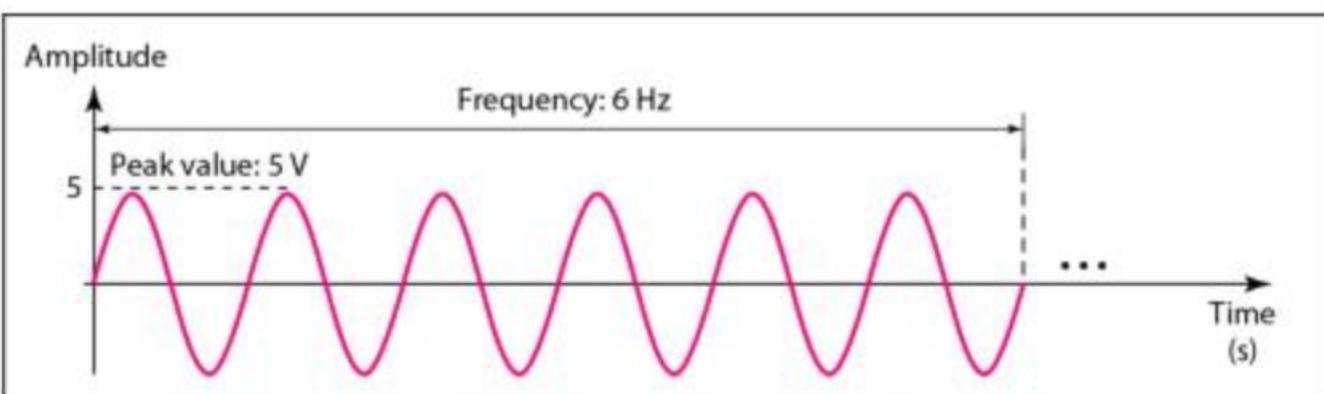
Wavelength and period

$$\begin{aligned}\text{Wavelength} &= \text{Propagation speed} \times \text{Period} \\ &= \text{Propagation speed} / \text{Frequency}\end{aligned}$$

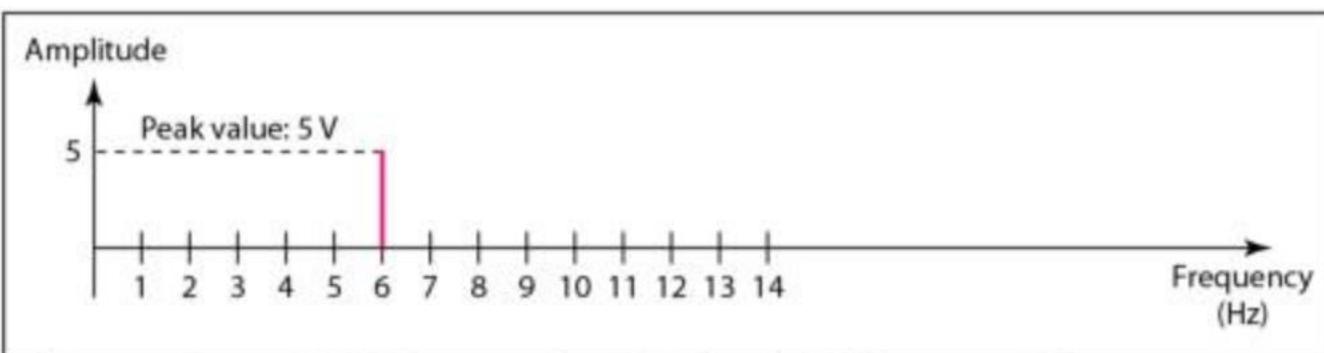


Time-domain and frequency-domain plots of a sine wave

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

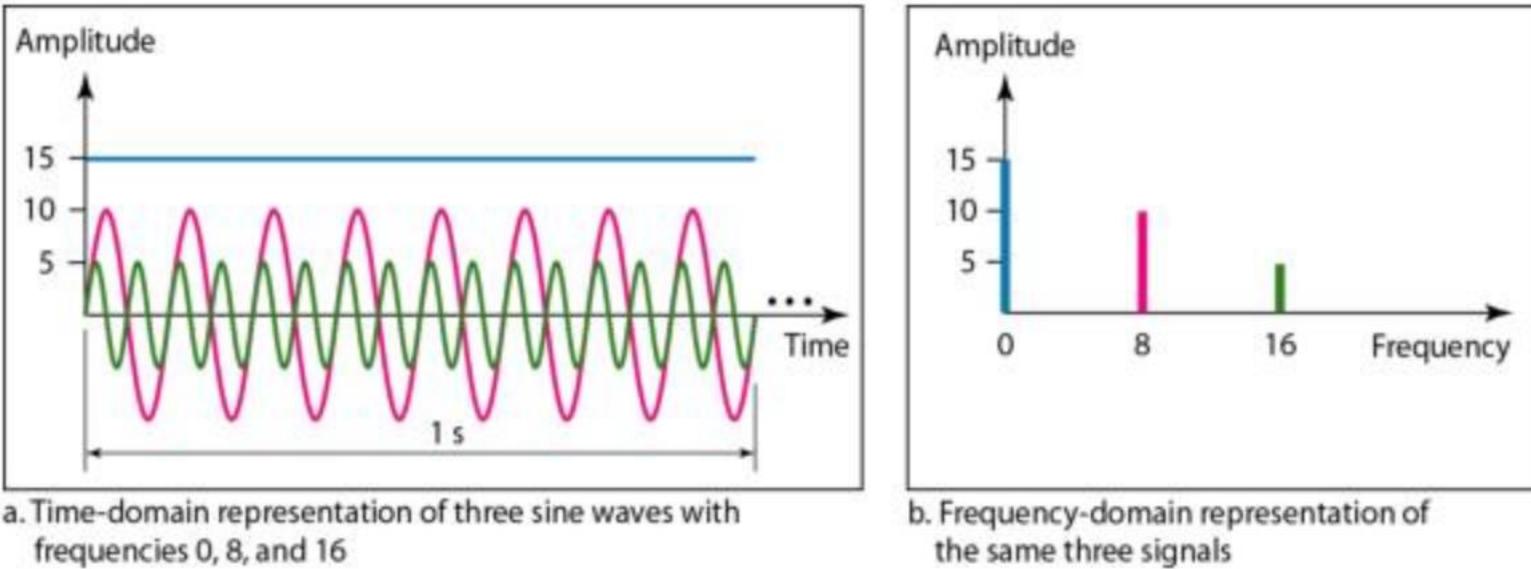


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)



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

Frequency Domain



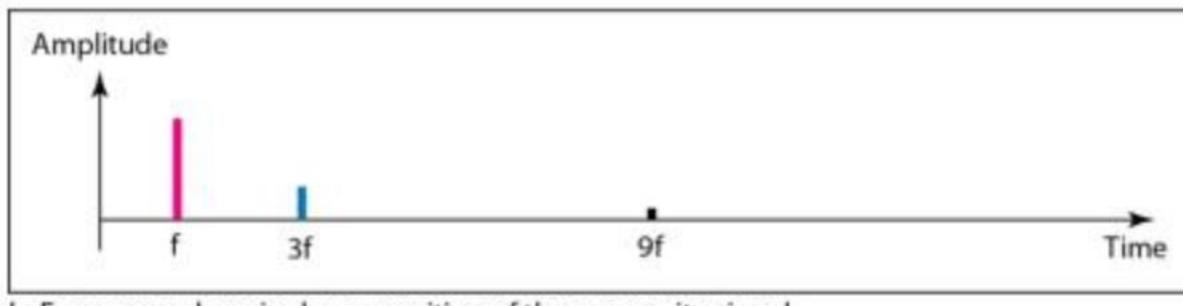
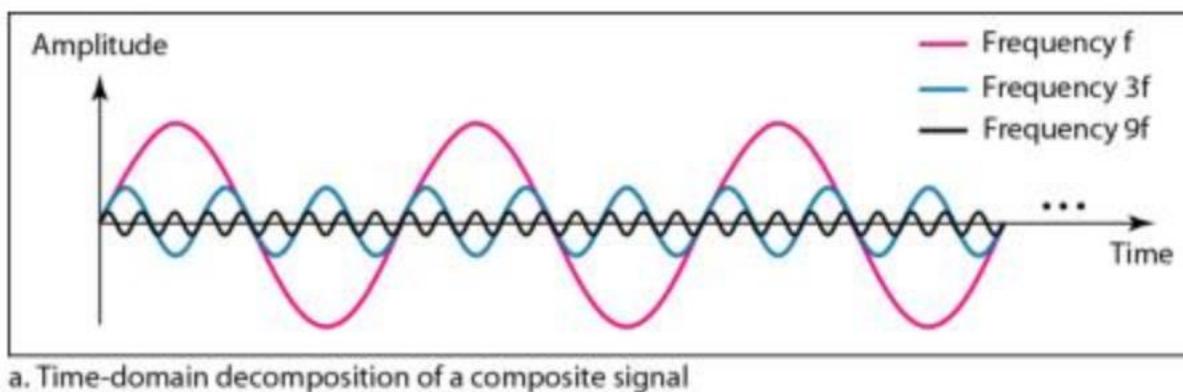
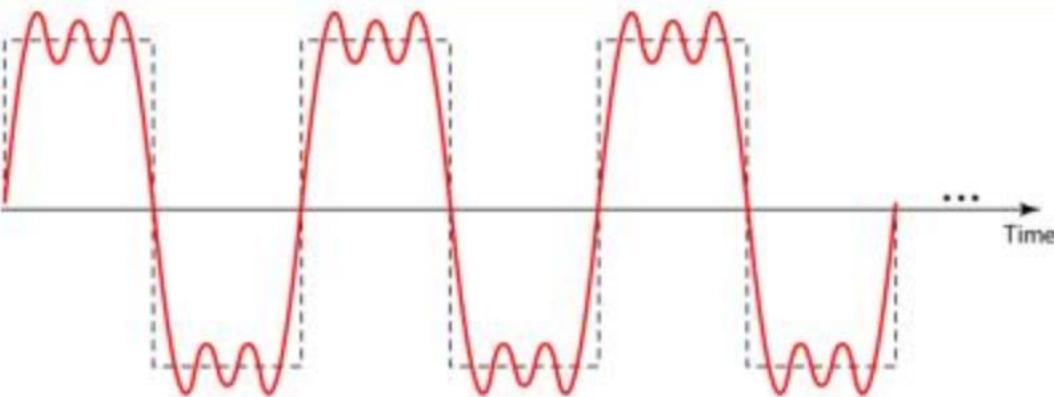
- The frequency domain is more compact and useful when we are dealing with more than one sine wave.
- A single-frequency sine wave is not useful in data communication
 - We need to send a **composite signal**, a signal made of many simple sine waves.

Fourier analysis

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*.

A composite periodic signal

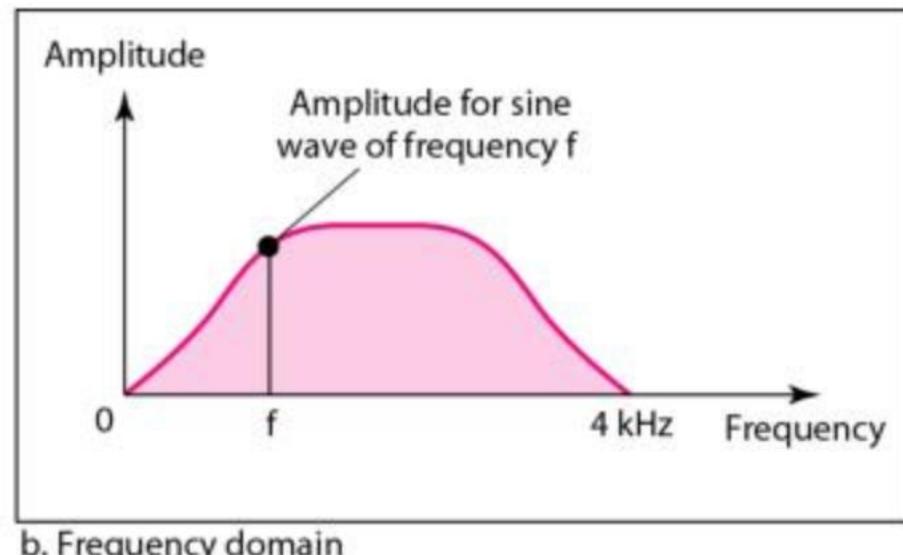
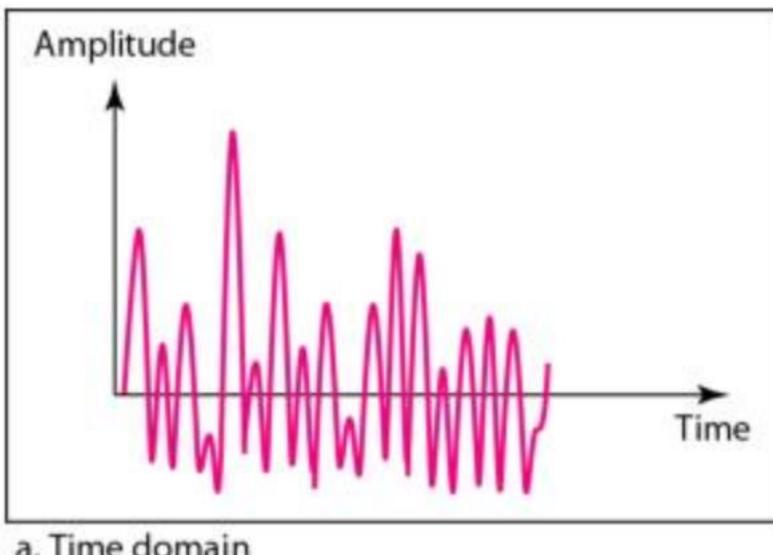


Decomposition of the composite periodic signal in the time and frequency domains

Time and frequency domains of a nonperiodic signal

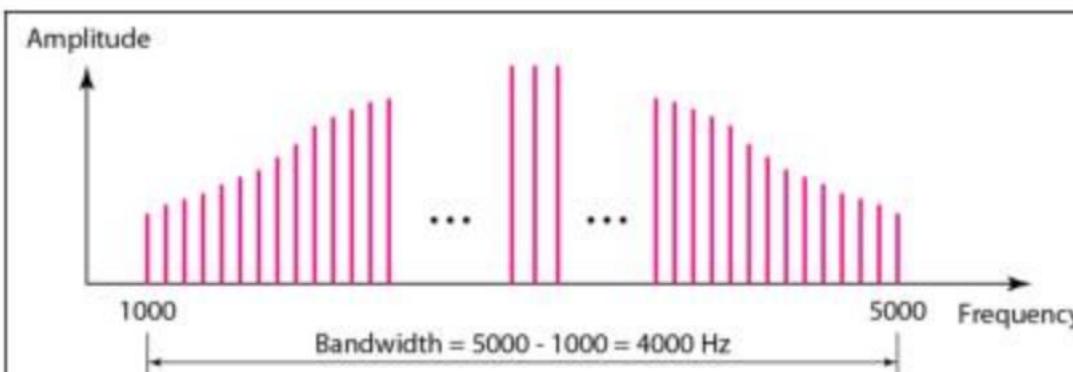
□ A nonperiodic composite signal

- It can be a signal created by a microphone or a telephone set when a word or two is pronounced.
- In this case, the composite signal cannot be periodic
➤ because that implies that we are repeating the same word or words with exactly the same tone.

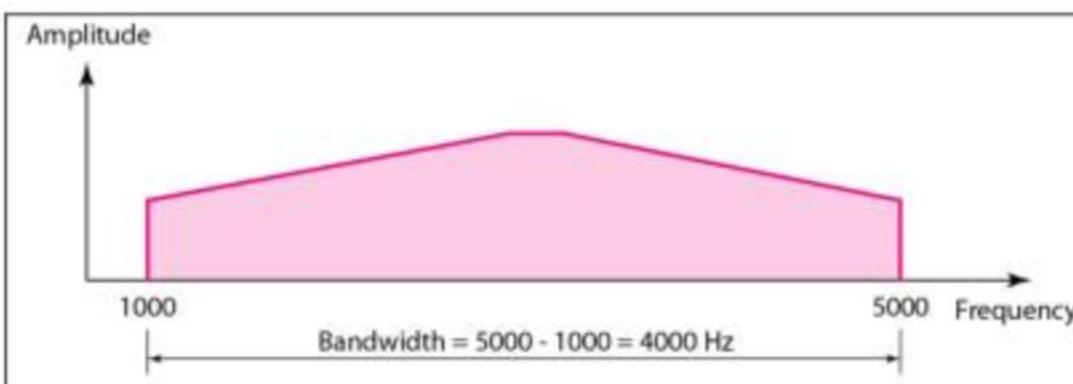


Bandwidth

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



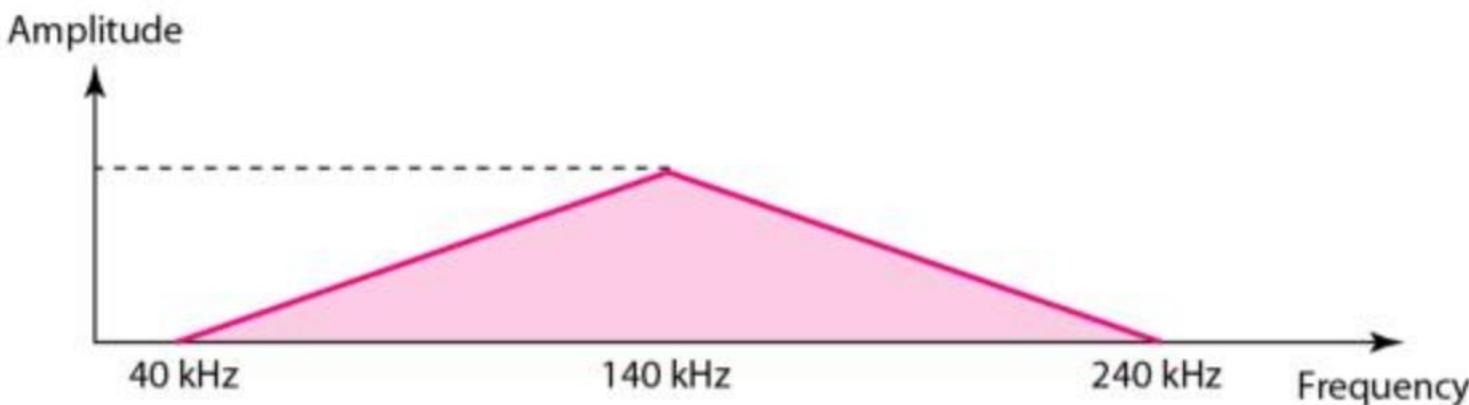
b. Bandwidth of a nonperiodic signal

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. Approximately, draw the frequency domain of the signal.

Solution

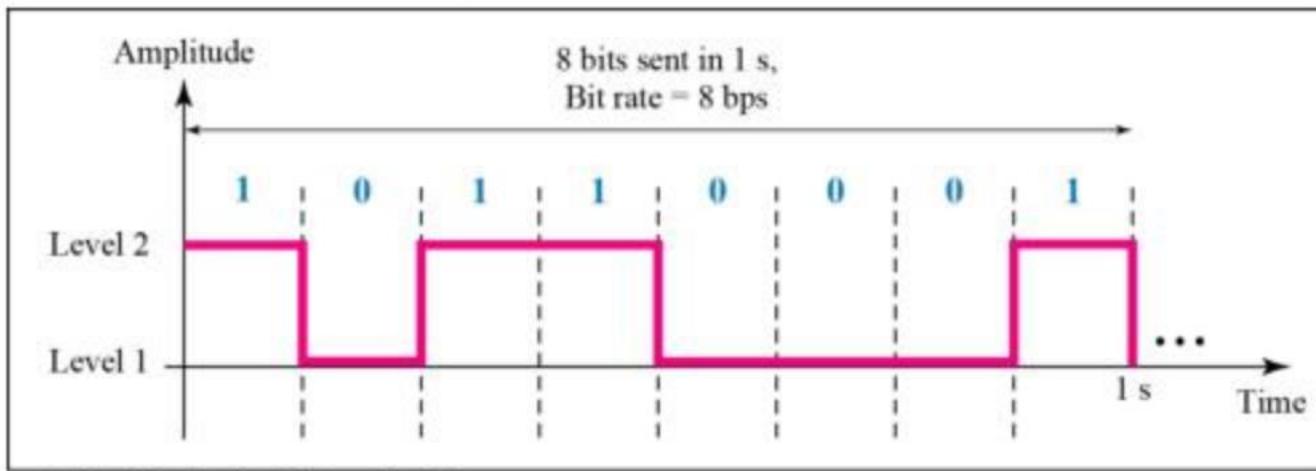
The lowest frequency must be at 40 kHz and the highest at 240 kHz.



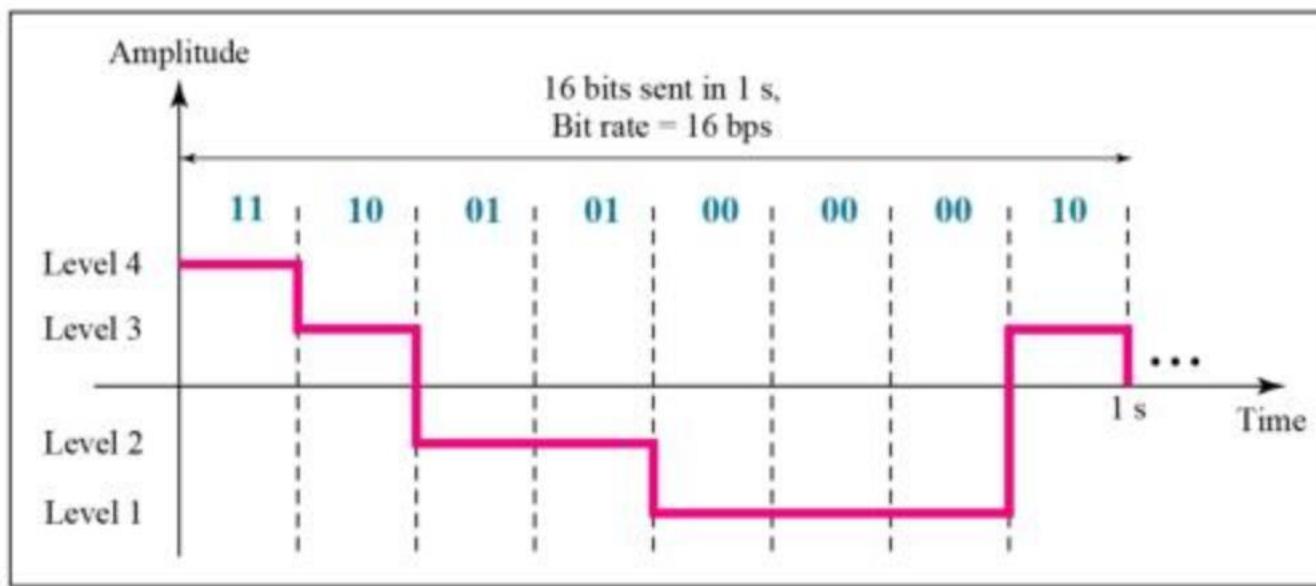
3-3 DIGITAL SIGNALS

- 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 represented by each level?

We calculate the number of bits from the formula

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

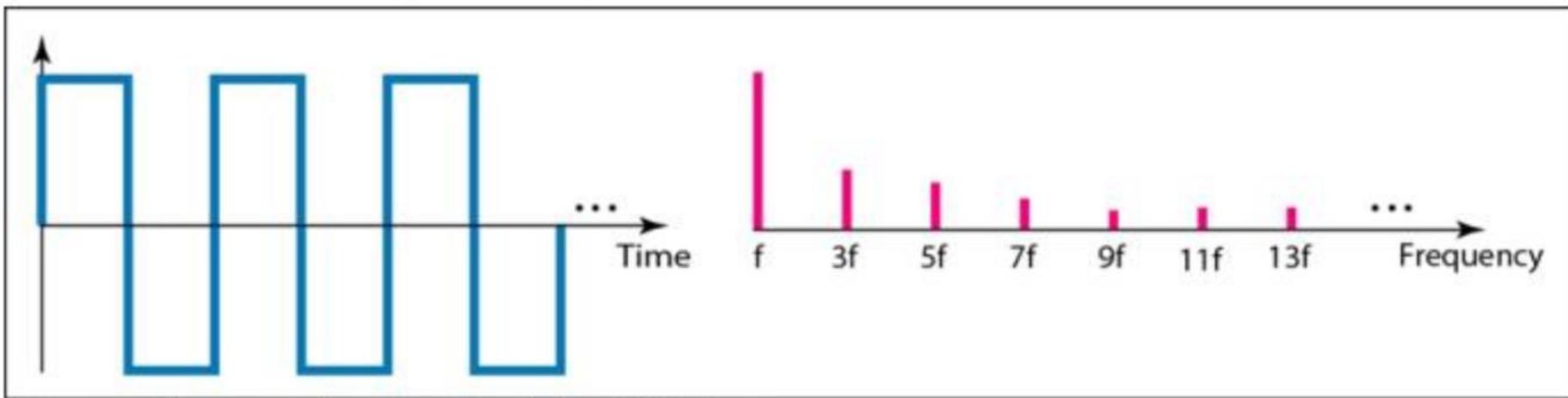
Each signal level is represented by 3 bits.

A digital signal has 9 levels. How many bits are represented by each level?

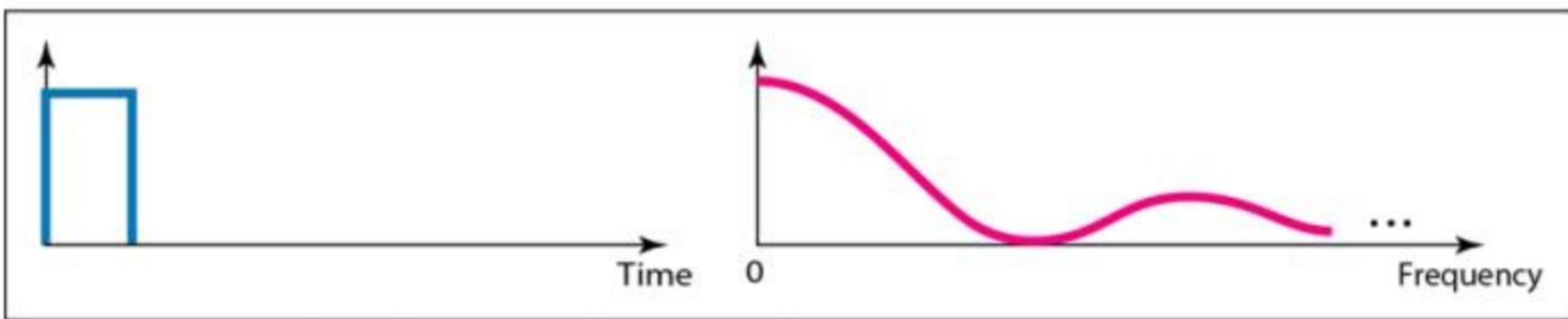
Each signal level is represented by 3.17 bits. Not realistic.
The number of bits sent per level needs to be an integer
as well as a power of 2.

Hence, 4 bits can represent one level.

The time and frequency domains of periodic and nonperiodic digital signals



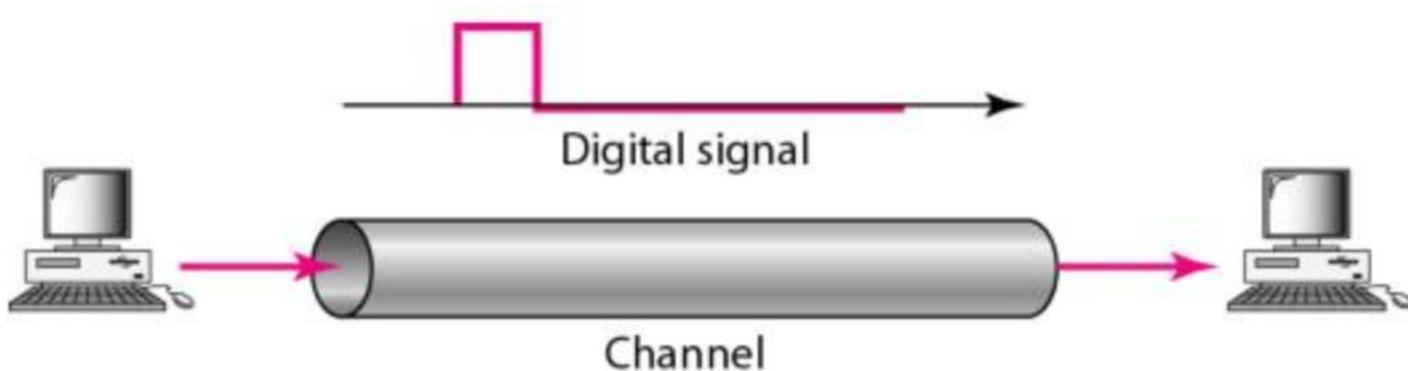
a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

Baseband transmission

Sending a digital signal over a channel without changing the digital signal to an analog signal.



A digital signal is a composite analog signal with an infinite bandwidth.

Bandwidths of two low-pass channels

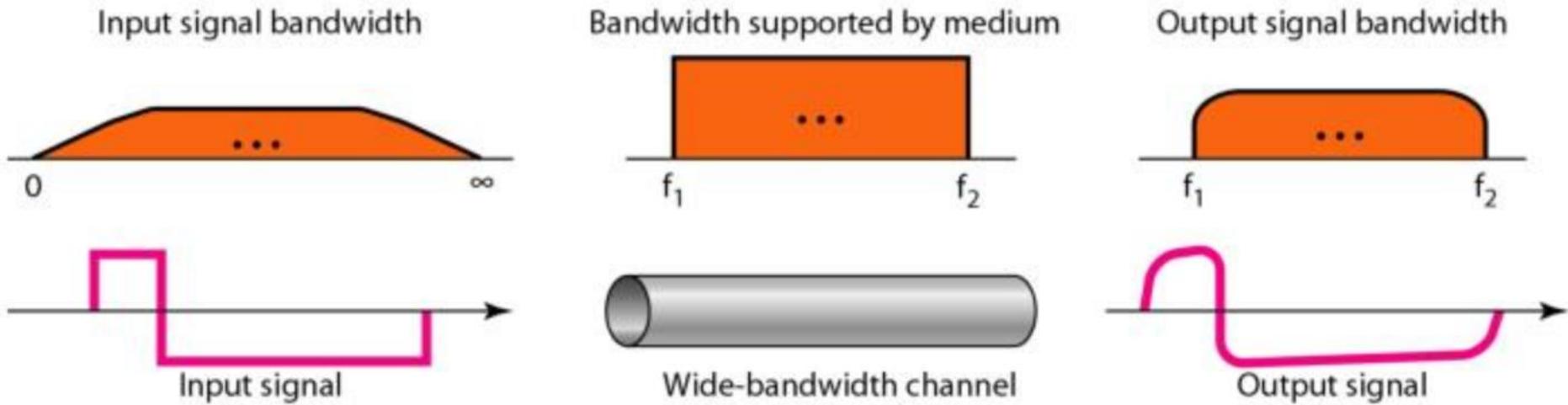


a. Low-pass channel, wide bandwidth



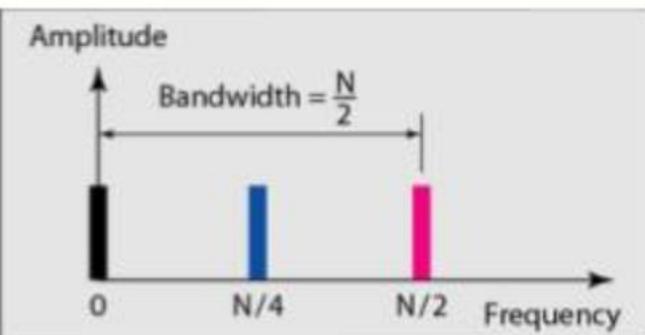
b. Low-pass channel, narrow bandwidth

Baseband transmission using a dedicated medium



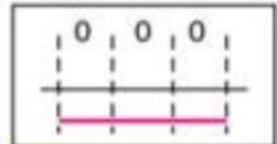
Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.

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



where N is the bitrate

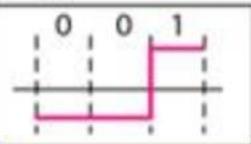
Digital: bit rate N



Analog: $f = 0, p = 180$



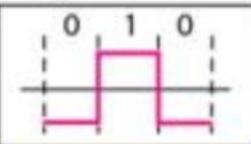
Digital: bit rate N



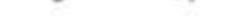
Analog: $f = N/4, p = 180$



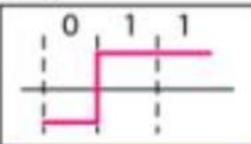
Digital: bit rate N



Analog: $f = N/2, p = 180$



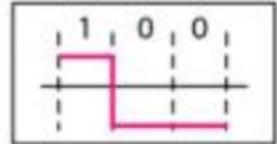
Digital: bit rate N



Analog: $f = N/4, p = 270$



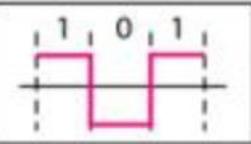
Digital: bit rate N



Analog: $f = N/4, p = 90$



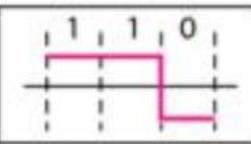
Digital: bit rate N



Analog: $f = N/2, p = 0$



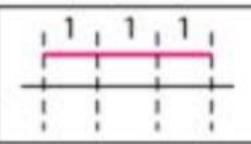
Digital: bit rate N



Analog: $f = N/4, p = 0$



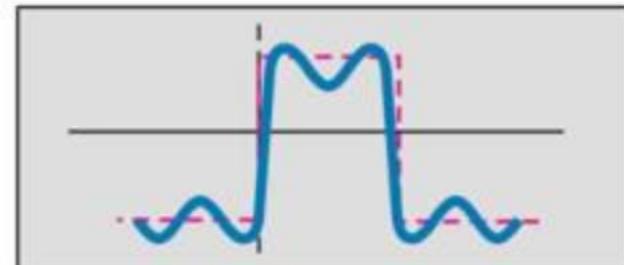
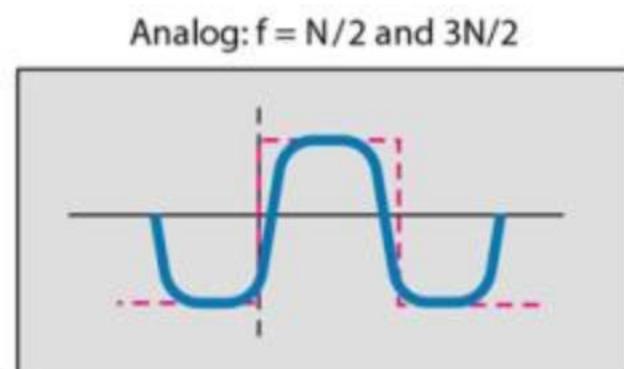
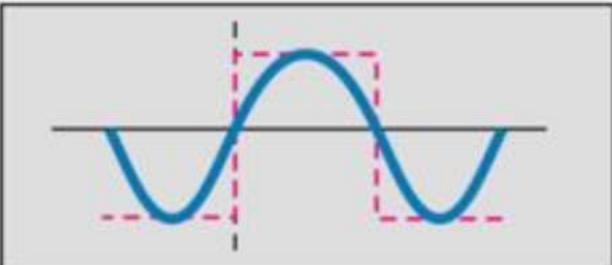
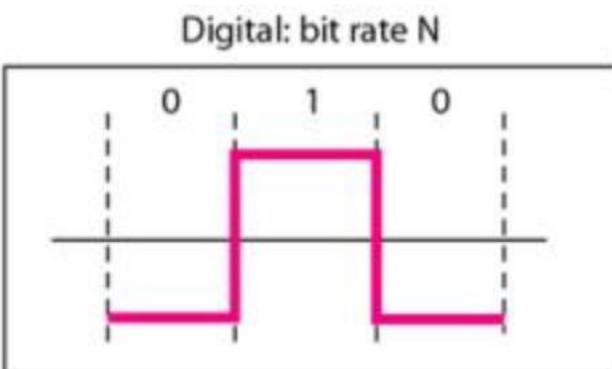
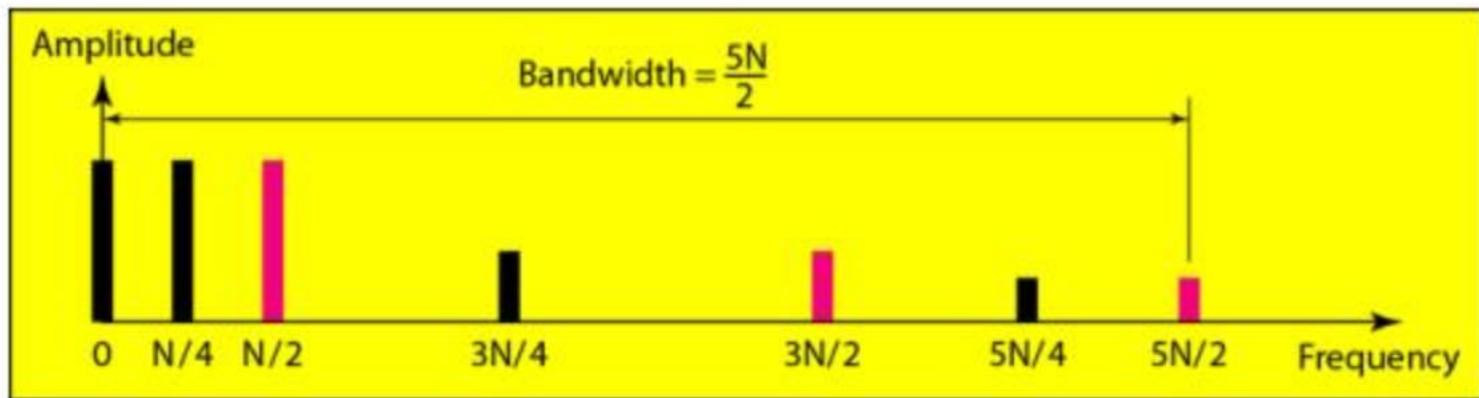
Digital: bit rate N



Analog: $f = 0, p = 0$



Simulating a digital signal with first three harmonics



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

Bandwidth requirements

<i>Bit Rate</i>	<i>Harmonic 1</i>	<i>Harmonics 1, 3</i>	<i>Harmonics 1, 3, 5</i>
$n = 1 \text{ kbps}$	$B = 500 \text{ Hz}$	$B = 1.5 \text{ kHz}$	$B = 2.5 \text{ kHz}$
$n = 10 \text{ kbps}$	$B = 5 \text{ kHz}$	$B = 15 \text{ kHz}$	$B = 25 \text{ kHz}$
$n = 100 \text{ kbps}$	$B = 50 \text{ kHz}$	$B = 150 \text{ kHz}$	$B = 250 \text{ kHz}$

Example

What is the required bandwidth of a low-pass channel if we need to send 1 Mbps by using baseband transmission?

Solution

The answer depends on the accuracy desired.

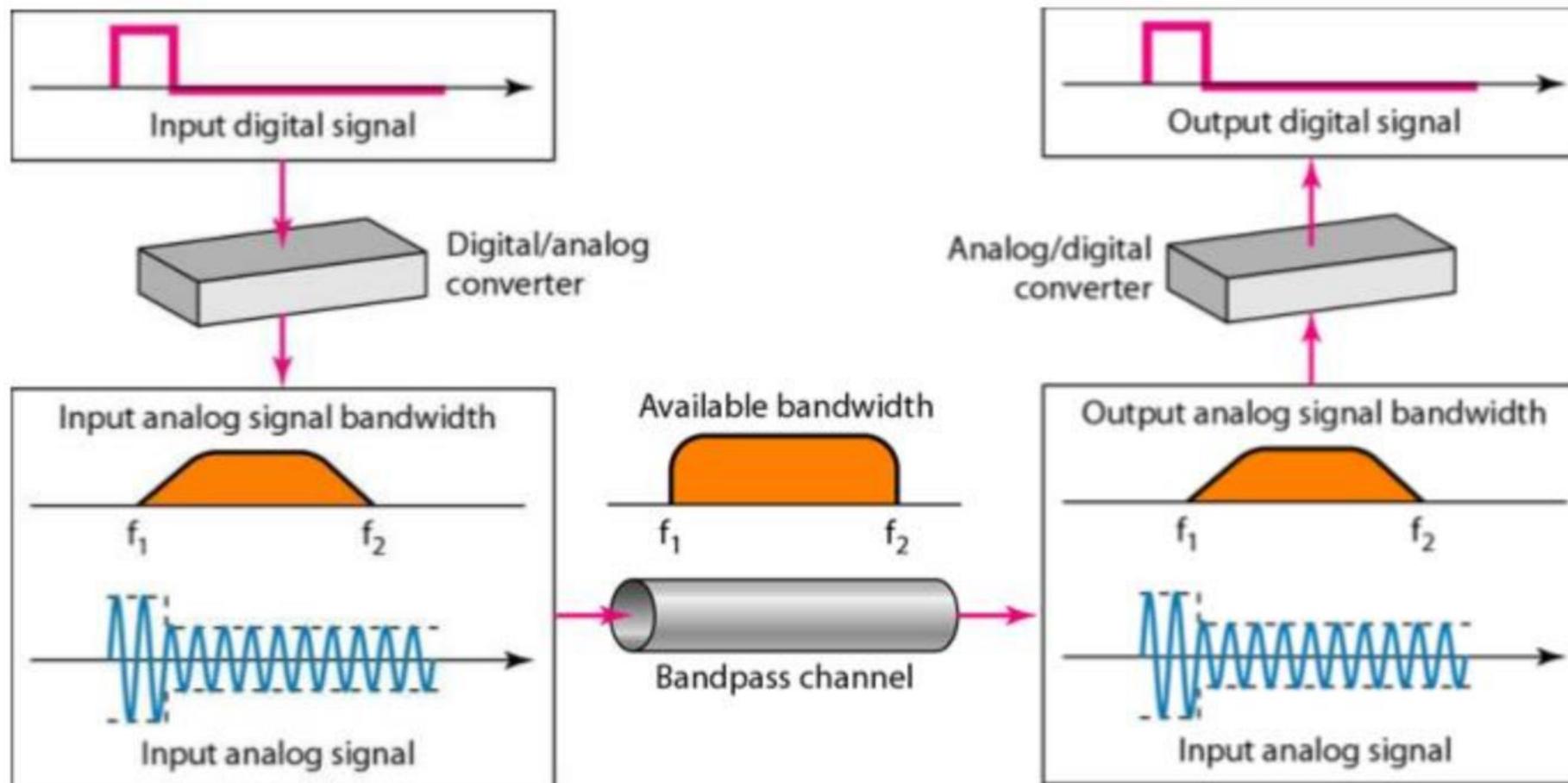
- a. The minimum bandwidth is $B = \text{bit rate} / 2$, or 500 kHz.
- b. A better solution is to use the first and the third harmonics with $B = 3N/2 = 3 \times 500 \text{ kHz} = 1.5 \text{ MHz}$.
- c. Still a better solution is to use the first, third, and fifth harmonics with $B = 5N/2 = 5 \times 500 \text{ kHz} = 2.5 \text{ MHz}$.

Bandwidth of a bandpass channel



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.

Modulation of a digital signal for transmission on a bandpass channel



Example

An example of broadband transmission using modulation is the sending of computer data through a telephone subscriber line, the line connecting a resident to the central telephone office.

These lines are designed to carry voice with a limited bandwidth.

The channel is considered a bandpass channel.

We convert the digital signal from the computer to an analog signal, and send the analog signal.

We can install two converters to change the digital signal to analog and vice versa at the receiving end.

The converter, in this case, is called a **modem**.

Example

A second example is the digital cellular telephone.

For better reception, digital cellular phones convert the analog voice signal to a digital signal.

Although the bandwidth allocated to a company providing digital cellular phone service is very wide, we still cannot send the digital signal without conversion.

The reason is that we only have a bandpass channel available between caller and callee.

We need to convert the digitized voice to a composite analog signal before sending.

Examples

Assume we need to download files at a rate of 100 pages per second. 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.

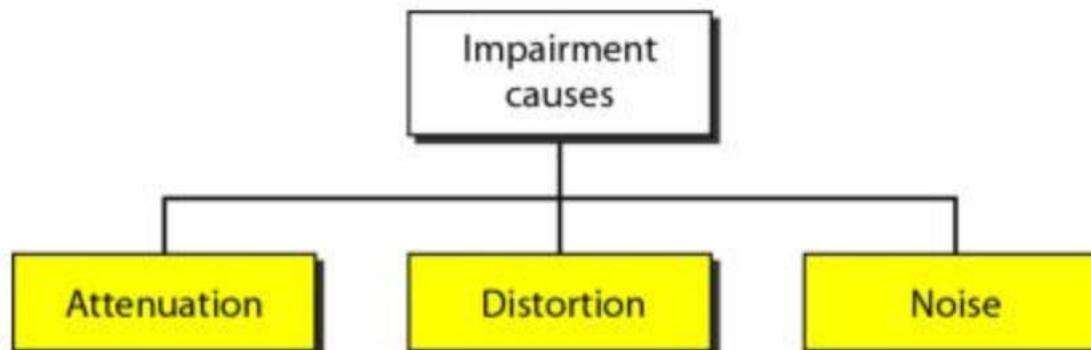
What is the bit rate for high-definition TV (HDTV)?

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

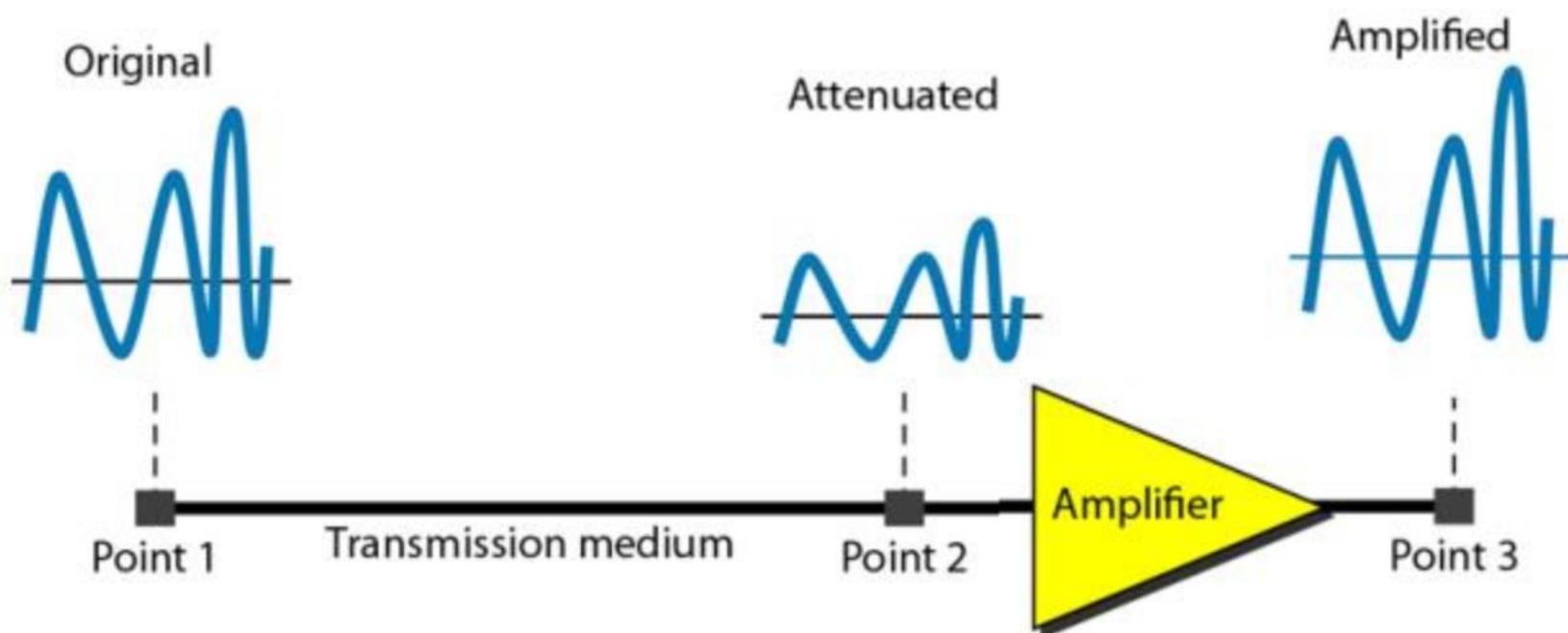
The TV stations reduce this rate to 20 to 40 Mbps through **compression**.

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



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

relative strength of signals

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)?

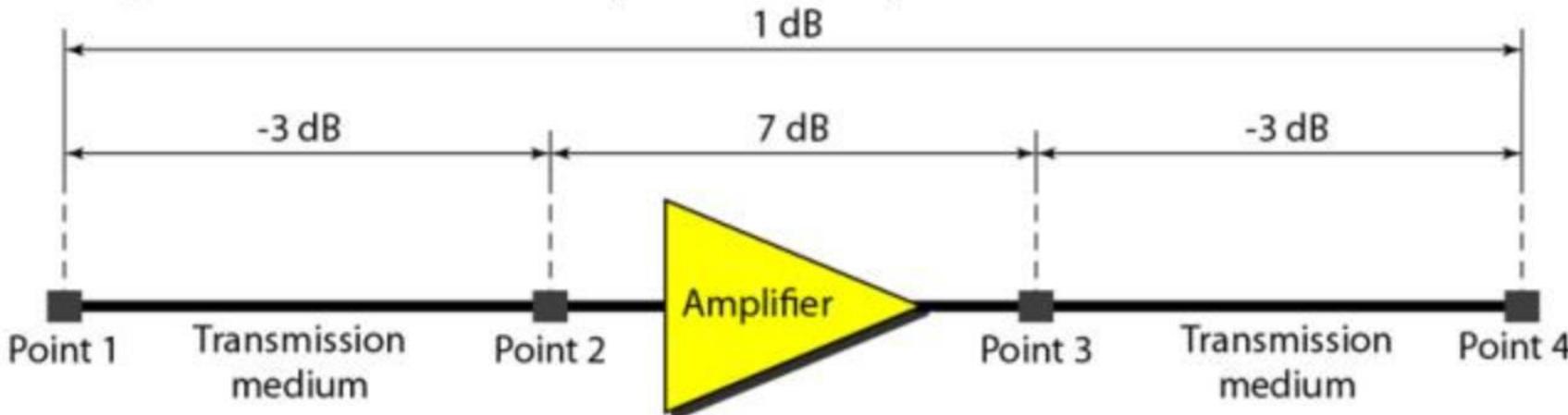
$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1}$$

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

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.

A signal travels from point 1 to point 4.



In this case, the decibel value can be calculated as

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

Example

The loss in a cable is usually defined in decibels per kilometer (dB/km).

If the signal at beginning of a cable with -0.3 dB/km has a power of 2 mW,

what is the power of the signal at 5 km?

Solution

The loss in the cable in decibels is $5 \times (-0.3) = -1.5$ dB.

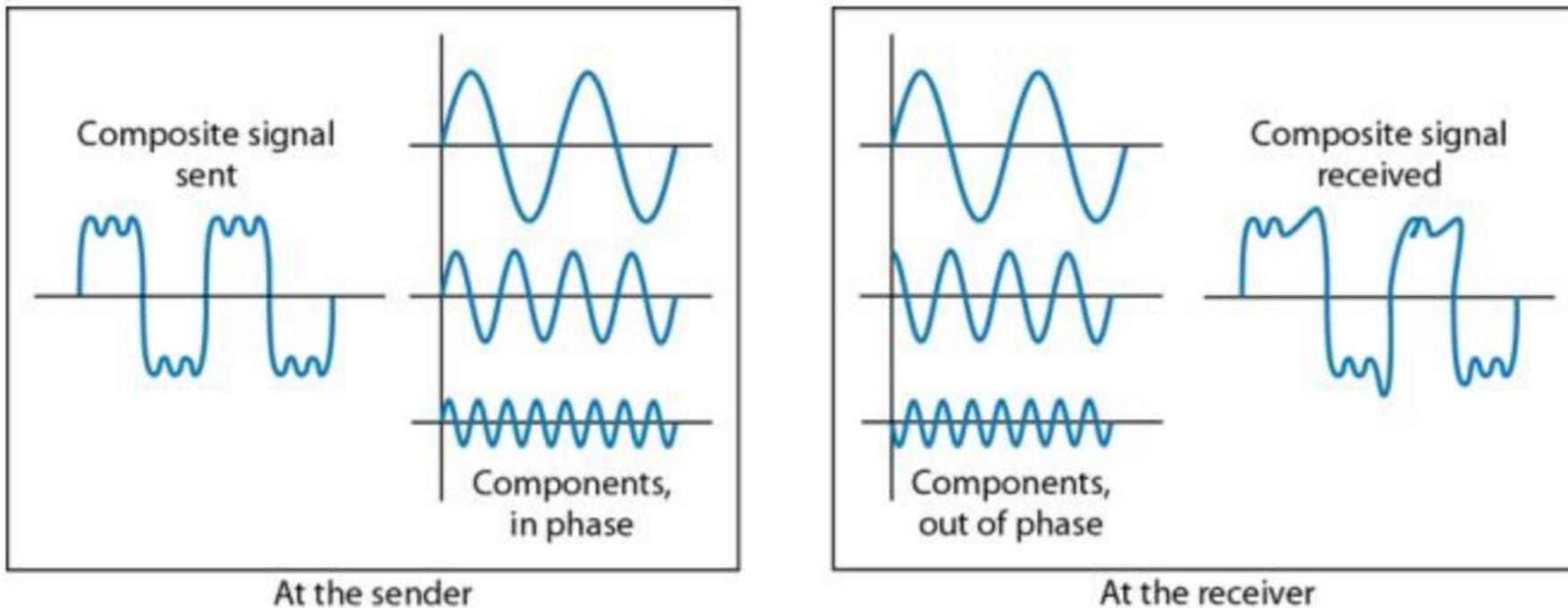
We can calculate the power as

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

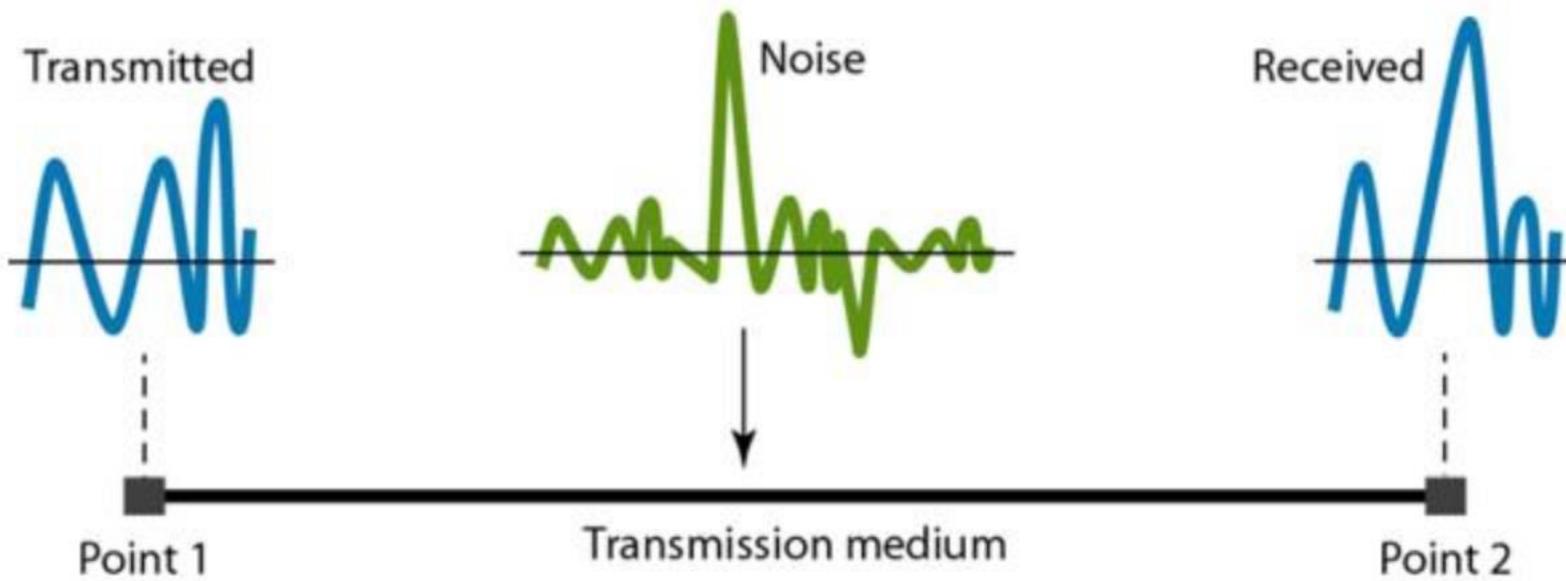
$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$

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

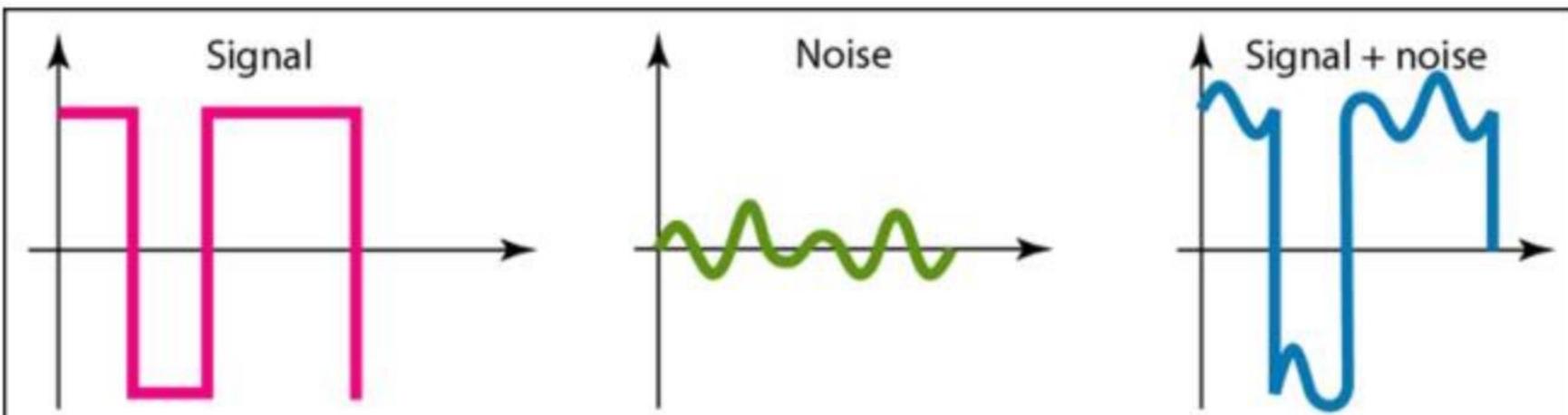
Distortion



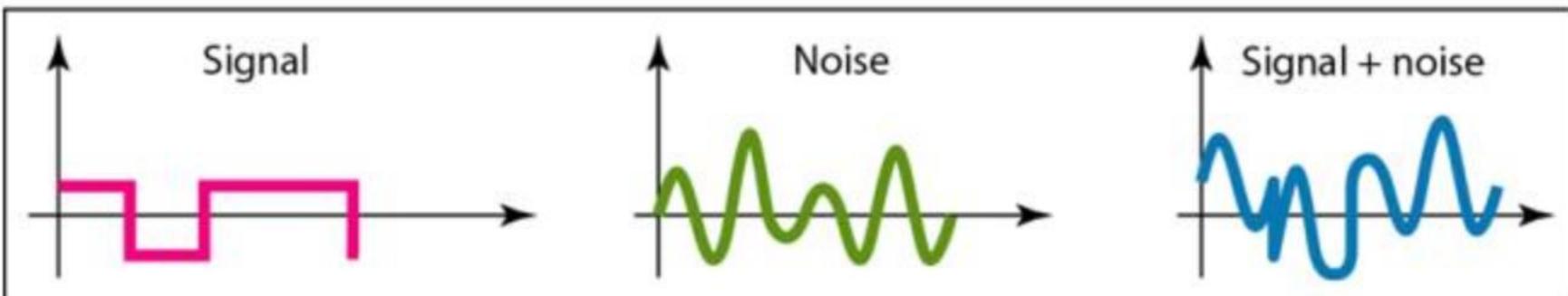
Noise



Signal-to-Noise Ratio (SNR): high vs. low



a. Large SNR



b. Small SNR

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:

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

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

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

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,

$$\text{BitRate} = 2 \times \text{Bandwidth} \times \log_2 \text{Levels}$$

In baseband transmission, we said the bit rate is 2 times the bandwidth if we use only the first harmonic in the worst case.

However, the Nyquist formula is more general than what we derived intuitively;

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

$$265,000 = 2 \times 20,000 \times \log_2 L$$
$$\log_2 L = 6.625 \quad L = 2^{6.625} = 98.7 \text{ levels}$$

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 noiseless channel

For noisy channel,

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

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.

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 Hz.

The signal-to-noise ratio is usually 3162.

What is the channel capacity?

Solution

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

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 $\text{SNR}_{\text{dB}} = 36$ and
the channel bandwidth is 2 MHz.

What is the theoretical channel capacity?

Solution

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

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

Example

For practical purposes, when the SNR is very high, we can assume that $\text{SNR} + 1$ is almost the same as SNR . In these cases, the theoretical channel capacity can be simplified to

$$C = B \times \frac{\text{SNR}_{\text{dB}}}{3}$$

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.

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

3-6 PERFORMANCE

One important issue in networking is the **performance** of the network
— how good is it?

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.

Examples

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.

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

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

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

Example

What is the propagation time if the distance between 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.

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 2.4×10^8 m/s.

Solution

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

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

Note that in this case, the dominant factor is the propagation time, not the transmission time.

because the message is short and the bandwidth is high

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

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

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

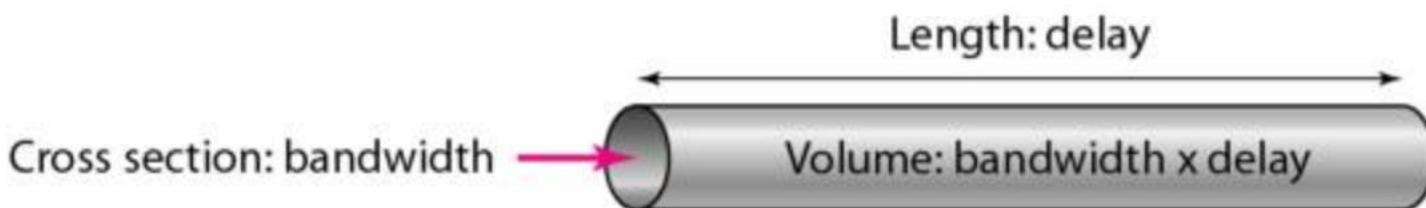
Note that in this case, the dominant factor is the transmission time, not the propagation time.

because the message is very long and the bandwidth is not very high

The propagation time can be ignored.

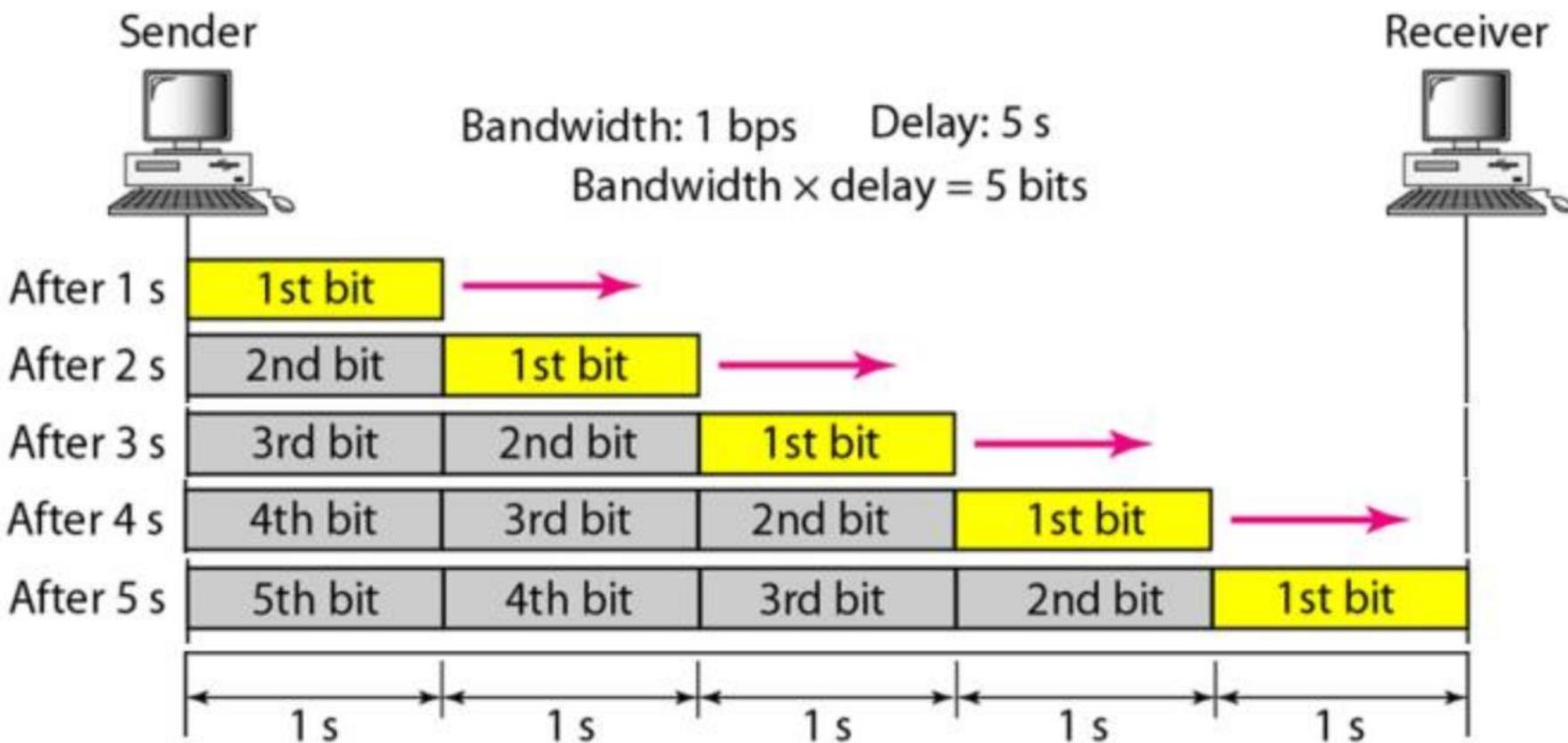
Concept of bandwidth-delay product

The bandwidth-delay product defines the number of bits that can fill the link.

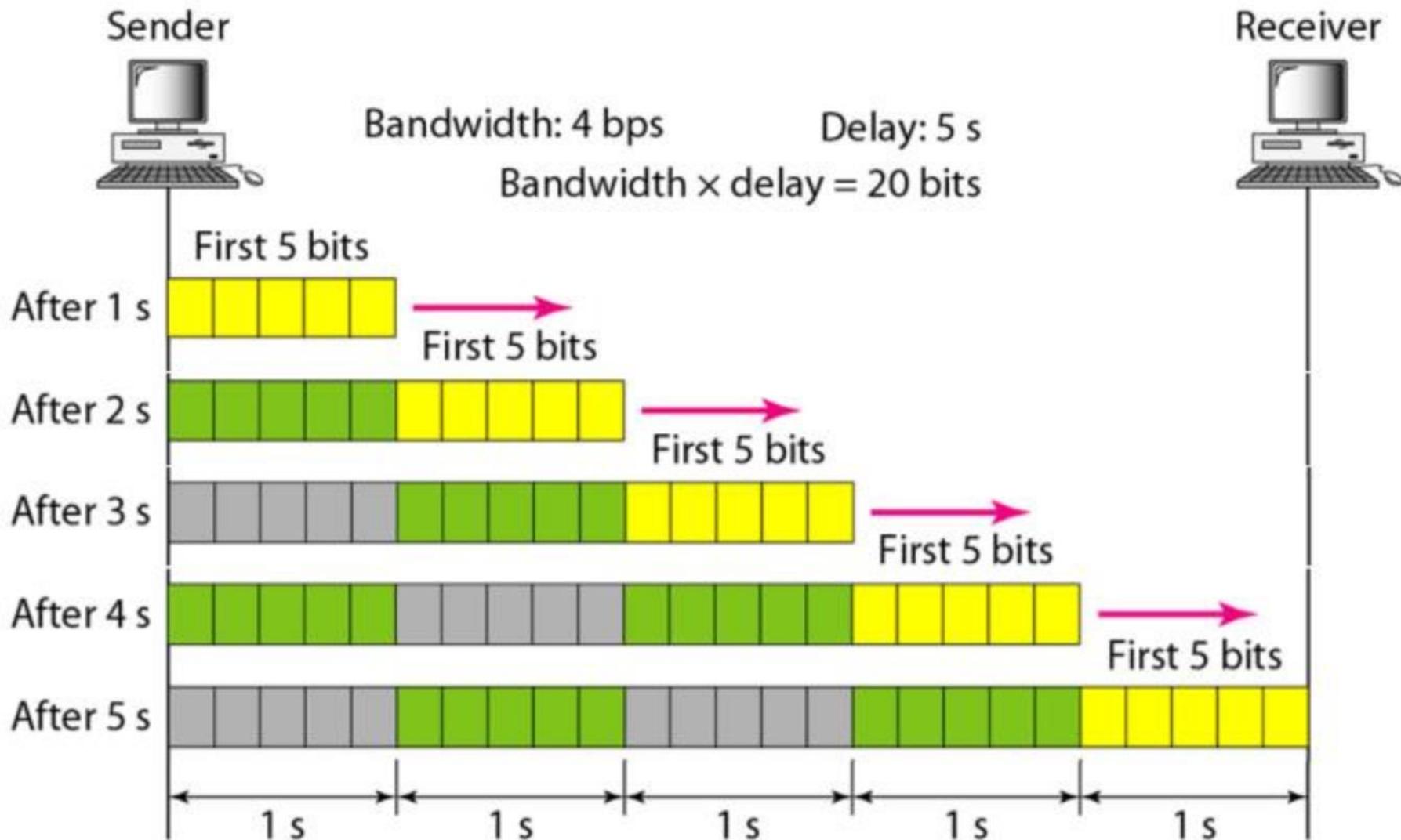


We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product.

Filling the link with bits in case 1



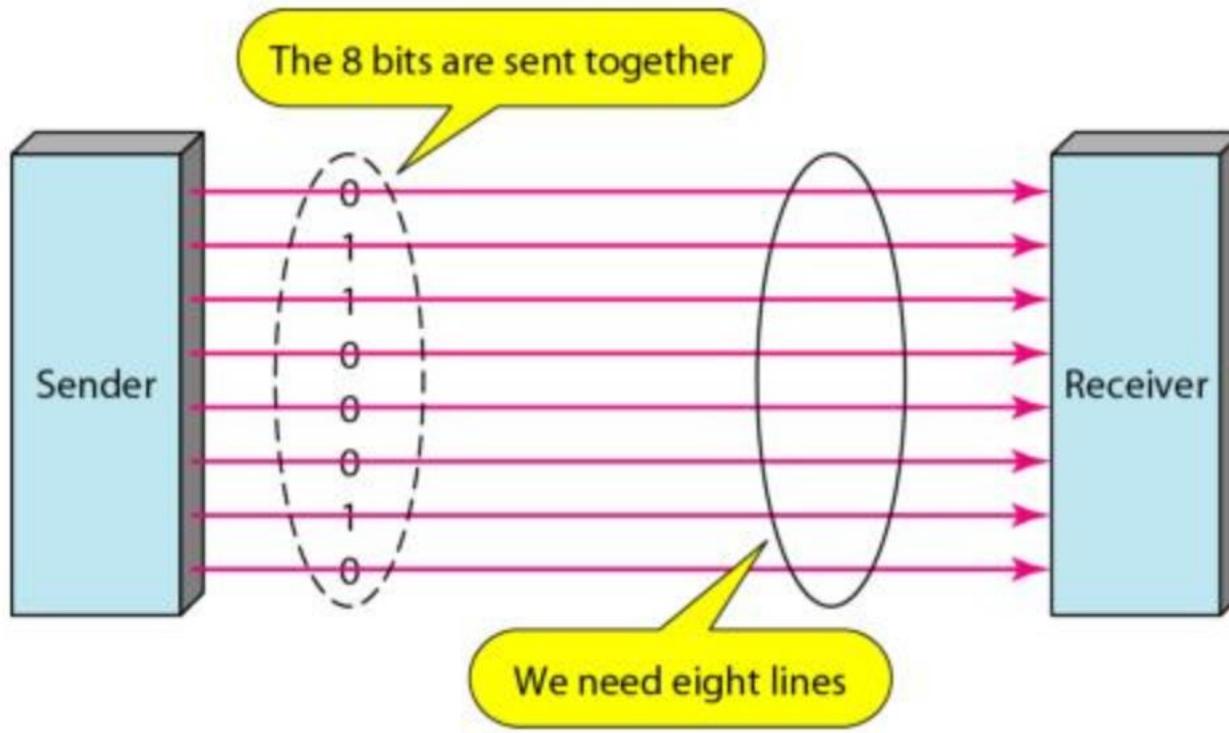
Filling the link with bits in case 2



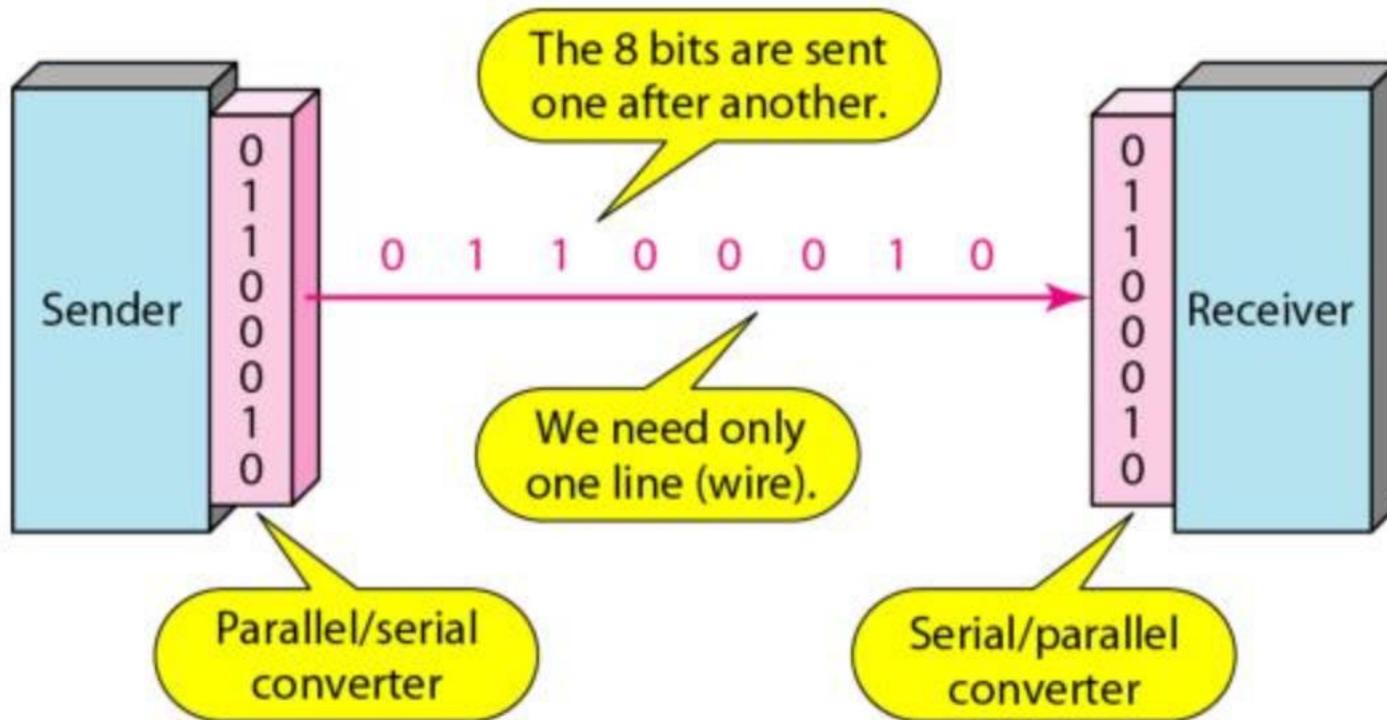
4-3 TRANSMISSION MODES

- The transmission of binary data across a link can be accomplished in either parallel or serial mode.
- In **parallel mode**, multiple bits are sent with each clock tick.
- In **serial mode**, 1 bit is sent with each clock tick.
- While there is only one way to send parallel data, there are three subclasses of serial transmission: *asynchronous*, *synchronous*, and *isochronous*.

Parallel transmission

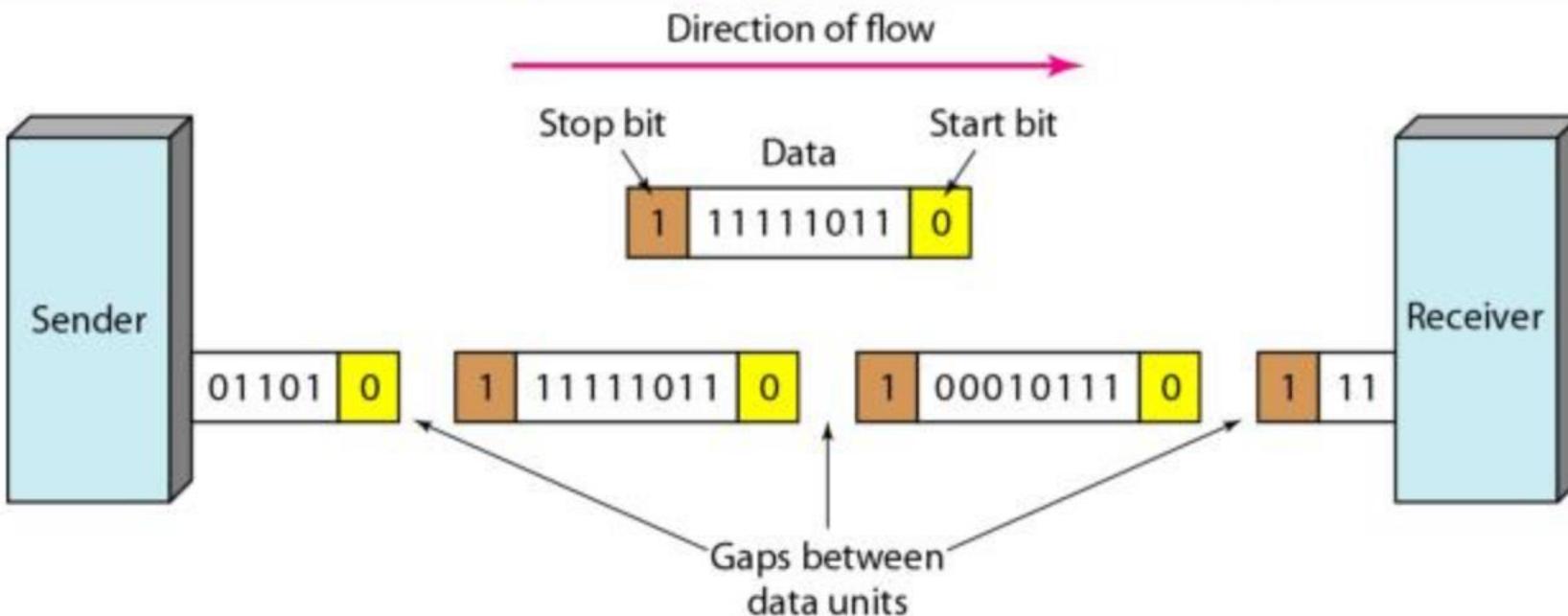


Serial transmission



Asynchronous transmission

We send 1 start bit (0) at the beginning and 1 or more stop bits (1s) at the end of each byte.
There may be a gap between each byte.



It is “asynchronous at the byte level,” bits are still synchronized; their durations are the same.

Synchronous transmission

We send bits one after another without start or stop bits or gaps.

It is the responsibility of the receiver to group the bits.

