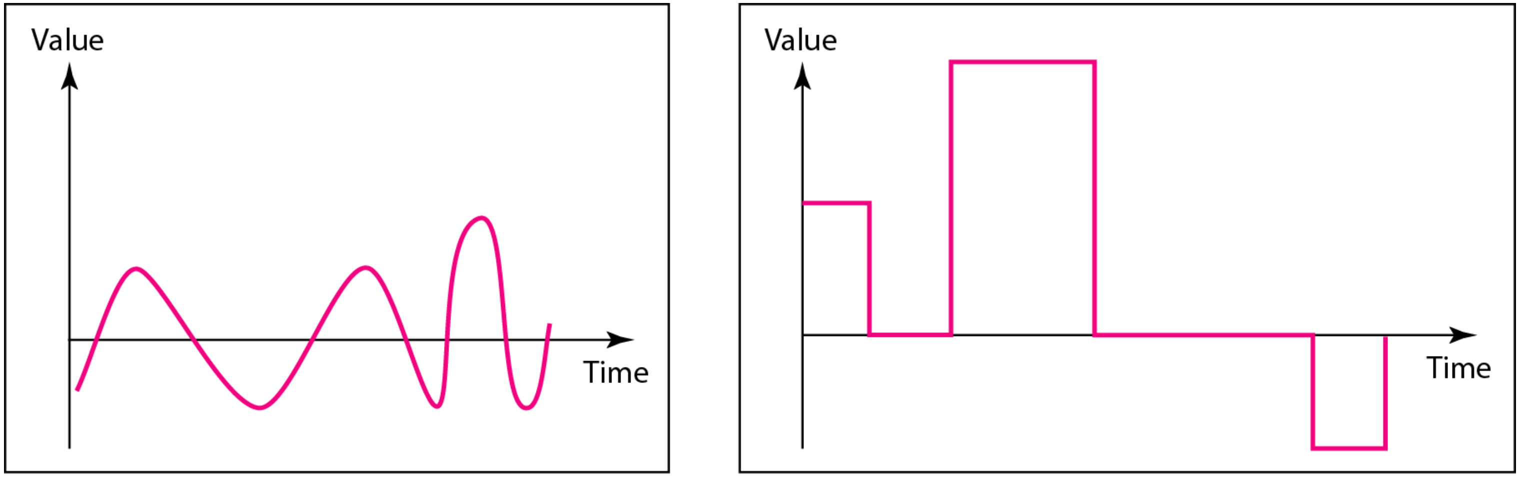
Chapter 3. Data and Signals

1. Analog and Digital
2. Periodic Analog Signals
3. Digital Signals
4. Transmission Impairment
5. Data Rate Limits
6. Performance

Analog and Digital

- To be transmitted, data must be transformed to electromagnetic signals
- Data can be analog or digital. Analog data are continuous and take continuous values. Digital data have discrete states and take on discrete values.
- Signals can be analog or digital. Analog signals can have an infinite number of values in a range; digital signals can have only a limited number of values.

Analog and Digital Signals

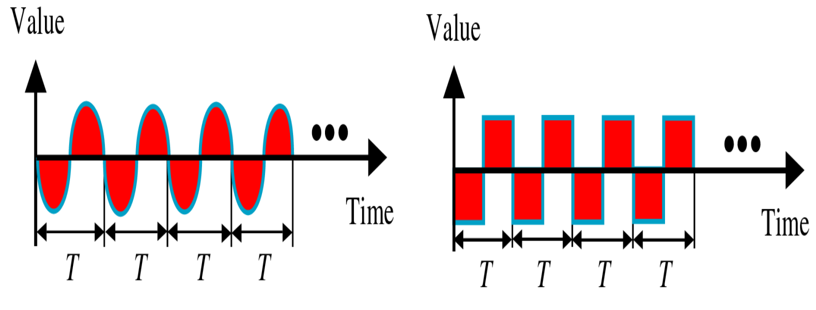


a. Analog signal

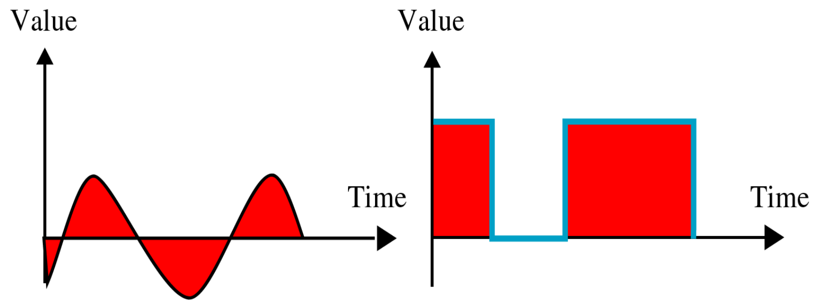
b. Digital signal

Periodic and Nonperiodic Signals

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



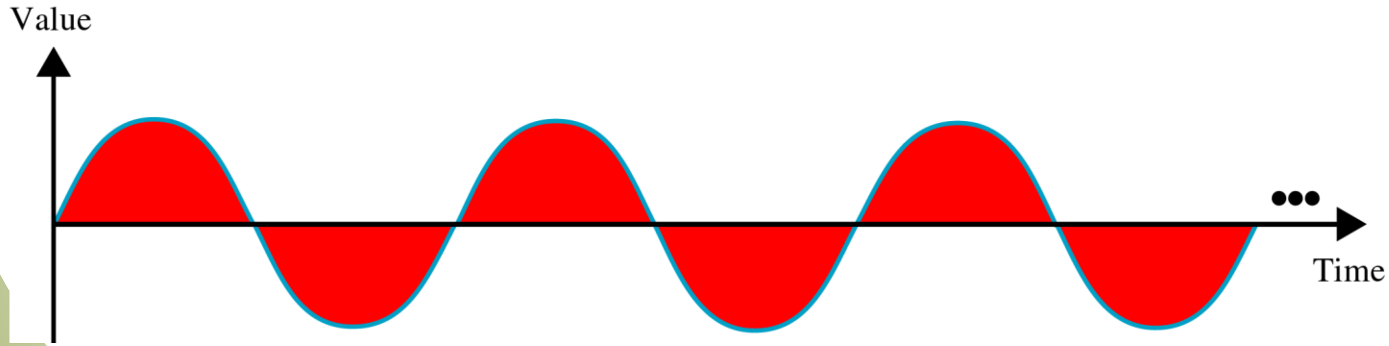
a. Analog b. Digital



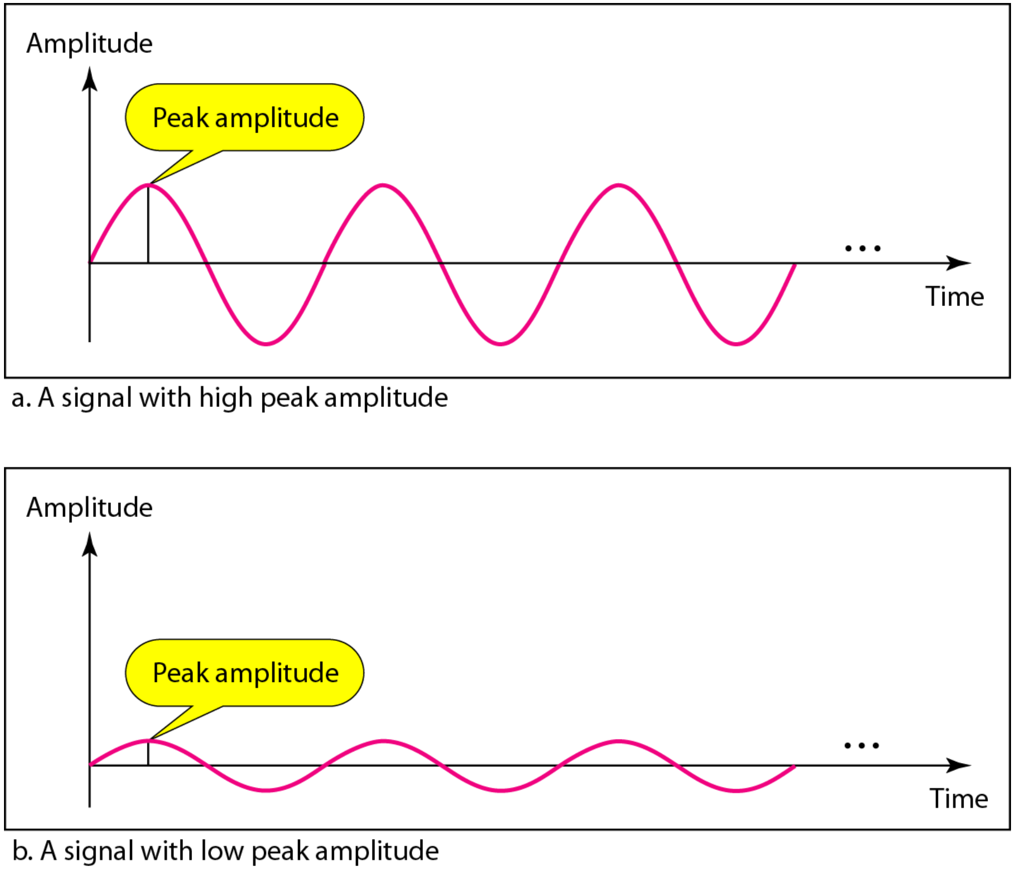
a. Analog signal b. Digital signal

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
- Sine wave is described by
  - Amplitude
  - Period (frequency)
  - phase

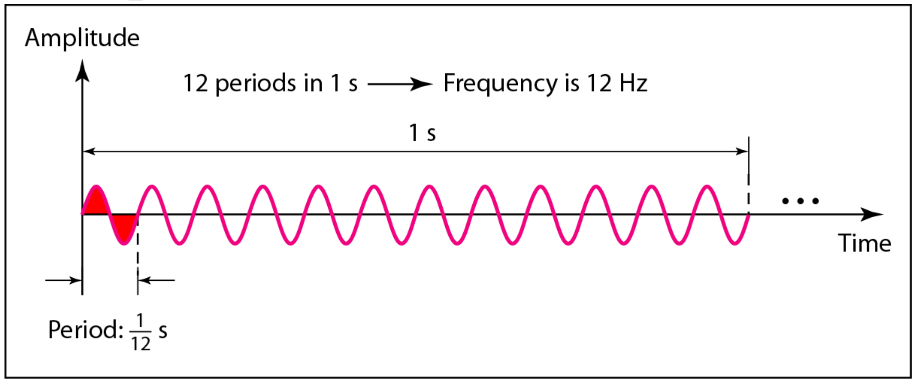


Amplitude

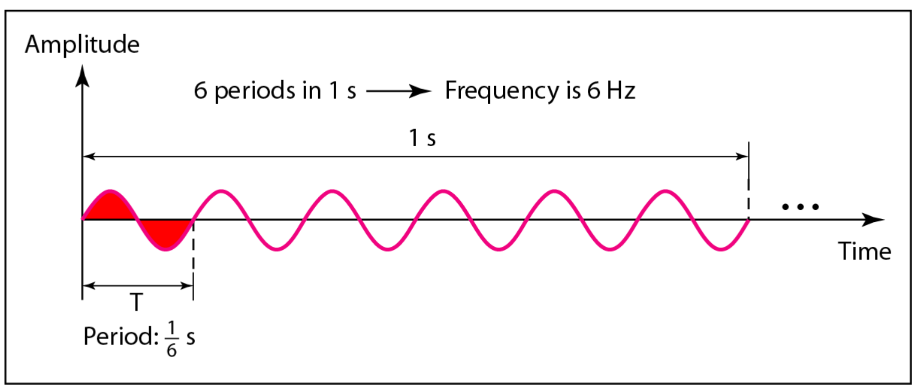

Amplitude
Peak amplitude
. . .
Time
a. A signal with high peak amplitude
Amplitude
Peak amplitude
. . .
Time
b. A signal with low peak amplitude

Period and Frequency

- Frequency and period are the inverse of each



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

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 3.5

- Express a period of 100 ms in microseconds, and express the corresponding frequency in kilohertz

From Table 3.1 we find the equivalent of 1 ms. We make the following substitutions:

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

Now we use the inverse relationship to find the frequency, changing hertz to kilohertz

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

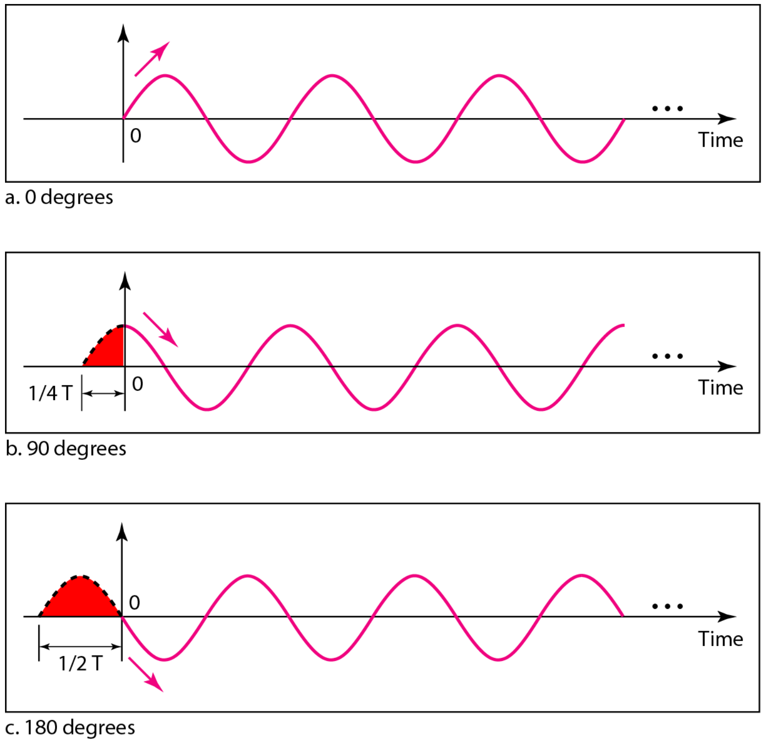
$$f = 1/10^{-1}\ Hz = 10 \times 10^{-3}\ KHz = 10^{-2}\ KHz$$

More About Frequency

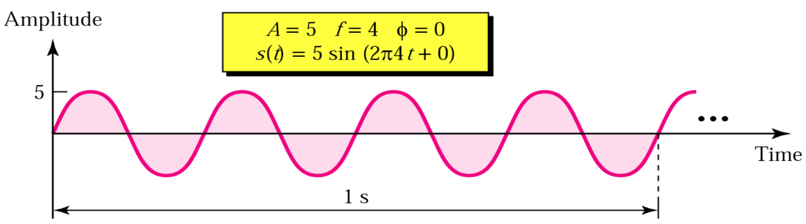
- Another way to look frequency
  - Frequency is a measurement of the rate of changes
  - Change in a short span of time means high frequency
  - Change over a long span of time means low frequency
- Two extremes
  - No change at all $\Rightarrow$ zero frequency
  - Instantaneous changes $\Rightarrow$ infinite frequency

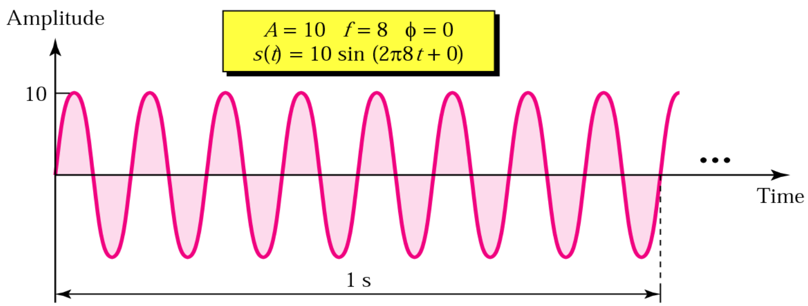
Phase

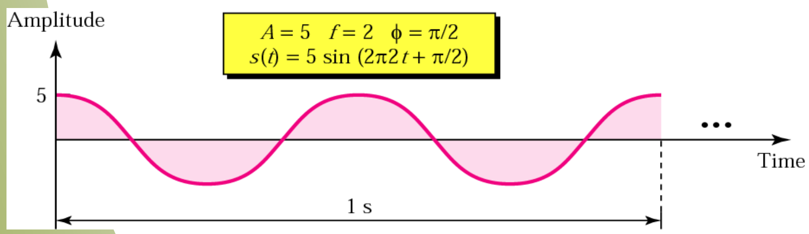
- Phase describes the position of the waveform relative to time zero



Sine Wave Examples







Example 3.6

- A sine wave is offset one-sixth of a cycle with respect to time zero. What is its phase in degrees and radians?

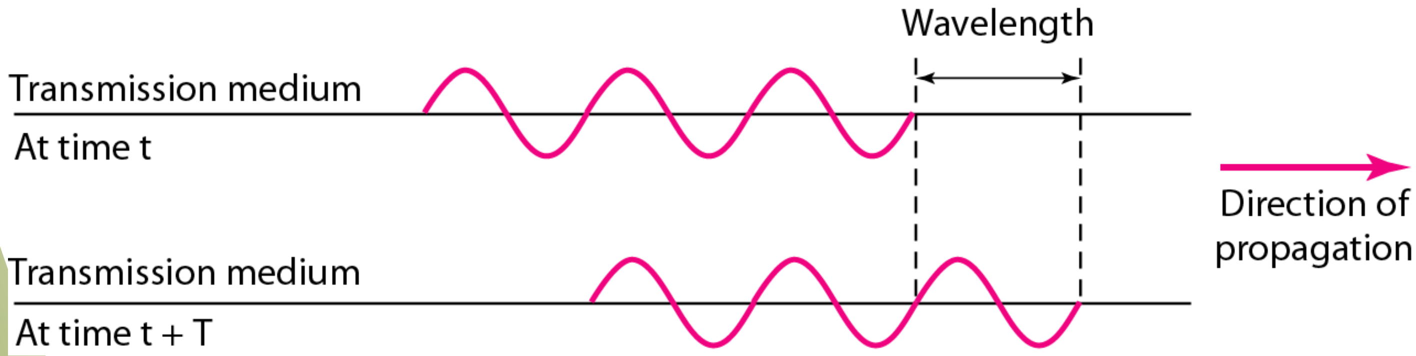
We know that one complete cycle is 360 degrees.

Therefore, 1/6 cycle is

(1/6) 360 = 60 degrees = 60 x 2π /360 rad = 1.046 rad

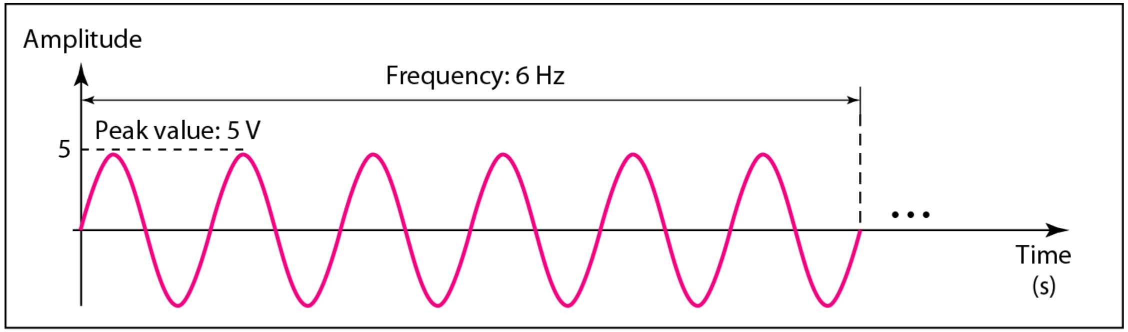
Wavelength

- Another characteristic of a signal traveling through a transmission medium
- Binds the period or the frequency of a simple sine wave to the propagation speed of the medium
- Wavelength = propagation speed x period
  = propagation speed/frequency

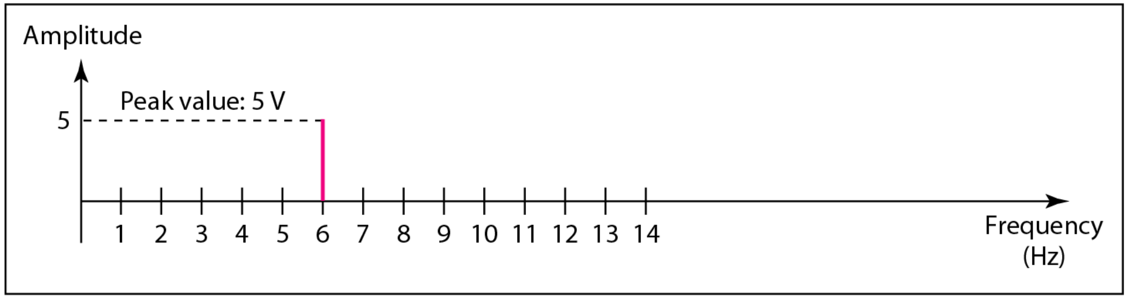


Time and Frequency Domains

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



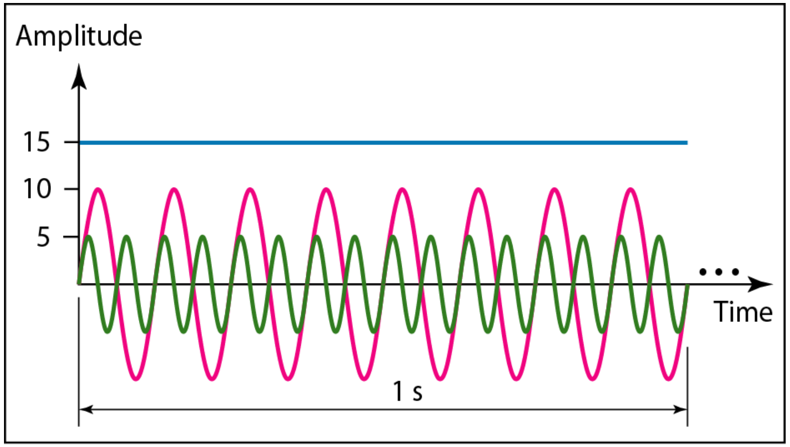
a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)



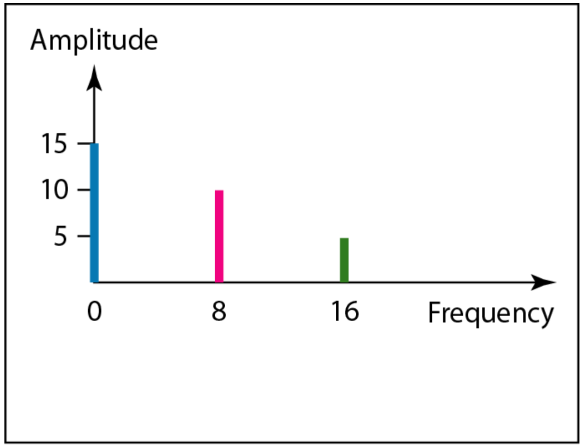
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Example 3.7

- Time domain and frequency domain of three sine waves with frequencies 0, 8, 16
- Frequency domain is more compact and useful when we are dealing with more than one sine waves.



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

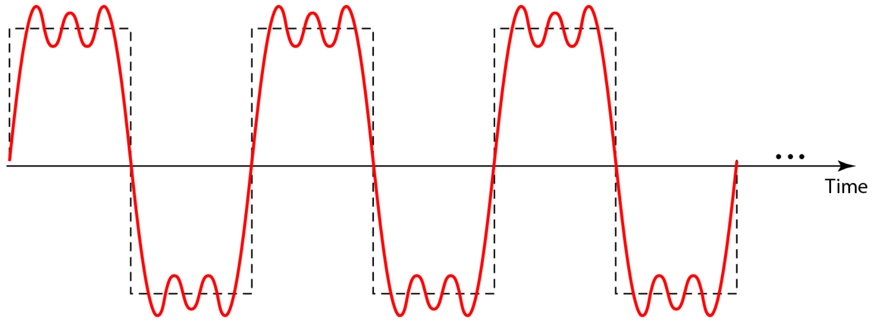


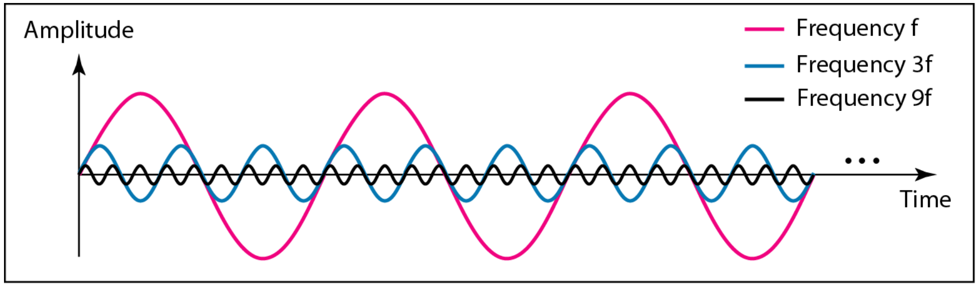
b. Frequency-domain representation of the same three signals

Composite Signals

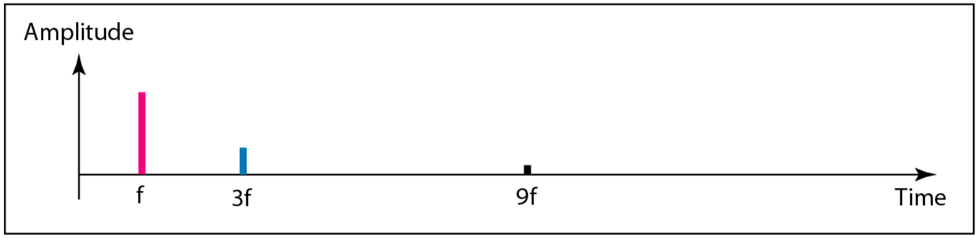
- A single-frequency sine wave is not useful in data communications; we need to send a composite signal, a signal made of many simple sine waves
- When we change one or more characteristics of a single-frequency signal, it becomes a composite signal made of many frequencies
- According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, phases, and amplitudes
- 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.

Composite Periodic Signal



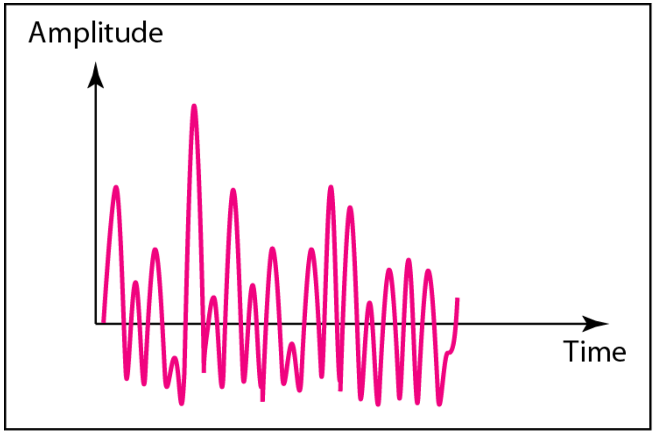


a. Time-domain decomposition of a composite signal

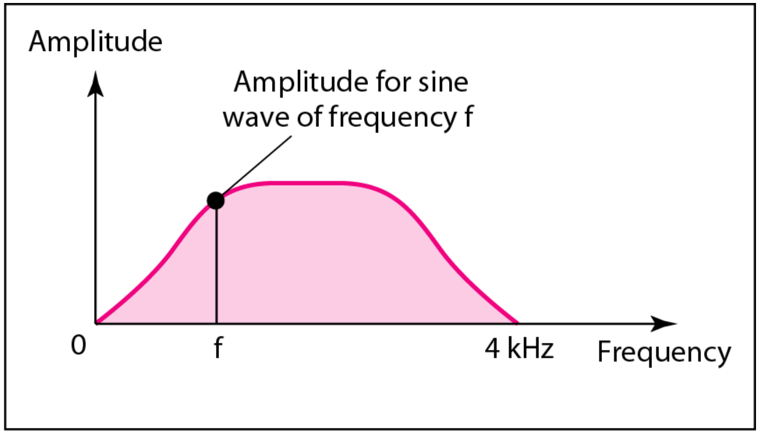


b. Frequency-domain decomposition of the composite signal

Composite Nonperiodic Signal



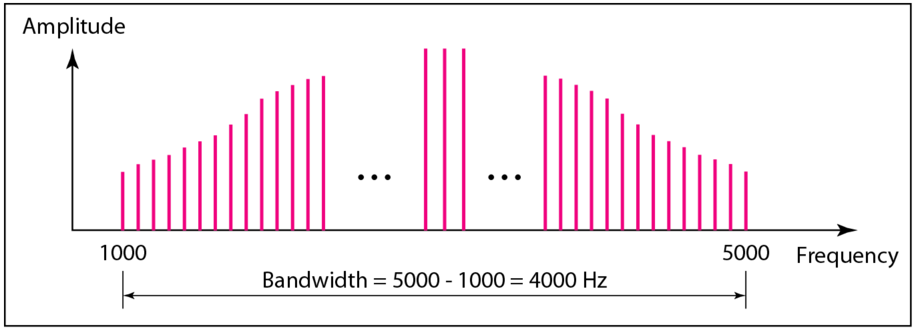
a. Time domain



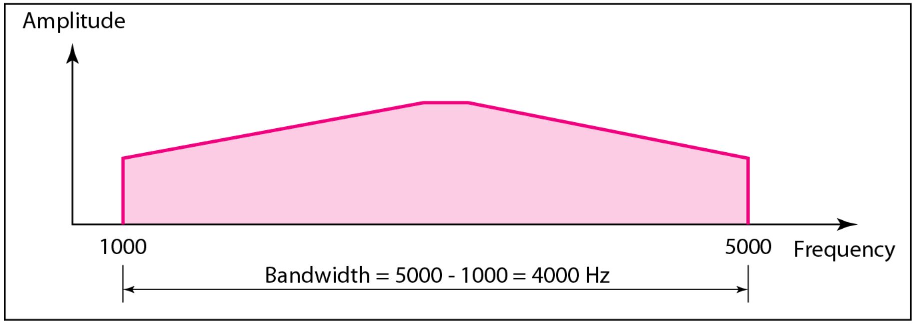
b. Frequency domain

Bandwidth

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

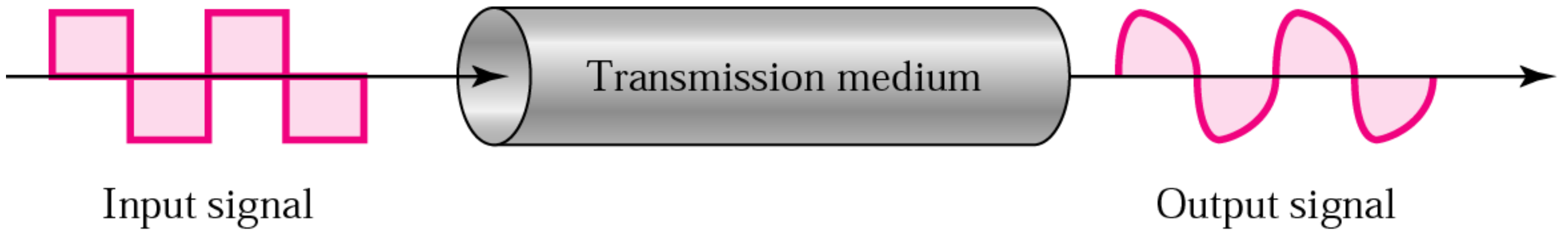


a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

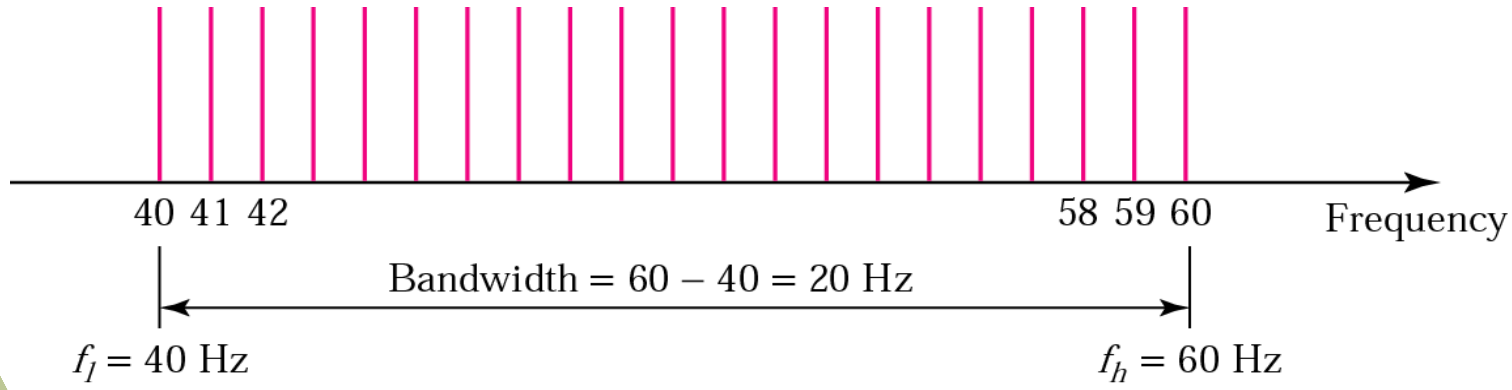
Signal Corruption



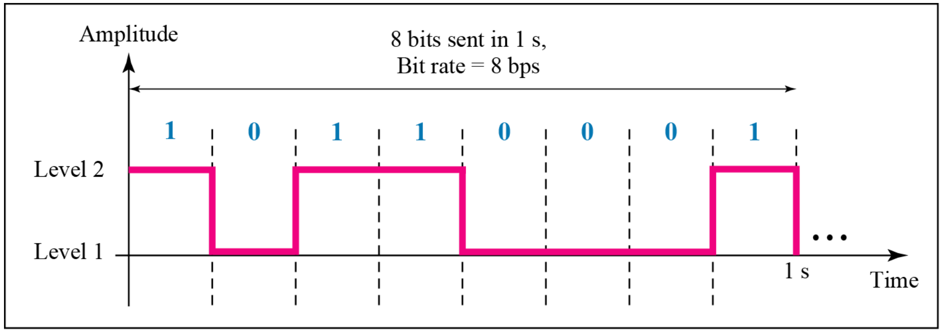
Example 3.11

- A signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all integral frequencies of the same amplitude

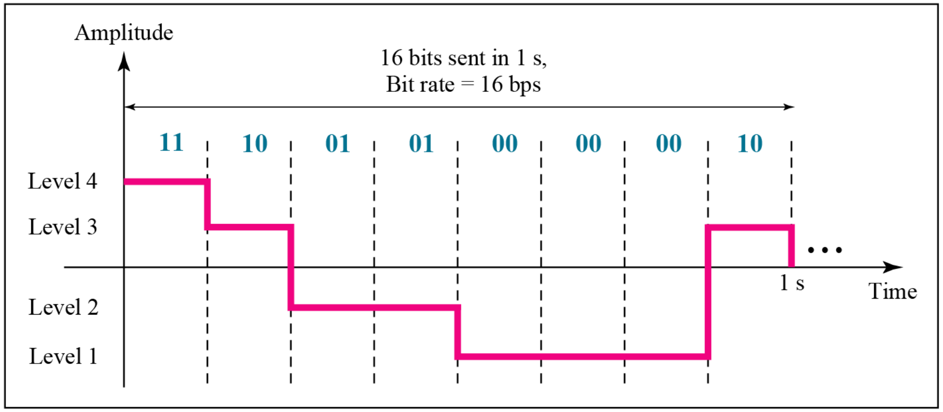
$B = f_h - f_l,\ 20 = 60 - f_l,\ f_l = 60 - 20 = 40\ Hz$



Digital Signals

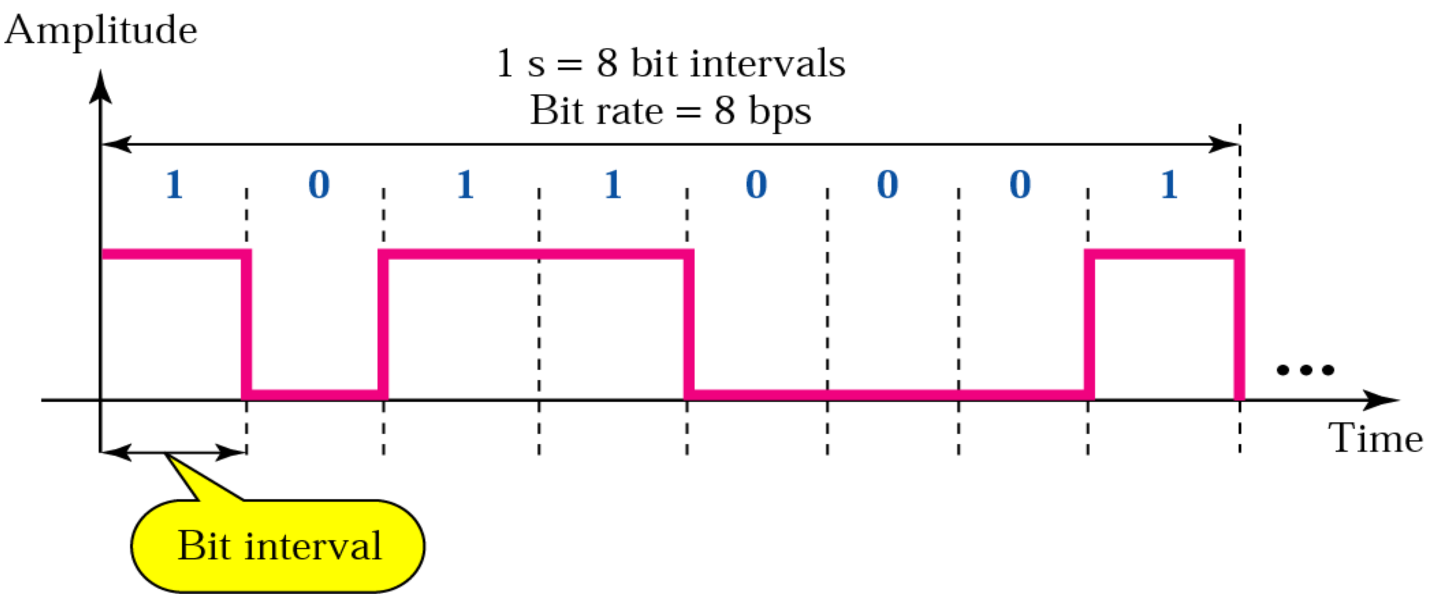


a. A digital signal with two levels



b. A digital signal with four levels

Bit Rate and Bit Interval



Example 3.18

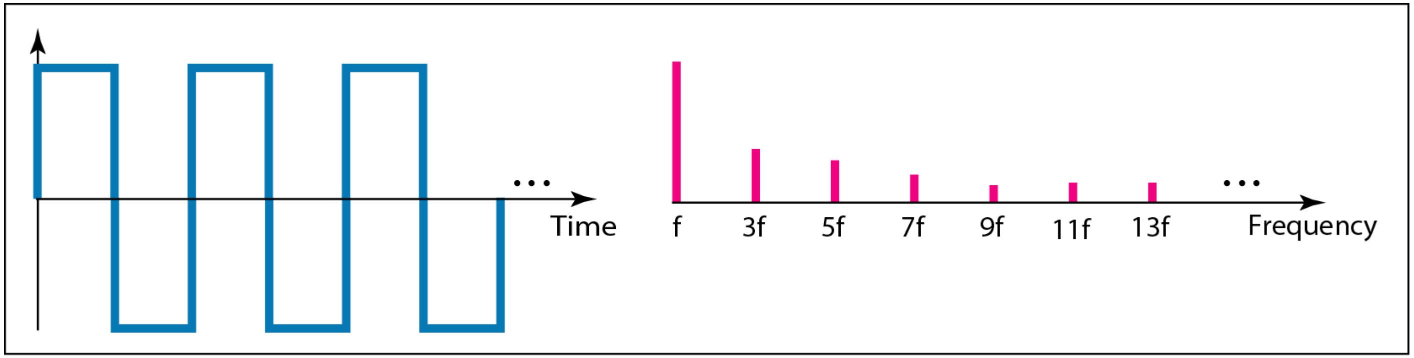
- Assume we need to download text documents at the rate of 100 pages per minute. What is the required bit rate of the channel?

Solution

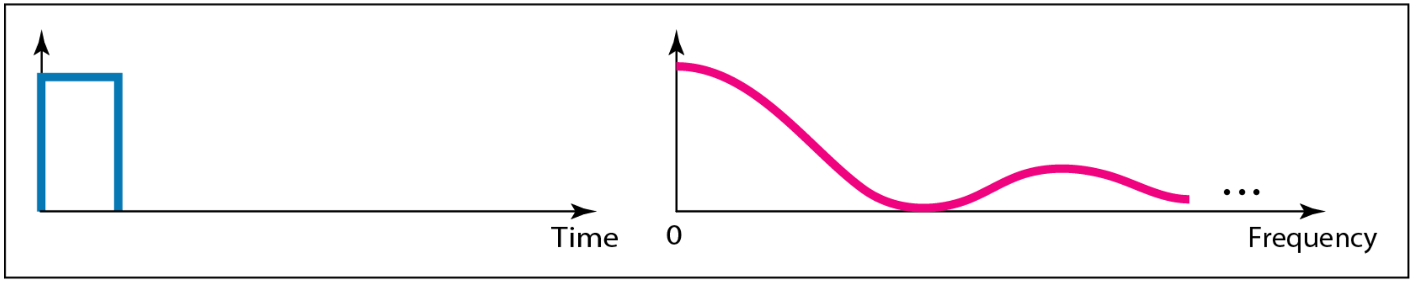
- A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is

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

Digital Signal as a Composite Analog Signal



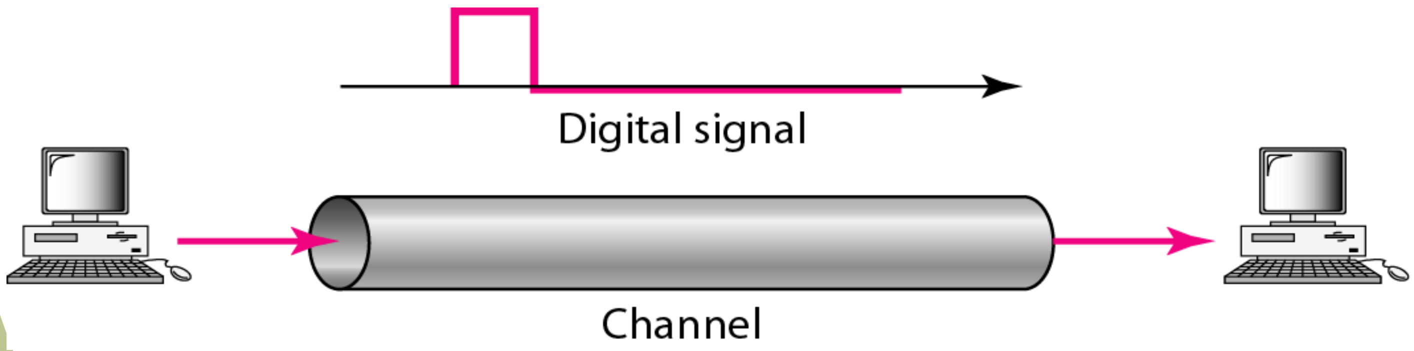
a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

Transmission of Digital Signals

- A digital signal is a composite analog signal with an infinite bandwidth
- Baseband transmission: Sending a digital signal without changing into an analog signal



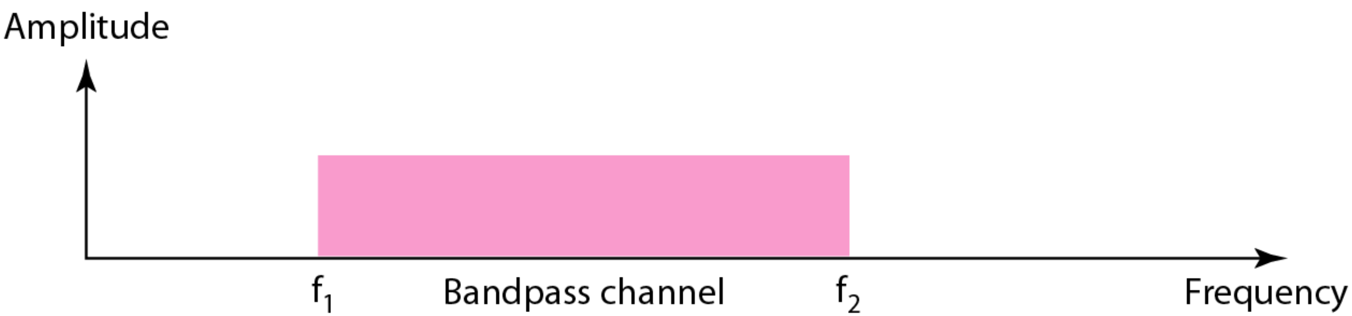
Bandwidth Requirement

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

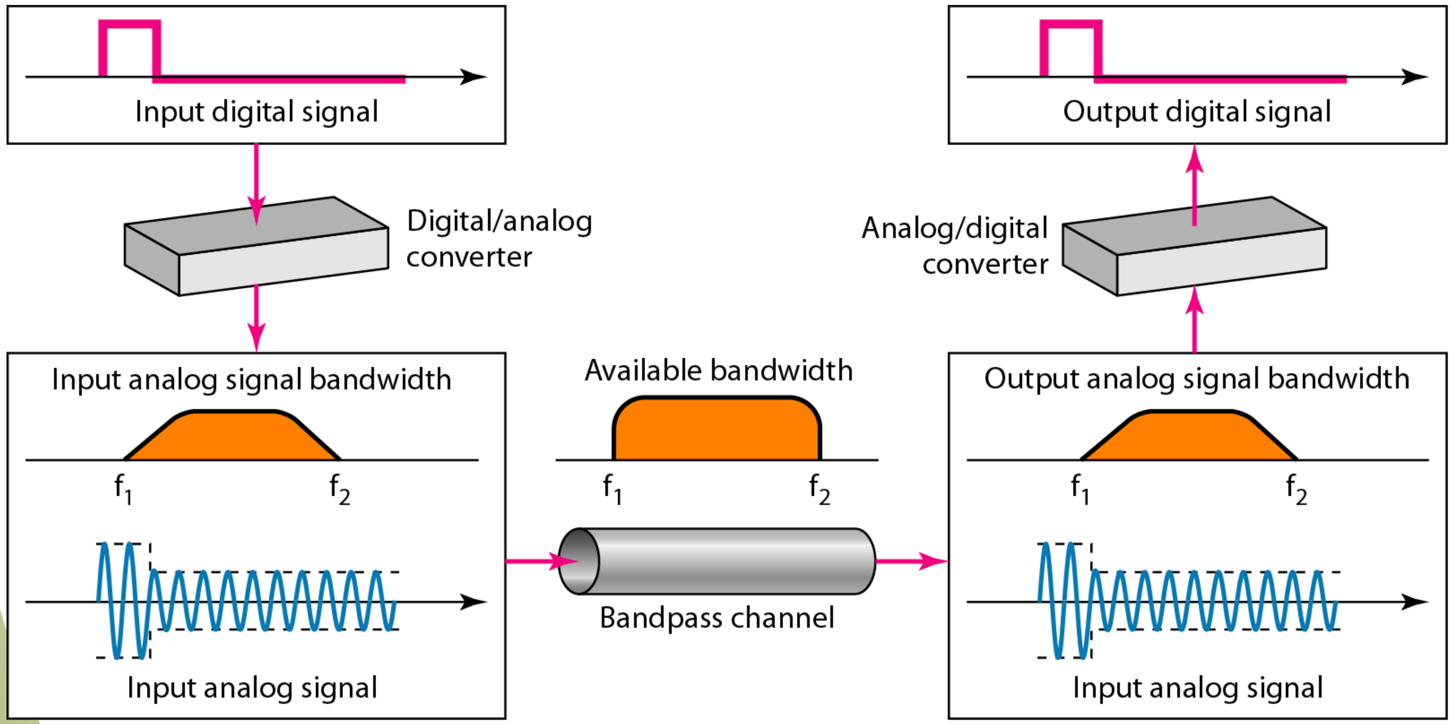
Bit Rate	*Harmonic 1*	*Harmonics 1, 3*	*Harmonics 1, 3, 5*
$n = 1$ kbps	$B = 500$ Hz	$B = 1.5$ kHz	$B = 2.5$ kHz
$n = 10$ kbps	$B = 5$ kHz	$B = 15$ kHz	$B = 25$ kHz
$n = 100$ kbps	$B = 50$ kHz	$B = 150$ kHz	$B = 250$ kHz

Broadband Transmission (Using Modulation)

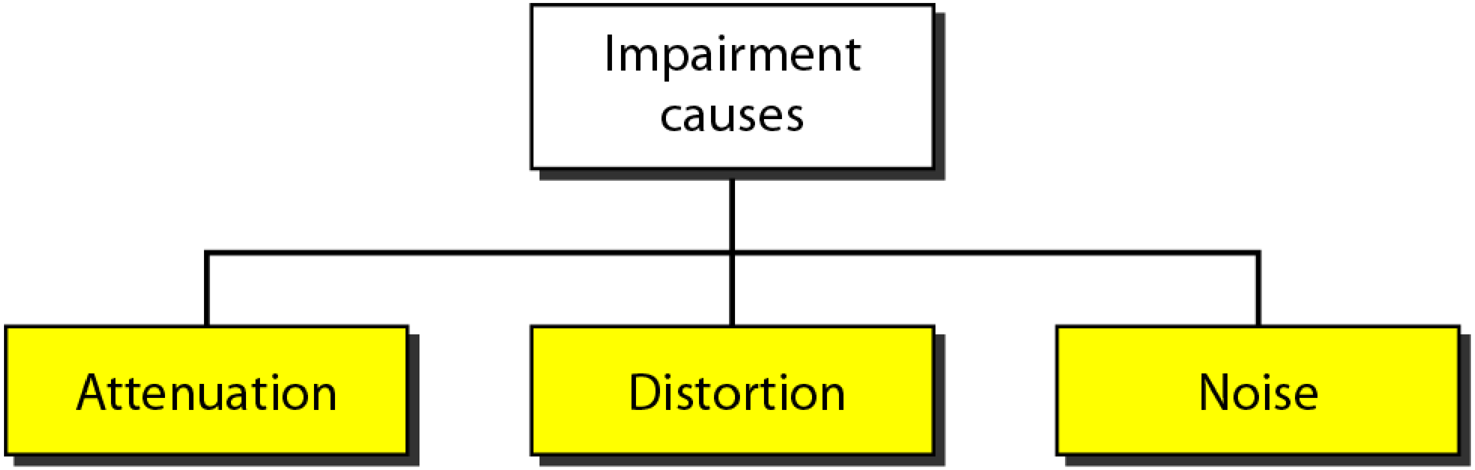
- Modulation allows us to use a bandpass channel
- If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.



Modulation for Bandpass Channel

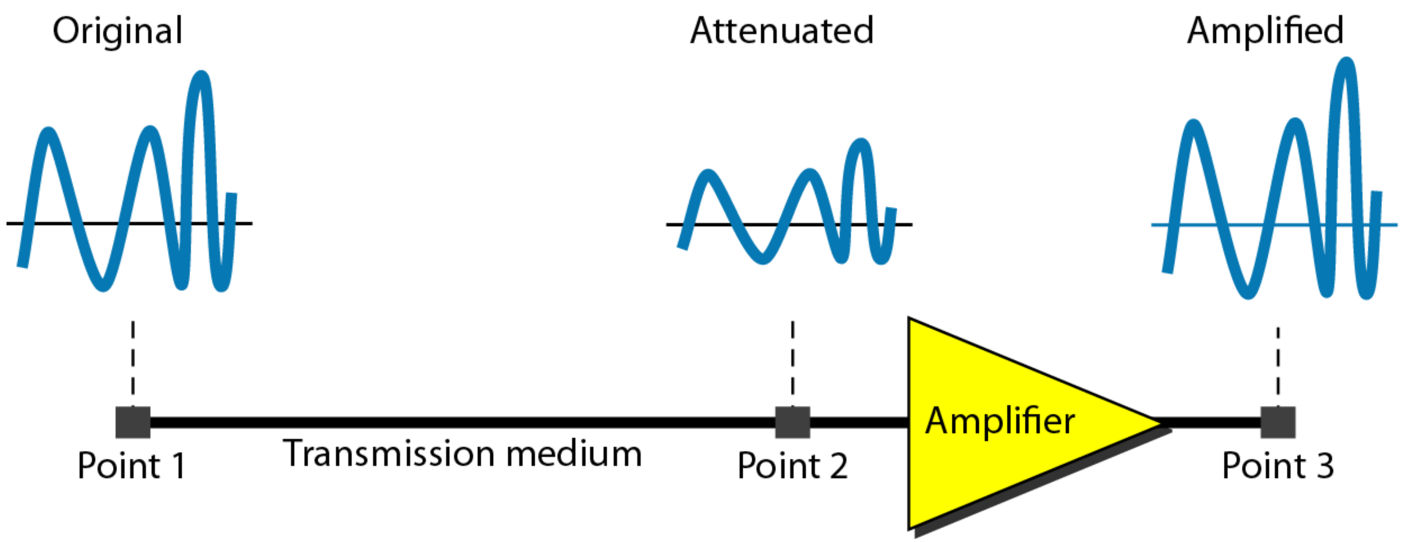


Transmission Impairment



Attenuation

- Loss of energy to overcome the resistance of the medium: heat

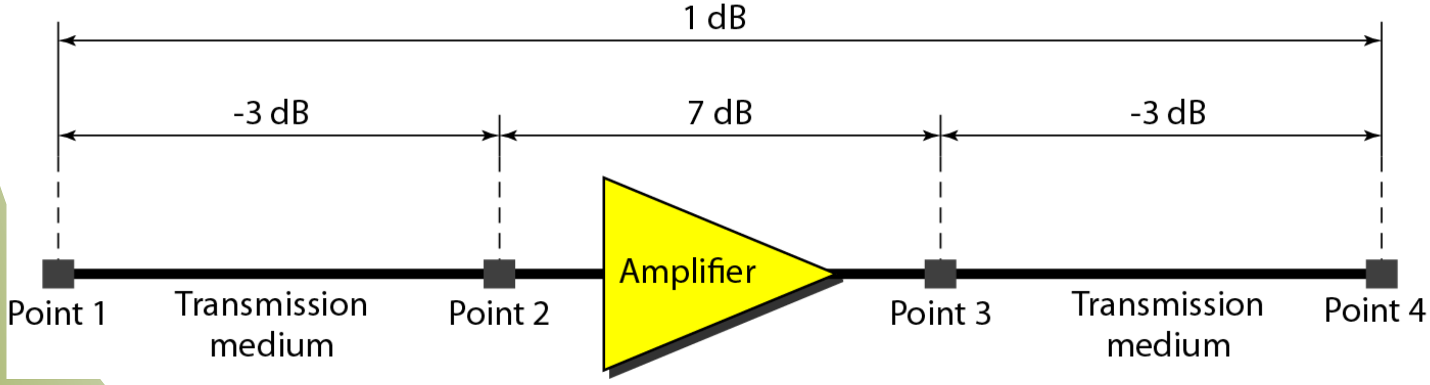


Decibel

- Example 3.26: 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

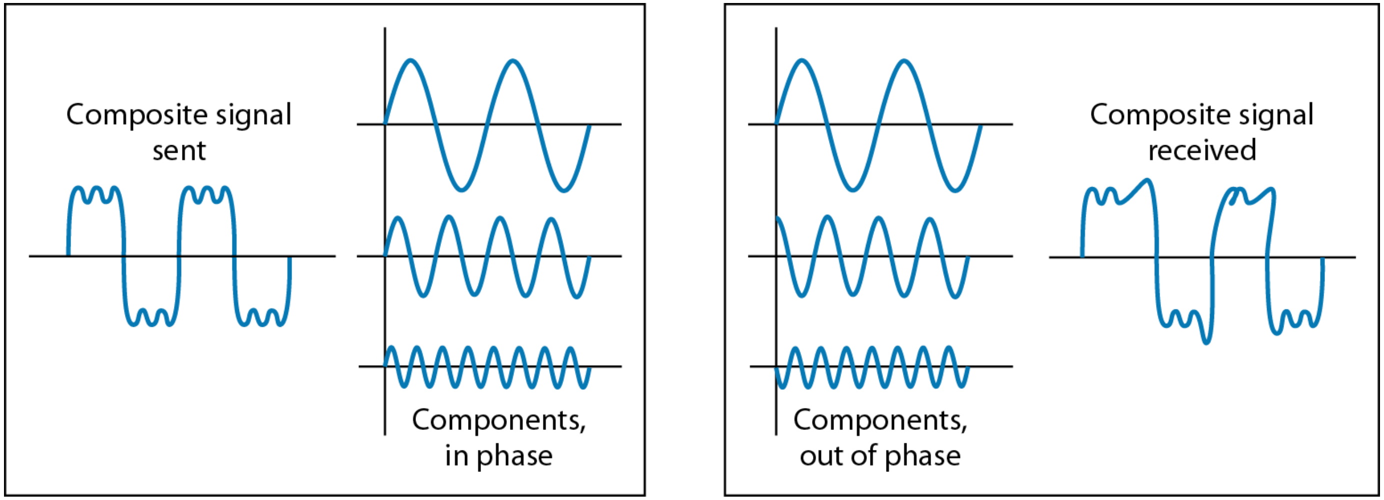
$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5 P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

- Example 3.28



Distortion

- The signal changes its form or shape
- Each signal component in a composite signal has its own propagation speed
- Differences in delay may cause a difference in phase

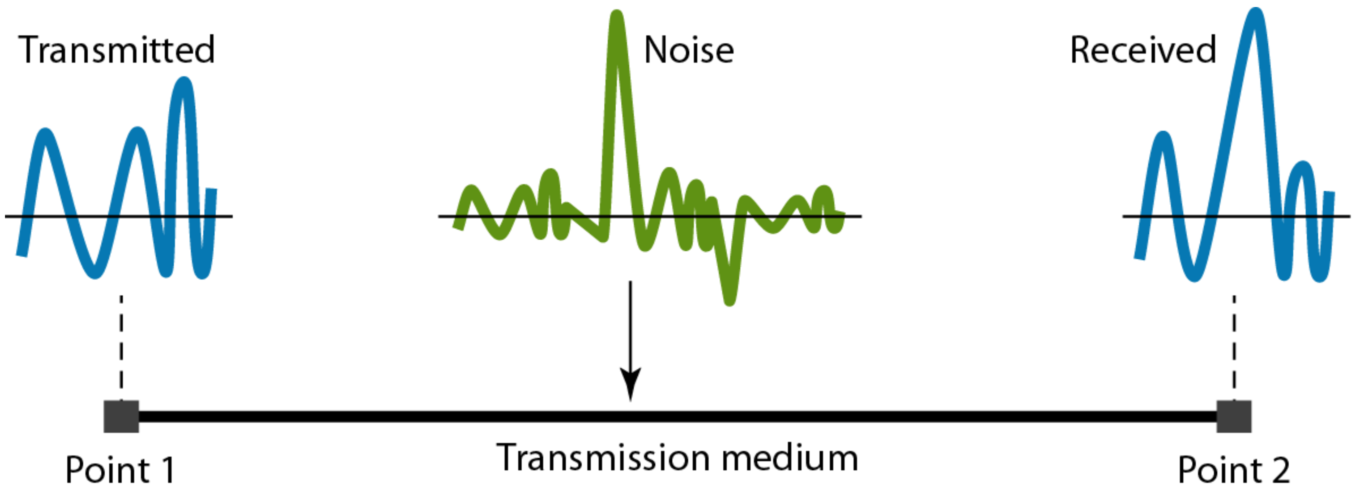


At the sender

At the receiver

Noise

- Several types of noises, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal
- Thermal noise is the random motion of elections in a wire which creates an extra signal not originally sent by the transmitter.



Signal-to-Noise Ratio (SNR)

- To find the theoretical bit rate limit
- SNR = average signal power/average noise power
- $SNR_{dB} = 10 \log_{10} SNR$

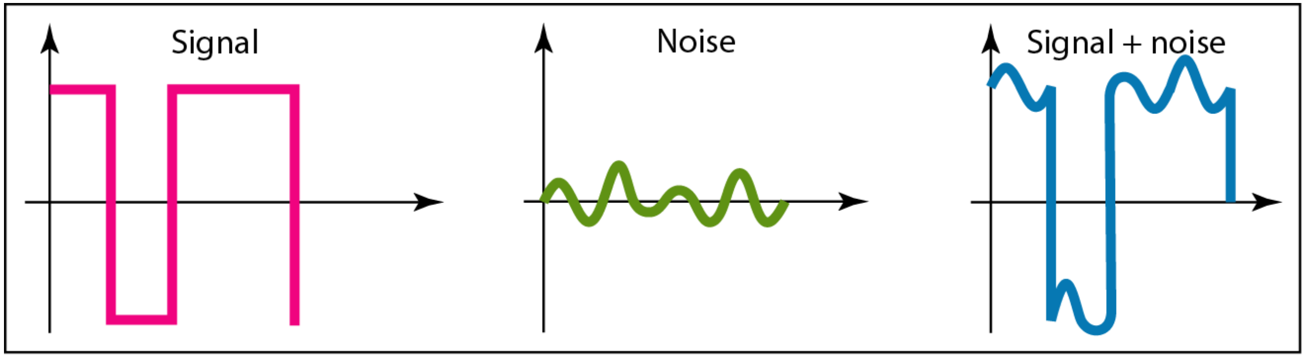
- Example 3.31: The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and SNR_{dB} ?

Solution:

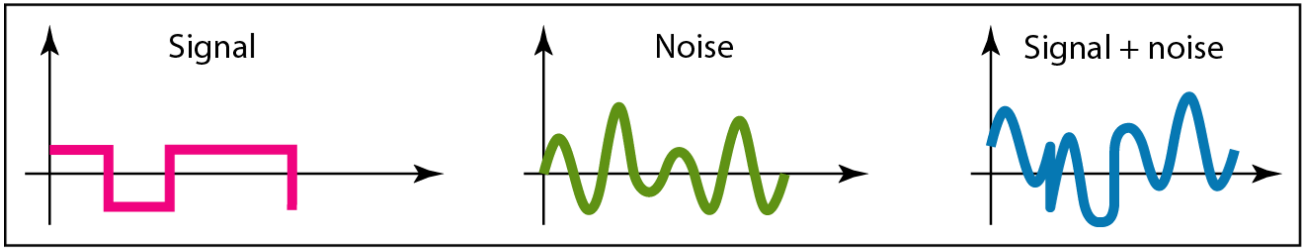
$$SNR = \frac{10{,}000\ \mu W}{1\ mW} = 10{,}000$$

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

Two Cases of SNRs



a. Large SNR



b. Small SNR

Data Rate Limits

- Data rate depends on three factors:
  - Bandwidth available
  - Level of the signals we use
  - Quality of the channel (the noise level)
- Noiseless channel: **Nyquist Bit Rate**
  - *Bit rate = 2 * Bandwidth * log*$_2$*L*
  - *Increasing the levels may cause the reliability of the system*
- Noisy channel: **Shannon Capacity**
  - *Capacity = Bandwidth * log*$_2$*(1 + SNR)*

Nyquist Bit Rate: 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

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

- Consider the same noiseless channel, transmitting a signal with four signal levels (for each level, we send two bits). The maximum bit rate can be calculated as:

$$\text{Bit Rate} = 2 \text{ x } 3000 \text{ x } \log_2 4 = 12{,}000 \text{ bps}$$

Shannon Capacity: Examples

- 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 is calculated as

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

- We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 Hz to 3300 Hz). The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + SNR) = 3000 \log_2 (1 + 3162) = 3000 \log_2 (3163)$$

$$C = 3000 \times 11.62 = 34{,}860 \text{ bps}$$

Using Both Limits

- The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.
- Example: We have a channel with a 1 MHz bandwidth. The SNR for this channel is 63; what is the appropriate bit rate and signal level?

First, we use the Shannon formula to find our upper limit

$C = B \log_2 (1 + SNR) = 106 \log_2 (1 + 63)$

$\quad = 106 \log_2 (64) = 6 \text{ Mbps}$

Then we use the Nyquist formula to find the number of signal levels

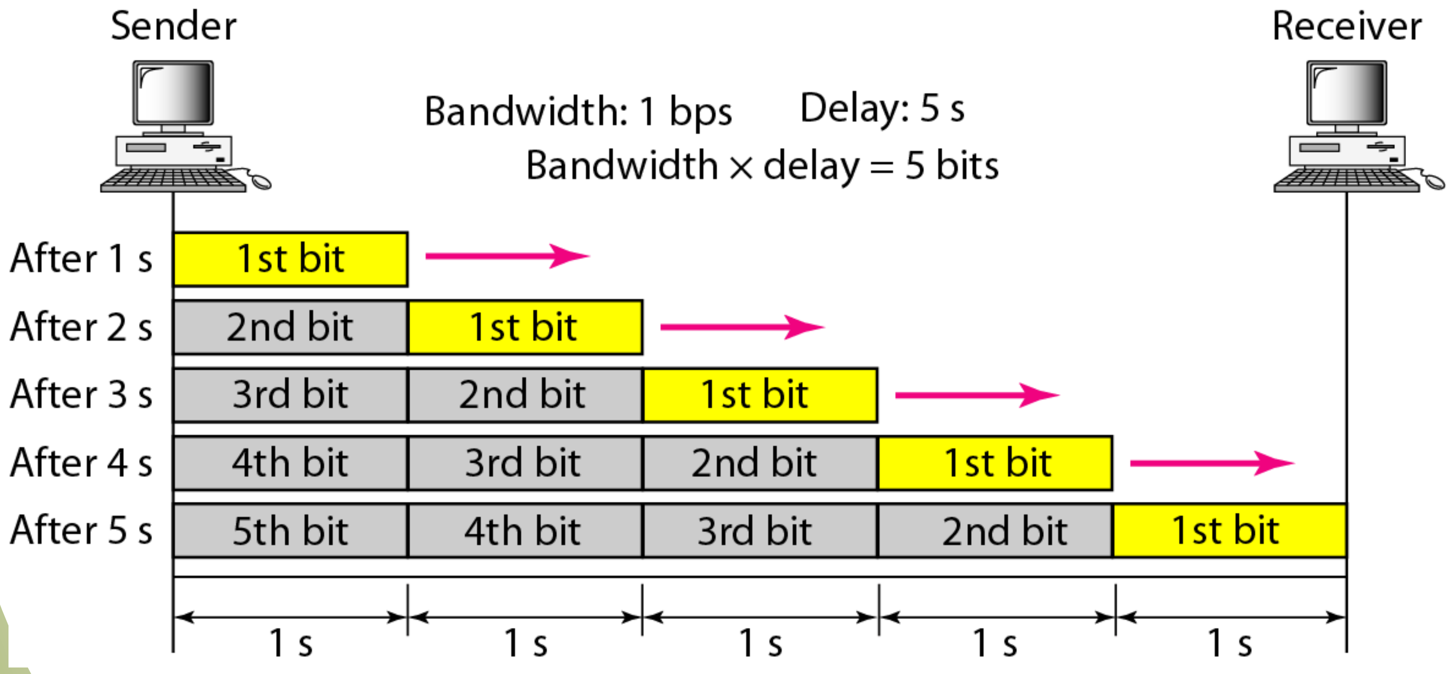
$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \rightarrow L = 4$

Performance

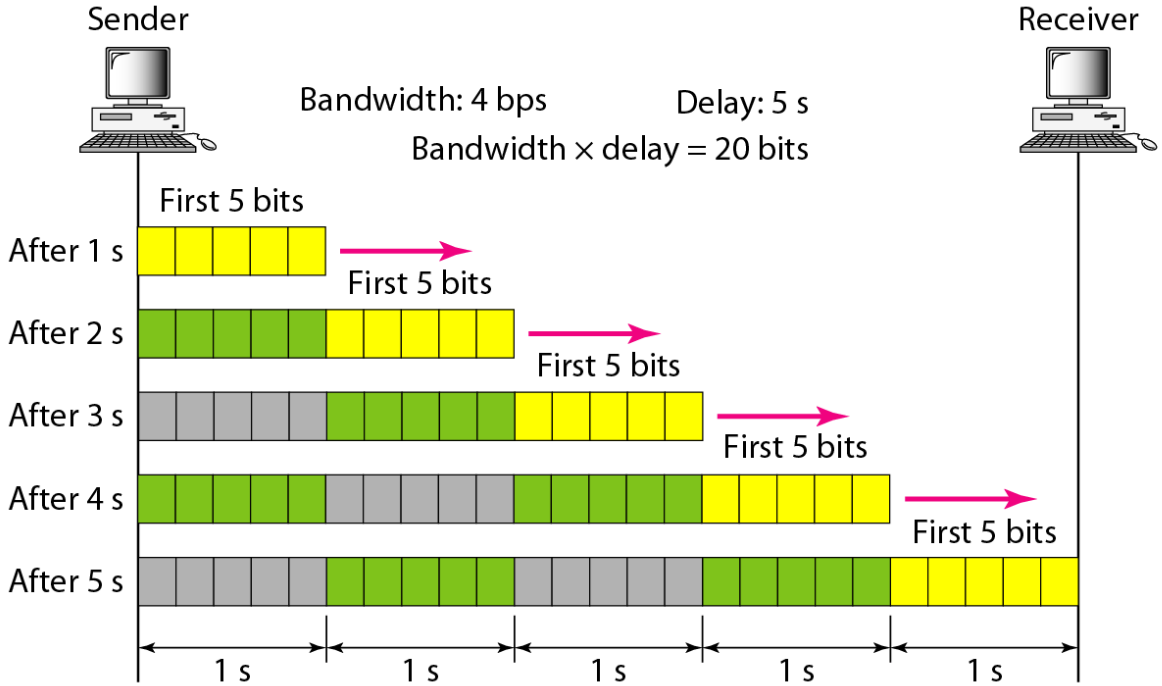
- Bandwidth (in two contexts)
  - Bandwidth in hertz, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.
  - Bandwidth in bits per second, refers to the speed of bit transmission in a channel or link.
- Throughput
  - Measurement of how fast we can actually send data through a network
- Latency (Delay)
  - Define 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
  - Latency = propagation time + transmission time + queuing time + processing delay
  - Propagation time = Distance/Propagation speed
  - Transmission time = Message size/Bandwidth
- Jitter

Bandwidth-Delay Product

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



Bandwidth-Delay Product



- Bandwidth-delay product concept