T3
Physical Layer: Digital Transmission Fundamentals

Layer 1: Physical Layer

- Service: transmitting raw bits (0/1) over wire/physical link between two systems

Transmitter:

- Converts information into signal/waveform suitable for transmission

Receiver:

- Converts received signal into form suitable for delivery to user

Roadmap

- Data and Signals
- Digital Transmission
- Analog Transmission
- Why Digital Communications?
- Block diagram of digital transmissions

Note

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

ANALOG AND DIGITAL

Data can be analog or digital. The term analog data refers to information that is continuous; digital data refers to information that has discrete states. Analog data take on continuous values. Digital data take on discrete values.

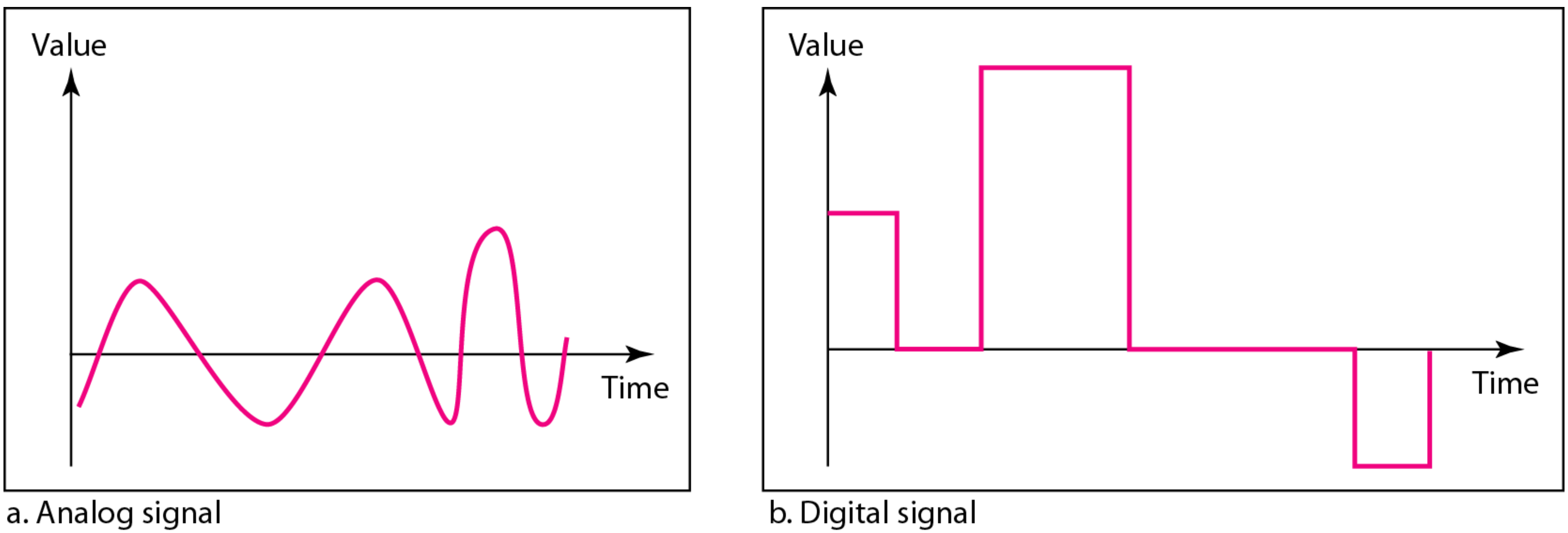
Topics discussed in this section:

Analog and Digital Signals
Periodic and Nonperiodic Signals

Note

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.

Comparison of analog and digital signals



Note

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

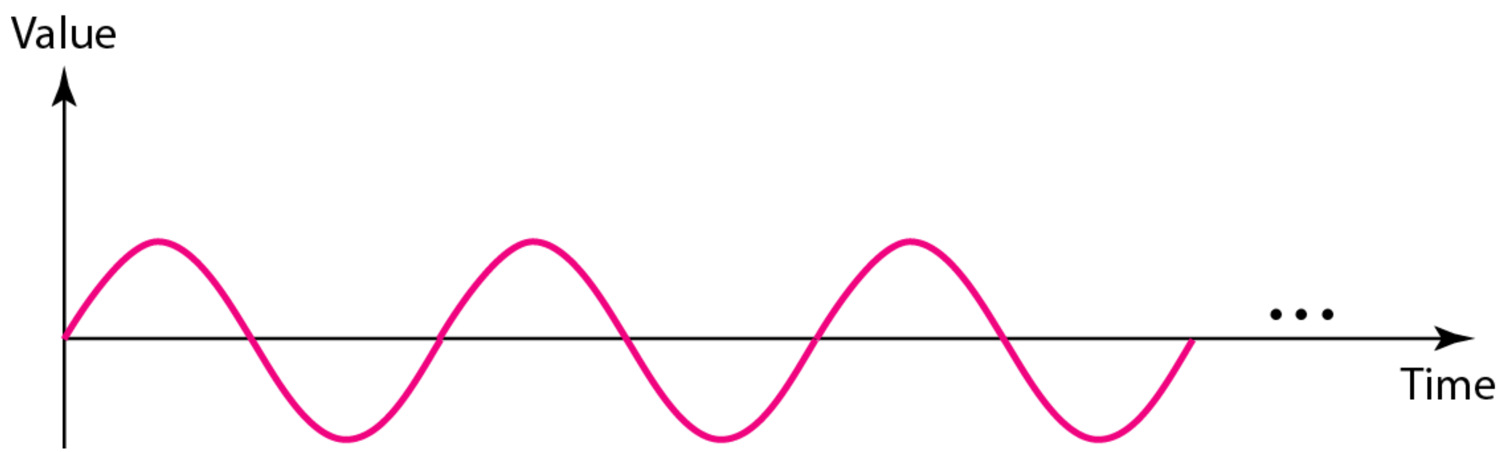
ANALOG SIGNALS

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.

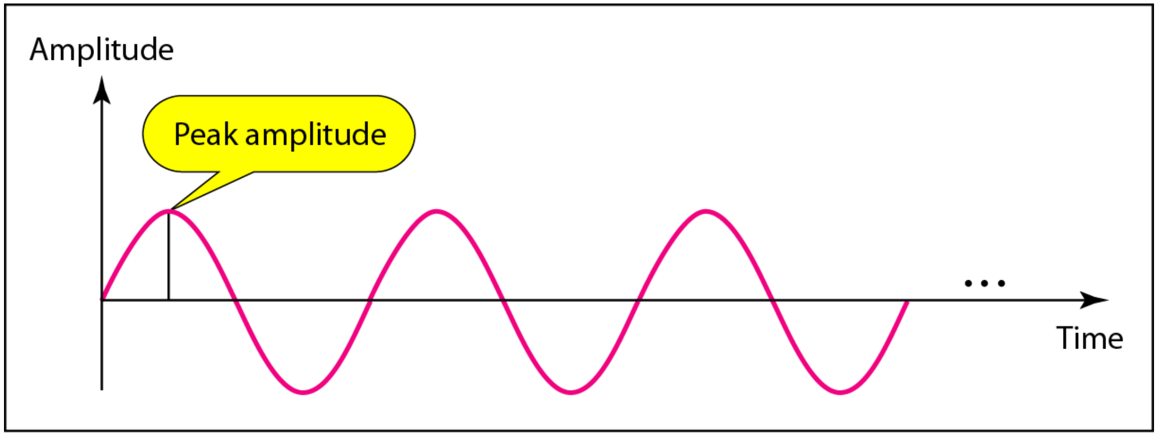
Topics discussed in this section:

Sine Wave
Wavelength
Time and Frequency Domain
Composite Signals
Bandwidth

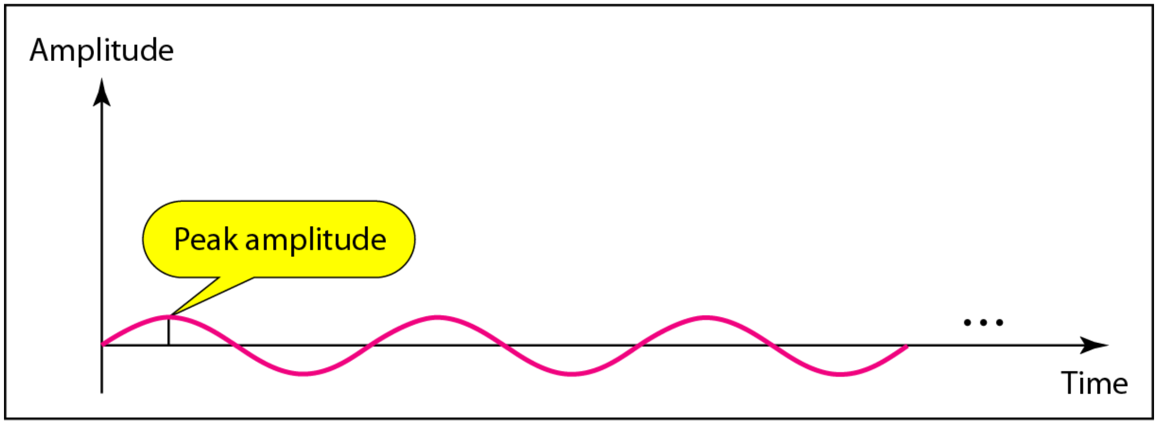
A sine wave



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



a. A signal with high peak amplitude



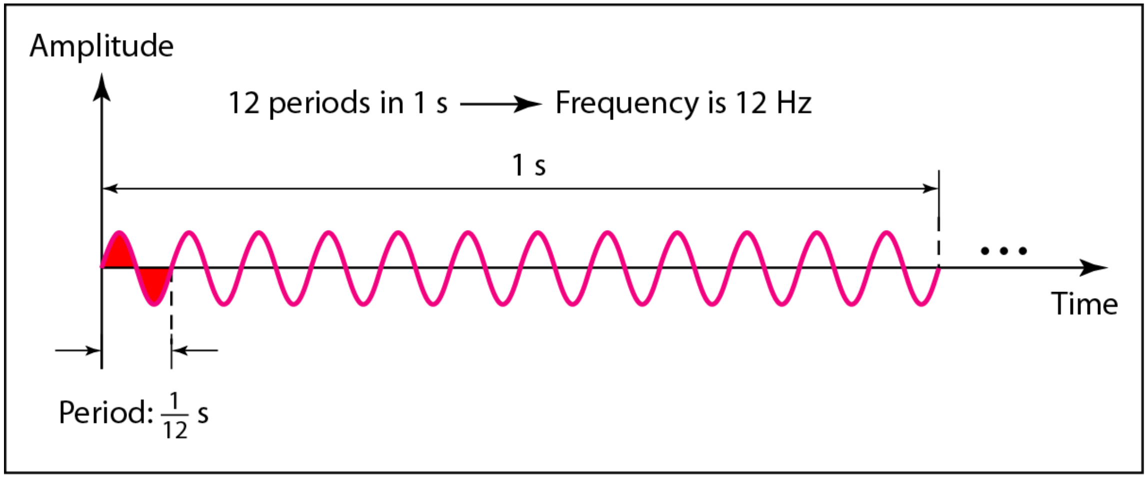
b. A signal with low peak amplitude

Note

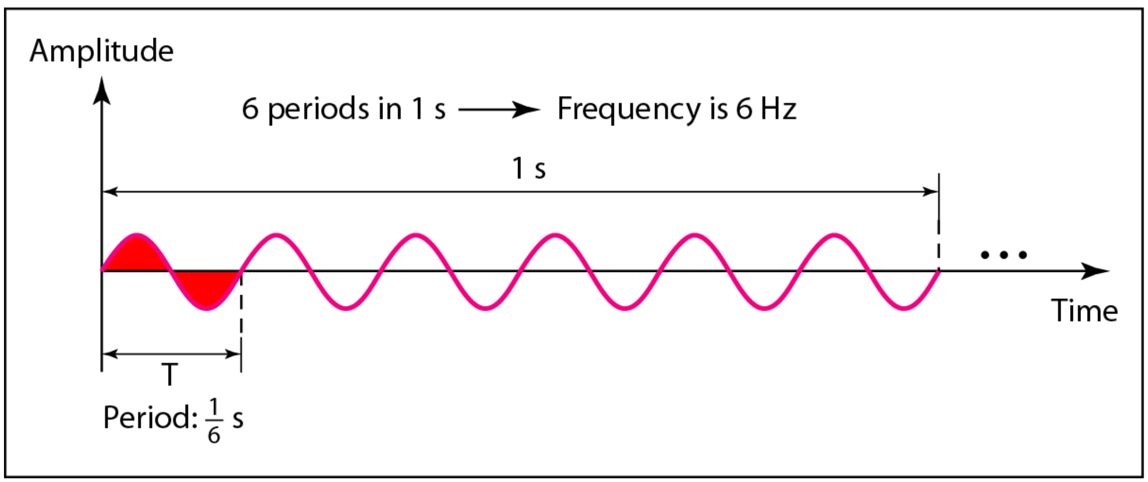
Frequency and period are the inverse of each other

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

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

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:

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

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.

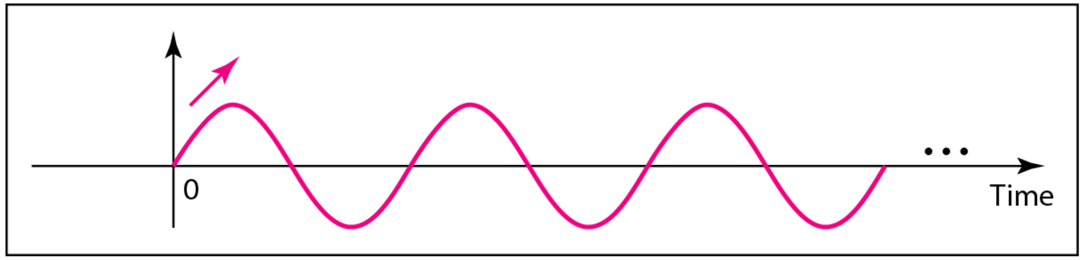
Note

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

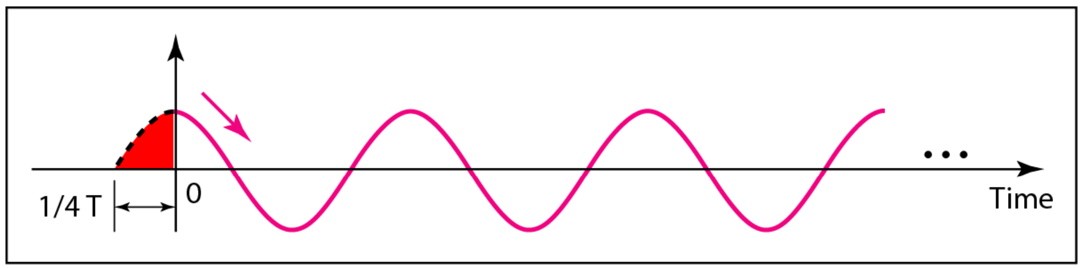
Note

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

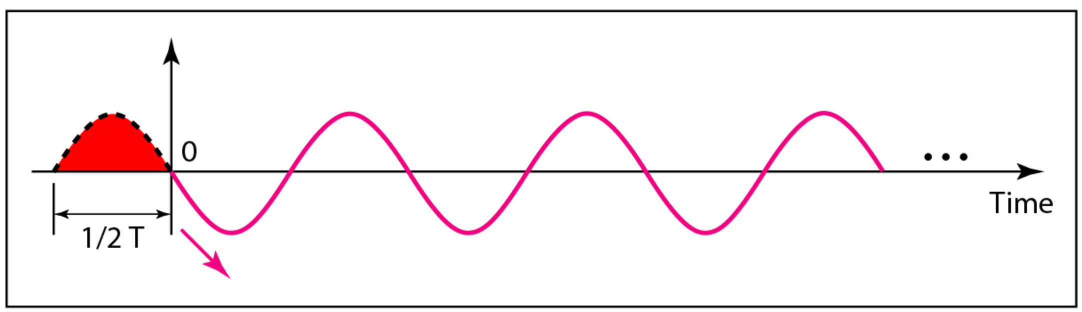
Three sine waves with the same amplitude and frequency, but different phases



a. 0 degrees

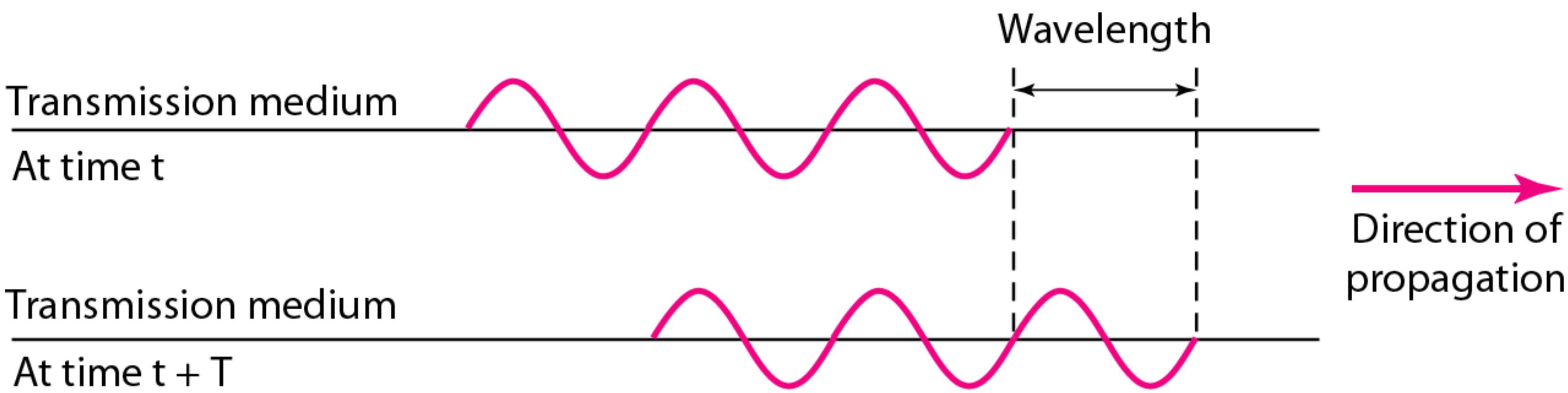


b. 90 degrees

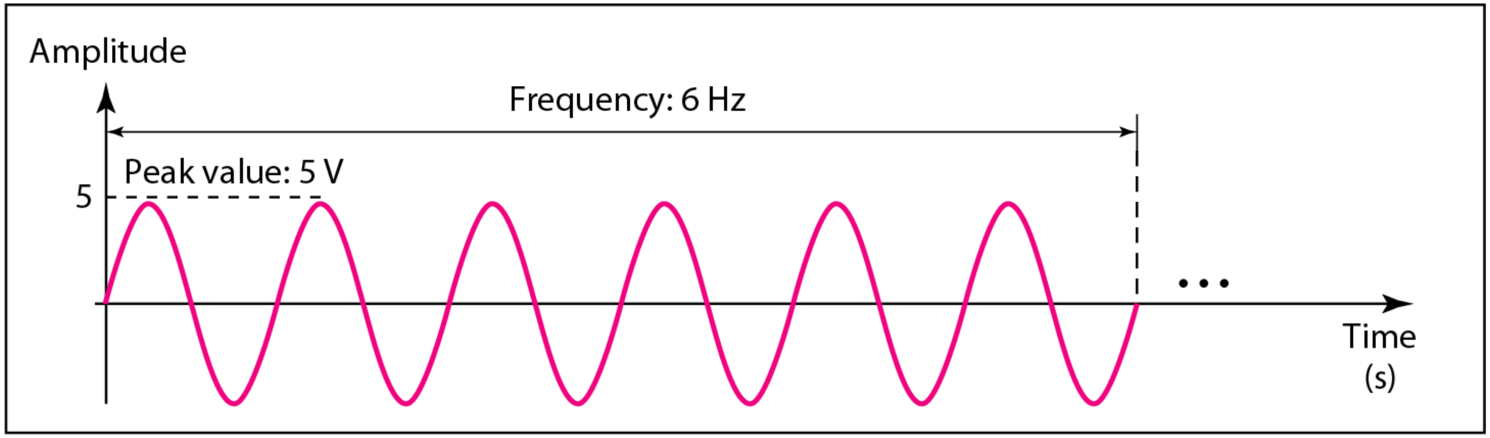


c. 180 degrees

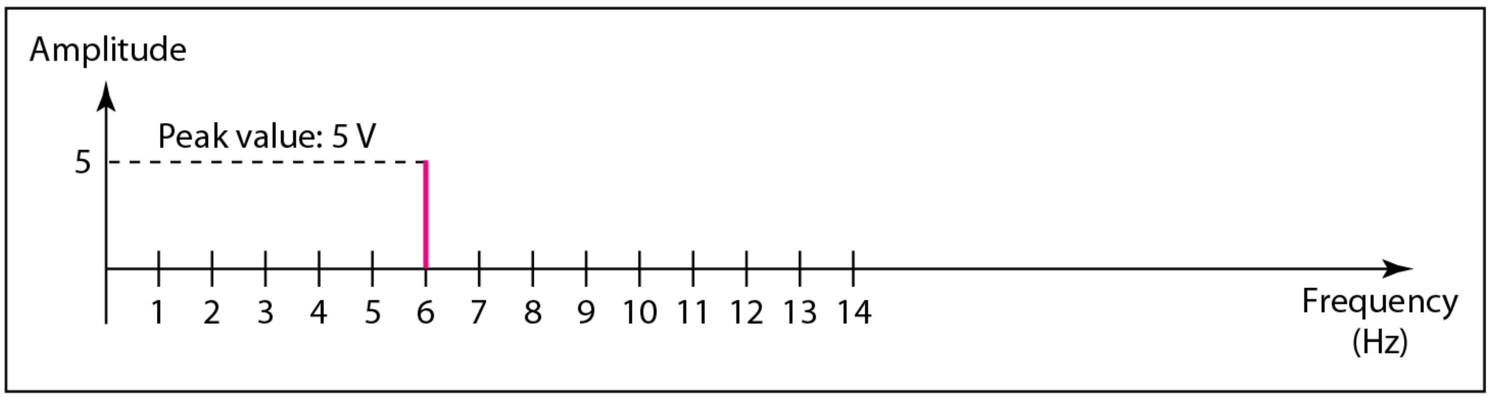
Wavelength and period



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)



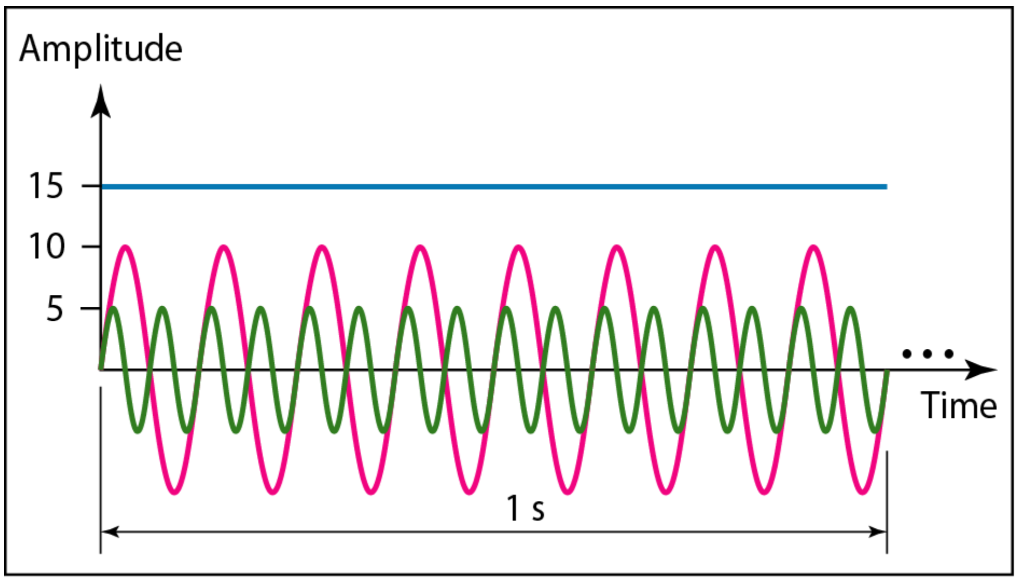
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Note

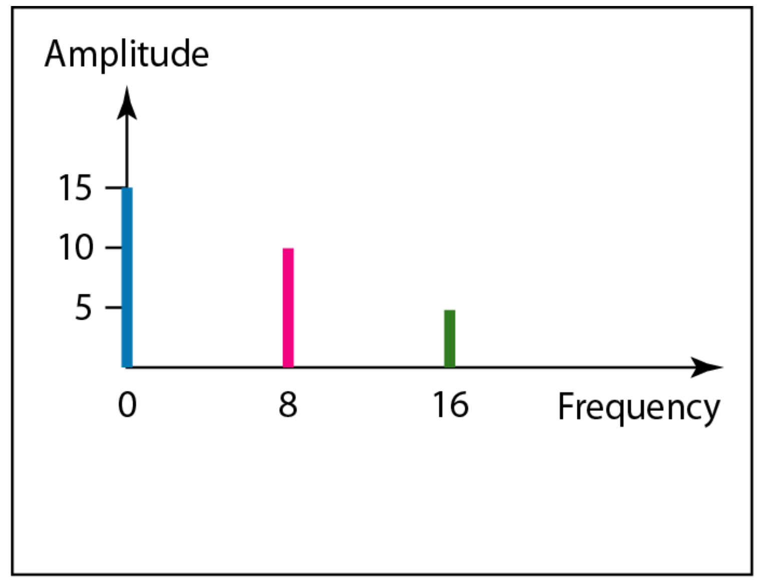
A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

The time domain and frequency domain of three sine waves

The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, the figure shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the 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

Note

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.

Note

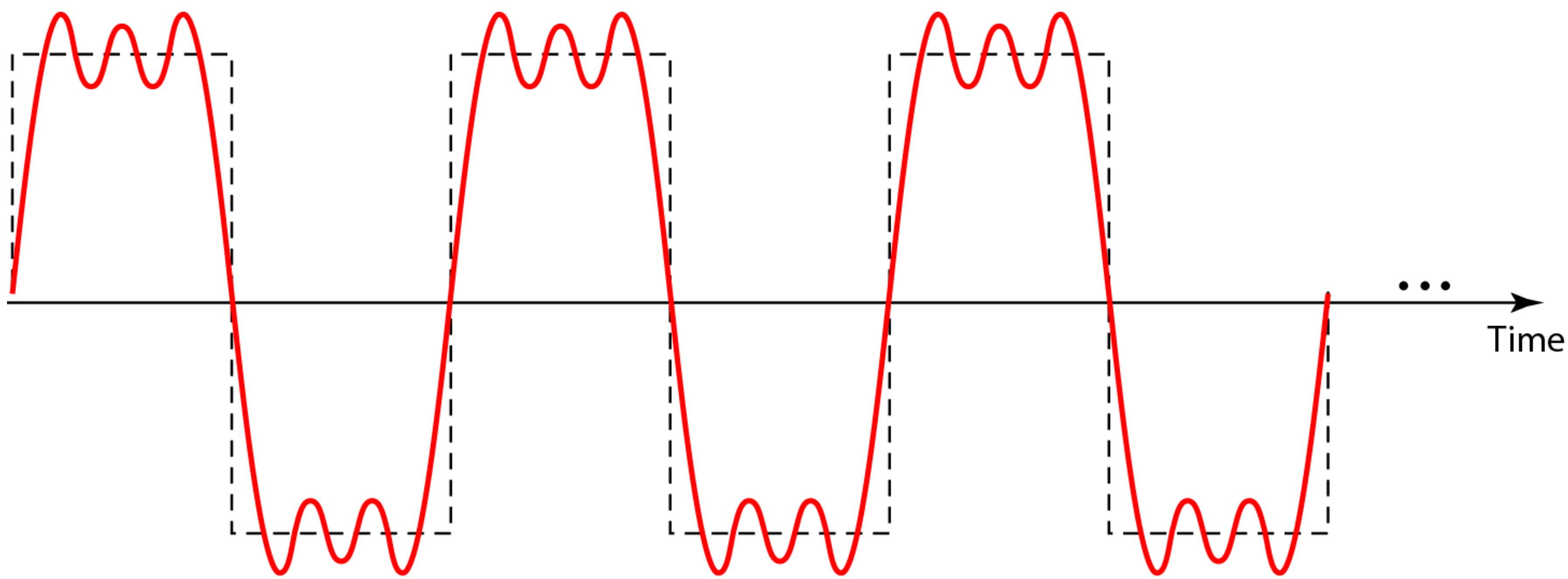
According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.

Note

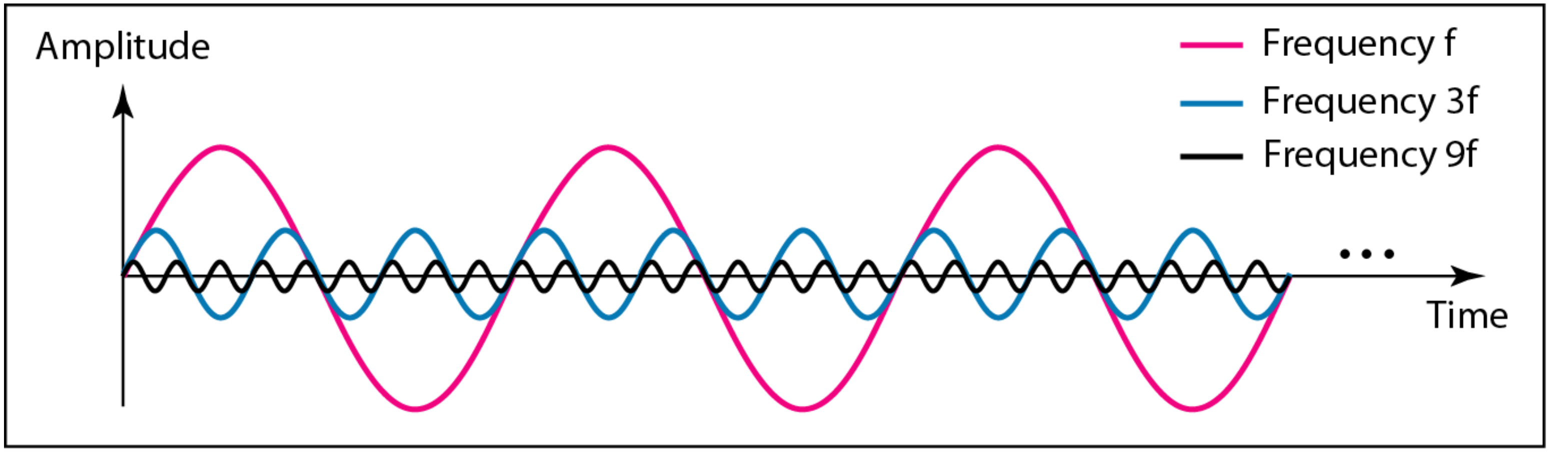
If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies;
if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

A composite periodic signal

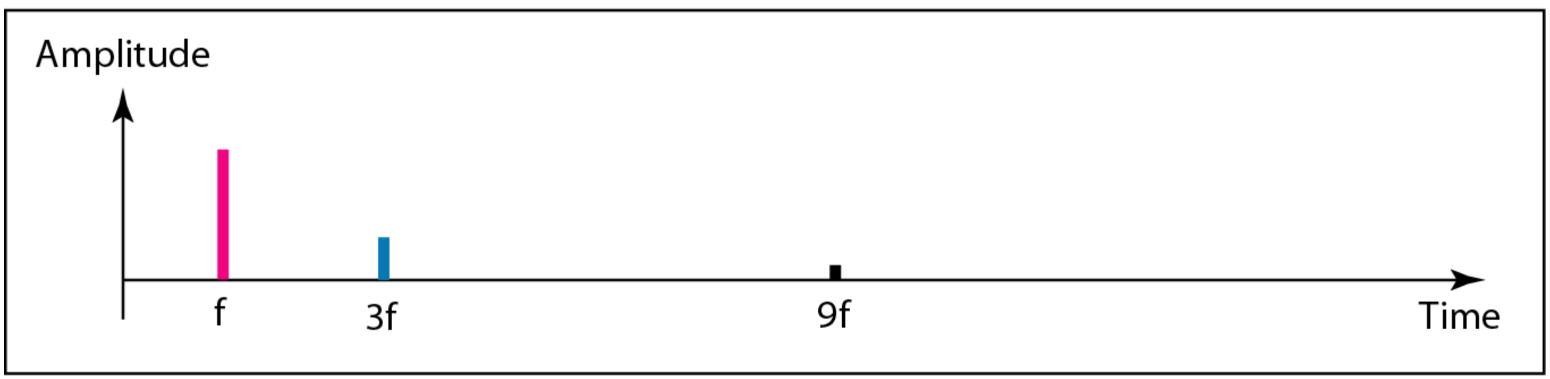
This figure shows a periodic composite signal with frequency f. This type of signal is not typical of those found in data communications. We can consider it to be three alarm systems, each with a different frequency. The analysis of this signal can give us a good understanding of how to decompose signals.



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



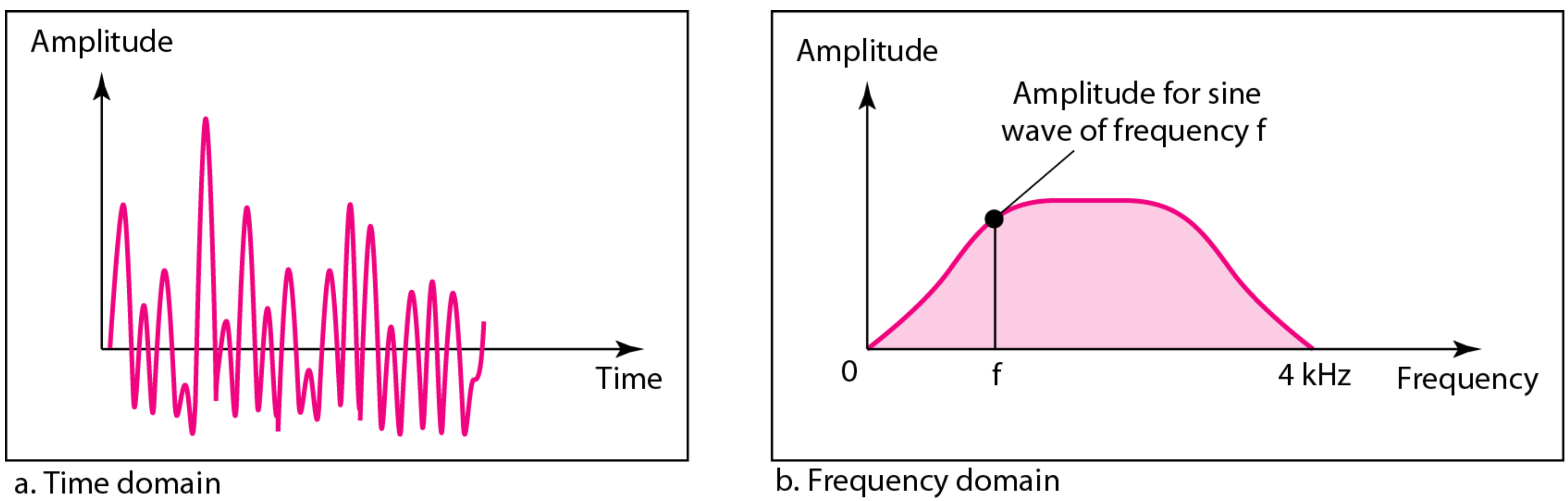
a. Time-domain decomposition of a composite signal



b. Frequency-domain decomposition of the composite signal

The time and frequency domains of a nonperiodic signal

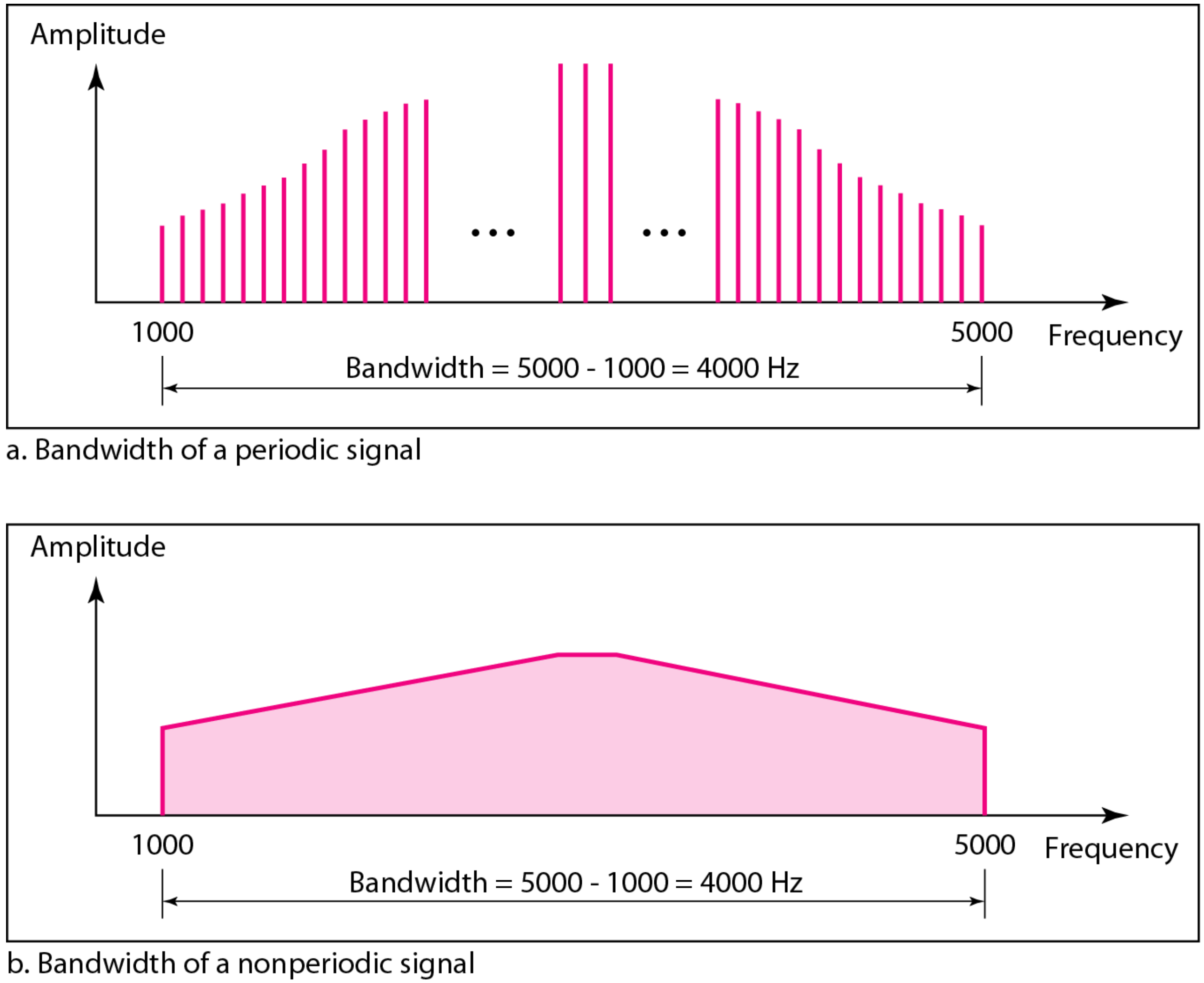
This figure shows a nonperiodic composite signal. It can be the signal created by a microphone or a telephone set when a word or two is pronounced. In this case, the composite signal cannot be periodic, because that implies that we are repeating the same word or words with exactly the same tone.



Note

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

The bandwidth of periodic and nonperiodic composite signals



Example

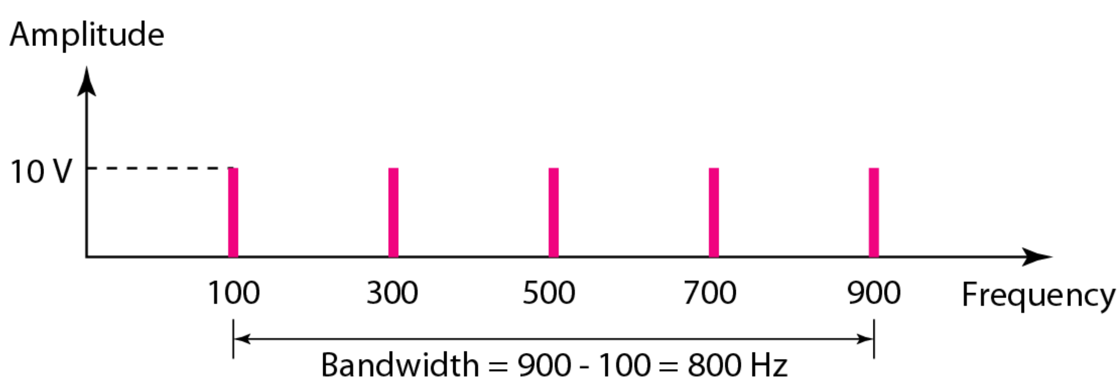
If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

Solution

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

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

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



Examples

An example of a nonperiodic composite signal is the signal propagated by an AM radio station. In the United States, each AM radio station is assigned a 10-kHz bandwidth. The total bandwidth dedicated to AM radio ranges from 530 to 1700 kHz.

Another example of a nonperiodic composite signal is the signal propagated by an FM radio station. In the United States, each FM radio station is assigned a 200-kHz bandwidth. The total bandwidth dedicated to FM radio ranges from 88 to 108 MHz.

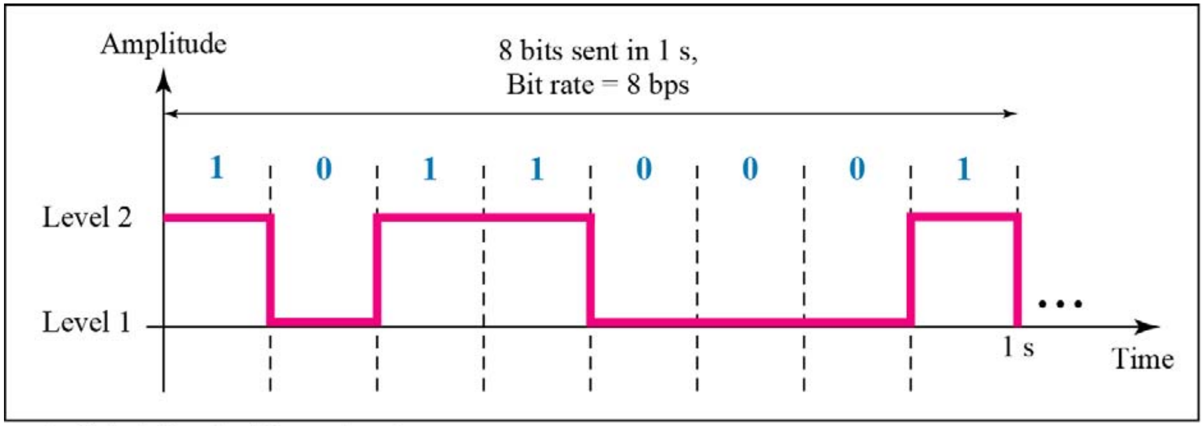
DIGITAL SIGNALS

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.

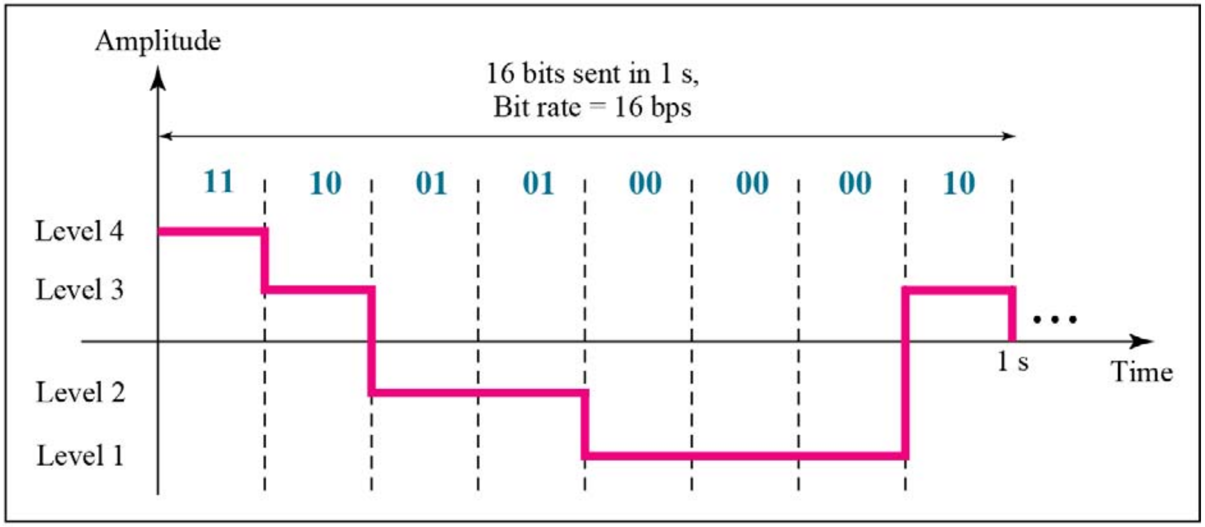
Topics discussed in this section:

Digital Signal as a Composite Analog Signal

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

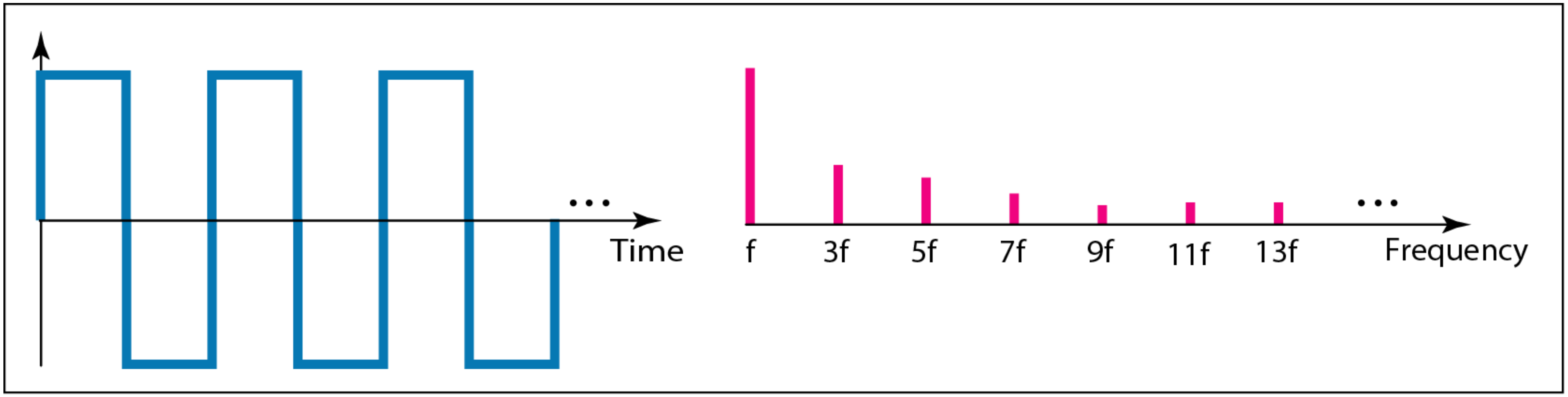


a. A digital signal with two levels

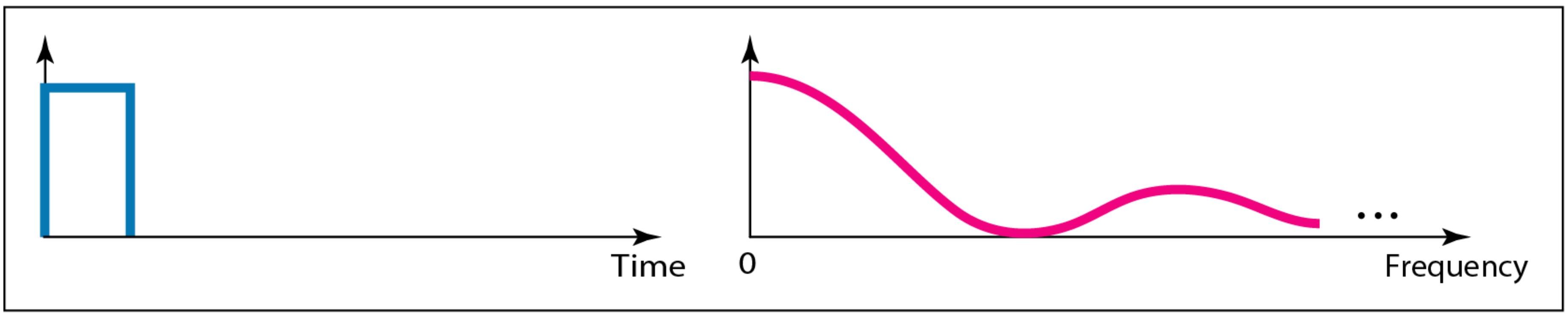


b. A digital signal with four levels

The time and frequency domains of periodic and nonperiodic digital signals

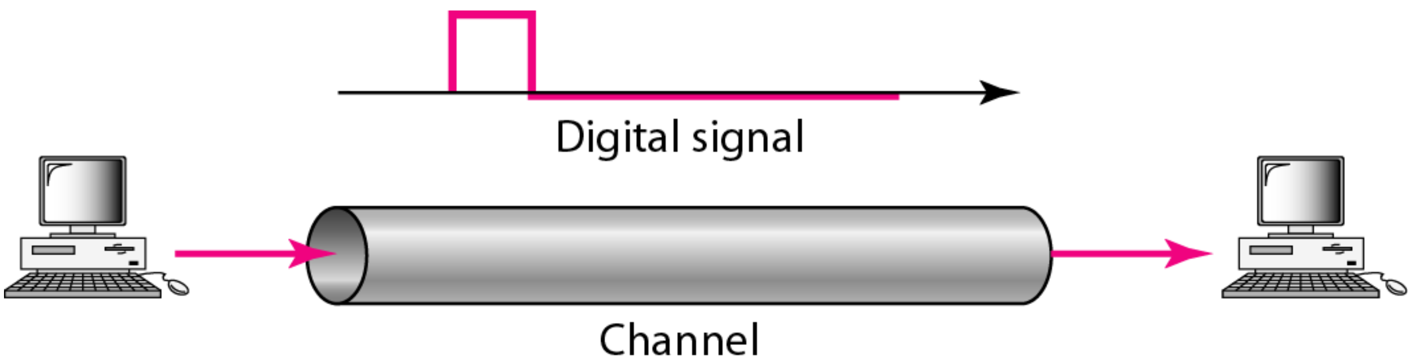


a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

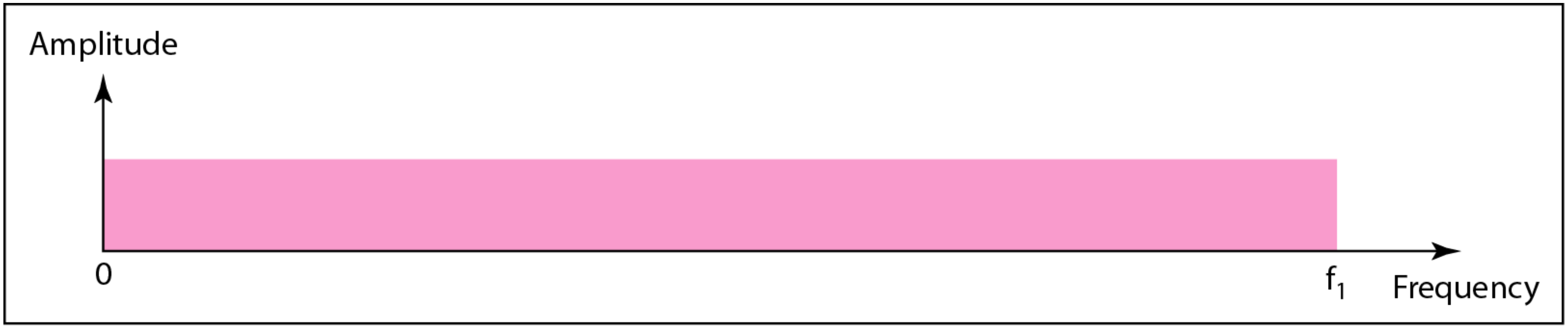
Baseband transmission



Note

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

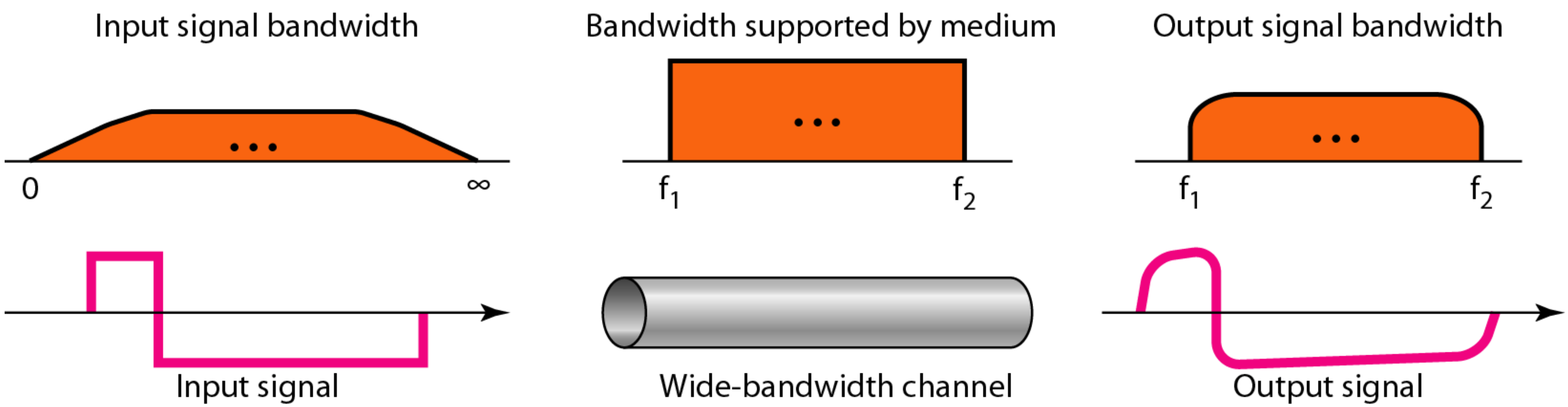
Bandwidths of two low-pass channels



a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

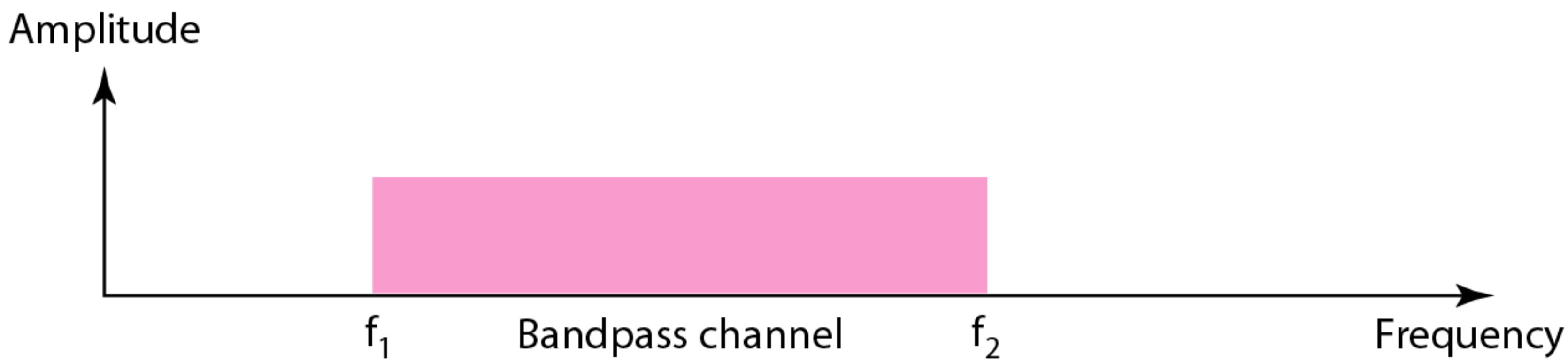
Baseband transmission using a dedicated medium



Note

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.

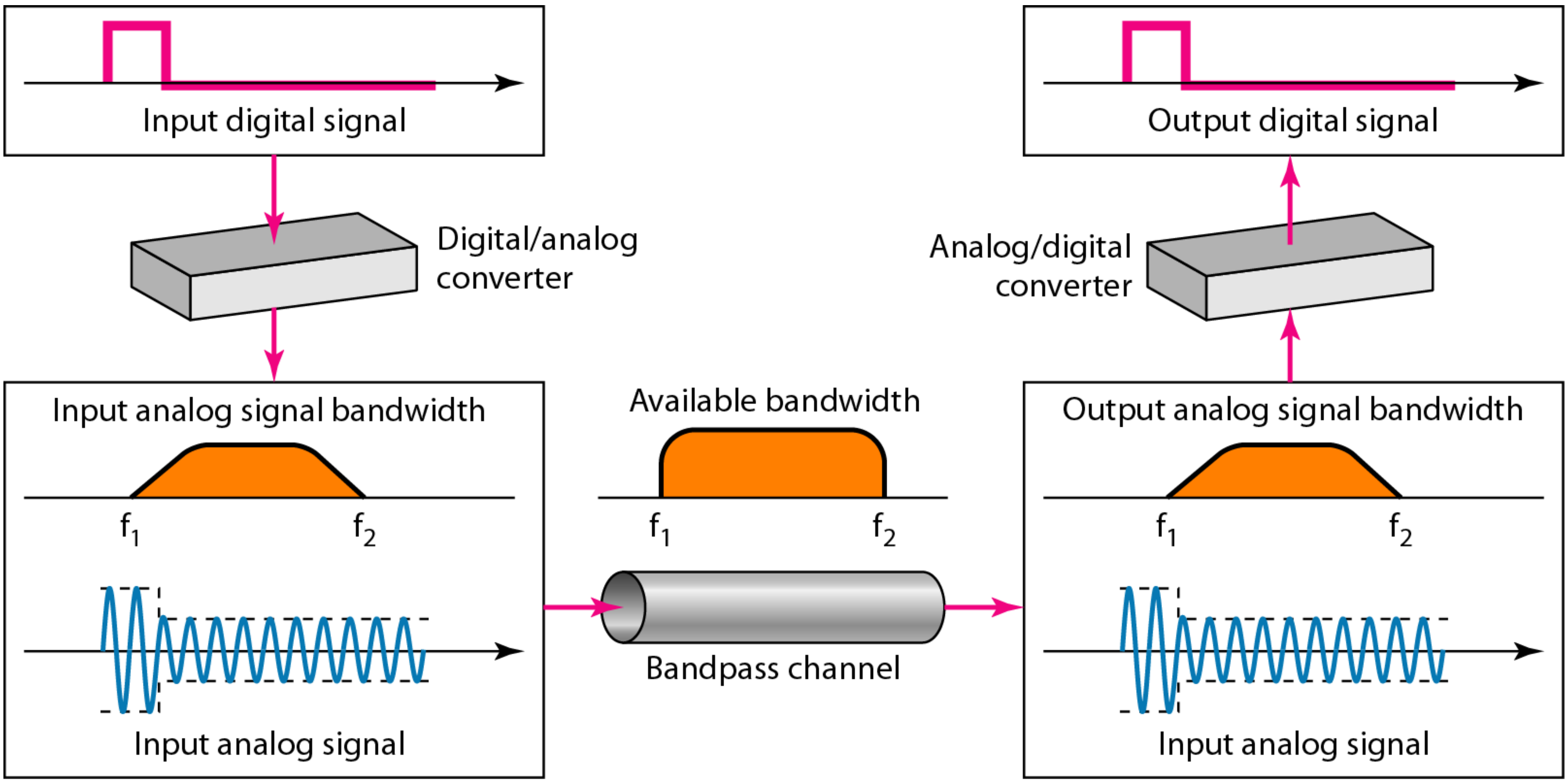
Bandwidth of a bandpass channel



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.

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

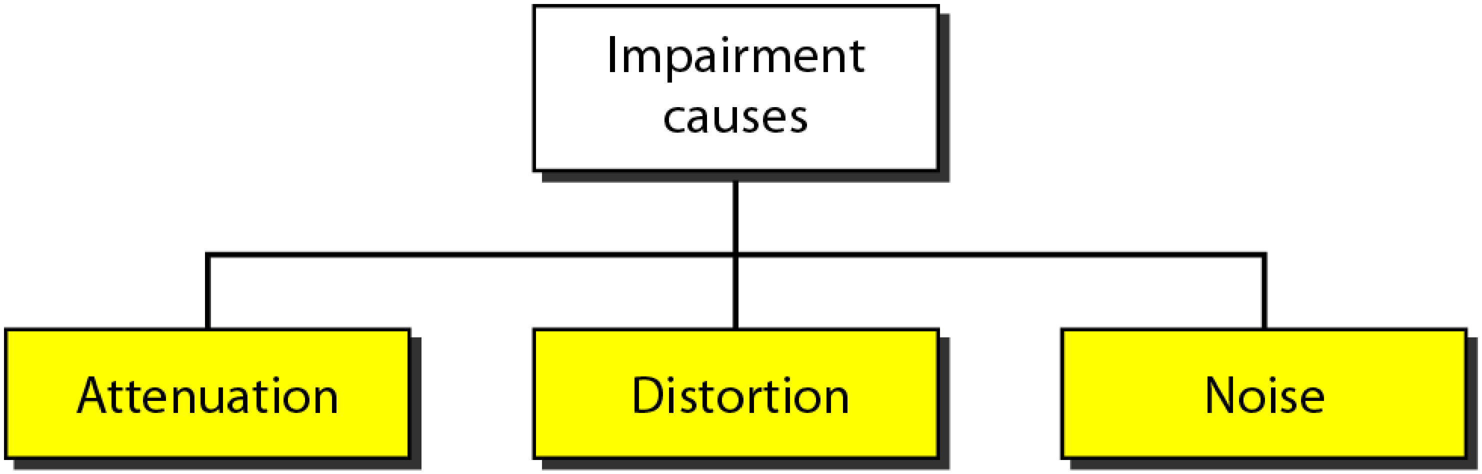
TRANSMISSION IMPAIRMENT

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.

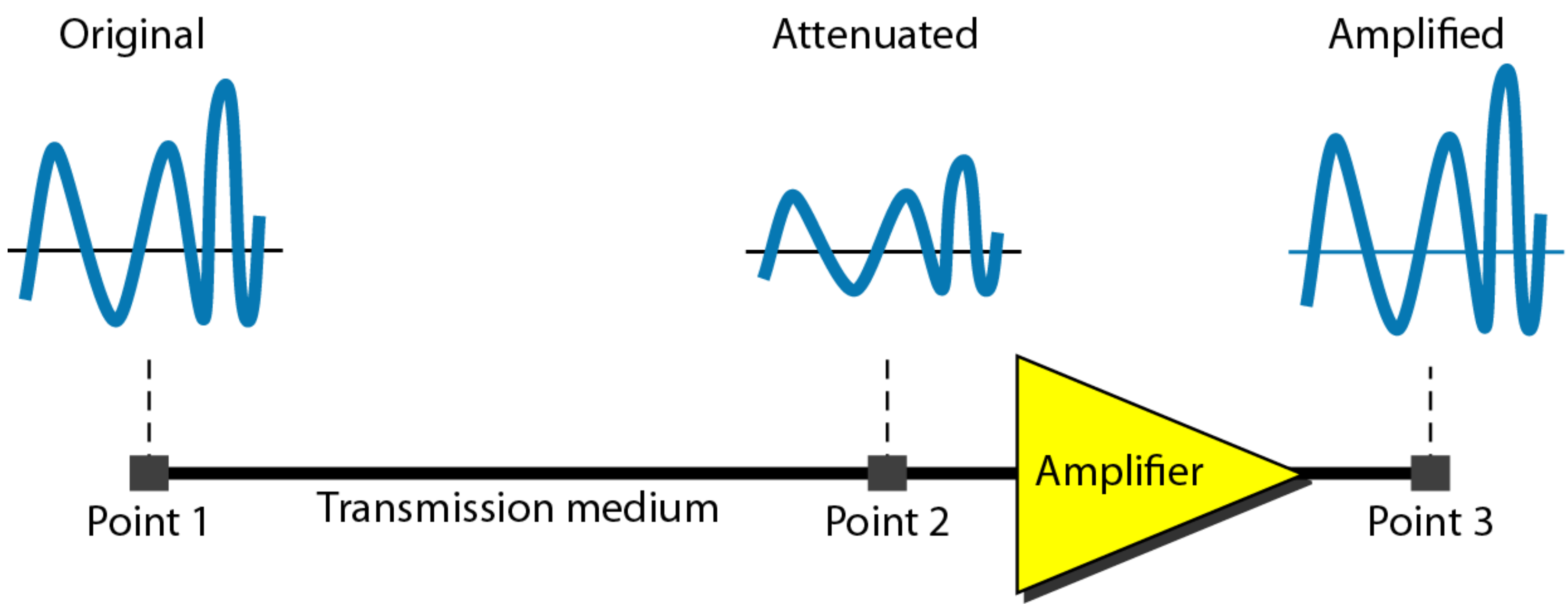
Topics discussed in this section:

- Attenuation
- Distortion
- Noise

Causes of impairment



Attenuation



Example

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P2 is (1/2)P1. In this case, the attenuation (loss of power) can be calculated as

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

A loss of 3 dB (–3 dB) is equivalent to losing one-half the power.

Example

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

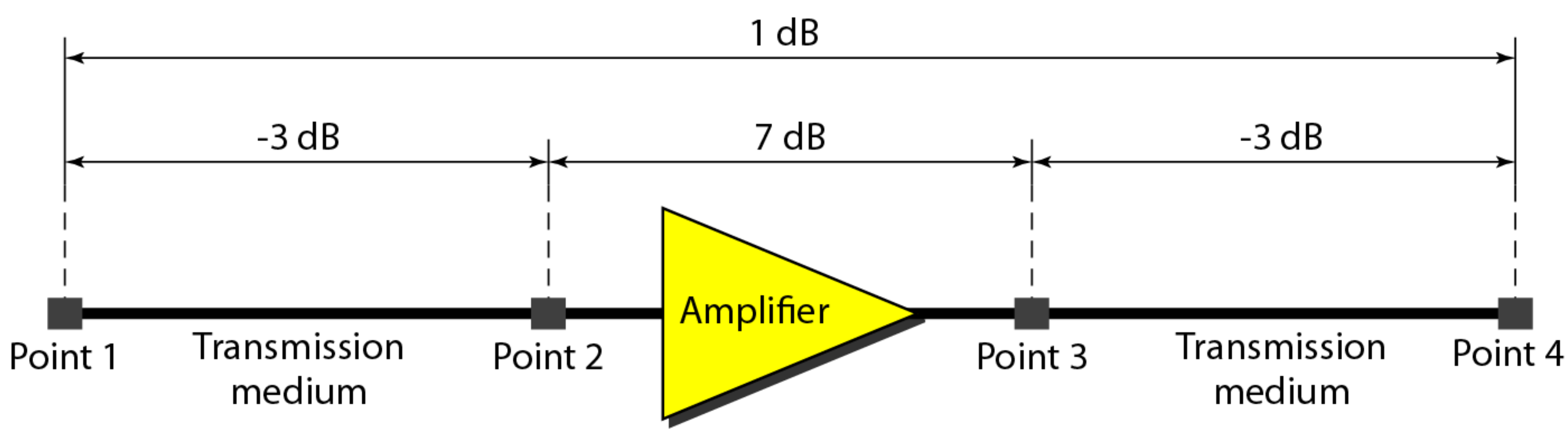
$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1}$$

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

Example

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In this figure a signal travels from point 1 to point 4. In this case, the decibel value can be calculated as

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



Example

Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as $dB_m = 10 \log10 P_m$, where P_m is the power in milliwatts. Calculate the power of a signal with $dB_m = -30$.

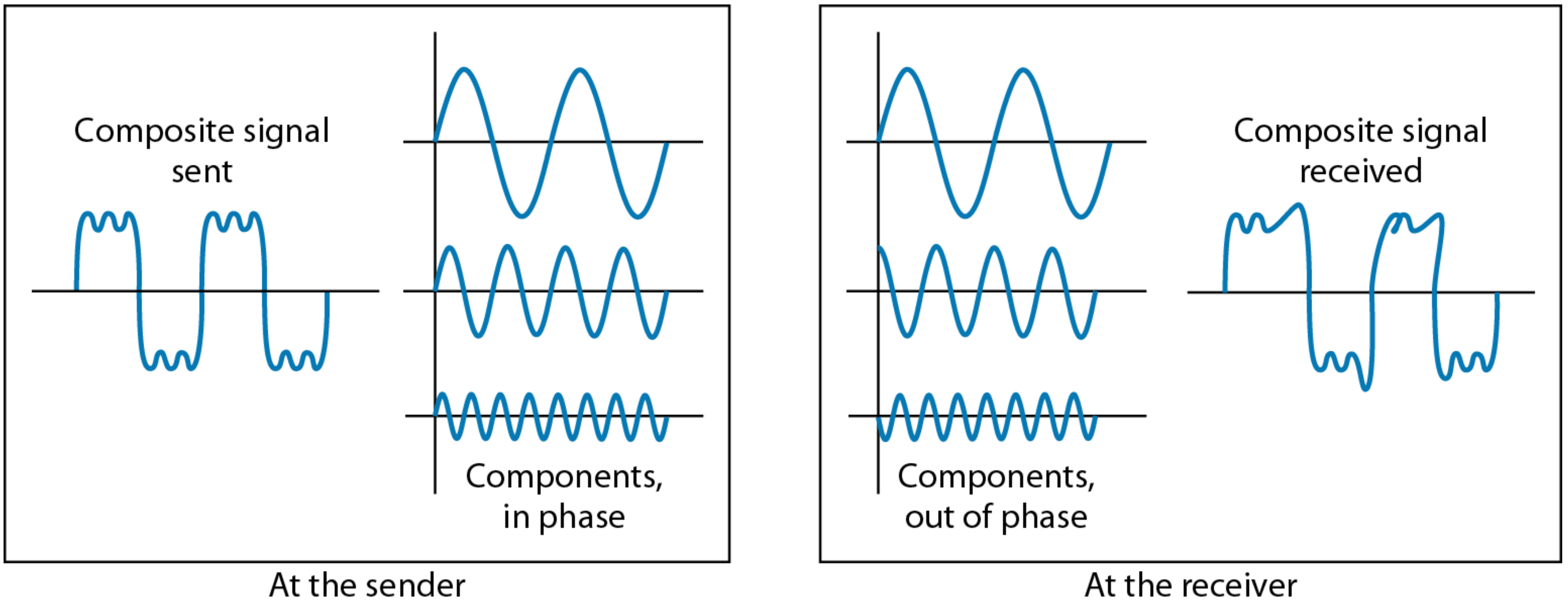
Solution

We can calculate the power in the signal as

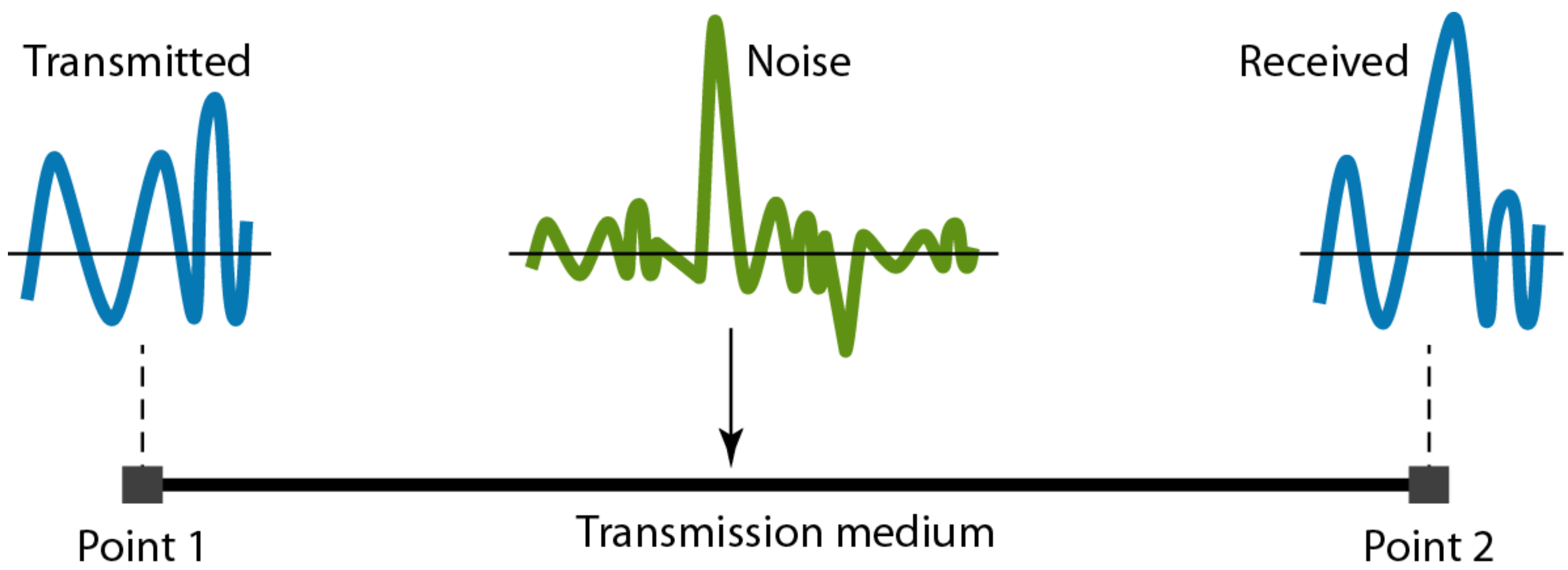
$$\mathrm{dB_m} = 10 \log_{10} P_m = -30$$

$$\log_{10} P_m = -3 \qquad P_m = 10^{-3}\ \mathrm{mW}$$

Distortion

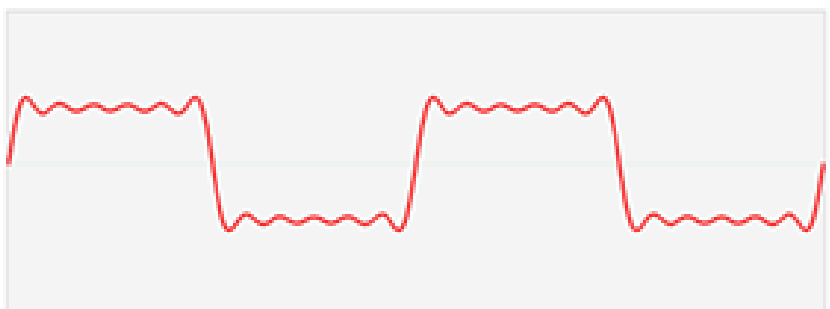

Composite signal sent
Components, in phase
At the sender
Components, out of phase
Composite signal received
At the receiver

Noise



Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Recap: Time domain vs Frequency domain



Signal-to-Noise Ratio (SNR)

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

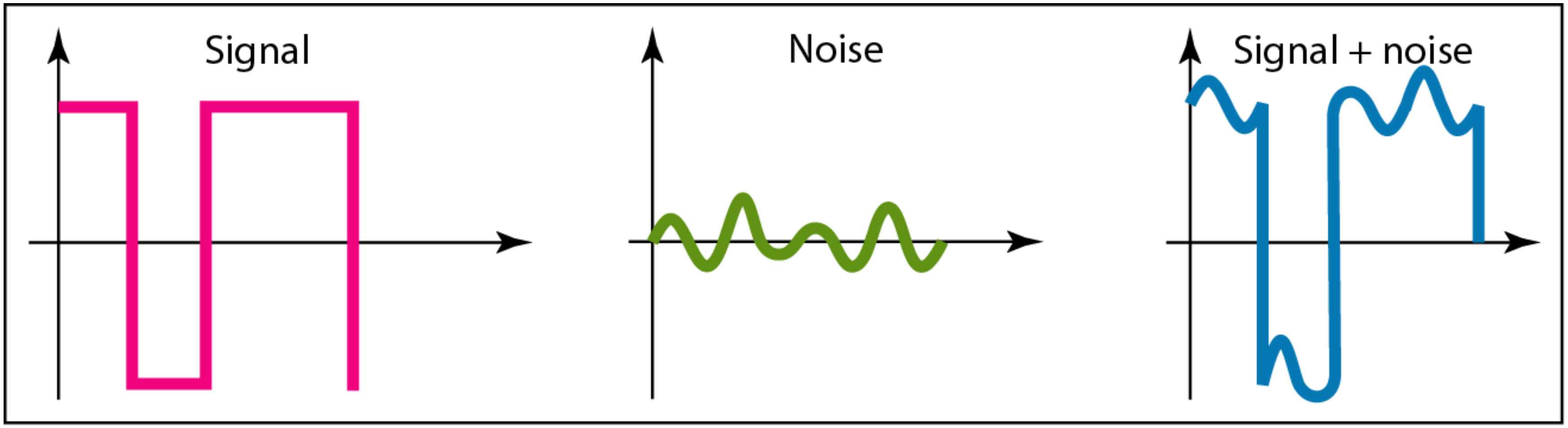
The values of SNR and SNRdB for a noiseless channel are

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

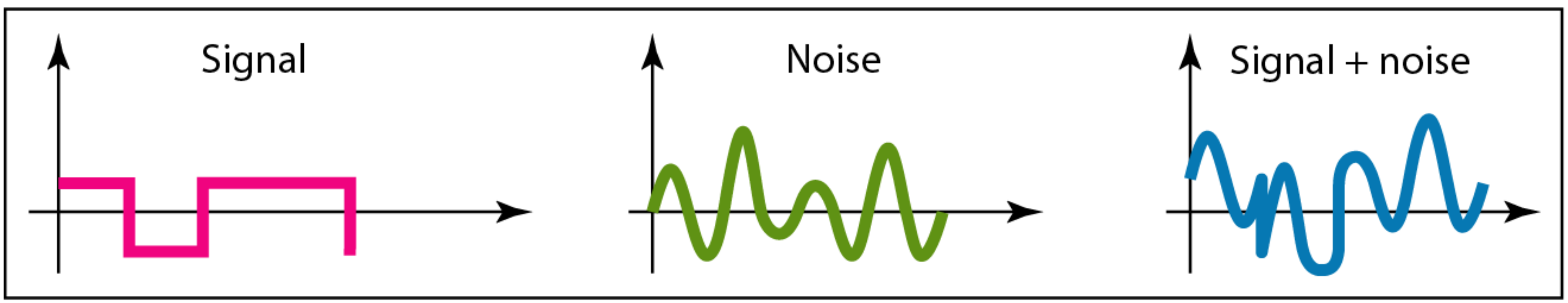
$$\mathrm{SNR_{dB}} = 10 \log_{10} \infty = \infty$$

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

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



a. Large SNR



b. Small SNR

Data Rate Limit

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel.

The upper limit is given by Shannon Capacity: the theoretical highest data rate for a noisy channel is given by

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

B is the bandwidth of the channel, SNR is the signal-to-noise ratio, and capacity is the capacity of the channel in bits per second

Example

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

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

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

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

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

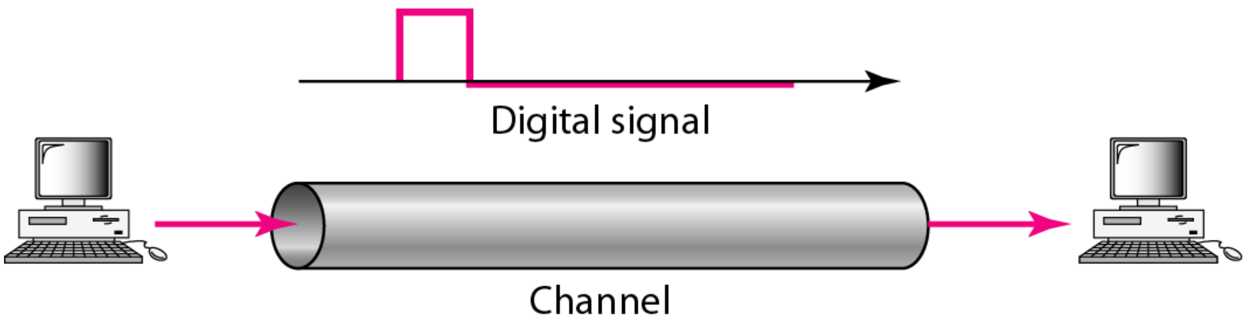
$$C = B \log_2 (1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$$

Roadmap

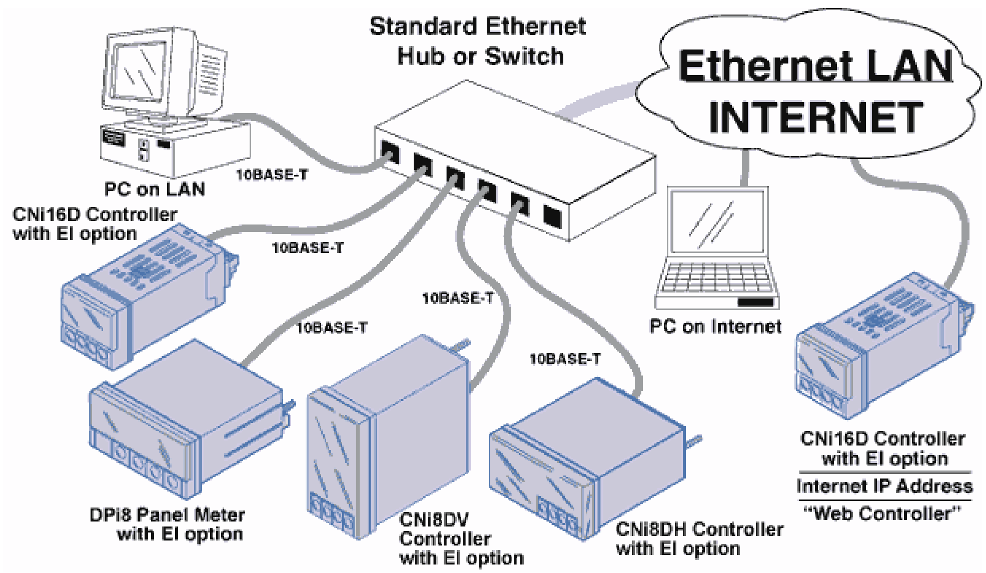
- Data and Signals
- Digital Transmission
- Analog Transmission
- Why Digital Communications?
- Block diagram of digital transmissions

Digital Transmission

- Baseband digital transmission

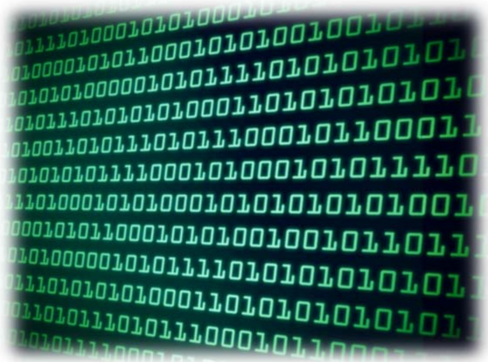


- Example: Ethernet transmission via twisted pair cable



Data Representation

- We have data of binary sequence

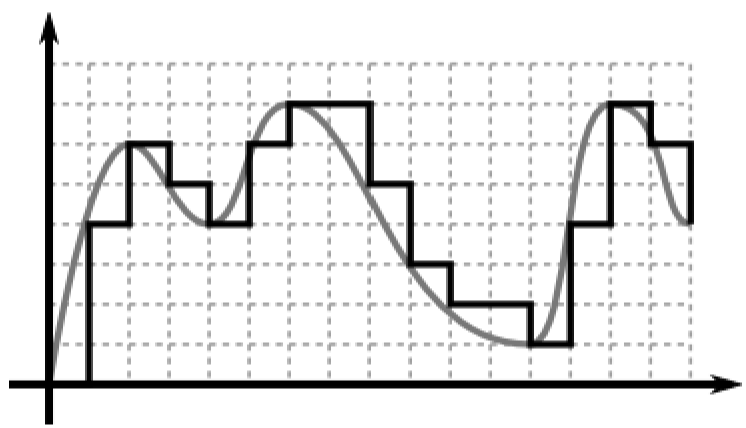


- Bit Rate (Data rate): N
  - The bit rate is the number of bits sent in 1 second.
  - Expressed in bits per second (bps)
  - Example: assume we need to download text documents at the rate of 100 pages per minute. A page is an average of 24 lines with 80 characters in each line. What is the required bit rate of the channel if we assume that one character requires 8 bits ?

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

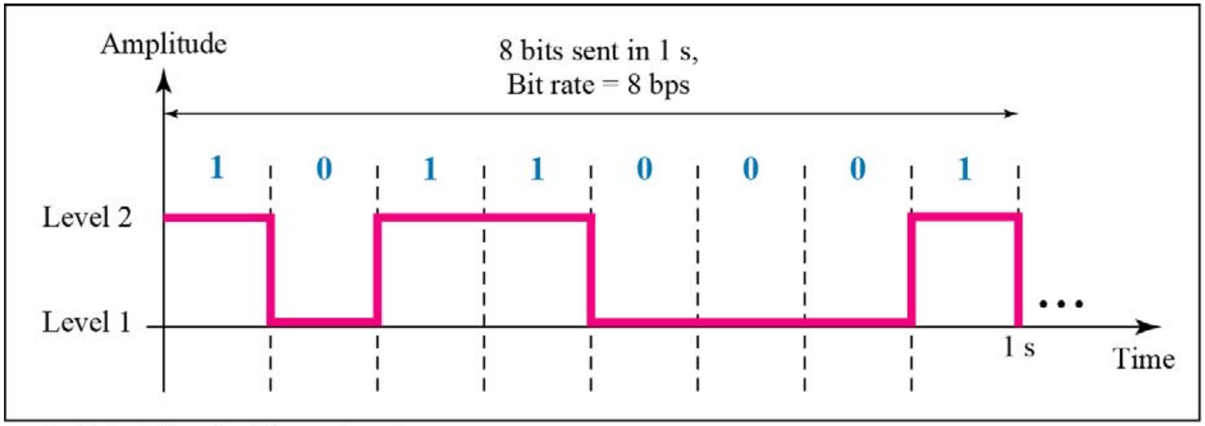
Digital Signals

- To be transmitted, data must be transformed to electromagnetic signals.
- Digital Signal
  - Binaries are represented by a digital signal
  - For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage.
  - In case of more than two levels, we can send more than 1 bit for each level.

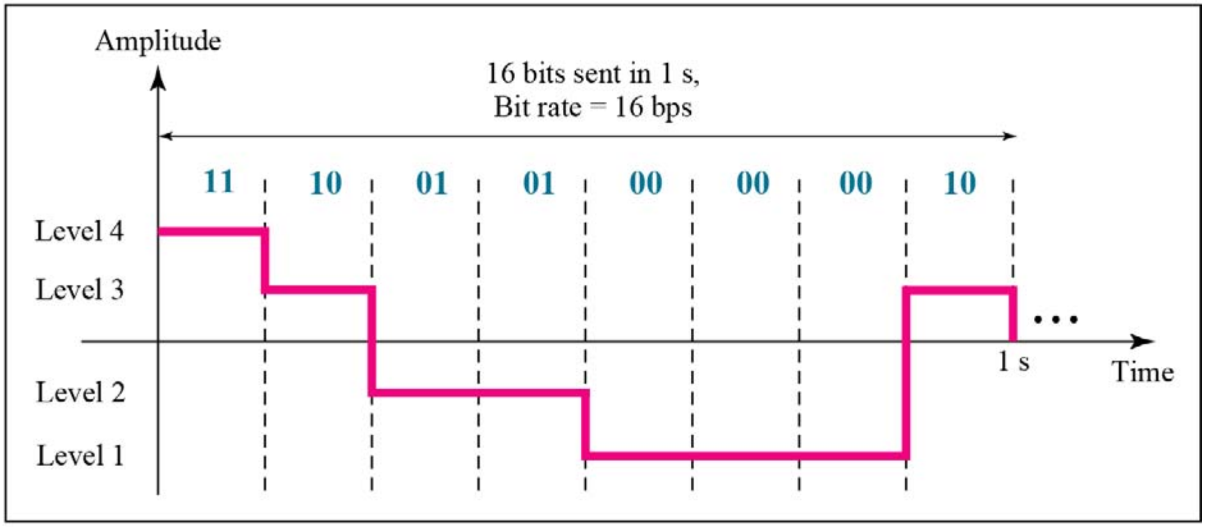


Example of Digital Signals

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



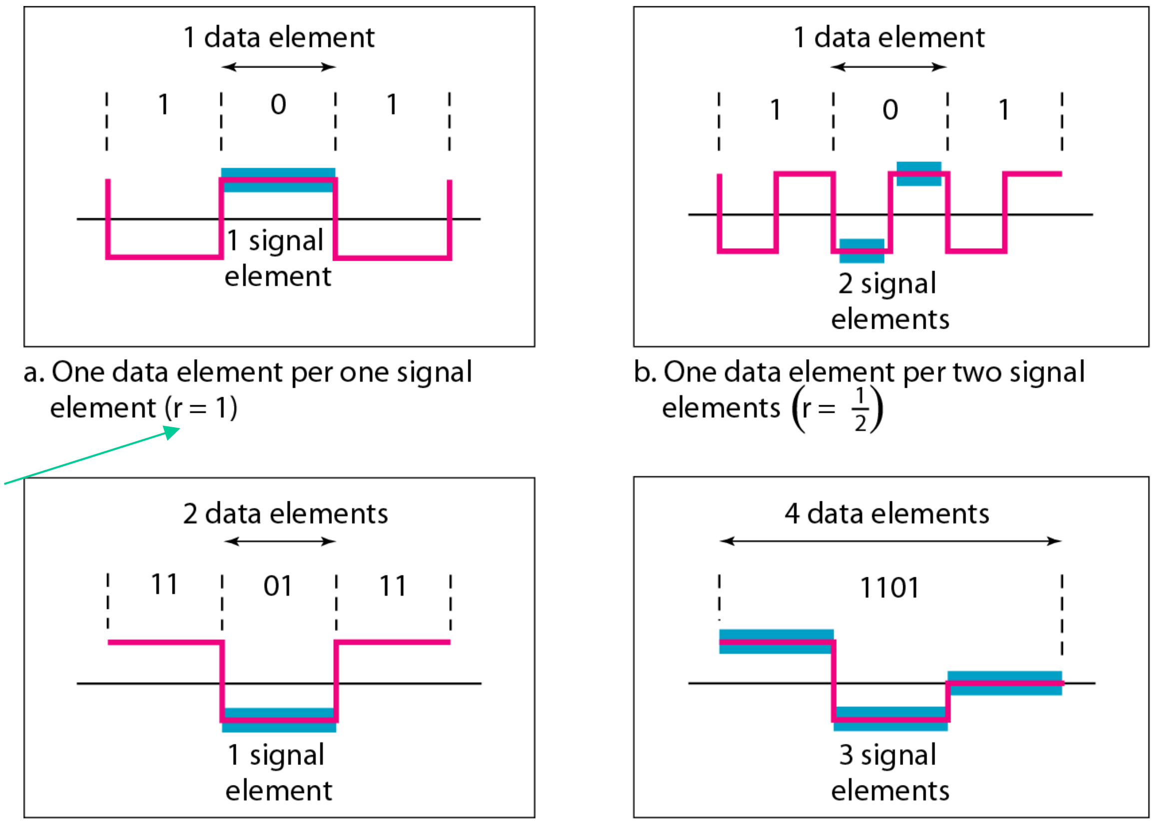
a. A digital signal with two levels



b. A digital signal with four levels

Baud Rate

- Baud Rate (Signal Rate): S
  - It is the number of distinct symbol (signal elements/levels) changes made to the transmission medium per second



a. One data element per one signal element ($r = 1$)

b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$

c. Two data elements per one signal element ($r = 2$)

d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

The number of bits carried by one symbol

S=N/r

Notes

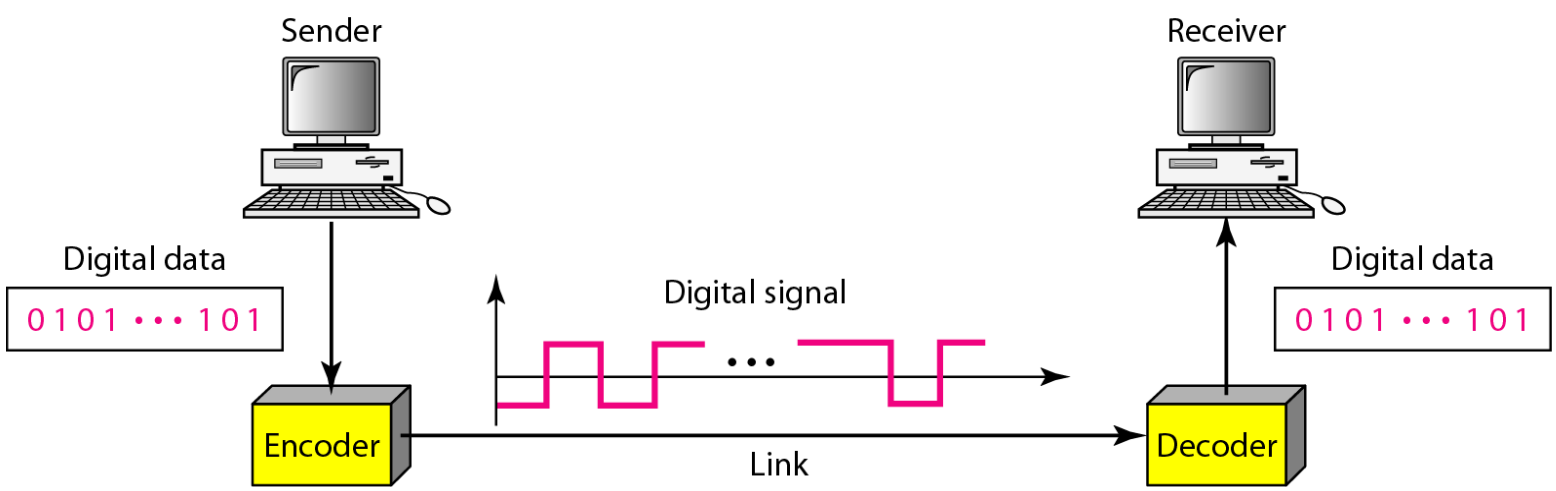
- One goal in data communications is to increase the data rate while decreasing the signal rate

- Transmitting one symbol requires certain network resource (i.e., CPU clocks). If one symbol represents more bits, one can increase the data rate.

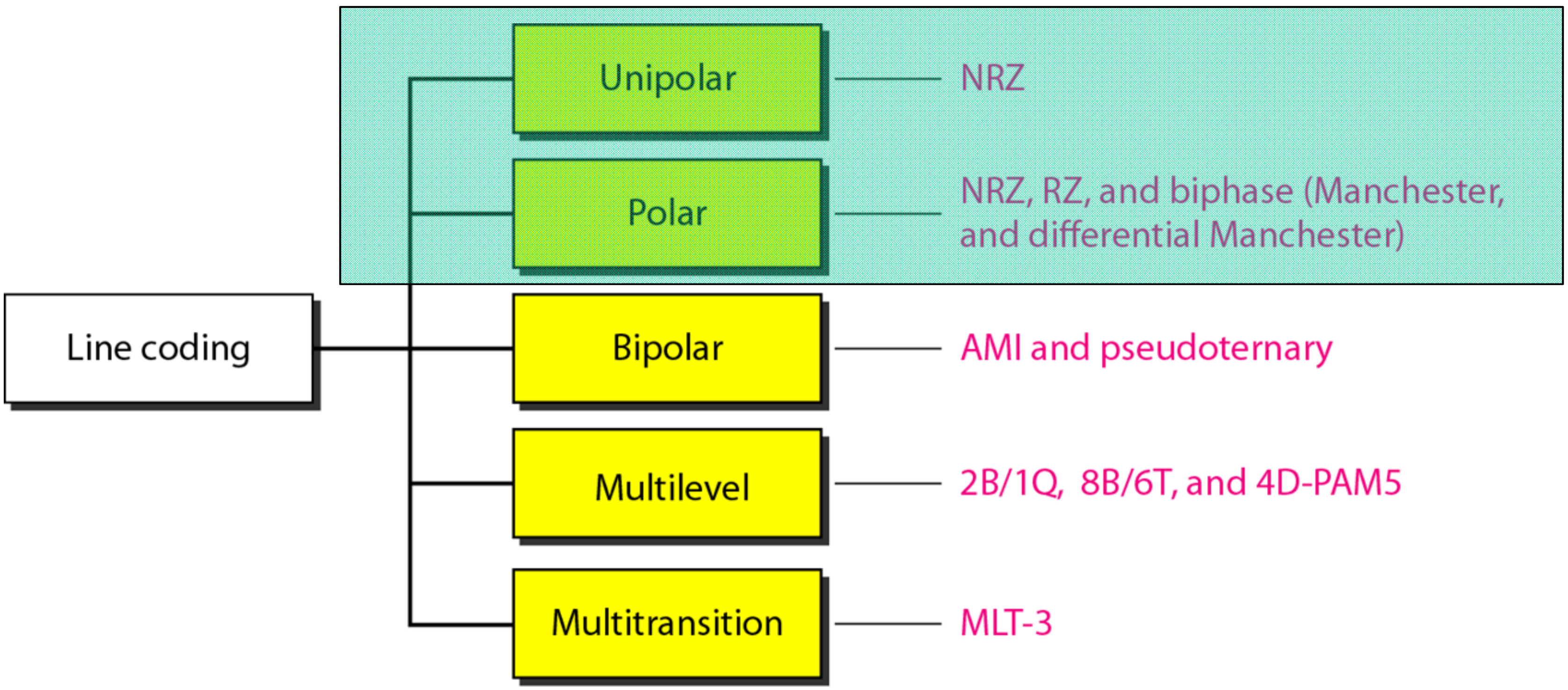
- Vehicle-people analogy
  - We need to carry more people in fewer vehicles to prevent traffic jams
  - Because we have limited bandwidth (resource) in our transportation system

Line Coding

- Line coding is the process of converting binaries to digital signals.
- At the sender, digital data are encoded into a digital signal.
- At the receiver, the digital data are recreated by decoding the digital signal.

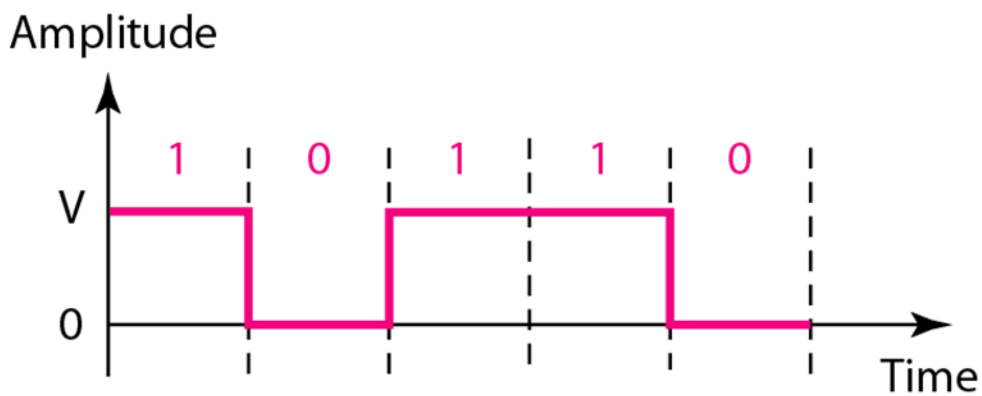


Line Coding Schemes



Unipolar Scheme

- In unipolar scheme: all the signal levels are on one side of the time axis, either above or below
- NRZ (Non-Return-to-Zero): the signal does not return to zero at the middle of the bit
  - Positive voltage defines bit 1
  - Zero voltage defines bit 0

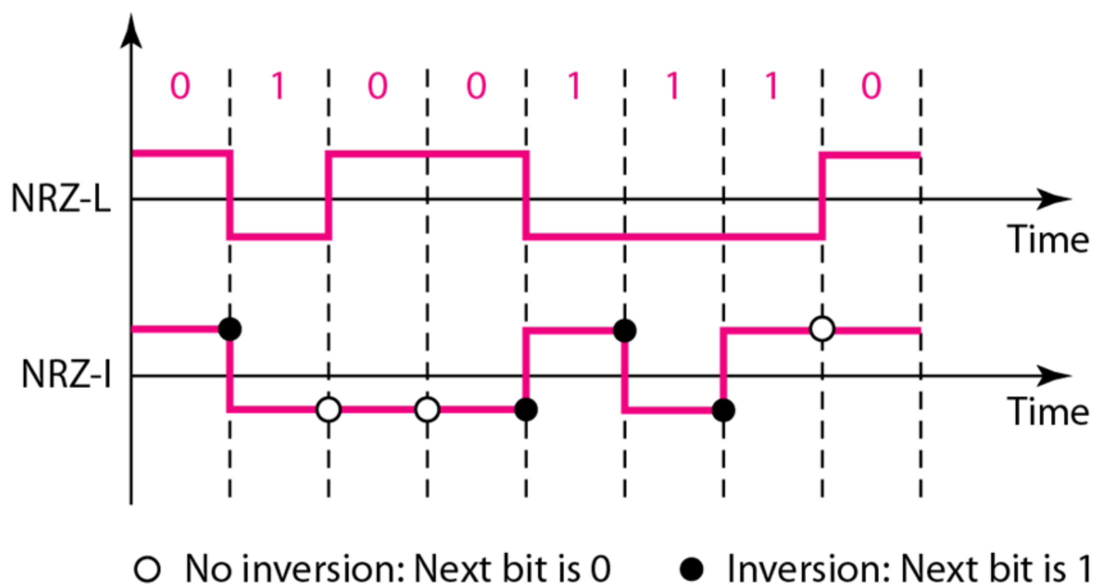


$$\frac{1}{2}V^2 + \frac{1}{2}(0)^2 = \frac{1}{2}V^2$$

Normalized power

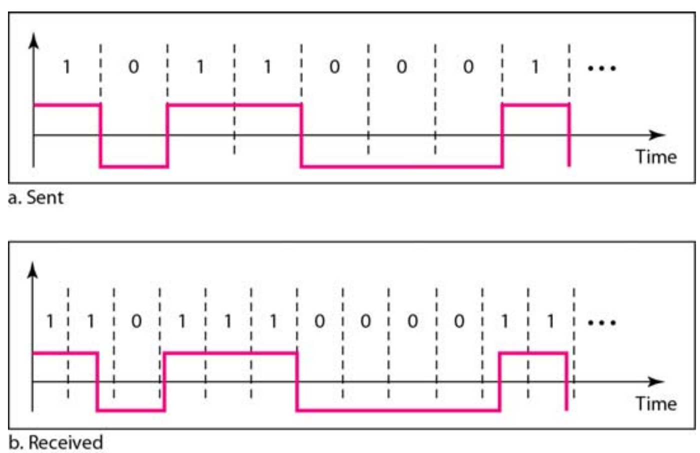
Polar Schemes

- In polar scheme: the voltages are on both sides of the time axis. For example, the voltage are level for 0 can be positive and the voltage level for 1 can be negative
- Polar NRZ
  - NRZ-L (NRZ-Level): the level of the voltage determines the value of bit
  - NRZ-I (NRZ-Invert): change voltage (1); no change (0)



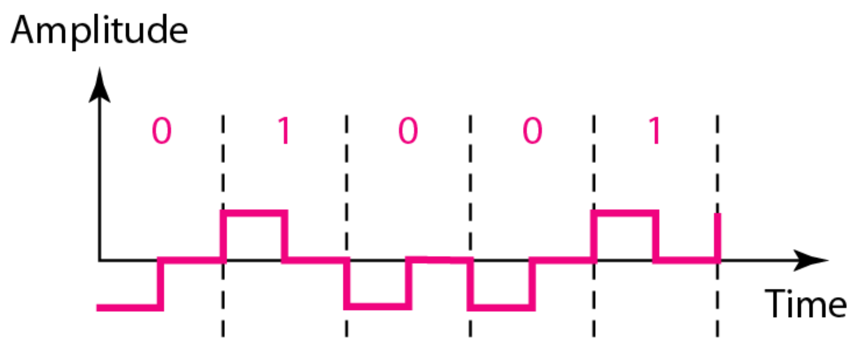
Criterion of Schemes Comparison

- Baseline Wandering
  - Baseline: a running average (in a time window) of the received signal power
  - Incoming signal power is evaluated against this baseline to determine the signal level
  - A long string of 0s and 1s can cause a drift in the baseline
  - A good line coding scheme needs to prevent baseline wandering
- Self-synchronization
  - If there are transitions in the signal that alert the receiver to the beginning, middle or end of the pulse
  - If the receiver's clock is out of synchronization, these points can reset the clock



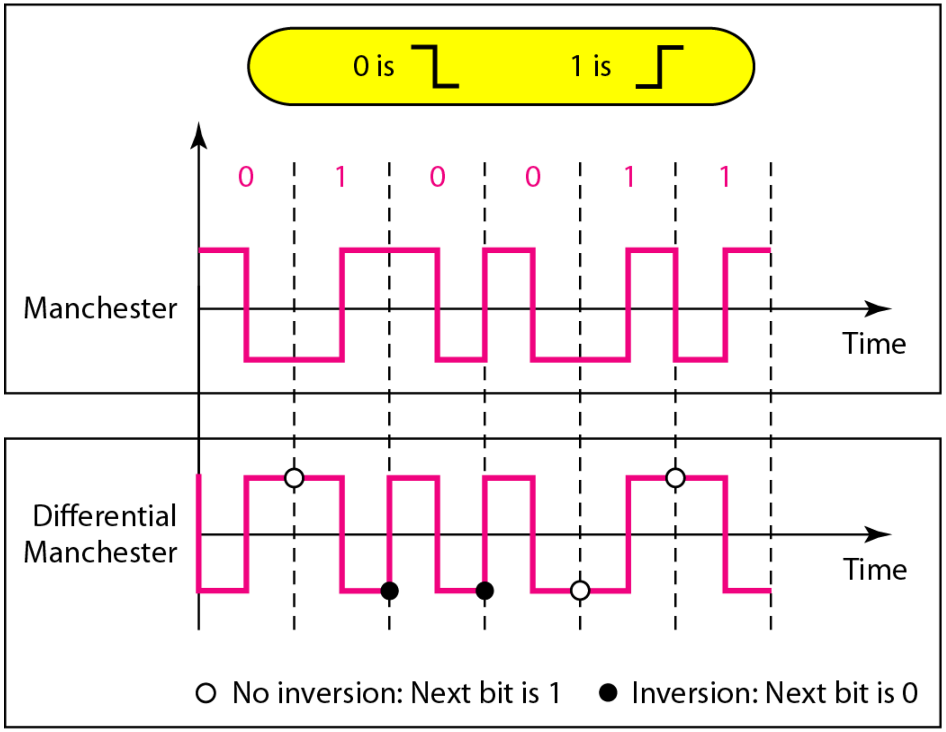
Polar RZ (Return-to-Zero)

- Polar RZ
  - Uses three voltages: positive, negative, and zero
  - The signal goes to 0 in the middle of each bit



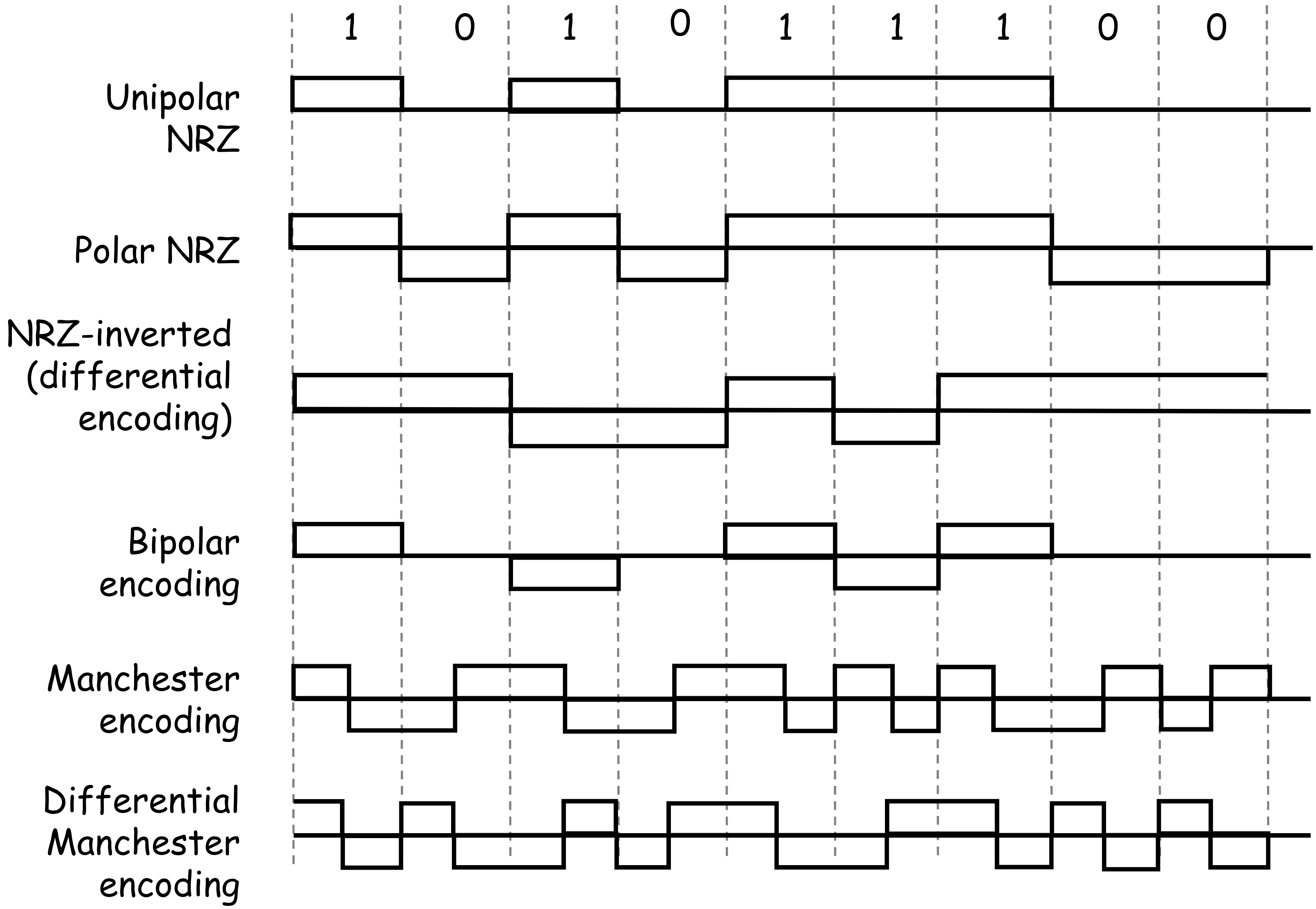
Polar Biphase

- Manchester
- Differential Manchester



In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization

Line coding examples



Roadmap

- Data and Signals
- Digital Transmission
- Analog Transmission
- Why Digital Communications?
- Block diagram of digital transmissions

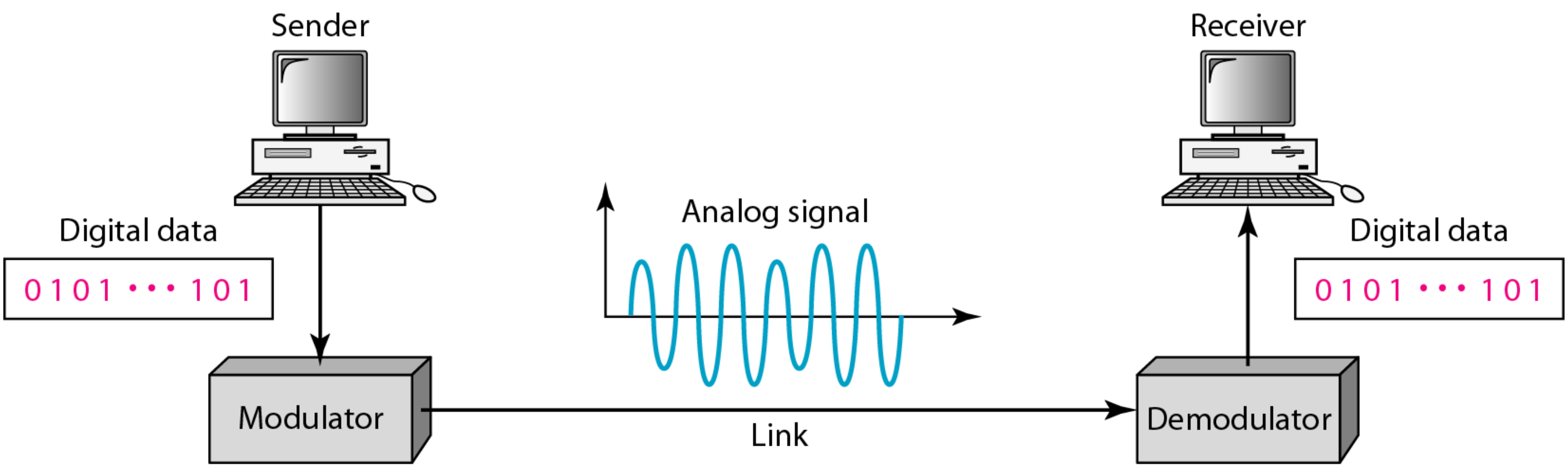
DIGITAL-TO-ANALOG CONVERSION

Digital-to-analog conversion is the process of changing one of the characteristics of an analog signal based on the information in digital data.

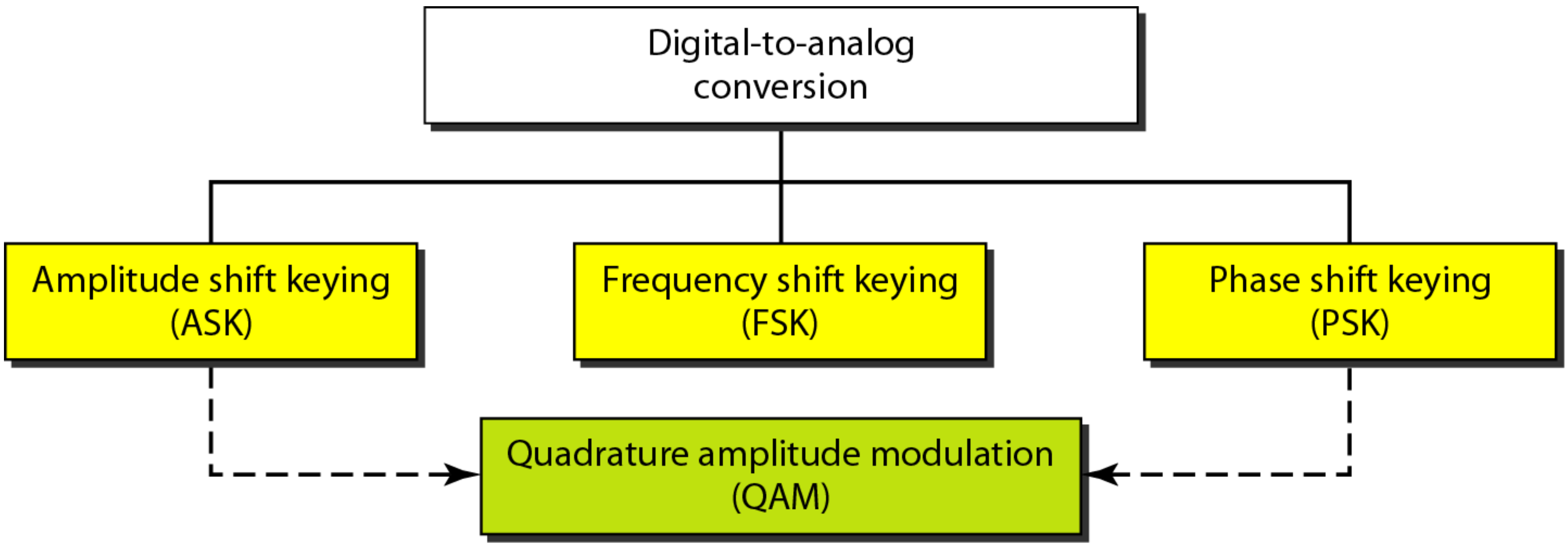
Topics discussed in this section:

Aspects of Digital-to-Analog Conversion
Amplitude Shift Keying
Frequency Shift Keying
Phase Shift Keying
Quadrature Amplitude Modulation

Digital-to-analog conversion



Types of digital-to-analog conversion



Note

Bit rate is the number of bits per second. Baud rate is the number of signal elements per second.

In the analog transmission of digital data, the baud rate is less than or equal to the bit rate.

Example

An analog signal carries 4 bits per signal element. If 1000 signal elements are sent per second, find the bit rate.

Solution

In this case, r = 4, S = 1000, and N is unknown. We can find the value of N from

$$S = N \times \frac{1}{r} \qquad \text{or} \qquad N = S \times r = 1000 \times 4 = 4000 \text{ bps}$$

Example

An analog signal has a bit rate of 8000 bps and a baud rate of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?

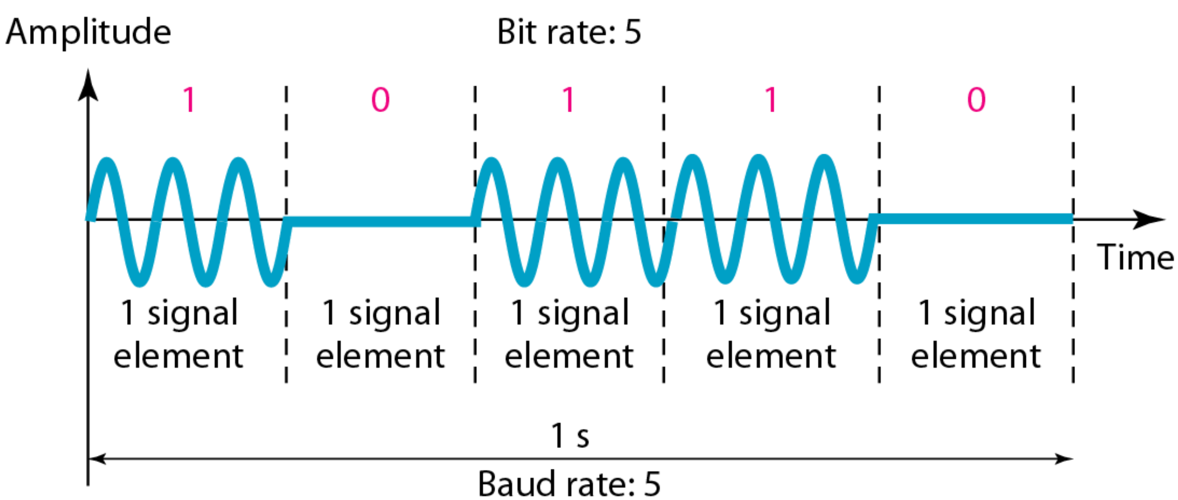
Solution

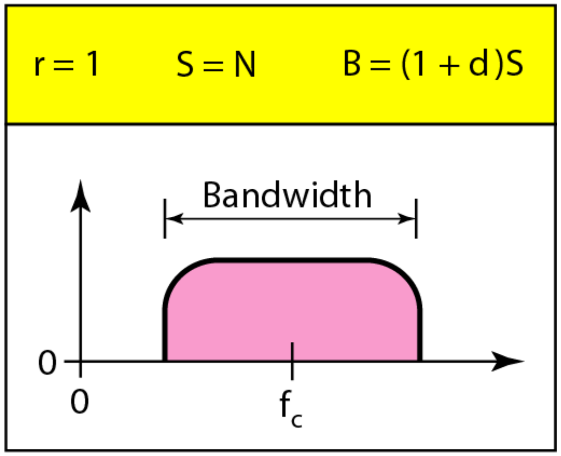
In this example, S = 1000, N = 8000, and r and L are unknown. We find first the value of r and then the value of L.

$$S = N \times \frac{1}{r} \quad \rightarrow \quad r = \frac{N}{S} = \frac{8000}{1000} = 8 \text{ bits/baud}$$

$$r = \log_2 L \quad \rightarrow \quad L = 2^r = 2^8 = 256$$

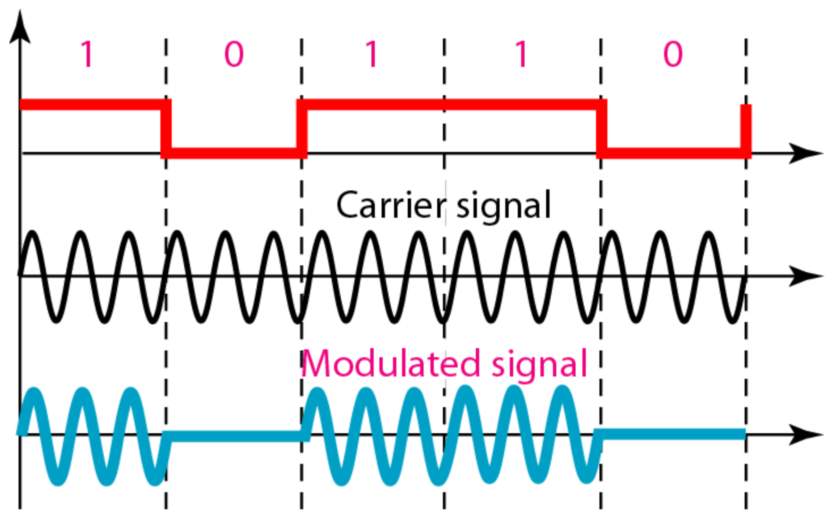
Binary amplitude shift keying (BASK)

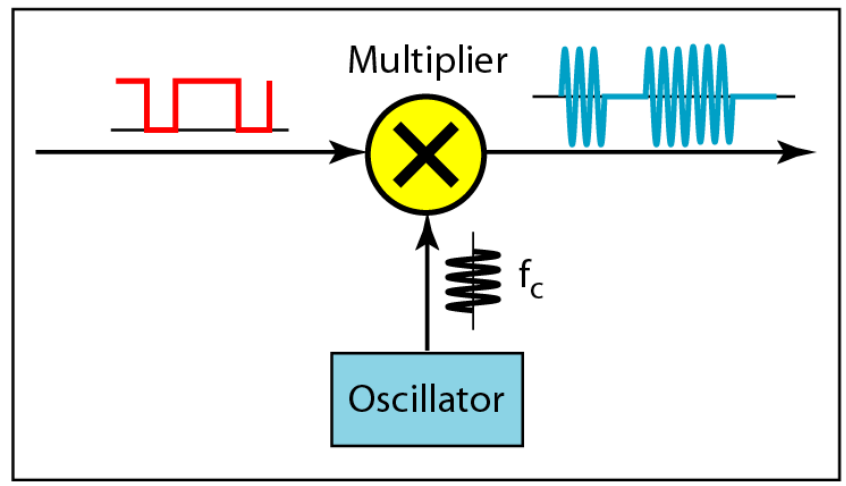




"d" is due to modulation and filtering, lies between 0 and 1.

Implementation of binary ASK





Example

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What are the carrier frequency and the bit rate if we modulated our data by using ASK with d = 1?

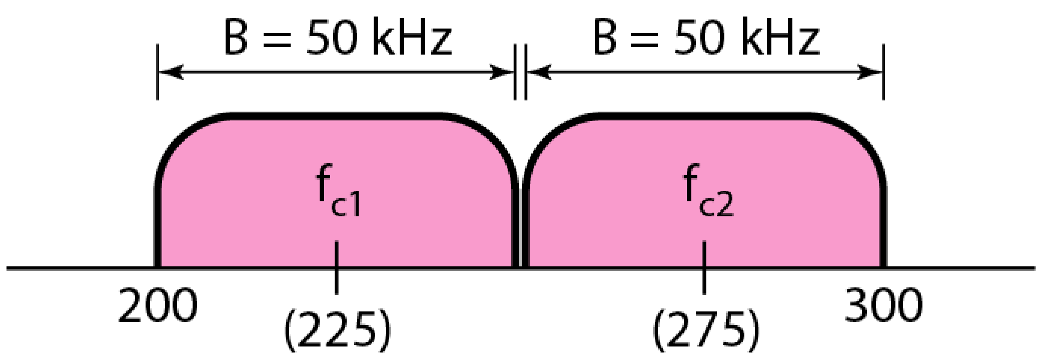
Solution

The middle of the bandwidth is located at 250 kHz. This means that our carrier frequency can be at f_c = 250 kHz. We can use the formula for bandwidth to find the bit rate (with d = 1 and r = 1).

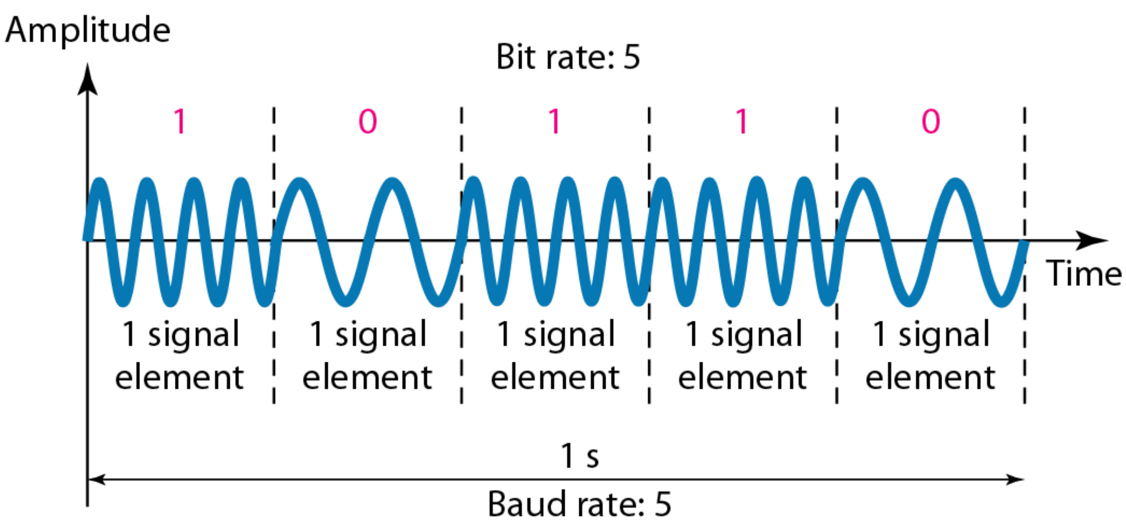
$$B = (1 + d) \times S = 2 \times N \times \frac{1}{r} = 2 \times N = 100 \text{ kHz} \quad \Rightarrow \quad N = 50 \text{ kbps}$$

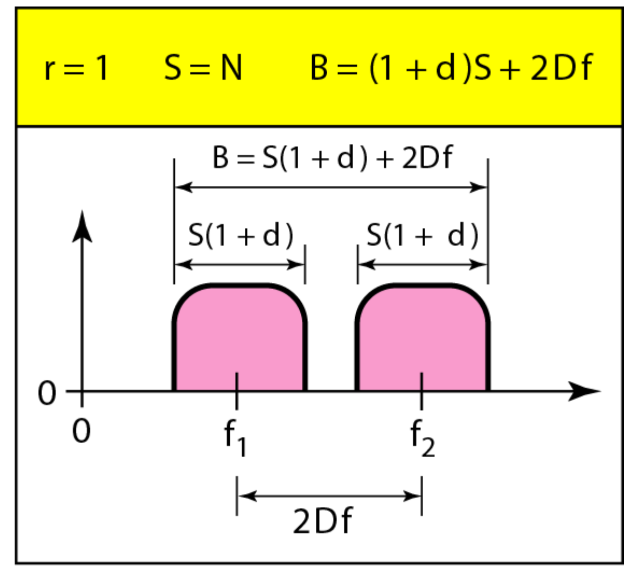
Bandwidth of full-duplex ASK used in previous example

In data communications, we normally use full-duplex links with communication in both directions. We need to divide the bandwidth into two with two carrier frequencies, as shown in the figure. The figure shows the positions of two carrier frequencies and the bandwidths. The available bandwidth for each direction is now 50 kHz, which leaves us with a data rate of 25 kbps in each direction.



Binary frequency shift keying (BFSK)





2Df is the difference between the two frequencies (f1 and f2)

Example

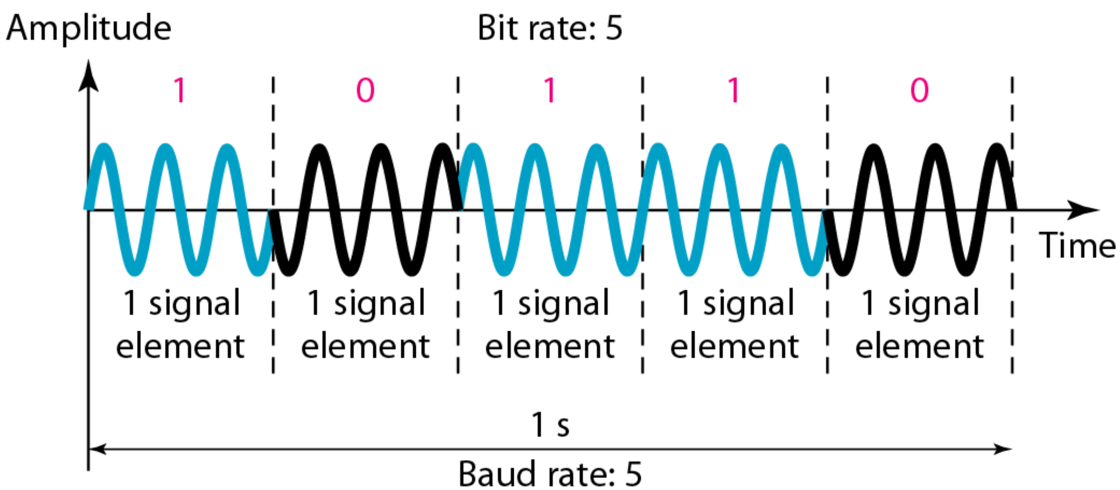
We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with d = 1?

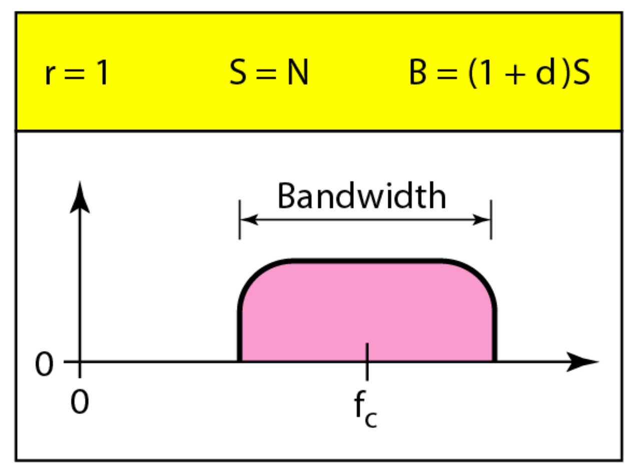
Solution

This problem is similar to BASK example, but we are modulating by using FSK. The midpoint of the band is at 250 kHz. We choose 2Δf to be 50 kHz; this means

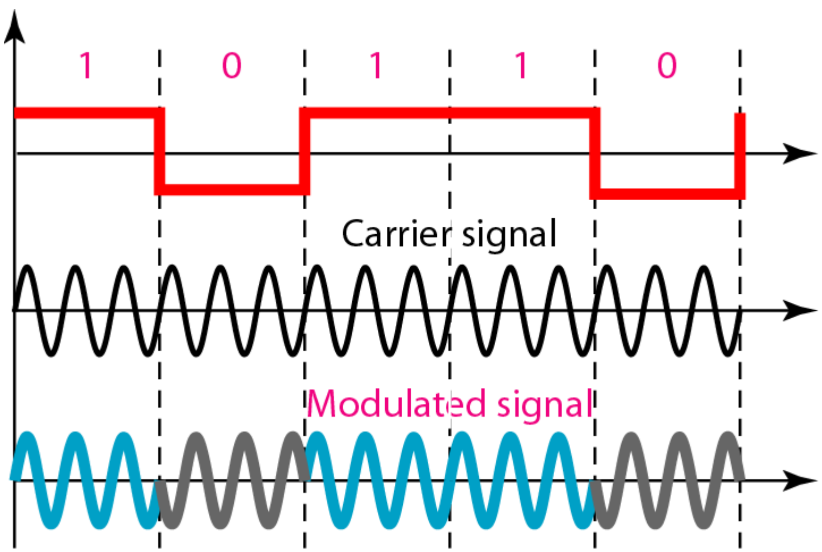
$$B = (1 + d) \times S + 2\Delta f = 100 \quad \Rightarrow \quad 2S = 50 \text{ kHz} \quad S = 25 \text{ kbaud} \quad N = 25 \text{ kbps}$$

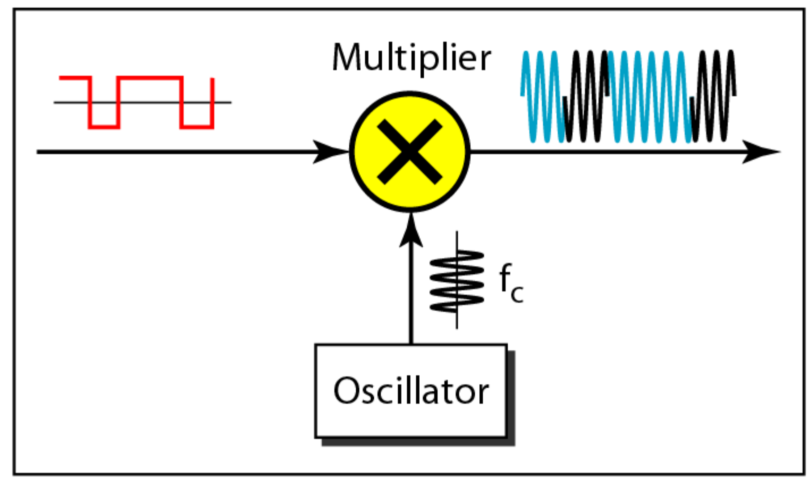
Binary phase shift keying (BPSK)



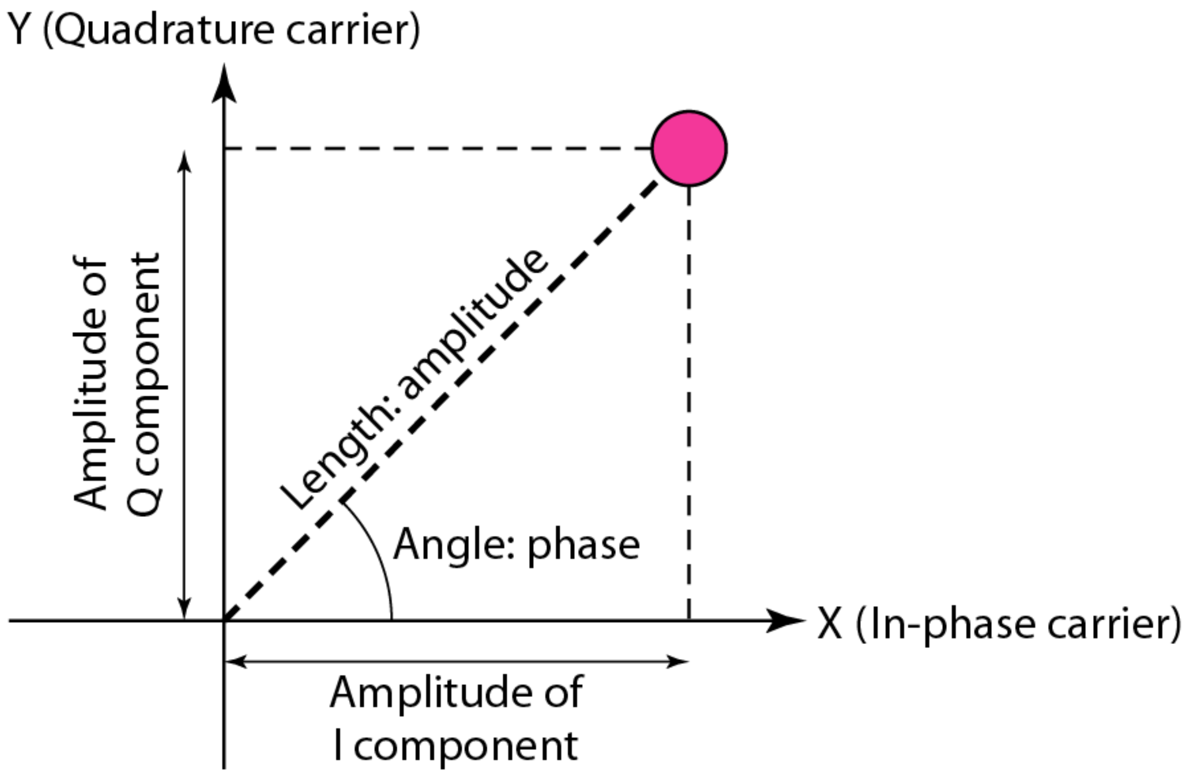


Implementation of BPSK





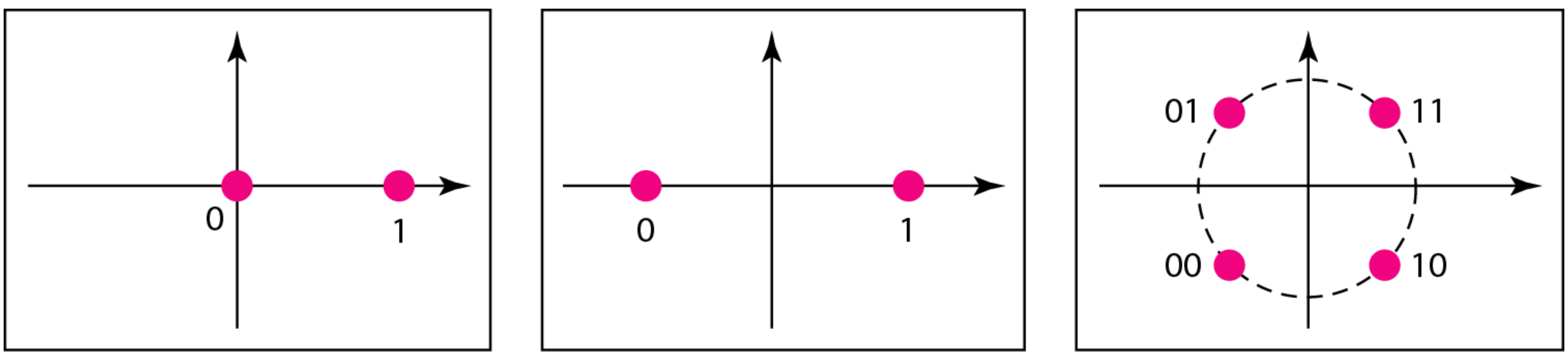
Concept of a constellation diagram



Example

Show the constellation diagrams for an ASK (OOK), BPSK, and QPSK signals.

Solution

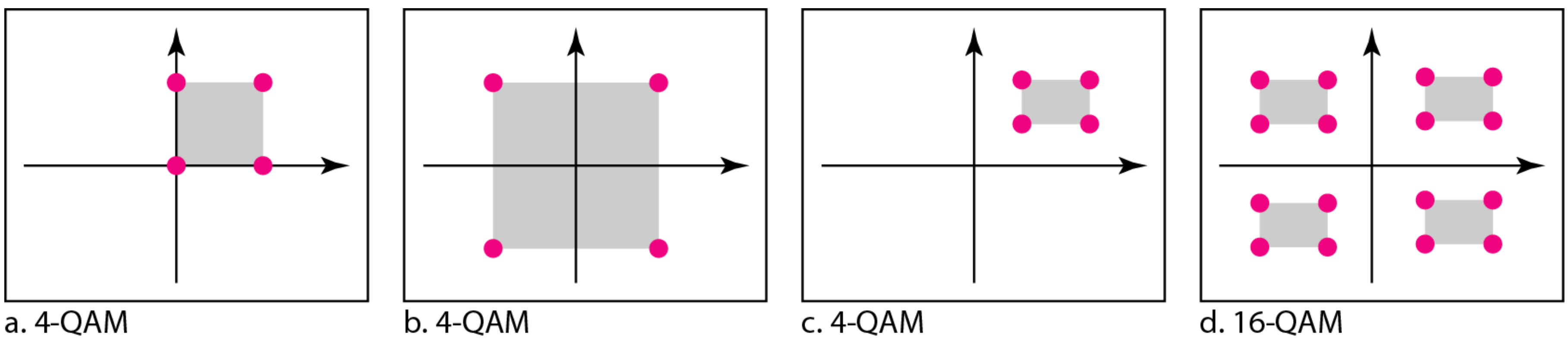


a. ASK (OOK) b. BPSK c. QPSK

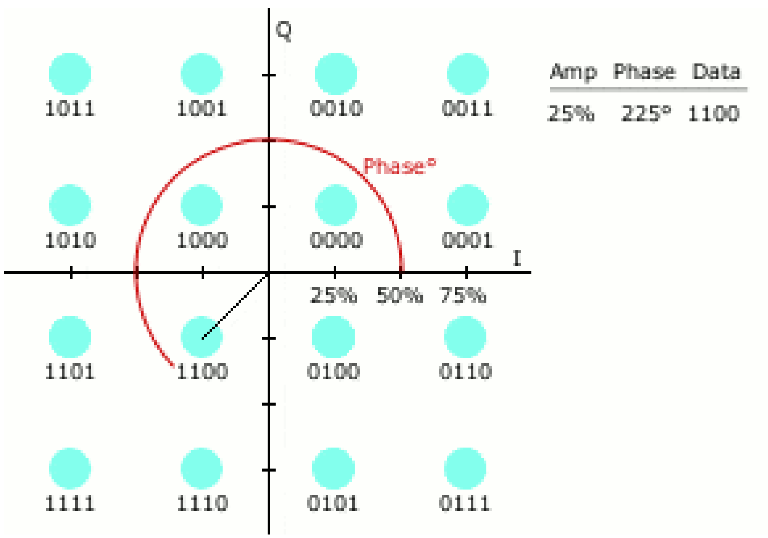
Note

Quadrature amplitude modulation (QAM) is a combination of ASK and PSK.

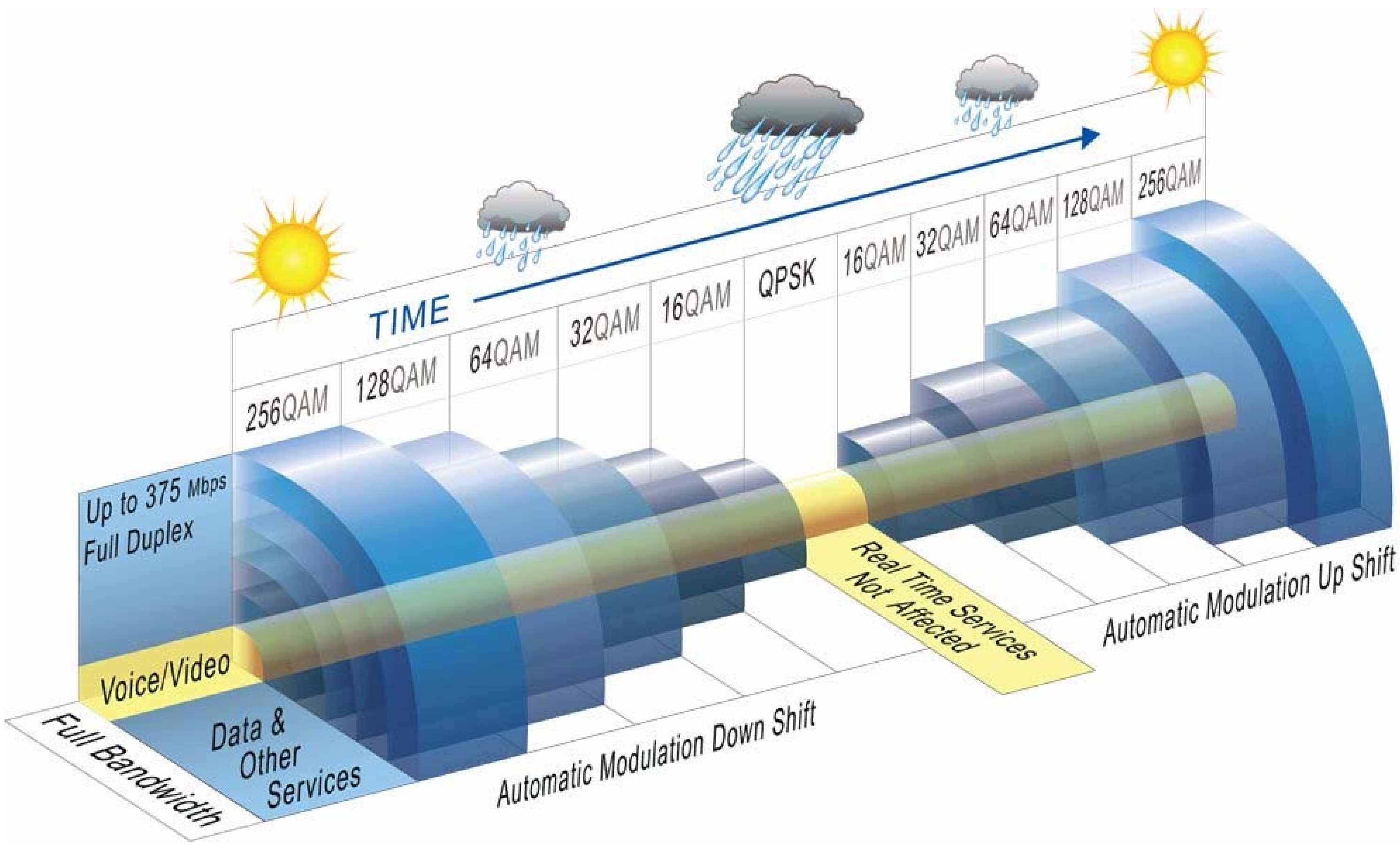
Constellation diagrams for some QAMs



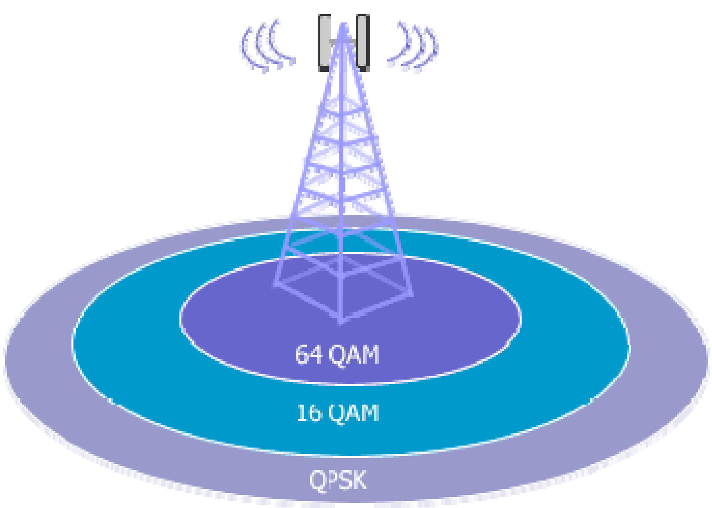
16 QAM

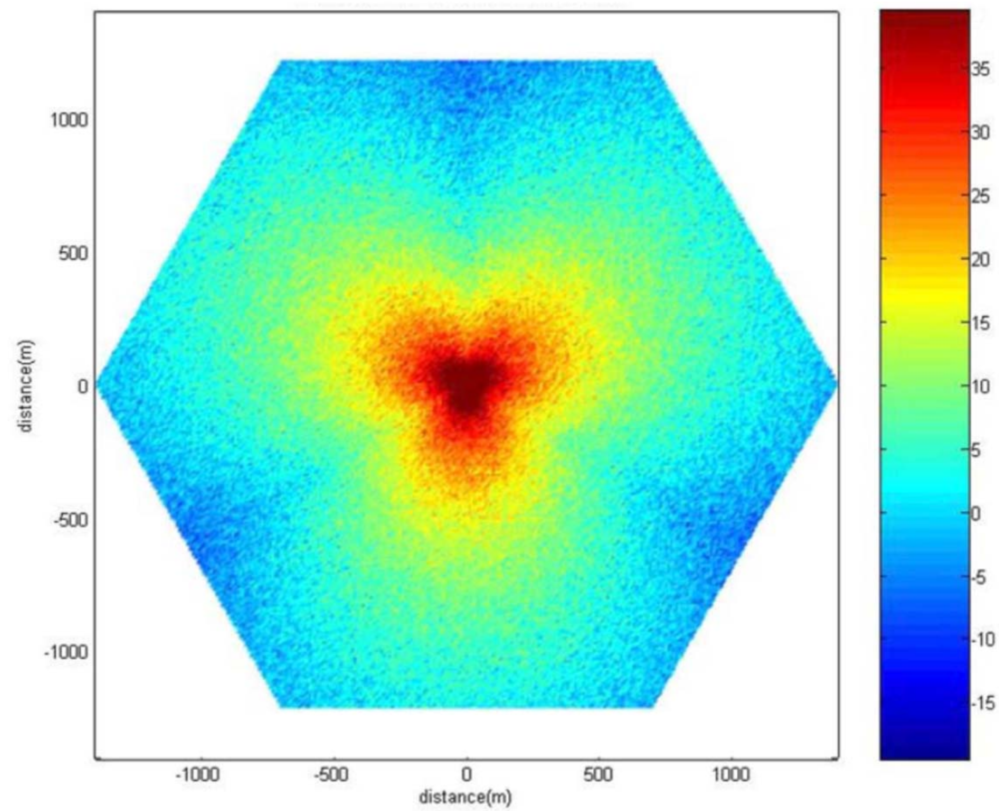

Q
I
1011
1001
0010
0011
1010
1000
0000
0001
1101
1100
0100
0110
1111
1110
0101
0111
Phase°
25%
50%
75%
Amp Phase Data
25% 225° 1100

Adaptive Modulation

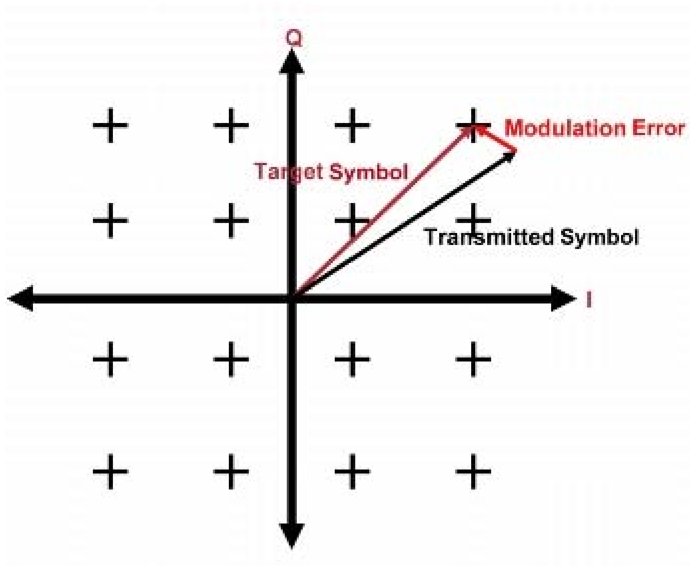


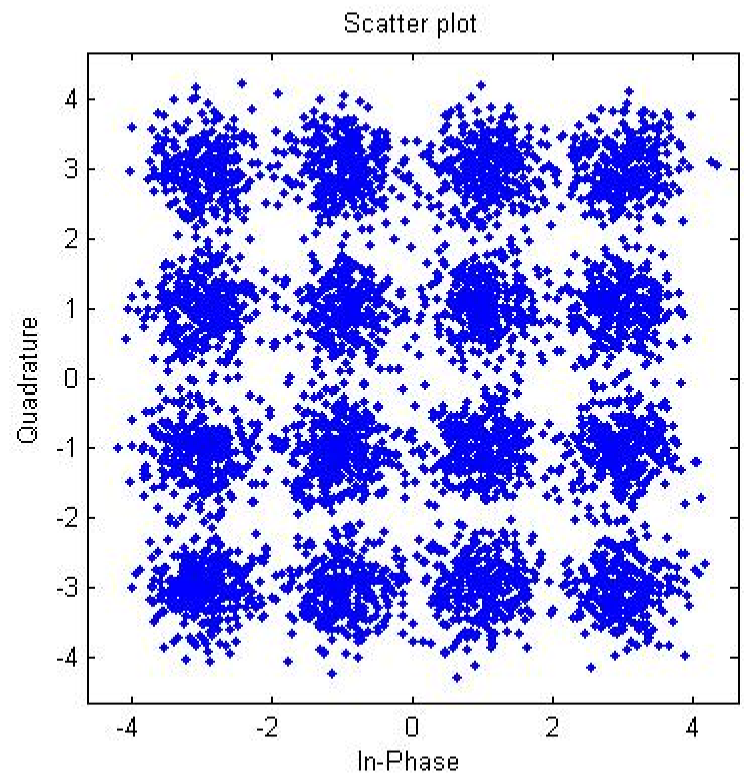
Adaptive Modulation in Cellular Networks





Recap: Constellation Diagrams





Roadmap

- Data and Signals
- Digital Transmission
- Analog Transmission
- Why Digital Communications?
- Block diagram of digital transmissions

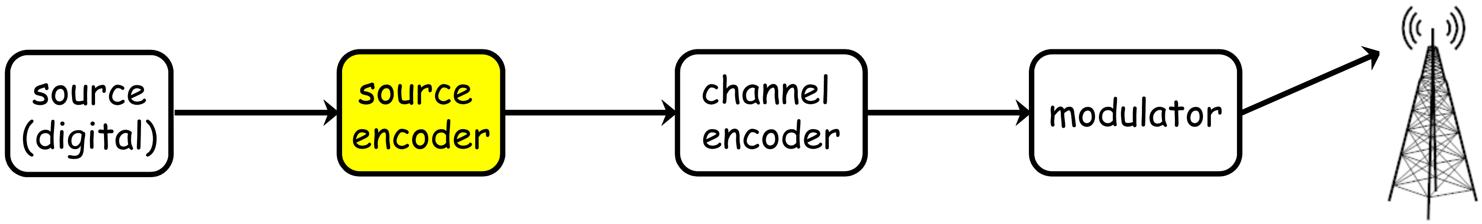
Why Digital Communication?

The resistance to signal distortion

- Distortion: unexpected change of signal during transmission due to imperfect channel
- Analog: cannot resist distortion, degraded performance, quality
- Digital: can correct the signal as long as the distortion is not severe enough to change the signal polarity (e.g., from 0 to 1)

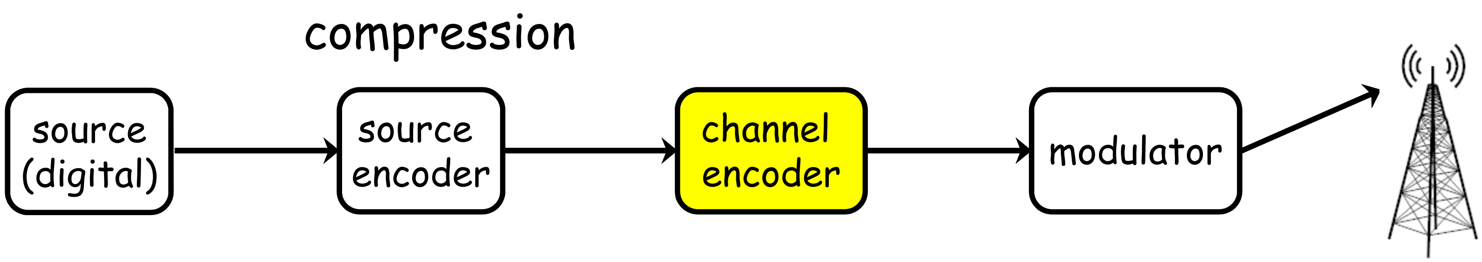
Many others: suitable for long-distance transmission, handling many types of services, various protocol (error correction, data encryption, etc.),…

Block diagram of digital transmissions



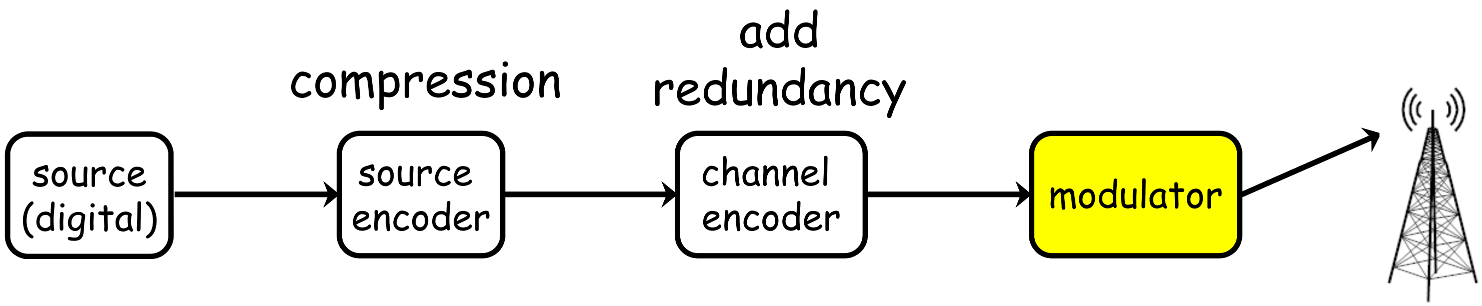
- eliminate redundancy in the data, send same information in fewer bits
- compression ratio: #bits (original file)/#bits (compressed file)
- lossless compression: Zip (in windows)
- lossy compression: JPEG (compression ratio of about 15), MPEG (e.g., 300Mbps to 6Mbps)

Block diagram of digital transmissions



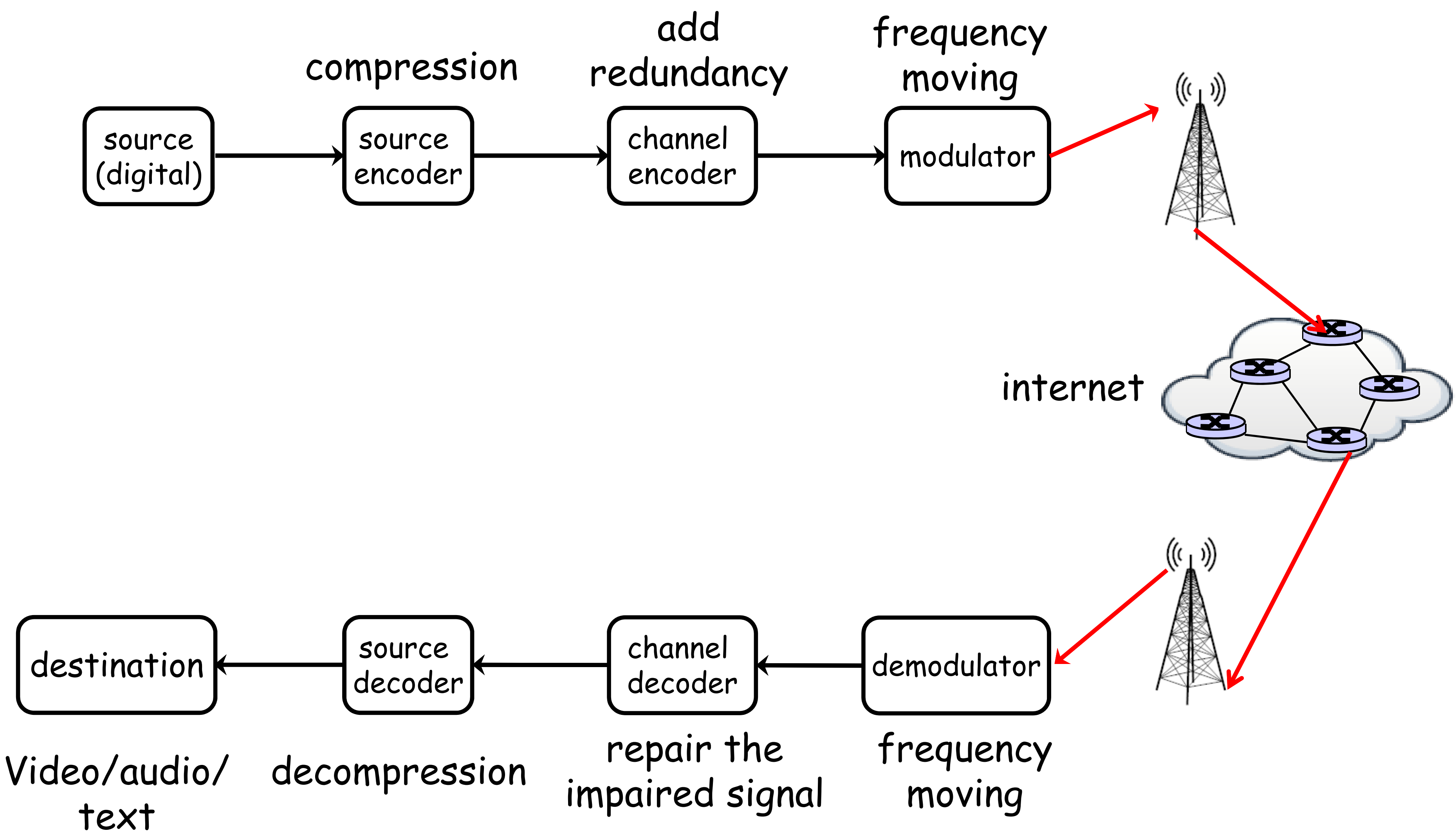
- Transforming signals to improve communications performance by increasing the robustness against channel impairments (noise, interference, fading, …)
- add redundancy: map binary source output sequences of k into binary channel input sequences of n (n>k)

Block diagram of digital transmissions



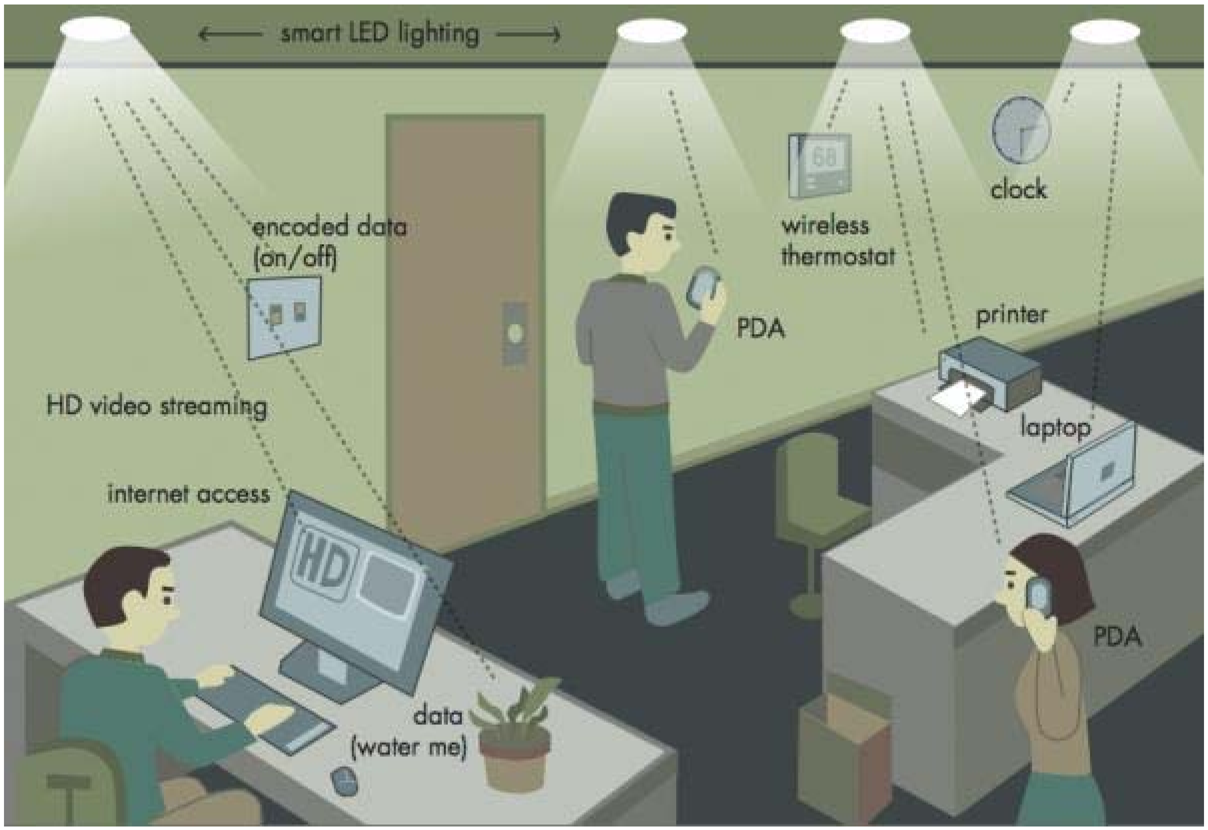
- Converts the electrical signals (from the source) into a form that is suitable for transmission over the physical media
  - DSL modem, Cable modem, wireless modulator

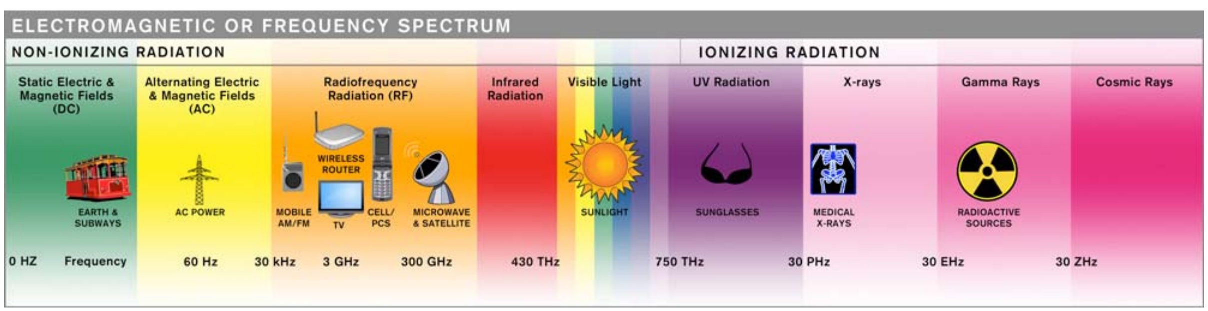
Block diagram of digital transmissions



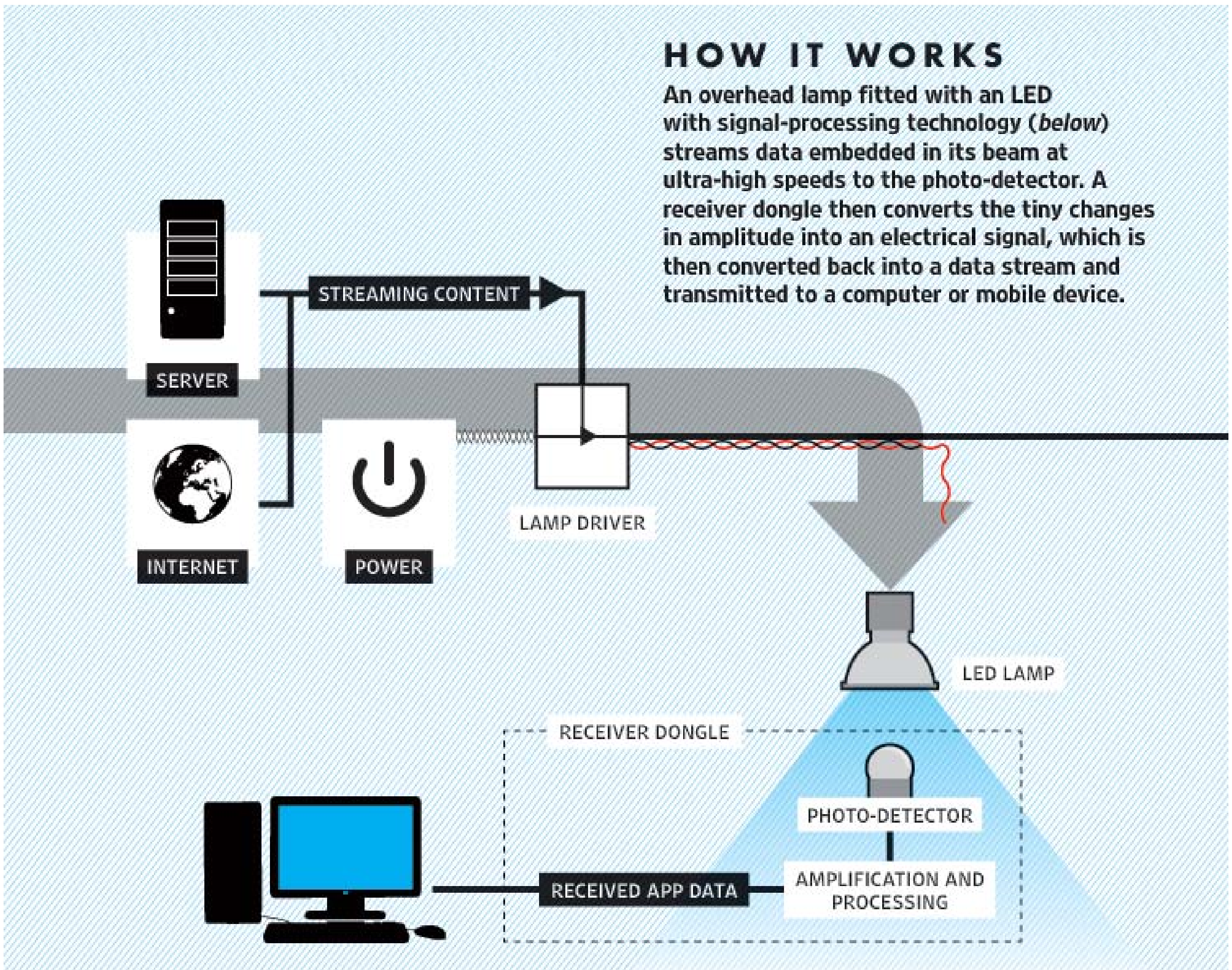
Cutting-Edge Communication Technology

Visible Light Communication





Visible Light Communication



Li-Fi vs Wi-Fi

LI-FI vs. WI-FI

LIFI

S. No.	Parameter	Li-fi	Wi-fi
1	SPEED	> 1 GB/S	around 150 Mb/s
2	Medium of data transfer	Use light as carrier	Use radio spectrum
3	Spectrum range	Visible light has 10000 times more	Having less spectrum range than VLC
4	Cost	Cheaper	Expensive
5	Network topology	Point to point	Point to point
6	Operating frequency	Hundreds of Tera Hz	2.4 GHz

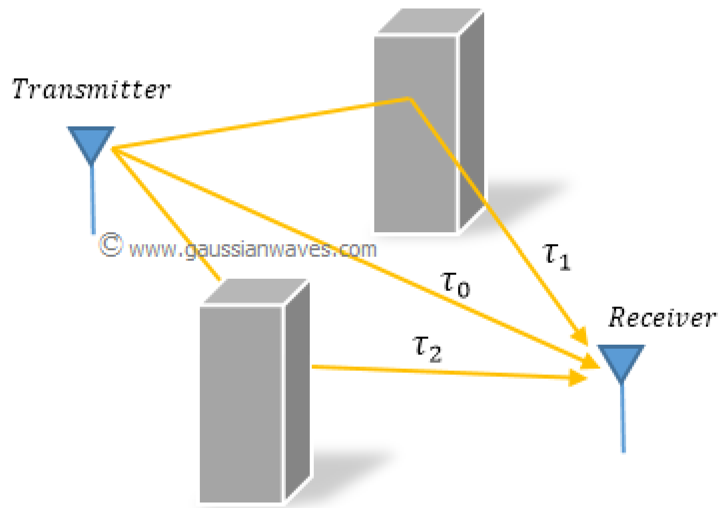
Li-Fi vs Wi-Fi

https://youtu.be/wqH9KX9o0vg

Ambient Backscatter

https://youtu.be/gX9cbxLSOkE

Multipath Propagation



Major Conferences

SIGCOMM is ACM's professional forum for discussing communications and computer networks.

Annual International Conference on Mobile Computing and Networking

IEEE International Conference on Computer Communications