Physical Layer

Outline

- Goal
  - Signal and its Characteristics
  - Digital signal transmission
  - Digital and Analog Signals
  - Transmission Impairment
  - Summary

Physical Layer

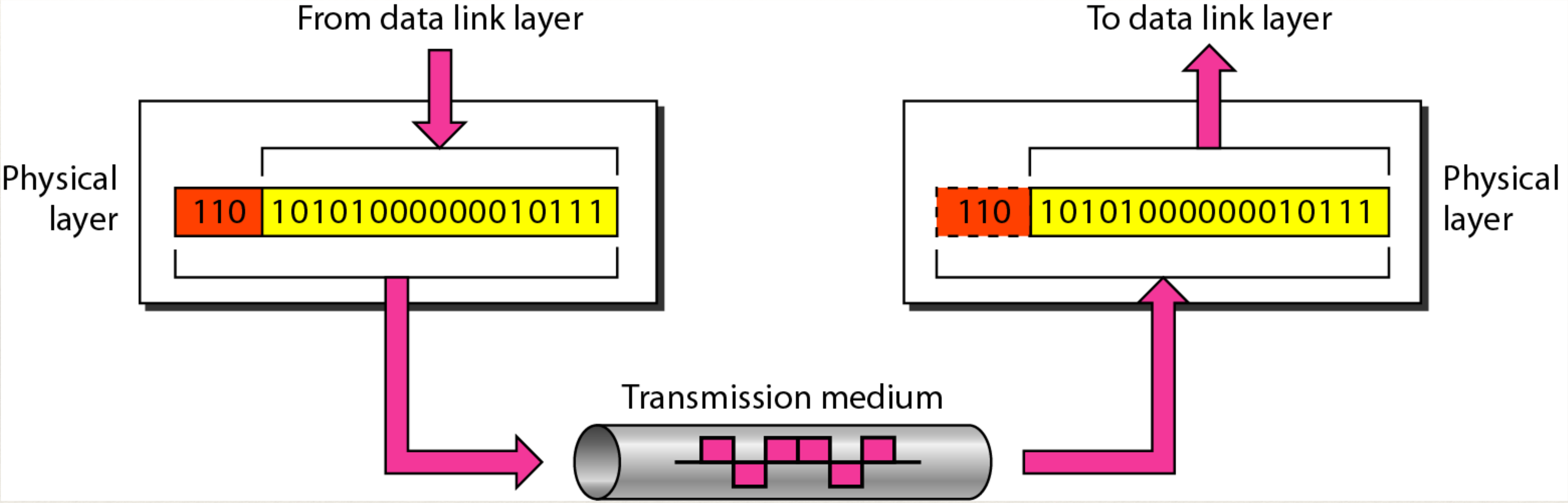


Fig: Physical Layer

- Responsible for movements of individual bits from one hop (node) to the next

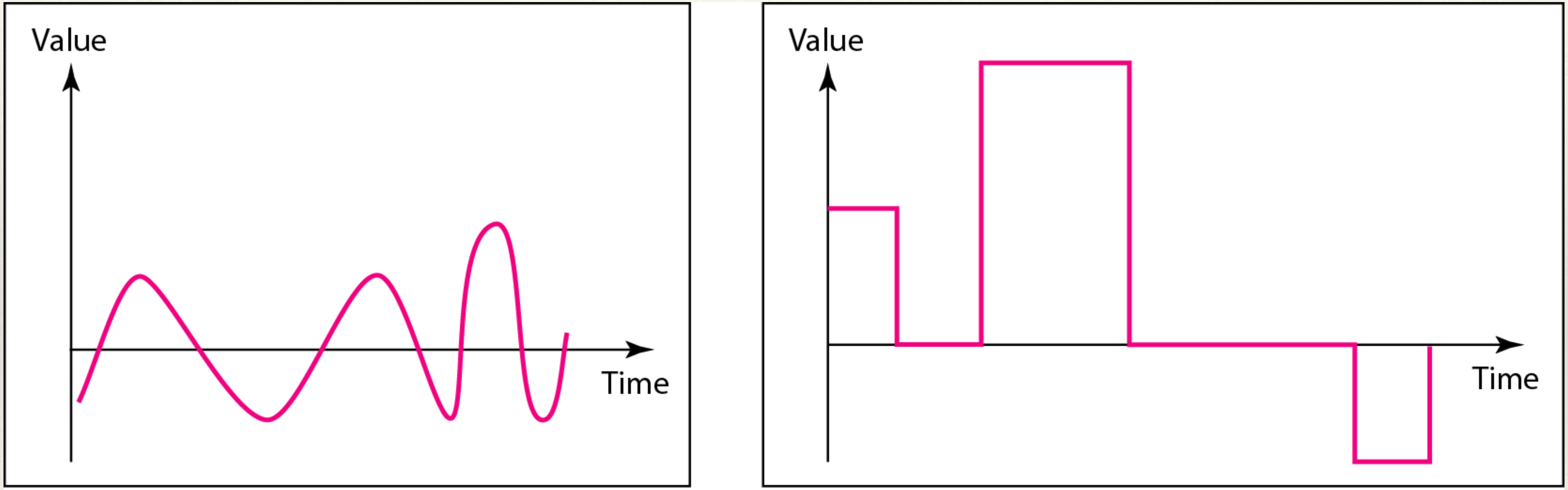
Physical Layer

- Other responsibilities of PL
  - Physical characteristics of **interfaces** and **medium**
  - Representation of **bits** (Stream of bits/sequence of 0s or 1s)
  - Defines the type of **encoding**
  - **Data rate**: The transmission rate-the **number of bits sent each second**
  - **Synchronization** of bits
  - Line configuration (Connection Type: Point-to-point/Multi-point)
  - Physical topology
  - Type of **Transmission Modes**

Data and Signals

- To be transmitted, data must be transformed to electromagnetic signals.
- Analog
  - The term 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
  - 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.

Analog and Digital Signals



a. Analog signal

b. Digital signal

Fig: Analog vs Digital Signals

Periodic Analog Signal

- Periodic signal is one that repeats the sequence of values exactly after a fixed length of time, known as the period
- 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.
- In data communications periodic analog signals and non-periodic digital signals are used in common.

Need less bandwidth

Can represent variation in Data

Sine wave

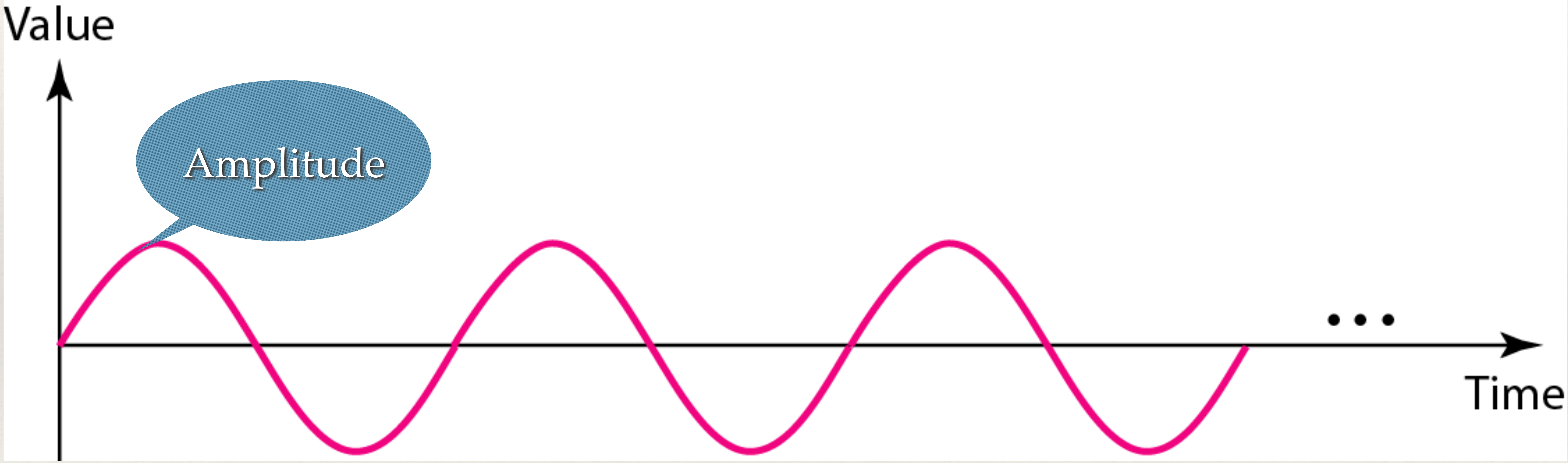


Fig : Sine wave (Periodic Signal)

Amplitude, Frequency, Period

- The peak amplitude of a signal is the absolute value of its highest intensity, proportional to the energy it carries.
- Period (T) refers to the amount of time, in seconds, a signal needs to complete 1 cycle
- Frequency (f) refers to the number of periods in 1 sec.
  - f=1/T and T=1/f

Note: Frequency and period are the inverse of each other.

Periodic Analog Signals

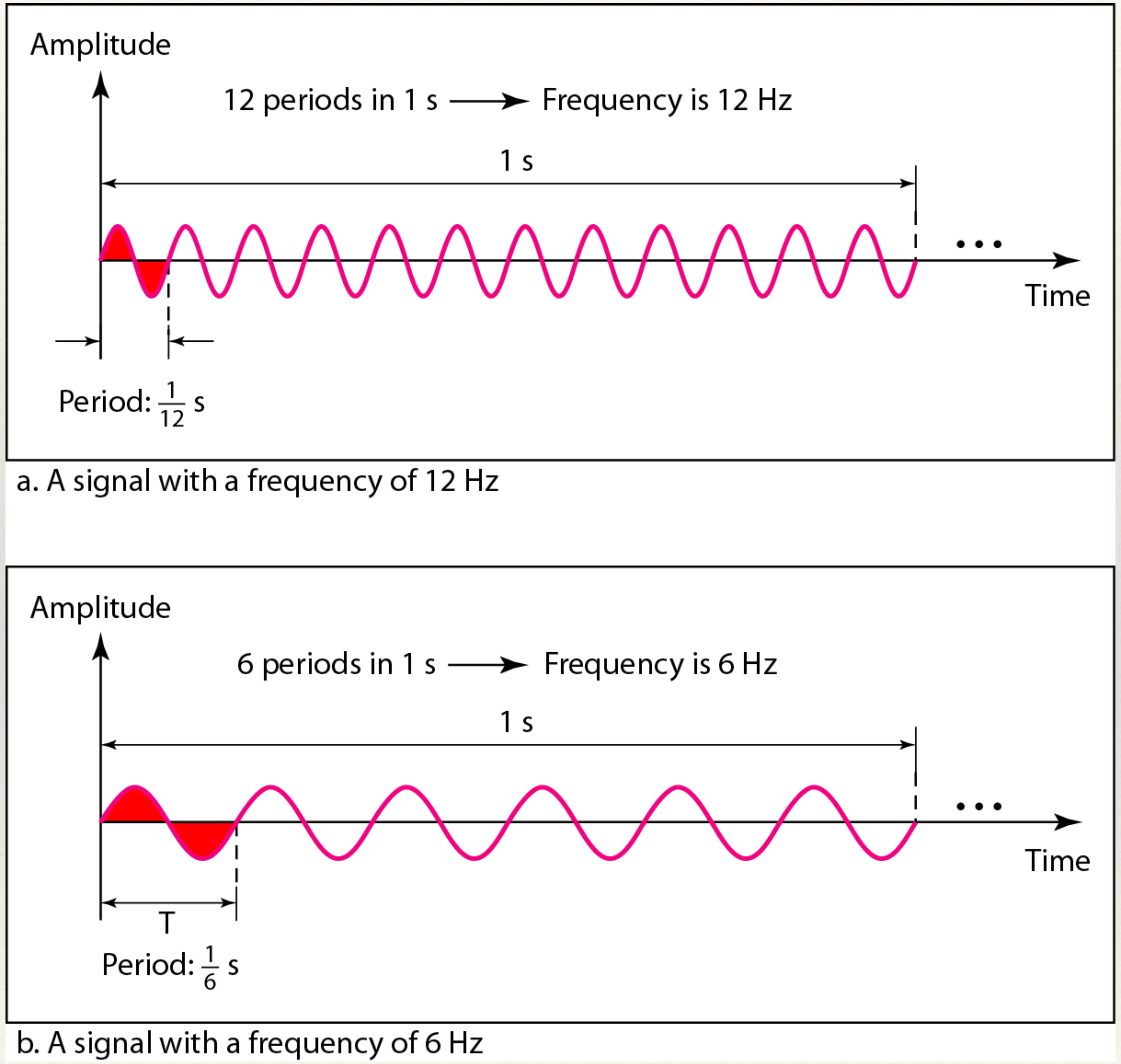


Fig : Two signals with the same amplitude and phase but different frequencies

Units of Period and Frequency

Q1. If the power we use at home has a frequency of 60Hz, then what is the Period of this sine wave?

Ans: 0.0166

Q2.The period of a signal is 100 ms. What is its frequency in kilohertz?

Ans: 10^{-2} KHz

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

Phase and Wavelength

- Phase describes the position of the waveform relative to time 0.
- Wavelength: Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium

Wavelength = Propagation Speed X Period or Propagation Speed / Frequency

Note: The wavelength is the distance a simple signal can travel in one period (distance between two successive crests (peaks) or trough in a wave)

Q1. What is the wavelength of the red-light which has a frequency of 4×10^{14} in air? Also compare the wavelength when light passes through the optic-fiber or coaxial cable?

Composite Signals

Composite Signals: A signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.

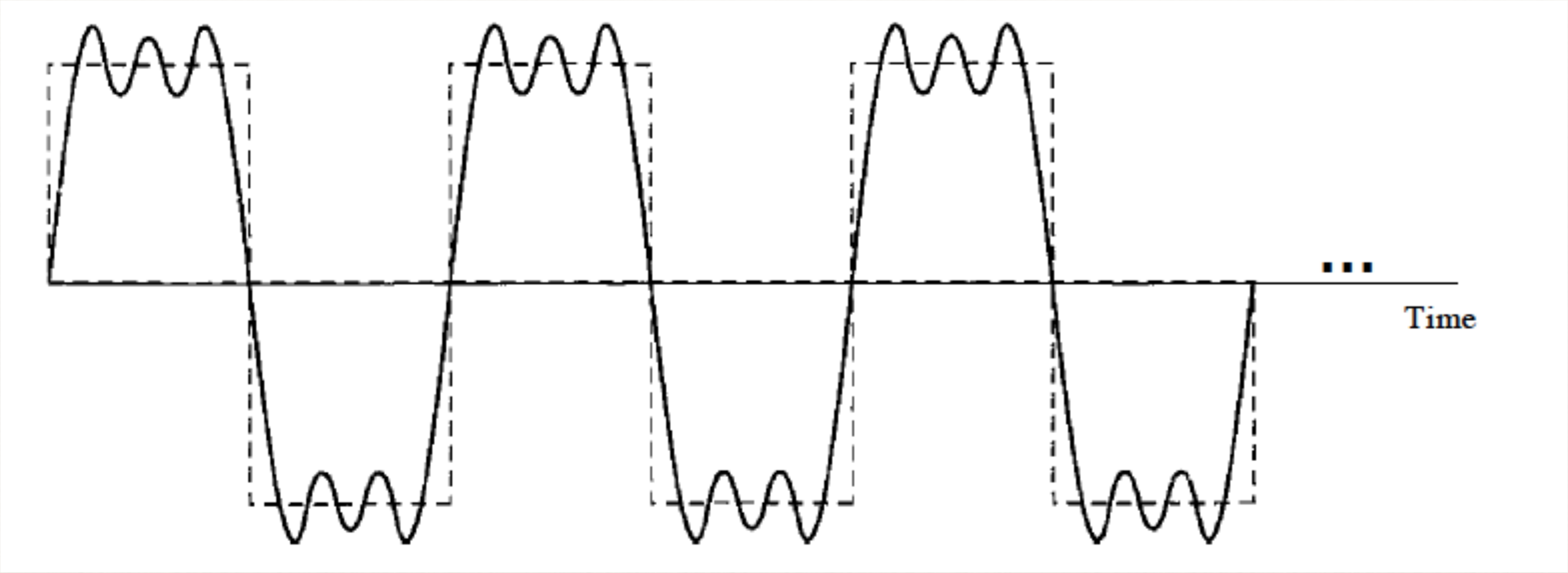


Fig. Composite Signals

Composite Signals

- The individual signals (decomposed signals) in a time domain is given as follows.
- Frequency of f,3f,9f

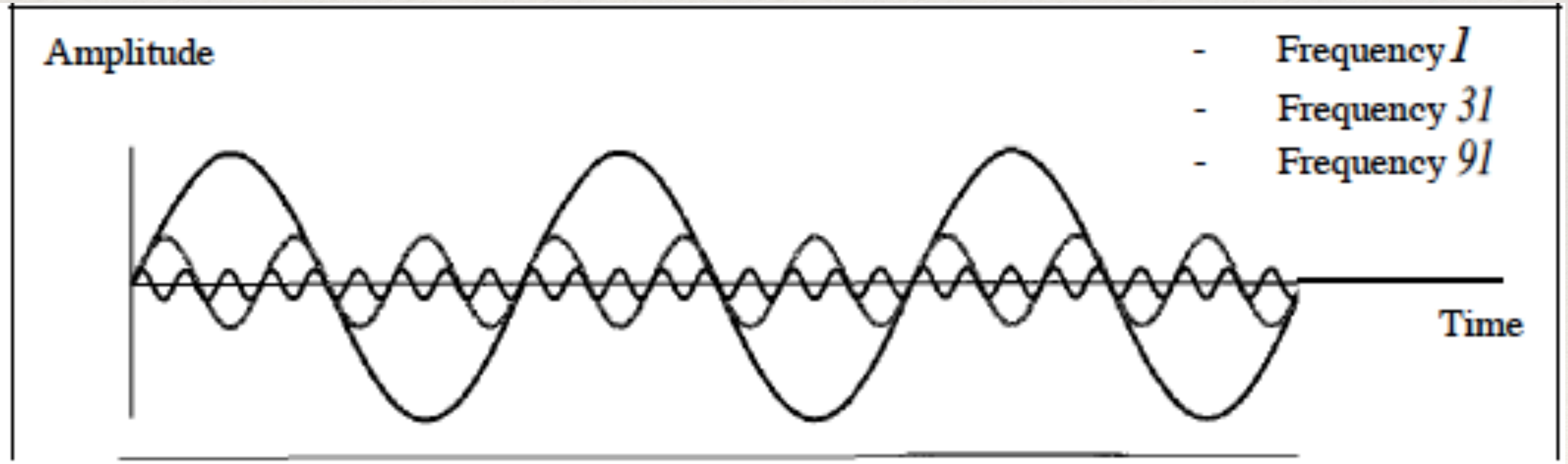


Fig: Decomposed Signals

Bandwidth

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

Q1.If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth?

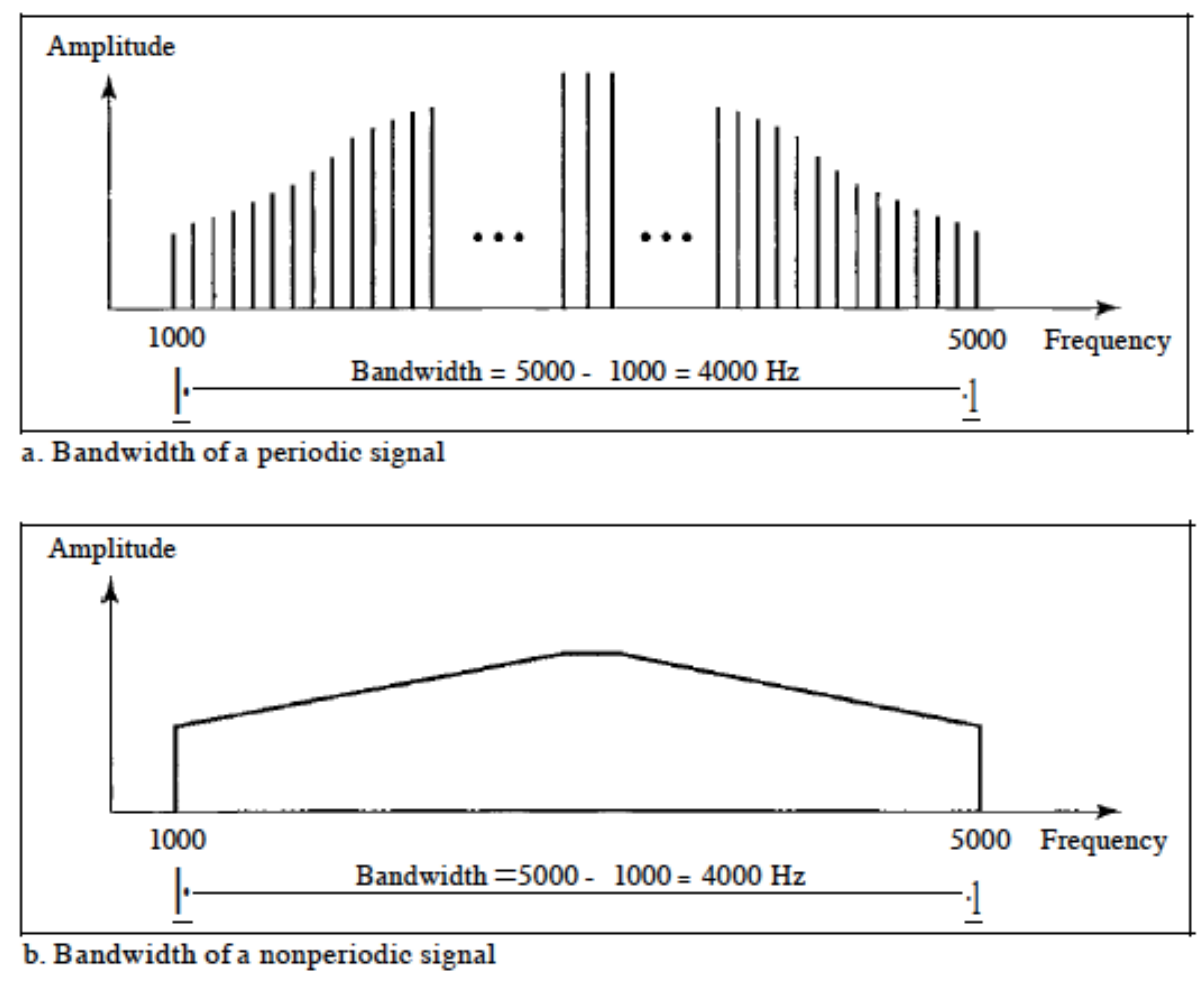
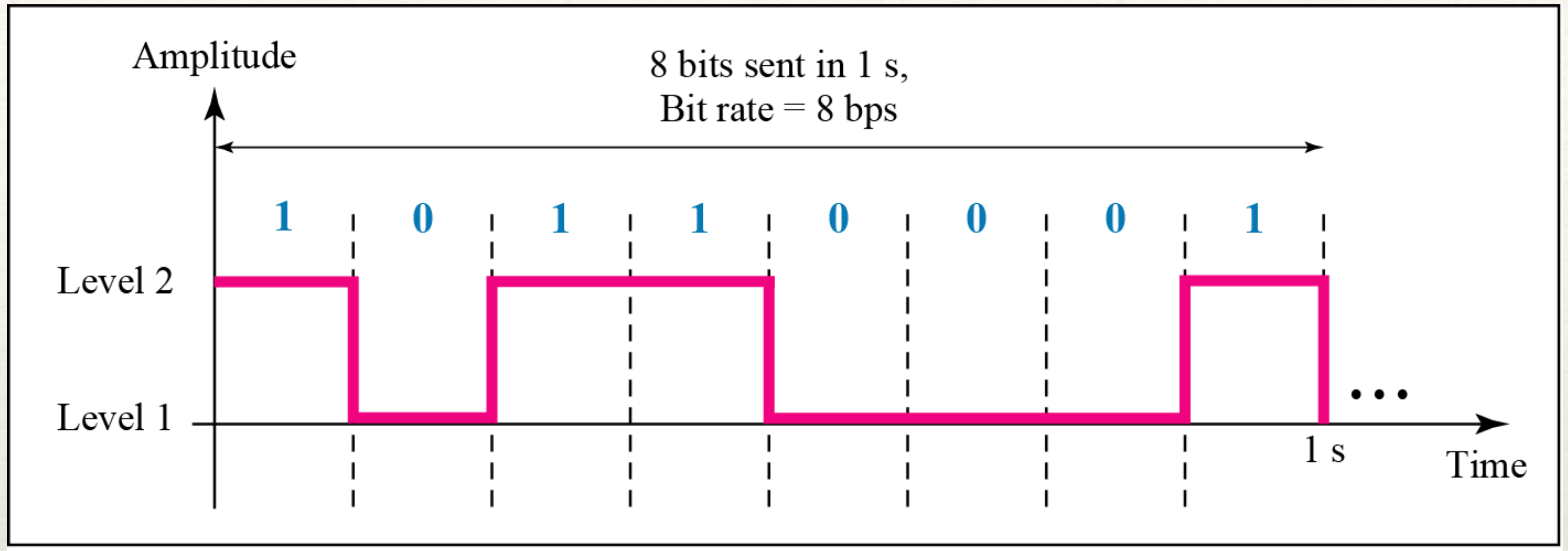


Fig. Bandwidth in Time and Frequency Domain

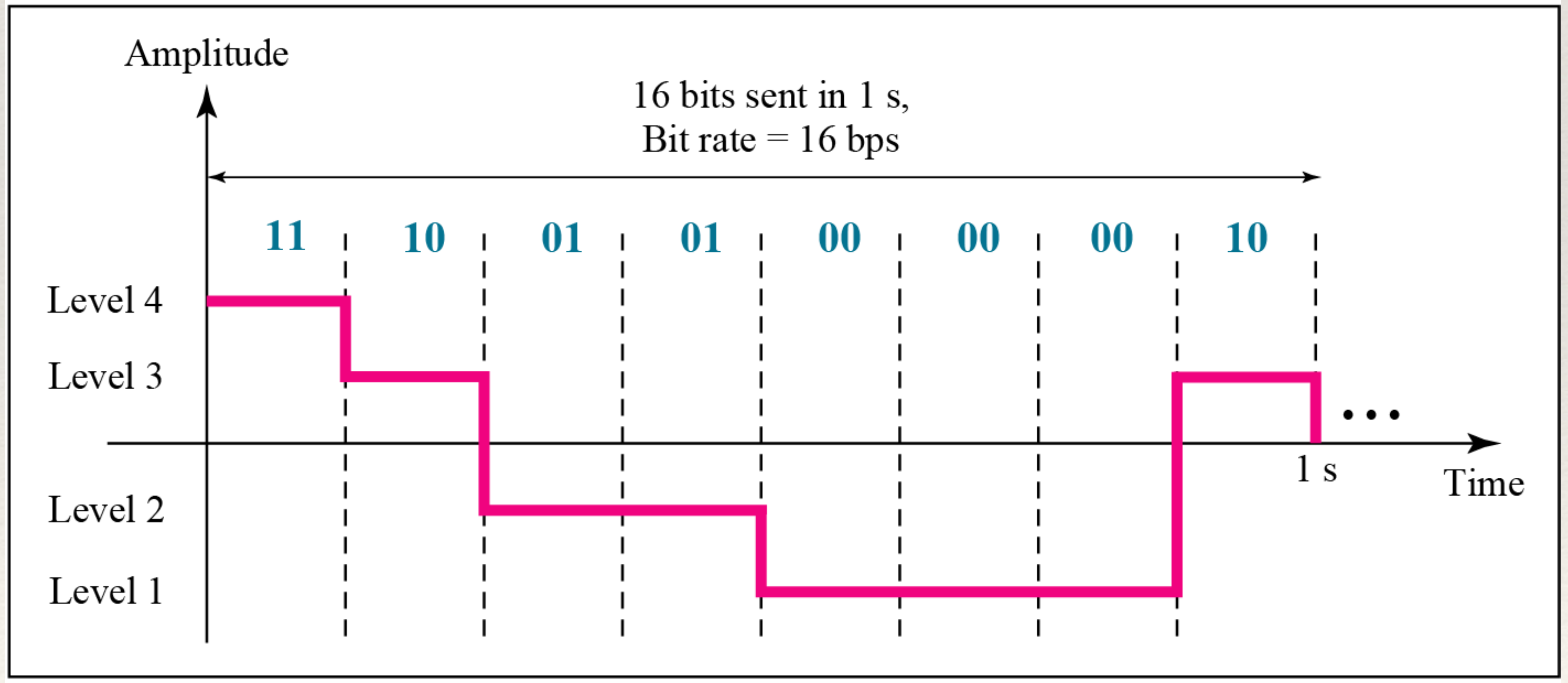
Digital Signals

- 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
- Bit Rate: The bit rate is the number of bits sent in Is, expressed in bits per second (bps).

Digital Signals



a. A digital signal with two levels



b. A digital signal with four levels

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

Digital Signals

Problem 1:

If a digital signal has eight levels, then how many bits are needed per level?

Solution: We calculate the number of bits from the formula

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

Each signal level is represented by 3 bits.

Digital Signal

Problem 2: A digitised voice channel is made by digitising a 4-kHz bandwidth analog voice signal. The Signal is sampled at twice the highest frequency (two samples per hertz). Consider that each sample requires 8 bits. What is the required bit rate?

Problem 3: Assume we need to download text documents at the rate of 100 pages per sec. What is the required bit rate of the channel? (Assume Number of lines is Max. Of 24, No of Character in each line is 80 and each character takes 8 bit for representation)

Problem 4: What is the bit rate for high-definition TV (HDTV)?

Digital Signal

Solution 2:

The bit rate can be calculated as,

2 X 4000 X 8=64000 bps=64Kbps

Solution 3:

100 X 24 X 80 X 8= 1636000 bps= 1.536 Mbps

Solution 4: HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. 24 bits represents one colour pixel.

1920 X 1080 X30 X 24

(Ans: ~=1.5Gbps)

Transmission of Digital Signal

How can we send a digital signal from point A to point B?

- A digital signal is transmitted by using one of two different approaches:
  - Baseband transmission

    Or

  - Broadband transmission (Uses Modulation)

Baseband Transmission

- Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal.
- For Baseband transmission it requires low-pass channel: a channel with bandwidth that starts from zero.
- Low-pass channel with infinite bandwidth is ideal for baseband transmission

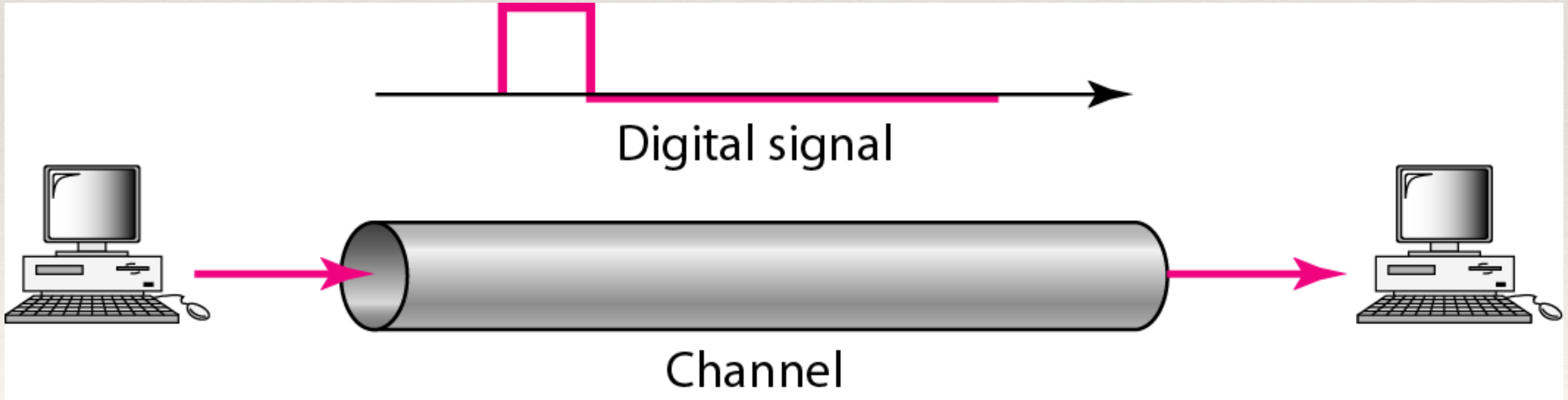


Fig. Baseband Transmission

Low Pass Channels

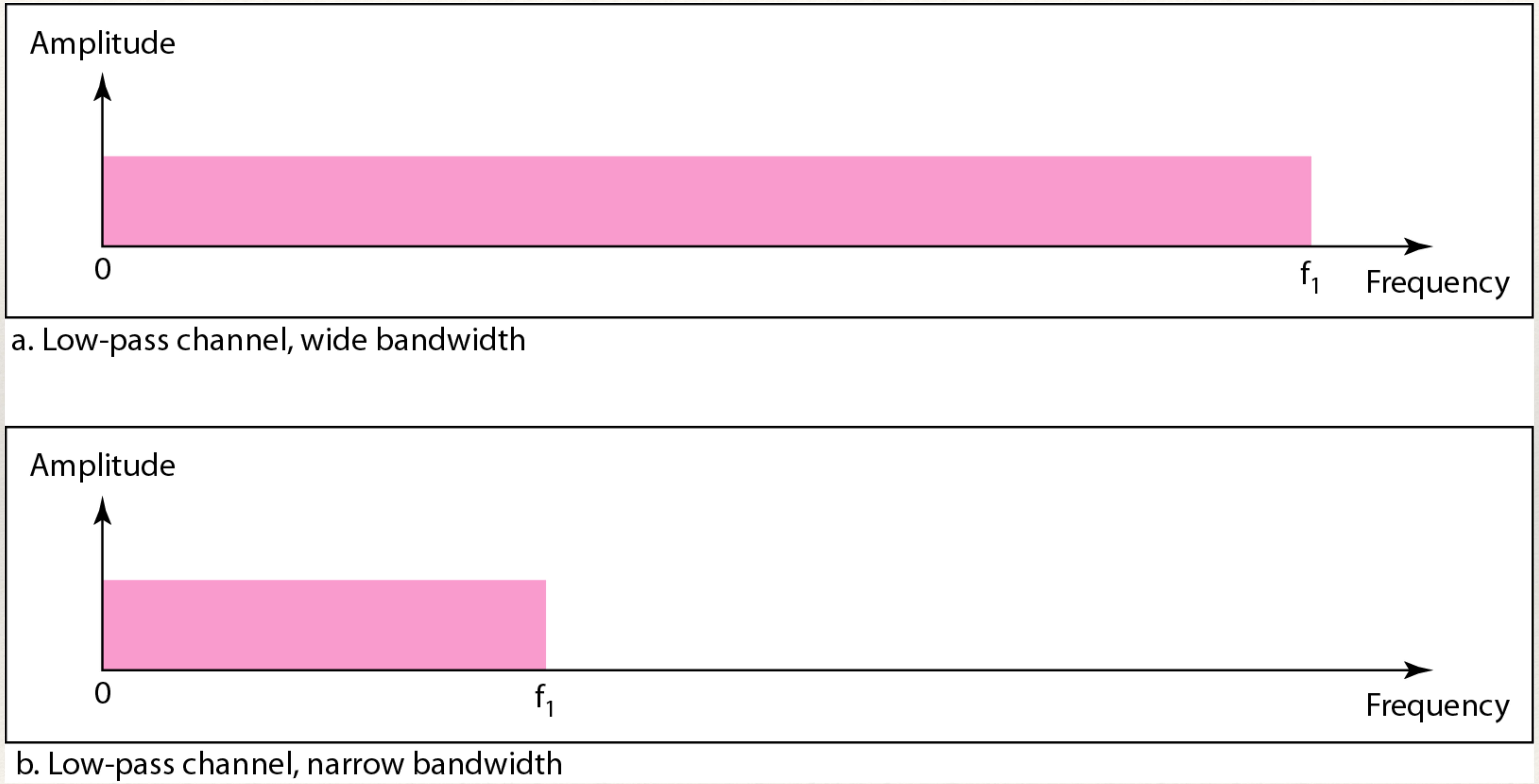


Fig. Bandwidth of Low Pass Channels

Baseband Transmission

Case 1: Baseband Transmission Using Wide Bandwidth

- In Baseband transmission of a digital signal, the shape of the digital signal is preserved only if we have a low-pass channel with an infinite or very wide bandwidth.
- If we have a medium, such as a coaxial cable or fiber optic, with a very wide bandwidth, two stations can communicate by using digital signals with very good accuracy.

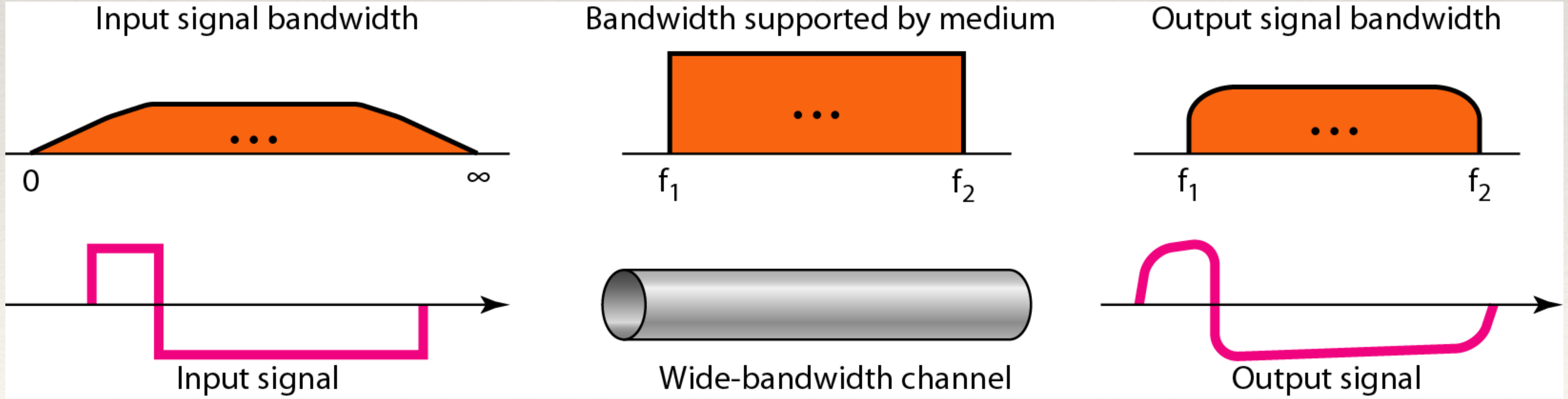


Fig. Baseband Transmission using a Dedicated Medium

Baseband Transmission

Case 2: Low-Pass Channel with Limited Bandwidth

- In a low-pass channel with limited bandwidth, we approximate the digital signal with an analog signal.
- The level of approximation depends on the bandwidth available.
- The Two Approximation Approach are:
  - Rough Approximation (Uses First Harmonic)
  - Better Approximation (Uses First,Third and Fifth Harmonic)

Note: Harmonic is defined as the signal content at a specific frequency, which is a multiple integral of the current frequency system or main frequency produced by the generators.

Rough Approximation

- Let us assume that we have a digital signal of bit rate N.
- Here 1=+5v (Level 0) and 0= -5V (Level 1)
- The two similar cases (000 and 111) are simulated with a signal with frequency 0 and a phase of 180° for 000 and a phase of 0° for 111. (No change in Signal/DC Components)
- The two worst cases (010 and 101) are simulated with an analog signal with frequency N/2 and phases of 180° and 0°.
- The other four cases can only be simulated with an analog signal with frequency N/4 and phases of 180°, 270°, 90°, and 0°. we
- need a channel that can handle frequencies 0,N/4 and N/2
- Bandwidth= N/2 (because, N/2-0) (First Harmonic)

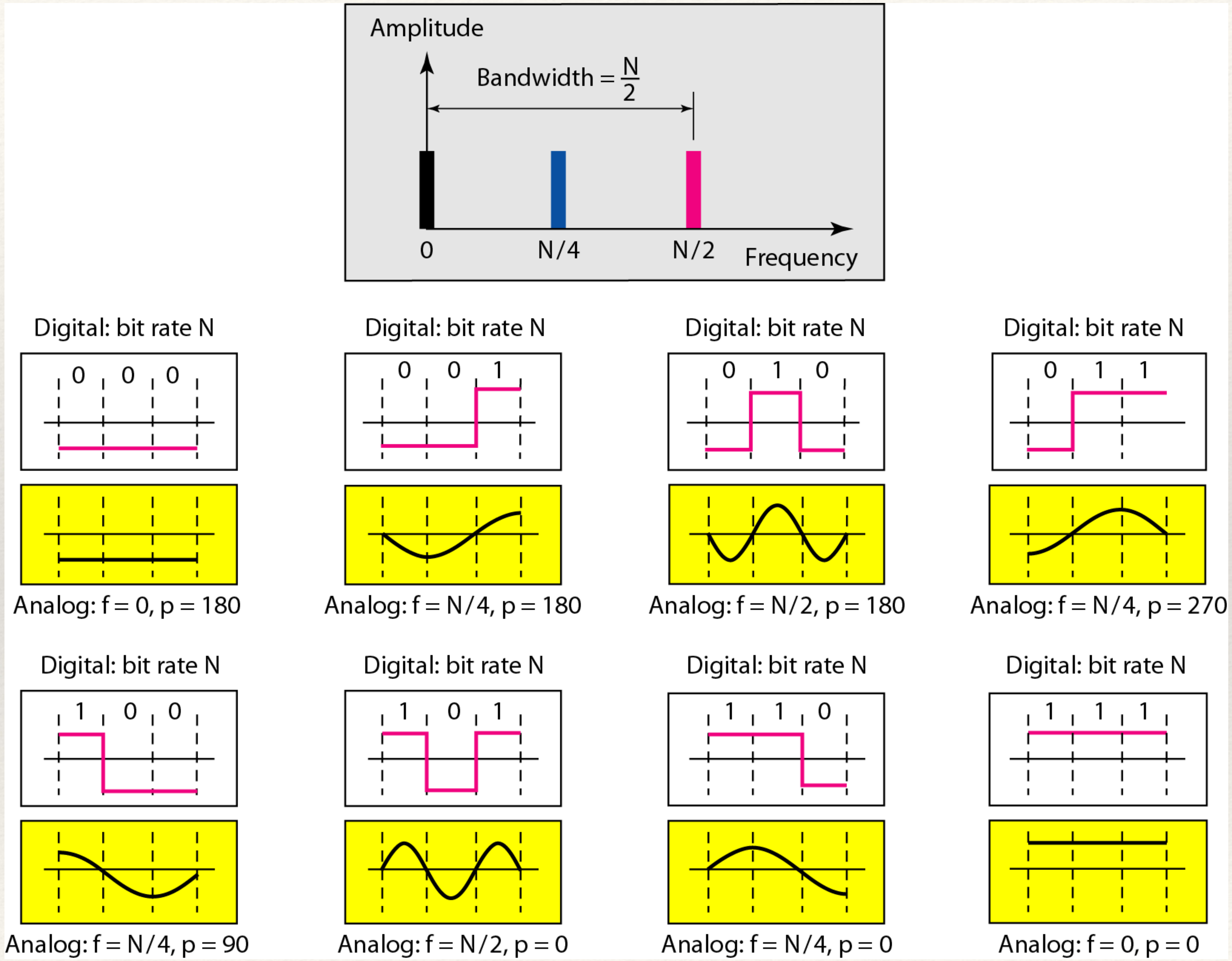


Fig. Rough Approximation of a digital Signal using the First harmonic for worst case

Better Approximation

- In baseband transmission, the required bandwidth is proportional to the bit rate;
- if we need to send bits faster, we need more bandwidth.
- First Harmonic N/2
- First &Third Harmonic 3N/2
- First, third and Fifth Harmonic 5N/2

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

Table: Bandwidth requirements

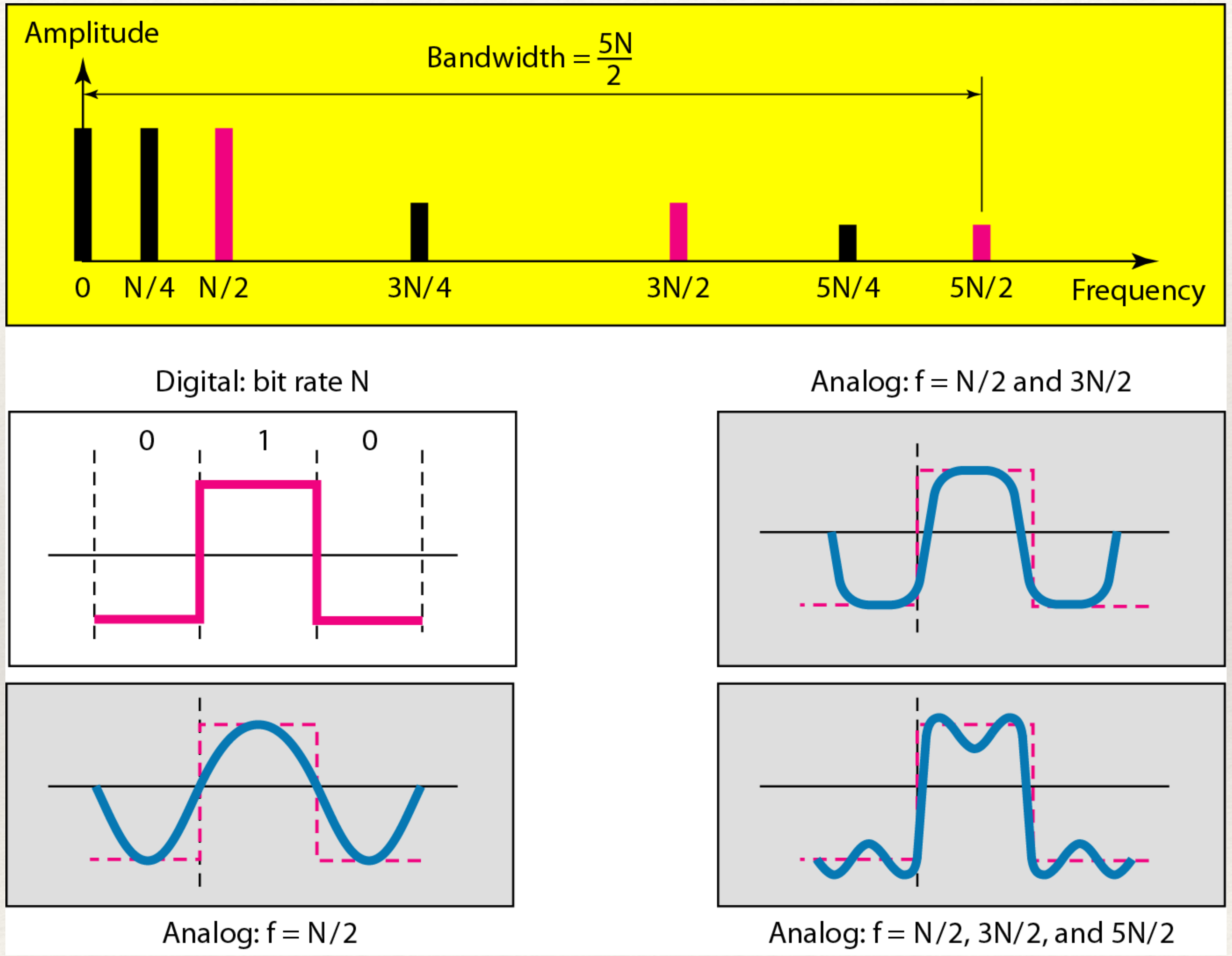


Fig. Better Approximation using first Three Harmonics

Example

Q1: 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,First Harmonic is $B = \text{bit rate } (N) / 2$, or 500 kHz.

b. A better solution is to use the first and the third harmonics with $B = 3 \times 500$ kHz $= 1.5$ MHz.

c. Still a better solution is to use the first, third, and fifth harmonics with $B = 5 \times 500$ kHz $= 2.5$ MHz.

Broadband Transmission

- Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.
- Modulation allows us to use a bandpass channel—a channel with a bandwidth that does not start from zero.

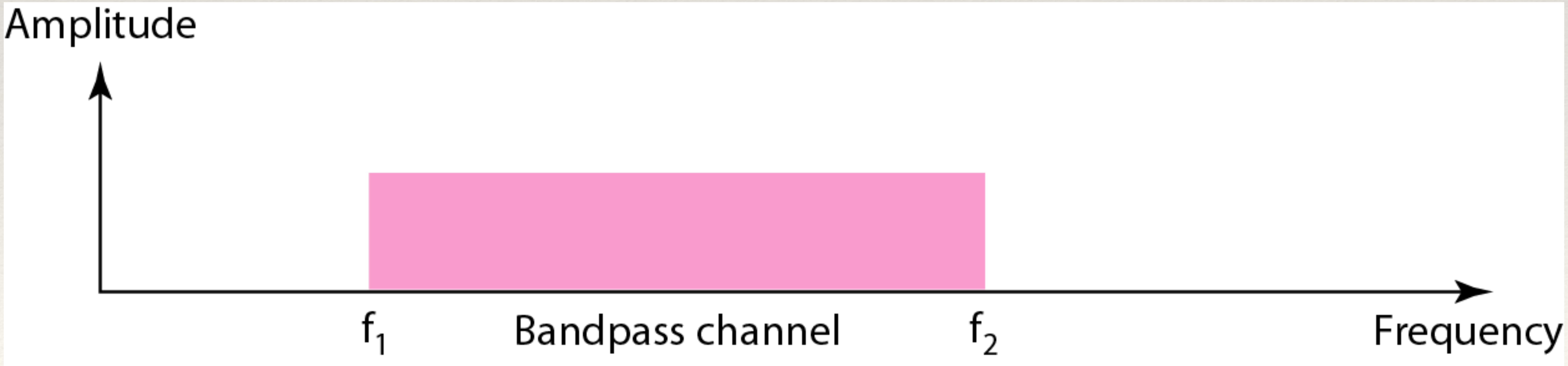


Fig. Bandpass Channel

Broadband Transmission

- Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.
- Modulation allows us to use a bandpass channel-a channel with a bandwidth that does not start from zero.
- low-pass channel can be considered a bandpass channel with the lower frequency starting at zero.
- 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.

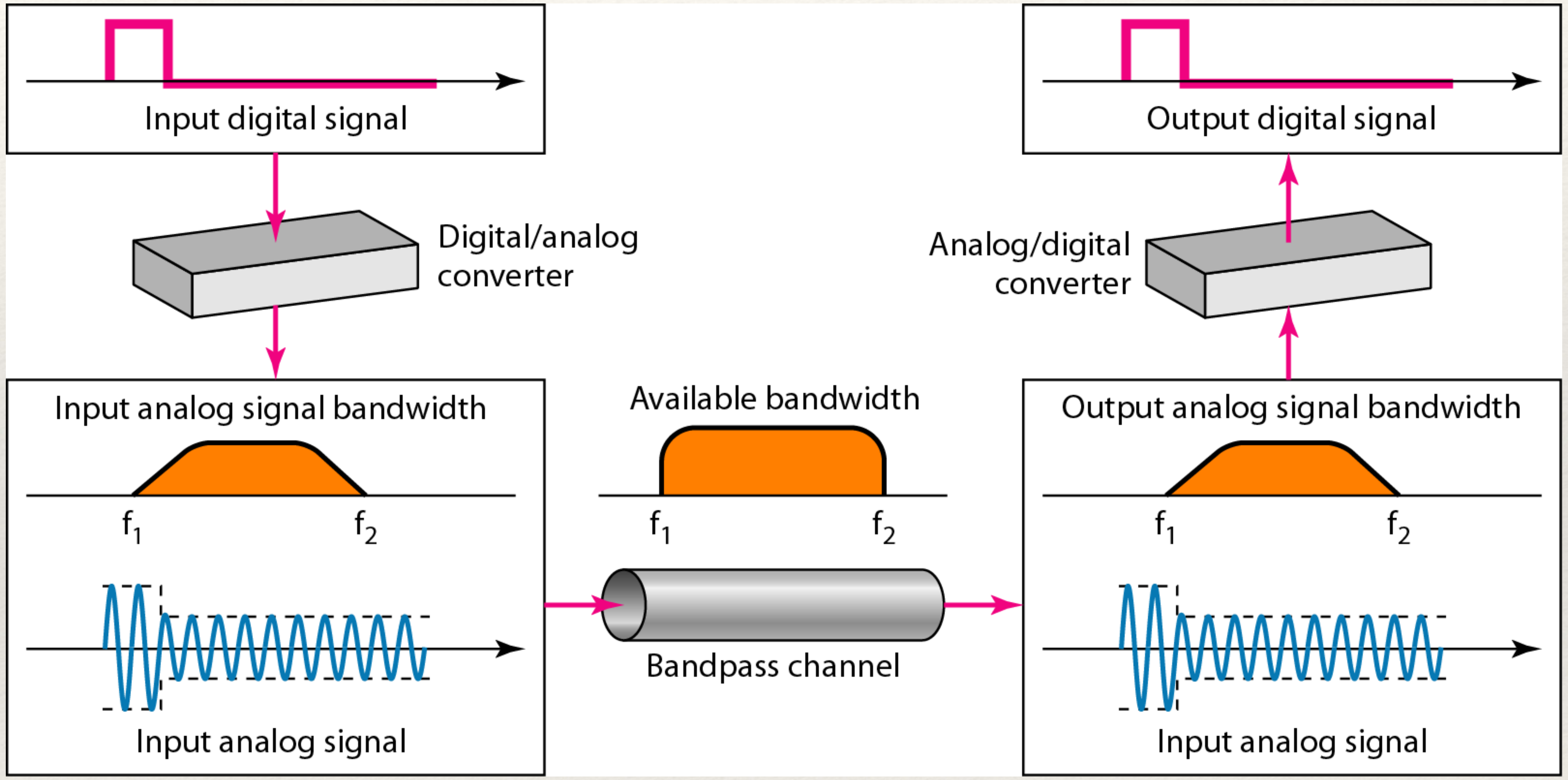


Fig. Modulation of a digital signal transmission on a bandpass channel

Transmission Impairment

- Impairment: 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?
- Causes for Impairment
  - Attenuation
  - Distortion
  - Noise

Imperfection causes impairment

Attenuation

Energy loss in overcoming the resistance of the medium
Eg. cable gets warm

- Attenuation: Attenuation means a loss of energy.
- The decibel (dB) measures the relative strengths of two signals or one signal at two different points.

$$dB = 10\log_{10}(P2/P1)$$

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

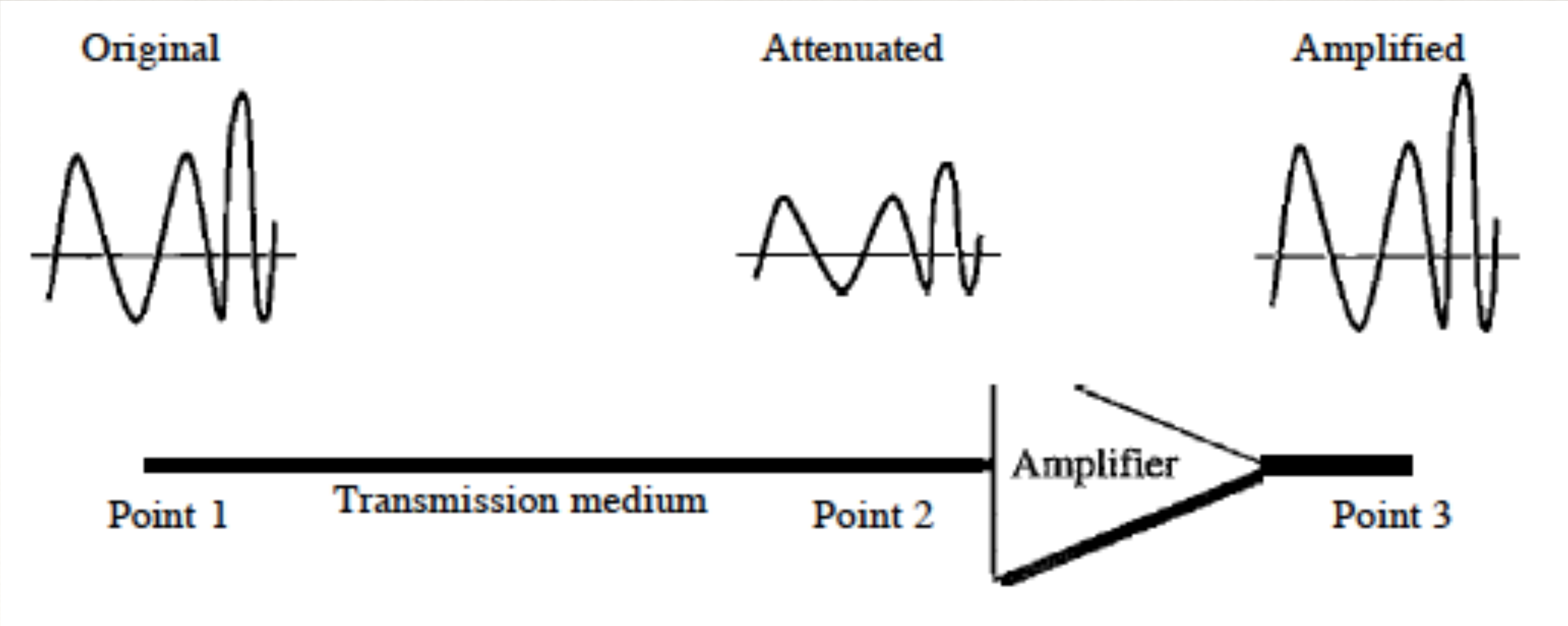


Fig. Amplify the signal

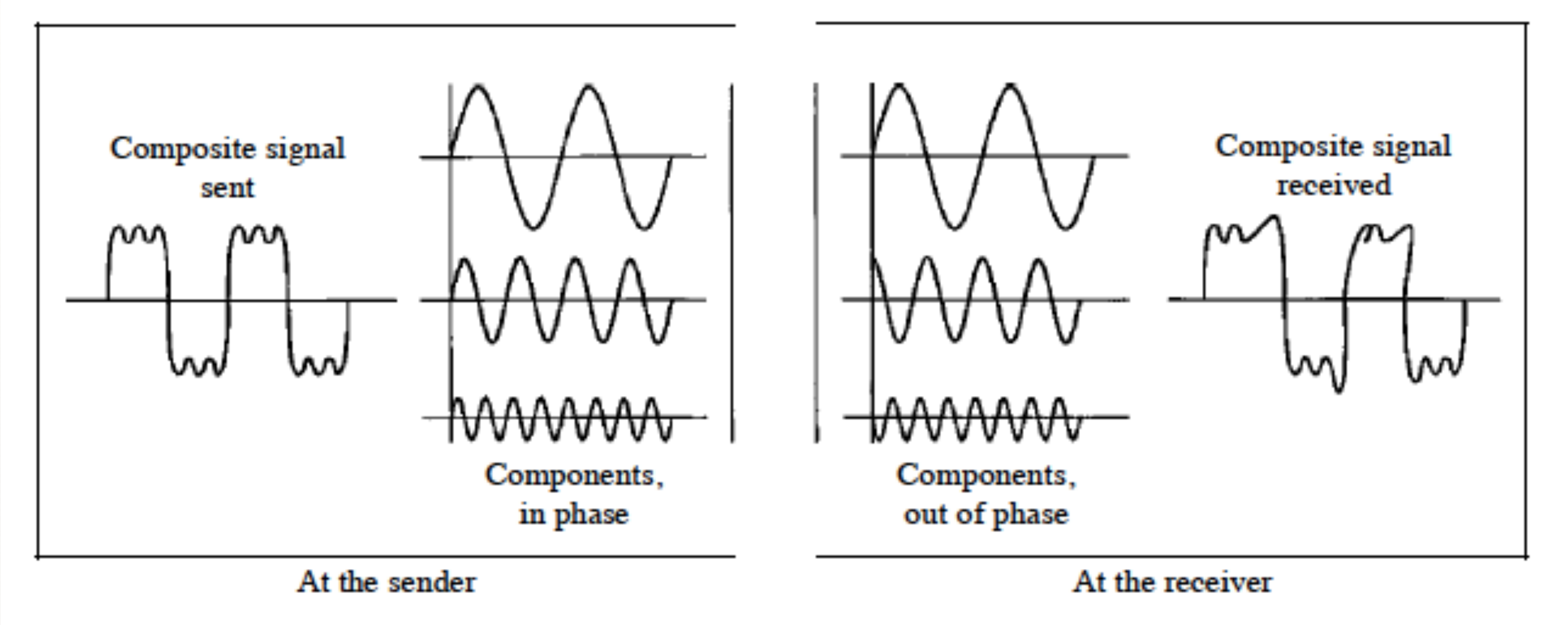
Attenuation: Problems

Problem 1: Suppose a signal travels through a transmission medium and its power is reduced to one-half, what is the power loss?

Problem 2: A signal travels through an amplifier, and its power is increased 10 times, what is the power gain of the signal?

Distortion

- Distortion: means that the signal changes its form or shape.
- Distortion can occur in composite signal made of different frequencies.
  - Causes: Differences in delay in arriving at the final destination may create the difference in the phase.



Distortion

Noise

- Noise: Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.
    - **Thermal Noise**: random motion of electrons in a wire which creates an extra signal not originally sent by transmitter.
    - **Induced Noise**: Induced noise comes from sources such as motors and appliances. These devices acts as the sender and the transmission medium acts as the receiving antenna.
    - **Crosstalk:** is the effect of one wire on the other
    - **Impulse Noise**: sudden Spike in the Signal (Signal With high energy in short time cause Spike in signal)

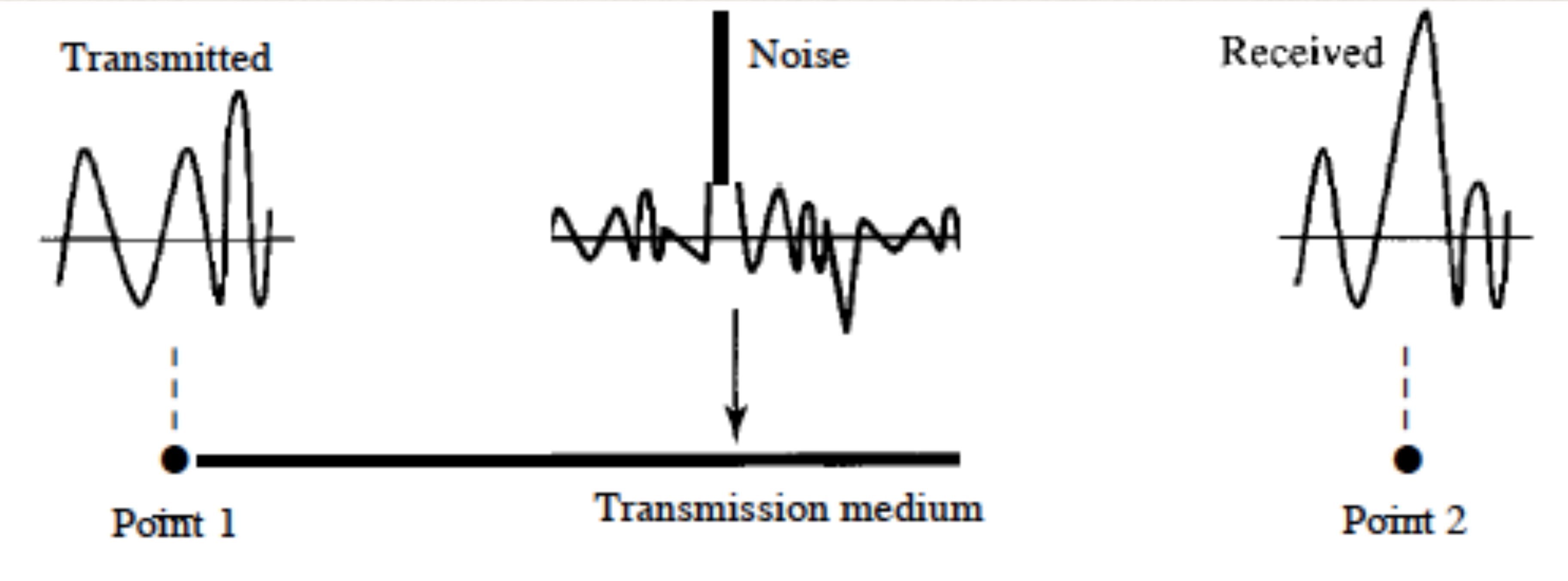


Fig: Noise

Signal to Noise Ratio (SNR)

- Signal power to the noise power is defines as Signal to Noise ratio (SNR).
  - SNR= Average Signal Power / Average Noise Power
  - Because SNR is the ratio of two powers, it is often described in decibel units, SNR_{dB}, defined as.

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

Problems on SNR

Problem 1. The Power of the Signal is 10mW and the power of the noise is 1μW. Find the values of SNR and $SNR_{dB?}$

Problem 2. What is the SNR and SNR_{dB} for Noiseless Channel?

Data Rate Limits

- How fast we can send data in bps over a channel.
- Data Rate depends on three factors
  - The bandwidth available
  - The level of the signals we use
  - The quality of the channel (the level of noise)
- Two theoretical formulas used to calculate the Data rate limits:
  - Nyquist Rate
  - Shannon Channel Capacity

Noiseless Channel: Nyquist Rate

- For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate is

$$\text{Bit Rate} = 2 \times \text{Bandwidth} \times \log_2 L,$$

L is number of Signal level used to represent data.

- Increasing the number of levels of a signal may reduce the reliability of the System.

PROBLEMS:

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

2. How many signal levels is required to send 280 kbps over a noiseless channel with a bandwidth of 20 kHz?

Shannon Channel Capacity

- For a Noisy Channel, the **Claude Shannon** introduced a formula called Shannon Capacity.
- It determine the theoretical maximum data rate for the Noisy Channels

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

PROBLEMS:

Q1. Assume the SNR_{dB}= 36 and the bandwidth of the channel is 2MHz, find the channel capacity?

Note: Sometime we may have to use both.

Q2. Find the bit rate and the signal level for the channel with the bandwidth of 1MHz and SNR of 71?

Note: **The Shannon Capacity gives us the upper limit of the channel.**

The Nyquist formula tells us how many signals levels we need.

Performance

- Bandwidth: measures network performance
  - Bandwidth in Hz: range of frequencies contained in a composite signal or the range of frequencies a channel can pass
  - Bandwidth in bps: bandwidth can also refer to the number of bits per second that a channel, a link, or even a network can transmit
    - Relationship: an increase in bandwidth in hertz means an increase in bandwidth in bits per second.
- Throughput: throughput is a measure of how fast we can actually send data through a network.

Problem 1: 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: Throughput= 12000X10000/60= 2Mbps (Actual throughput is one fifth of the actual bandwidth)

Performance

- Latency (Delay): 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= transmission time + propagation time + queuing time+ processing delay

- Transmission time: transmission of a message depends on the size of the message and the bandwidth of the channel.

Transmission time= Message Size/Bandwidth

- Propagation time: time required for a bit to travel from the source to the destination

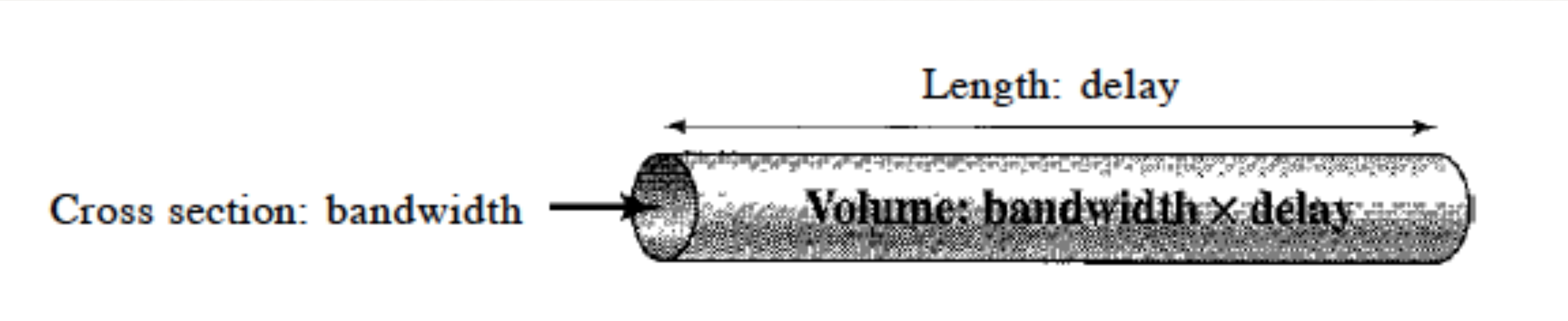
Propagation time= Distance/Speed

Speed= $3X10^8$ (Speed of light in Vacuum)

Performance

Problem 1: What are the propagation time and the transmission time for a 5-Mbyte message (an image), if the bandwidth of the network is 1 Mbps? Consider the distance between the sender and the receiver is 12,000 km and that light travels at 2.4 X 10^8. (Ans: Tp= 50ms and Tt= 40s)

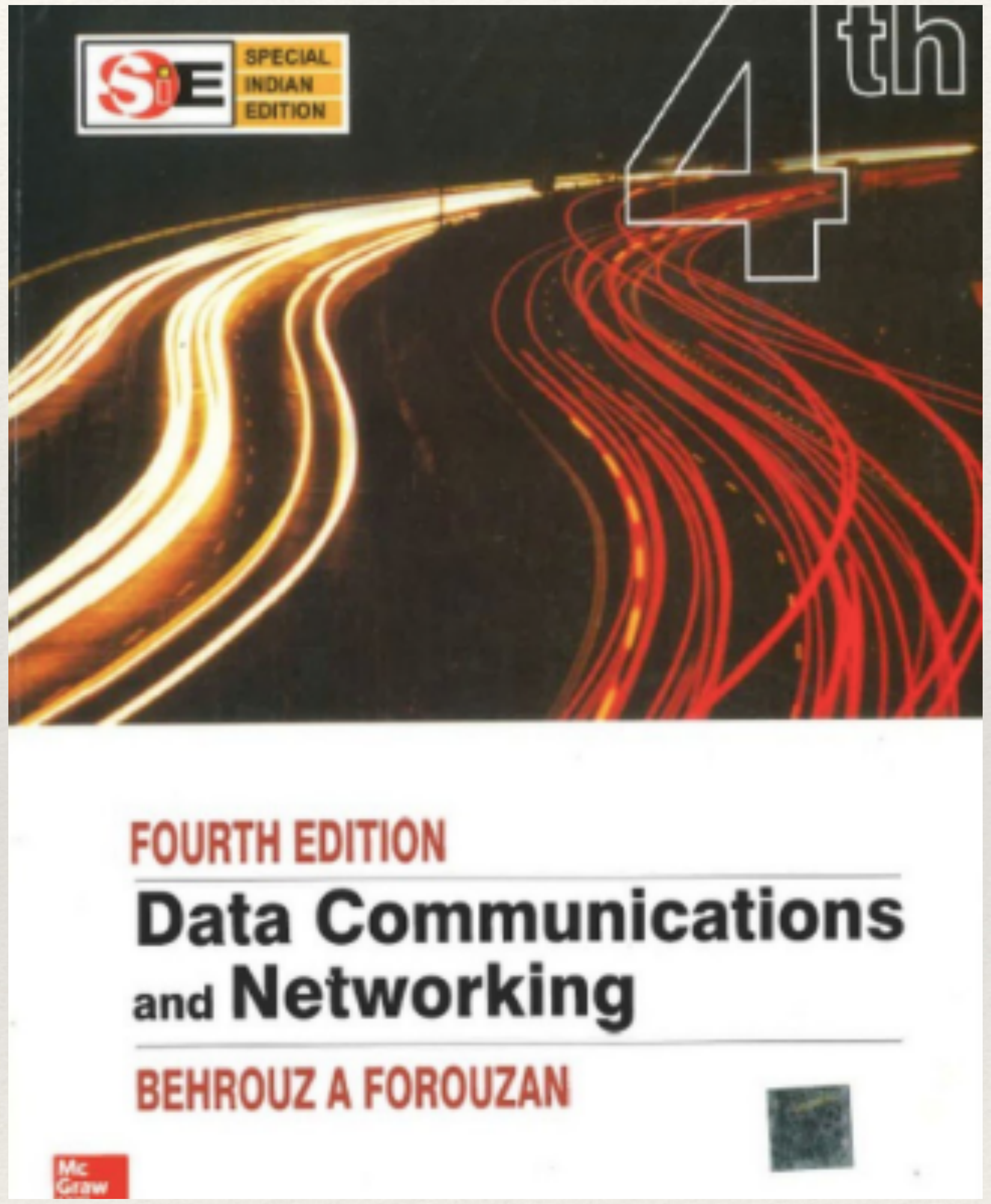
- Bandwidth Delay Product: defines the number of bits that can fill the link. (Volume)



- Jitter: problem if different packets of data encounter different delays.

Summary

- Understand the basic responsibilities of the Physical Layer
- Type of Signals : Digital and Analog Signals
- Digital Signal Transmission
- Transmission Impairment
- Performance metrics



Note: Refer Textbook Chapter 3