The Physical Layer

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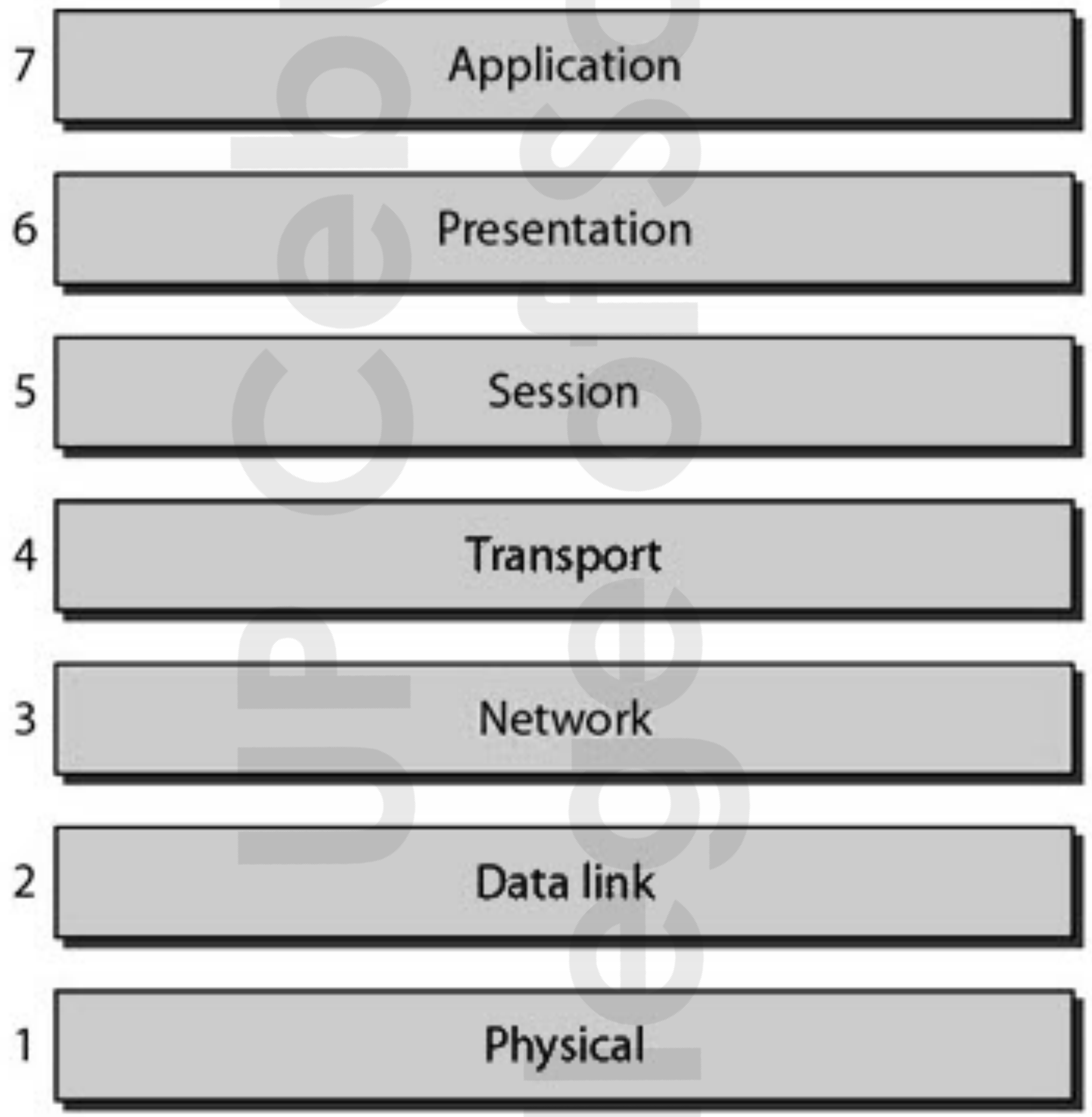
- Theoretical Basis
- The Telephone System
- Transmission and Multiplexing
- Terminal Handling
- Errors

Recall the OSI Model

- Open Systems Interconnection model
- established in 1957 by ISO (International Standards Organization)
- layered model that dominated data communications and networking literature before 1990 (replaced by TCP/IP)
- purpose of the OSI model is to show how to facilitate communication between different systems without requiring changes to the logic of the underlying hardware and software
- a layered framework for the design of network systems that allows communication between all types of computer systems
- consists of seven separate layers, each of which defines a part of the process of moving information across a network

User Support Layers
- allow interoperability among unrelated software systems

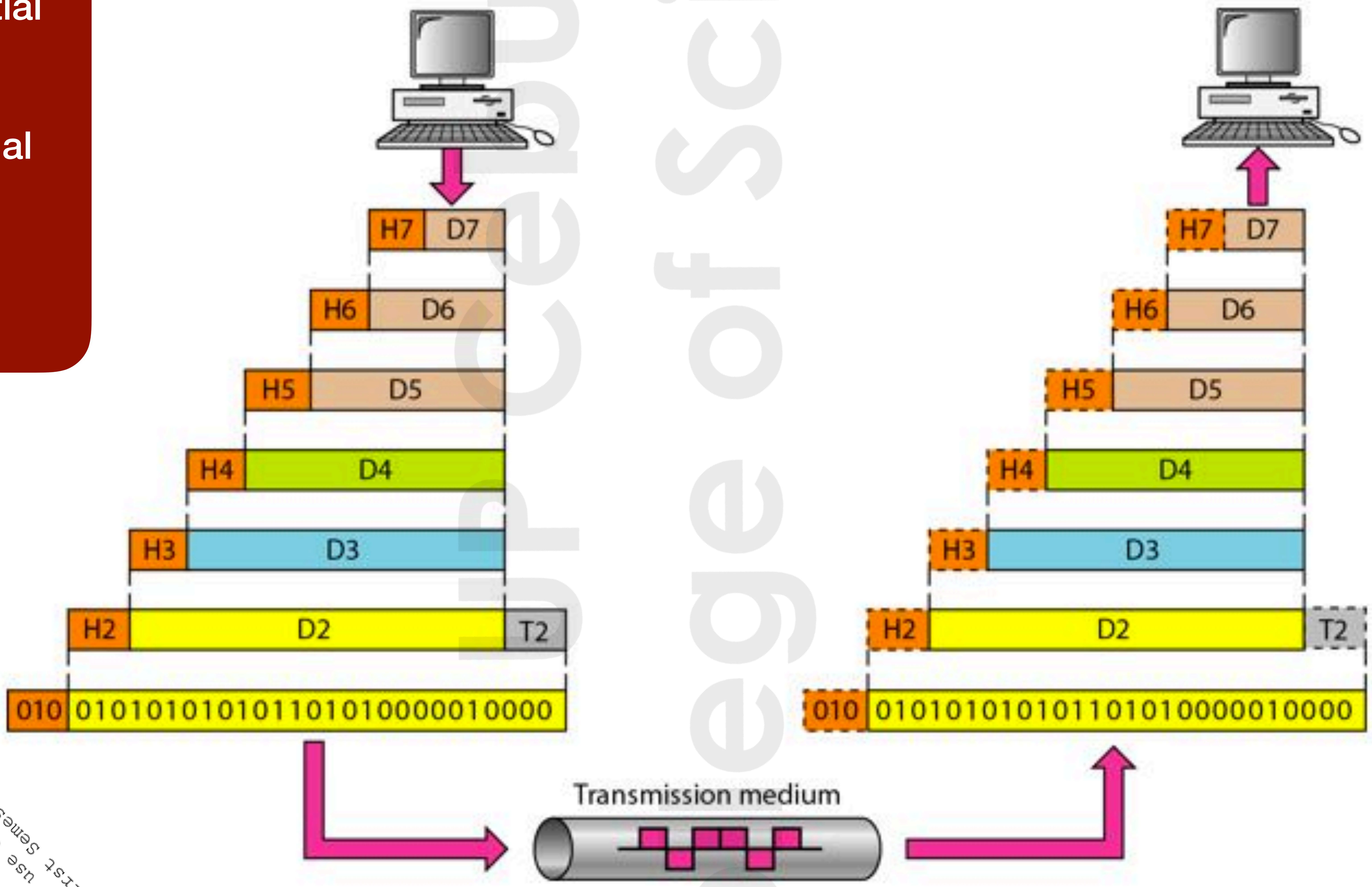
Network Support Layers
- deal with the physical aspects of moving data from one device to another (such as electrical specifications, physical connections, physical addressing, and transport timing and reliability)



Transport Layer
- links the two subgroups and ensures that what the lower layers have transmitted is in a form that the upper layers can use

An exchange using the OSI model…

- descending, sequential
- data unit, packet
- header or trailer
- electromagnetic signal (electrical/optical)
- digital form
- encapsulation

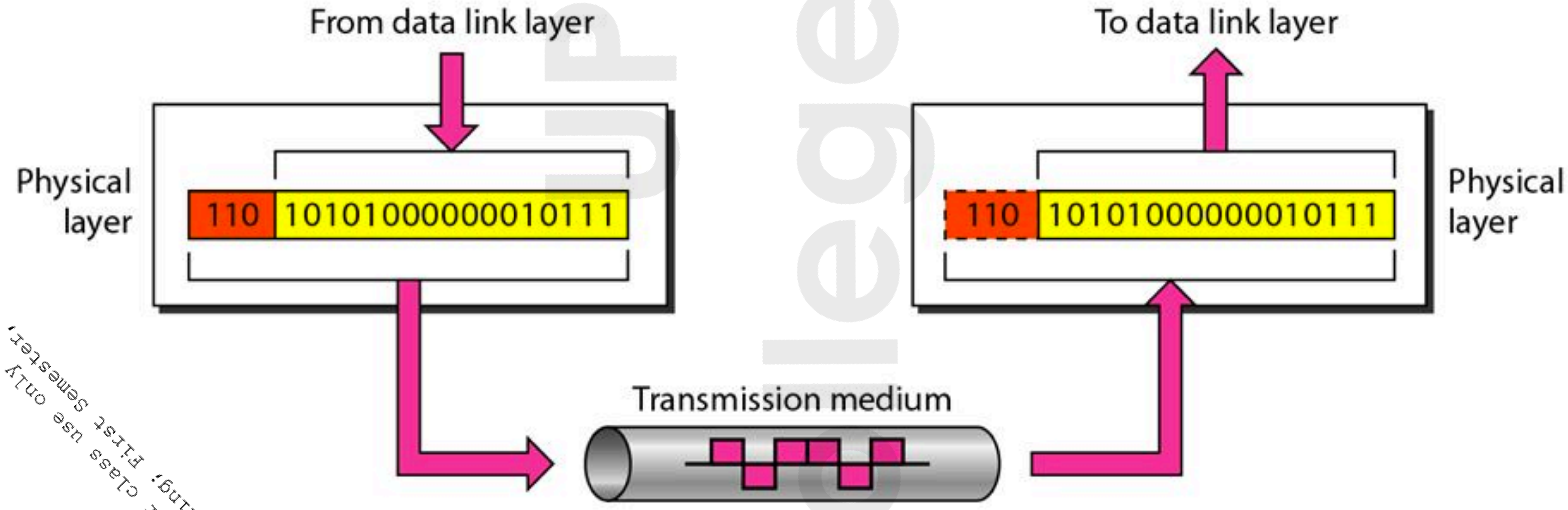


Layers in the OSI Model

1. Physical Layer
2. Data Link Layer
3. Network Layer
4. Transport Layer
5. Session Layer
6. Presentation Layer
7. Application Layer

1. Physical Layer

- coordinates the functions required to carry a bit stream over a physical medium
- deals with the mechanical and electrical specifications of the interface and transmission medium
- defines the procedures and functions that physical devices and interfaces have to perform for transmission to occur



The Physical Layer is concerned of…

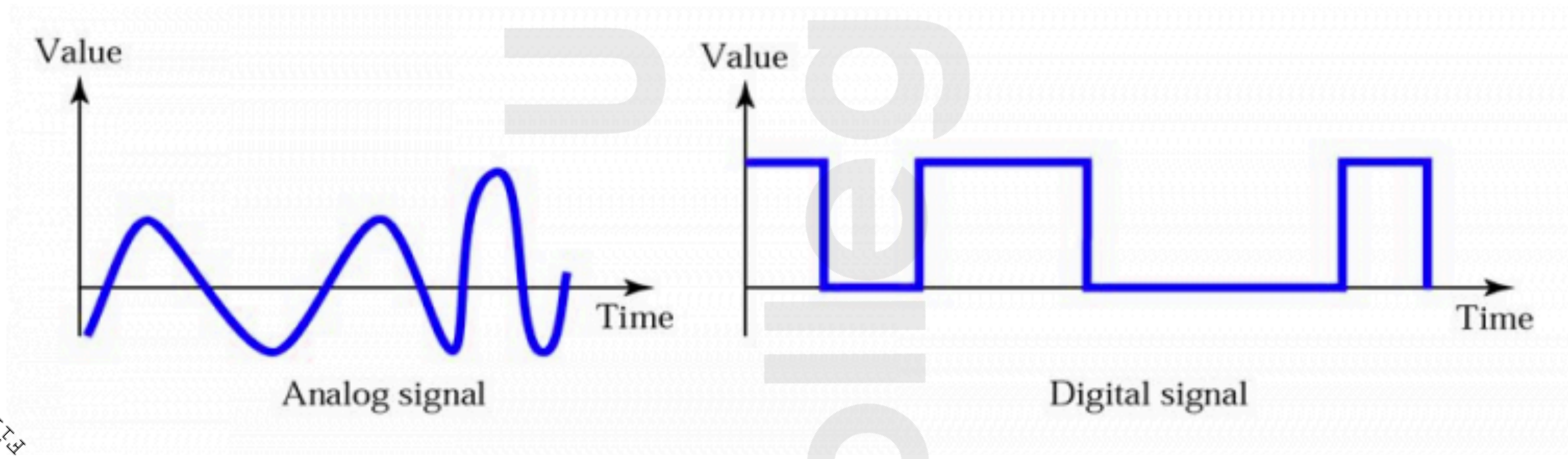
- Physical characteristics of interfaces and medium
- Representation of bits for transmission
- Data rate
- Synchronisation of bits
- Line configuration
- Physical topology
- Transmission mode

Theoretical Basis

- analog data versus digital data
- periodic and non-periodic signals
- simple and composite analog signals
- digital signals

Analog and Digital

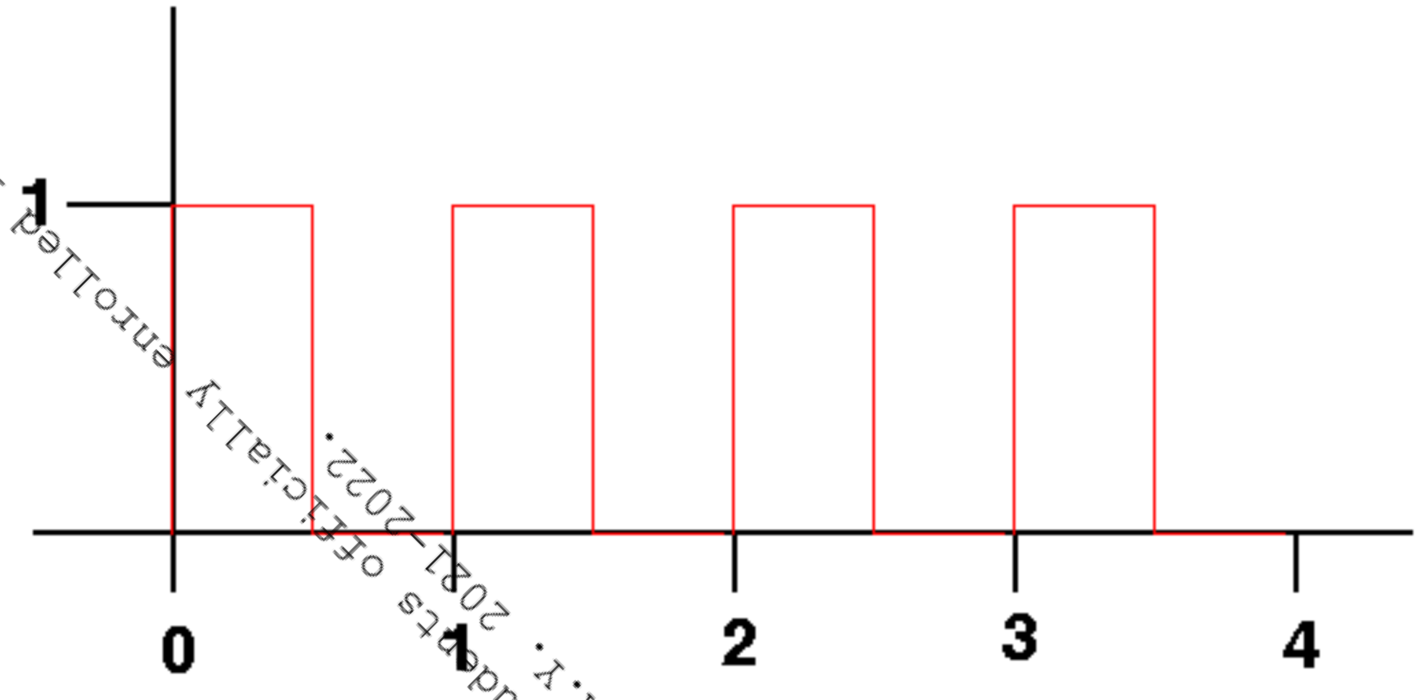
- **analog data**
  - refers to information that is continuous
  - infinite number of values in a range
- **digital data**
  - refers to information that has discrete states
  - limited number of values

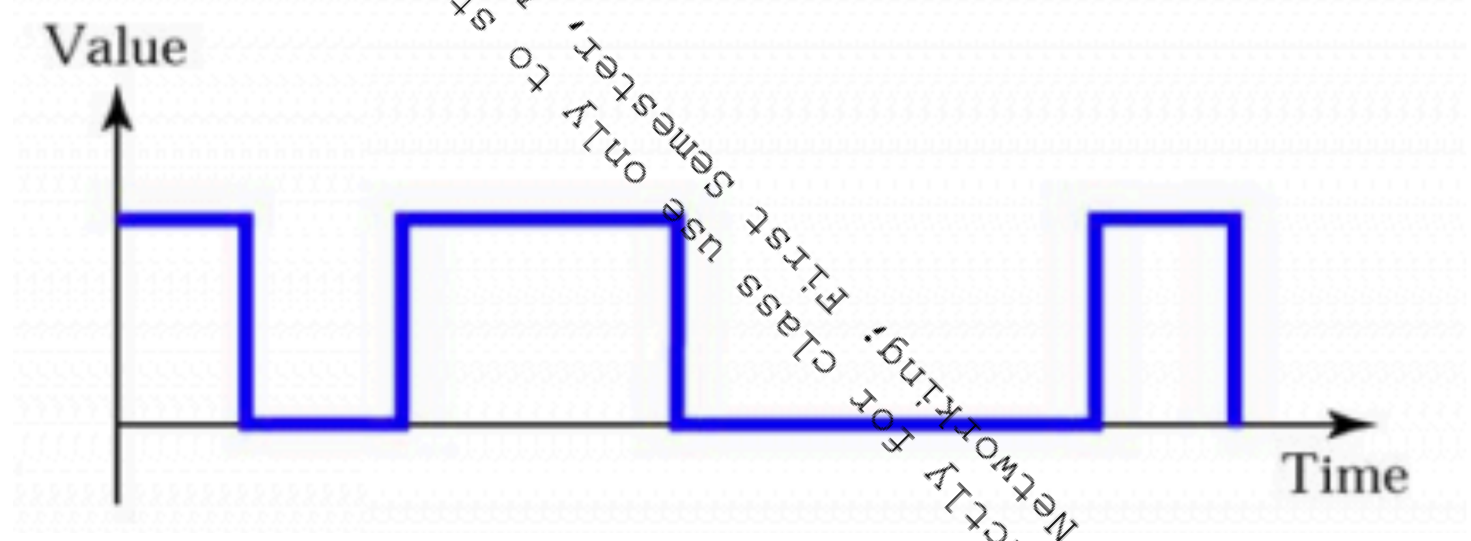


Periodic and Non-periodic (Aperiodic) Signals

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

- **periodic signal**
  - completes a pattern within a measurable time frame called a *period,* and repeats the pattern over subsequent identical periods
  - the completion of one full pattern is called a *cycle*
- **non-periodic signal**
  - changes without exhibiting a pattern or cycle that repeats over time





Periodic Analog Signals

- can be classified as simple or composite
  - simple periodic analog signal: a sine wave, cannot be decomposed into simpler signals
  - composite periodic analog signal: composed of multiple sine waves

Sine Wave

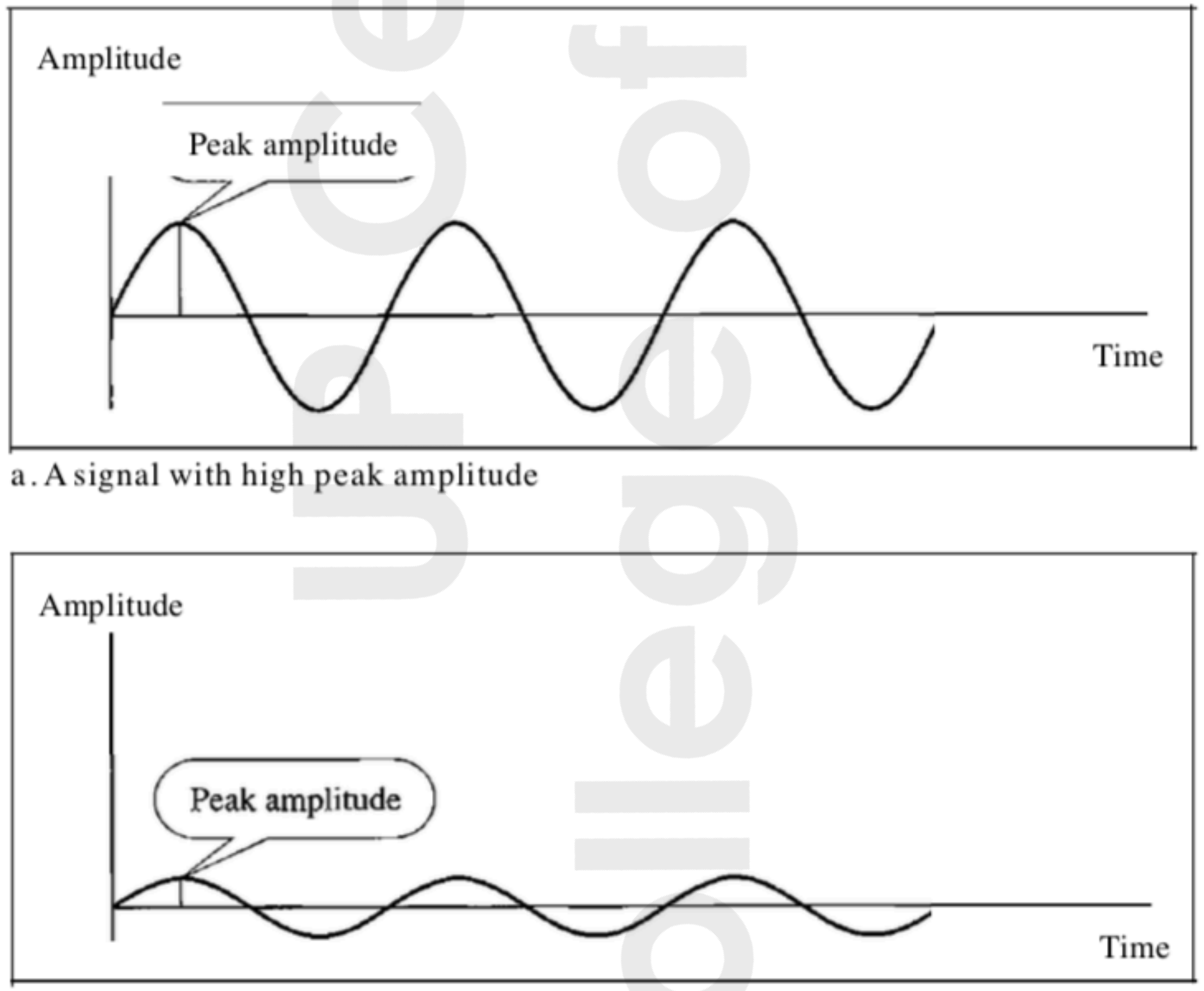
- the most fundamental form of a periodic analog signal
- characterized by a smooth, consistent, continuous, rolling flow
- each cycle consists of a single arc above the time axis followed by a single arc below it
- can be represented by three parameters: the *peak amplitude*, the *frequency*, and the *phase*

Figure 3.2 *A sine wave*

Peak Amplitude

- the absolute value of its highest intensity, proportional to the energy it carries
- for electric signals, peak amplitude is normally measured in volts

Figure 3.3 *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

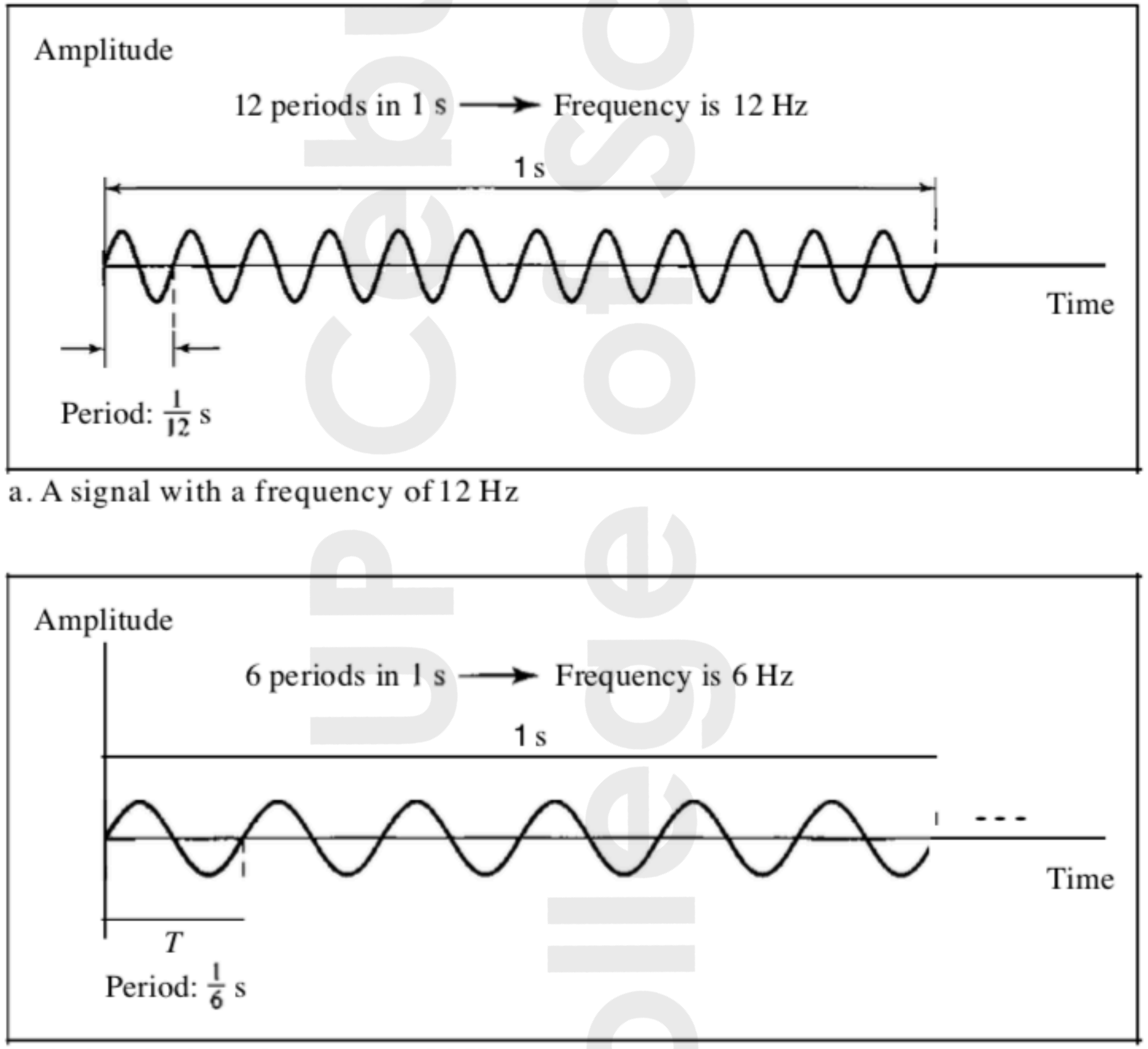
Period and Frequency

- period refers to the amount of time, in seconds, a signal needs to complete 1 cycle
- frequency refers to the number of periods in 1s (expressed in hertz Hz)
- period and frequency are just one characteristic defined in two ways
- period is the inverse of frequency, and frequency is the inverse of period

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

Frequency and period are the inverse of each other.

Figure 3.4 *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

Table 3.1 *Units ofperiod andfrequency*

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 3.3

The power we use at home has a frequency of 60 Hz (50 Hz in Europe). The period of this sine wave can be determined as follows:

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

This means that the period of the power for our lights at home is 0.0116 s, or 16.6 ms. Our eyes are not sensitive enough to distinguish these rapid changes in amplitude.

Example 3.4

Express a period of 100 ms in microseconds.

Solution

From Table 3.1 we find the equivalents of 1 ms (1 ms is 10^{-3} s) and 1 s (1 s is 10^{6} μs). We make the following substitutions:

$$100 \text{ ms} = 100 \times 10^{-3} \text{ s} = 100 \times 10^{-3} \times 10^{6} \ \mu\text{s} = 10^{2} \times 10^{-3} \times 10^{6} \ \mu\text{s} = 10^{5} \ \mu\text{s}$$

Example 3.5

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

Solution

First we change 100 ms to seconds, and then we calculate the frequency from the period (1 Hz = 10^{-3} kHz).

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

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

More about frequency…

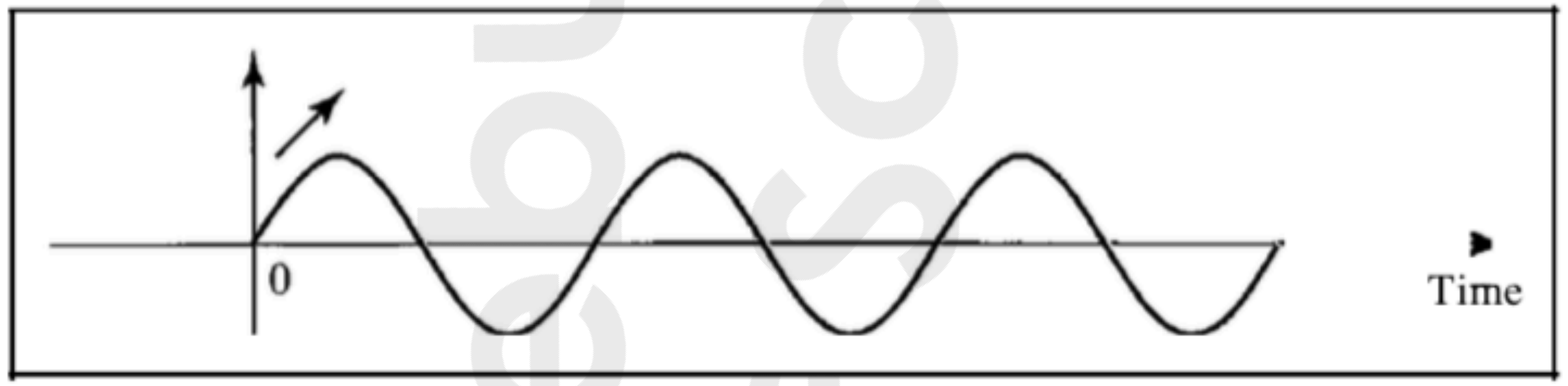
- frequency is the rate of change with respect to time
- change in a short span of time means high frequency
- change over a long span of time means low frequency
- two extremes:
  - if a signal does not change at all, its frequency is zero
  - if a signal changes instantaneously, its frequency is infinite

Phase

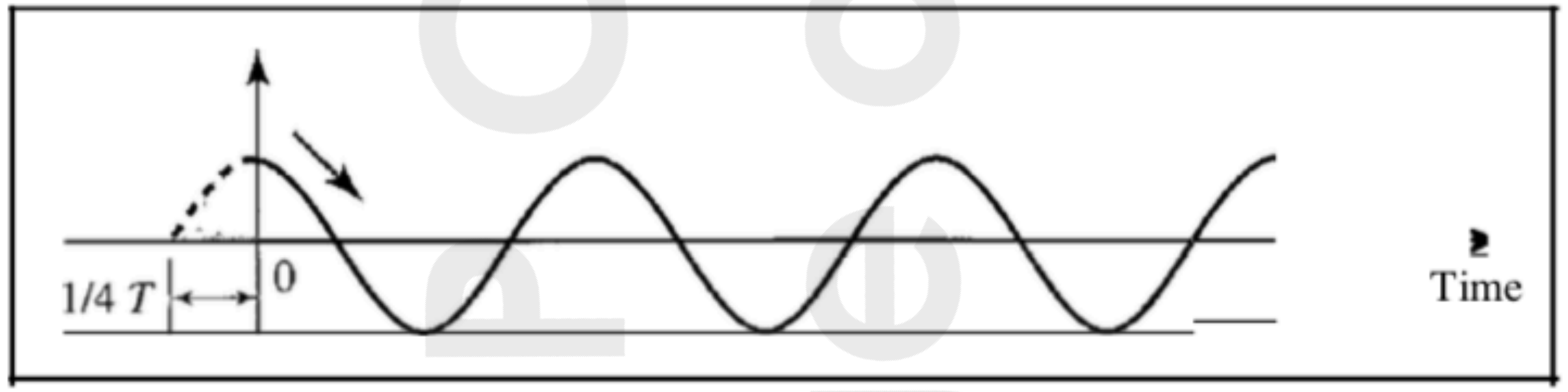
- describes the position of the waveform relative to time 0
- if we think of the wave as something that can be shifted backward or forward along the time axis, phase describes the amount of that shift
- measured in degrees or radians (1° is 2π/360° rad)
- a phase shift of 360° corresponds to a shift of a complete period
- a phase shift of 180° corresponds to a shift of one-half of a period
- a phase shift of 90° corresponds to a shift of one-quarter of a period

a. A sine wave with a phase shift of 0° starts at time 0 with a zero amplitude. The amplitude is increasing.
b. A sine wave with a phase of 90° starts at time 0 with a peak amplitude. The amplitude is decreasing.
c. A sine wave with a phase of 180° starts at time 0 with a zero amplitude. The amplitude is decreasing.

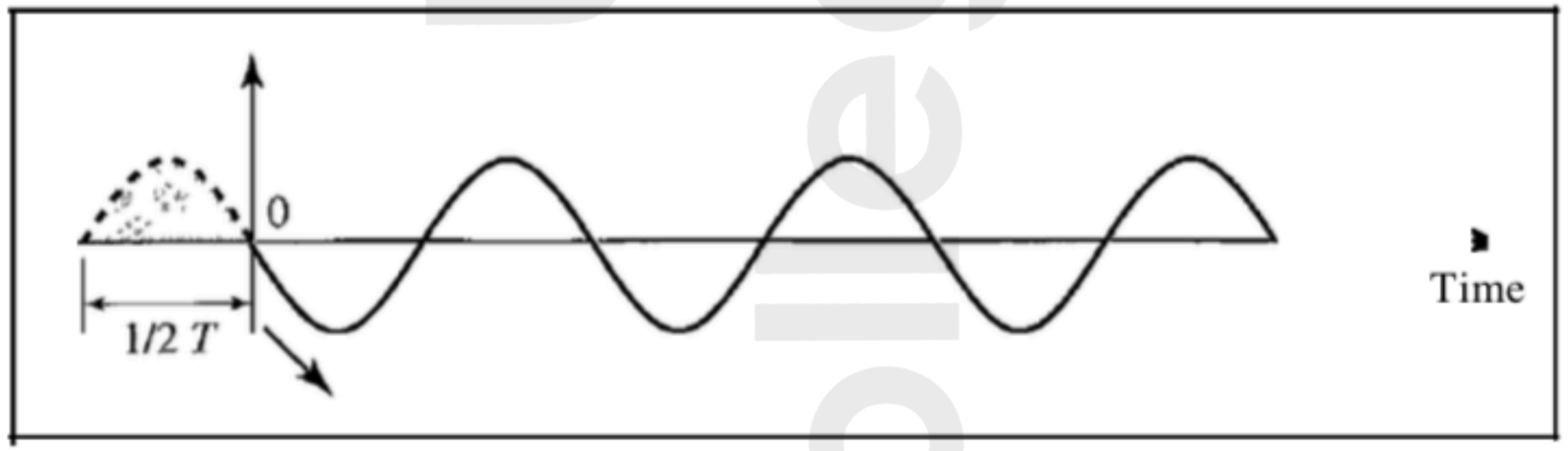
Figure 3.5 *Three sine waves with the same amplitude andfrequency, but different phases*



a. 0 degrees



b. 90 degrees



c. 180 degrees

In terms of shift or offset:
a. A sine wave with a phase of 0° is not shifted.
b. A sine wave with a phase of 90° is shifted to the left by 1/4 cycle. However, note that the signal does not really exist before time 0.
c. A sine wave with a phase of 180° is shifted to the left by 1/2 cycle. However, note that the signal does not really exist before time 0.

Example 3.6

A sine wave is offset $\frac{1}{6}$ cycle with respect to time 0. What is its phase in degrees and radians?

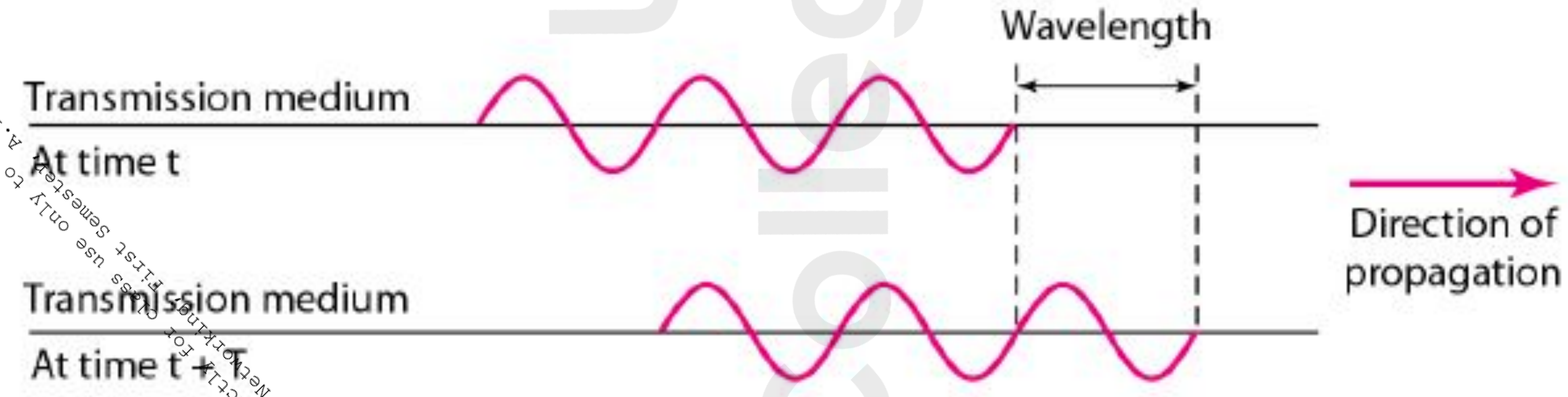
Solution

We know that 1 complete cycle is 360°. Therefore, $\frac{1}{6}$ cycle is

$$\frac{!}{6} \times 360;::; 60^\circ = 60 \times \frac{2\pi}{360} \text{ tad;::; } \frac{\pi}{3} \text{ fad;::; } 1.046 \text{ rad}$$

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
- while the frequency of a signal is independent of the medium, the wavelength depends on both the frequency and the medium
- in data communications, we often use wavelength to describe the transmission of light in an optical fiber
- in essence, the *wavelength* is the distance a simple signal can travel in one period



- wavelength λ can be calculated if one is given the propagation speed (the speed of light c) and the period of the signal (T or f)

$$\text{Wavelength} = \text{propagation speed} \times \text{period} = \frac{\text{propagation speed}}{\text{frequency}}$$

- the propagation speed of electromagnetic signals depends on the medium and on the frequency of the signal
- for example, in a vacuum, light is propagated with a speed of 3 x 10^8 ms; the speed is lower in air and even lower in cable
- wavelength is normally measured in micrometers (microns) instead of meters
- example, wavelength of red light (frequency = 4 x 10^{14}) in air is

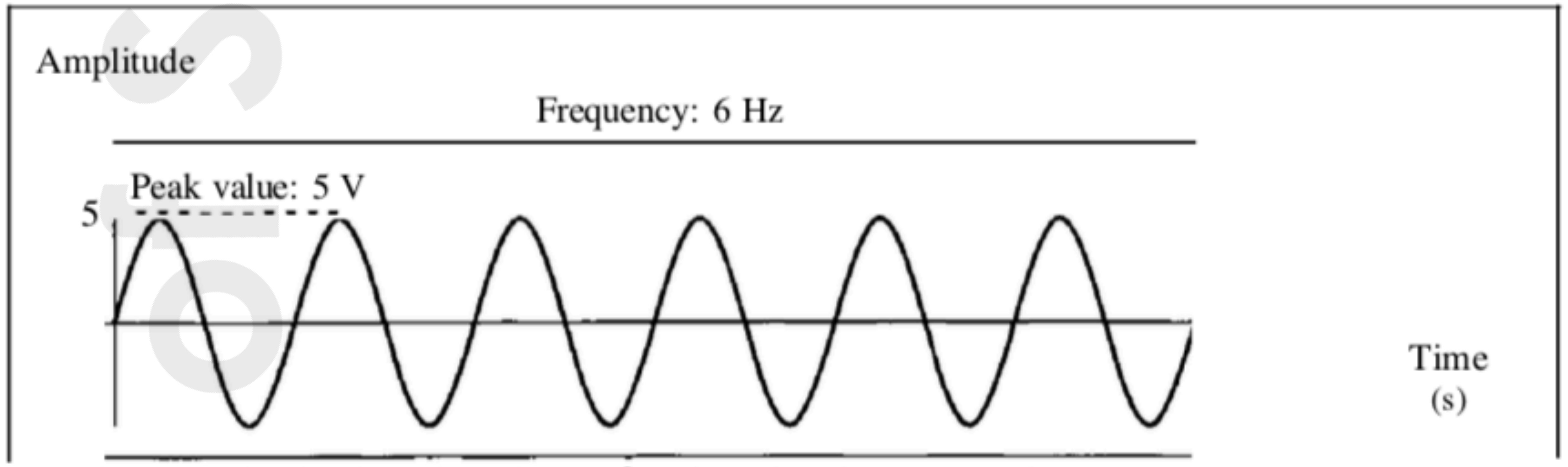
$$\lambda = \frac{c}{f} = \frac{3\times10^{8}}{4\times10^{14}} = 0.75 \times 10^{-6}\ \text{m} = 0.75\ \mu\text{m}$$

In coaxial or fiber-optic cable, however, the wavelength is shorter (0.5 μm) because the propagation speed in the cable is decreased.

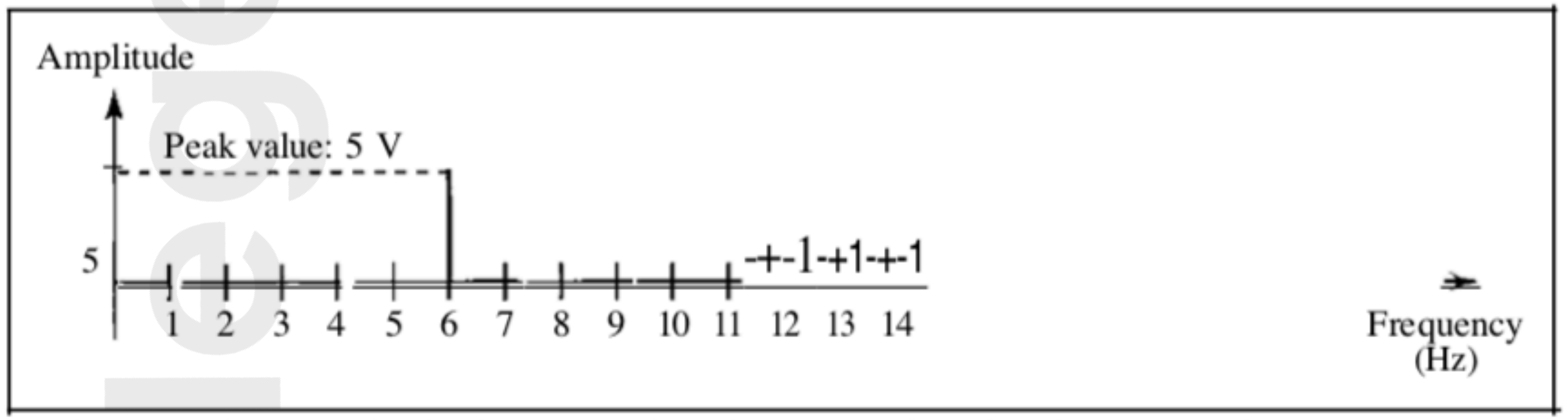
Time and Frequency Domains

- *time-domain plot*: shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot); phase is not explicitly shown on a time-domain plot
- *frequency-domain plot*: shows the relationship between amplitude and frequency; concerned with only the peak value and the frequency; changes of amplitude during one period are not shown

Figure 3.7 *The time-domain andfrequency-domain plots ofa sine wave*



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

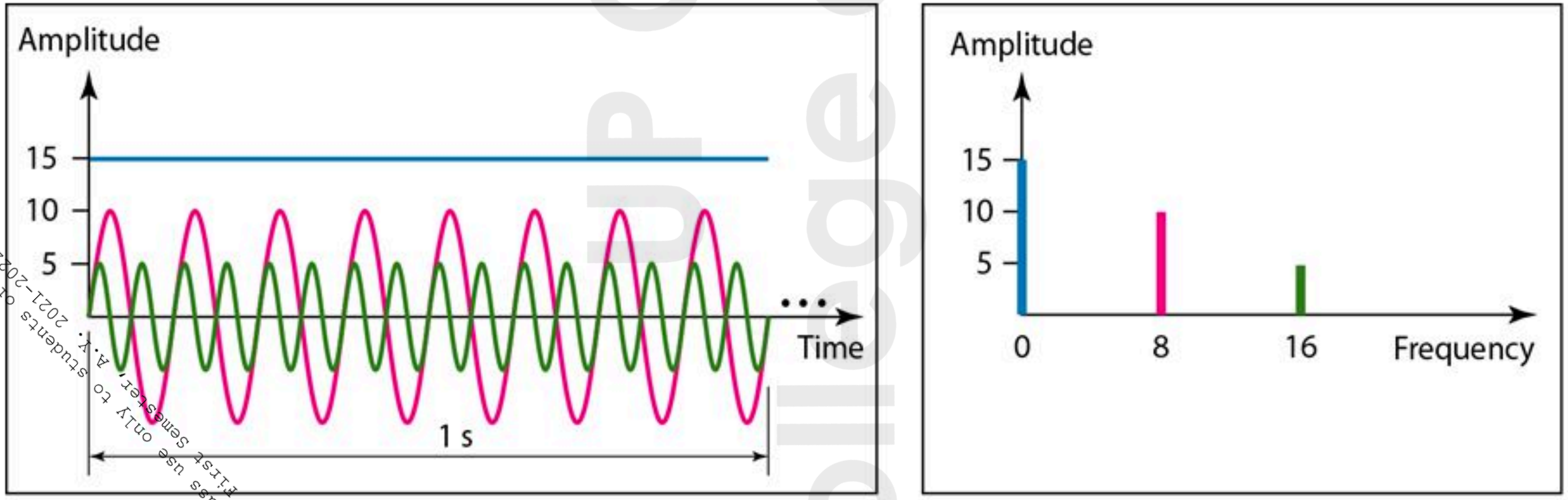


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Example 3.7

The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, Figure 3.8 shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

Figure 3.8 *The time domain andfrequency domain ofthree sine waves*

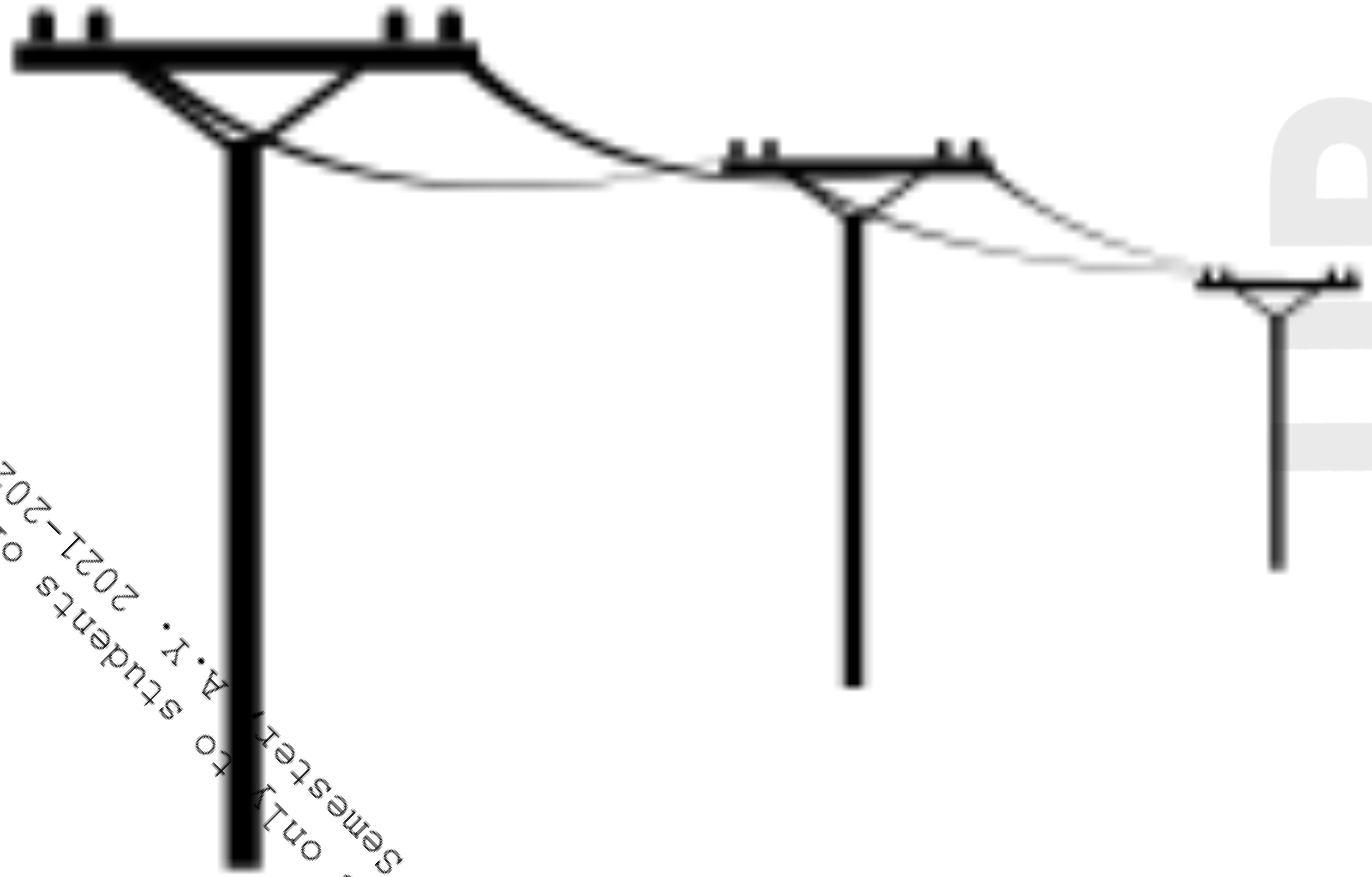


a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

b. Frequency-domain representation of the same three signals

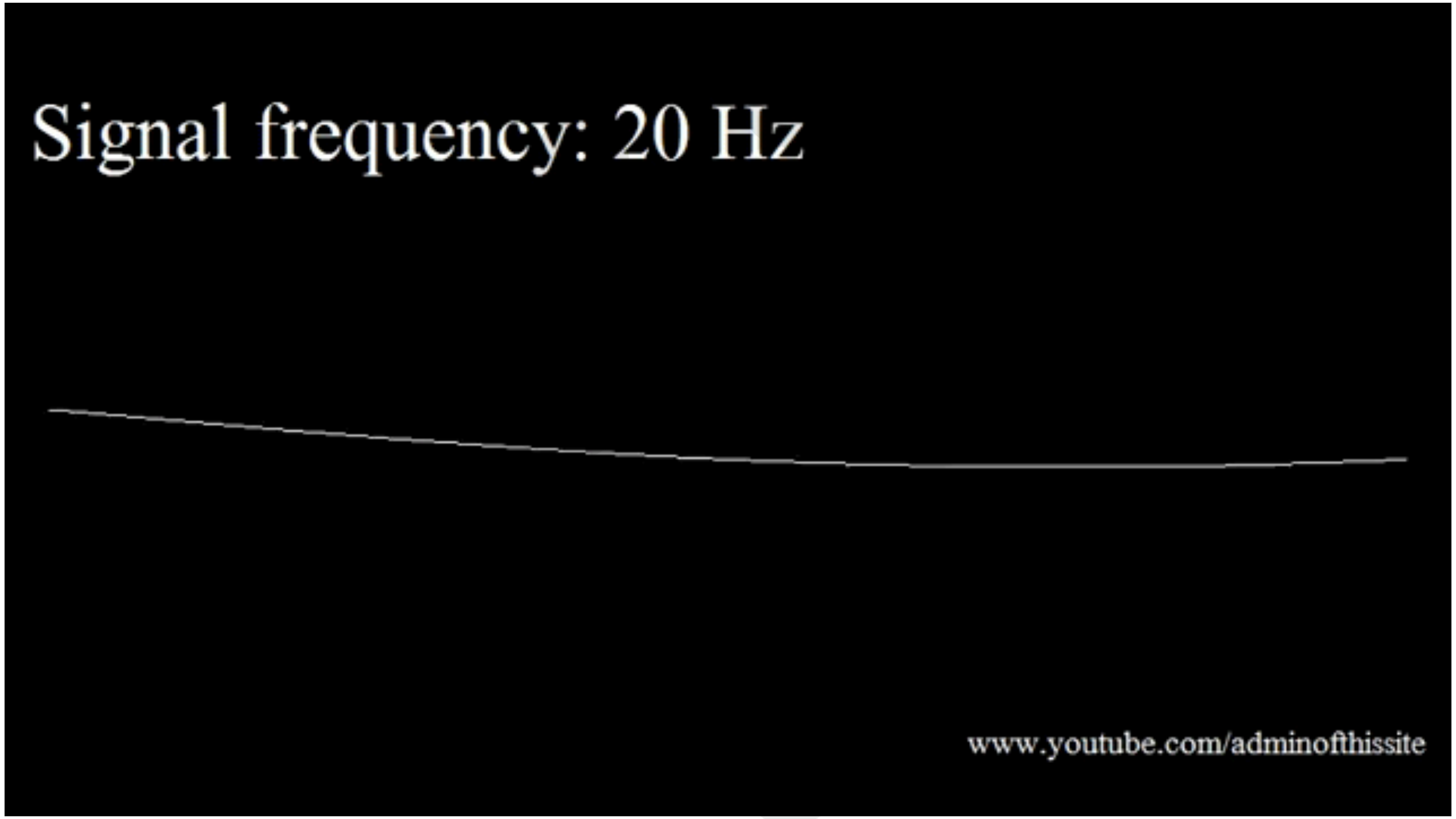
Applications of Simple Sine Waves

- power company sends a single sine wave with a frequency of 60 Hz to distribute electric energy to houses and businesses (sine wave carrying energy)
- send an alarm to a security center when a burglar opens a door or window in the house (sine wave is a signal of danger)



In data communication:

- if we had only one single sine wave to convey a conversation over the phone, it would make no sense and carry no information; just hear a buzz



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.

Composite Signals

- in the early 1900s, the French mathematician Jean-Baptiste Fourier showed that any composite signal is actually a combination of simple sine waves with different frequencies, amplitudes, and phases (Fourier analysis)
- a composite signal can be periodic or non-periodic
  - *periodic composite signal*: can be decomposed into a series of simple sine waves with discrete frequencies that have integer values (1, 2, 3, and so on)
  - *non-periodic composite signal*: can be decomposed into a combination of an infinite number of simple sine waves with continuous frequencies that have real values

Example 3.8

Figure 3.9 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.

Figure 3.9 *A composite periodic signal*

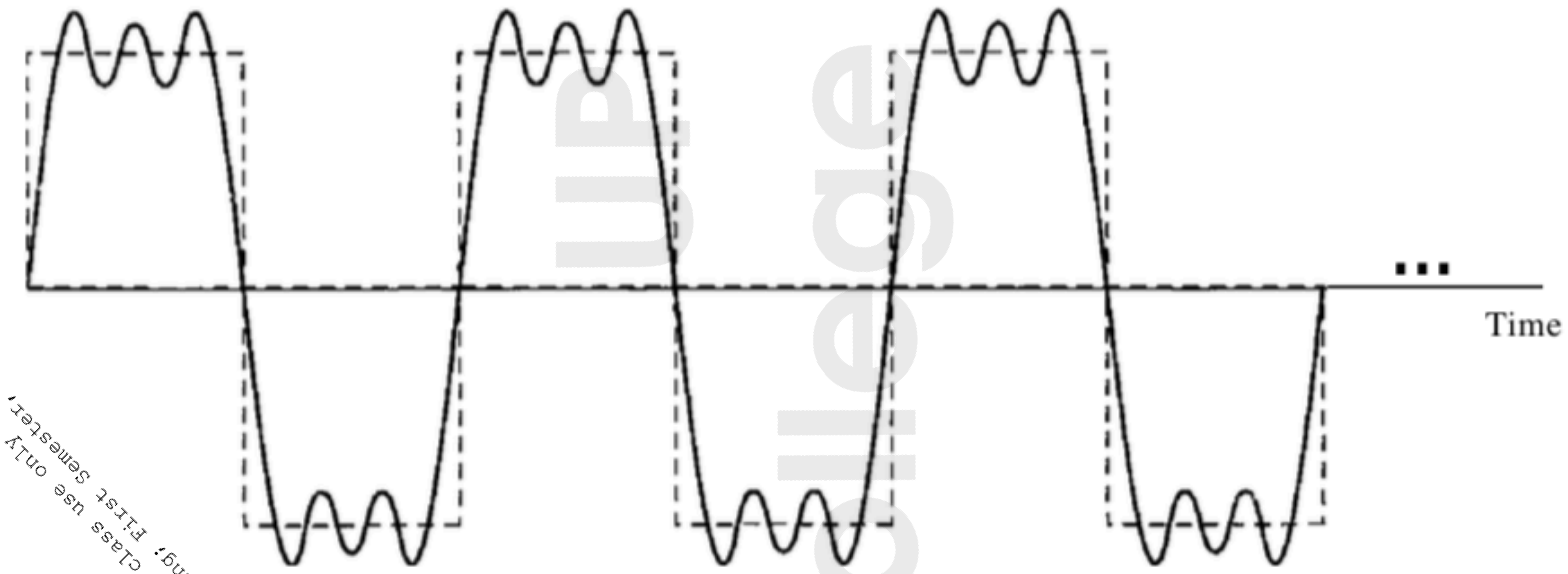
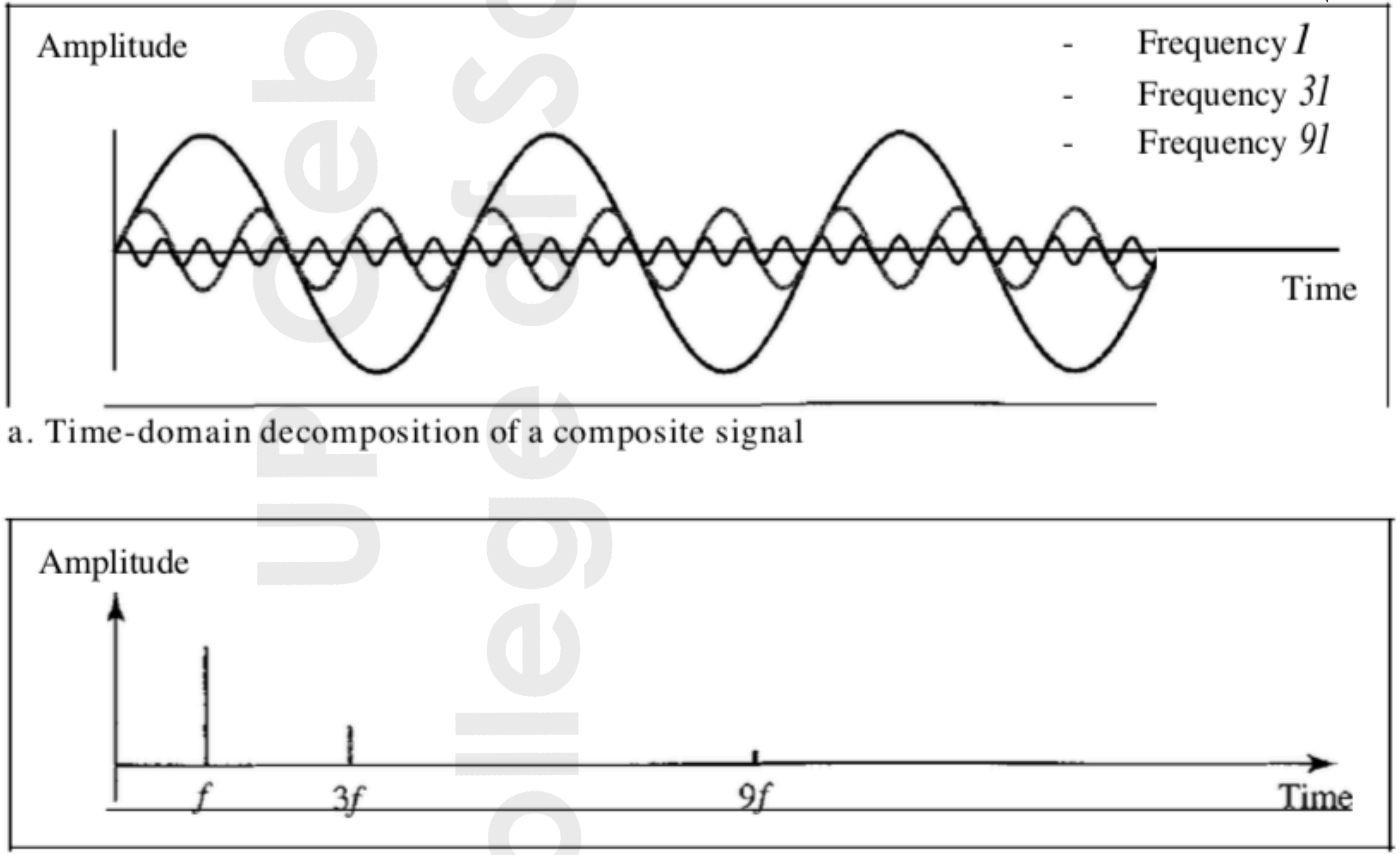


Figure 3.10 *Decomposition of a composite periodic signal in the time and frequency domains*

- the amplitude of the sine wave with frequency f is almost the same as the peak amplitude of the composite signal.
- the amplitude of the size wave with frequency 3f is one-third of that of the first, and one with 9f is one-ninth of the first
- the frequency of the sine wave with frequency f is the same as the frequency of the composite signal; it is called the fundamental frequency, or first harmonic

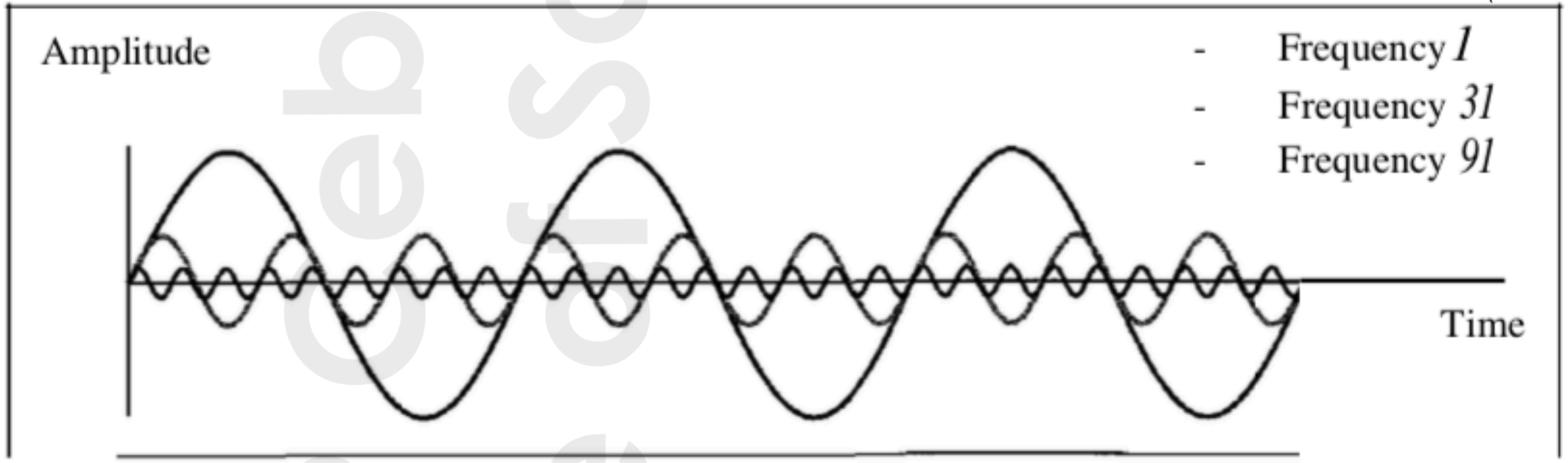


a. Time-domain decomposition of a composite signal

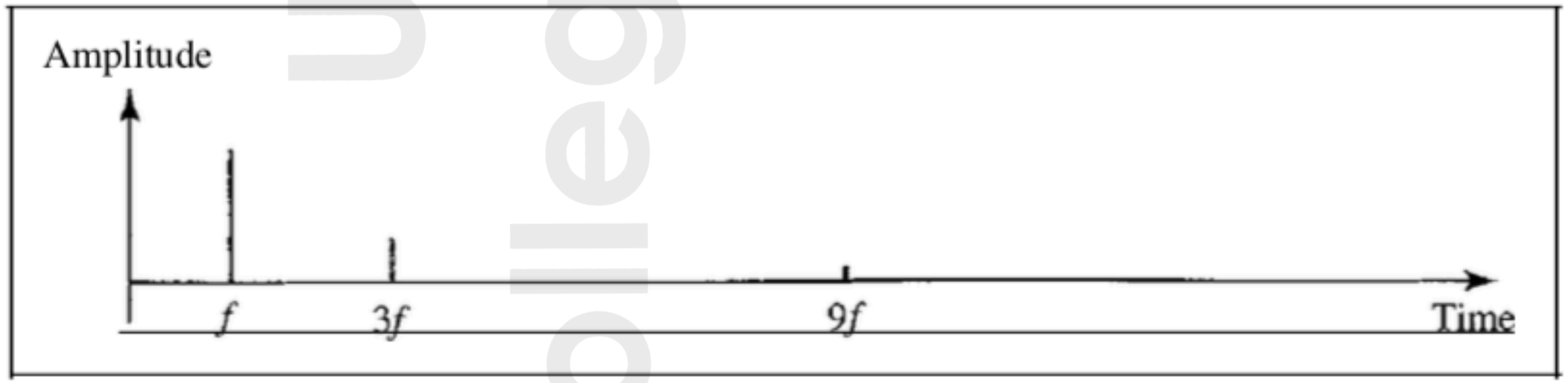
b. Frequency-domain decomposition of the composite signal

Figure 3.10 *Decomposition ofa composite periodic signal in the time andfrequency domains*

- the sine wave with frequency 3f has a frequency of 3 times the fundamental frequency; it is called the third harmonic
- the third sine wave with frequency 9f has a frequency of 9 times the fundamental frequency; it is called the ninth harmonic
- note that the frequency decomposition of the signal is discrete



a. Time-domain decomposition of a composite signal



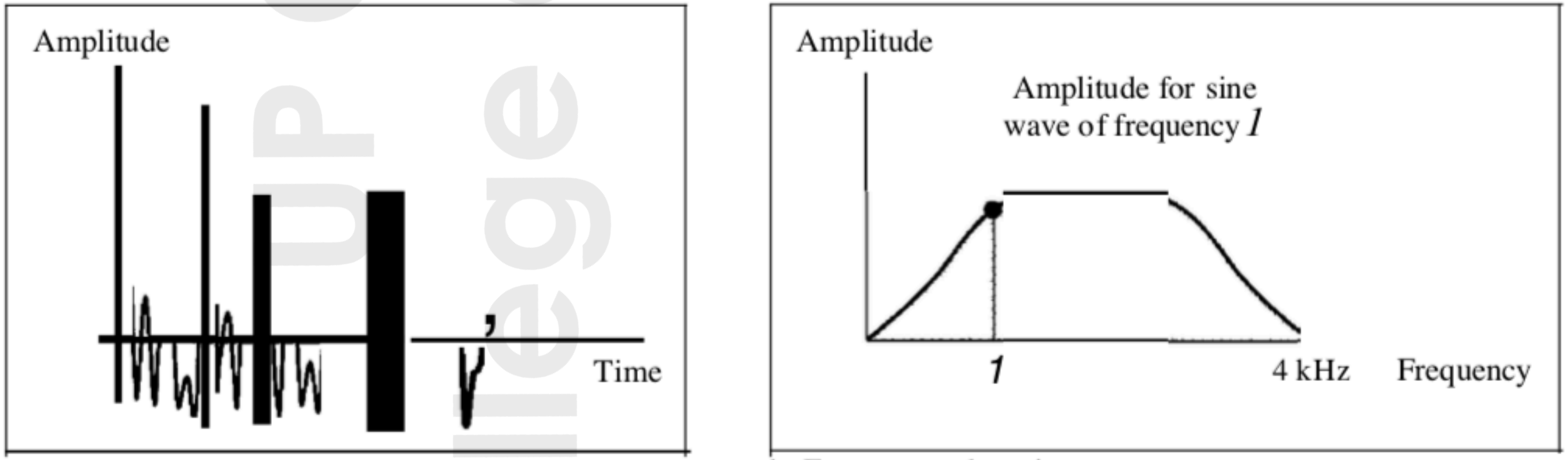
b. Frequency-domain decomposition of the composite signal

- in a time-domain, there are an infinite number of simple sine frequencies
- although number of frequencies in a human voice is infinite, the range is limited
- normal human being create continuous range from 0 and 4 kHz
- frequency decomposition of the signal yields a continuous curve
- infinite number of frequencies between 0.0 and 4000.0
- to find amplitude related to frequency J, we draw a vertical ilne at f to intersect the envelope curve
- height of vertical line is the amplitude of frequency

Example 3.9

Figure 3.11 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.

Figure 3.11 *The time andfrequency domains ofa nonperiodic signal*



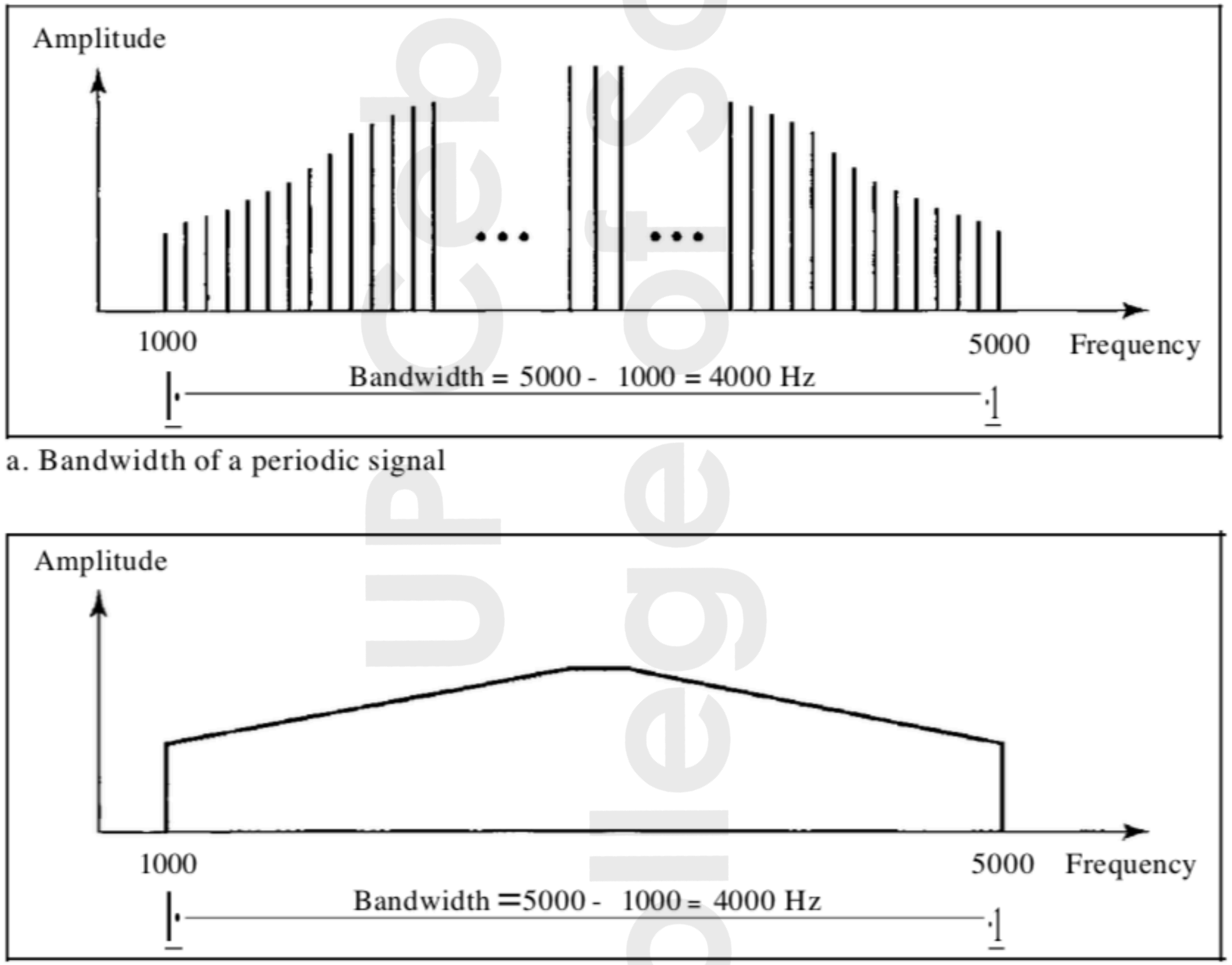
a. Time domain

b. Frequency domain

Bandwidth

- range of frequencies contained in a composite signal
- normally a difference between two numbers
- bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal
- e.g., if a composite signal contains frequencies between 1000 and 5000, its bandwidth is 5000 - 1000, or 4000

Figure 3.12 *The bandwidth of periodic and nonperiodic composite signals*



b. Bandwidth of a nonperiodic signal

- the bandwidth of the periodic signal contains all integer frequencies between 1000 and 5000 (1000, 1001, 1002, …)
- the bandwidth of the nonperiodic signals has the same range, but the frequencies are continuous

Example 3.10

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

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

The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz (see Figure 3.13).

Example 3.11

A periodic 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 frequencies of the same amplitude.

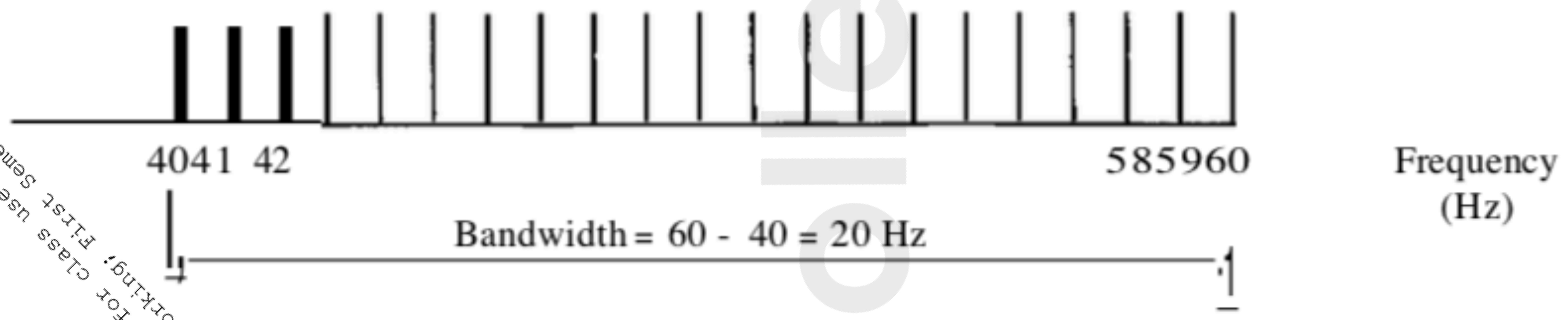
Solution

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

$$B = f_h - f_l \Rightarrow 20 = 60 - f_l \Rightarrow f_l = 60 - 20 = 40 \text{ Hz}$$

The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.14).

Figure 3.14 *The bandwidth for Example 3.11*



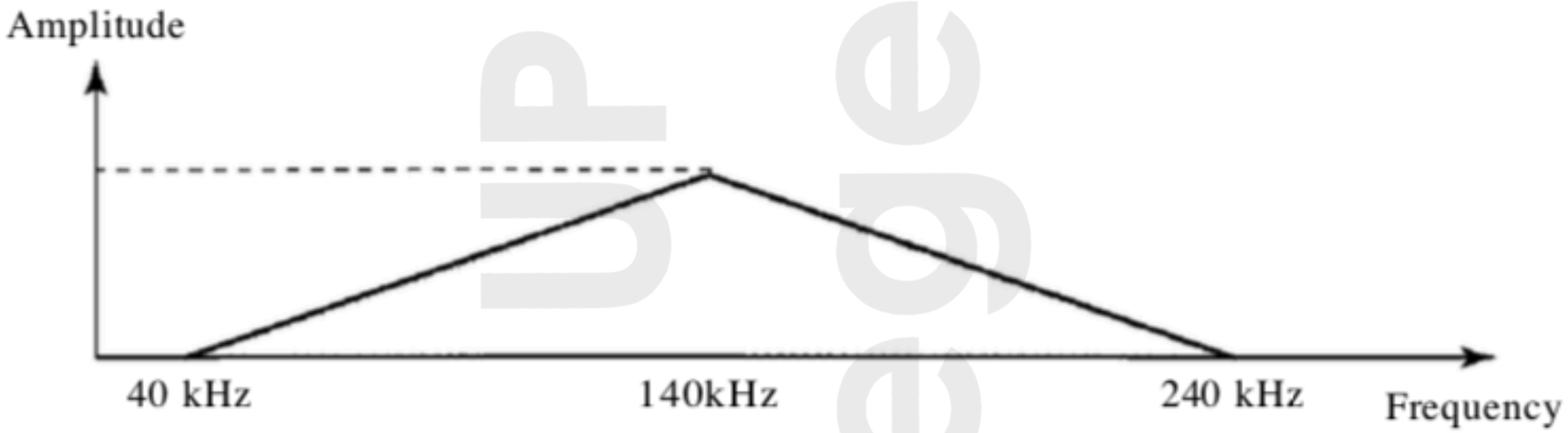
Example 3.12

A nonperiodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20 V. The two extreme frequencies have an amplitude of 0. Draw the frequency domain of the signal.

Solution

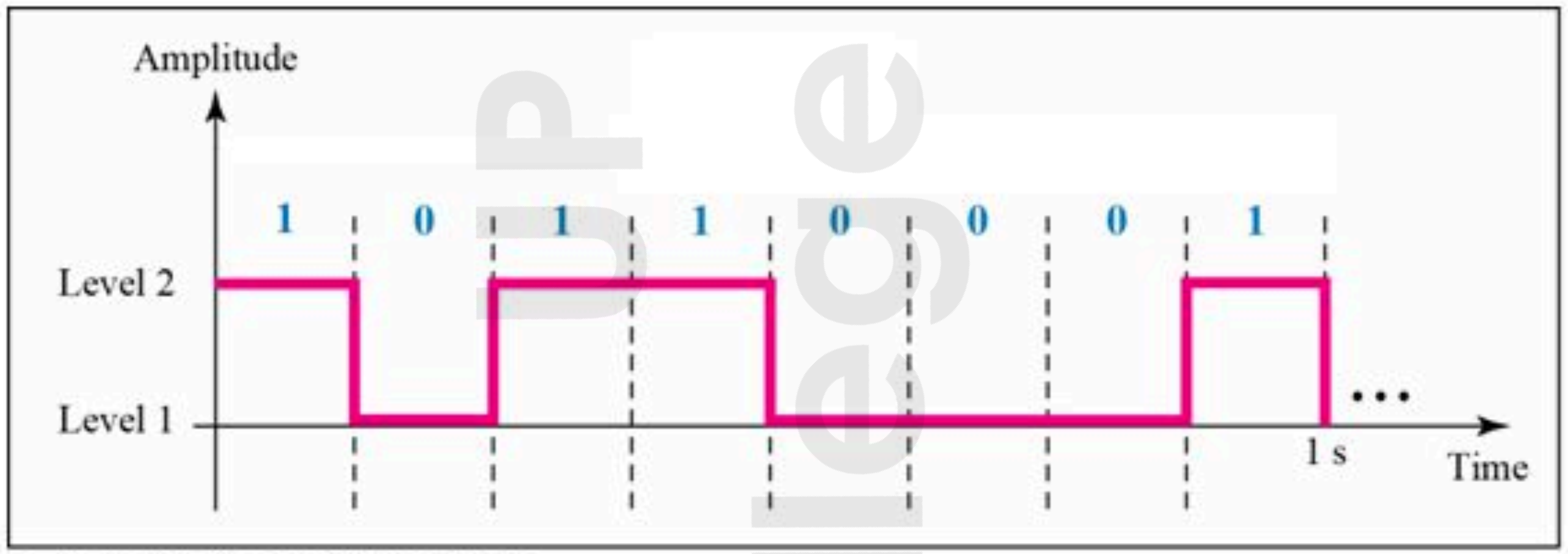
The lowest frequency must be at 40 kHz and the highest at 240 kHz. Figure 3.15 shows the frequency domain and the bandwidth.

Figure 3.15 *The bandwidth for Example 3.12*



Digital Signals

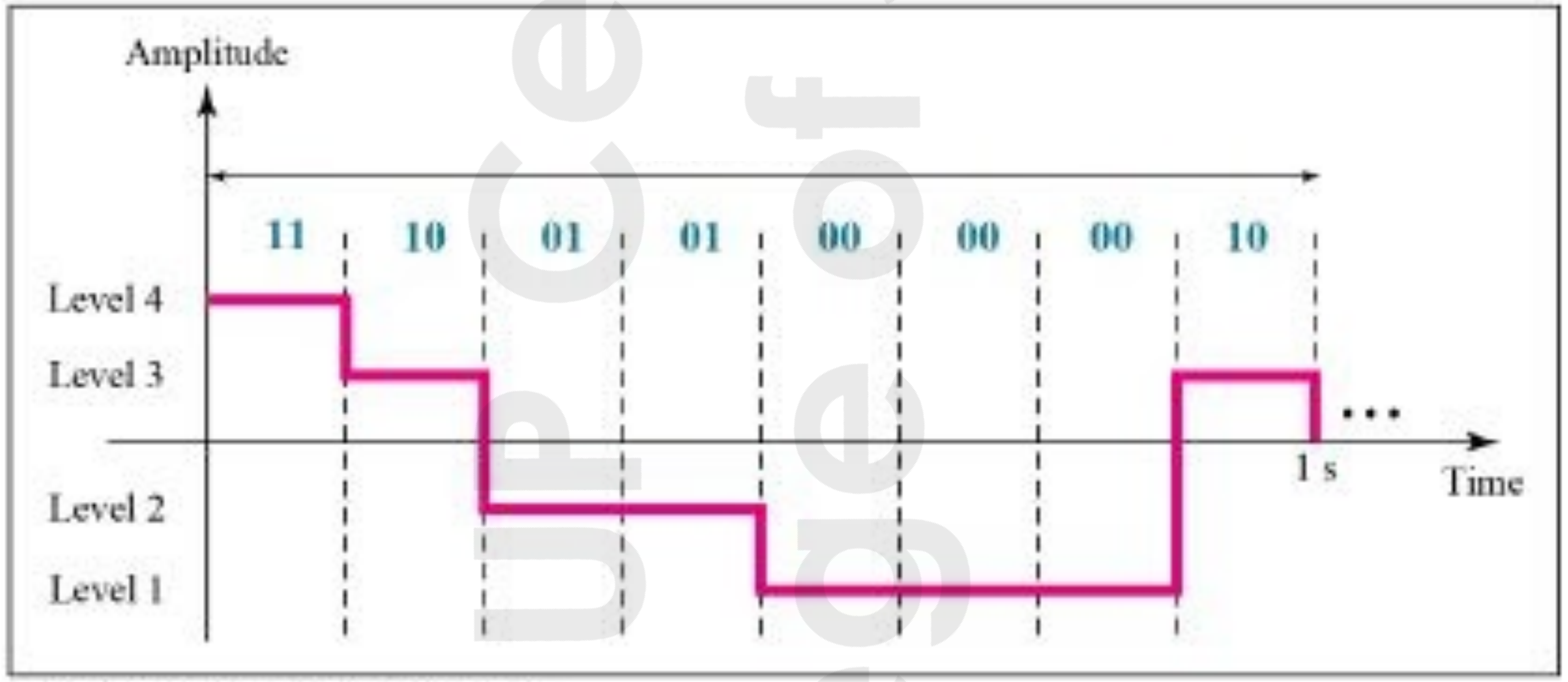
- in addition to being represented by an analog signal, information can also be represented by a digital signal
- a 1 can be encoded as a positive voltage
- a 0 as a zero voltage



a. A digital signal with two levels

We send 1 bit per level.

A digital signal can have more than two levels...



b. A digital signal with four levels

We send 2 bits per level.

In general, if a signal has *L* levels, each level needs log2*L* bits.

Example 3.16

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

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

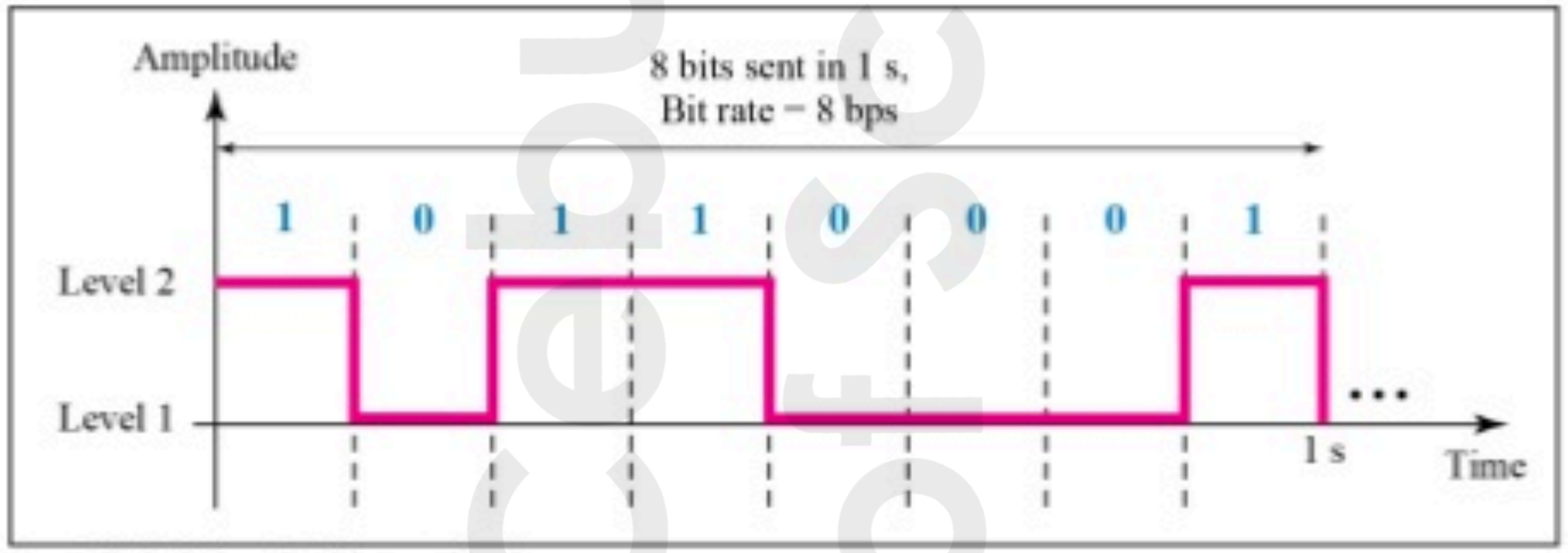
Each signal level is represented by 3 bits.

Example 3.17

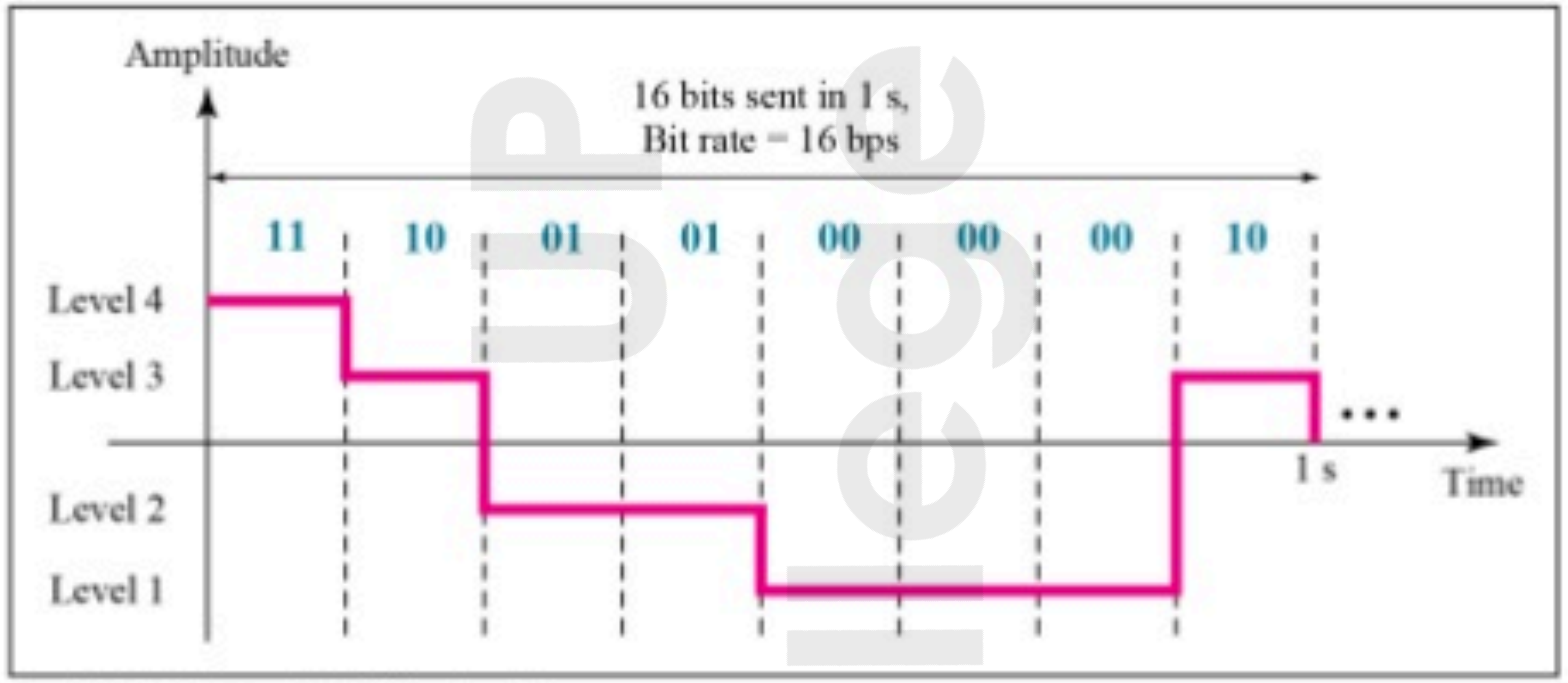
A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula. Each signal level is represented by 3.17 bits. However, this answer is not realistic. The number of bits sent per level needs to be an integer as well as a power of 2. For this example, 4 bits can represent one level.

Bit Rate

- most digital signals are non-periodic, and thus period and frequency are not appropriate characteristics
- bit rate (instead of frequency) is used to describe digital signals
- is the number of bits sent in 1 second, expressed in bits per second (bps)



a. A digital signal with two levels



b. A digital signal with four levels

Example 3.19

A digitized voice channel, as we will see in Chapter 4, 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). We assume that each sample requires 8 bits. What is the required bit rate?

Solution

The bit rate can be calculated as

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

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

$$\frac{100 \text{ pages}}{\text{minute}} \times \frac{24 \text{ lines}}{\text{page}} \times \frac{80 \text{ char}}{\text{line}} \times \frac{8 \text{ bits}}{\text{char}} \times \frac{1 \text{ minute}}{60 \text{ sec}} = \begin{array}{c}25,600 \text{ bps} \\ \text{or } 25.6 \text{ Kbps}\end{array}$$

Example 3.20

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

Solution

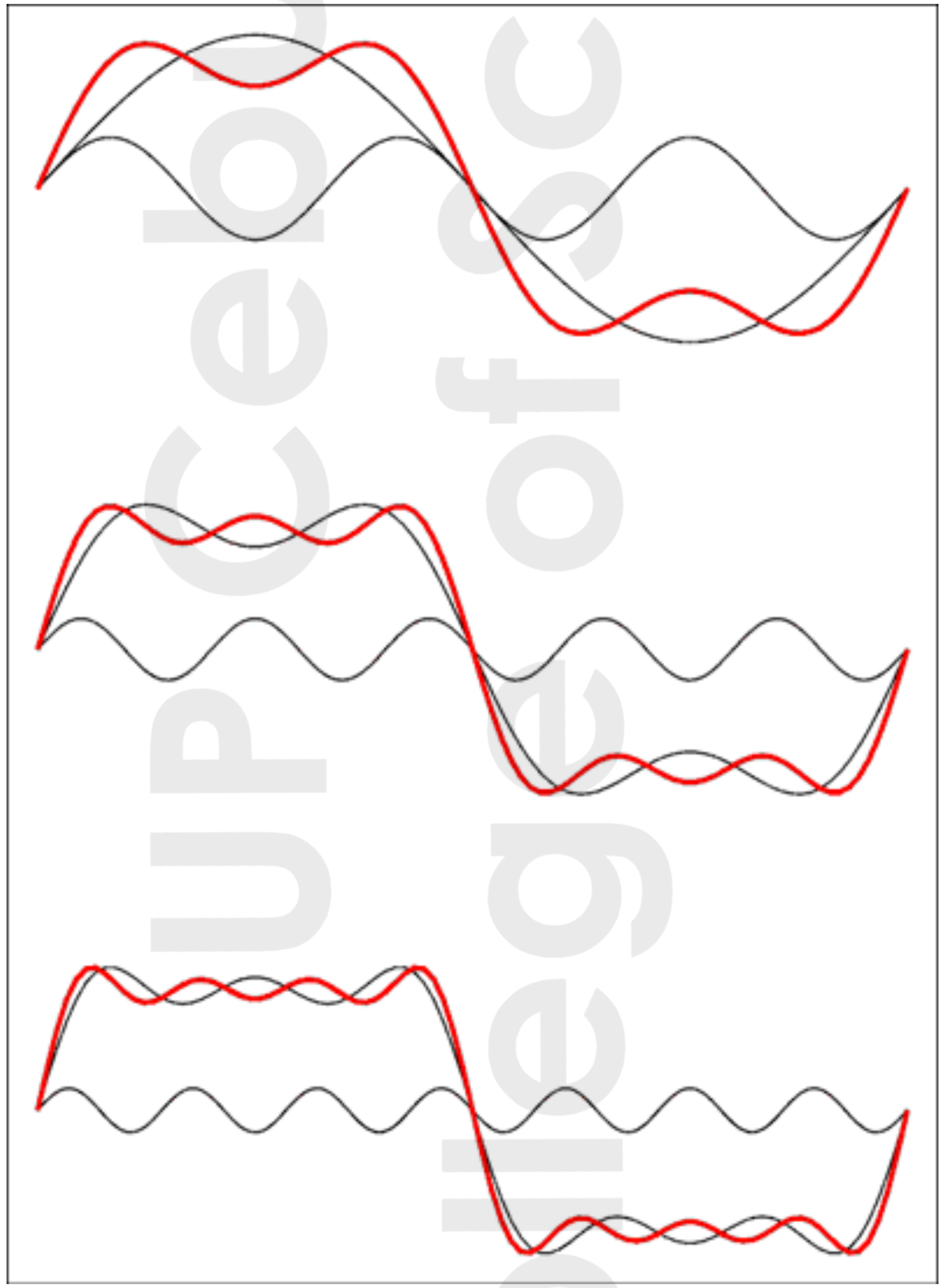
HDTV uses digital signals to broadcast high quality video signals. The HDTV Screen is normally a ratio of 16 : 9 (in contrast to 4 : 3 for regular TV), which means the screen is wider. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel. We can calculate the bit rate as

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

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

Digital Signal as a Composite Analog Signal

- based on Fourier analysis, a digital signal is a composite analog signal
- the bandwidth is infinite
- in the time domain, comprises of connected vertical and horizontal line segments
- vertical line in the time domain means frequency of infinity (sudden change in time)
- horizontal line in the time domain means a frequency of zero (no change in time)
- going from a frequency of zero to a frequency of infinity (and vice versa) implies all frequencies in between are part of the domain



- an ideal digital signal has infinitely steep edges
- how? compose signal from sines: one fundamental and a number of harmonics
- neither of those sines has infinite steepness
- the only way to get steep edge is by adding infinite number of harmonics

https://electronics.stackexchange.com/questions/18706/why-all-digital-signals-have-infinite-bandwidth

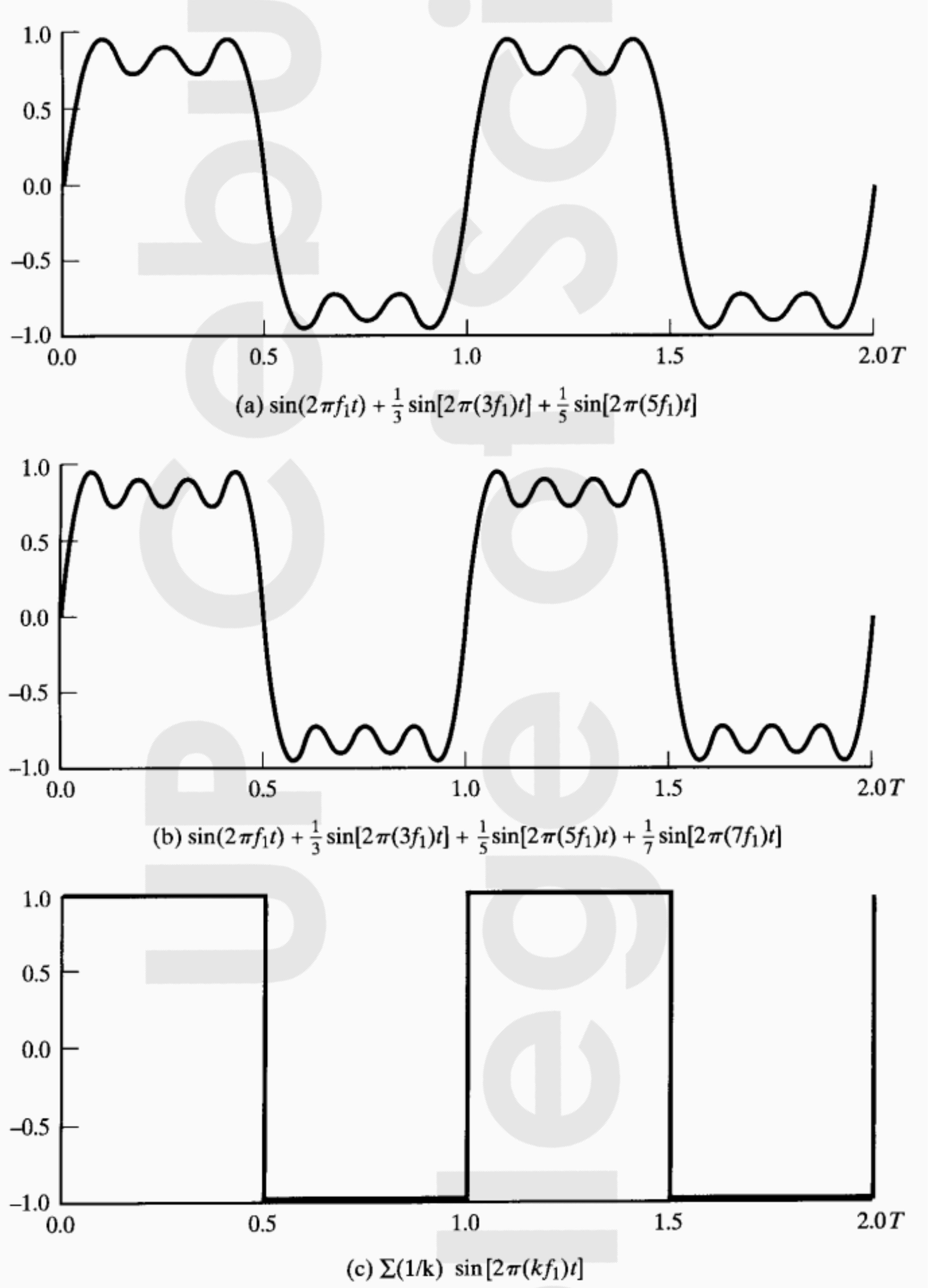
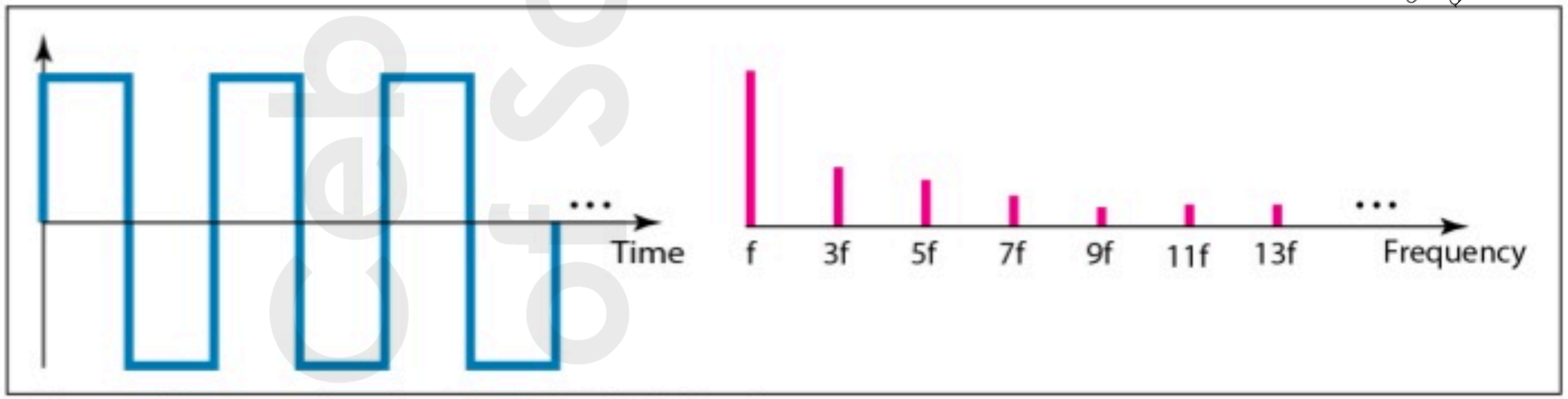


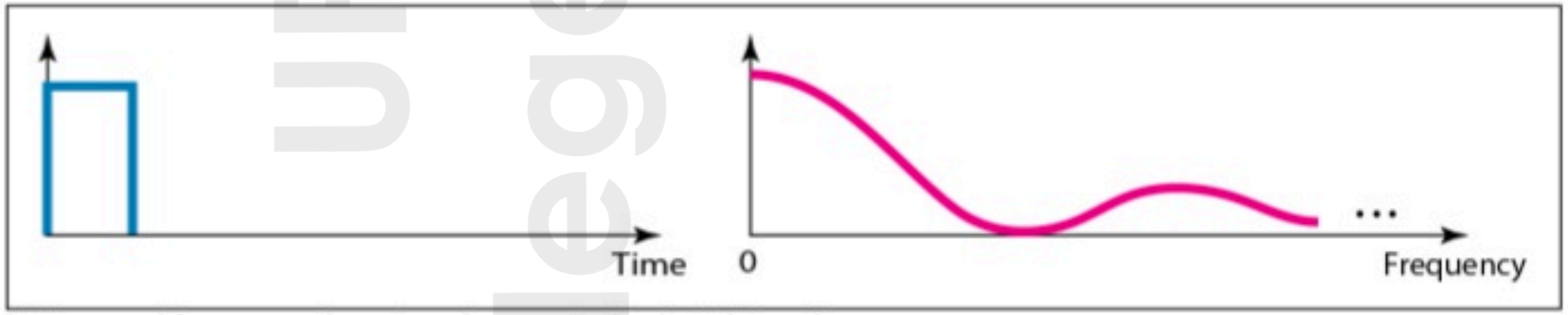
FIGURE 4.6 Frequency Components of a Square Wave ($T = 1/f_1$).

https://pdfs.semanticscholar.org/presentation/76d3/6d32958cf0b8b6380cfae72b133c36be9102.pdf

- **periodic digital signal:** infinite bandwidth and discrete frequencies (rare in data communications)
- **non-periodic digital signal:** infinite bandwidth but continuous frequencies



a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

The Telephone System

- originally created to provide voice communication
- timeline:
  - the need to communicate digital data resulted in the invention of the dial-up modem
  - with the advent of the Internet came the need for high-speed downloading and uploading: the modem was just too slow
  - the telephone companies added a new technology, the digital subscriber line (DSL): much faster than dial-up modem
- here:
  - basic structure of the telephone network
  - see how dial-up modems and DSL technology use telephone networks to access the Internet

Telephone Network

- use circuit switching
- had its beginnings in the late 1800s
- referred to as the plain old telephone system (POTS), originally an analog system using analog signals to transmit voice
- in the 1980s, began to carry data in addition to voice
- now digital as well as analog

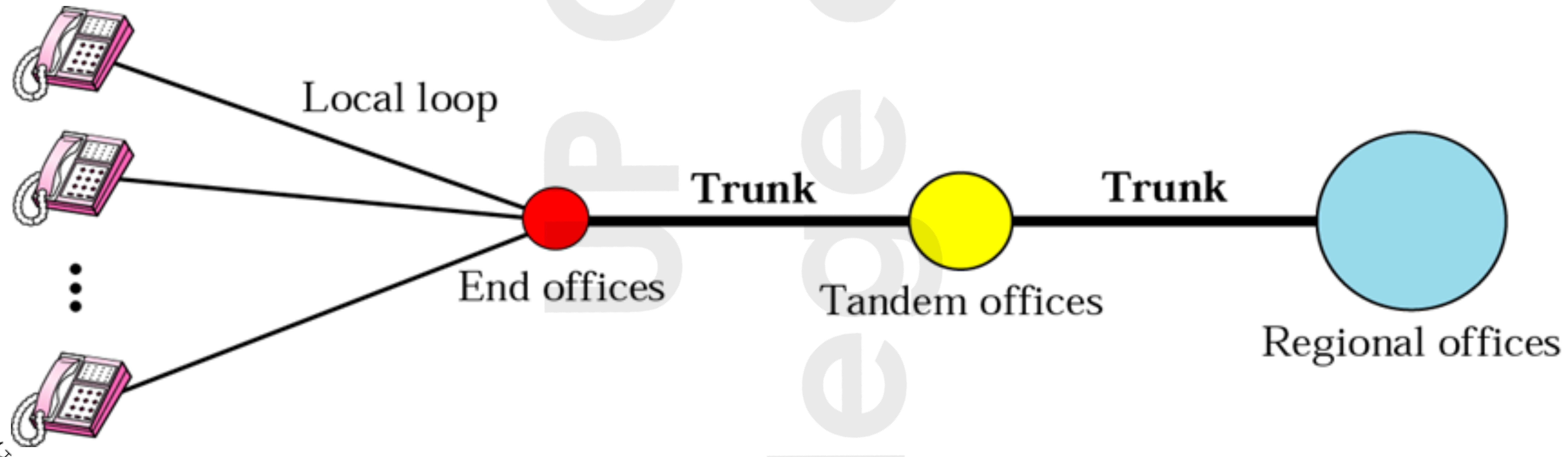
Circuit Switching is connection-oriented that means a path is established between source and destination before the transmission occurs. On the other hand, **Packet Switching** is connectionless that means a dynamic route is decided for each packet while transmitting.

Major Components of a Telephone Network

1. local loops
2. trunks
3. switching offices

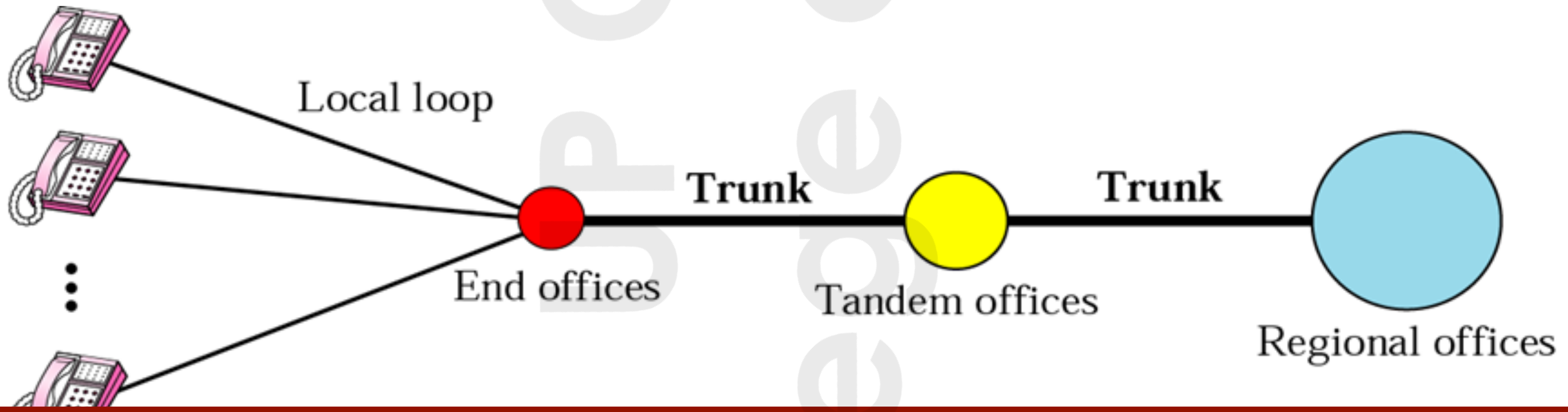
Levels of Switching Offices:

1. **end offices**
2. **tandem offices**
3. **regional offices**



1. Local Loops

- a twisted-pair cable that connects the subscriber telephone to the nearest end office or local central office
- when used for voice, has a bandwidth of 4000 Hz (4 kHz)
- the first three digits of a local telephone number define the office, and the next four digits define the local loop number

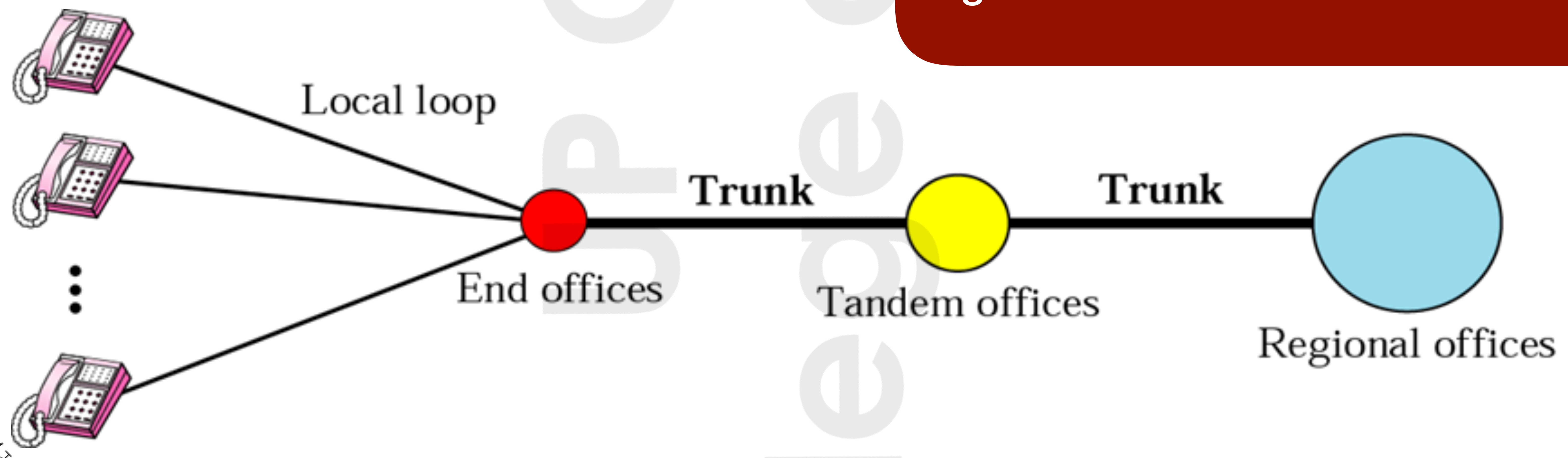


PBX stands for Private Branch Exchange, which is a private telephone network used within a company or organization. The users of the PBX phone system can communicate internally (within their company) and externally (with the outside world), using different communication channels like Voice over IP, ISDN or analog. A PBX also allows you to have more phones than physical phone lines (PTSN) and allows free calls between users. [https://www.3cx.com/pbx/pbx-phone-system/]

2. Trunks

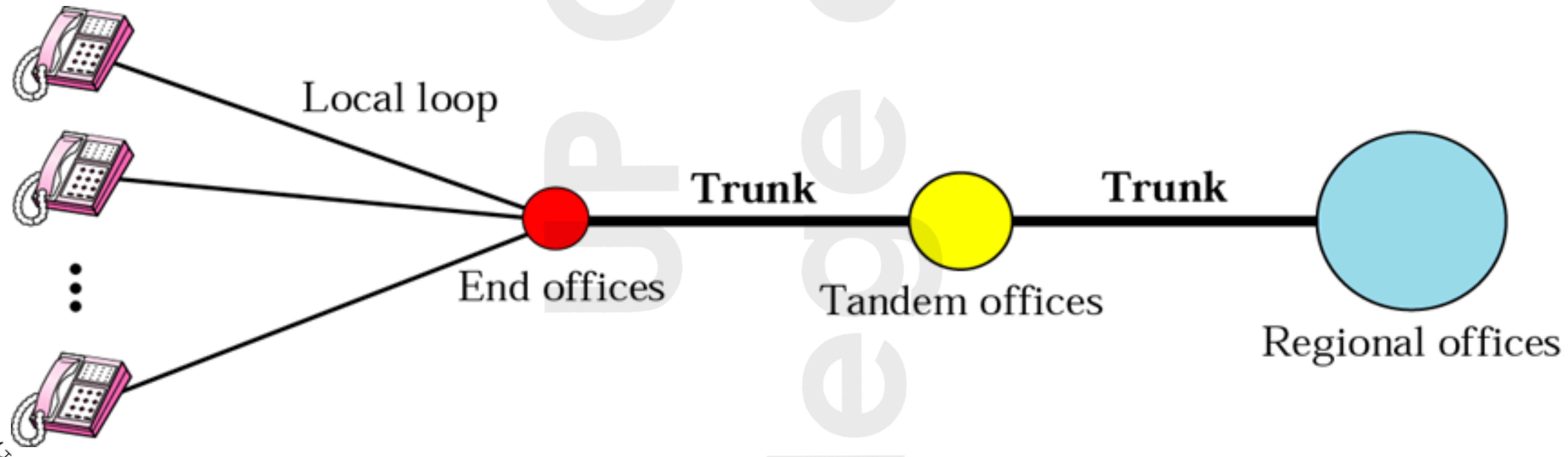
- transmission media that handle the communication between offices
- normally handles hundreds or thousands of connections through multiplexing
- transmission is usually through optical fibers or satellite links

Multiplexing is a popular networking technique that integrates multiple analog and digital signals into a signal transmitted over a shared medium.



3. Switching Offices

- purpose is to avoid having a permanent physical link between any two subscribers
- a switch connects several local loops or trunks and allows a connection between different subscribers



Dial-Up Modems

- traditional telephone lines can carry frequencies between 300 and 3300 Hz, giving them a bandwidth of 3000 Hz; range used for transmitting voice; where a great deal of interference and distortion can be accepted without loss of intelligibility
- data signals require higher degree of accuracy to ensure integrity; therefore, edges of this range are not used for data communications
- in general, signal bandwidth for data transmission must be smaller than the cable bandwidth: 2400 Hz, from 600 to 3000 Hz (modern lines capable of higher bandwidth than traditional lines)

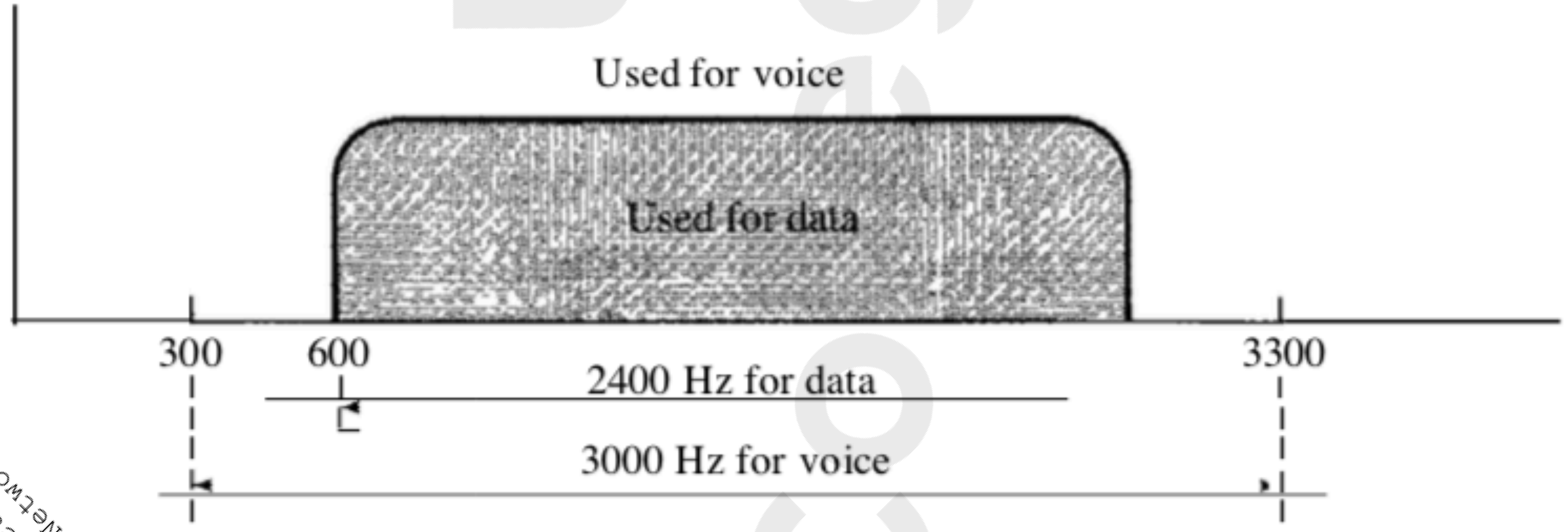
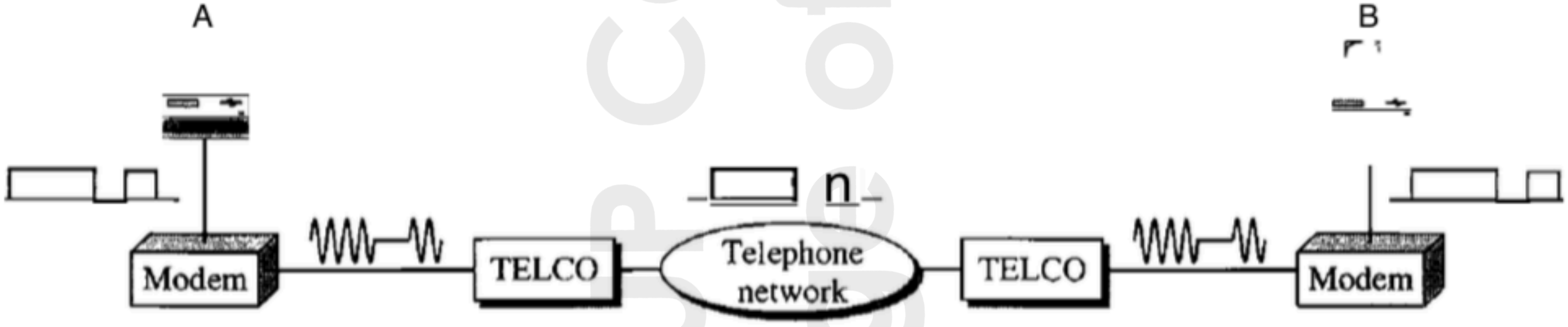


Figure 9.7 *Modulation/demodulation*

TELCO: Telephone company



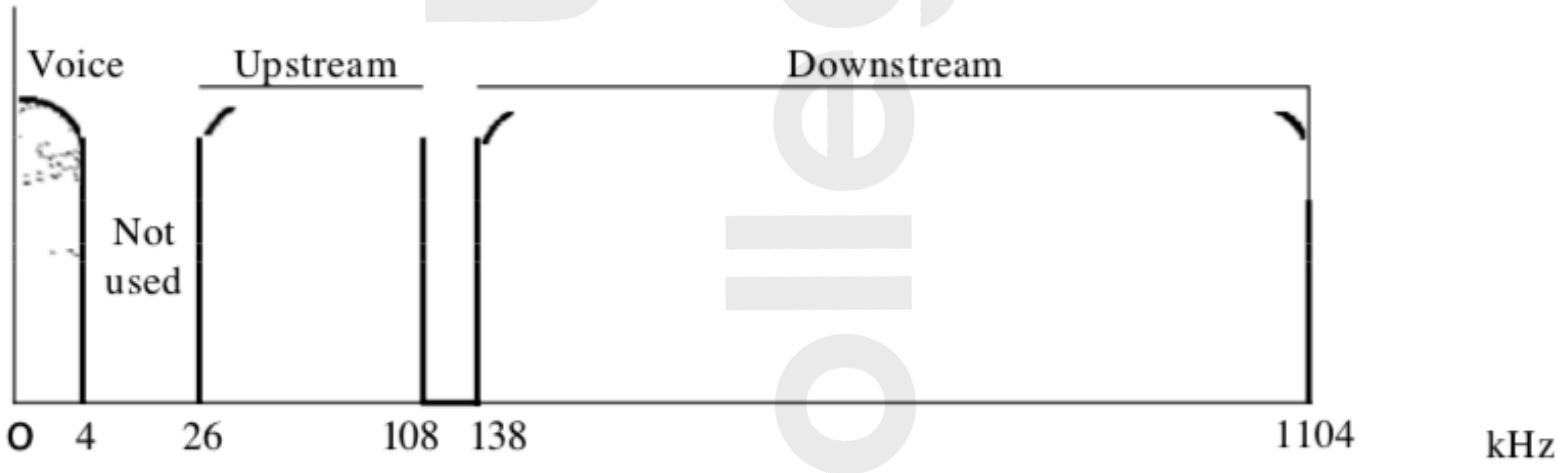
Digital Subscriber Line (DSL)

- developed when traditional modems reached peak data rate
- to provide higher-speed access to the Internet
- DSL technology is a set of technologies, each differing in the first letter (ADSL, VDSL, HDSL, and SDSL); set referred as xDSL

ADSL

- asymmetric DSL
- provides higher speed (bit rate) in the downstream direction (from the Internet to the resident) than in the upstream direction (from the resident to the Internet); hence, asymmetric
- designed for residential users; it is not suitable for businesses
- typically, available bandwidth of 1.104 MHz is divided into 256 channels; each channel uses a bandwidth of 4.312 kHz

Figure 9.11 *Bandwidth division in ADSL*



Summary of DSL

Table 9.2 ***Summary of DSL technologies***

Technology	Downstream Rate	Upstream Rate	Distance (ft)	Twisted Pairs	Line Code
ADSL	1.5–6.1 Mbps	16–640 kbps	12,000	1	DMT
ADSL Lite	1.5 Mbps	500 kbps	18,000	1	DMT
HDSL	1.5–2.0 Mbps	1.5–2.0 Mbps	12,000	2	2B1Q
SDSL	768 kbps	768 kbps	12,000	1	2B1Q
VDSL	25–55 Mbps	3.2 Mbps	3000–10,000	1	DMT

Cable TV Networks

- started as a video service provider, but has moved to the business of Internet access
- called community antenna TV (CATV) because an antenna at the top of a tall hill or building received signals from the TV stations and distributed them, via coaxial cables, to the community

Figure 9.14 *Traditional cable TV network*

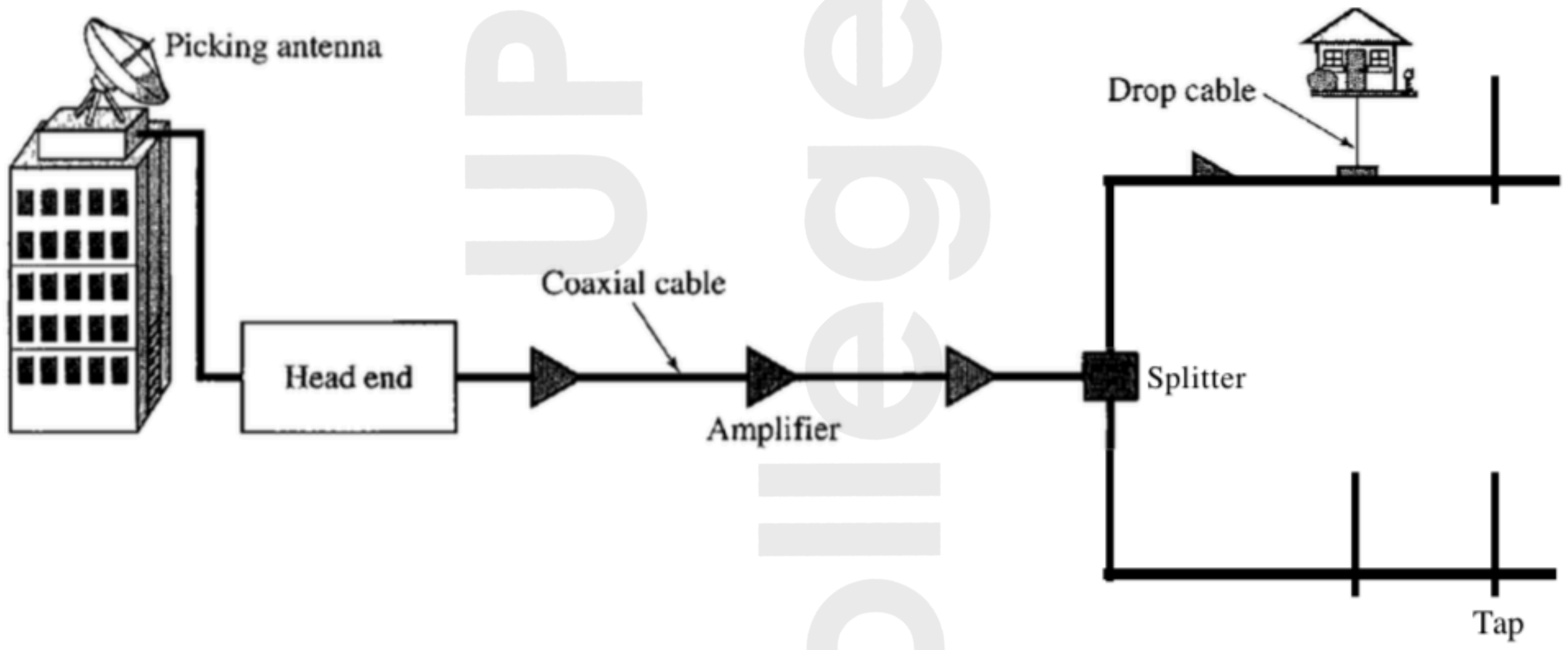
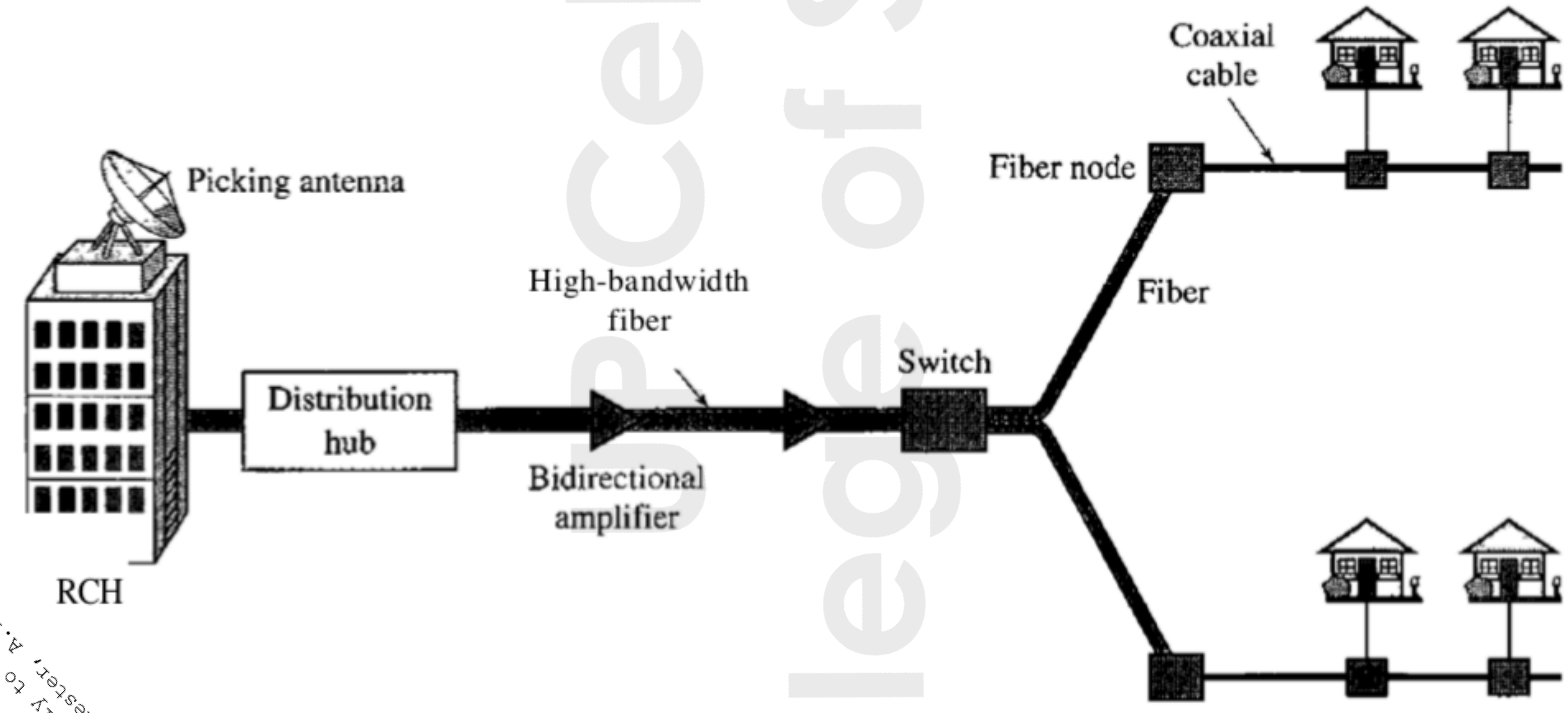


Figure 9.15 *Hybridfiber-coaxial (HFC) network*



Cable TV for Data Transfer

- coaxial cable has bandwidth that ranges from 5 to 750 MHz
- to provide Internet access, the cable company has divided bandwidth into three bands: video, downstream data, and upstream data

Figure 9.16 *Division of coaxial cable band by CATV*

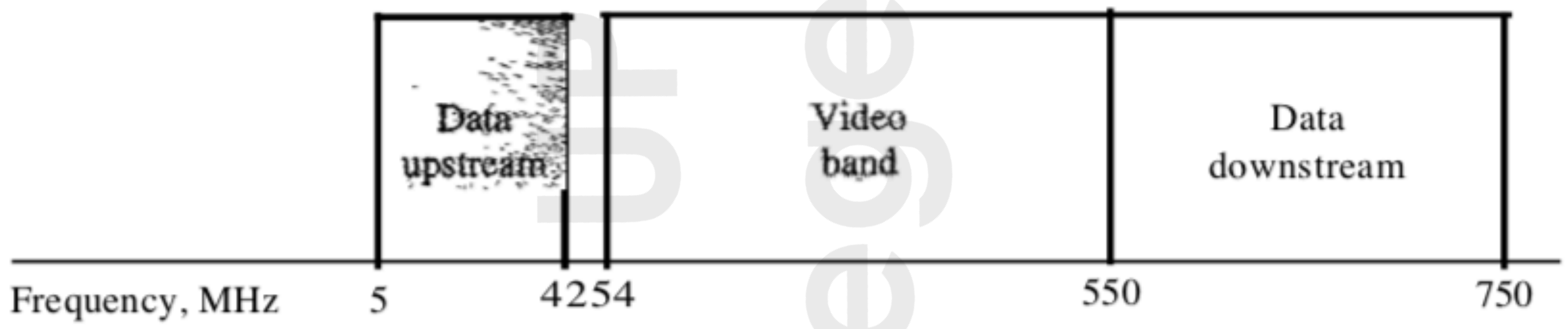
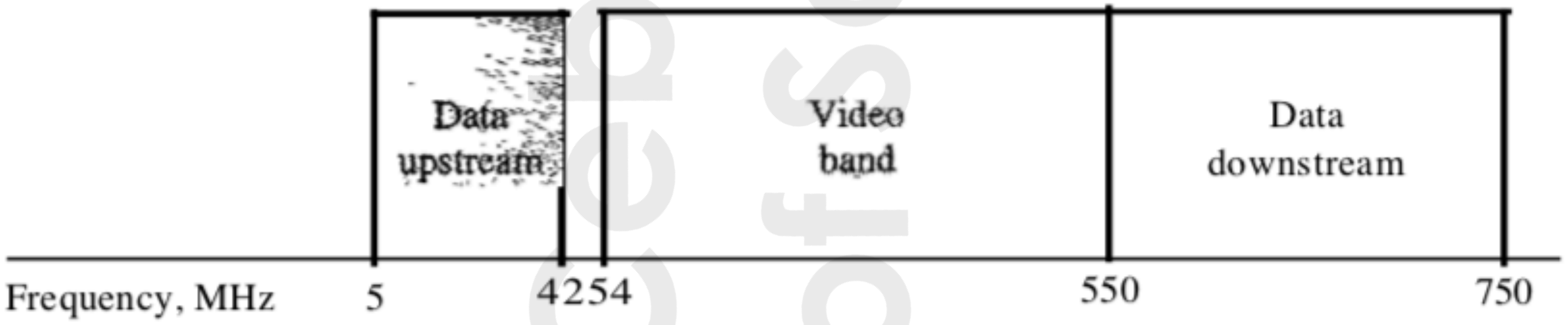


Figure 9.16 *Division of coaxial cable band by CATV*

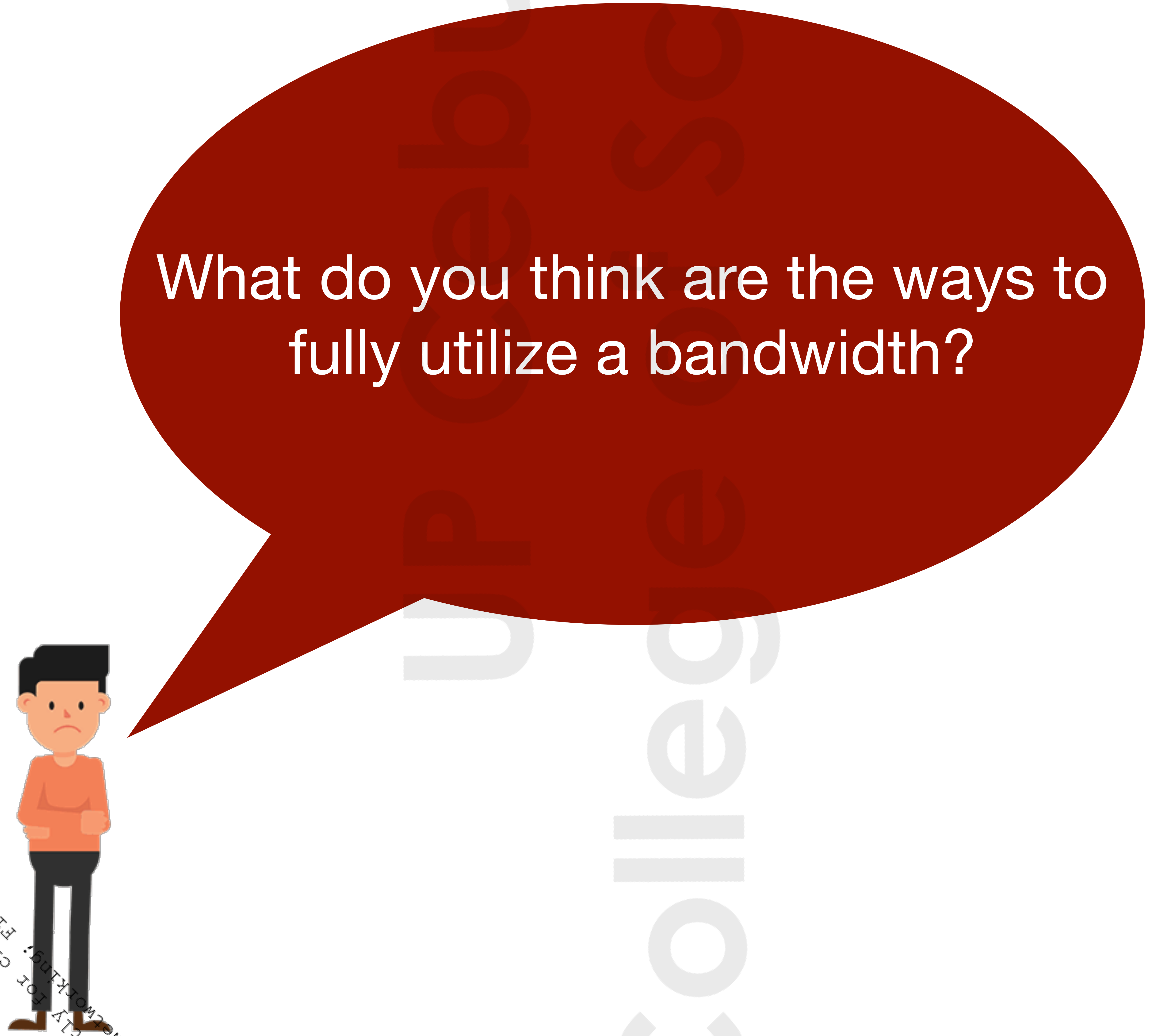


Downstream Video Band
- occupies frequencies from 54 to 550 MHz
- since each channel occupies 6 MHz, this can accommodate more than 80 channels

Downstream Data Band
- occupies the upper band, from 550 to 750 MHz
- theoretical downstream data rate is 30 Mbps

Upstream Data Band
- occupies the lower band, from 5 to 42 MHz
- theoretical upstream data rate is 12 Mbps

In OS, if the goal of CPU utilization is to make the CPU 100% busy, what do you think is the goal of *bandwidth utilization*?


What do you think are the ways to fully utilize a bandwidth?

Bandwidth Utilization

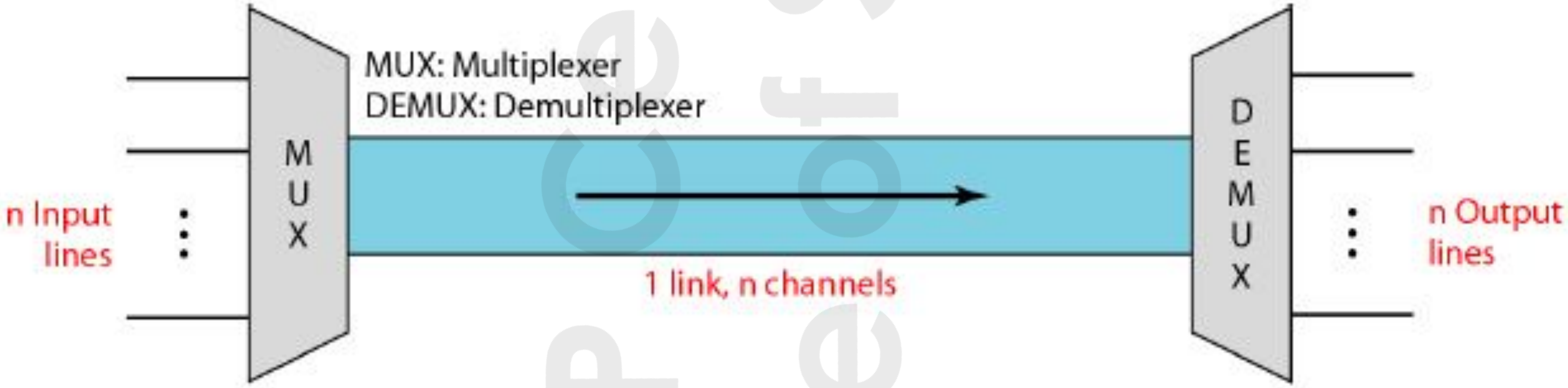
- Motivation: in reality, links are limited in bandwidth
- Needs:
  - To have a larger bandwidth
  - To achieve privacy and anti-jamming
- Categories of bandwidth utilization:
  1. **Multiplexing**: goal is efficiency
  2. **Spreading**: goal is privacy and anti-jamming

1. Multiplexing

- Refers to the set of techniques that allows the simultaneous transmission of multiple signals across a single data link
- Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, some bandwidth is wasted hence can the link can be shared

- In a multiplexed system, *n* lines share the bandwidth of one link

The lines on the left direct their transmission streams to a multiplexer (MUX), which combines them into a single stream (many-to-one)



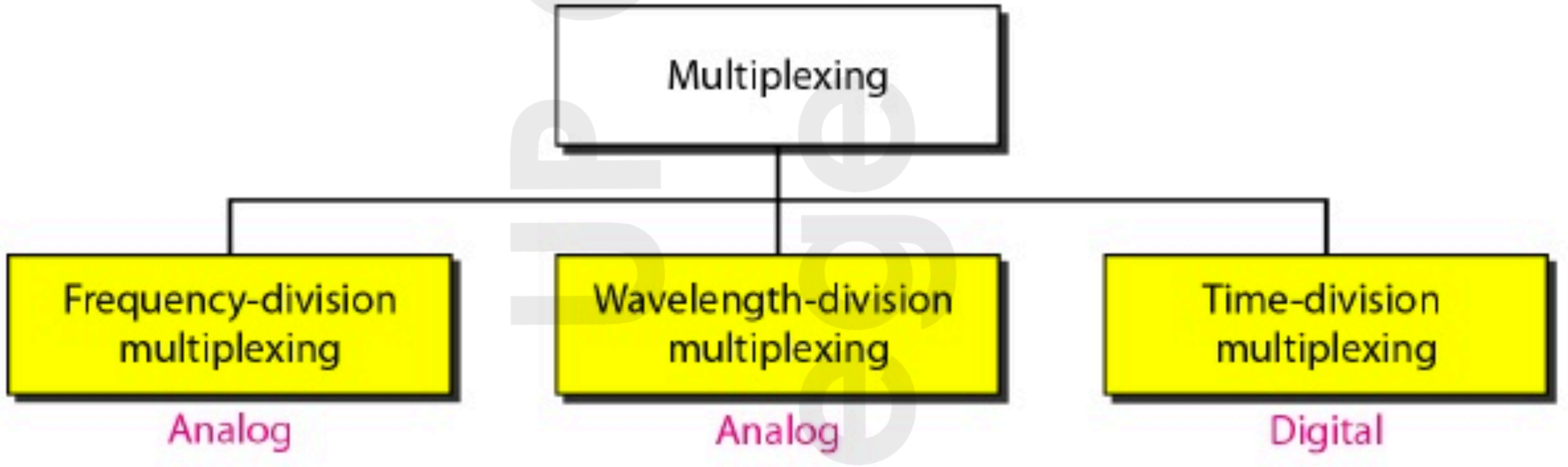
At the receiving end, that stream is fed into a demultiplexer (DEMUX), which separates the stream back into its component transmissions (one-to-many) and directs them to their corresponding lines

Link - refers to the physical path
Channel - refers to the portion of a link that carries a transmission between a given pair of lines

One link can have many (*n*) channels.

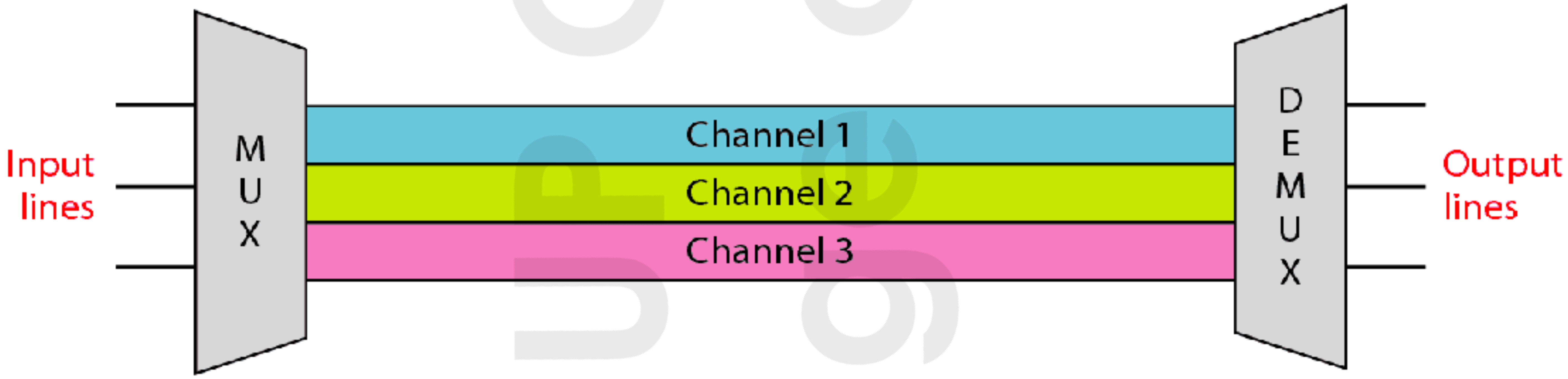
Basic Multiplexing Techniques

1. Frequency-division multiplexing
2. Wavelength-division multiplexing
3. Time-division multiplexing



1. Frequency-Division Multiplexing (FDM)

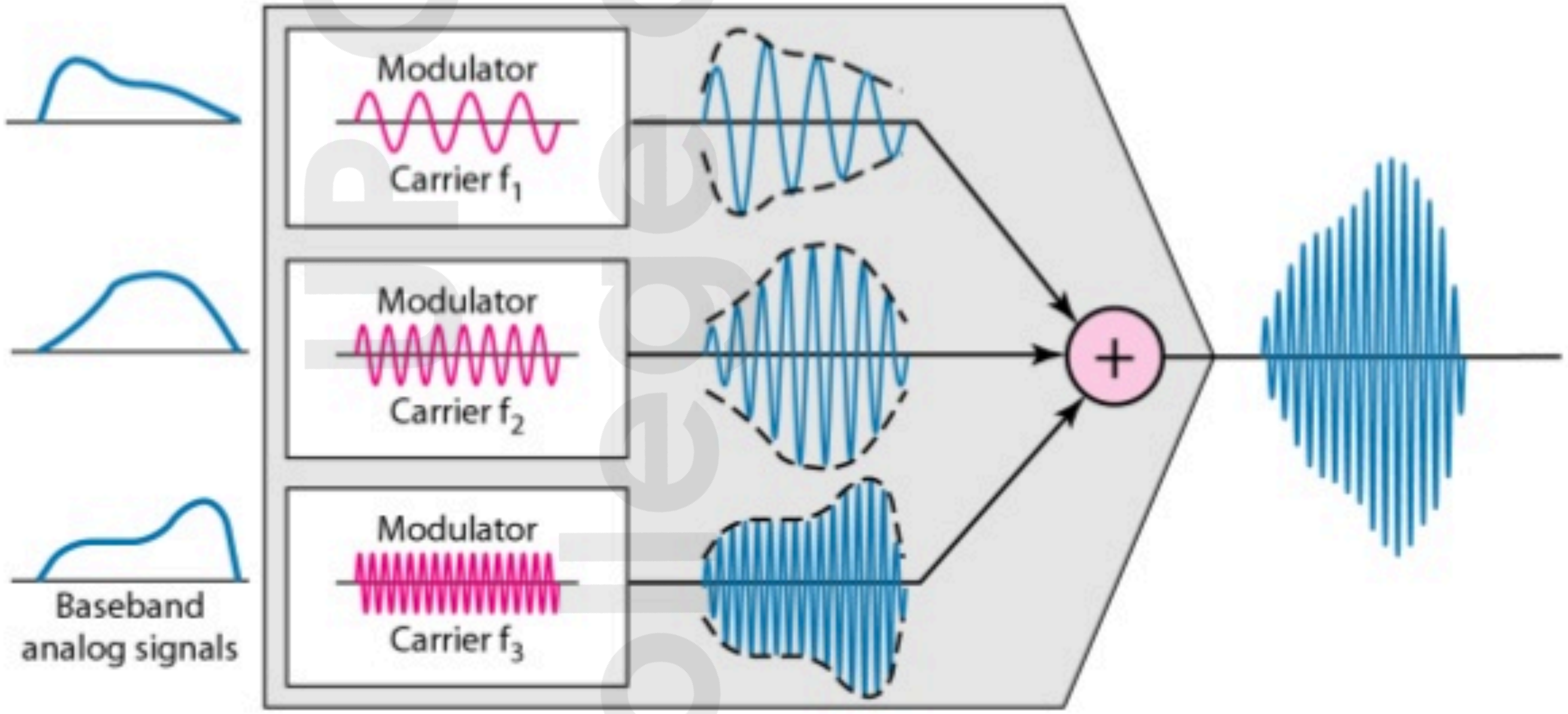
- An analog technique that can be applied when the bandwidth of a link (in hertz) is greater than the combined bandwidths of the signals to be transmitted
- Channels can be separated by strips of unused bandwidth called *guard bands* to prevent signals from overlapping



Transmission path is divided into three parts, each representing a channel that carries one transmission

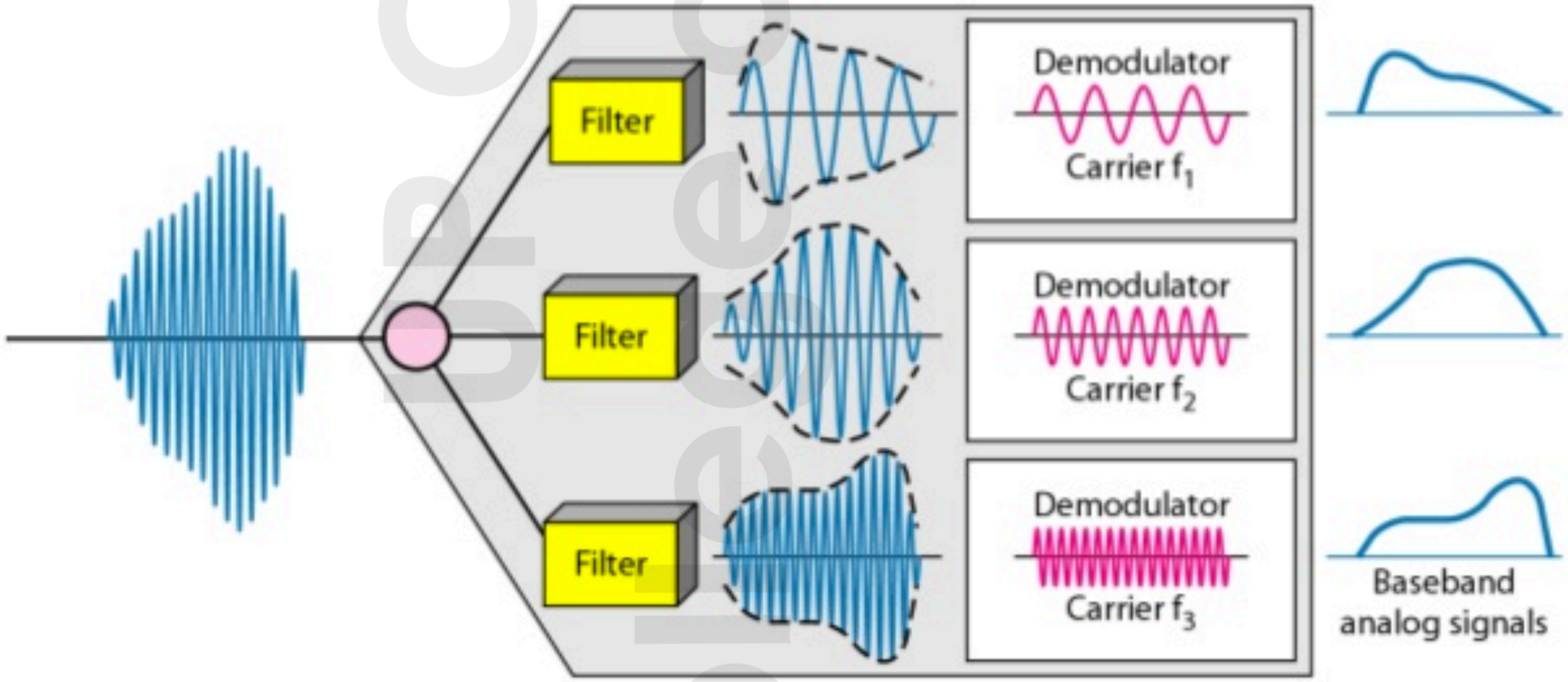
Multiplexing Process

- Each source generates a signal
- Inside the multiplexer, these signals modulate different carrier frequencies (f_1, f_2, and f_3)
- The resulting modulated signals are then combined into a single composite signal that is sent out over a media link that has enough bandwidth to accommodate it



Demultiplexing Process

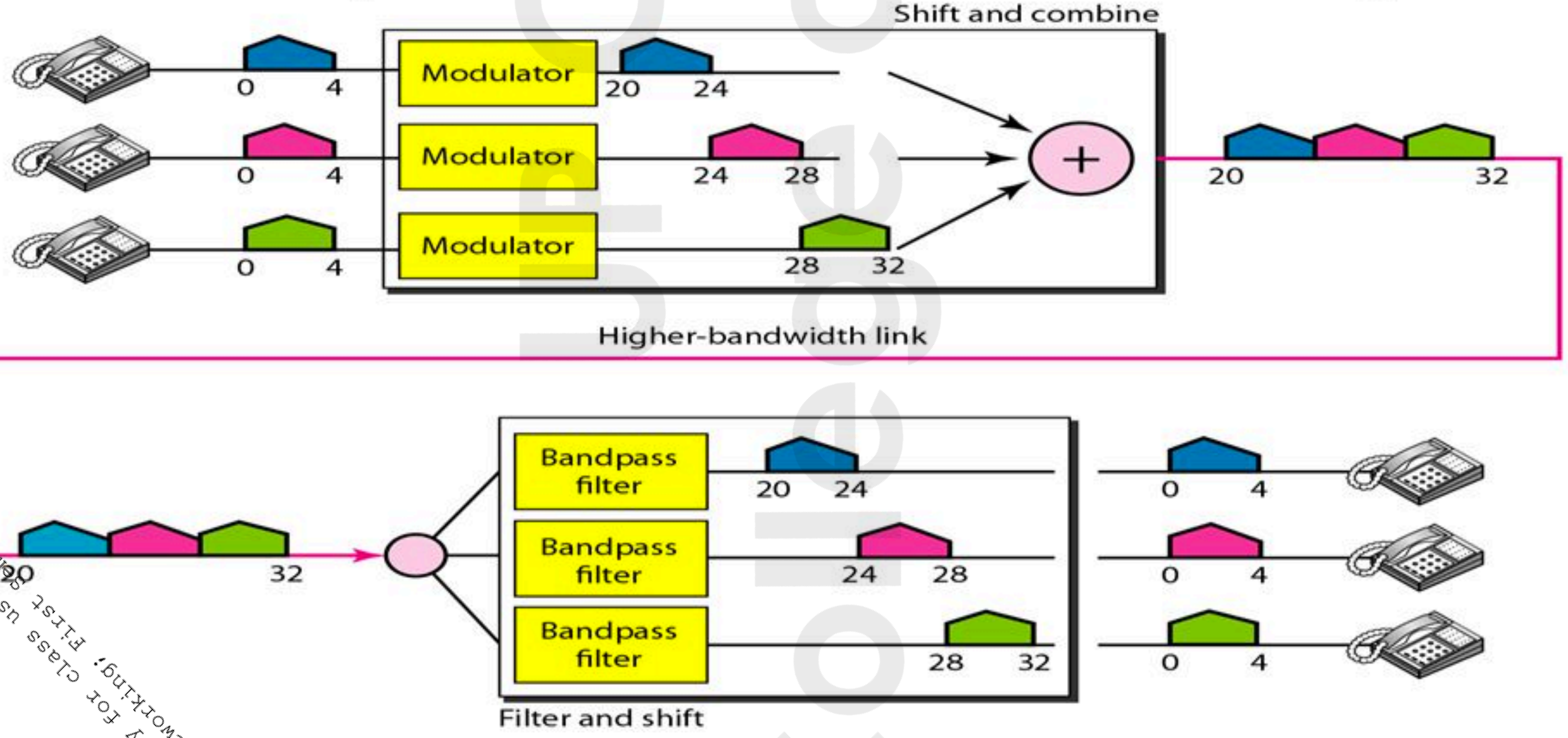
- The demultiplexer uses a series of filters to decompose the multiplexed signal into its constituent component signals
- The individual signals are then passed to a demodulator that separates them from their carriers and passes them to the output lines



Example 6.1: *Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.*

Solution

We shift (modulate) each of the three voice channels to a different bandwidth, as shown in Figure 6.6. We use the 20- to 24-kHz bandwidth for the first channel, the 24 to 28kHz bandwidth for the second channel, and the 28- to 32-kHz bandwidth for the third one. Then we combine them as shown in Figure



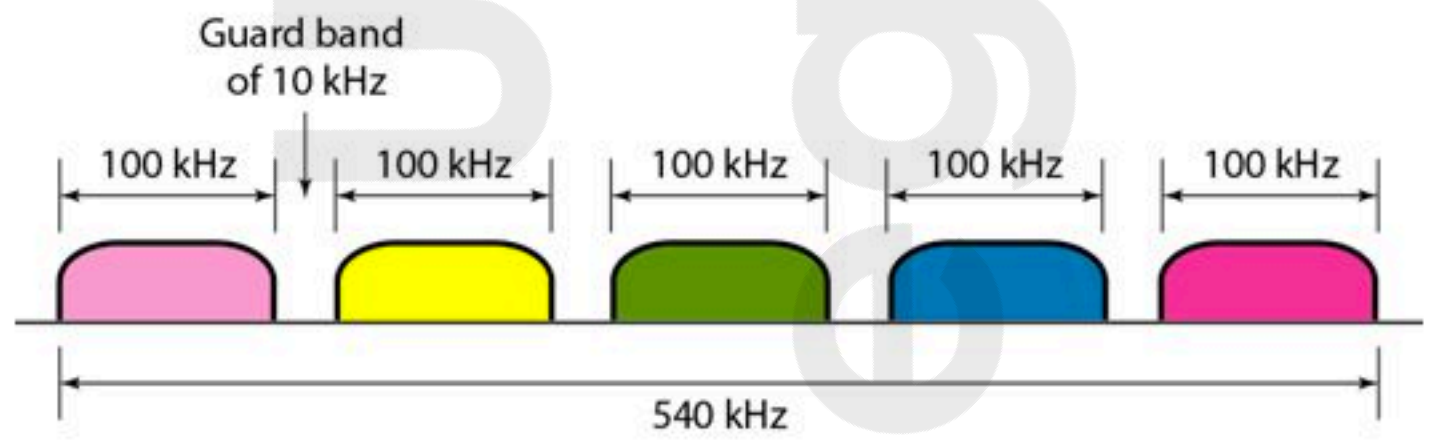
Example 6.2

Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?

Solution

For five channels, we need at least four guard bands. This means that the required bandwidth is at least

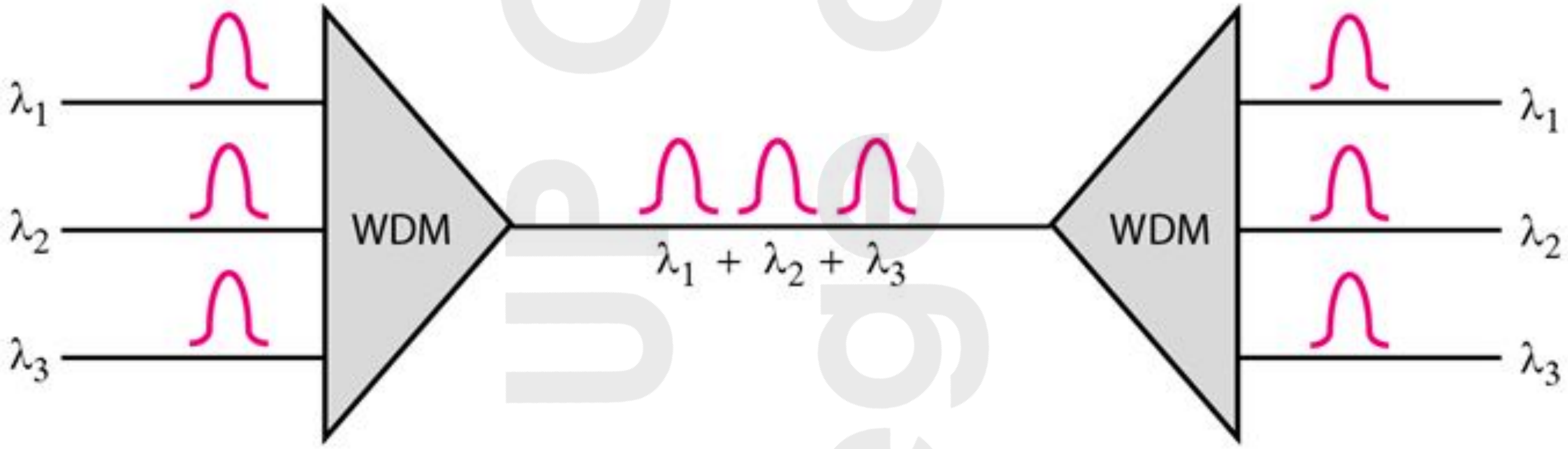
$$5 \times 100 + 4 \times 10 = 540 \text{ kHz},$$



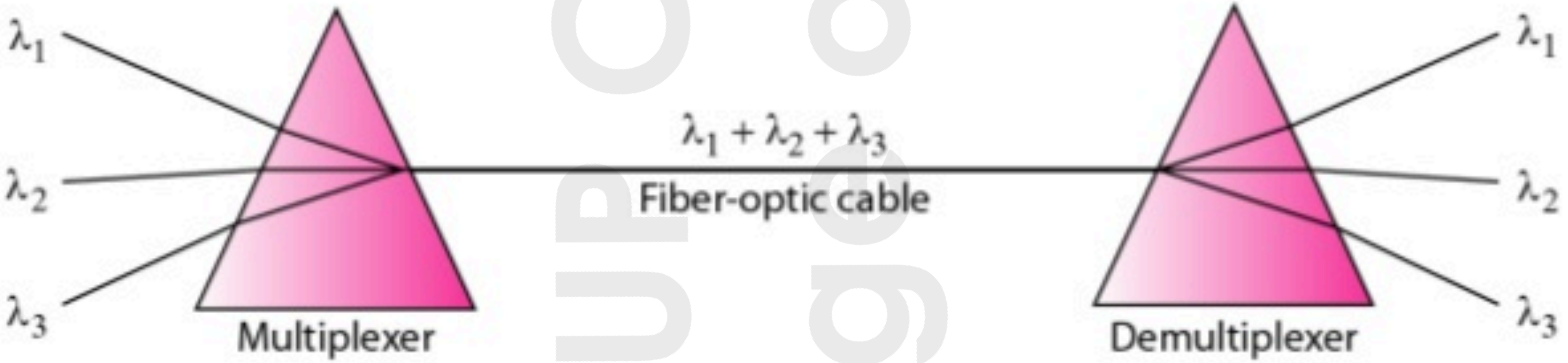
2. Wavelength-Division Multiplexing (WDM)

- WDM is conceptually the same as FDM, except that the multiplexing and demultiplexing involve optical signals transmitted through fiber-optic channels
- The optical fiber data rate is higher than the data rate of metallic transmission cable
- In WDM, the frequencies are very high

- Combine multiple light sources into one single light at the multiplexer and do the reverse at the demultiplexer

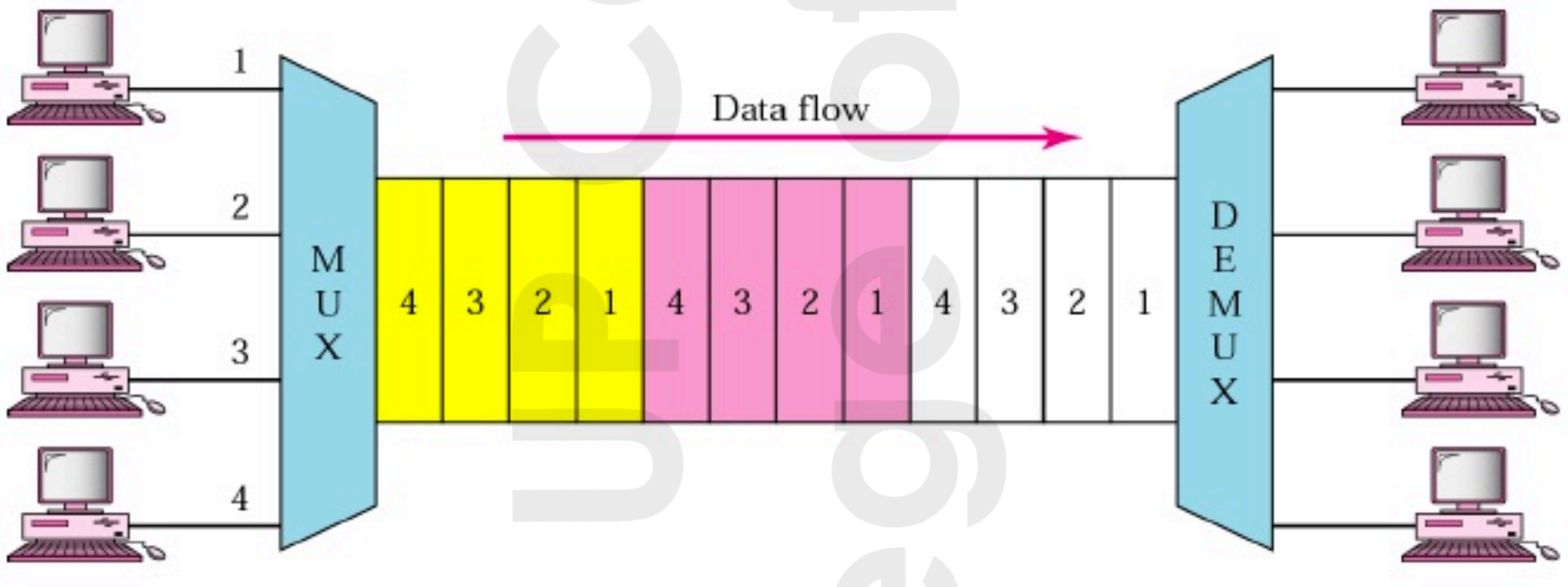


- The combining and splitting of light sources are easily handled by a *prism*
- In physics, a prism bends a beam of light based on the angle of incidence and the frequency



3. Time-Division Multiplexing (TDM)

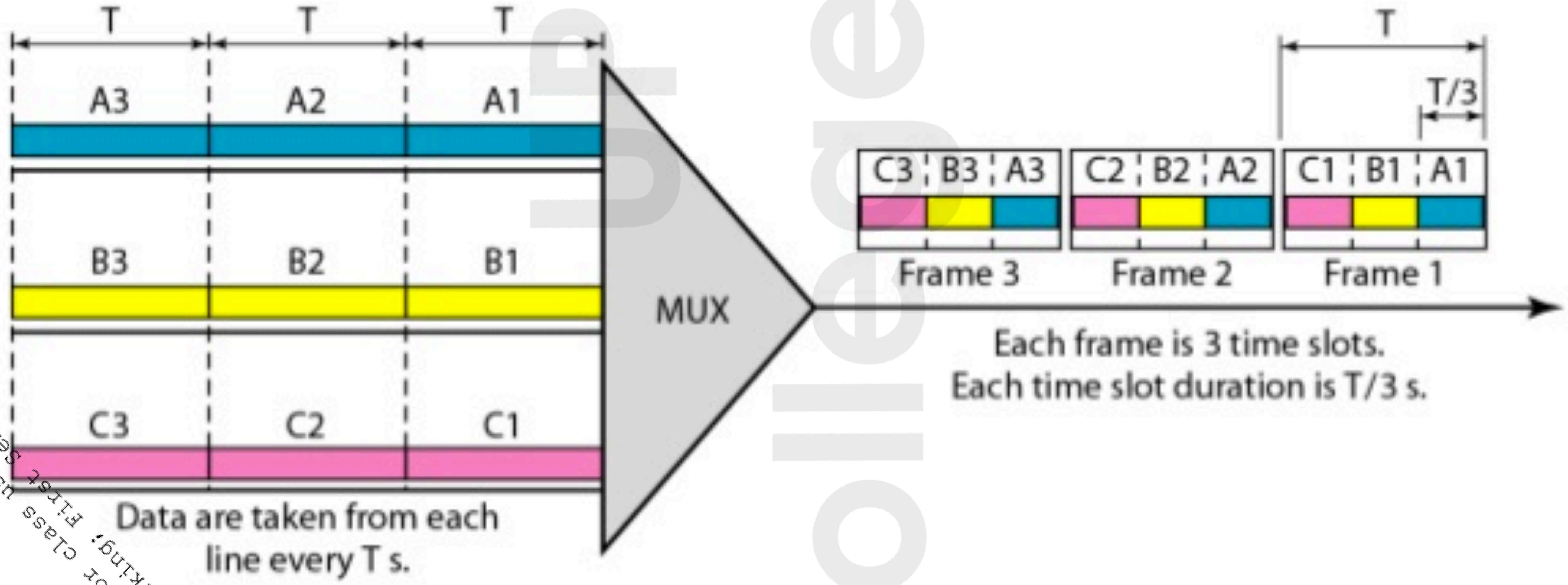
- A digital process that allows several connections to share a link but instead of sharing a portion of the bandwidth as in FDM, *time* is shared
- Each connection occupies a portion of time in the link rather than frequency
- Portions of signals 1, 2, 3, and 4 occupy the link sequentially



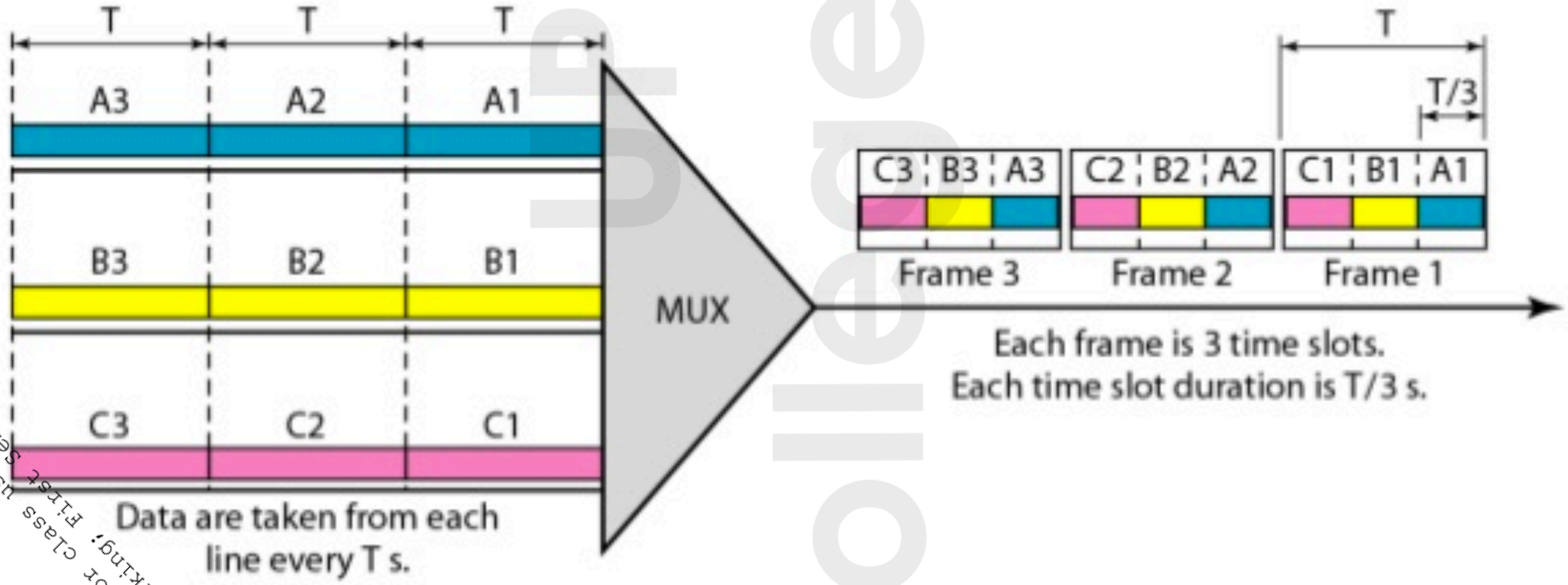
Digital data from different sources are combined. However, this does not mean that the sources cannot produce analog data; analog data can be sampled, changed to digital data.

Time Slots and Frames

- In TDM, the data flow of each input connection is divided into units, where each input occupies one input time slot
- A unit can be 1 bit, one character, or one block of data
- Each input unit becomes one output unit and occupies one output time slot
- However, the duration of an output time slot is *n* times shorter than the duration of an input time slot

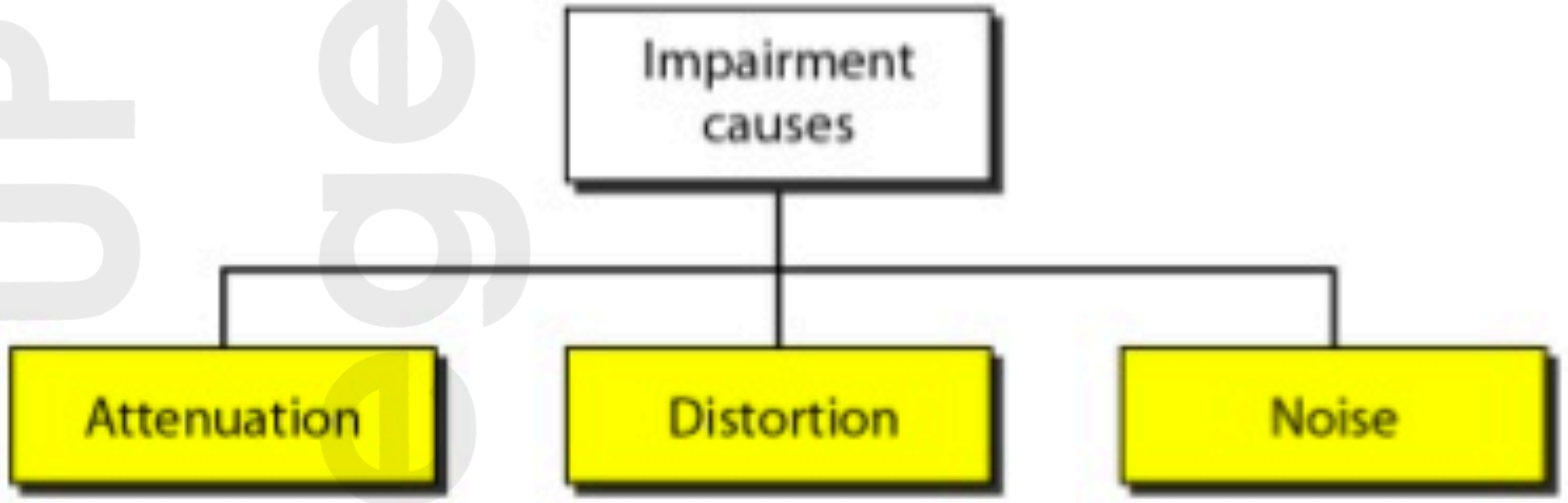


- If an input time slot is *T* s, the output time slot is *T/n* s, where *n* is the number of connections
- In other words, a unit in the output connection has a shorter duration; it travels faster
- In TDM, a round of data units from each input connection is collected into a frame. A *frame* consists of one complete cycle of time slots, with one slot dedicated to each sending device.



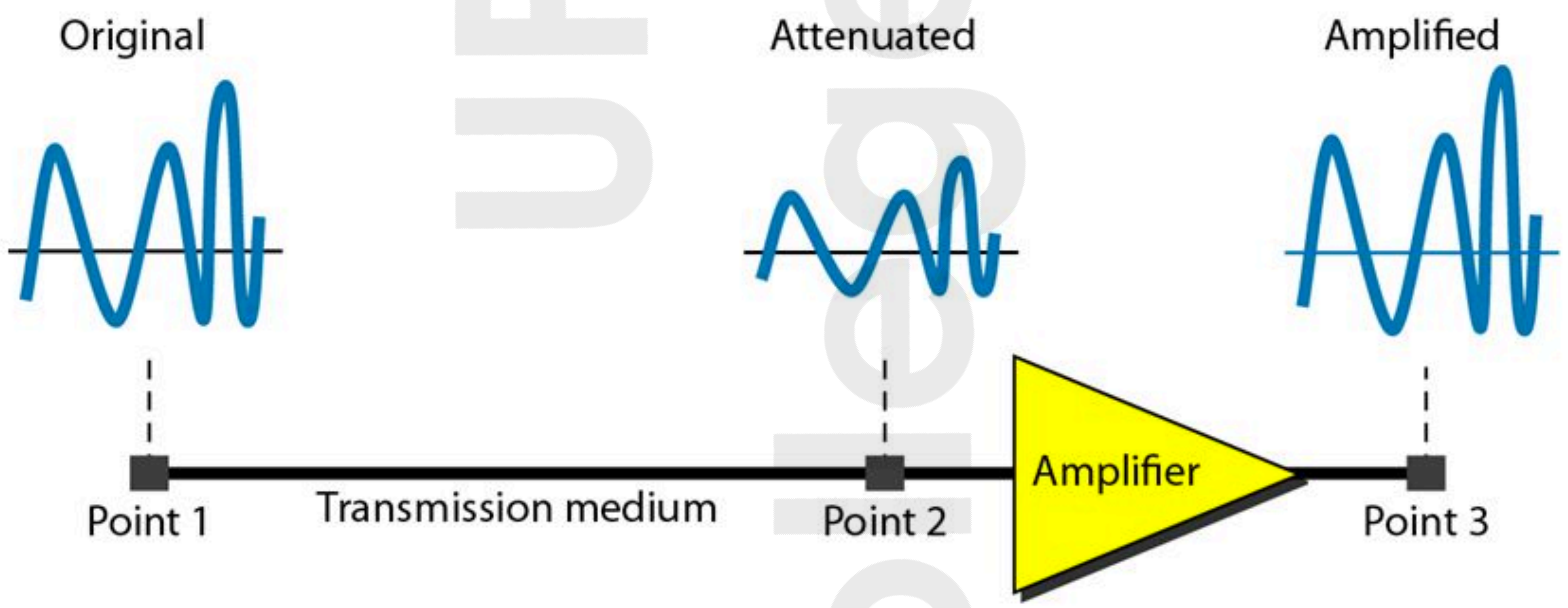
Transmission Impairment

- Signals travel through transmission media, which are not perfect; this 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
- Three causes of impairment:
  1. Attenuation
  2. Distortion
  3. Noise



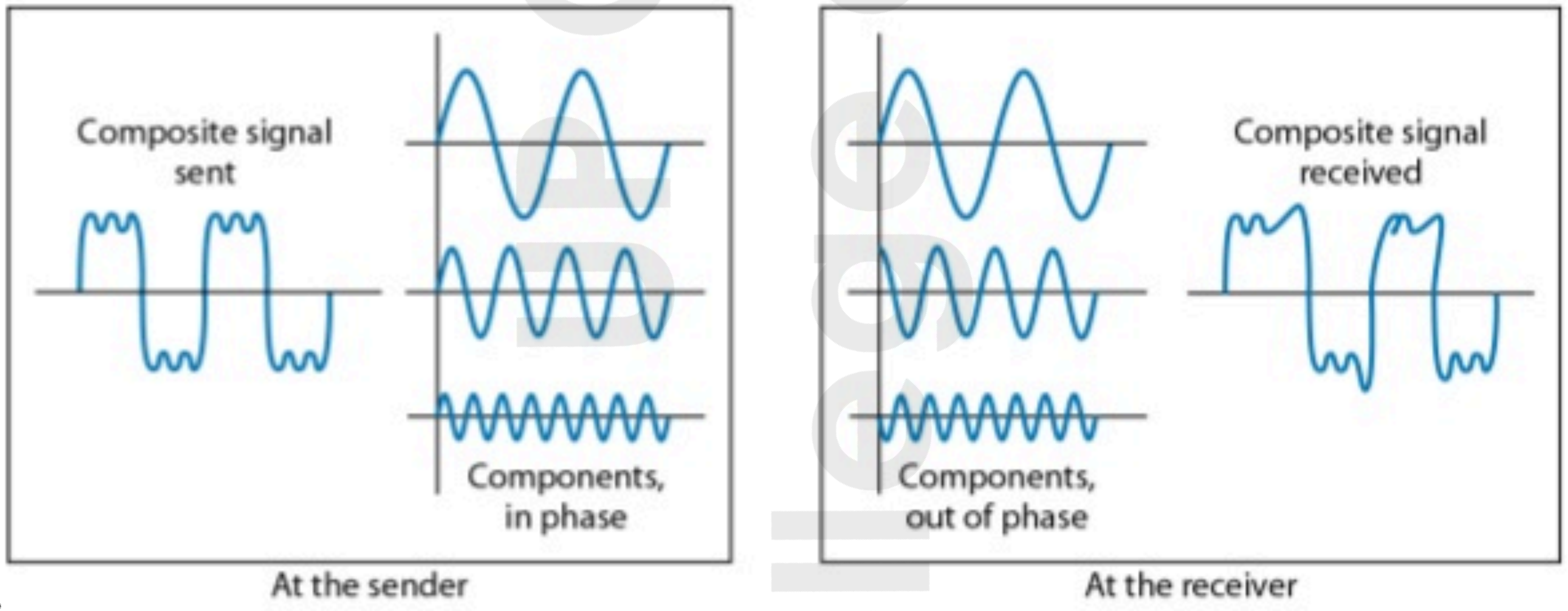
1. Attenuation

- Means loss of energy
- Cause: When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium; some energy is converted to heat
- Solution: Amplifiers are used to amplify the signal



2. Distortion

- Means that the signal (esp. composite) changes its form or shape
- Cause: Each signal component has its own propagation speed through a medium and, therefore, its own delay in arriving at the final destination. Differences in delay may create a difference in phase if the delay is not exactly the same as the period duration



3. Noise

- A general term which is used to describe an unwanted signal which affects a wanted signal
- Several types:
  1. Thermal - random motion of electrons in a wire which creates an extra signal not originally sent by the transmitter
  2. Induced - comes from sources such as motors and appliances
  3. Crosstalk - effect of one wire on the other
  4. Impulse - a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on