COMP 3721
Introduction to Data Communications

06a - Week 6 - Part 1

Learning Outcomes

- By the end of this lecture, you will be able to
  - Explain what is bandwidth utilization.
  - Explain what is multiplexing.
  - Explain multiplexing techniques in physical layer.

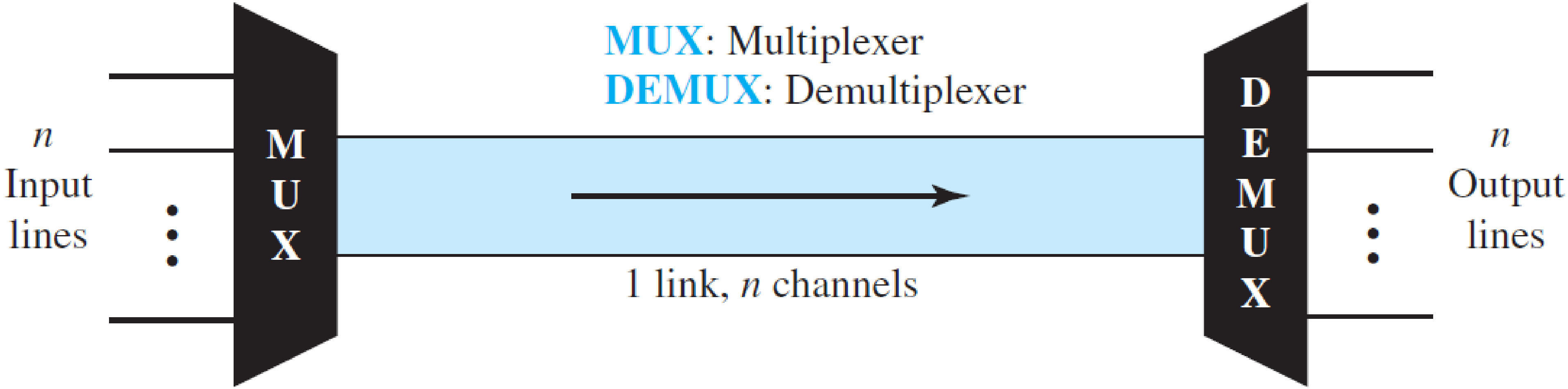
Bandwidth Utilization

- **Bandwidth utilization** is the wise use of available bandwidth.
  - We have links with limited bandwidths in real life!
- Two broad categories:
  - One technique is called "**multiplexing**".
    - Goal: efficiency
    - We combine several channels into one.
  - Other technique is called "**spectrum spreading**".
    - Goal: privacy
    - We do not discuss this technique in this class.

What is Multiplexing?

- Whenever the bandwidth of a medium linking two devices **is greater than** the bandwidth needs of the devices, the link can be **shared**.
  - High-bandwidth media such as **optical fiber** has a bandwidth far in excess of that needed for the average transmission signal.
- **Multiplexing** is the set of techniques that allow the simultaneous transmission of **multiple signals** across a single data link
- Easy definition: Combining **several** channels into **one**.

What is Multiplexing?



Link refers to the physical path.
Channel refers to the **portion** of a link.

Multiplexing Techniques

- Frequency-Division Multiplexing (FDM)
- Wavelength-Division Multiplexing (WDM)
- Time-Division Multiplexing (TDM)

Multiplexing Techniques

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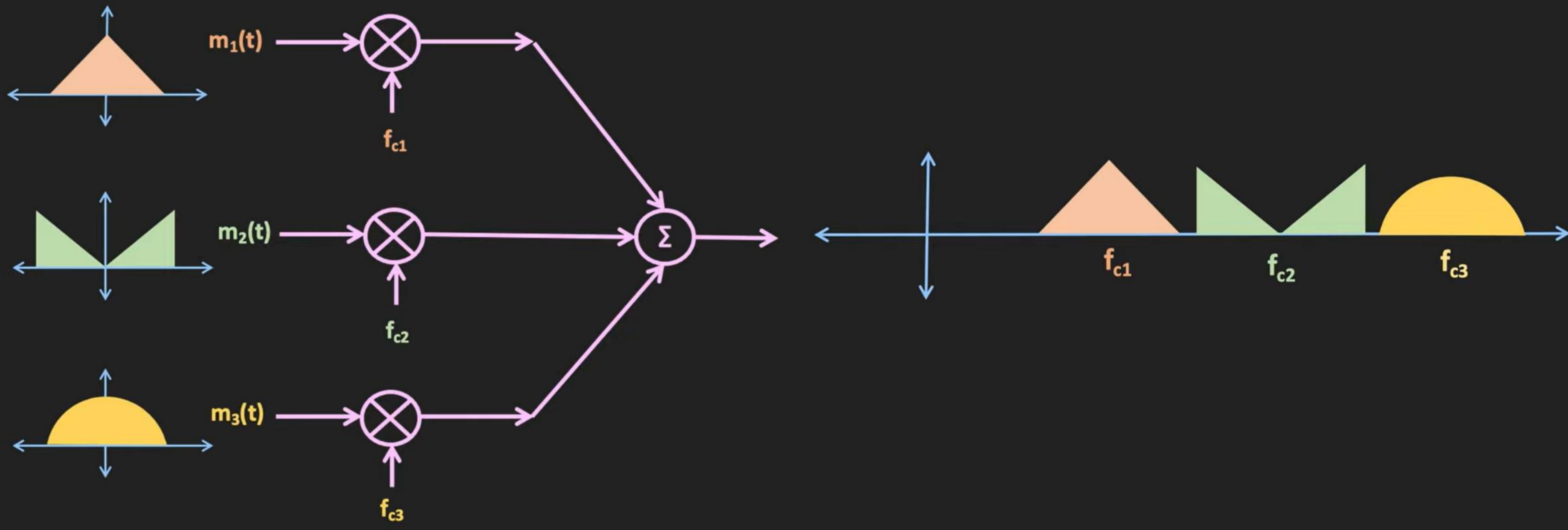
$\left.\begin{array}{l}\text{FDM}\\ \text{WDM}\end{array}\right\}$ **Analog signals**

$\left.\text{TDM}\right\}$ **Digital signals**

Frequency-Division Multiplexing (FDM)

- An **analog multiplexing technique**.
- Analog signals generated by each sending device **modulate different carrier frequencies**.
  - The modulated signals are combined into a single composite signal that can be transported by the link.
- **Guard bands**
  - Strips of unused bandwidth that separate channels from each other.
    - To prevent signals from **overlapping** and **interference**.
- FDM can be used when the bandwidth of a link (in hertz) **is greater than** the combined bandwidths of the signals to be transmitted.

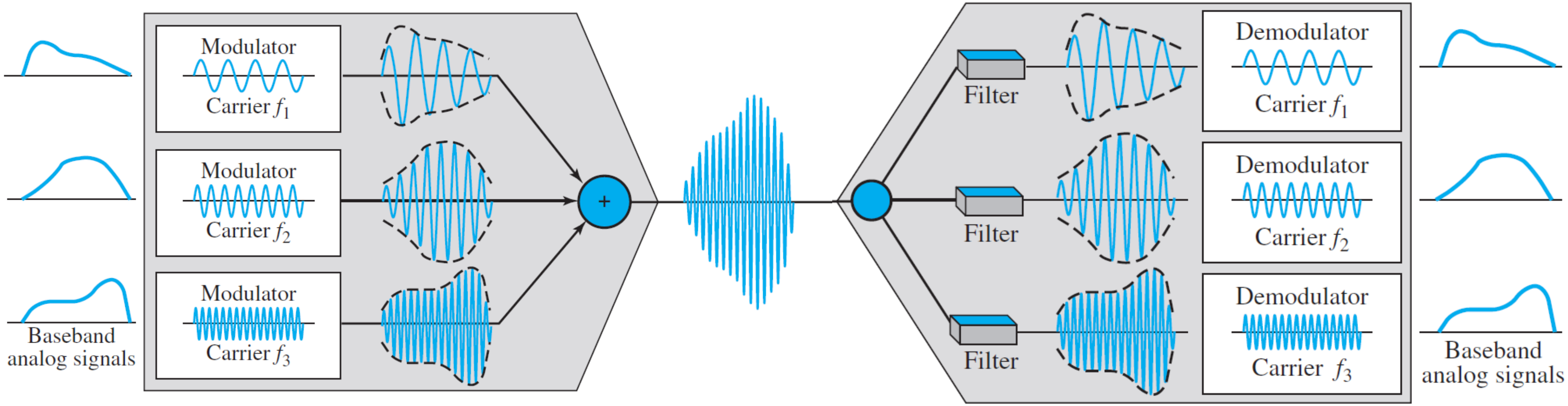
Frequency Division Multiplexing



A Conceptual View of FDM

- Each channel corresponds to a specific carrier frequency allocated to an individual signal source

FDM Process and Demultiplexing Process



FDM Process **Demultiplexing Process**

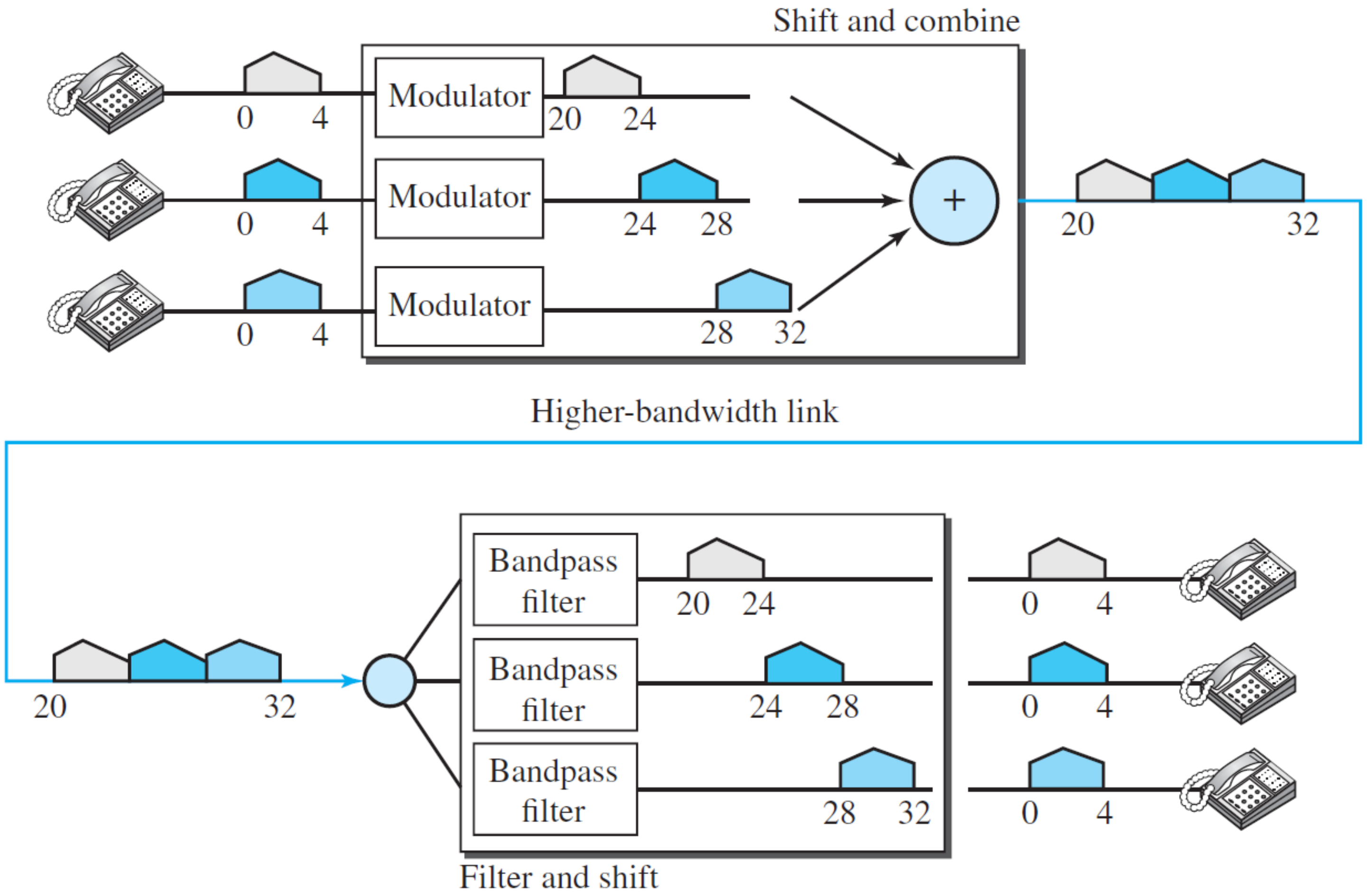
Applications of FDM

- Telephone companies
- AM and FM radio broadcasting
- Television broadcasting
- …

Applications of FDM – Example

- 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.

Applications of FDM – Example Solution

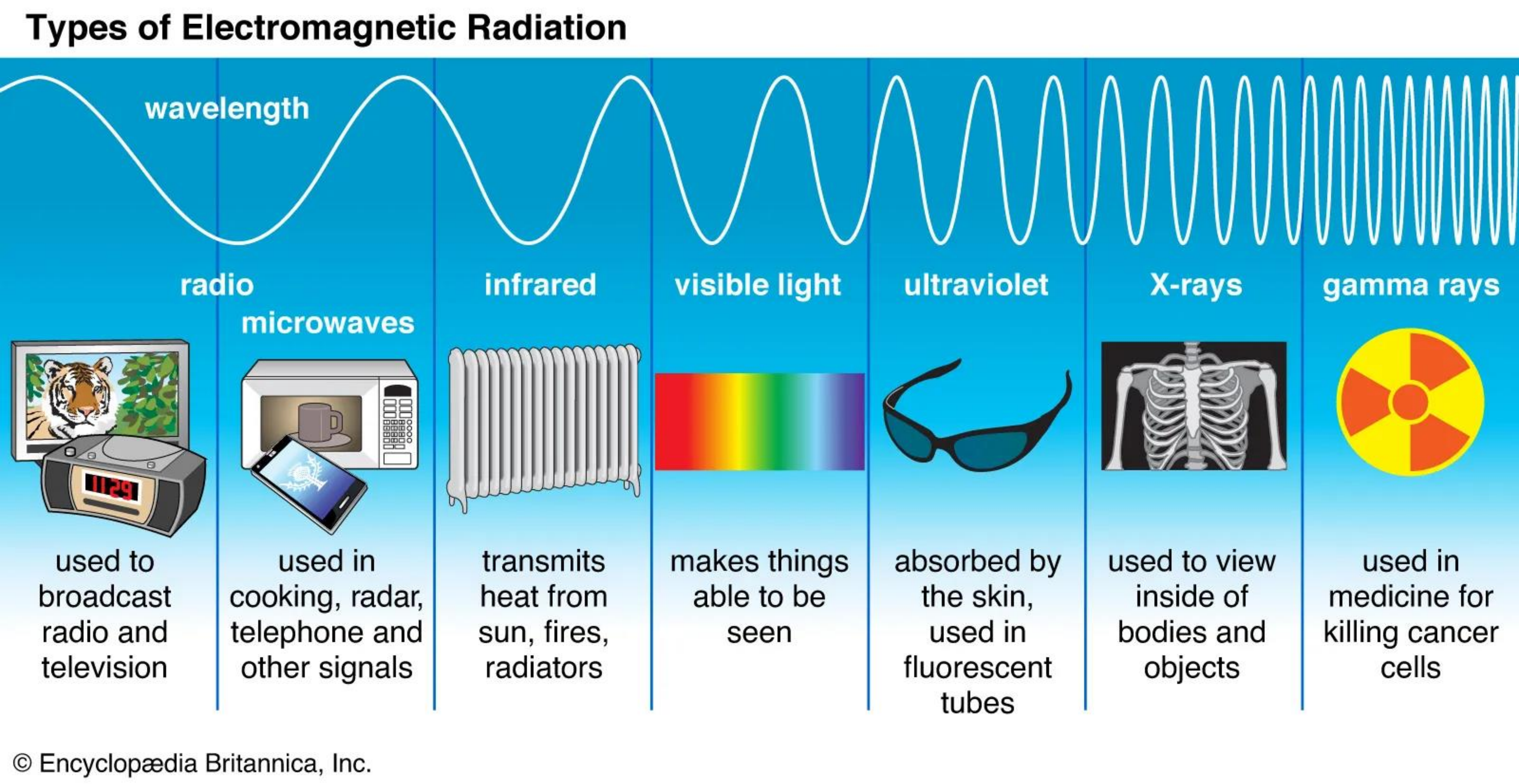


FDM Implementation

- In many cases, no need for a physical multiplexer/demultiplexer. E.g.:
  - In **radio** and **TV broadcasting**, stations agree to send their broadcasts to the air using different carrier frequencies.
  - In case of **cellular telephone systems**, a base station assigns a carrier frequency to the telephone user (when the user hangs up, her/his bandwidth is assigned to another user).

Wavelength-Division Multiplexing

- An **analog** multiplexing technique to combine **optical signals**.
- Due to the **high data rate** of a **fiber-optic cable**, using it for a single line wastes the available bandwidth.
- **WDM** vs **FDM**
  - **Similarity**: Both combine different signals of different frequencies.
  - **Difference**: In WDM, the multiplexing/demultiplexing involve **optical signals** transmitted through fiber-optic channels and the **frequencies** are **very high**.
  - The combining and splitting of light sources are easily handled by a **prism**.


Types of Electromagnetic Radiation
wavelength
radio
microwaves
infrared
visible light
ultraviolet
X-rays
gamma rays
used to broadcast radio and television
used in cooking, radar, telephone and other signals
transmits heat from sun, fires, radiators
makes things able to be seen
absorbed by the skin, used in fluorescent tubes
used to view inside of bodies and objects
used in medicine for killing cancer cells
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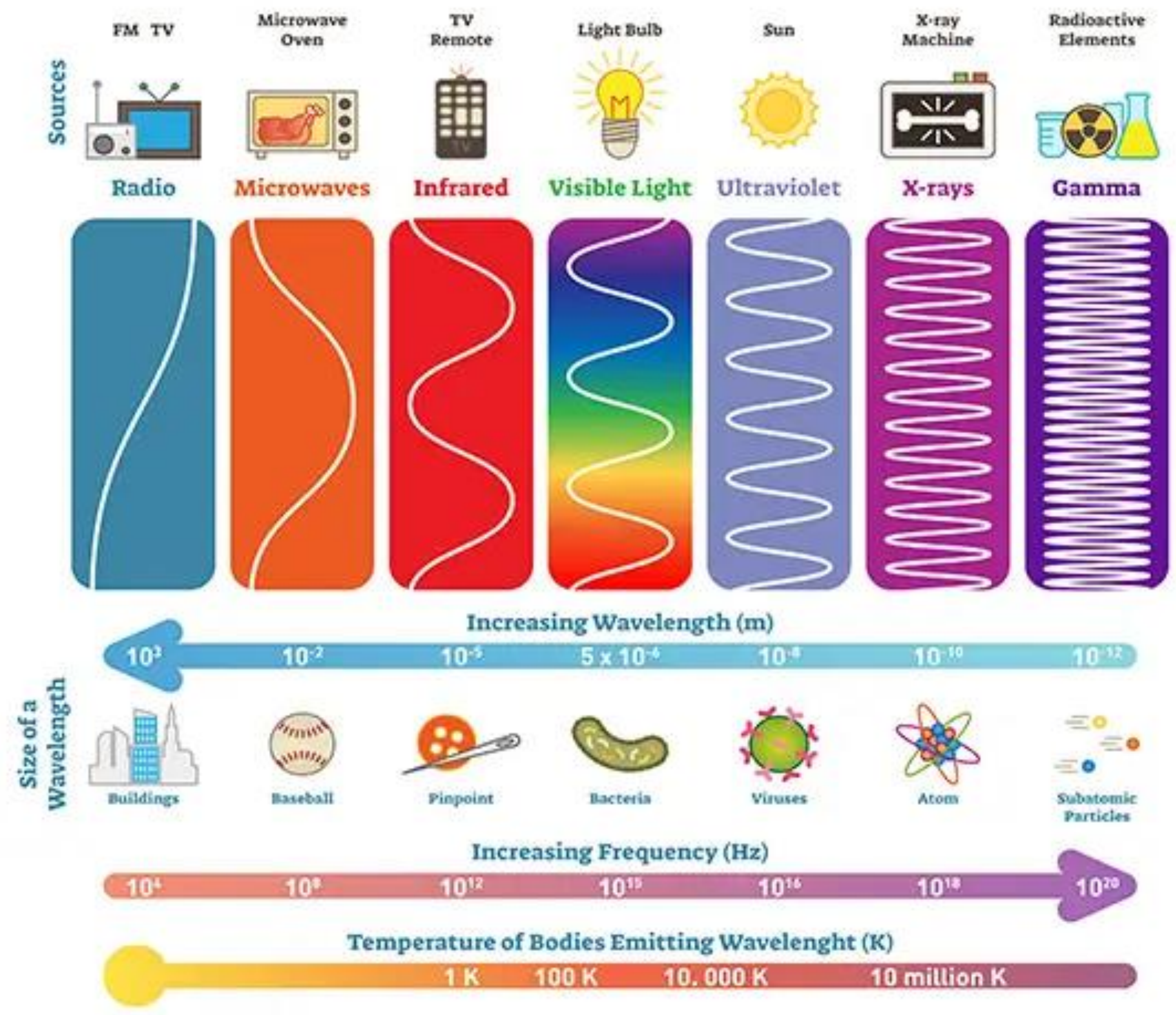
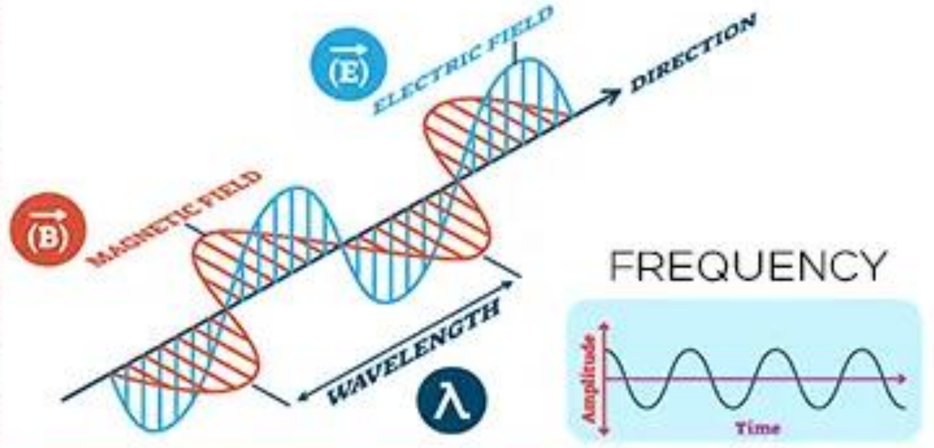
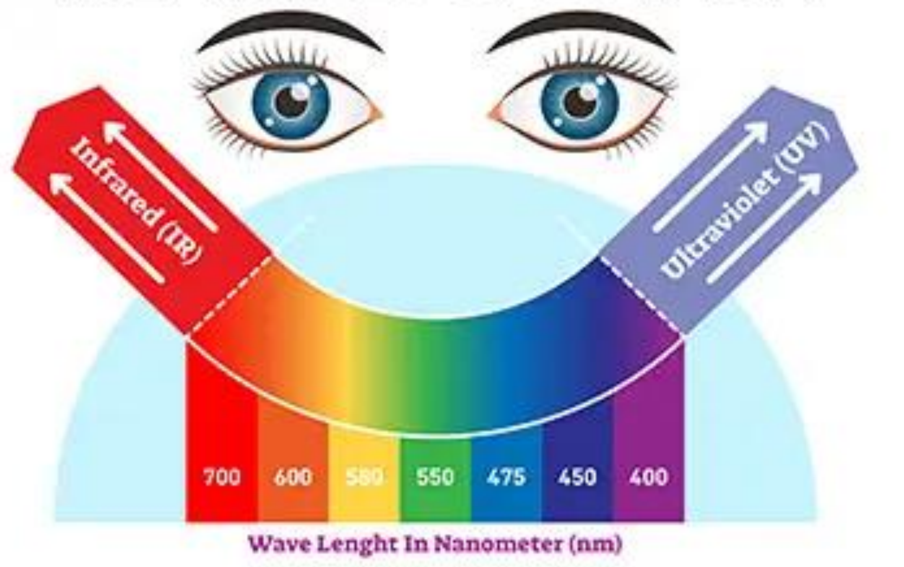
THE ELECTROMAGNETIC SPECTRUM

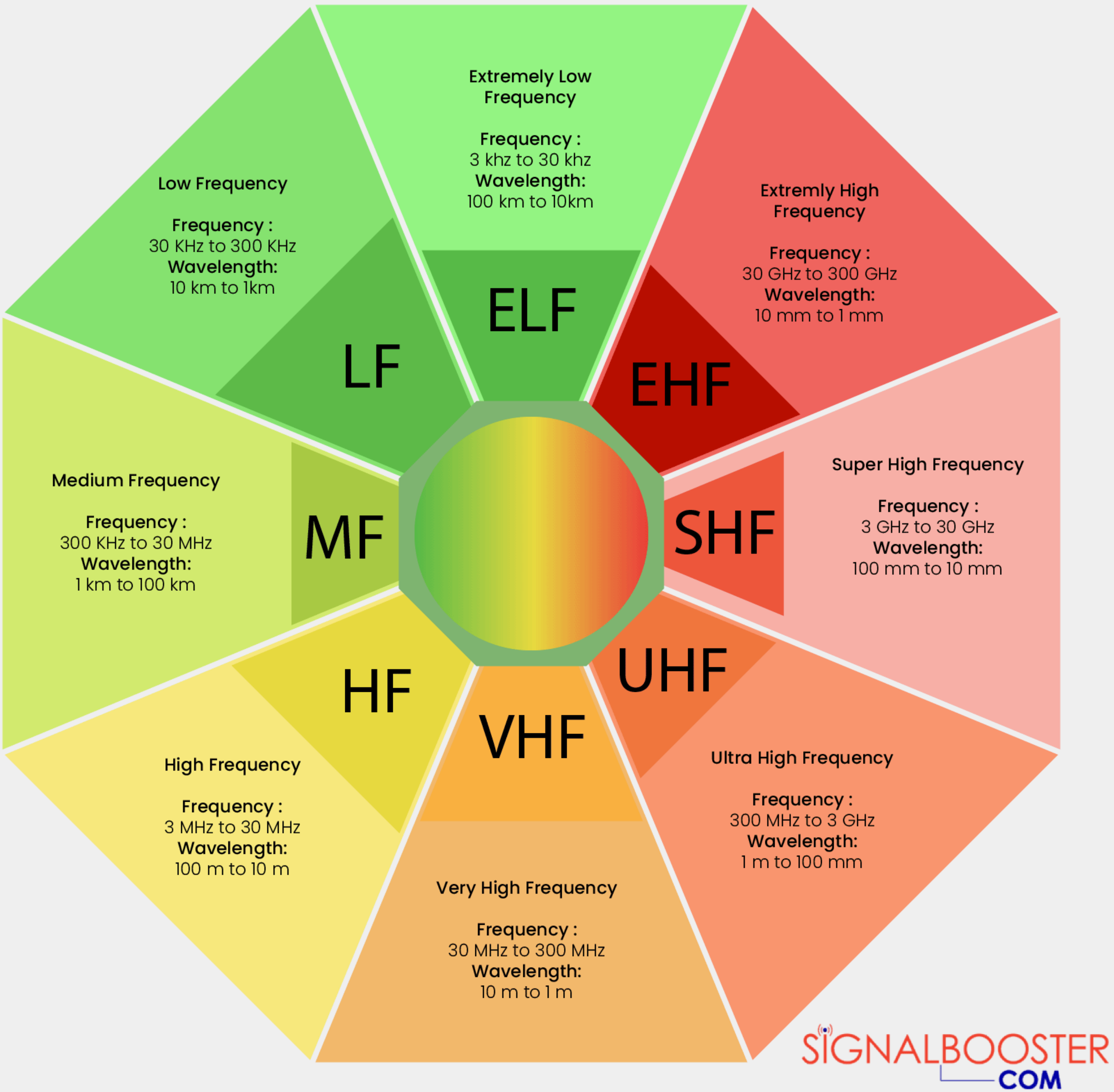


ELECTROMAGNETIC WAVES



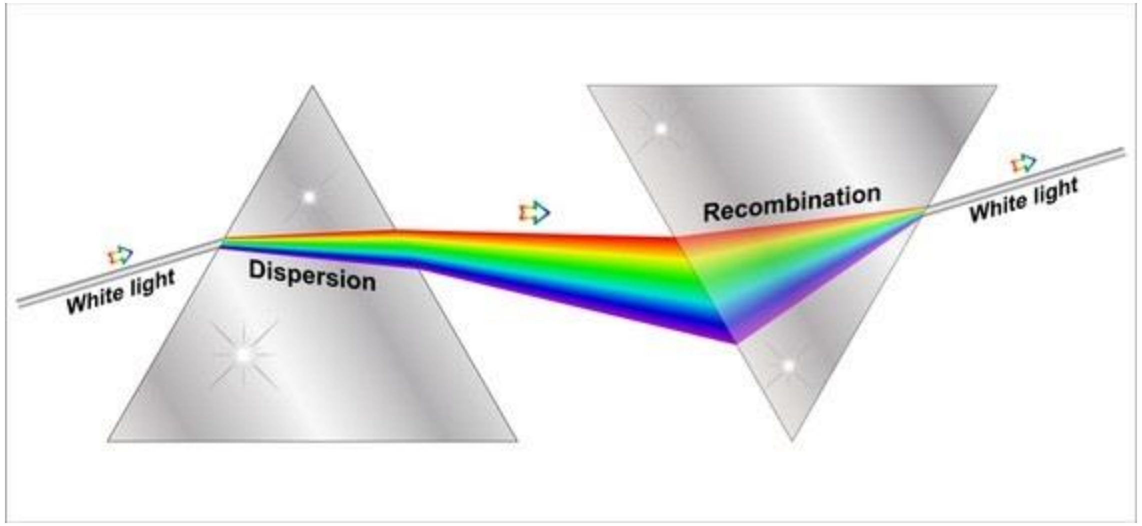
THE VISIBLE SPECTRUM

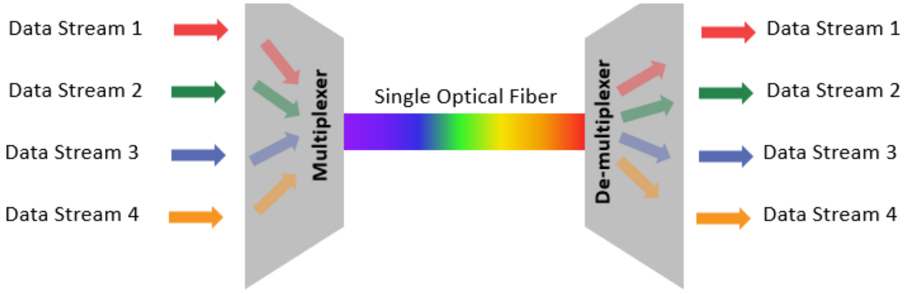


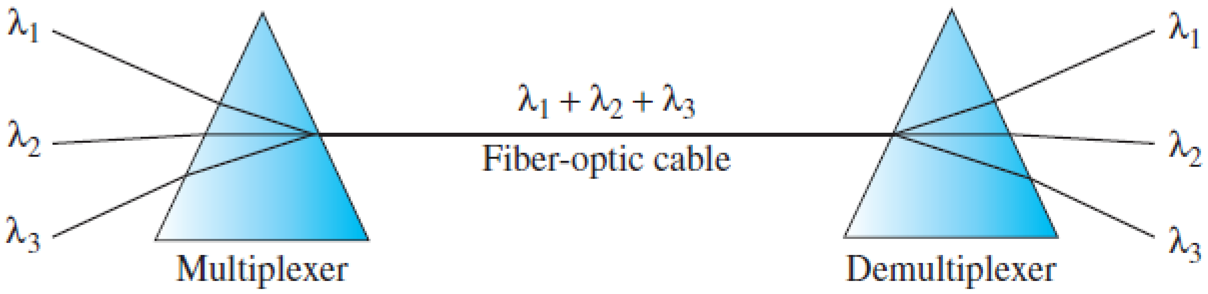


Radio Frequency Spectrums

Wavelength-Division Multiplexing

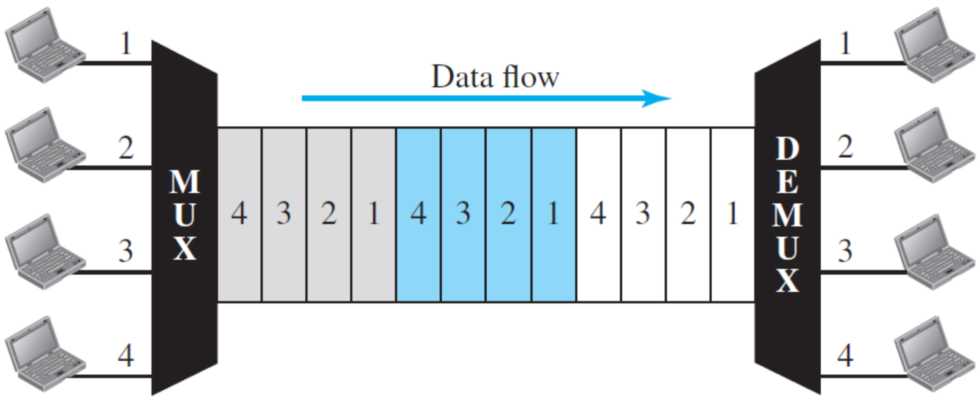






Time-Division Multiplexing

- A **digital multiplexing technique** that allows several **digital signals** to share the high bandwidth of a link in **time**.
  - Each connection occupies a **portion** of **time** in the link.
  - TDM is a digital multiplexing technique for **combining** several **low-rate channels** into a **high-rate one**.
- Instead of sharing a portion of the bandwidth as in FDM, **time** is shared.



Time-Division Multiplexing (Cont.)

- Is it possible to use TDM for analog signal? How?

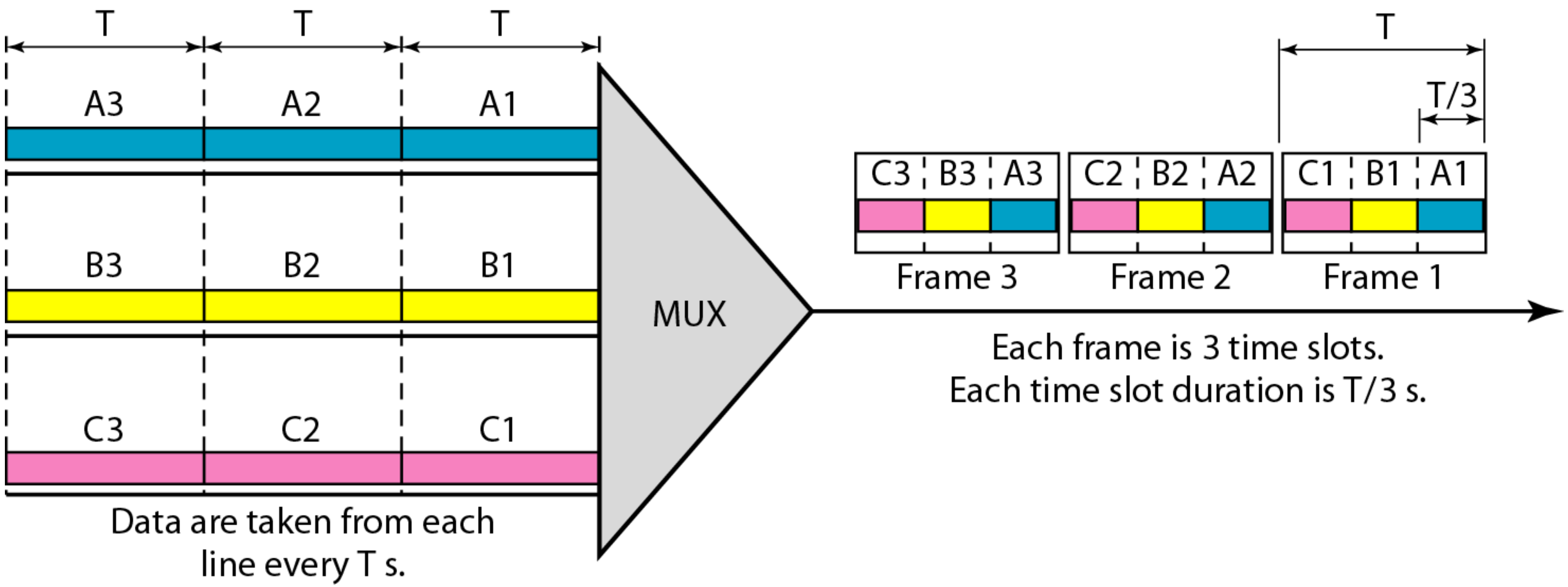
Time-Division Multiplexing (Cont.)

- Is it possible to use TDM for analog signal? How?
  - An **analog signal** can be sampled, changed to digital data, and then multiplexed by using TDM.

Time-Division Multiplexing (Cont.)

- In TDM, the data flow of each input connection is divided into **units**.
- A unit can be **1 bit**, **one character**, or **one block of data**.
- A round of data units from each input connection is collected into a **frame**.
- If we have *n* connections, a frame is **divided** into ***n* timeslots,** and **one slot** is allocated for each unit.
- If the duration of the input unit is ***T***, **the duration of each frame is *T***, and the duration of each slot is ***T/n***.

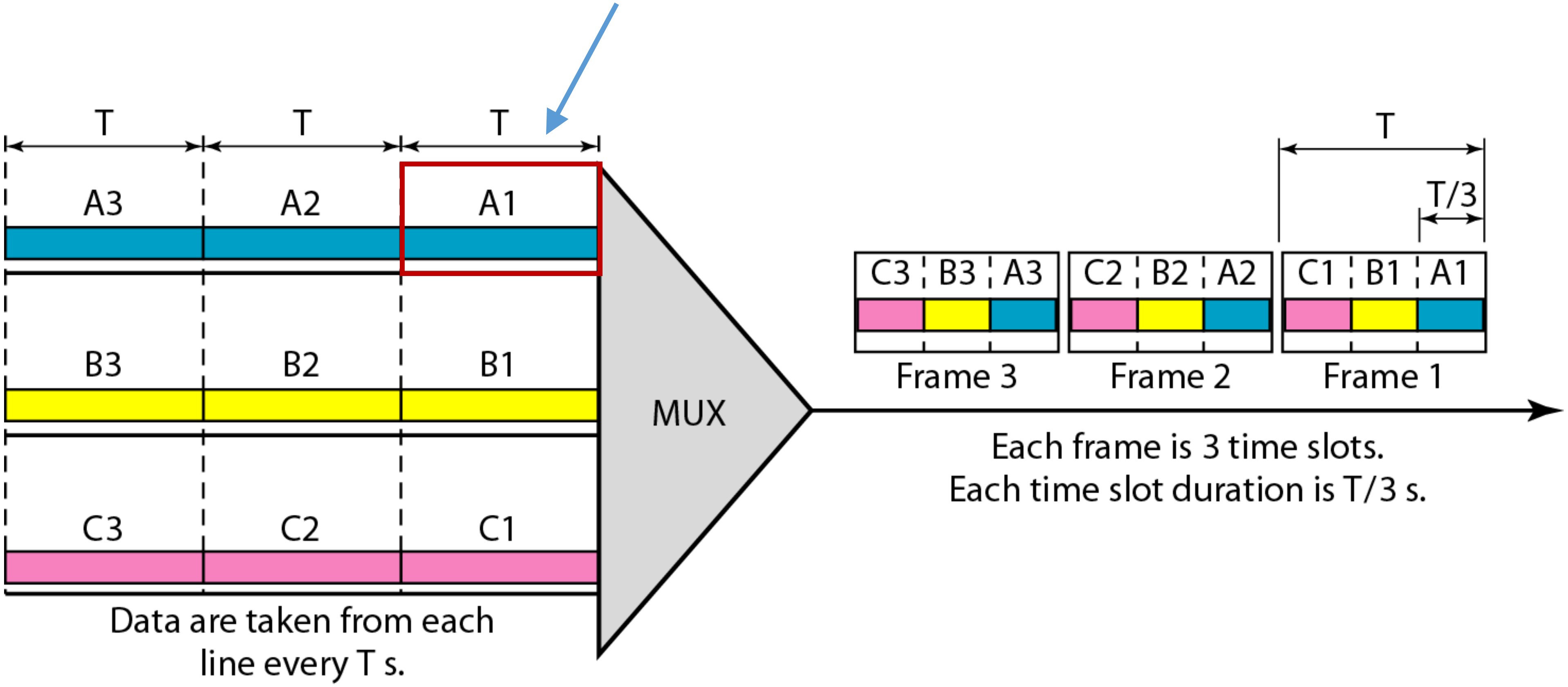
Synchronous TDM



The data rate of the output link must be ***n* times** the data rate of a connection to **guarantee the flow of data**.

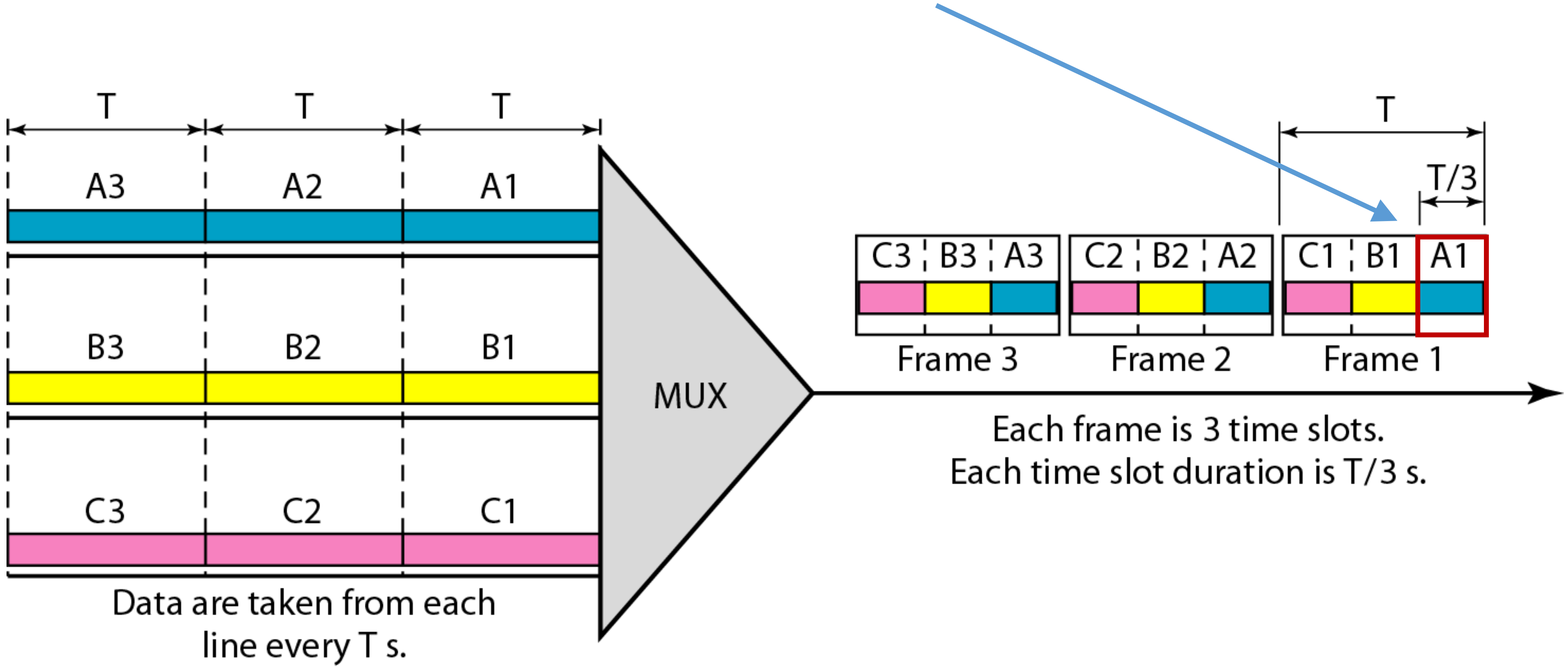
Synchronous TDM

The data flow of each input connection is divided into **units** (e.g., A1, A2, …), where each unit occupies one **input time slot** (with duration T).



Synchronous TDM

Each input unit becomes one output unit. However, the duration of an **output time slot** is ***n* times shorter** than the duration of an **input time slot** (*n* is the number of connections). Here, *n* = 3.



Synchronous TDM (Cont.)

- In synchronous TDM, the **data rate of the link** is ***n* times faster**, and the **unit duration** is ***n* times shorter**.

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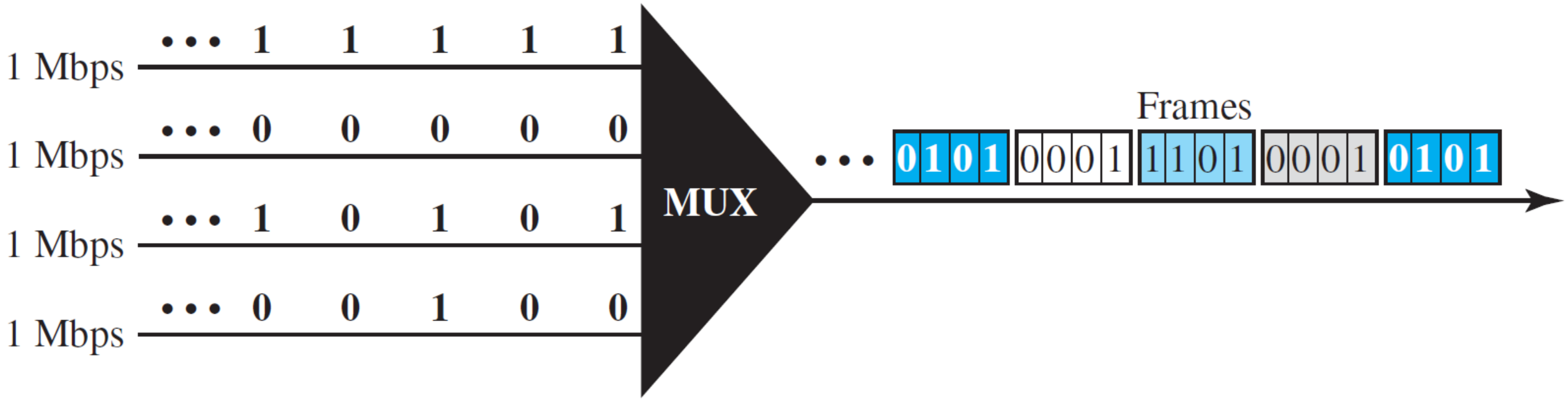
- In a system with ***n* input lines**, each frame has ***n* slots**, with each slot allocated to carrying data from a specific input line.

Synchronous TDM (Cont.)

- In synchronous TDM, the **data rate of the link** is ***n* times faster**, and the **unit duration** is ***n* times shorter**.
- In a system with ***n* input lines**, each frame has ***n* slots**, with each slot allocated to carrying data from a specific input line.
- The duration of a frame is the same as the duration of an **input unit**. The frame rate is always the same as any **input rate**.

Synchronous TDM – Example

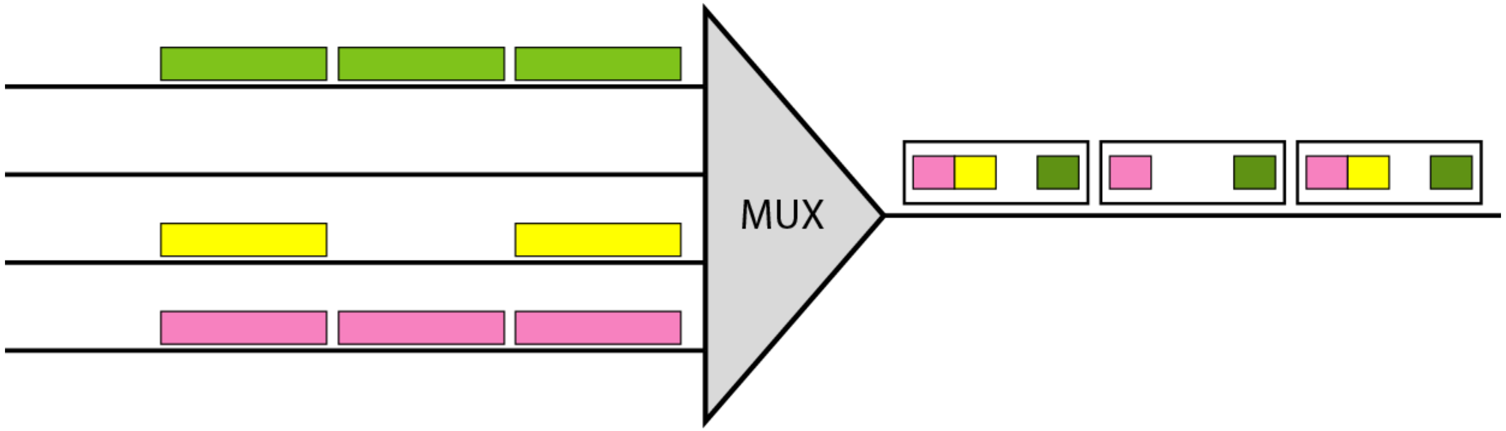


- Bit rate: **1 Mbps**
- Bit duration = 1/(Bit rate) = **1 µs**

- Bit rate: **4 Mbps**
- Bit duration = **0.25 µs**
- **1 Mbps** input rate
  → **1,000,000 frames/s**

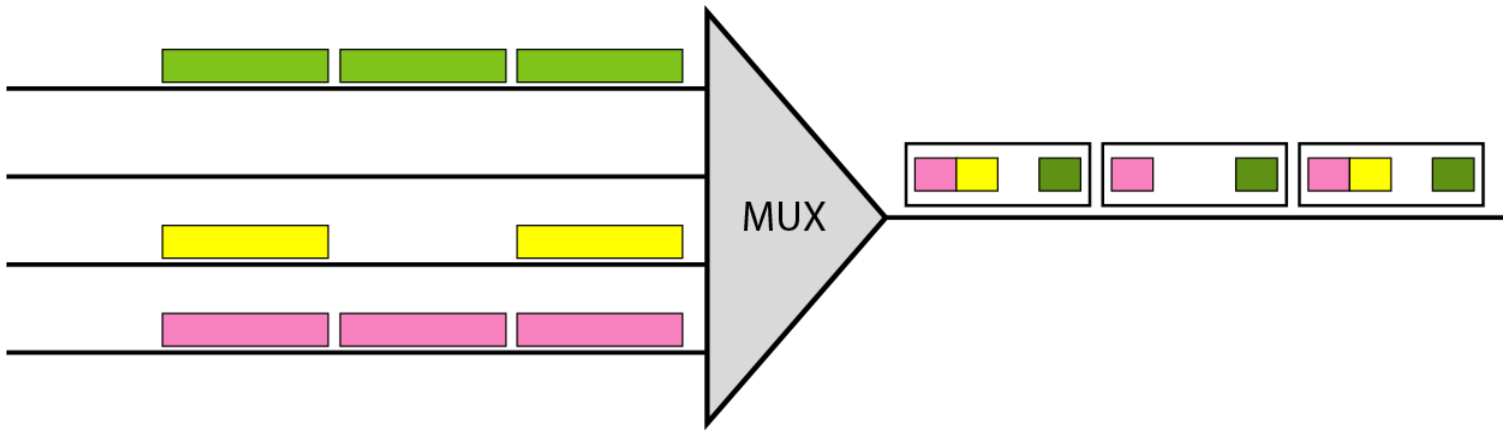
Synchronous TDM – Efficiency and Empty Slots

- **Synchronous TDM is not efficient**. Why?



Synchronous TDM – Efficiency and Empty Slots

- **Synchronous TDM is not efficient**. Why?
  - If a source does not have data to send, the corresponding slot in the output frame is empty.
  - **Statistical TDM** can improve the efficiency by removing the empty slots from the frame.

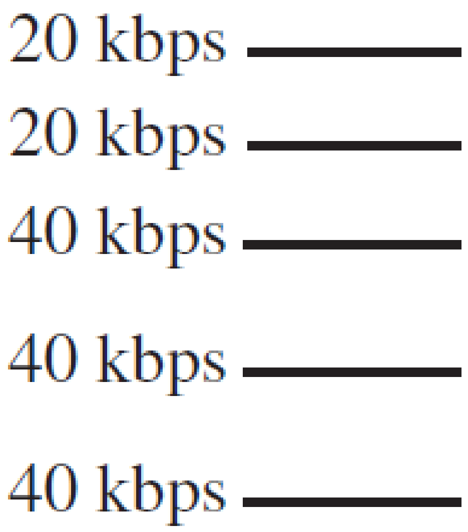


Synchronous TDM – Data Rate Management

- How to handle a **disparity** in the **input data rates**?
- **Three strategies**, or a combination of them, can be used:
  1. Multilevel multiplexing
  2. Multiple-slot allocation
  3. Pulse stuffing

Multilevel Multiplexing

- It is a technique used when the **data rate** of an **input line** is a **multiple** of others.



Multilevel Multiplexing

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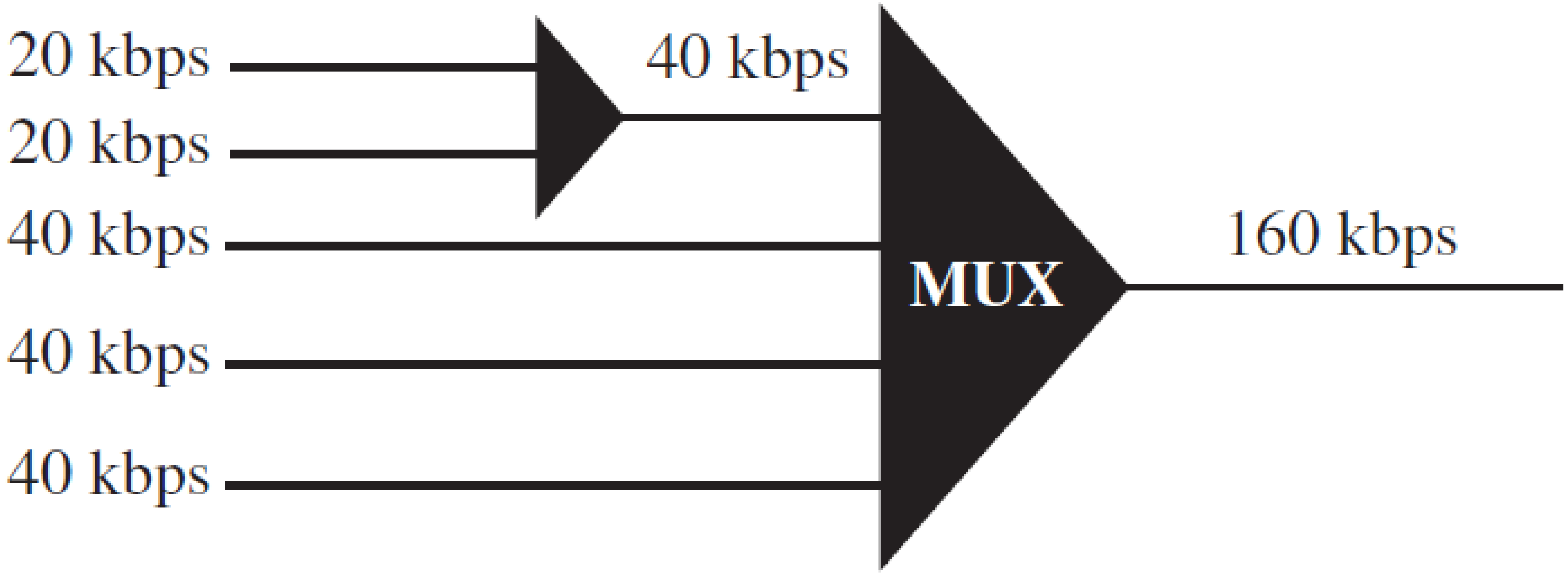
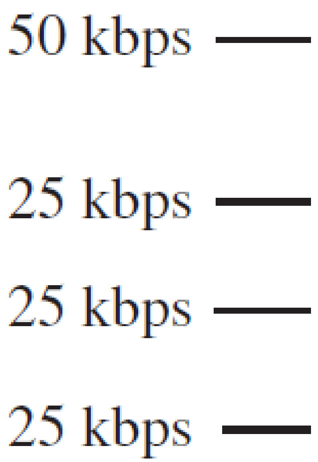


Multiple-Slot Allocation

- Allocating **more than one slot** in a frame to a single input line.
  - When an input line has **multiple rates** of the others.



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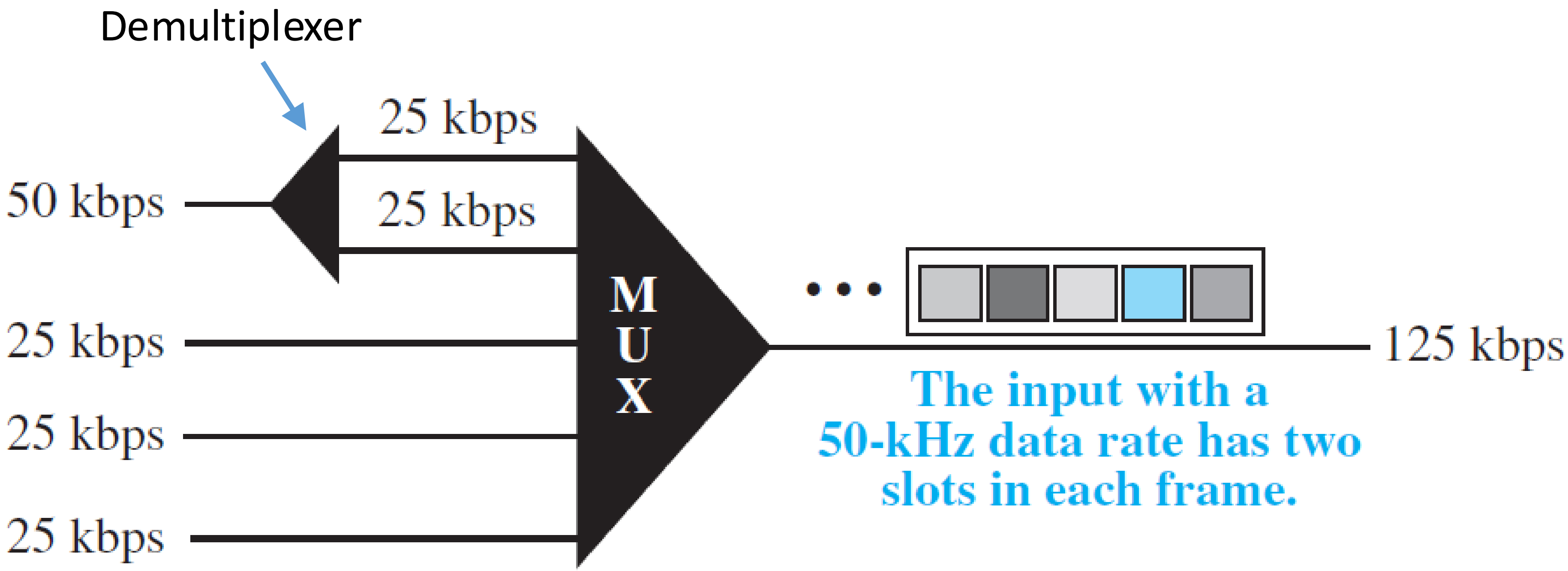
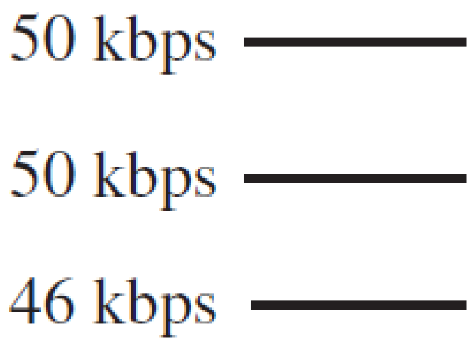


Pulse Stuffing

- **Pulse stuffing** or **bit padding** or **bit stuffing**
  - Used when the bit rates of sources are **not integer multiples** of each other.
  - Makes the **highest input data rate** the **dominant data rate** and then adds **dummy bits** to the input lines with lower rates → their rates are increased.



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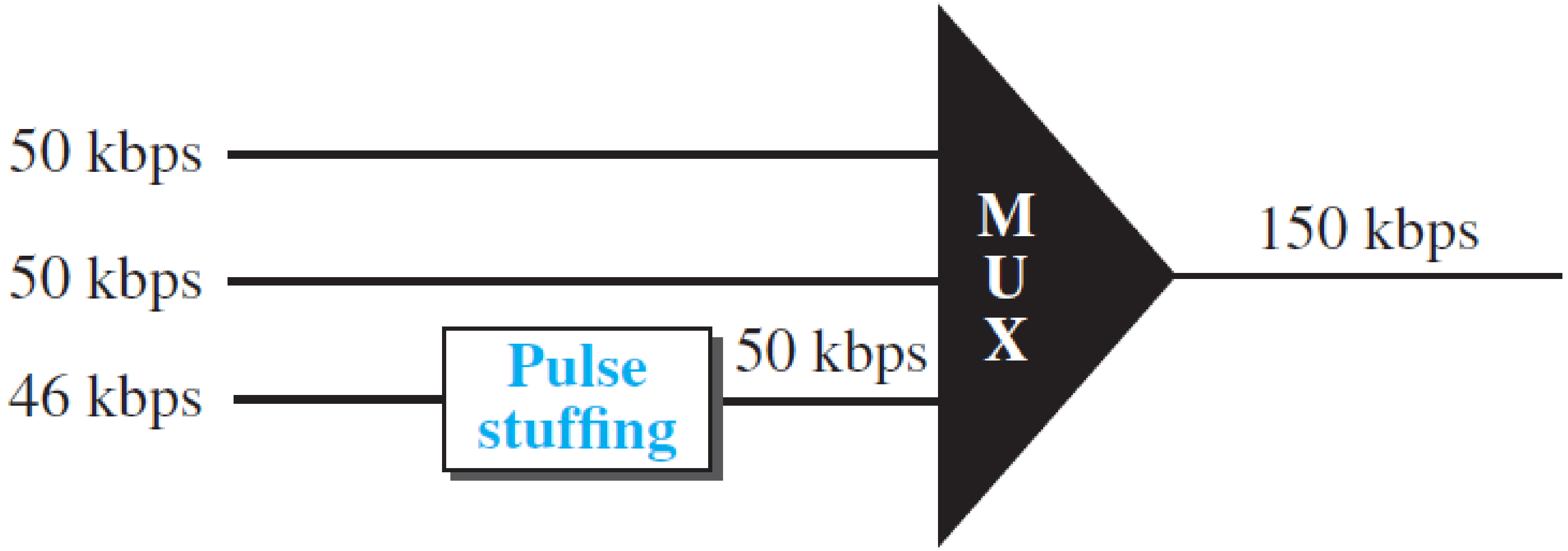
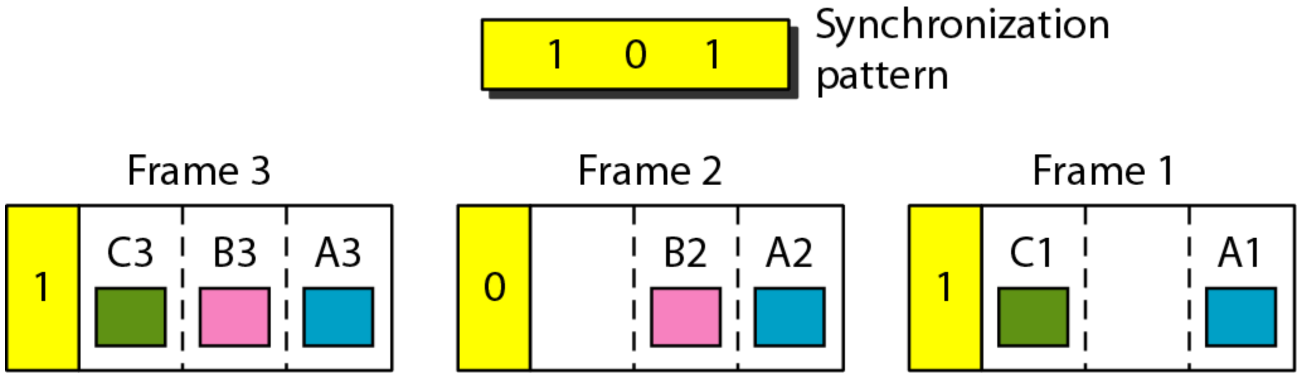


Synchronous TDM – Frame Synchronizing

- **Synchronization** between the **multiplexer** and **demultiplexer** is a major issue (to maintain the integrity of the frames exchange between source and destination).
- **Framing bits**
  - One or more synchronization bits that are usually added to the beginning of each frame.
  - Follow a pattern (e.g., 1 0 1 …) frame to frame → Allow the demultiplexer to synchronize with the incoming stream so that it can separate the time slots accurately.



Example 1

- 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?

Example 1 – Answer

- 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?

- 5 channels → at least 4 guard bands
- The minimum bandwidth = (5 × 100khz) + (4 × 10khz) = **540 kHz**

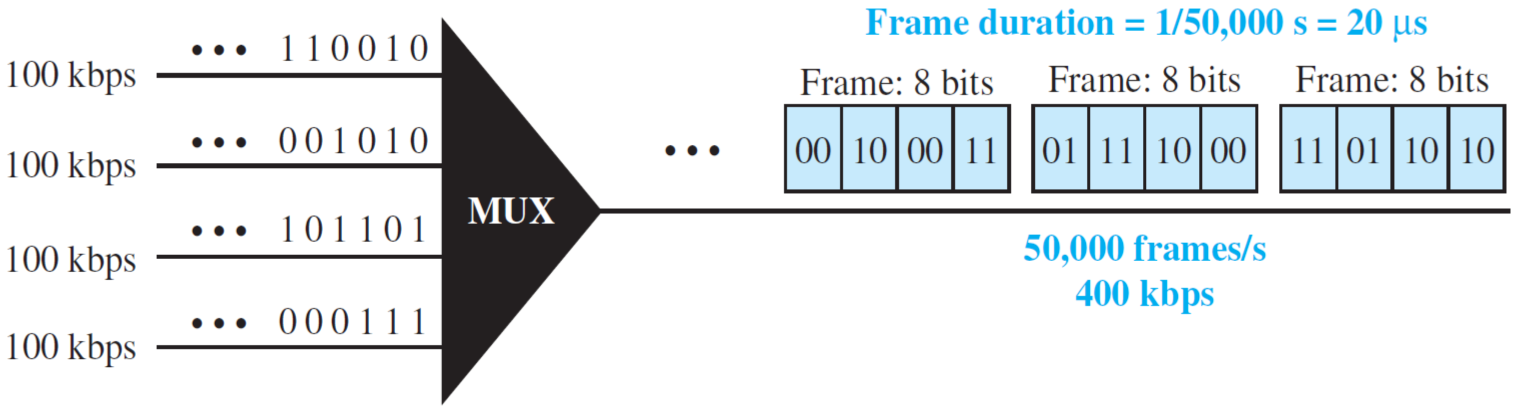
Example 2

- A multiplexer combines four 100 kbps channels using a time slot of 2 bits.
    1. What is the frame rate?
    2. What is the frame duration?
    3. What is the bit rate of the shared channel?
    4. What is the bit duration?

Example 2 – Answer

1. Frame rate = input unit rate = 100 kbps / 2 = **50,000 frames per second**
2. Frame duration = 1/50,000 s = **20 μs**
3. Bit rate = 4 × 100 kbps = **400 kbps**
4. Bit duration = 1/400 kbps = **2.5 μs**

- Note that the **frame duration** is **8 times** the **bit duration** because each frame is carrying 8 bits.



Summary

- Bandwidth utilization
- Multiplexing → Efficiency
- Multiplexing techniques: FDM, WDM, and TDM

References

[1] Behrouz A.Forouzan, Data Communications & Networking with TCP/IP Protocol Suite, 6th Ed, 2022, McGraw-Hill companies.

Reading

- Chapter 2 of the textbook, section 2.5
- Chapter 2 of the textbook, section 2.8 (Practice Test)