Multiplexing

Lecture 5

MULTIPLEXING

- **Multiplexing** is the set of **techniques** that **allows** the **simultaneous transmission** of multiple signals across a **single data link.**

- **Why Multiplexing is being used?:**
  - To achieve better **utilization** of **available bandwidth.**
  - To achieve **Efficiency** i.e., **sharing** of the **bandwidth** between **multiple users.**
  - **Whenever** the **bandwidth** of a medium **linking two devices** is **greater** than the **bandwidth needs of the devices,** the **link** can be **shared.**

MULTIPLEXING

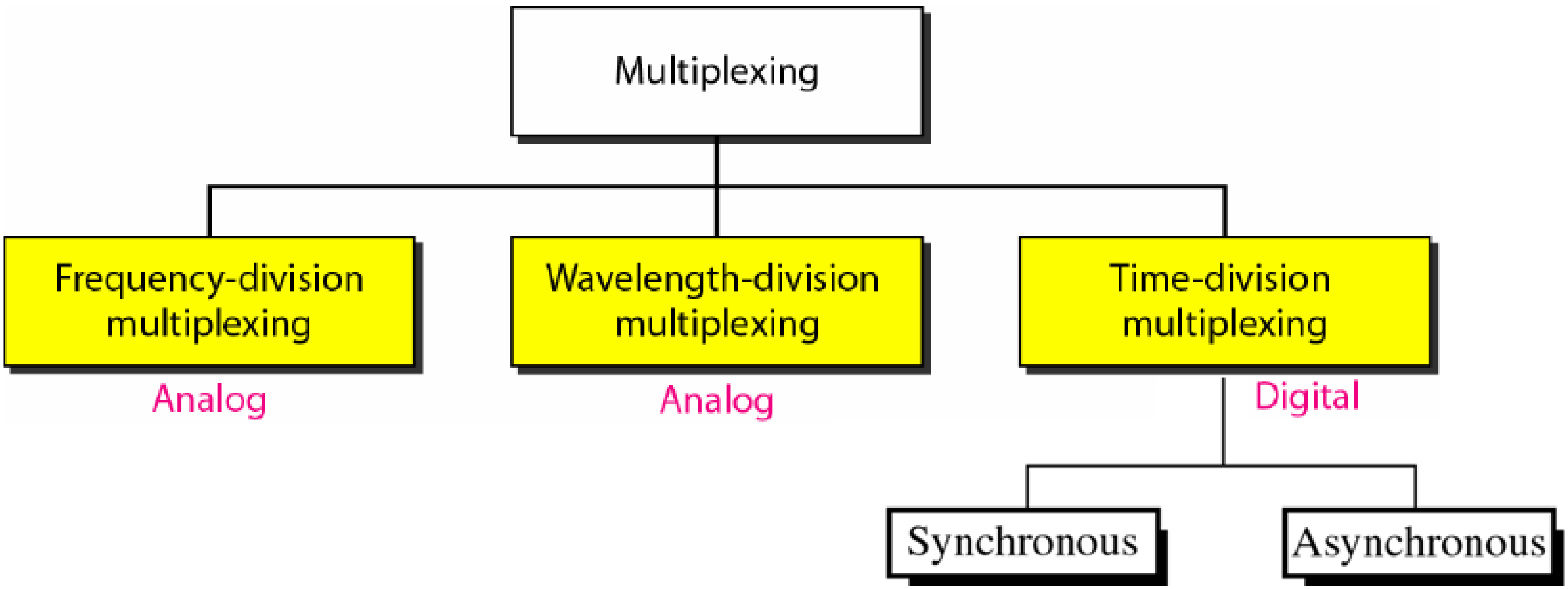
- In **analog transmission**, signals are commonly multiplexed using **frequency-division multiplexing (FDM),** in which the carrier bandwidth is divided into sub channels of different frequency widths, each carrying a signal at the same time in parallel.

- In some optical fiber networks, multiple signals are carried together as separate wavelengths of light in a multiplexed signal using **Wavelength Division Multiplexing (WDM).** This is one special kind of FDM

- In **digital transmission**, signals are commonly multiplexed using time-division multiplexing (TDM), in which the multiple signals are carried over the same channel in alternating time slots.

- TDM can be further divided into synchronous TDM and asynchronous TDM

Categories of multiplexing



MULTIPLEXING

- **Multiplexer (MUX):** device to **combine n number of signals** to one composite signal.
- **Demultiplexer (DEMUX):** device to **separate the composite signal** into n number of signals.
- **Path:** refers to the **physical link.**
- **Channel:** refers to a **portion** of a **path.**

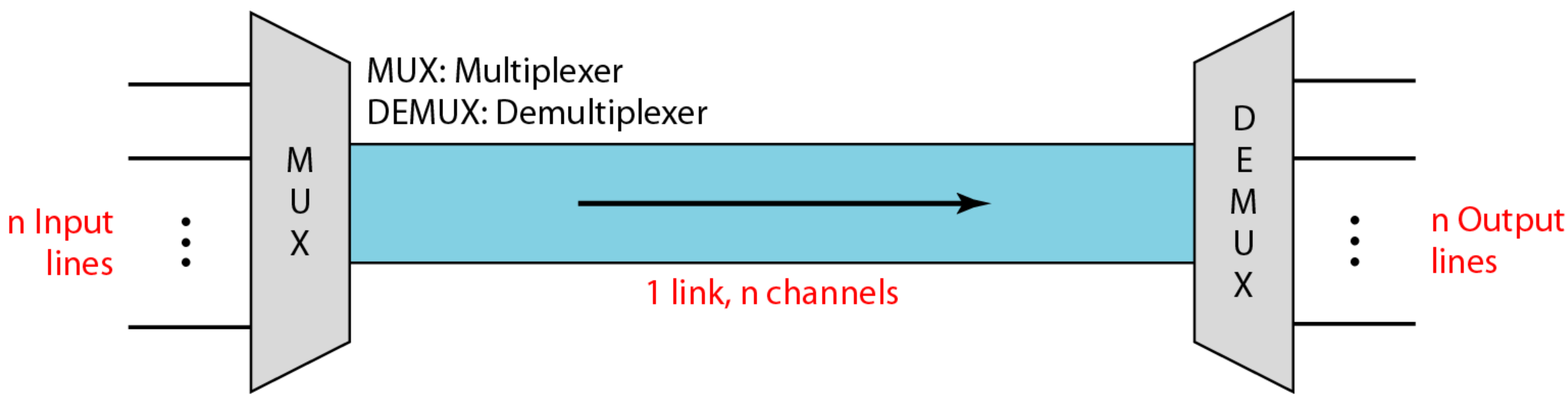


Fig. 1: Dividing a link into channels.

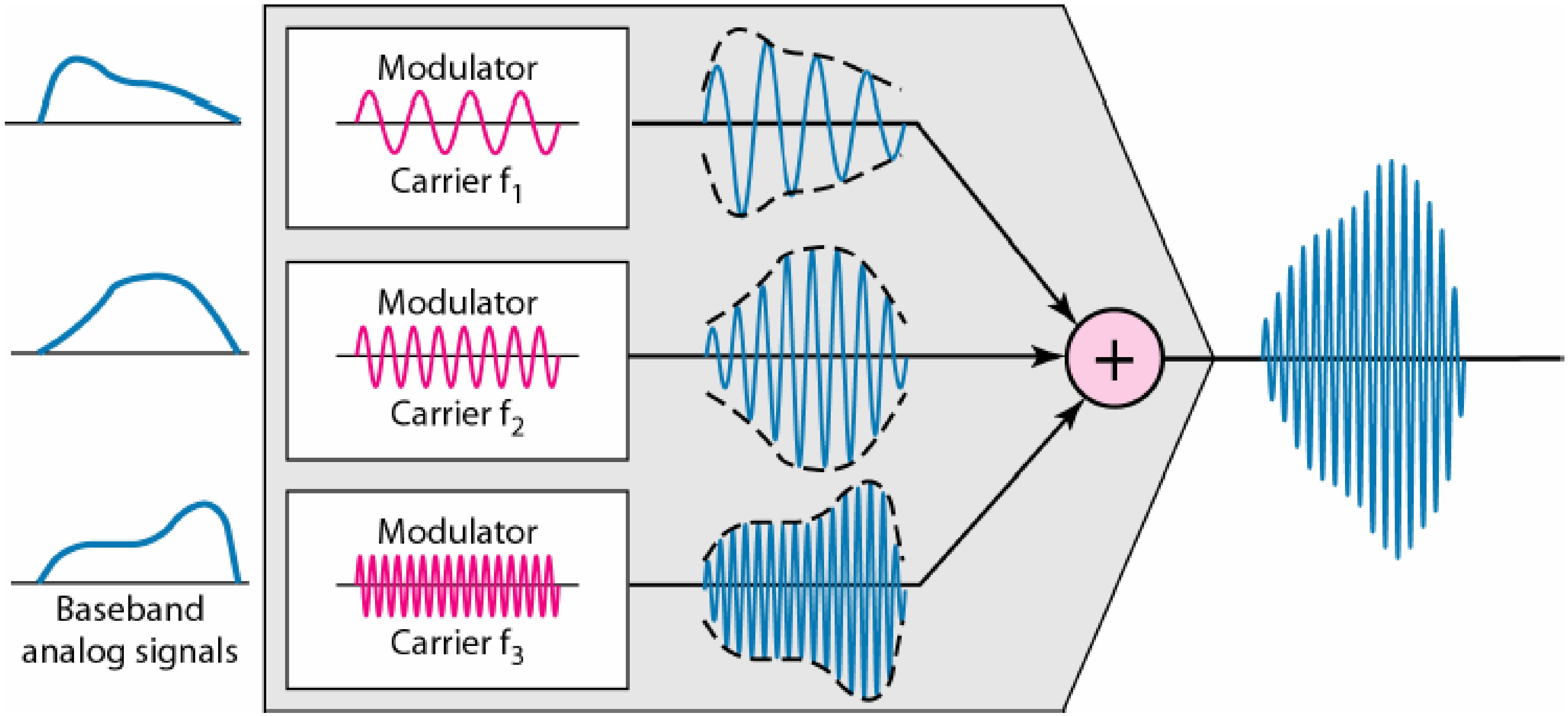
Frequency Division Multiplexing (FDM)

- FDM can be used when the BW of a link is greater than the combined BW of signals to be transmitted.
- Signals generated by each sending device modulate different carrier frequencies, which are then combined into a single composite signal
- **Guard bands** are used to prevent signals from overlapping

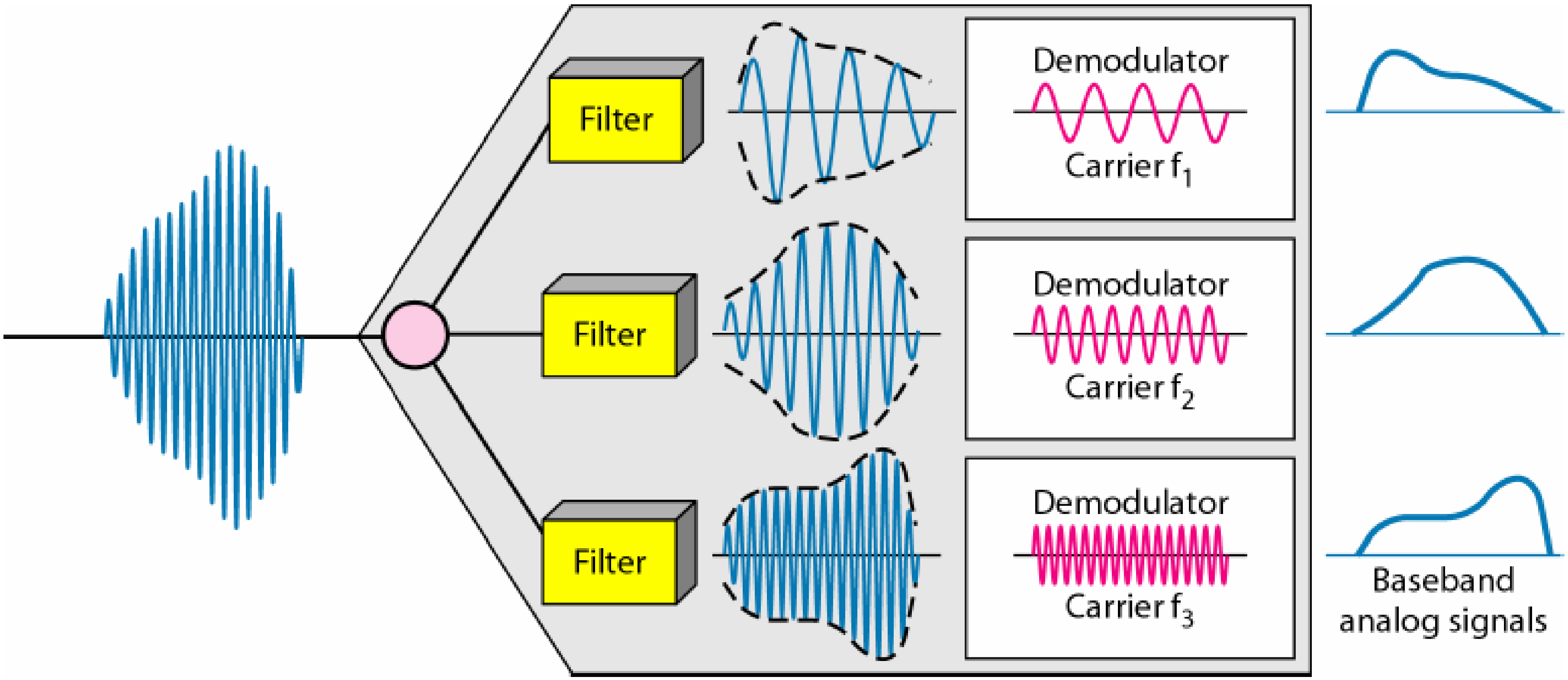
Note

FDM is an analog multiplexing technique that combines analog signals.

FDM multiplexing example



FDM demultiplexing example



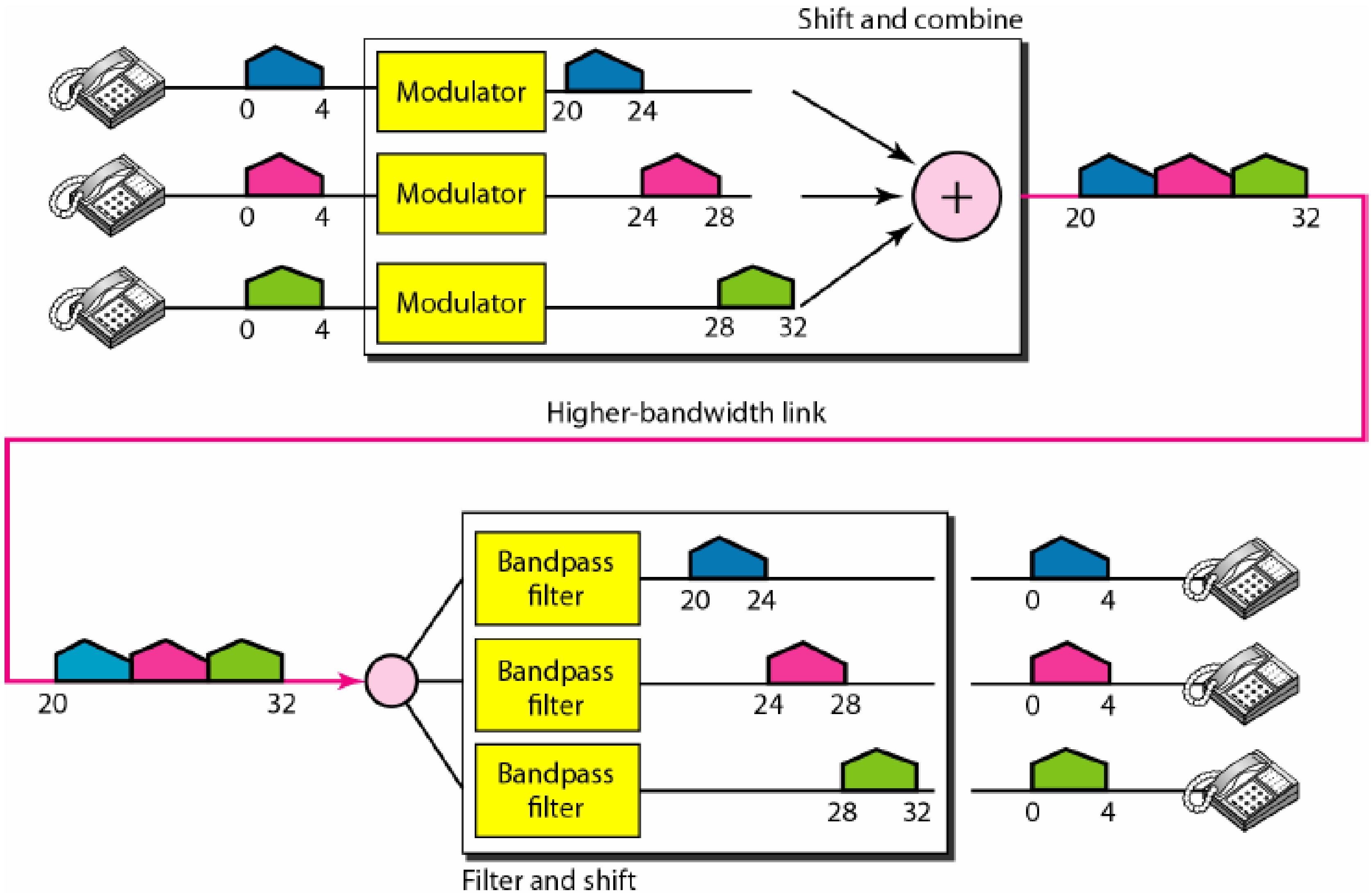
Example 1

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 in next slide. We use the 20-24 kHz bandwidth for the first channel, the 24-28 kHz bandwidth for the second channel, and the 28-32 kHz bandwidth for the third one. Then we combine them as shown in the figure.

Example 1



Shift and combine
Modulator
Modulator
Modulator
0
4
0
4
0
4
20
24
24
28
28
32
20
32
Higher-bandwidth link
20
32
Bandpass filter
Bandpass filter
Bandpass filter
20
24
24
28
28
32
0
4
0
4
0
4
Filter and shift

Example 2

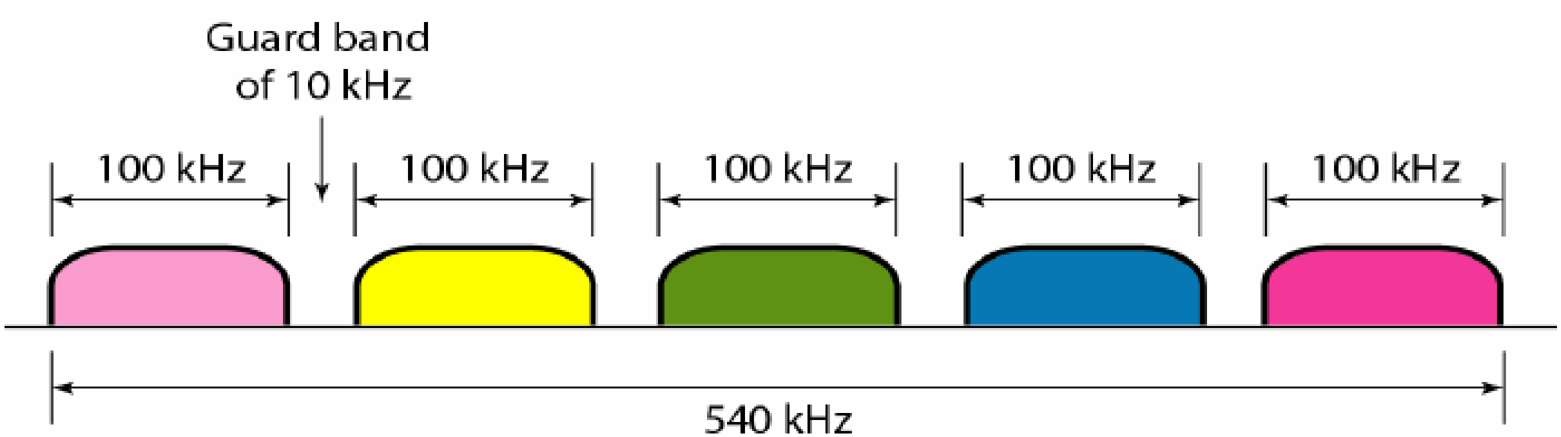
Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?

Solution

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

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

as shown in the figure below.

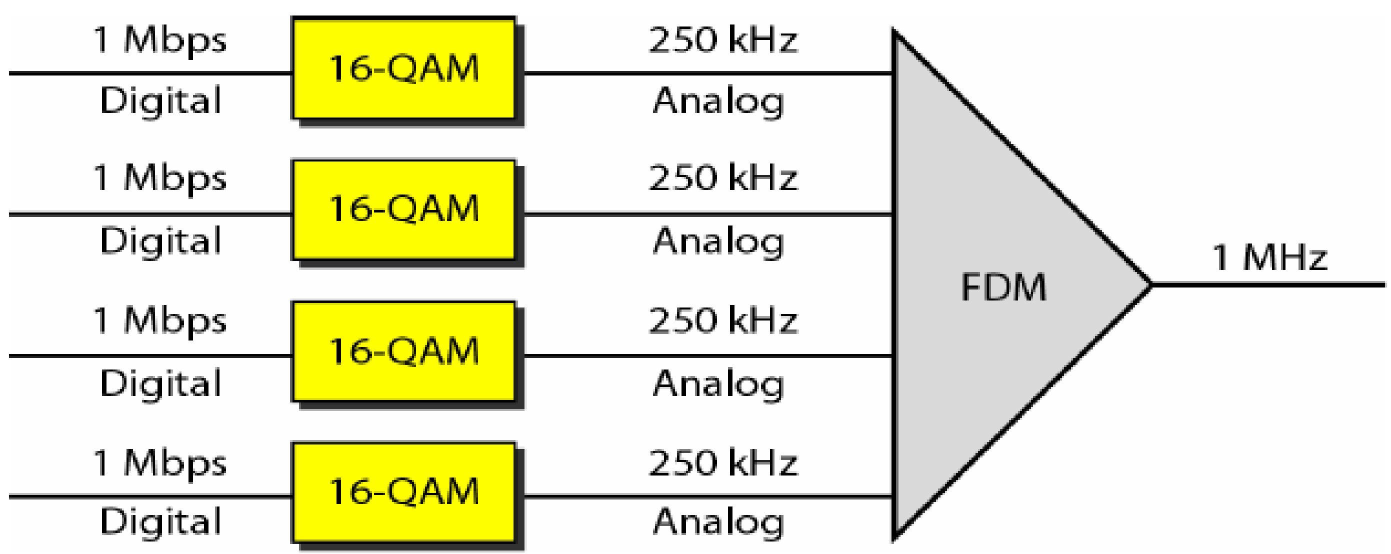


Example 3

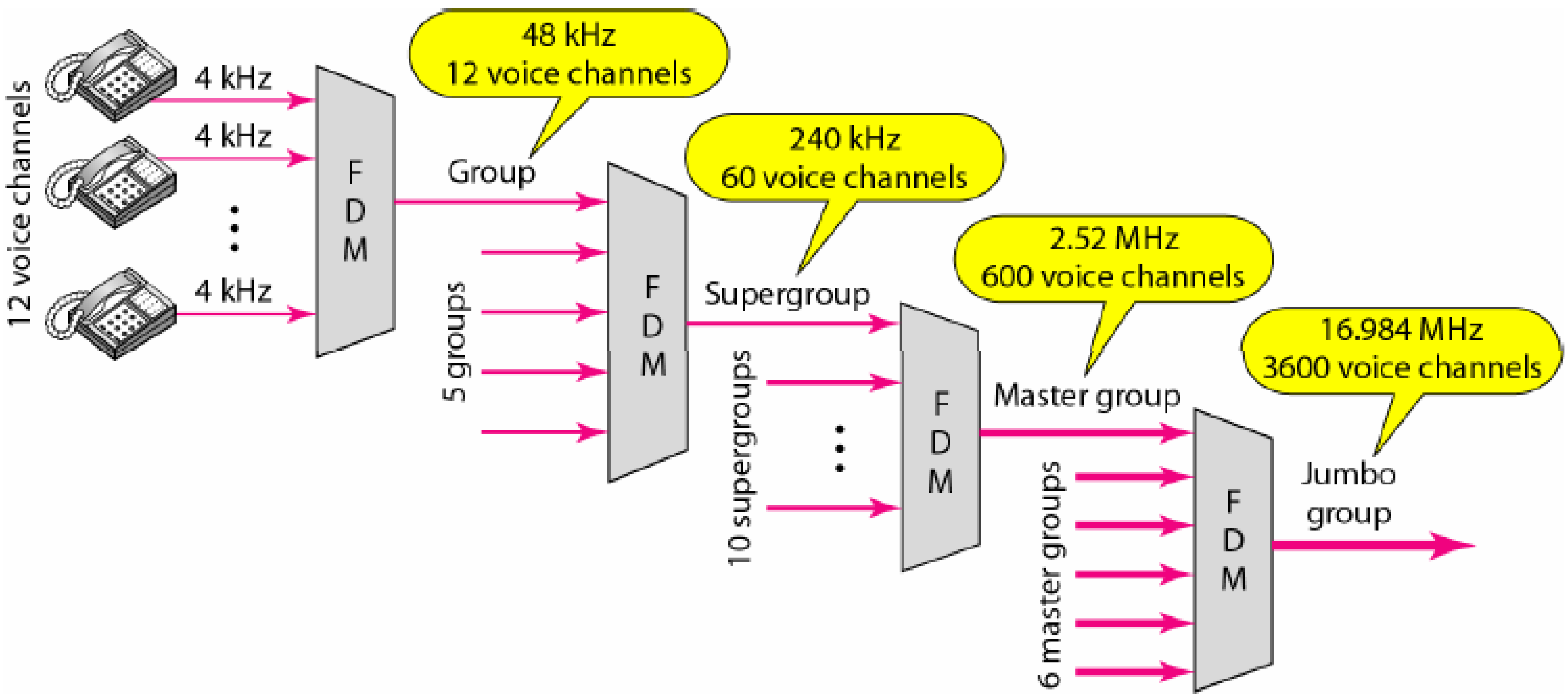
Four data channels (digital), each transmitting at 1 Mbps, use a satellite channel of 1 MHz. Design an appropriate configuration, using FDM.

Solution

The satellite channel is analog. We divide it into four channels, each channel having a 250-kHz bandwidth. Each digital channel of 1 Mbps is modulated such that each 4 bits is modulated to 1 Hz. One solution is 16-QAM modulation. Figure below shows one possible configuration.



Analog hierarchy



Example 4

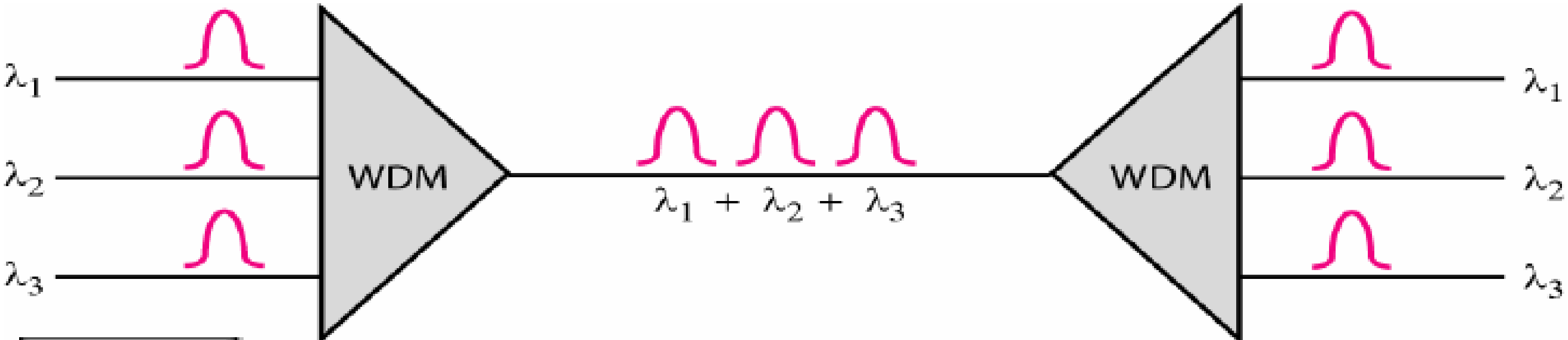
The Advanced Mobile Phone System (AMPS) uses two bands. The first band of 824 to 849 MHz is used for sending, and 869 to 894 MHz is used for receiving. Each user has a bandwidth of 30 kHz in each direction. How many people can use their cellular phones simultaneously?

Solution

Each band is 25 MHz. If we divide 25 MHz by 30 kHz, we get 833.33. In reality, the band is divided into 832 channels. Of these, 42 channels are used for control, which means only 832-42=790 channels are available for cellular phone users.

Wavelength Division Multiplexing (WDM)

• WDM is designed to use the high data rate capability of fiber optic cable.
• Using a fiber-optic cable for one single line wastes the available bandwidth. Multiplexing allows us to connect several lines into one.
• WDM is conceptually the same as FDM, except that the multiplexing and demultiplexing involve optical signals

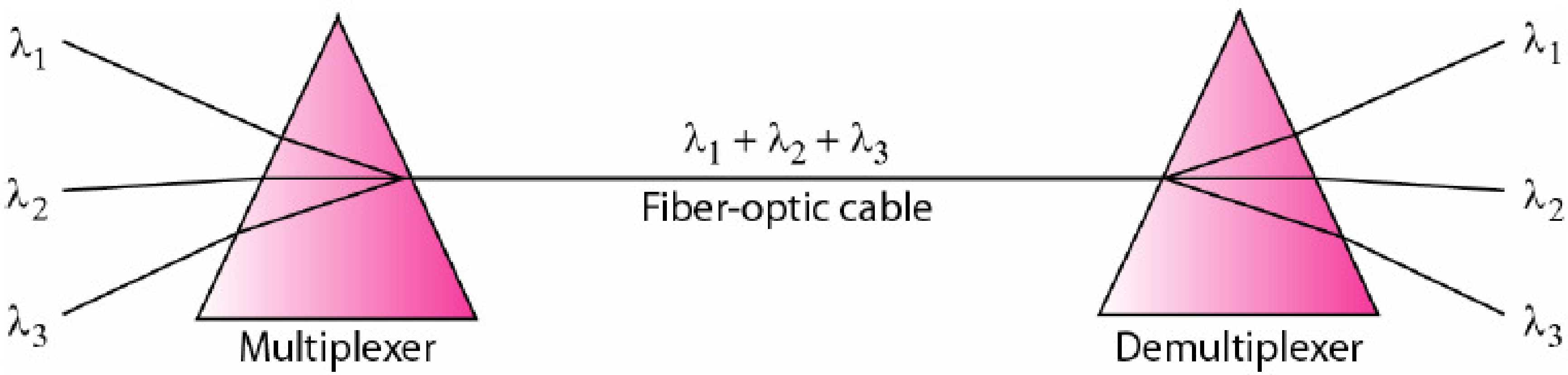


Note

WDM is an analog multiplexing technique to combine optical signals.

Prisms in wavelength-division multiplexing and demultiplexing

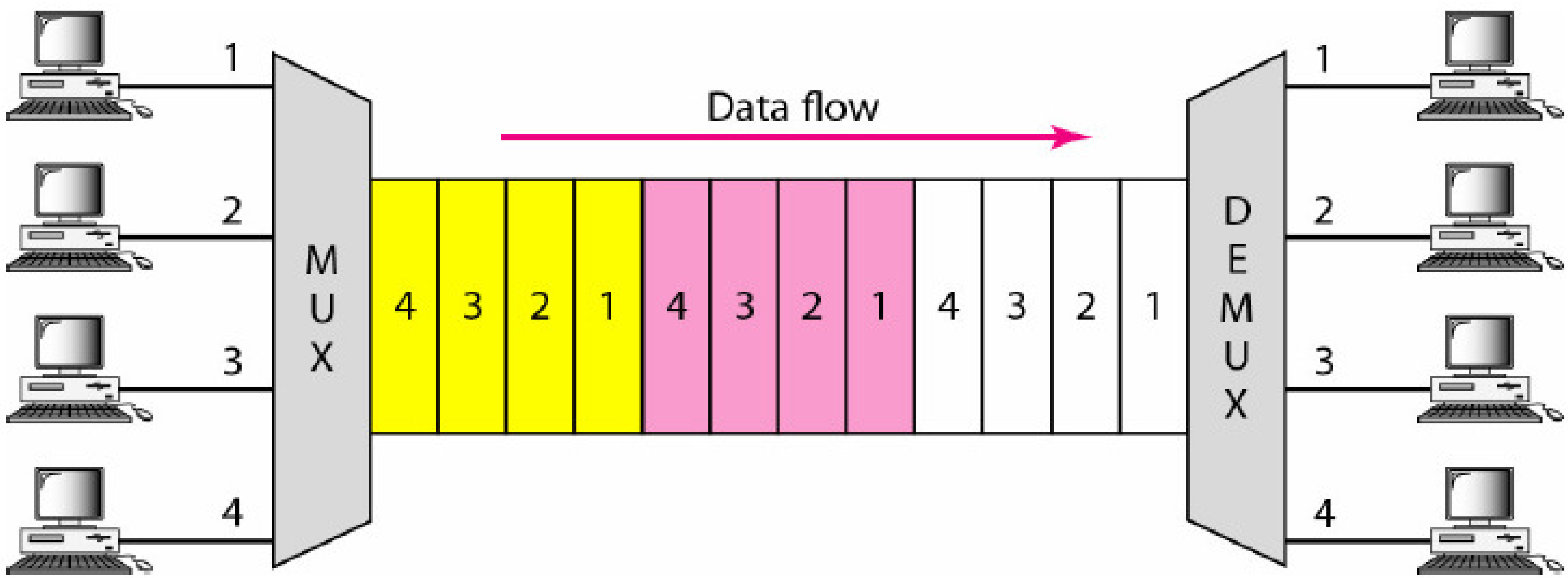
- Combining and splitting of light sources are easily handled by a prism
  - A prism bends a beam of light based on the angle of incidence and the frequency
  - Using this technique, a MUX can be made to combine several input beams of light, each containing a narrow band of frequencies, into one beam of wider band of frequencies
  - A DEMUX can be made to reverse the process



Time Division Multiplexing (TDM)

TDM is a digital multiplexing technique for combining several low-rate channels into one high-rate one.

- **It is a digital process that can be applied when the data rate capacity of the transmission medium is greater than the data rate required by the sending and receiving device.**



Synchronous Time Division Multiplexing

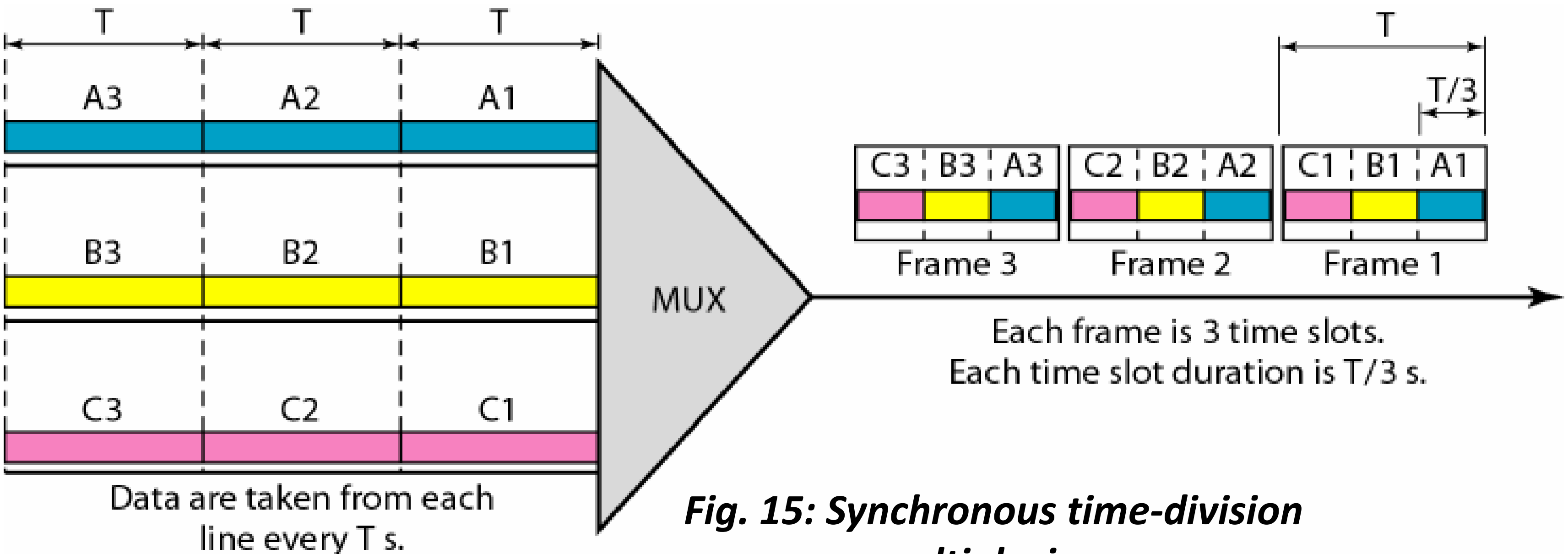


Fig. 15: Synchronous time-division multiplexing.

- In **synchronous TDM,** 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*** **time slots** and **one slot** is allocated for **each unit,** one for each **input line.**
- If the duration of the input unit is ***T,*** the duration of each slot is T_{in} **= *T/3*** and the duration of each frame is ***T.***

Example 5

In ***Figure 15,*** the **data rate** for each one of the ***3* input** connection is ***1 kbps.*** If ***1 bit*** at a time is multiplexed (a unit is 1 bit), what is **the duration** of **(a) each input slot, (b) each output slot, and (c) each frame?**

- **Solution:**

a. **The data rate** of each input connection is ***1 kbps.*** This means that the **bit duration** is ***1/1000 s*** or ***1 ms.*** The **duration** of the input time slot is ***1 ms*** (same as bit duration).

b. The **duration** of each **output** time slot is ***one-third*** of the input time slot. This means that the duration of the output time slot is ***1/3 ms.***

c. **Each frame** carries **three output** time slots. So the duration of a frame is $3 \times 1/3$ ***ms,*** or ***1 ms.***

Note: The **duration** of a **frame** is the same as the **duration** of an **input** unit.

Example 6

Figure 16 shows **synchronous TDM** with **four *1Mbps*** data stream inputs and one data stream for the output. The unit of data is ***1 bit.*** Find ***(a) the input bit duration, (b) the output bit duration, (c) the output bit rate, and (d) the output frame rate.***

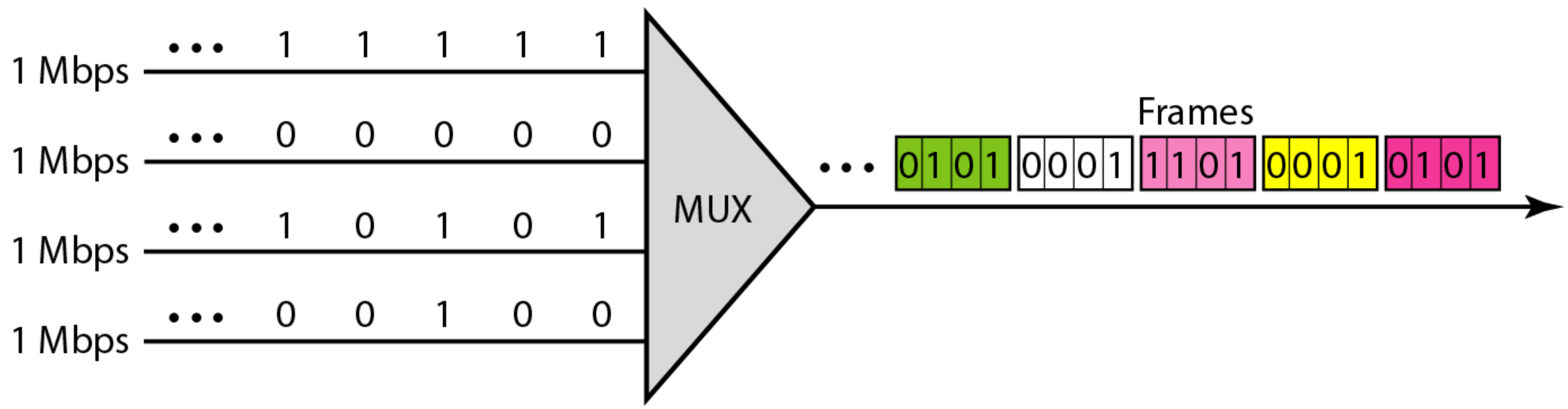


Fig. 16: Example 6

- **Solution:**

a. The **input bit duration** is the **inverse** of the bit rate: ***1/1 Mbps = 1 μs.***

b. The **output bit duration** is ***one-fourth*** of the input bit duration, or ***1/4 μs.***

c. The **output bit rate** is the **inverse** of the **output bit duration** or ***1/(4μs) or 4 Mbps.*** This can also be deduced from the fact that the output rate is ***4 times*** as fast as any input rate; so the **output rate = *4 × 1 Mbps = 4 Mbps.***

d. The **frame rate** is always the **same** as any **input rate.** So the **frame rate** is ***1,000,000 frames per second.*** Because we are sending ***4 bits*** in each frame, we can verify the result of the previous question by **multiplying** the **frame rate** by the **number of bits per frame.**

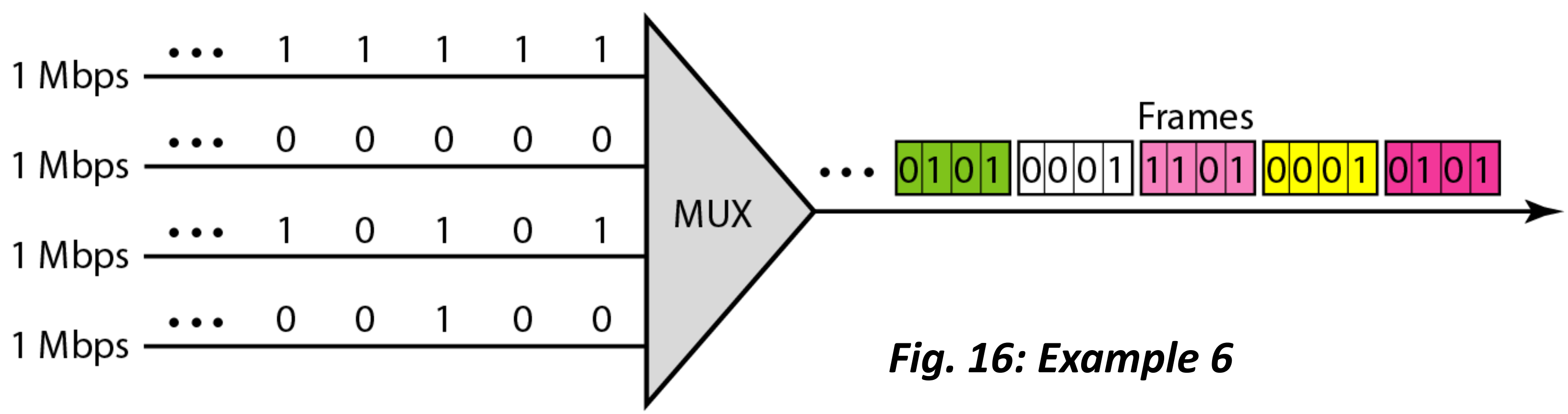


Fig. 16: Example 6

Example 7

Four 1-kbps connections are multiplexed together. A unit is 1 bit. Find (a) the duration of 1 bit before multiplexing, (b) the transmission rate of the link, (c) the duration of a time slot, and (d) the duration of a frame.

Solution

a. The duration of 1 bit before multiplexing is 1 / 1 kbps, or 0.001 s (1 ms).

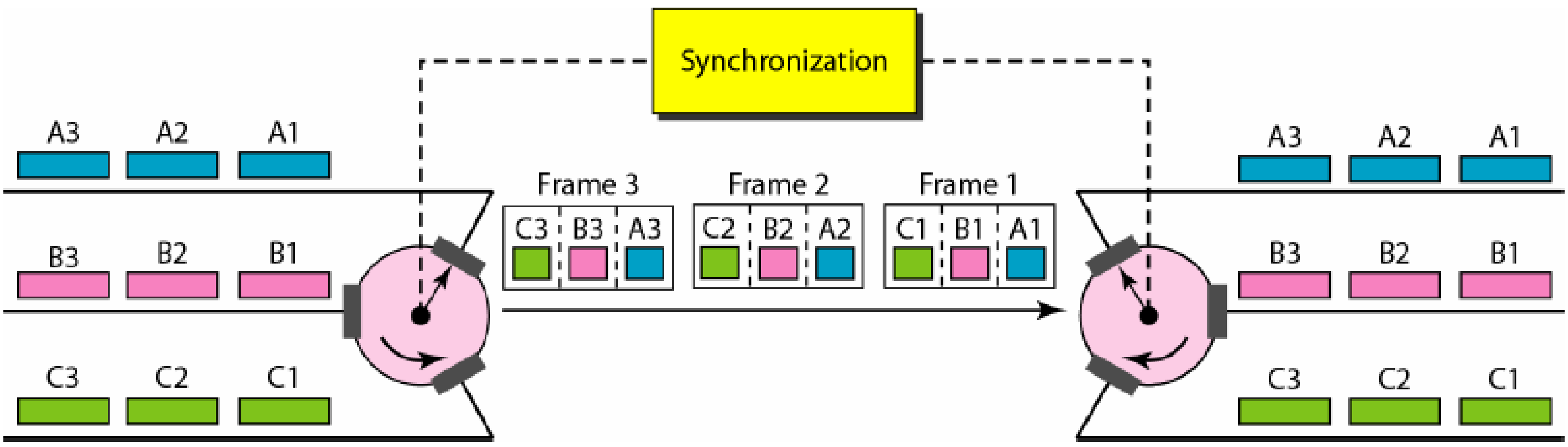
b. The rate of the link is 4 times the rate of a connection, or 4 kbps.

c. The duration of each time slot is one-fourth of the duration of each bit before multiplexing, or 1/4 ms or 250 μs. Note that we can also calculate this from the data rate of the link, 4 kbps. The bit duration is the inverse of the data rate, or 1/4 kbps or 250 μs.

d. The duration of a frame is always the same as the duration of a unit before multiplexing, or 1 ms. We can also calculate this in another way. Each frame in this case has four time slots. So the duration of a frame is 4 times 250 μs, or 1 ms.

Interleaving

• TDM can be visualized as two fast rotating switches, one on the MUX side and the other on the DEMUX side. The switches are synchronized and rotate at the same speed but in opposite directions. On the MUX side, as the switch opens in front of a connection, that connection has the opportunity to send a unit onto the path. This process is called **inteleaving**.

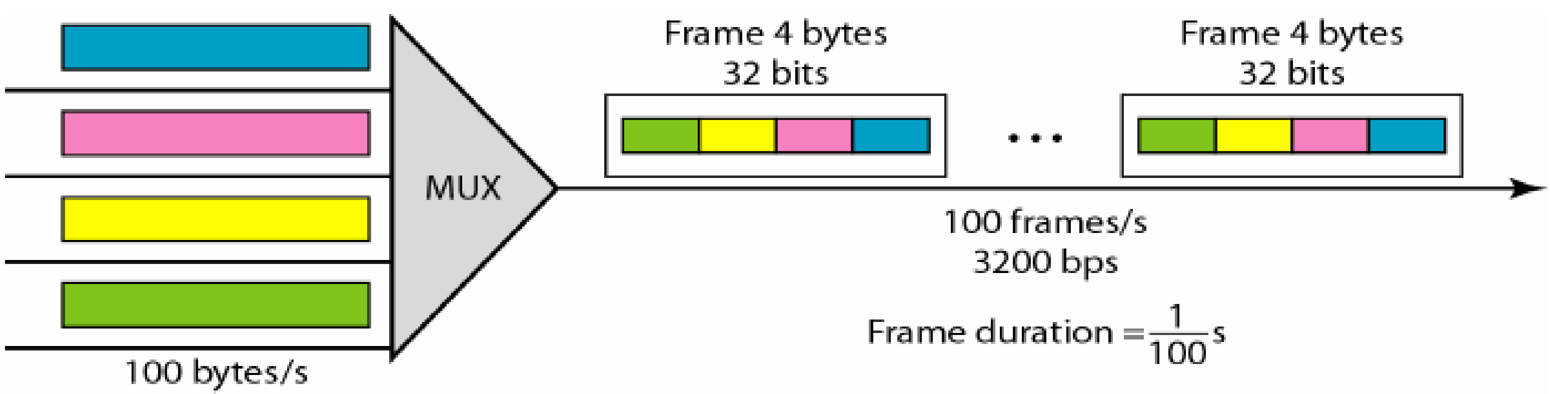


Example 8

Four channels are multiplexed using TDM. If each channel sends 100 bytes /s and we multiplex 1 byte per channel, show the frame traveling on the link, the size of the frame, the duration of a frame, the frame rate, and the bit rate for the link.

Solution

The multiplexer is shown below. Each frame carries 1 byte from each channel; the size of each frame, therefore, is 4 bytes, or 32 bits. Because each channel is sending 100 bytes/s and a frame carries 1 byte from each channel, the frame rate must be 100 frames per second. The bit rate is 100 × 32, or 3200 bps.

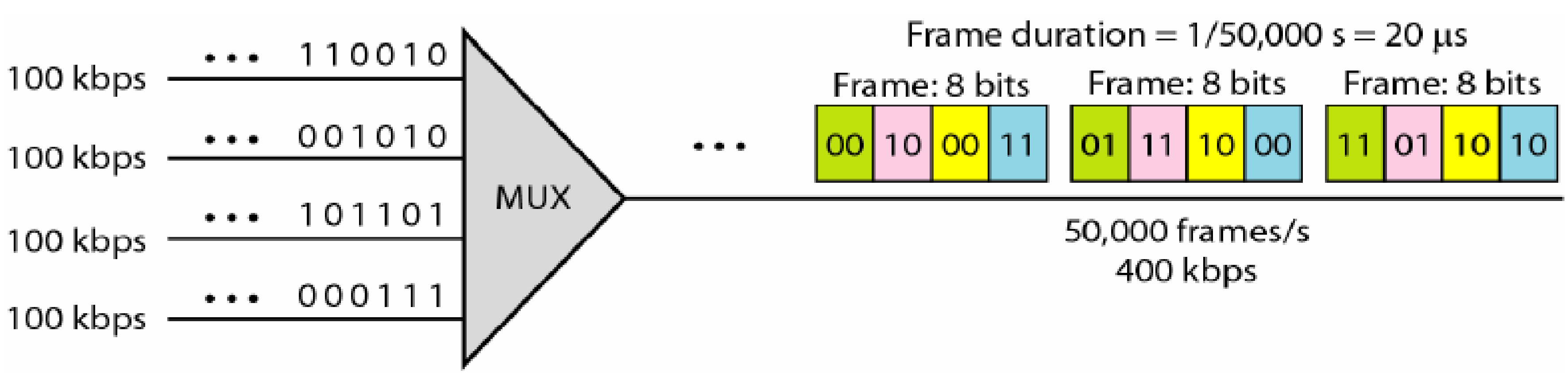


Example 9

A multiplexer combines four 100-kbps channels using a time slot of 2 bits. Show the output with four arbitrary inputs. What is the frame rate? What is the frame duration? What is the bit rate? What is the bit duration?

Solution

Figure below shows the output for four arbitrary inputs. The link carries 50,000 frames per second. The frame duration is therefore 1/50,000 s or 20 μs. The frame rate is 50,000 frames per second, and each frame carries 8 bits; the bit rate is 50,000 × 8 = 400,000 bits or 400 kbps. The bit duration is 1/400,000 s, or 2.5 μs.



Empty Slots

- Sometimes an input link may **have no data to transmit.**
- When that happens, **one or more slots** on the output link will go **unused.**
- That is **wastage** of **bandwidth.**
- **Statistical TDM** can improve the efficiency.

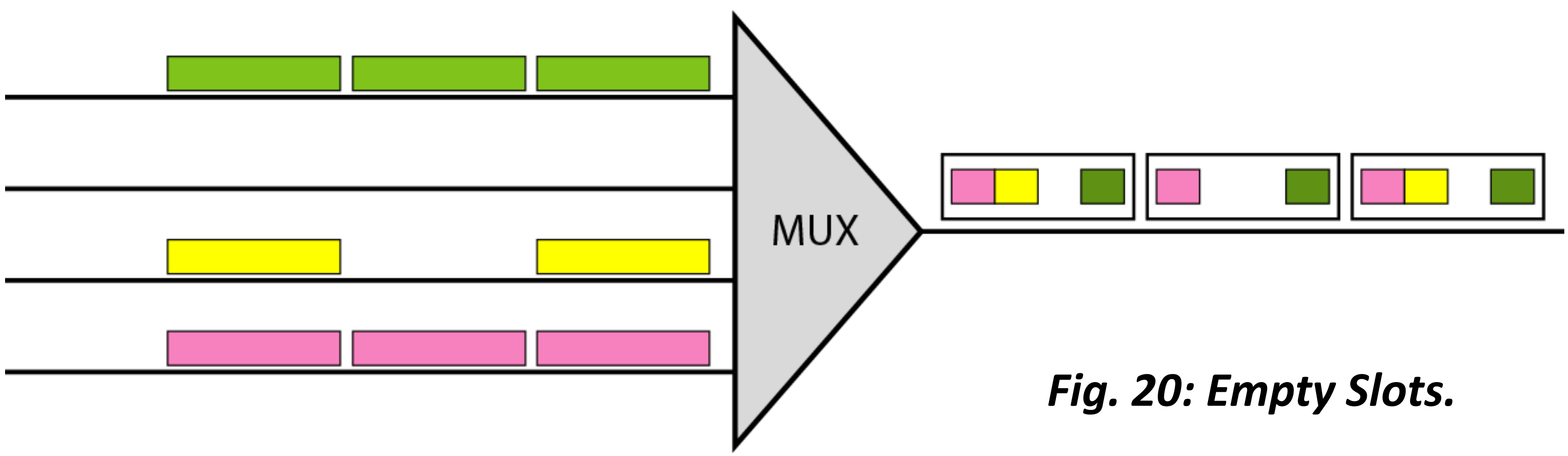


Fig. 20: Empty Slots.

Data rate management:

- **Not all input links** maybe have the **same data rate.**
- Some links maybe **slower.** There maybe several different input link speeds.
- There are **three strategies** that can be used to overcome the data rate mismatch: ***multilevel, multislot and pulse stuffing.***

Data rate matching:

- **Multilevel:** used when the **data rate of the input links** are **multiples** of each other.
- **Multislot:** used when there is a **GCD(Greatest Common Divisor)** between the data rates. The **higher bit rate channels** are **allocated** more slots per frame, and the **output frame rate** is a multiple of each input link.

- **Pulse Stuffing:** used when there is **no GCD between the links.** The **slowest** speed link will be **brought up to the speed** of the other links by **bit insertion,** this is called **pulse stuffing.**

Data rate management:

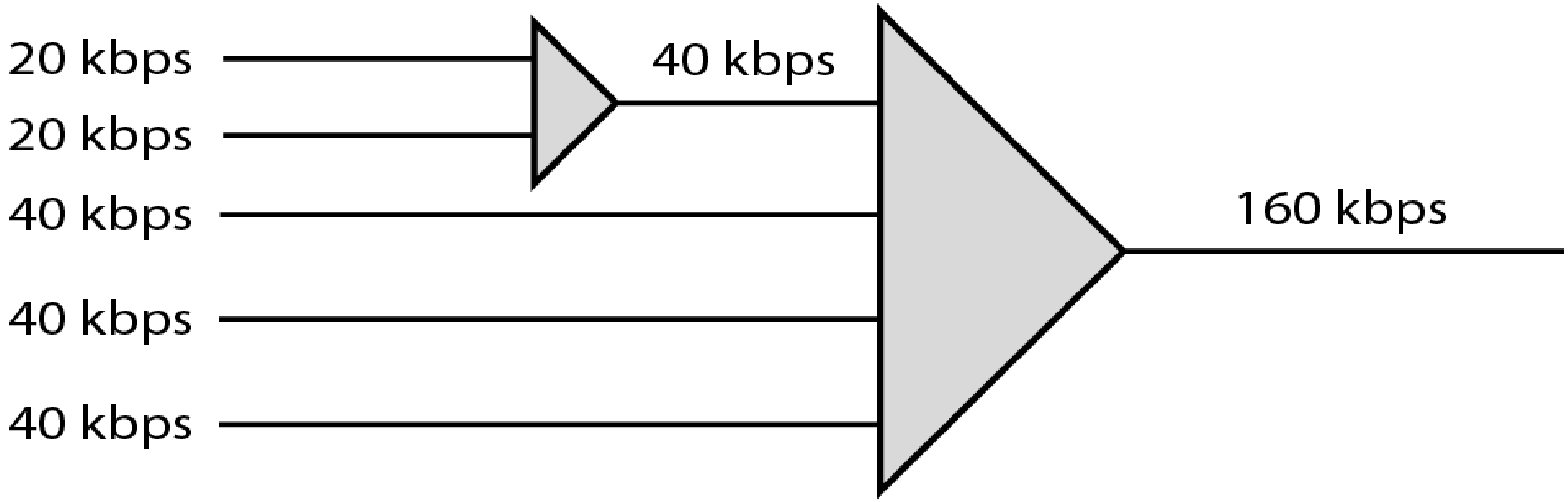


Fig. 21: Multilevel Multiplexing.

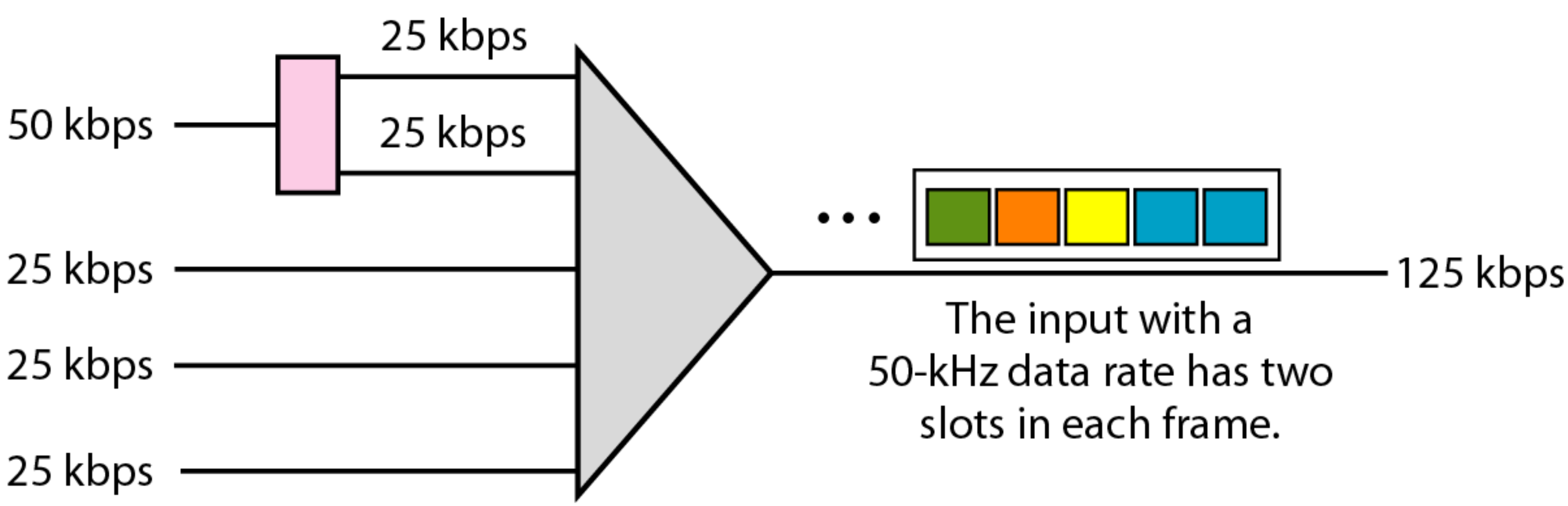


Fig. 22: Multislot Multiplexing.

Data rate management:

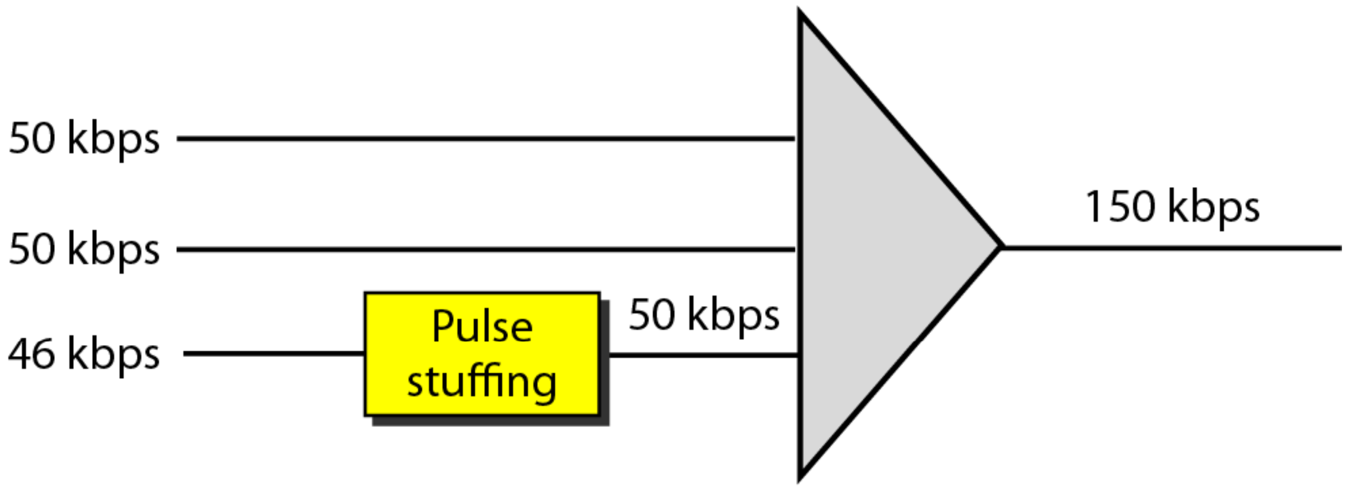


Fig. 23: Pulse Stuffing Multiplexing.

Frame Synchronization:

- **Synchronization** between the **multiplexer** and **demultiplexer** is a major issue.
- If the **multiplexer** and the **demultiplexer** are **not synchronized, a bit belonging to one channel** may be **received** by **the wrong channel.**
- For this reason, **one or more synchronization bits** are usually **added** to the **beginning** of each frame.
- These bits, called **framing bits,** follow a **pattern,** frame to frame, that **allows** the **demultiplexer to synchronize** with the **incoming stream** so that it can **separate** the time slots **accurately.**
- In most cases, this synchronization information consists of ***1 bit* per frame,** alternating between ***0*** and ***1***, as shown in ***Figure 24.***

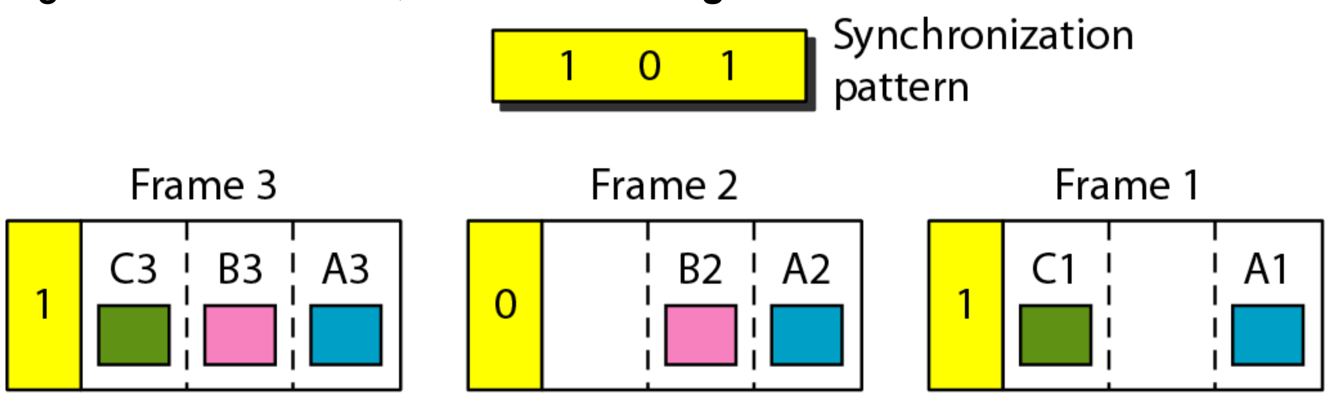


Fig. 24: Multislot Multiplexing.

Example 10

We have **four sources,** each creating **250** ***8-bit*** characters per second. If the **interleaved** unit is a **character** and ***1*** **synchronizing bit** is **added** to each frame, find **(a) the data rate of each source, (b) the duration of each character in each source, (c) the frame rate, (d) the duration of each frame, (e) the number of bits in each frame, and (f) the data rate of the link.**

Solution:

a. The **data rate** of each source is ***250 × 8 = 2000 bps = 2 kbps.***

b. Each source sends ***250 characters per second;*** therefore, the **duration** of a character is ***1/250 s, or 4 ms.***

c. Each **frame** has **one character** from each source, which means the link needs to send ***250 frames per second*** to keep the transmission rate of each source.

d. The **duration** of each frame is ***1/250 s, or 4 ms.*** Note that the **duration** of each frame is the **same** as the duration of **each character** coming from each source.

e. Each frame **carries** ***4 characters*** and ***1 extra synchronizing bit.*** This means that each frame is ***4 × 8 + 1 = 33 bits.***

f. Each frame carries 33 bits and there are ***250 Frames/second*** at the output of the multiplexer. So the data rate of the link is: ***250x33 = 8250 bits/second***.

Example 11

Two channels, one with a **bit rate** of ***100 kbps*** and another with a ***bit rate*** of ***200 kbps,*** are to be multiplexed. **How this can be achieved? What is the frame rate? What is the frame duration? What is the bit rate of the link?**

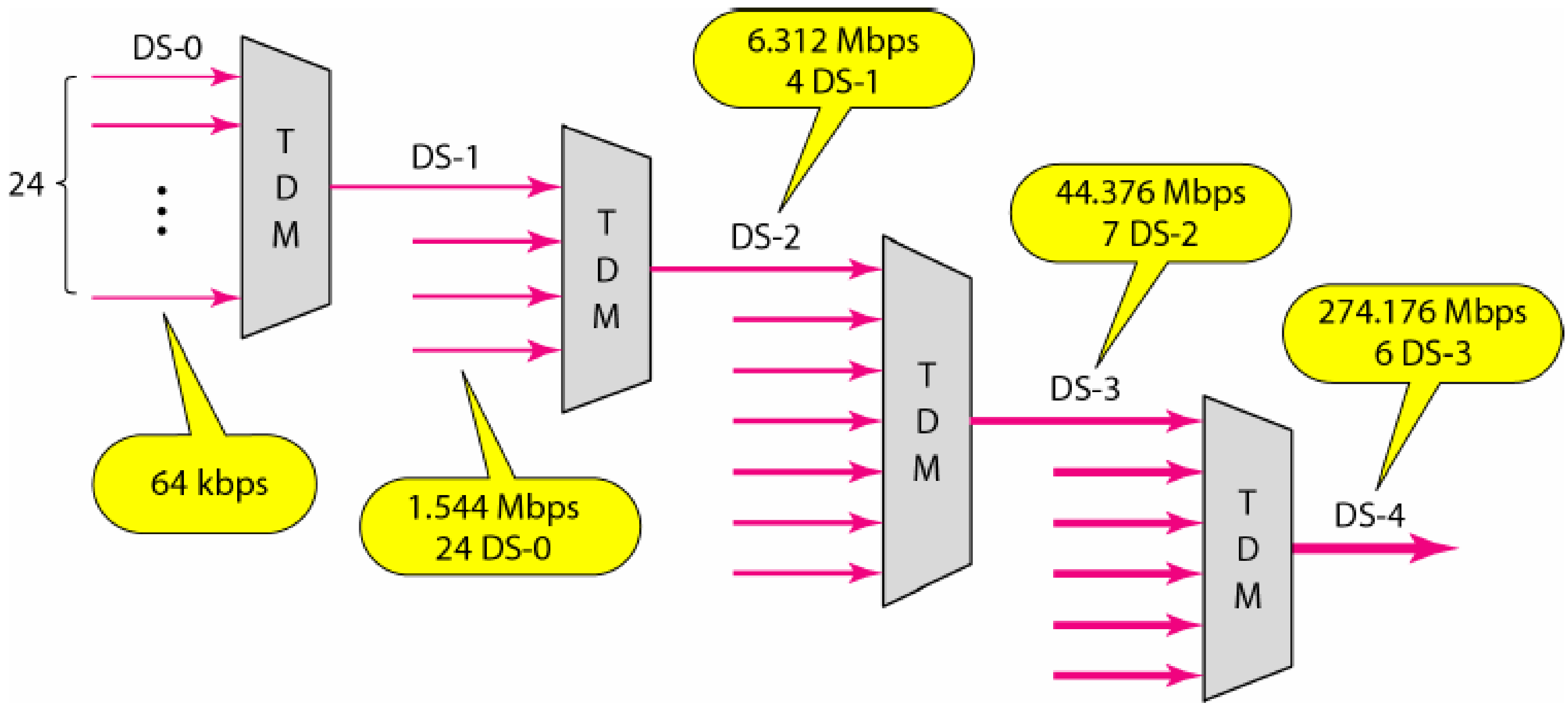
- **Solution:**

We can **allocate** one slot to the **first channel** and **two slots** to the **second channel.** Each frame carries ***3 bits.*** The **frame rate** is ***100,000 frames per second*** because it carries ***1 bit*** from the first channel. The ***bit rate*** is ***100,000 frames/s × 3 bits per frame, or 300 kbps.***

Digital hierarchy

Telephone companies implement TDM through a hierarchy of digital signals, called **Digital Signal** (DS) Service.

The following figure shows the data rates supported by each level:



Digital Hierarchy

- **T Lines:**

  DS-0, DS-1, and so on are the ***names of services.*** To implement those services, the telephone companies use ***T lines (T-1 to T-4).*** These are lines with capacities precisely matched to the data rates of the ***DS-1* to *DS-4*** services (see ***Table 1***). So far only ***T-1 and T-3*** lines are commercially available.

Service	*Line*	*Rate (Mbps)*	*Voice Channels*
DS-1	T-1	1.544	24
DS-2	T-2	6.312	96
DS-3	T-3	44.736	672
DS-4	T-4	274.176	4032

Table 1

Digital Hierarchy

- **T Lines for Analog Transmission:**

  T lines are digital lines designed for the transmission of digital data, audio, or video. However, they also can be **used** for **analog transmission (regular telephone connections),** provided the **analog signals** are first **sampled,** then **time-division multiplexed.**

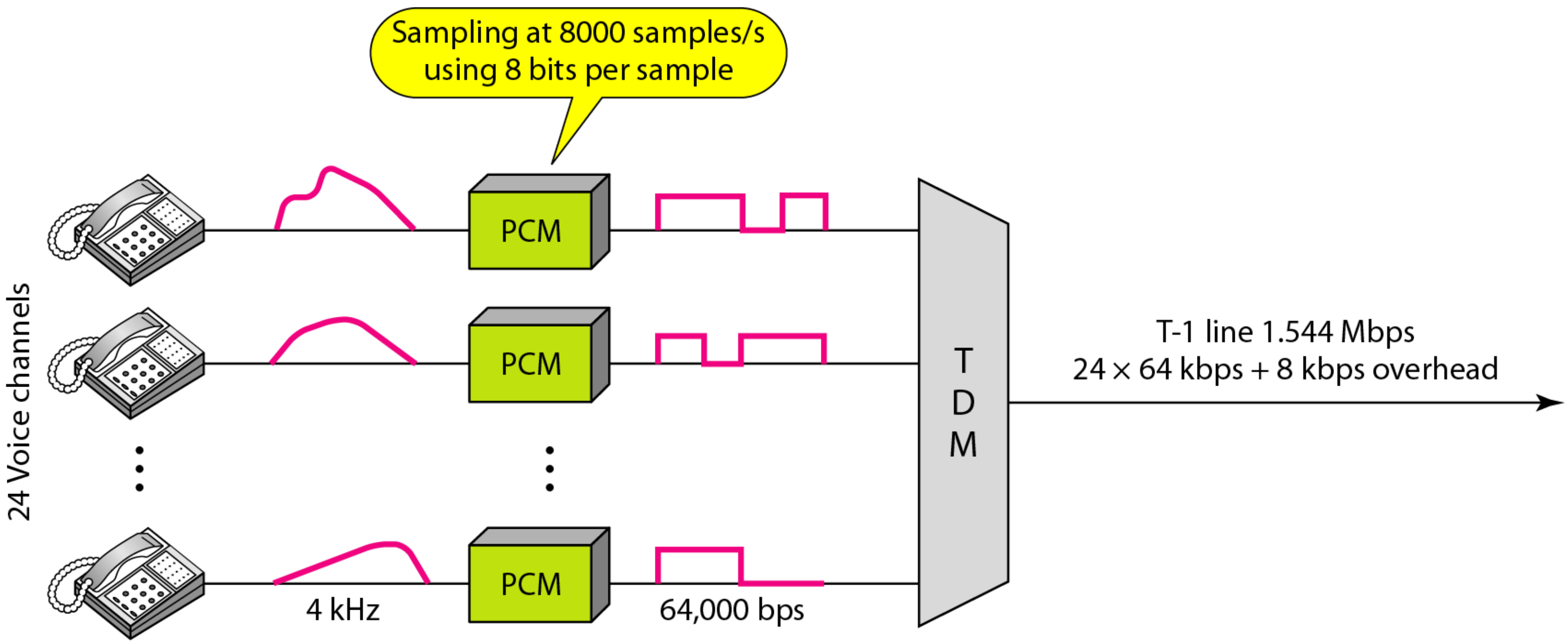


Fig. 26: T-1 line for multiplexing telephone lines.

T-1 frame structure

- **T-1 frame structure:**

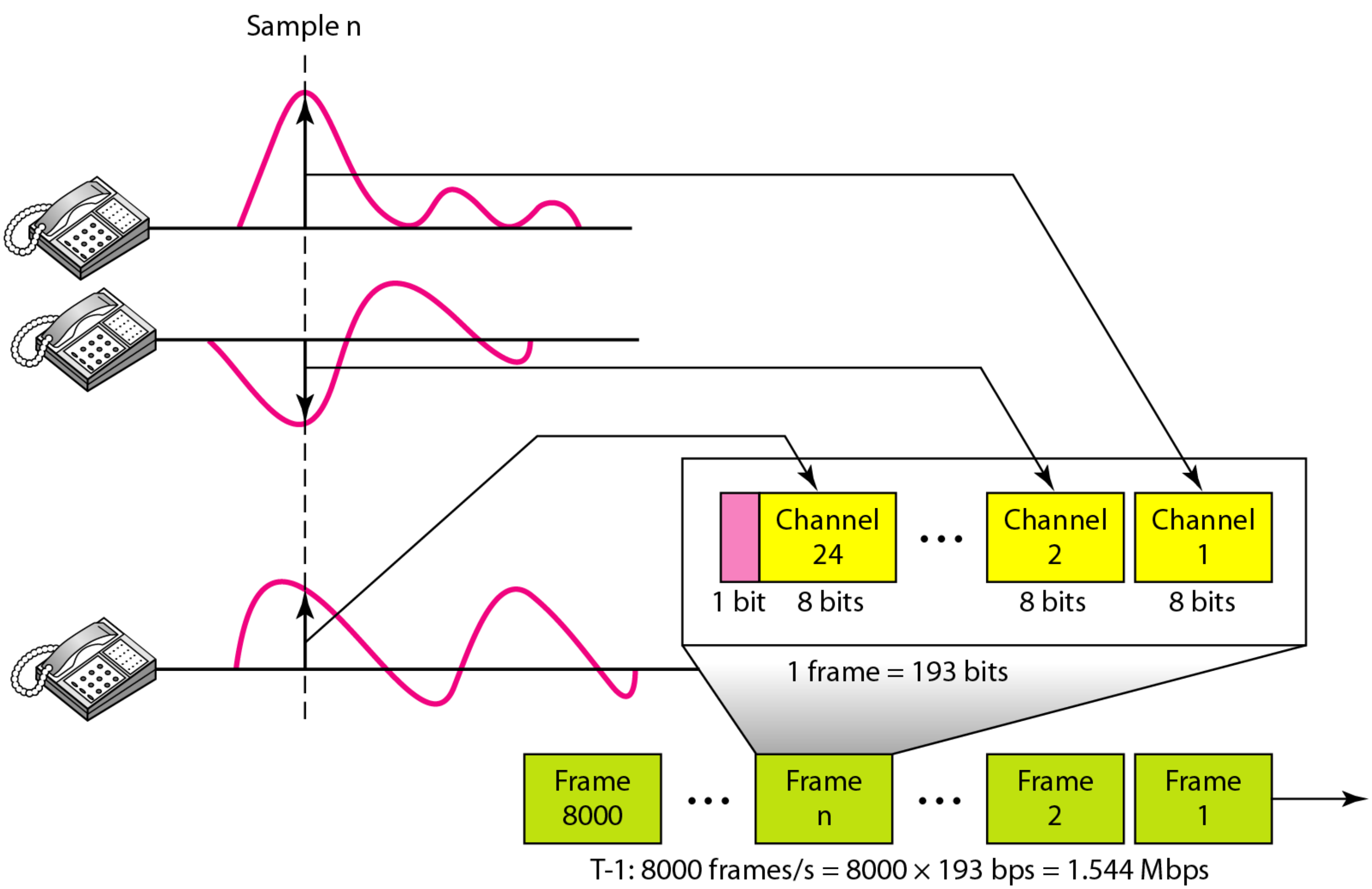


Fig. 27: T-1 Frame Structure.

E line rates

- **E line rates:**

  Europeans use a version of T lines called E lines. The two systems are conceptually identical, but their capacities differ.

Line	*Rate (Mbps)*	*Voice Channels*
E-1	2.048	32
E-2	8.448	128
E-3	34.368	512
E-4	139.264	2048

Table 2

Systems Comparison

T-carrier and E-carrier systems comparison

T-carrier and E-carrier systems	North American	Japanese	European (CEPT)
Level zero (channel data rate)	64 kbit/s (DS0)	64 kbit/s	64 kbit/s
First level	1.544 Mbit/s (DS1) (24 user channels) (T1)	1.544 Mbit/s (24 user channels)	2.048 Mbit/s (32 user channels) (E1)
(Intermediate level, T-carrier hierarchy only)	3.152 Mbit/s (DS1C) (48 Ch.)	–	–
Second level	6.312 Mbit/s (DS2) (96 Ch.) (T2)	6.312 Mbit/s (96 Ch.), or 7.786 Mbit/s (120 Ch.)	8.448 Mbit/s (128 Ch.) (E2)
Third level	44.736 Mbit/s (DS3) (672 Ch.) (T3)	32.064 Mbit/s (480 Ch.)	34.368 Mbit/s (512 Ch.) (E3)
Fourth level	274.176 Mbit/s (DS4) (4032 Ch.)	97.728 Mbit/s (1440 Ch.)	139.264 Mbit/s (2048 Ch.) (E4)
Fifth level	400.352 Mbit/s (DS5) (5760 Ch.)	565.148 Mbit/s (8192 Ch.)	565.148 Mbit/s (8192 Ch.) (E5)

Statistical Time-Division Multiplexing :

In **synchronous TDM,** each input has a **reserved** slot in the **output frame.** This can be **inefficient** if **some input lines** have **no data** to send.

In **statistical time-division multiplexing,**

Slots are **dynamically** allocated to improve **bandwidth efficiency.** Only when an input line has a slot's worth of data to send, then it is given a slot in the output frame.

In **statistical multiplexing,**

The **number of slots** in each frame is **less** than the **number of input lines.**

1. The **multiplexer checks** each input line in **round robin fashion;**
2. it **allocates** a slot for an input line if the **line has data to send;** otherwise,
3. it **skips** the **line** and **checks** the **next line.**

Statistical TDM: Addressing

- **Addressing:** In **statistical TDM,** a slot **needs** to carry **data as well as** the **address** of the **destination.**

- We **need** to **include** the **address** of the receiver **inside** each slot to show **where** it is to be **delivered.**

- In **statistical multiplexing,** there is **no fixed relationship** between the inputs and outputs because there are **no pre-assigned or reserved slots.**

- In **synchronous TDM,** there is **no need** for **addressing;** synchronization and pre assigned relationships between the inputs and outputs serve as an address. If the multiplexer and the demultiplexer are synchronized, this is guaranteed.

Synchronous VS Statistical TDM

Figure 28 also shows a major **difference** between slots in **synchronous TDM** and **statistical TDM.**

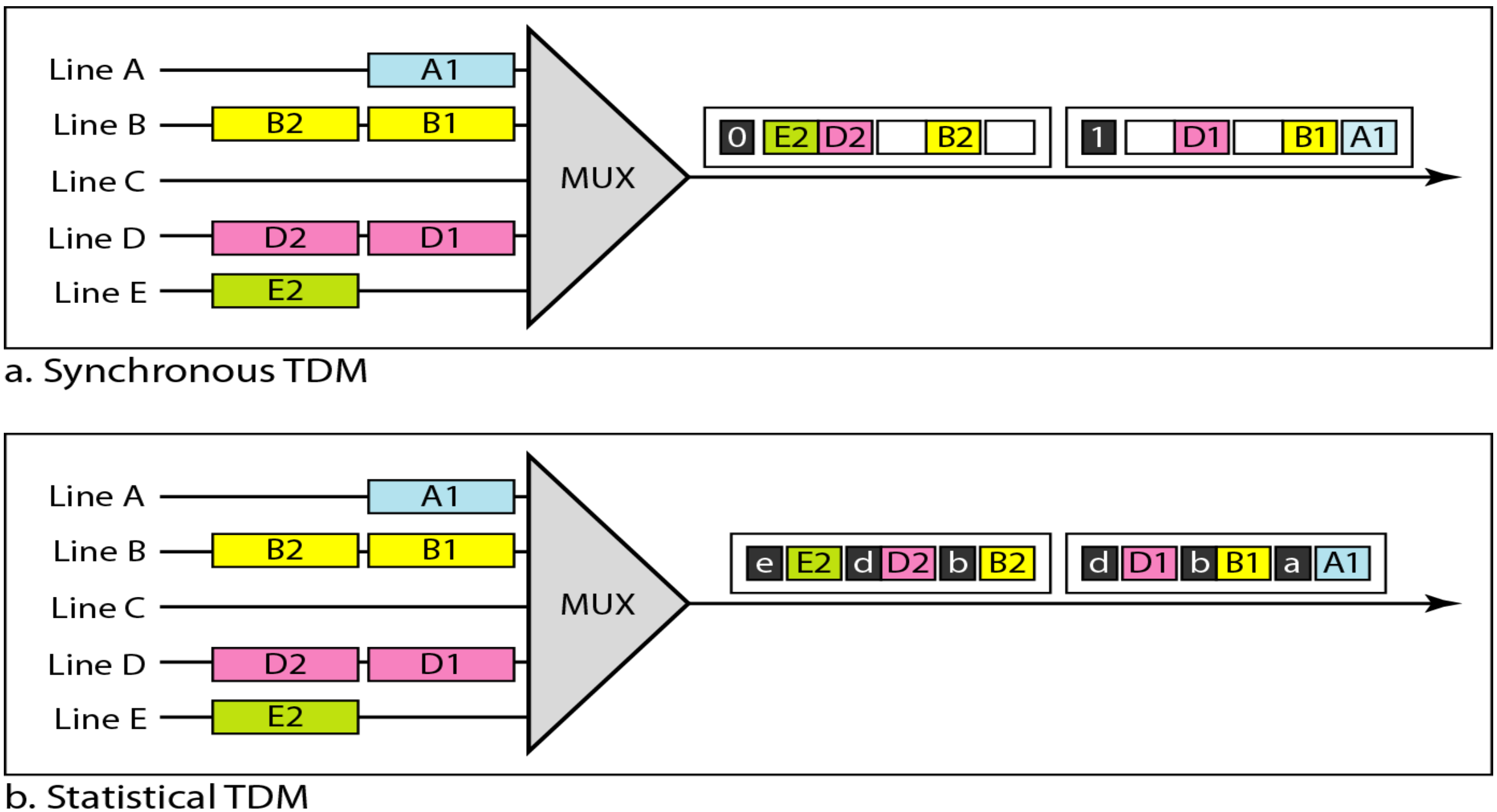


Fig. 28: TDM slot comparison.

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