Chapter 6: Multiplexing

Outline

6.1 MULTIPLEXING

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As data and telecommunications use increases, so does traffic. We can accommodate this increase by

a) adding individual links each time a new channel is needed, or

b) installing higher-bandwidth links and use them to carry multiple signals.

General idea: when the link bandwidth of a medium linking two devices is greater than the bandwidth requirements of the devices, the link can be shared.

Figure 6.1: Dividing a link into channels

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

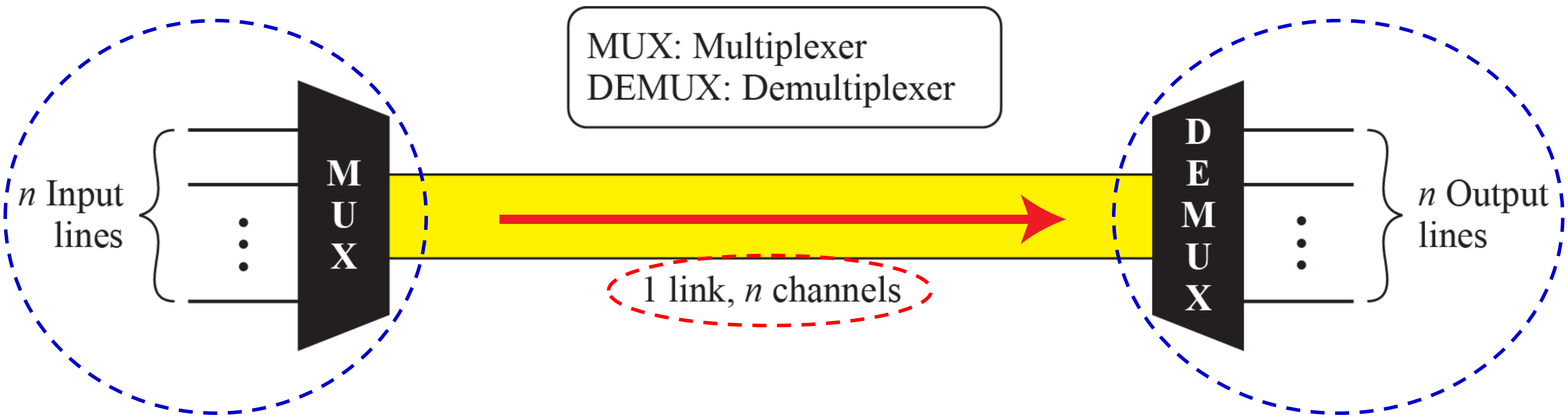
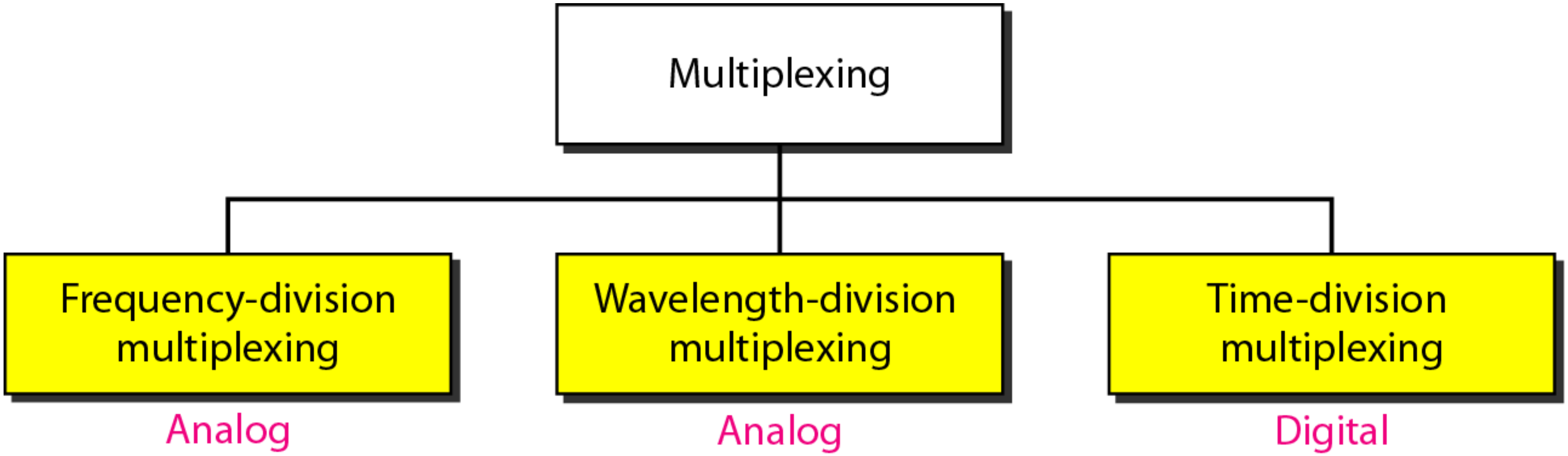


Figure 6.2: *Categories of multiplexing*



6.1.1 Frequency-Division Multiplexing

Frequency-division multiplexing (FDM) is an <u>analog multiplexing technique</u> that can be applied when the <u>bandwidth of a link</u> is <u>greater</u> than the <u>combined bandwidths of the signals</u> to be transmitted.

In FDM, <u>signals generated by each sending device</u> are <u>modulated</u> to <u>different carrier frequencies</u>. The carrier frequencies are <u>separated</u> by sufficient bandwidth (also known as <u>guard bands</u>) to <u>prevent signals from overlapping</u>. It is important that the carrier frequencies <u>do not interfere</u> with the original frequencies.

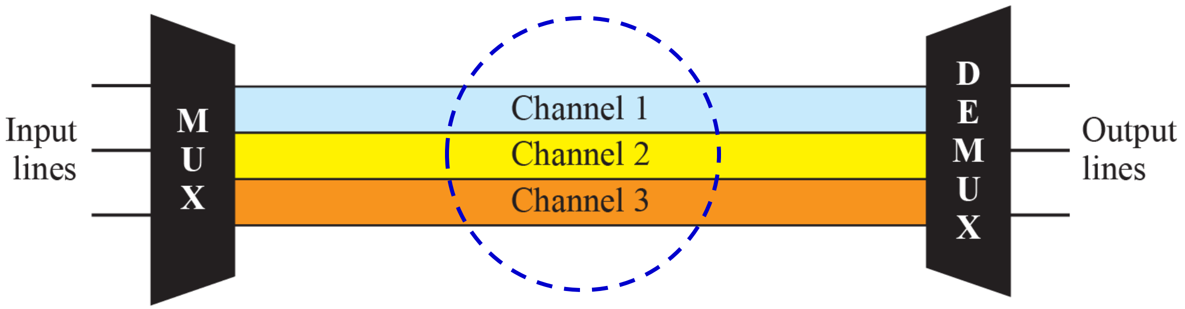
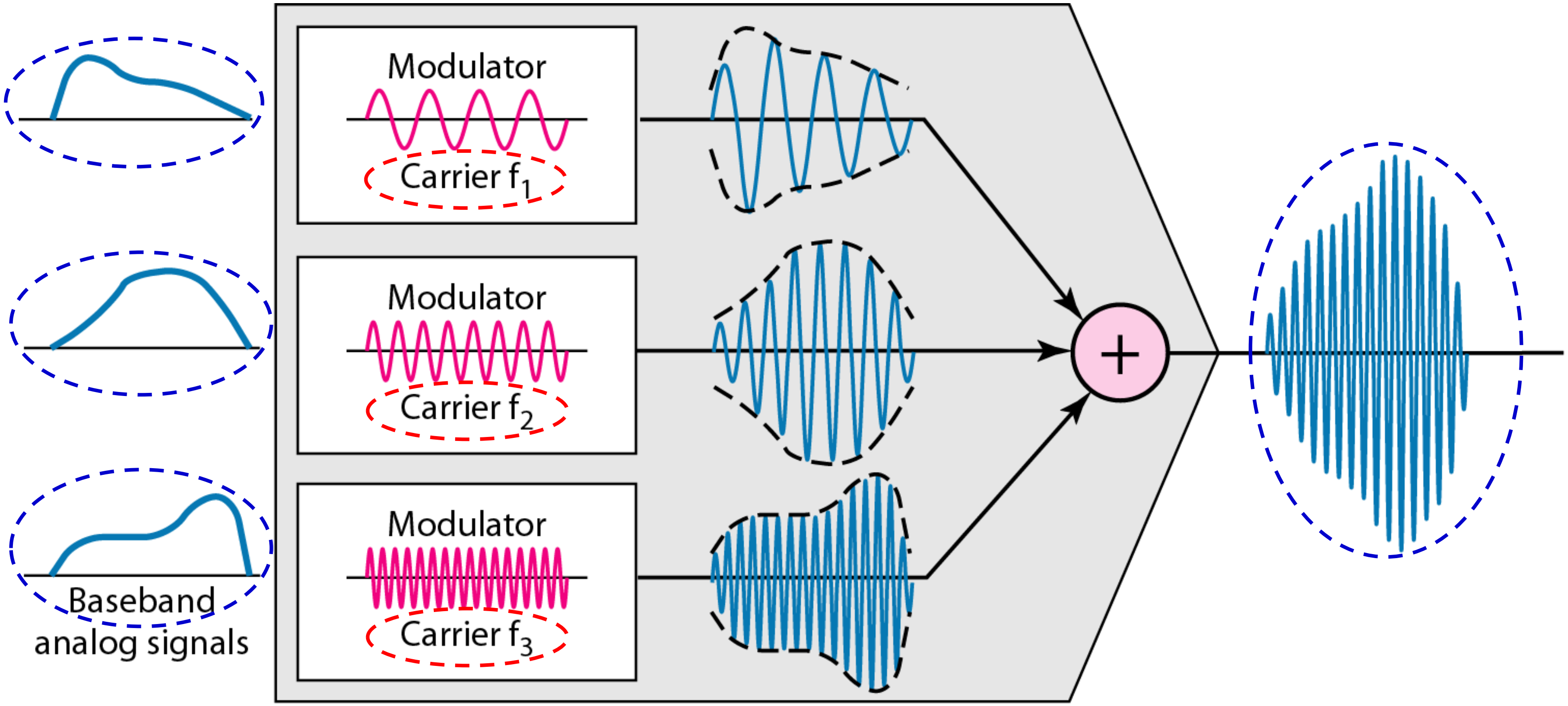


Figure 6.4: *FDM Process*

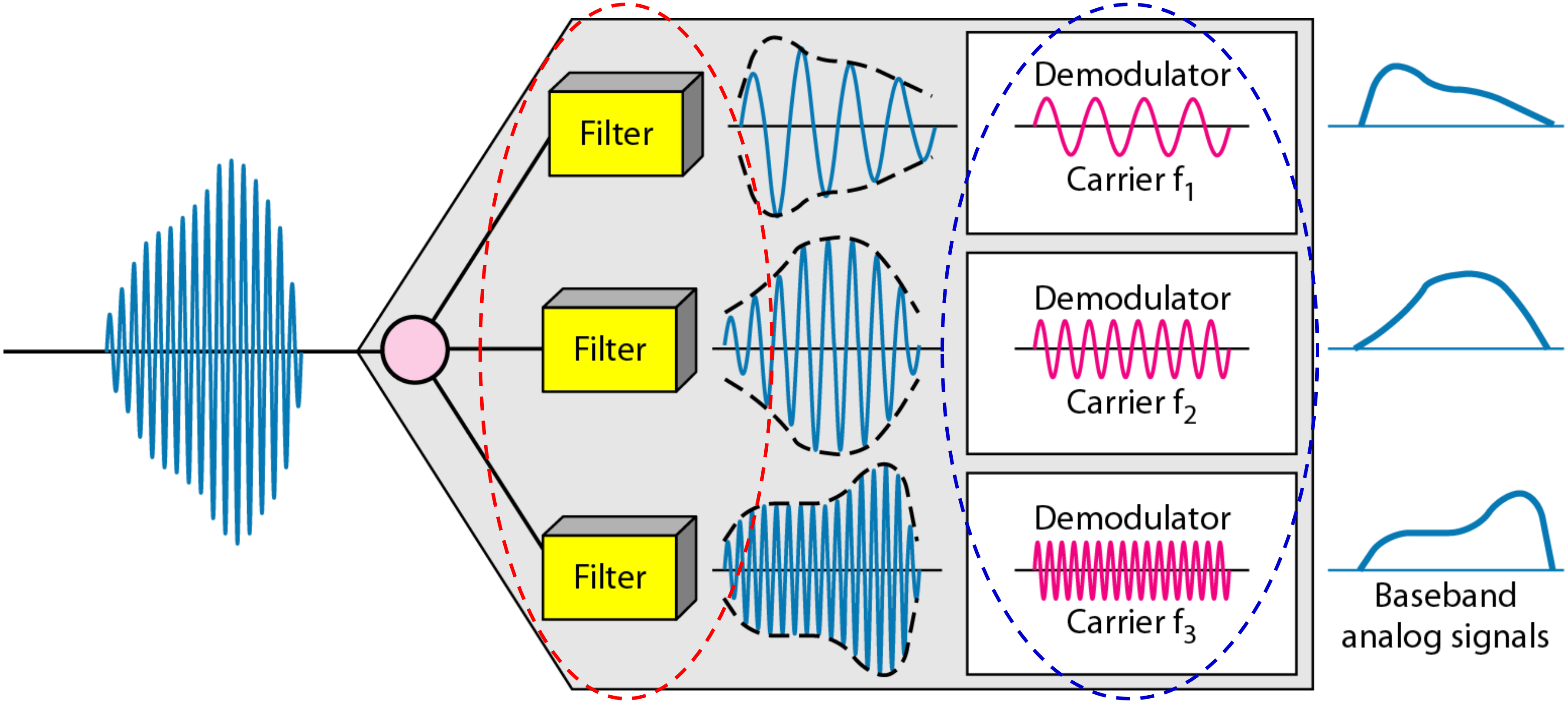


Note:
FDM is considered as an <u>analog multiplexing</u> technique that combines analog signals; this <u>does not mean</u> that <u>FDM cannot be used</u> to combine sources sending <u>digital signals</u>. A digital signal can be converted to an analog signal, e.g., <u>digital-to-analog conversion</u>, before FDM is used for multiplexing.

Figure 6.5: *FDM demultiplexing example*

A series of filters decompose the multiplexed signal into its individual component signals.

The individual signals are then passed through a demodulator that separates them from their carriers.



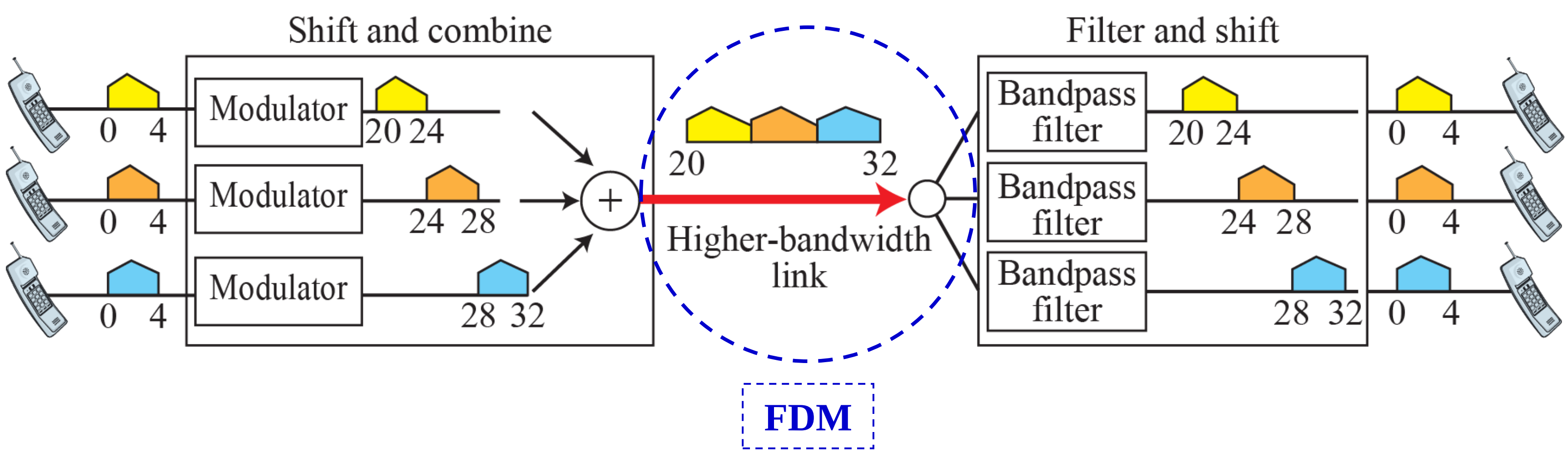
FDM can be implemented relatively easily. In many cases, such as radio and television broadcast, there is no need for a physical multiplexer or demultiplexer. As long as the stations agree to send their broadcasts using different carrier frequencies, FDM is achieved.

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 FDM configuration, assuming there are no guard bands.

Solution

We modulate each of the three voice channels to a different carrier frequency, as shown in the FDM configuration below:

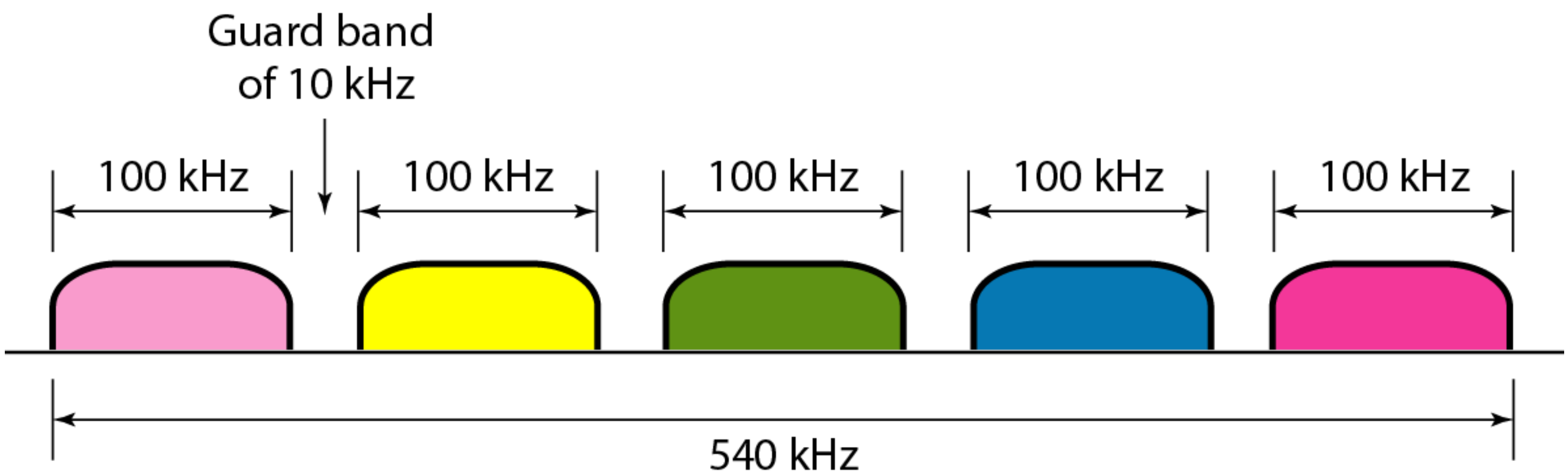


Example

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 $(5\times100) + (4\times10) = 540$ kHz.

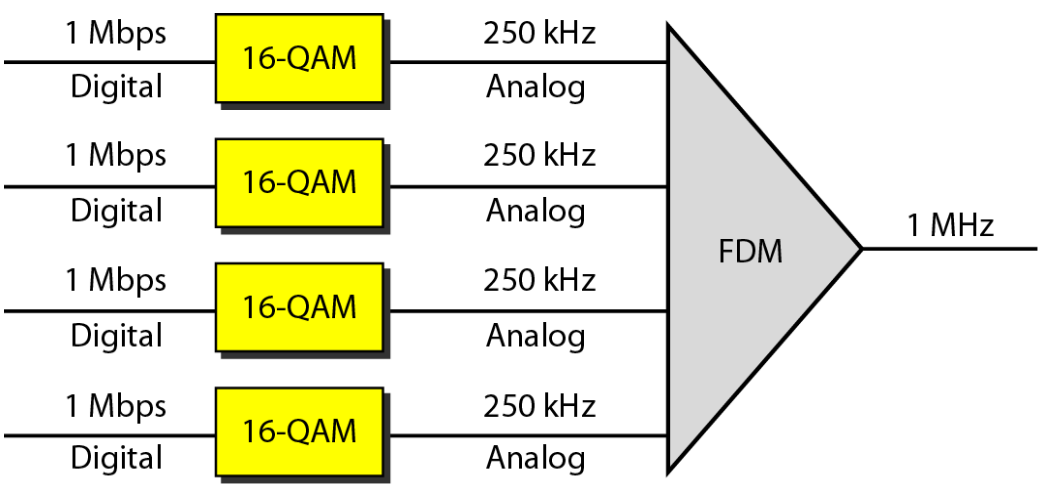


Problem

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

Solution

We can divide the analog satellite channel into four channels, with each channel having a 250 kHz bandwidth. Each digital channel of 1 Mbps is modulated so that each 4 bits is modulated to 1 Hz. A possible solution is to use 16-QAM as follows:



6.1.2 Wavelength-Division Multiplexing

Wavelength-division multiplexing (WDM) is an <u>analog multiplexing technique</u> used to <u>combine optical signals</u> to take advantage of the high data rate capability of <u>fiber optic cable</u>.

WDM is a complex technology, but the basic idea is simple: <u>combine multiple light sources</u> (i.e., <u>different wavelengths</u>) into <u>one single light</u> at the multiplexer and do the reverse at the demultiplexer.

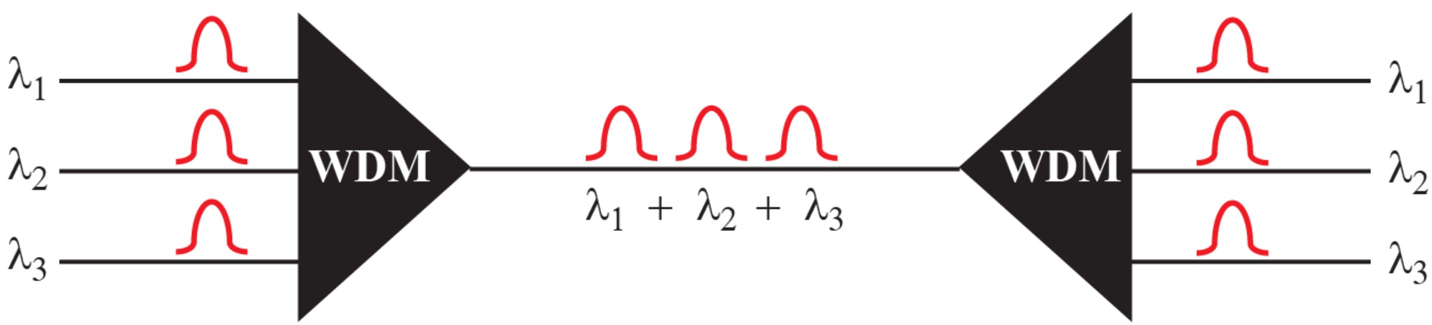
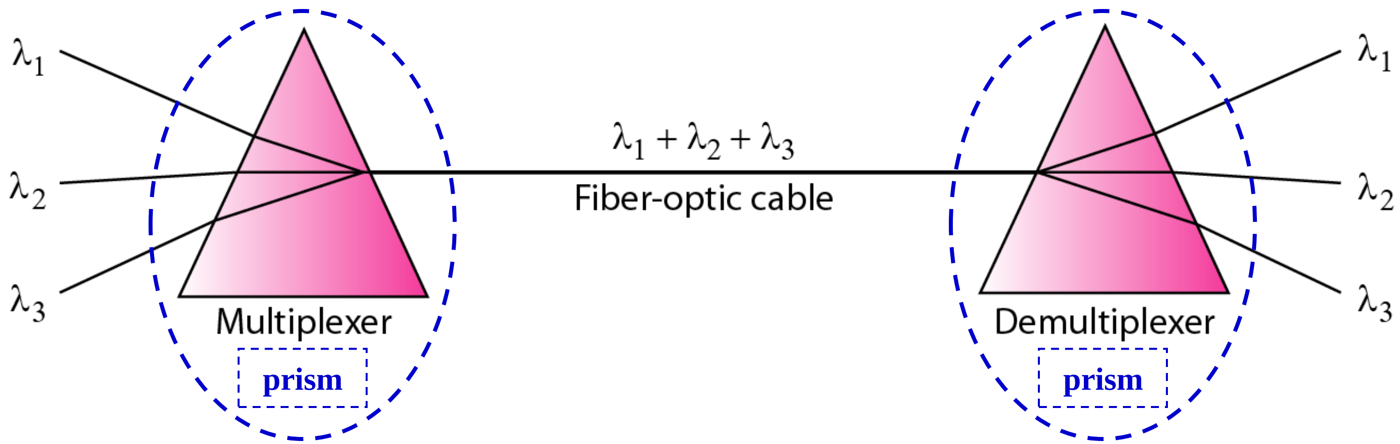


Figure 6.10: *Wavelength-division multiplexing*

The implementation of <u>combining and splitting of light sources</u> can be handled by <u>prisms</u>: a multiplexing prism combines several input beams of light into one output beam and a demultiplexing prism reverses the process:



6.1.3 Time-Division Multiplexing

Time-division multiplexing (TDM), synchronous or statistical, is a <u>digital multiplexing technique</u> that allows <u>several connections</u> to share the high bandwidth of a link. Instead of sharing a portion of the frequency spectrum as in FDM, <u>time is shared</u>. Each connection occupies a portion of time in the link.

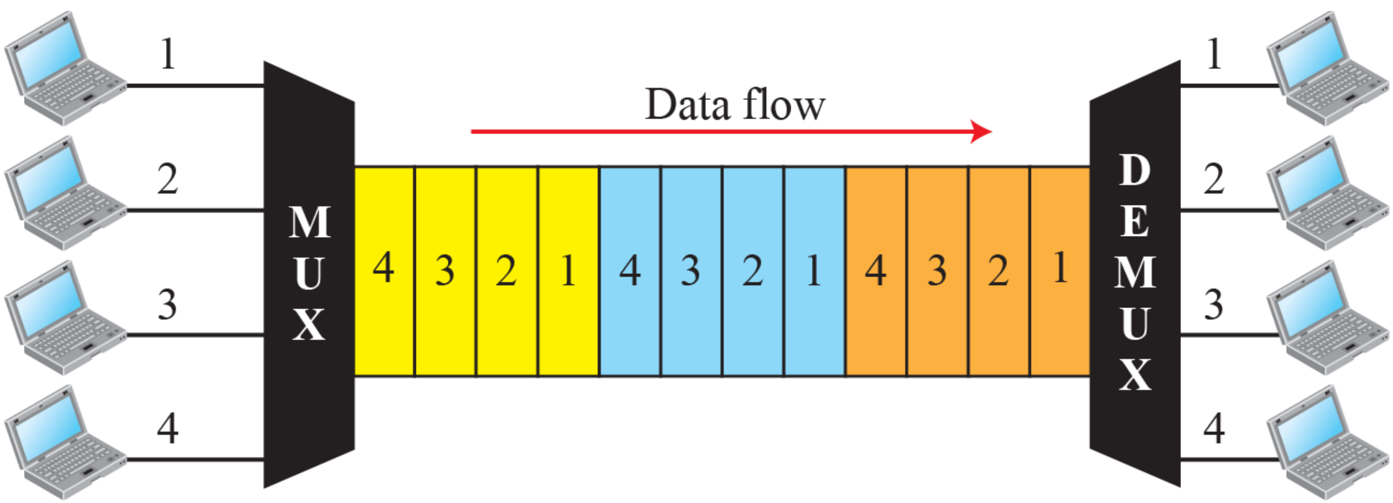
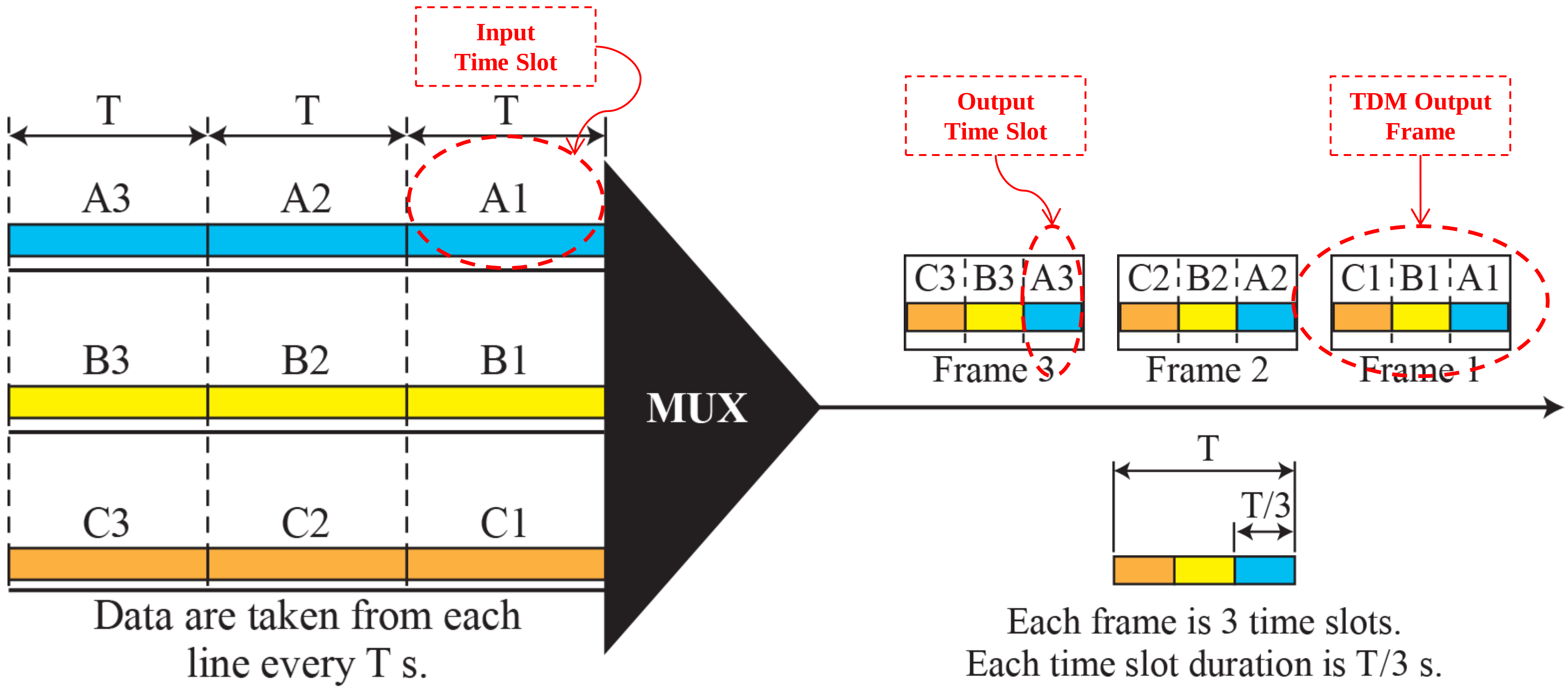


Figure 6.13: Synchronous time-division multiplexing

In <u>synchronous</u> TDM, each input connection has an <u>allotment</u> in the output frame <u>even if it's not sending data</u>.

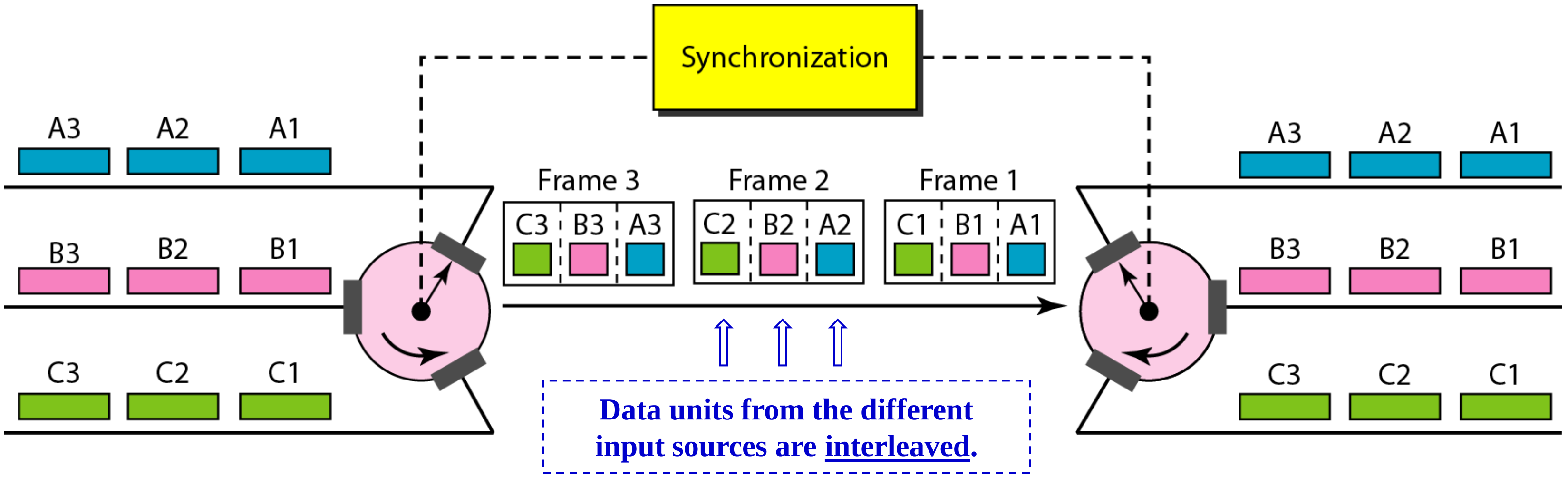


Notes:

1) **The duration of each <u>TDM Output Frame</u> (a complete cycle of time slots) is *T* (same as the duration of an <u>Input Time Slot</u>).**
2) **The duration of an <u>Output Time Slot</u> is <u>*n* times shorter</u> than the duration of an <u>Input Time Slot</u>, i.e., if the duration of the Input Time Slot is *T*, the duration of each Output Time Slot is *T/n*.**
3) **The <u>data rate</u> of the <u>output link</u> is <u>*n* times</u> the data rate of <u>an input connection</u> to ensure the flow of data.**

Figure 6.15: ***Interleaving***

Synchronous TDM can be visualized as two fast-rotating switches that are synchronized and rotate at the same speed but in opposite directions.

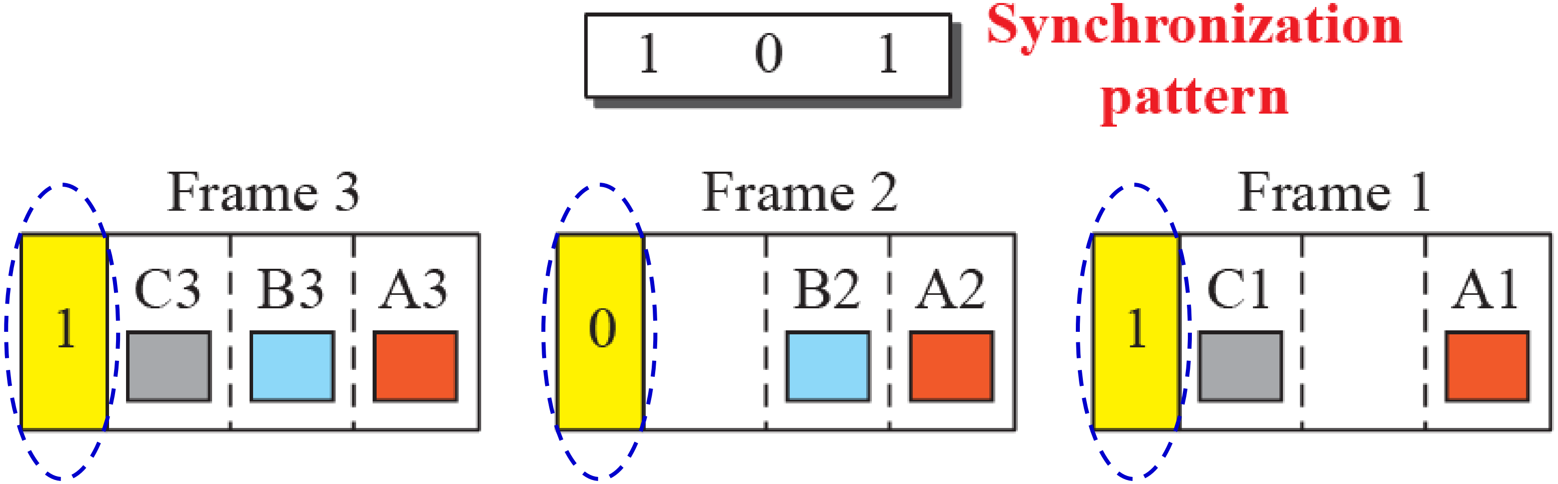


On the multiplexing side, as the switch opens in front of a connection, that connection has the opportunity to send a unit onto the path.

On the demultiplexing side, as the switch opens in front of a connection, that connection has the opportunity to receive a unit from the path.

Figure 6.22: **Framing bits**

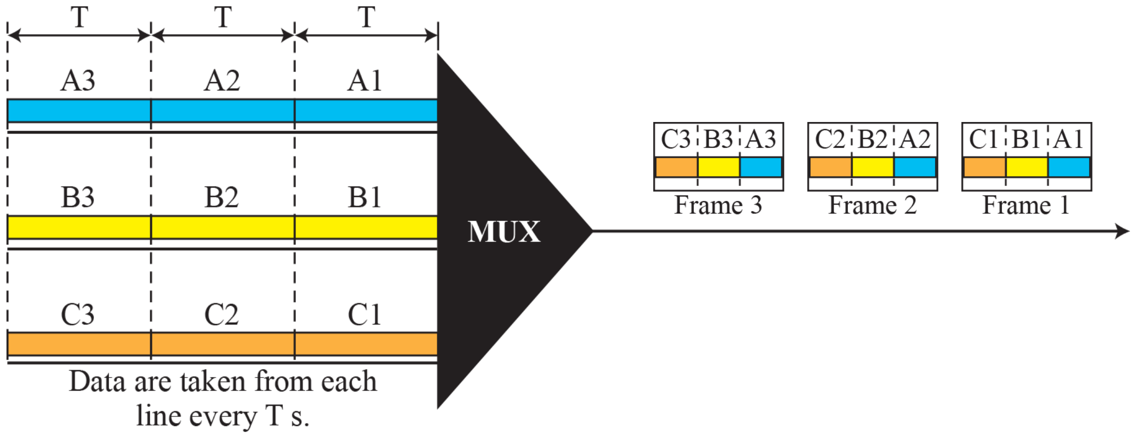
Framing bits are added to each frame to allow the demultiplexer to separate the time slots accurately in the implementation of synchronous TDM.



If the multiplexer and demultiplexer are not synchronized, a bit belonging to one channel may be received by the wrong channel.

Example

Consider the following synchronous TDM system. The data rate for each input connection is 1 kbps. If 1 bit at a time is multiplexed, what is the duration of (a) each input time slot (b) each output time slot and (c) each output frame?



Solution

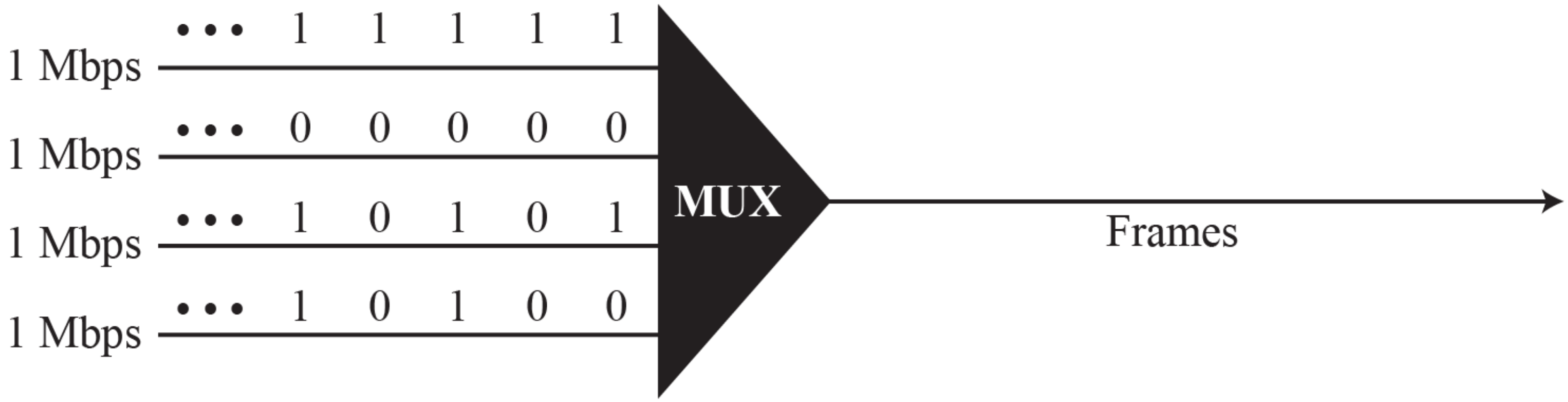
(a) The data rate of each input connection is 1 kbps. If 1 bit at a time is multiplexed, the duration of each input time slot is 1/1000 s (1 ms).

(b) For a synchronous TDM with 3 input connections, the duration of each output time slot is 1/3 of the input time slot, i.e., 1/3 ms.

(c) Each frame carries three output time slots. The duration of each frame is $3 \times 1/3$ ms, or 1 ms (which is the same as the duration of an input time slot).

Example

Consider the following synchronous TDM with a data stream for each input and a data stream for the output. 1 bit is multiplexed at a time. Determine the (a) output bit rate and (b) output frame rate.



Solution

(a.1) With 4 input connections of 1 Mbps, the output bit rate is 4 x 1 Mbps = 4 Mbps.

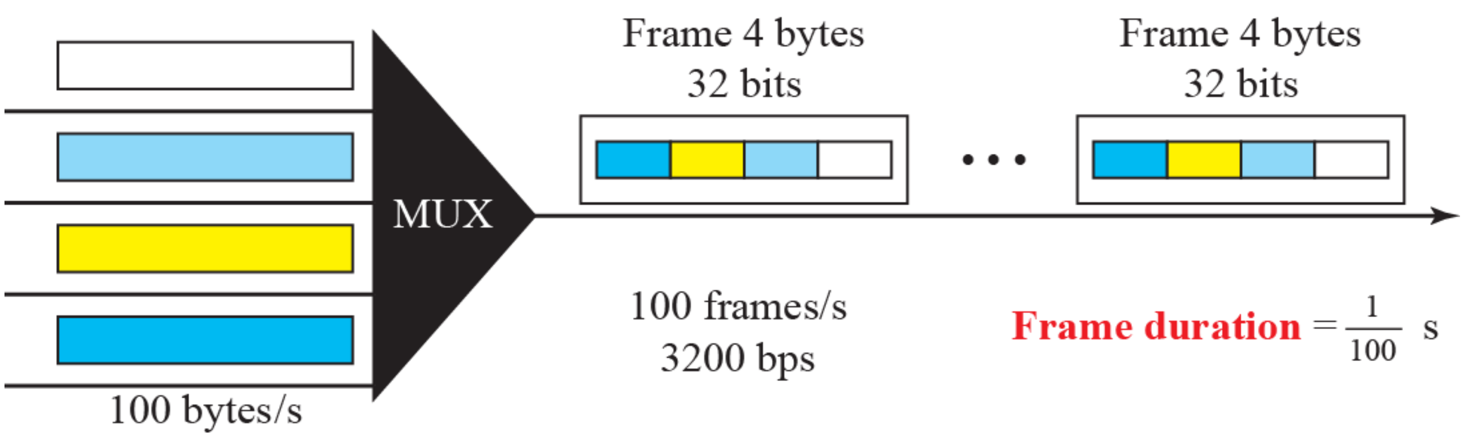
(a.2) The output bit rate is the inverse of the output bit duration. The input bit duration is 1/(1 Mbps) = 1 μs. With 4 input connections, the output bit duration is 1/4 μs. Hence, the output bit rate = 1/(1/4 μs) = 4 Mbps.

(b) The output frame rate is the same as the input connection rate. With an input connection of 1 Mbps (with 1 bit multiplexed at a time), the output frame rate is 1 M frames per second.

Problem

Four channels are multiplexed using synchronous TDM. Each channel sends 100 bytes/s and we multiplex 1 byte per channel. Determine (a) the size of the TDM frame (b) the TDM frame rate (c) the duration of a TDM frame and (d) the bit rate for the link.

Solution



(a) Each TDM frame carries 1 byte from each channel. Therefore, the size of each TDM frame is 4 bytes, or 32 bits.

(b) The TDM frame rate is 100 frames per second.

(c) With a frame rate of 100 frames/s, the duration of a TDM frame is 1/100 s.

(d) The bit rate for the link is $100 \times 32 = 3200$ bps.

Problem

We have four sources, each creating 250 8-bit characters per second. The interleaved unit is 1 character and 1 synchronizing bit is added to each TDM frame. Determine

(a) the data rate of each source

(b) the duration of each character in each source

(c) the TDM frame rate

(d) the number of bits in each TDM frame

(e) the data rate of the link.

Solution

(a) The data rate of each source is $250 \times 8 = 2000$ bps.

(b) Each source sends 250 characters per second. The duration of each character is 1/250 s.

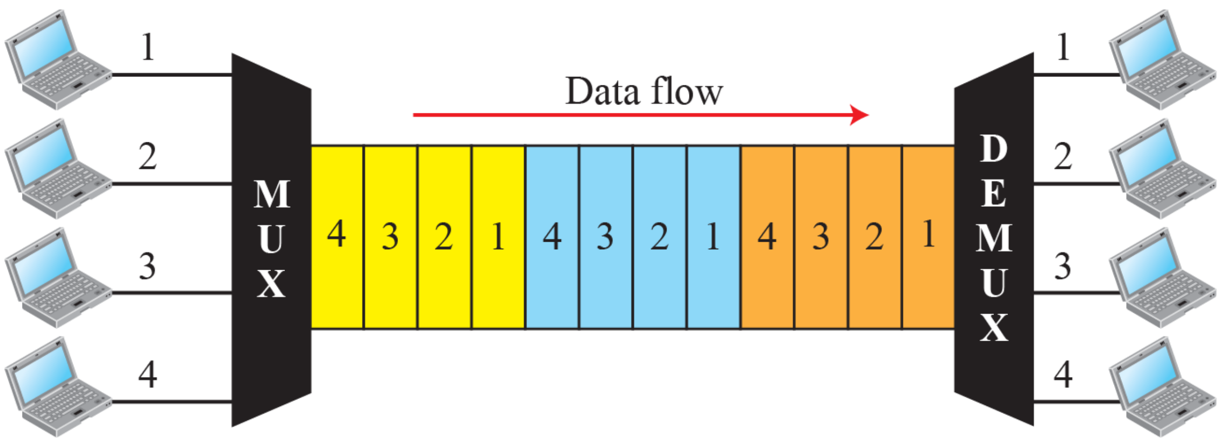
(c) The link needs to send 250 frames per second (with duration of 1/250 s).

(d) Each frame carries 4 characters and 1 extra synchronizing bit. The number of bits in each TDM frame is $(4 \times 8) + 1 = 33$ bits.

(e)The link sends 250 frames per second, and each frame contains 33 bits. The data rate of the link is $250 \times 33 = 8250$ bps.

Data Rate Management

So far in TDM, the assumption is that the data rates of all input lines are the same. What if there is a disparity in the input data rates?

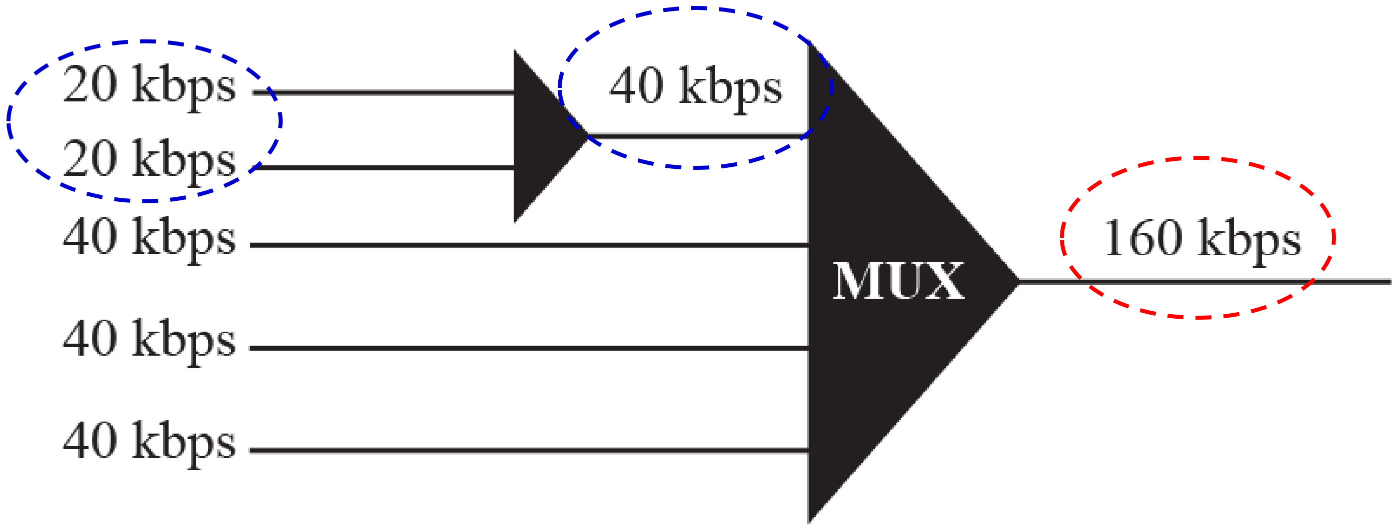


Three strategies, <u>or a combination of them</u>, can be used:

1) ***multilevel multiplexing***
2) ***multiple-slot allocation***
3) ***pulse stuffing***

Figure 6.19: ***Multilevel multiplexing***

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



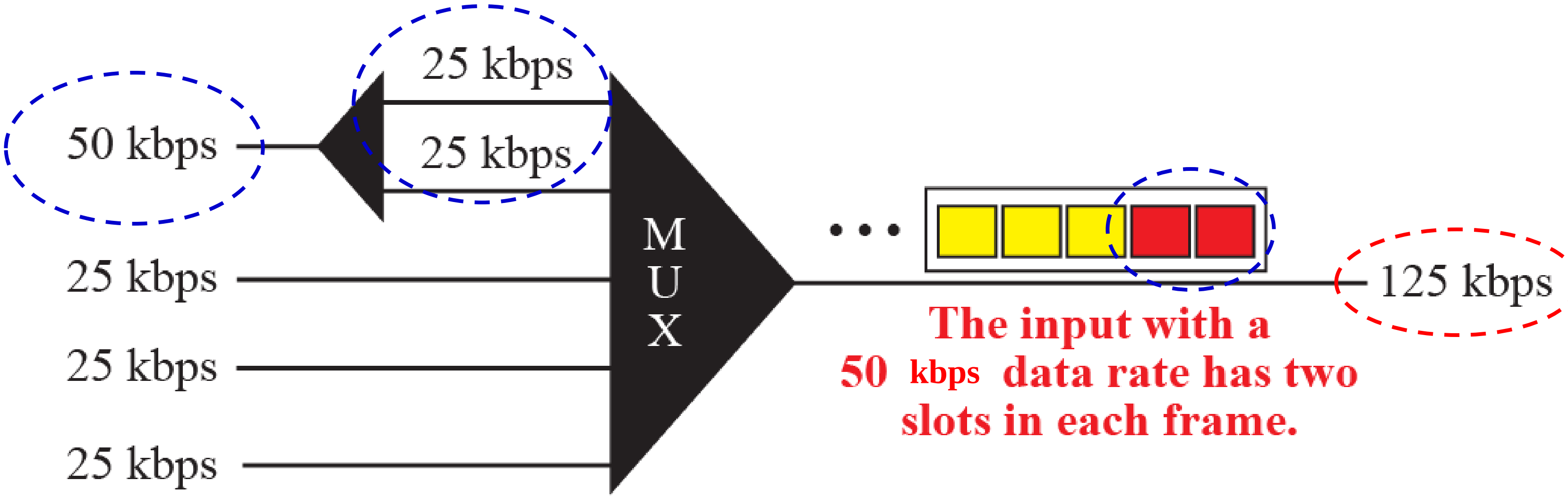
Example:
Given 2 inputs @20 kbps and 3 inputs @40 kbps:

The first 2 input lines can be multiplexed together to provide a data rate of 40 kbps in the first level of multiplexing.

A second level of multiplexing can create an output frame of 160 kbps.

Figure 6.20: Multiple-slot allocation

Multiple-slot allocation ***is a technique to <u>allot more than one slot</u> in an output frame to a <u>single input line</u> when an input line has a data rate that is a multiple of another input.***

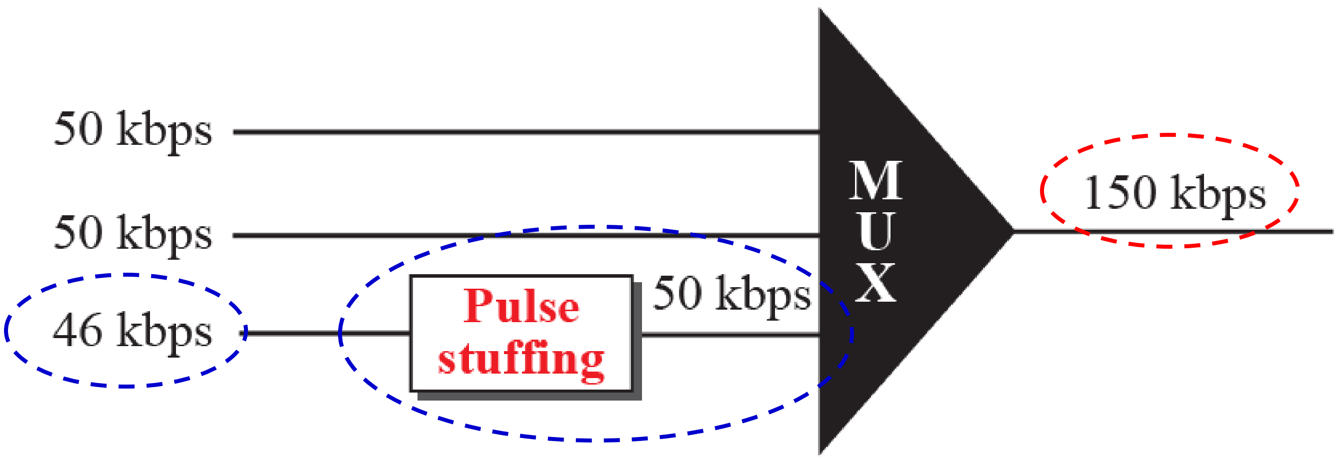


Example:
Given <u>1 input @50 kbps</u> and <u>3 inputs @25 kbps</u>:

The first input line can be demultiplexed to attain <u>2 inputs @25 kbps</u> and be given <u>two slots</u> in the <u>output frame</u>.

Figure 6.21: Pulse stuffing

Pulse Stuffing ***(bit padding, bit stuffing) is a technique used when the <u>bit rates</u> of the <u>input lines</u> are not <u>integer multiples</u> of each other. A solution is to make the <u>highest input data rate</u> the <u>dominant</u> data rate and <u>add "dummy" bits</u> to the input lines with <u>lower input data rates</u>.***



Example:
Given <u>2 inputs @50 kbps</u> and <u>1 input @46 kbps</u>:

The input line with 46 kbps is <u>pulse stuffed</u> to increase the data rate to <u>50 kbps</u>.

Problem

Two channels, one with a bit rate of 100 kbps and another with a bit rate of 200 kbps, are to be multiplexed using multiple-slot allocation. What is (a) the frame rate (if 1 bit at a time is multiplexed) (b) the frame duration and (c) the bit rate of the link?

Solution

Using multiple-slot allocation, we can allocate one slot to the first channel and two slots to the second channel, hence, each frame carries 3 bits. Note that the bit rates for both channels are preserved.

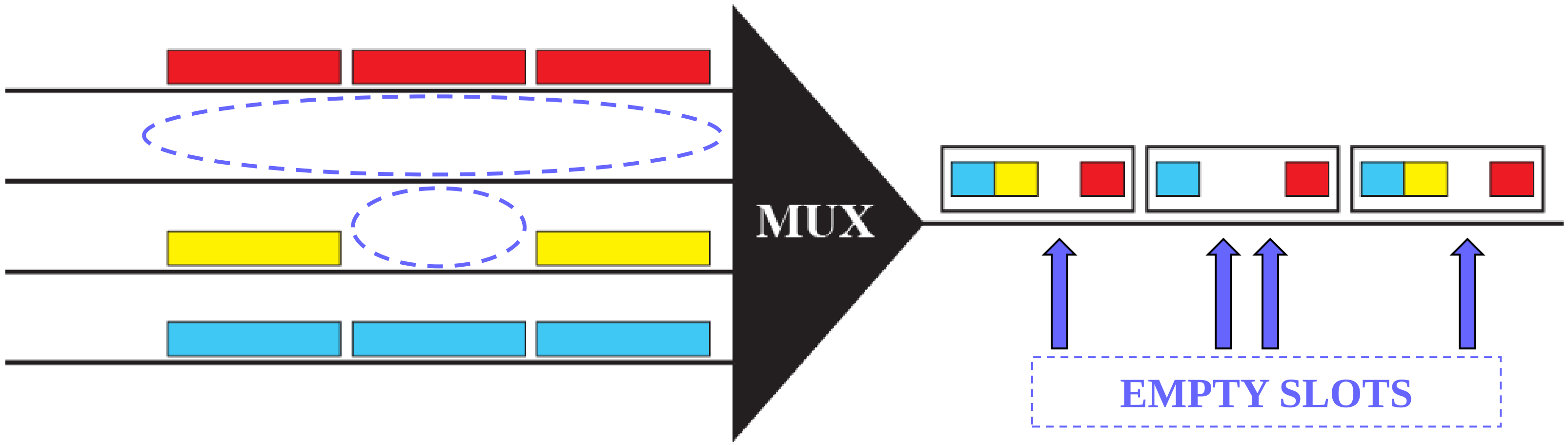
(a) The frame rate is 100,000 frames per second (1 bit from the first channel, 2 bits from the second channel).

(b) The frame duration is 1/100,000 s.

(c) The bit rate is 100,000 frames/s × 3 bits/frame = 300 kbps.

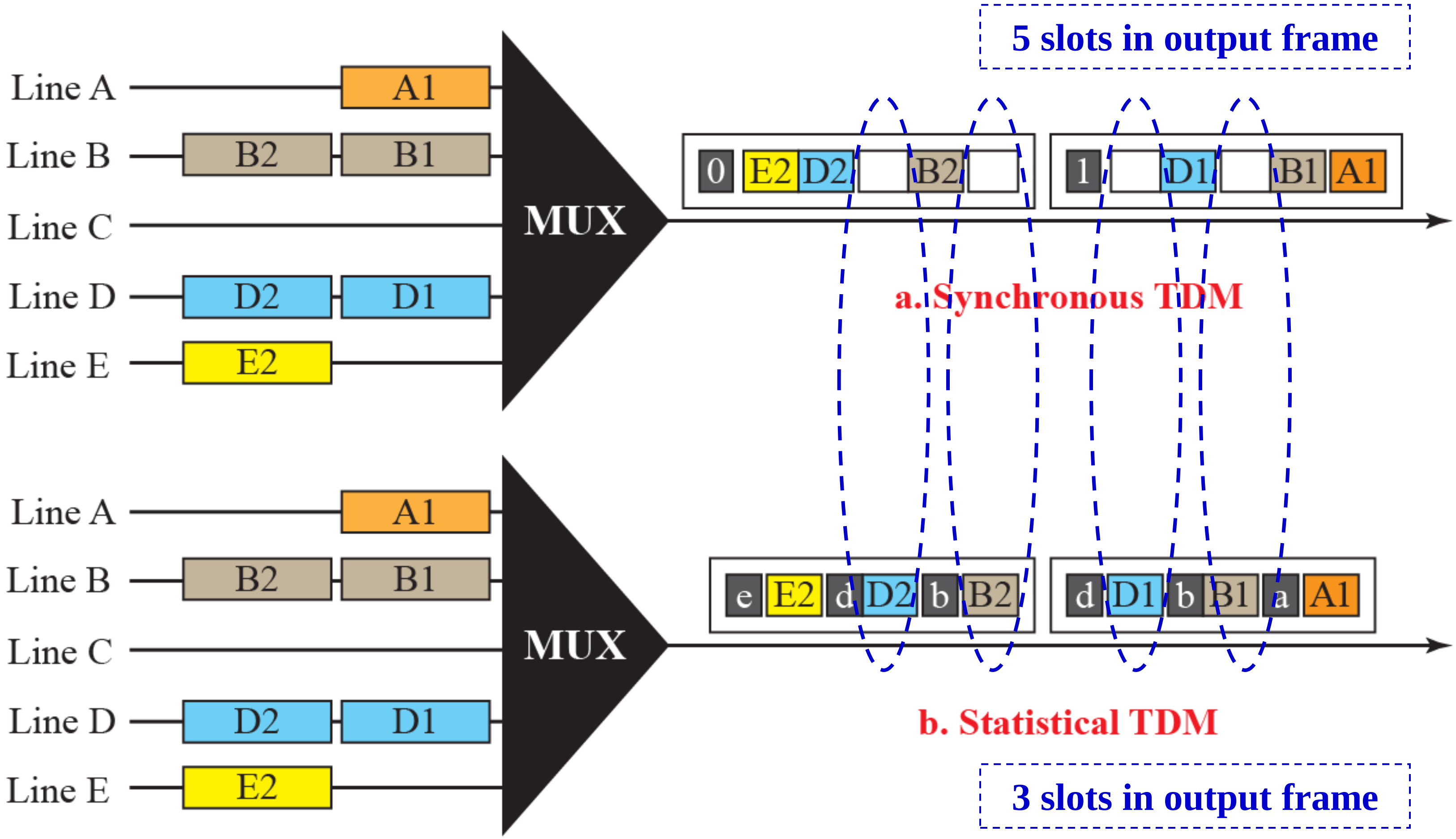
Figure 6.18: *Statistical time-division multiplexing*

Synchronized TDM can be inefficient. If a source does not have data to send, the corresponding slot in the output frame is empty.



In statistical TDM, slots are dynamically allocated to improve bandwidth efficiency. Only when an input line has data to send is it given a slot in the output frame. Note that the number of slots in each frame may be less than the number of input lines.

Figure 6.26: TDM comparison



Additional notes:

1) In synchronous TDM, there is no need for addressing; whereas an output frame in statistical TDM needs to carry data as well as the address of the destination.
2) The output frames in statistical TDM need not be synchronized and hence no synchronization framing bits are required.

Figure 6.24: *T-1 line*

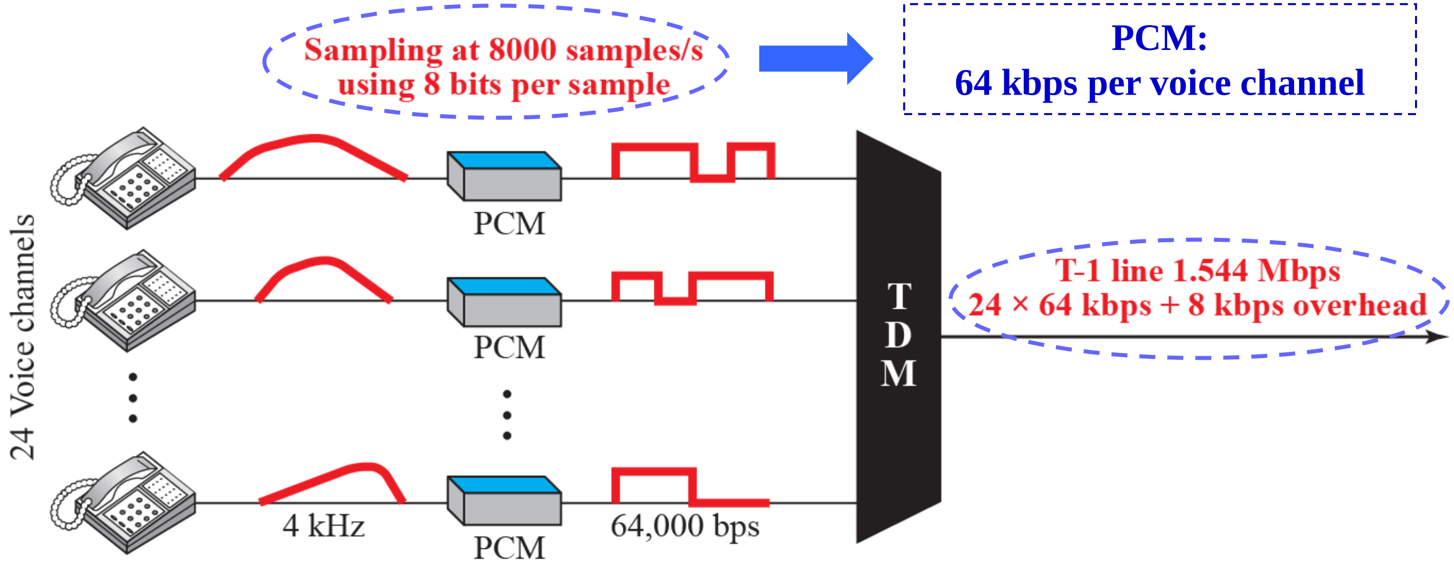


Figure 6.25: *T-1 line frame structure*

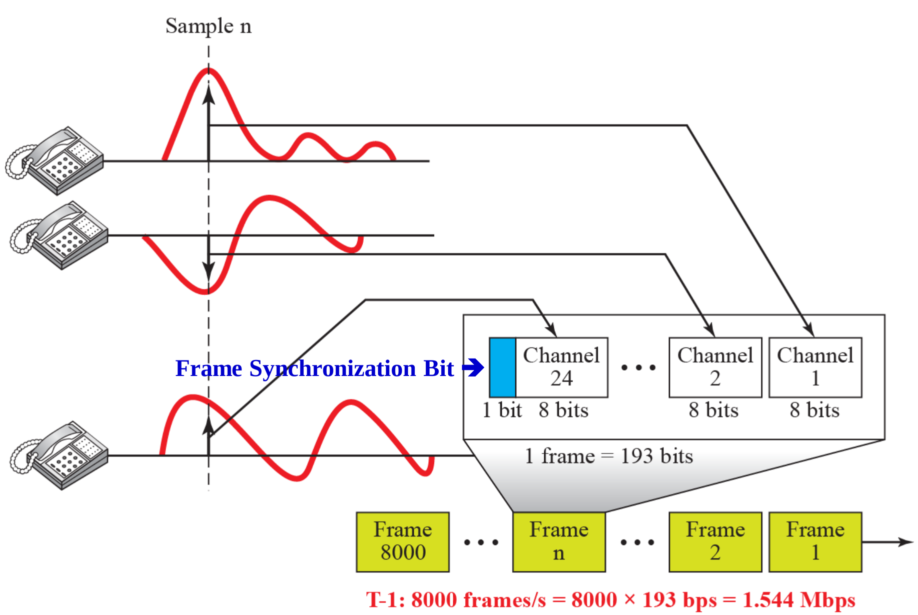
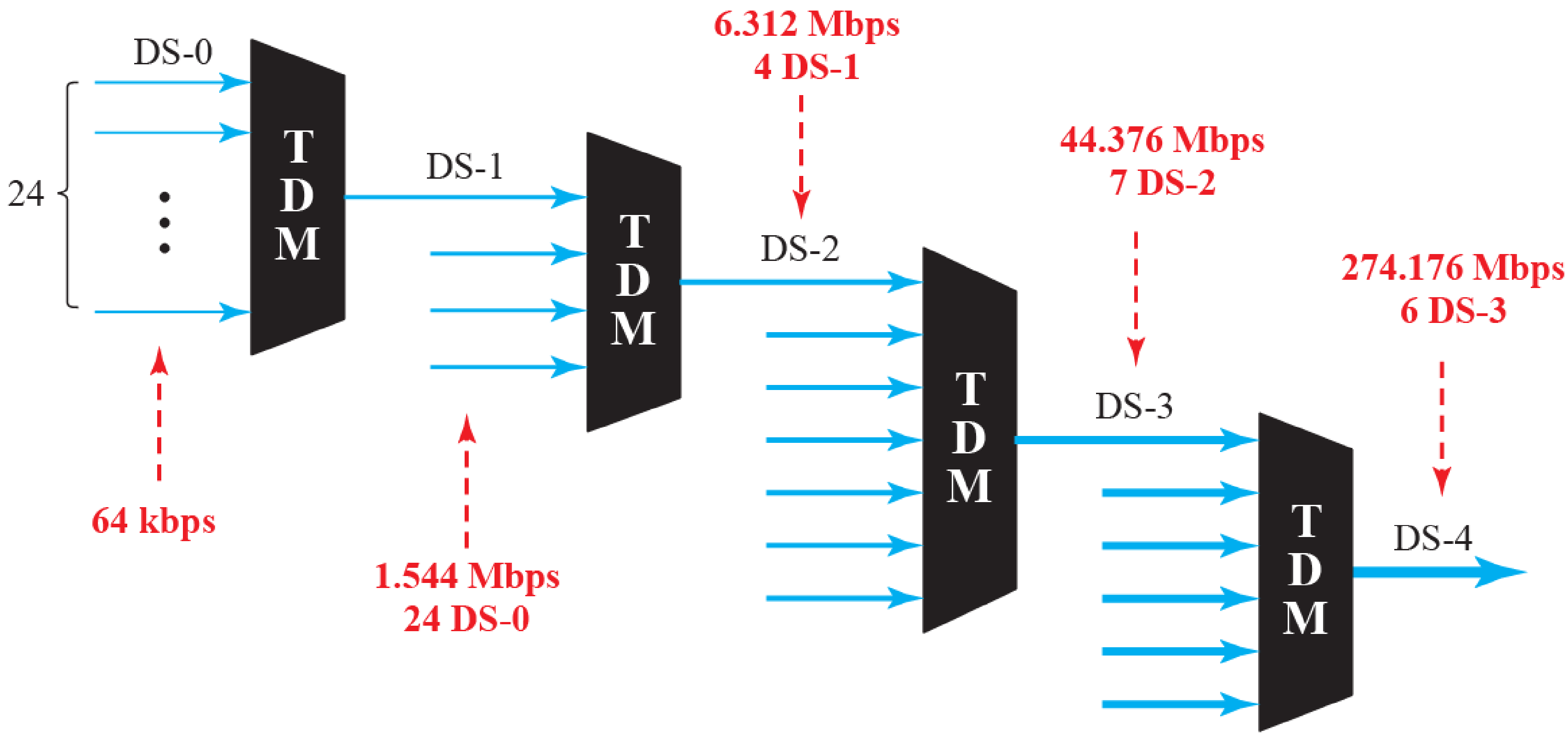


Figure 6.23: Digital hierarchy



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