



Chapter 6

Bandwidth Utilization: Multiplexing and Spreading



Note

Bandwidth utilization is the wise use of available bandwidth to achieve specific goals.

Efficiency can be achieved by multiplexing; privacy and anti-jamming can be achieved by spreading.

6-1 MULTIPLEXING

*Whenever the bandwidth of a medium linking two devices is **greater than** the bandwidth needs of the devices, the link can be **shared**. Multiplexing is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link. As data and telecommunications use increases, so does traffic.*

Topics discussed in this section:

Frequency-Division Multiplexing

Wavelength-Division Multiplexing

Synchronous Time-Division Multiplexing

Statistical Time-Division Multiplexing

Figure 6.1 *Dividing a link into channels*

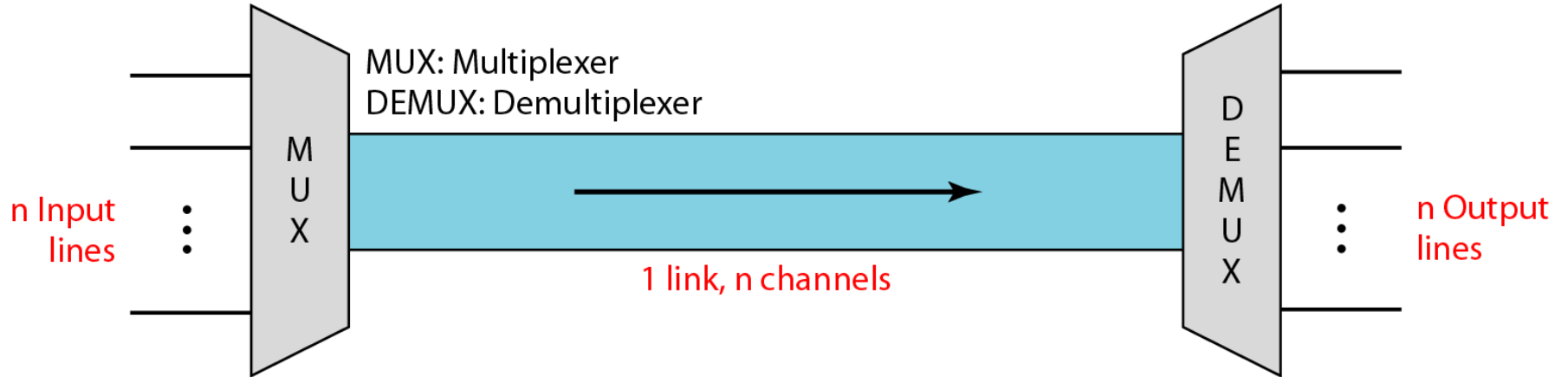


Figure 6.2 *Categories of multiplexing*

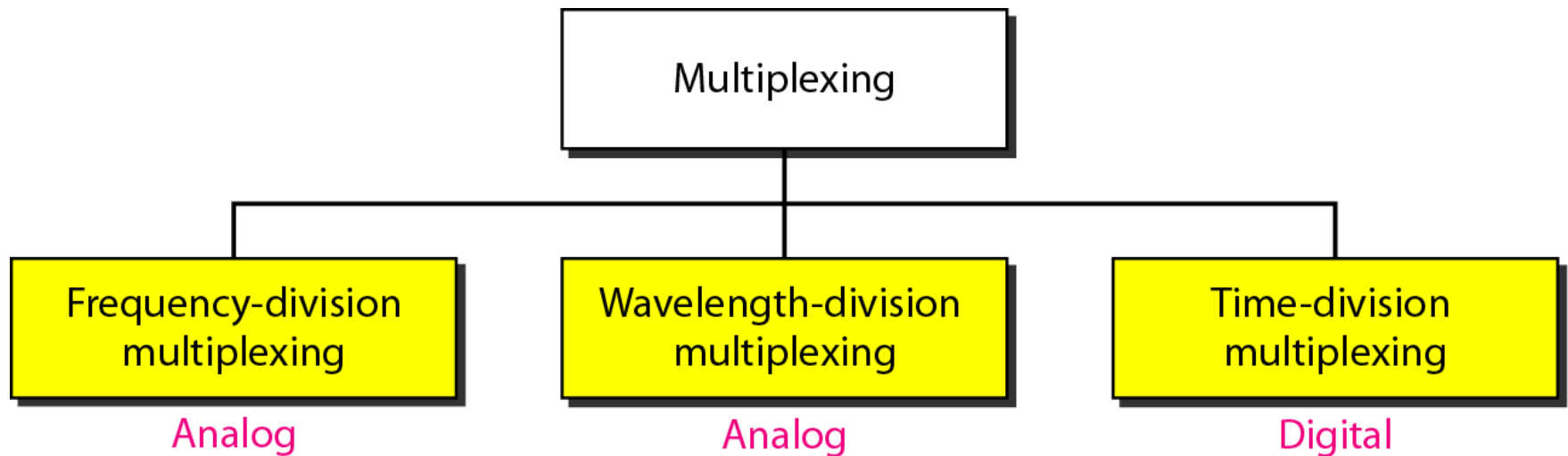


Figure 6.3 *Frequency-division multiplexing*





Note

FDM is an analog multiplexing technique that combines analog signals.

Figure 6.4 FDM process

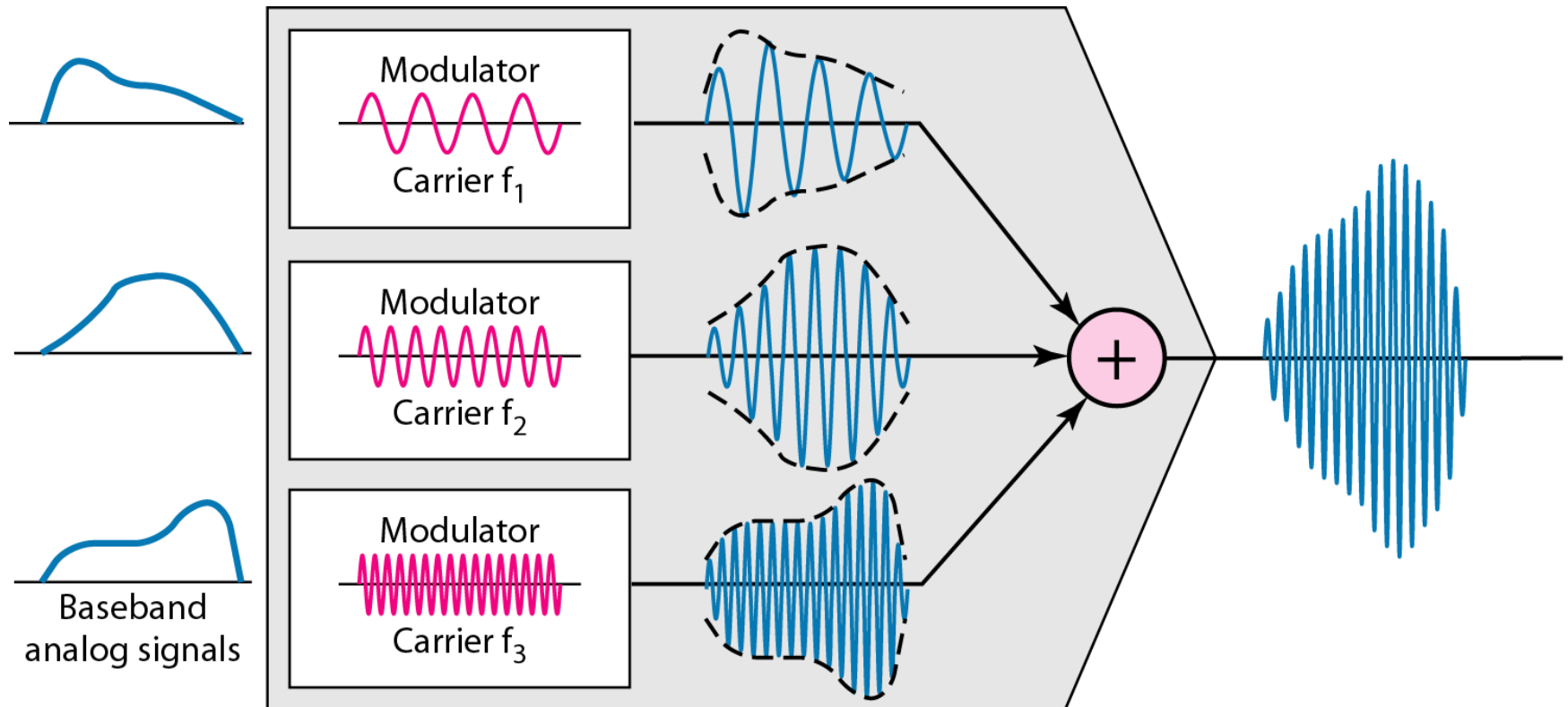
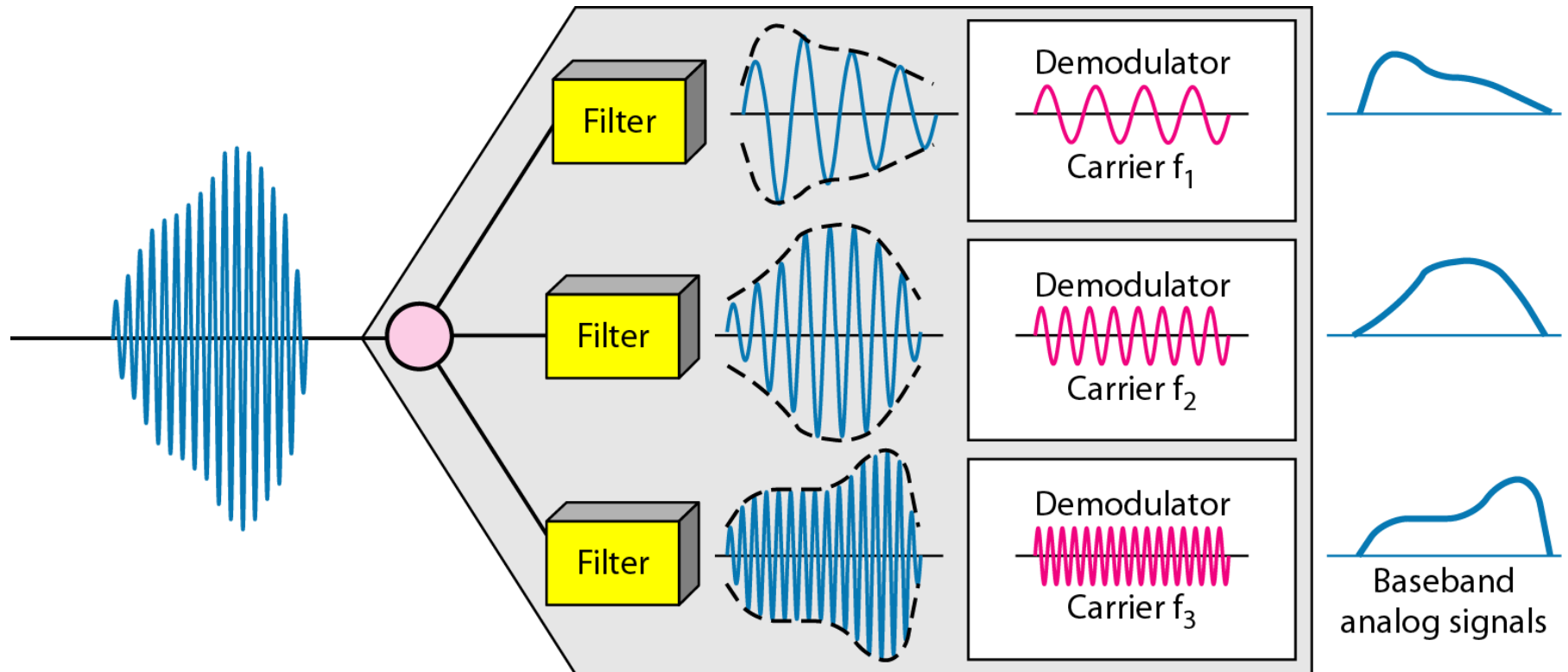


Figure 6.5 *FDM demultiplexing example*





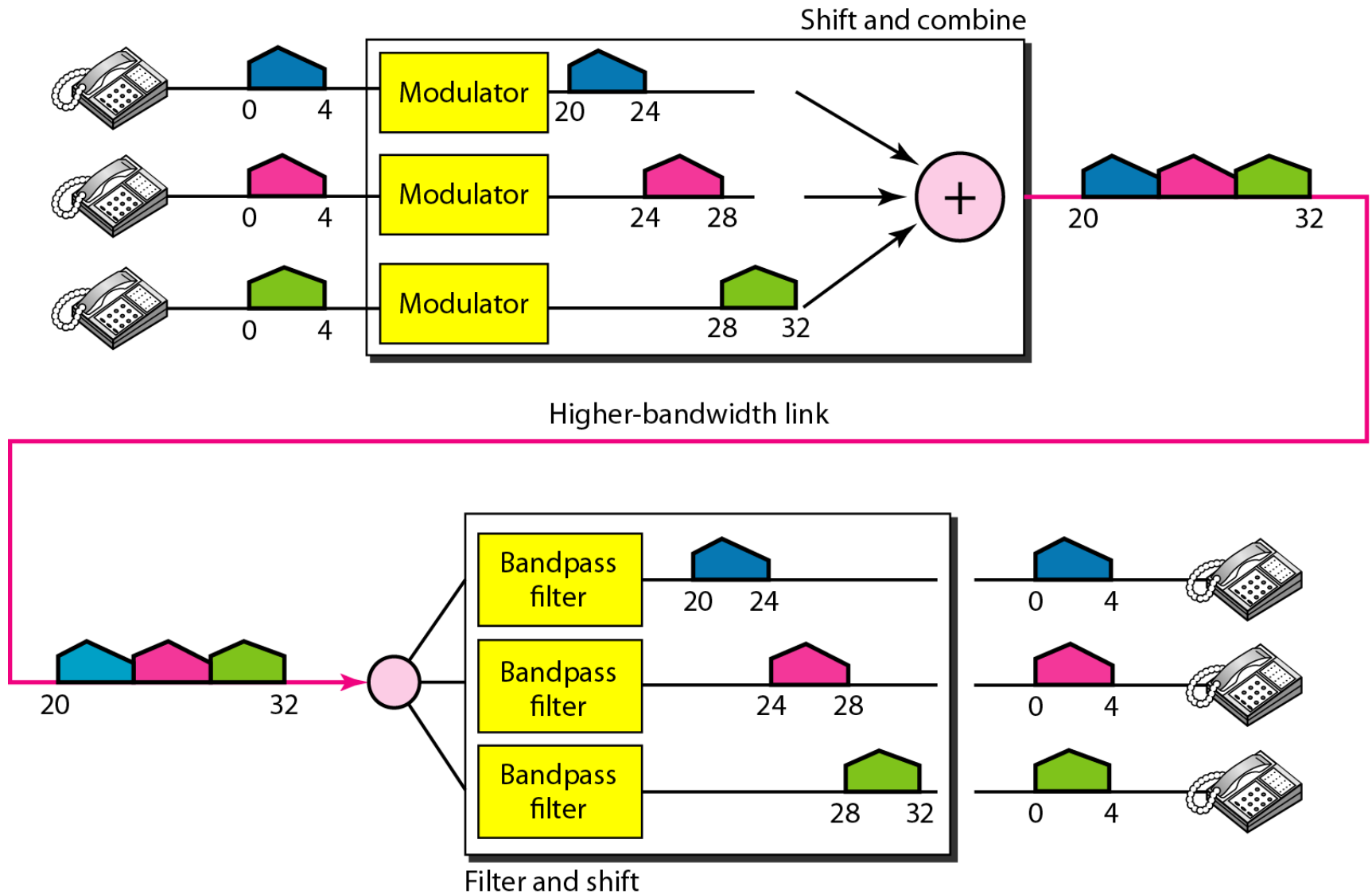
Example 6.1

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 28-kHz bandwidth for the second channel, and the 28- to 32-kHz bandwidth for the third one. Then we combine them as shown in Figure 6.6.

Figure 6.6 *Example 6.1*





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?

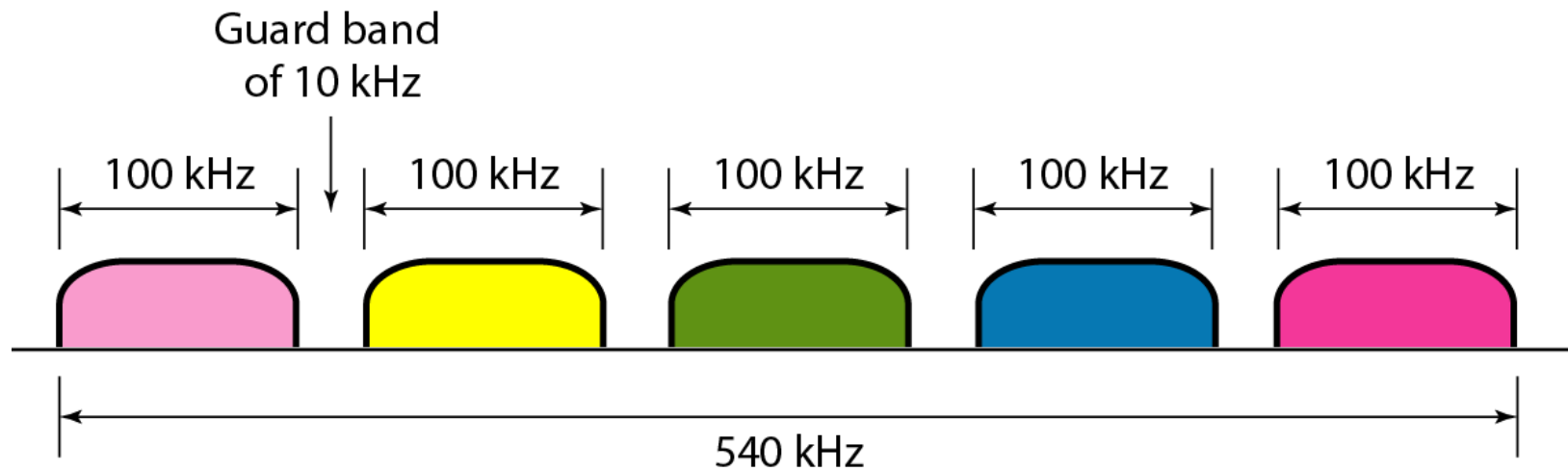
Solution

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

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

as shown in Figure 6.7.

Figure 6.7 Example 6.2





Example 6.3

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 6.8 shows one possible configuration.

Figure 6.8 Example 6.3

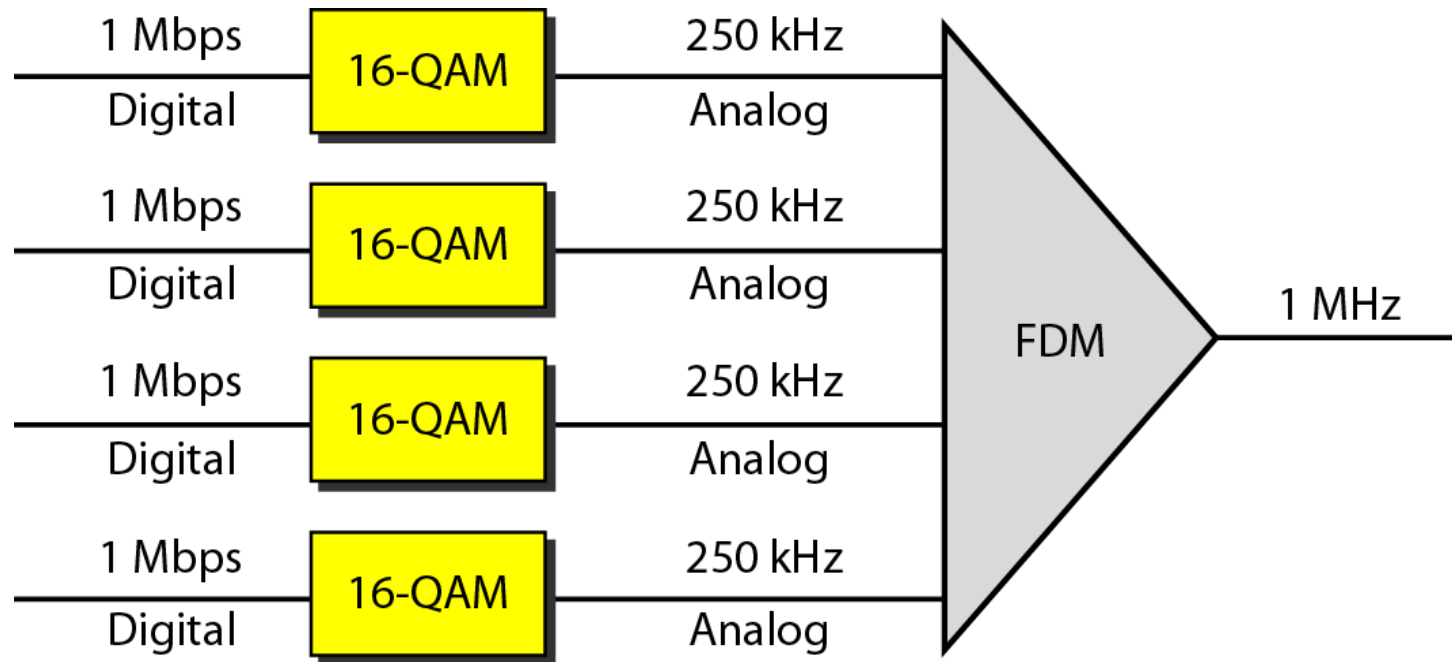


Figure 6.9 *Analog hierarchy*

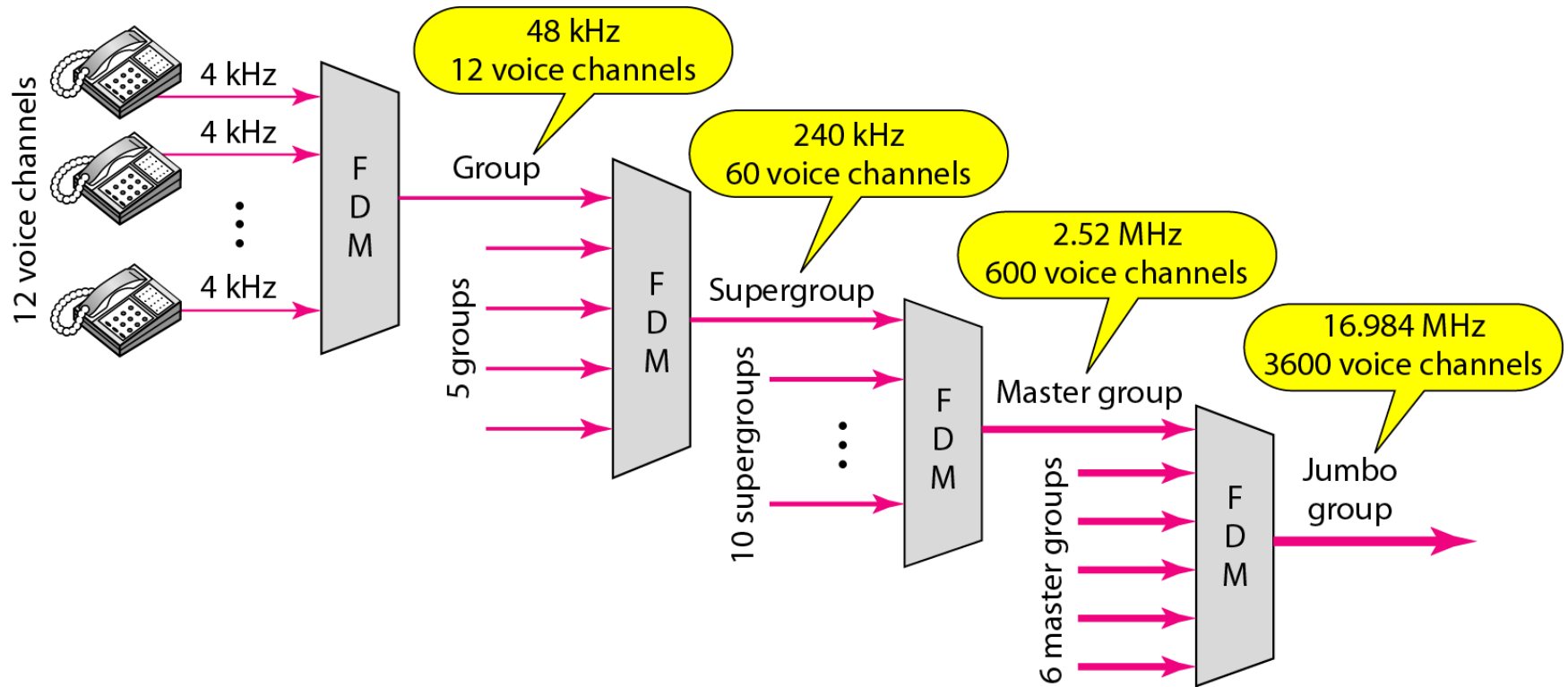
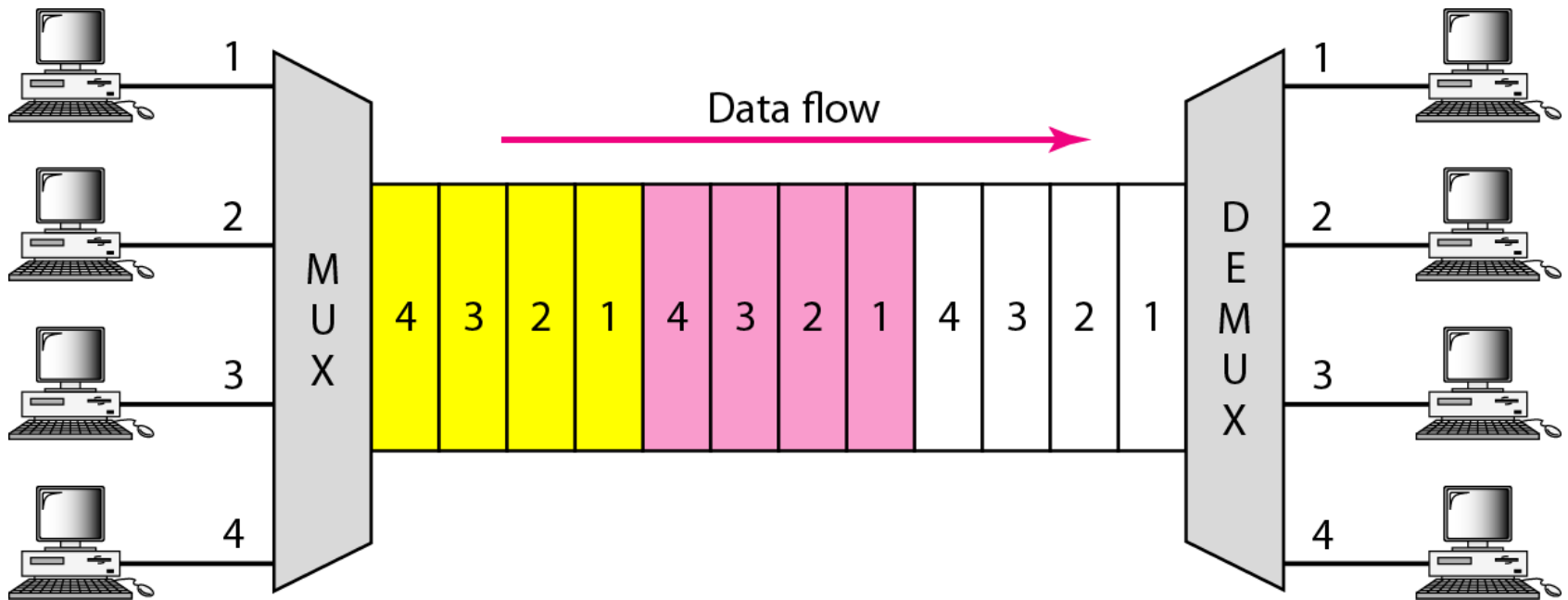


Figure 6.12 *TDM (Time-division Multiplexing)*

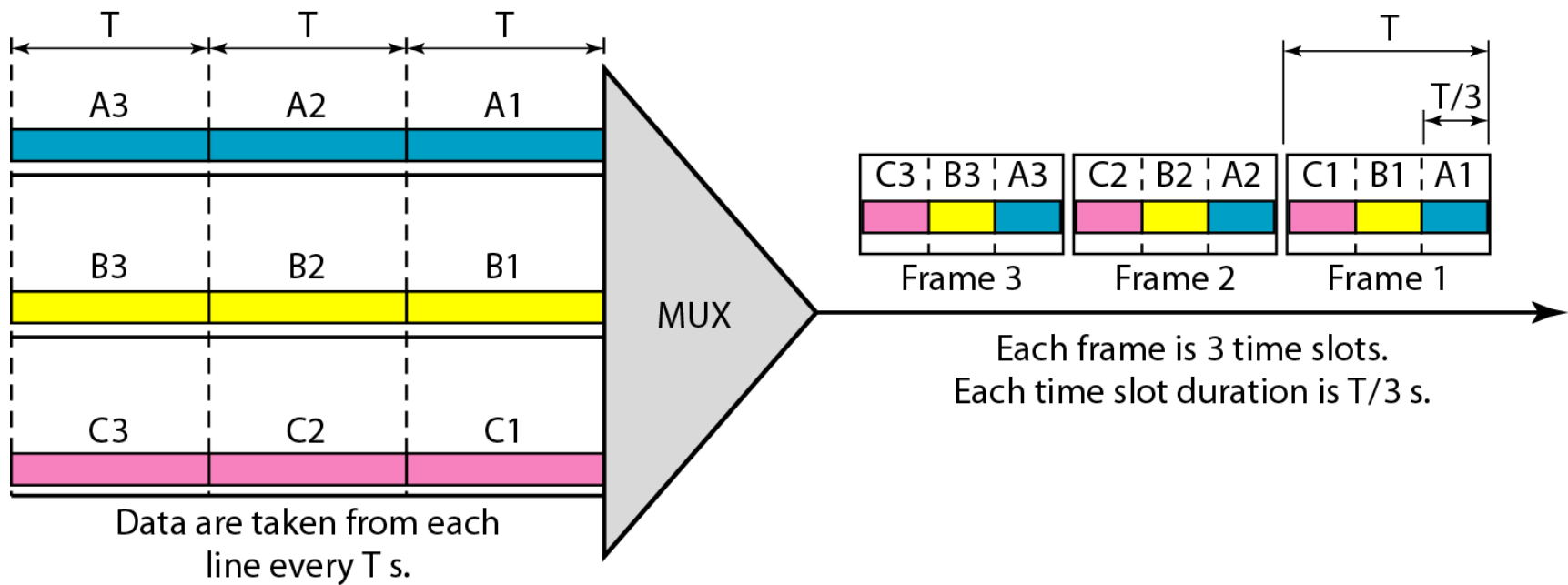




Note

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

Figure 6.13 *Synchronous time-division multiplexing*





Note

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



Example 6.5

In Figure 6.13, the data rate for each input connection is 3 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

We can answer the questions as follows:

- 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).*



Example 6.5 (continued)

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



Example 6.6

Figure 6.14 shows synchronous TDM with a data stream for each input 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.

Solution

We can answer the questions as follows:

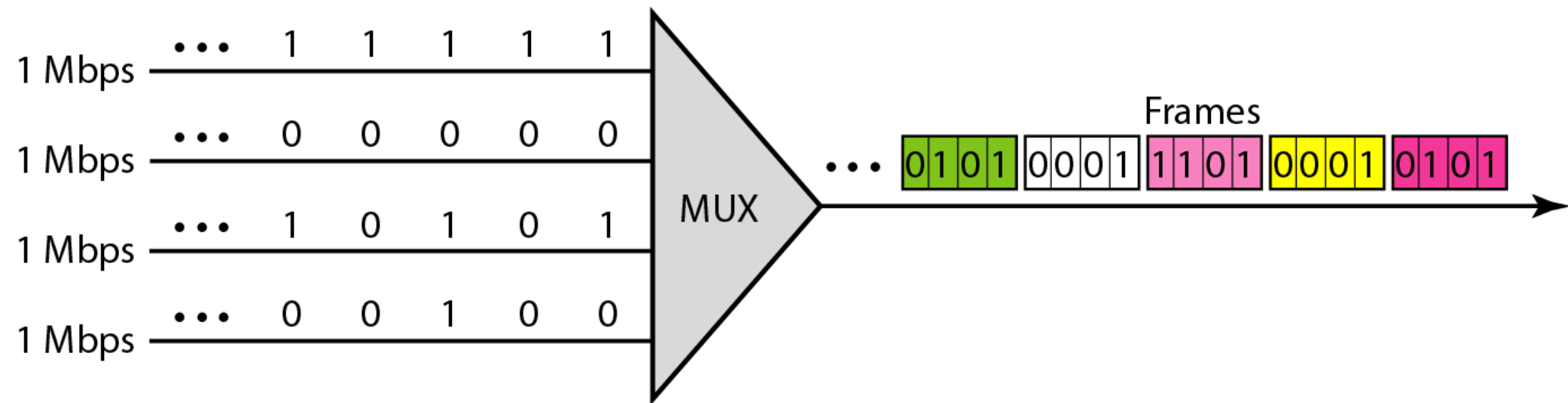
- a. The input bit duration is the inverse of the bit rate:
 $1/1 \text{ Mbps} = 1 \mu\text{s}.$*
- b. The output bit duration is one-fourth of the input bit duration, or $\frac{1}{4} \mu\text{s}.$*



Example 6.6 (continued)

- c. The output bit rate is the inverse of the output bit duration or $1/(4\mu\text{s})$ 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 = $4 \times 1 \text{ Mbps} = 4 \text{ Mbps}$.***
- 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.***

Figure 6.14 Example 6.6





Example 6.7

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

We can answer the questions as follows:

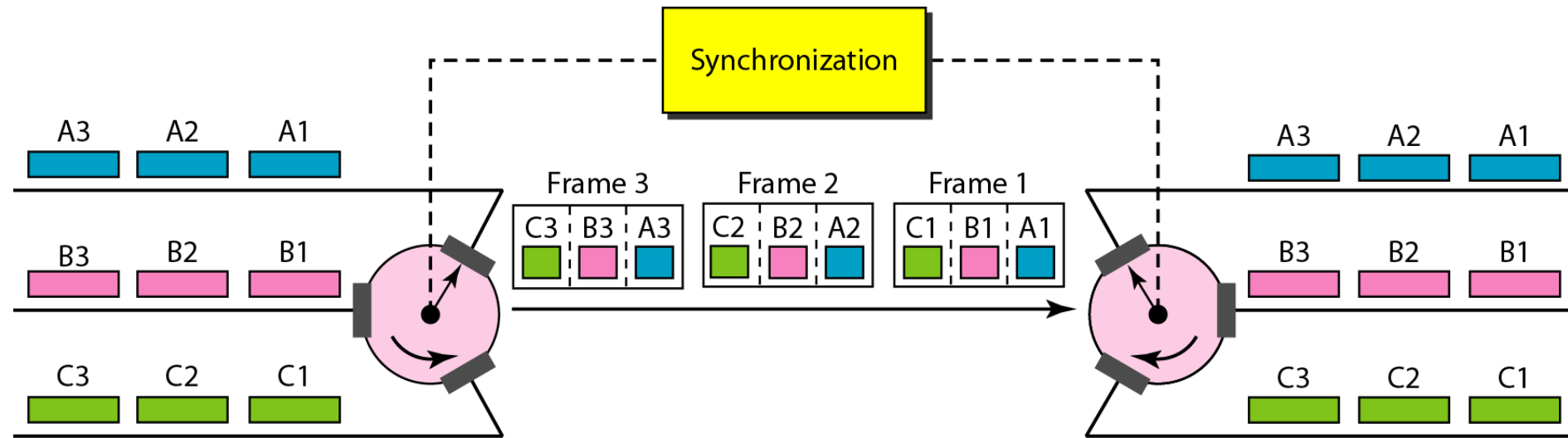
- a. The duration of 1 bit before multiplexing is $1 / 1$ kbps, or 0.001 s (1 ms).*
- b. The rate of the link is 4 times the rate of a connection, or 4 kbps.*



Example 6.7 (continued)

- c.*** *The duration of each time slot is one-fourth of the duration of each bit before multiplexing, or 1/4 ms or 250 μ s. 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 μ s.*
- 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 μ s, or 1 ms.*

Figure 6.15 Interleaving





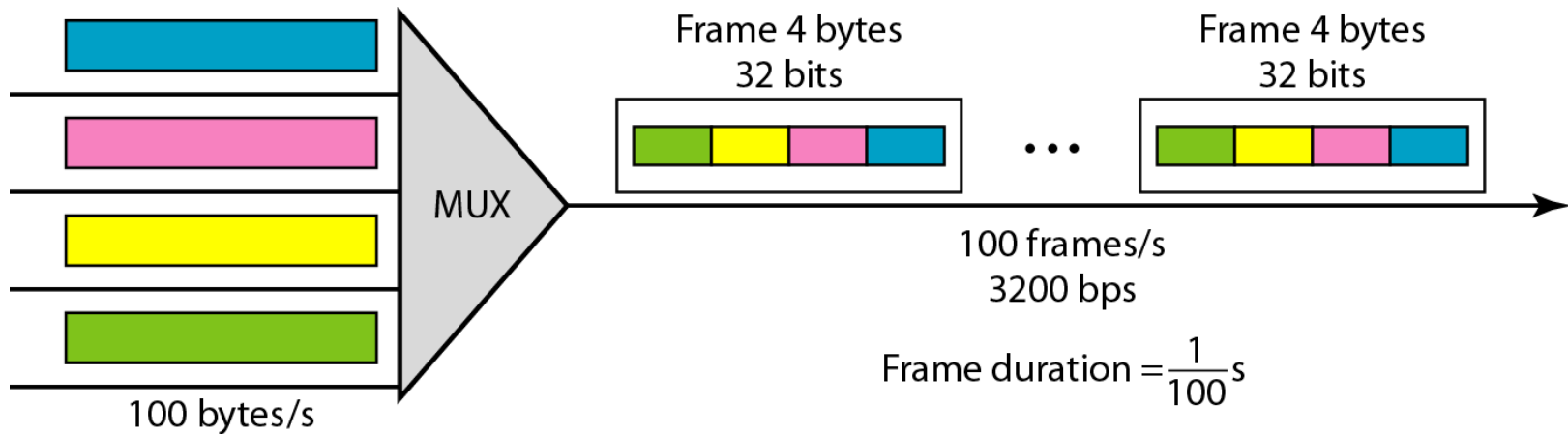
Example 6.8

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 in Figure 6.16. 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.

Figure 6.16 Example 6.8





Example 6.9

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 6.17 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 $20\ \mu\text{s}$. The frame rate is 50,000 frames per second, and each frame carries 8 bits; the bit rate is $50,000 \times 8 = 400,000$ bits or 400 kbps. The bit duration is $1/400,000$ s, or $2.5\ \mu\text{s}$.

Figure 6.17 *Example 6.9*

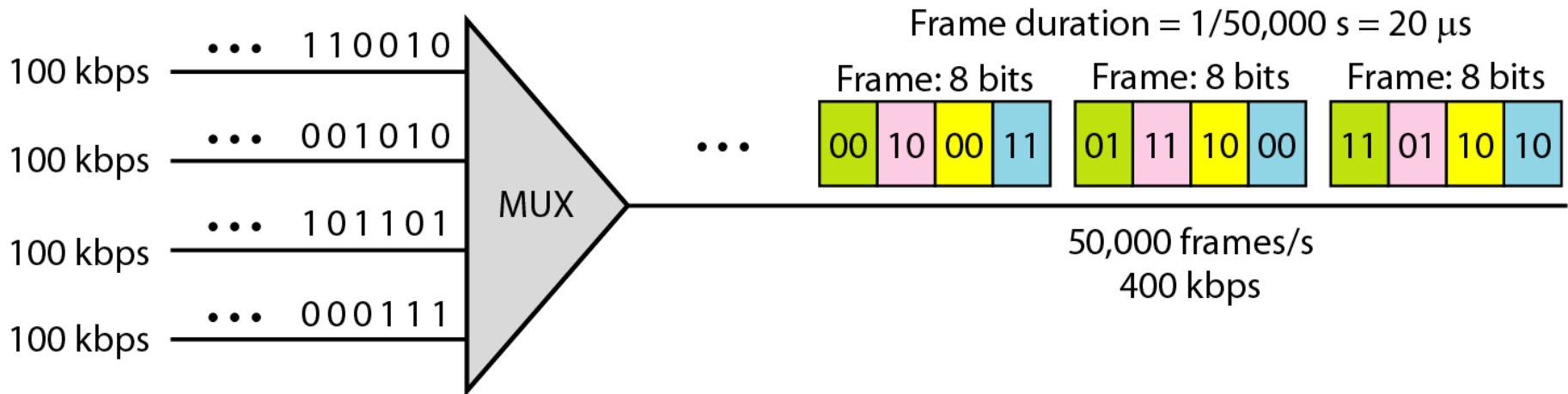


Figure 6.18 *Empty slots – low efficiency of Synchronous TDM*

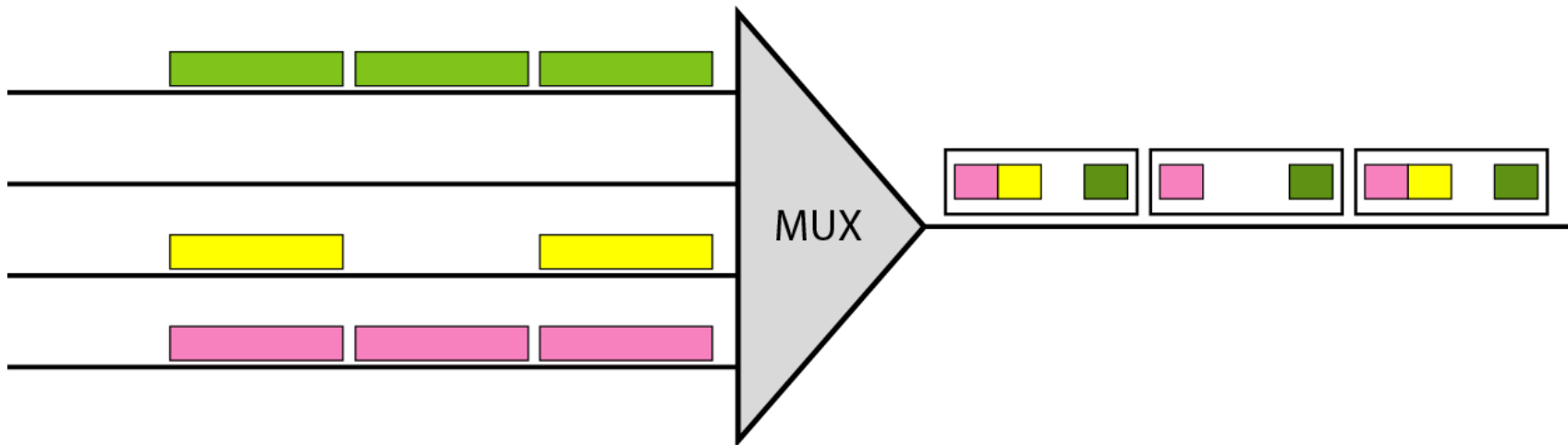


Figure 6.19 *1-Multilevel multiplexing*

If the input data rates are *not the same*, three strategies, or a combination of them, can be used (*multilevel multiplexing, multiple-slot allocation, and pulse stuffing*).

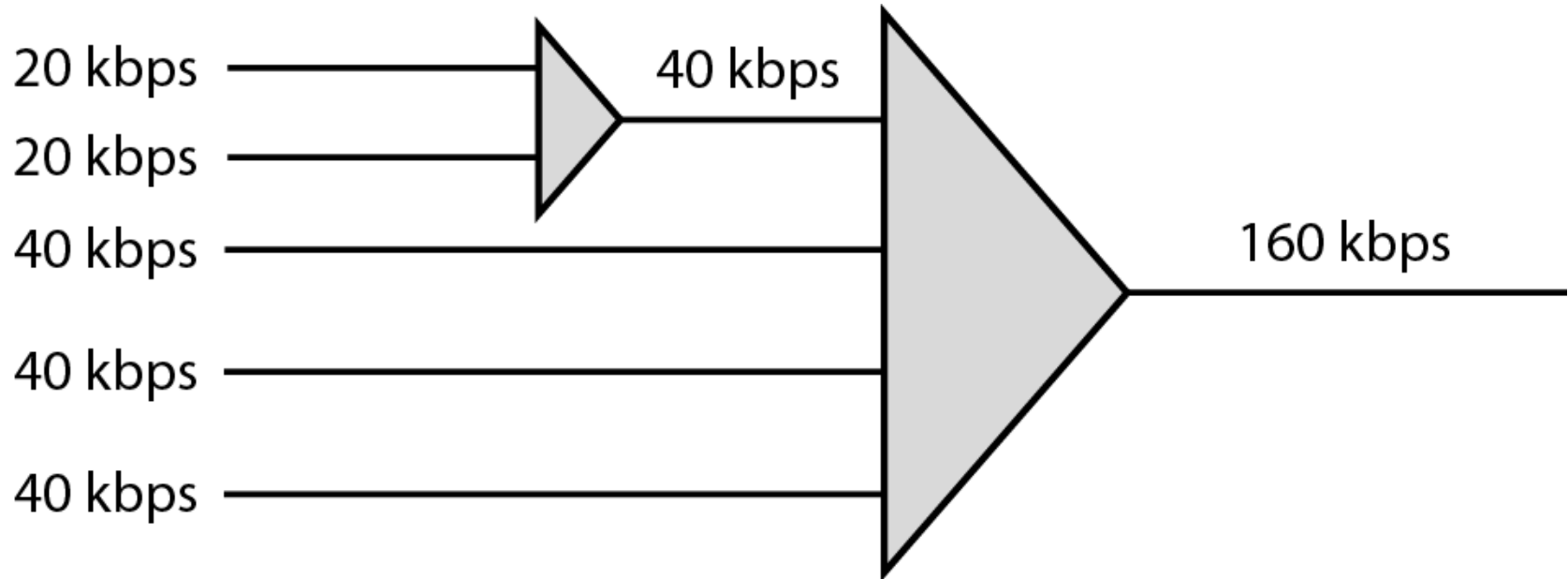


Figure 6.20 *2-Multiple-slot multiplexing*

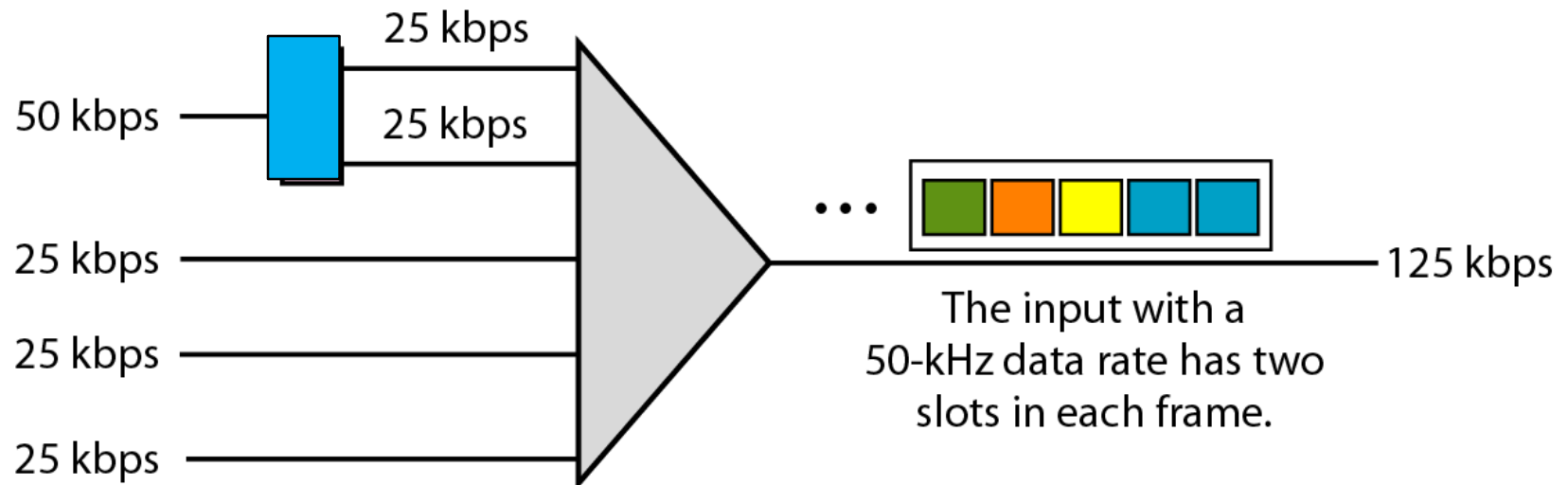


Figure 6.21 3-Pulse stuffing

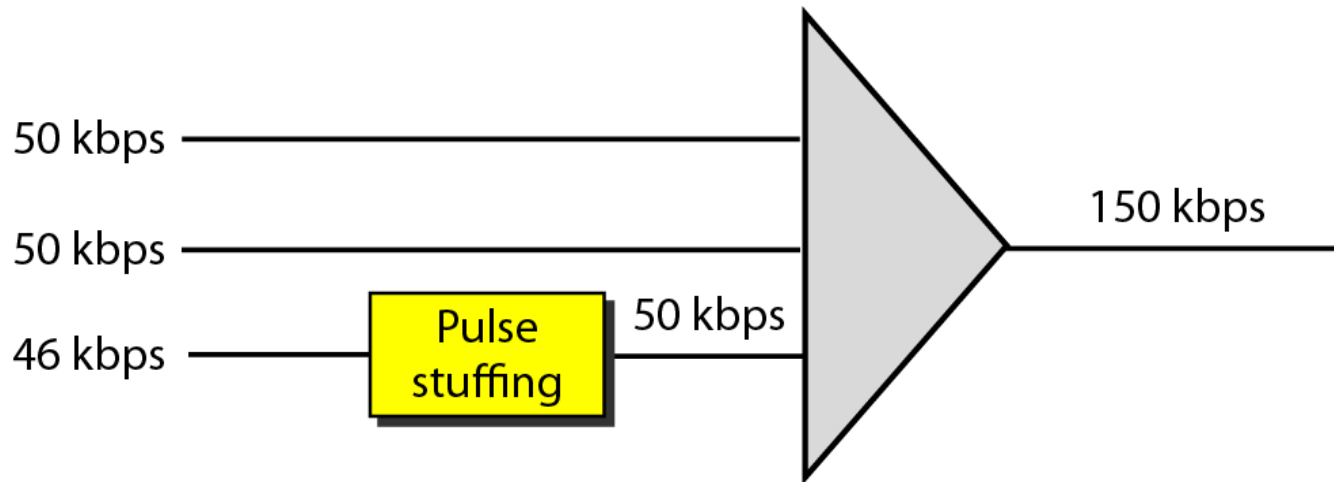
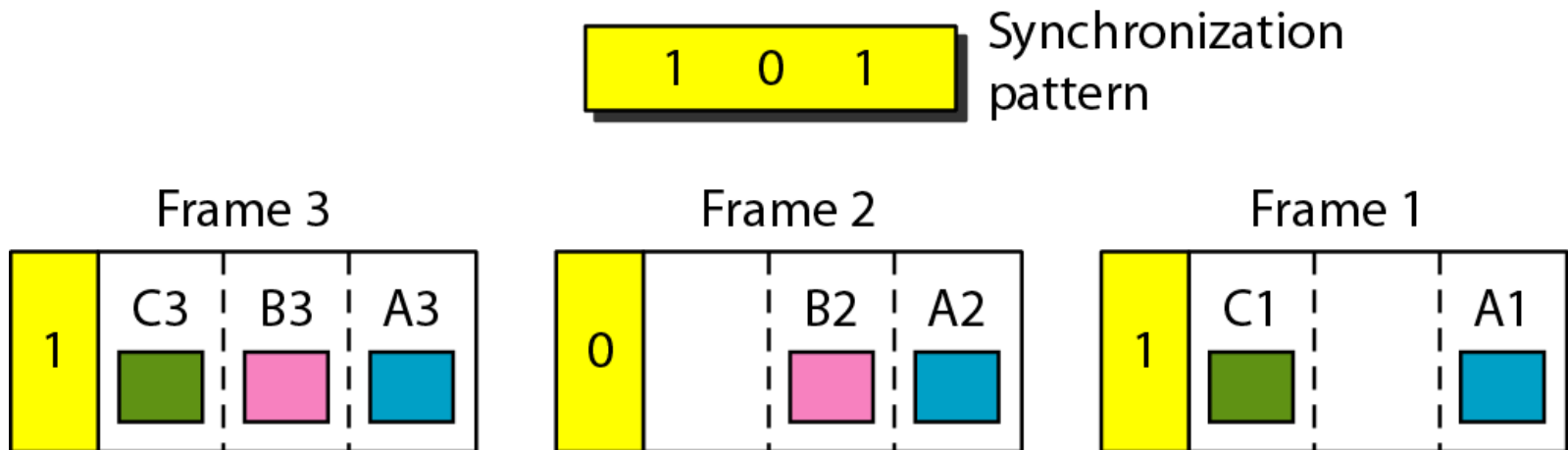


Figure 6.22 *Framing bits*

If the multiplexer and the demultiplexer are not synchronized, one or more **synchronization bits** are usually added to the beginning of each frame. This bits called framing bits.





Example 6.10

We have four sources, each creating 250 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

We can answer the questions as follows:

- a.** *The data rate of each source is $250 \times 8 = 2000 \text{ bps} = 2 \text{ kbps}$.*



Example 6.10 (continued)

- 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 $4 \times 8 + 1 = 33$ bits.***



Example 6.11

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 $100,000 \text{ frames/s} \times 3 \text{ bits per frame}$, or 300 kbps.

Figure 6.23 *Digital hierarchy*

Telephone companies implement TDM through a hierarchy of digital signals, called **digital signal (DS) service** or digital hierarchy.

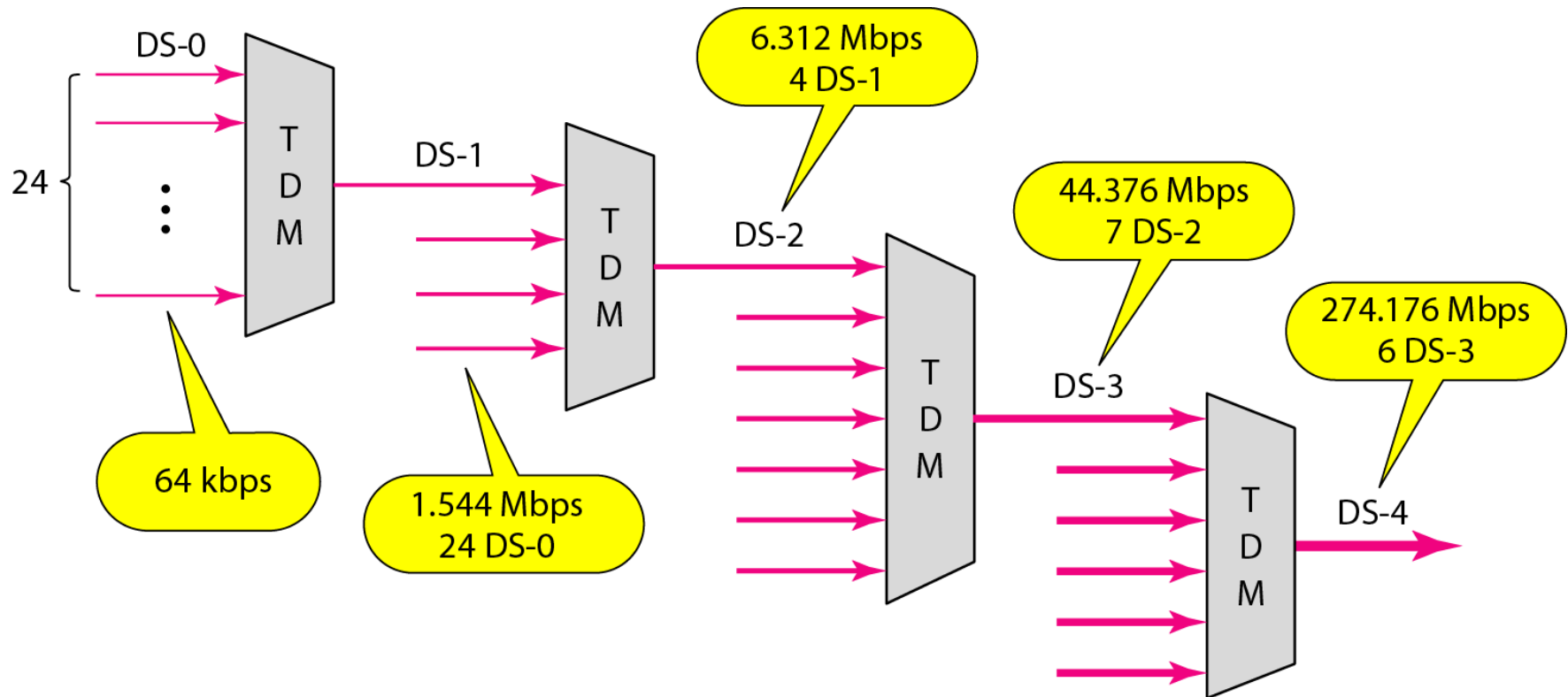
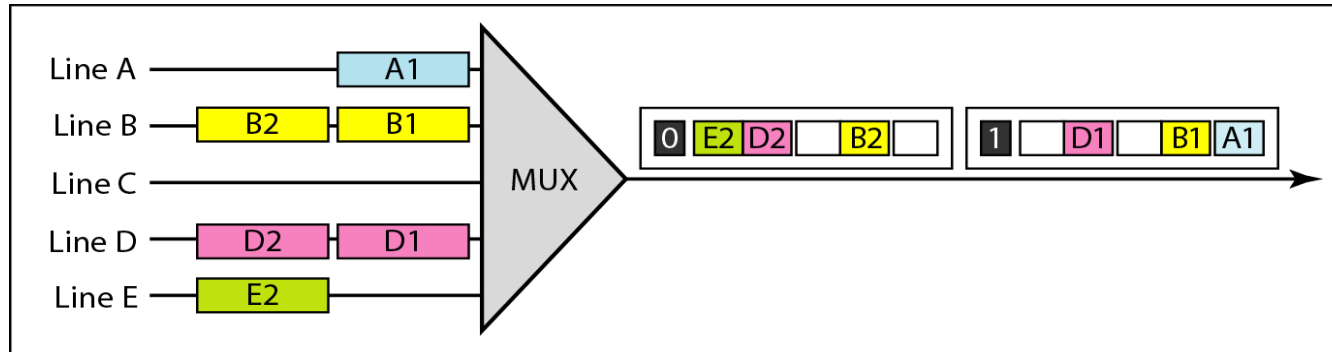


Table 6.1 DS and T line rates

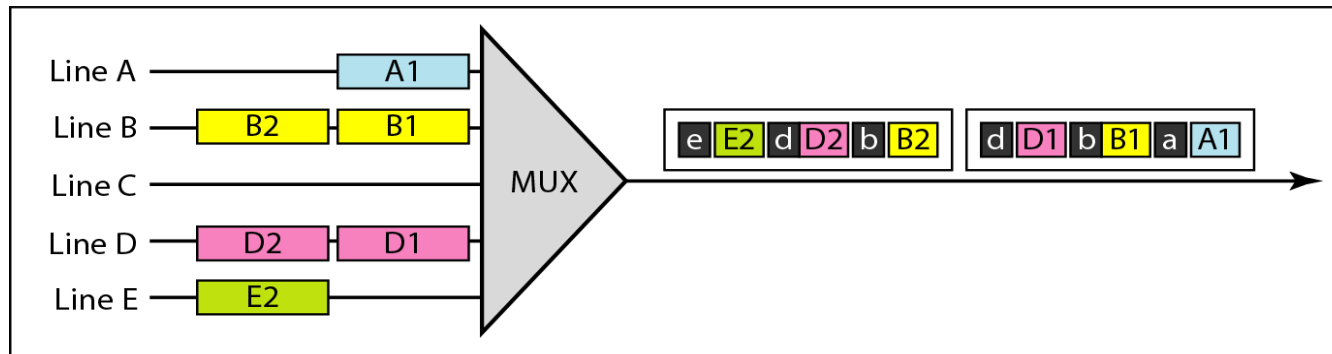
<i>Service</i>	<i>Line</i>	<i>Rate (Mbps)</i>	<i>Voice Channels</i>
DS-1	T-1	1.544	24
DS-2	T-2	6.312	96
DS-3	T-3	44.736	672
DS-4	T-4	274.176	4032

DS-O, 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. So far only T-1 and T-3 lines are commercially available

Figure 6.26 *Synchronous vs Statistical TDM*



a. Synchronous TDM



b. Statistical TDM

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