Module 3

Bandwidth Utilization: Multiplexing and Spreading Spectrum

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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*

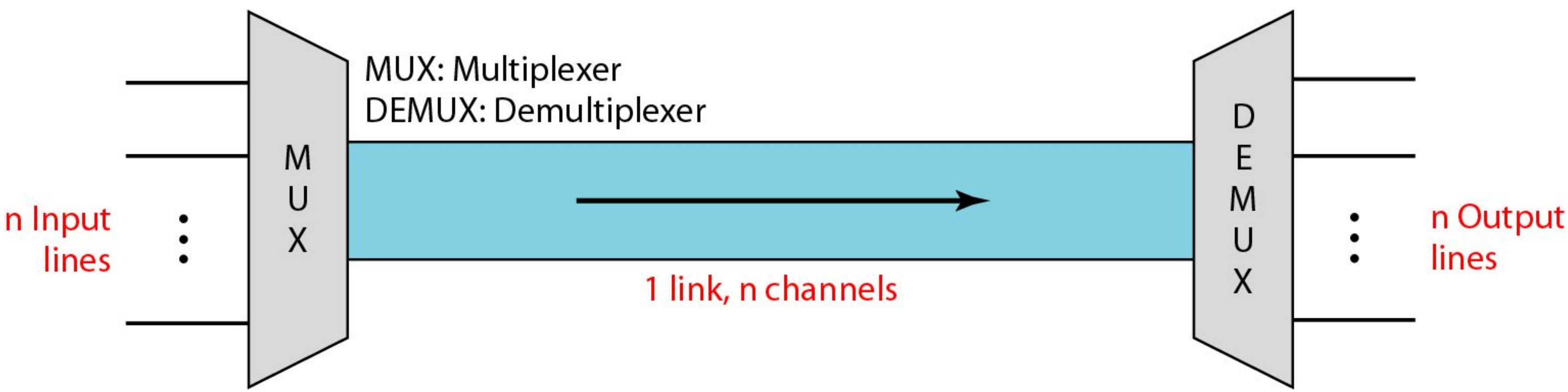


Figure 6.2 *Categories of multiplexing*

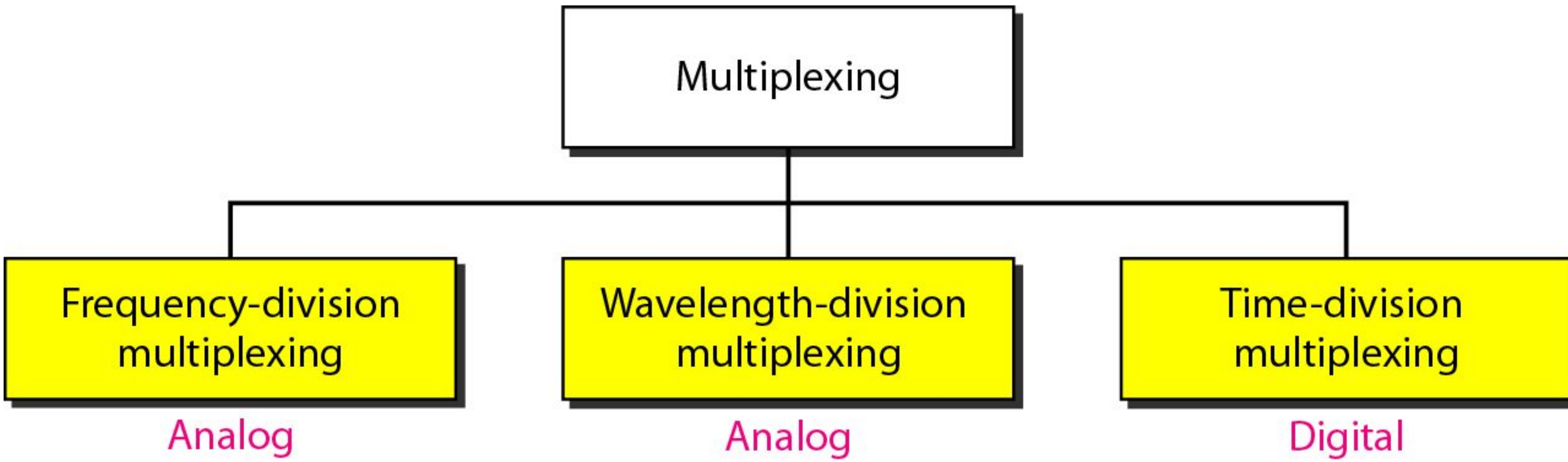
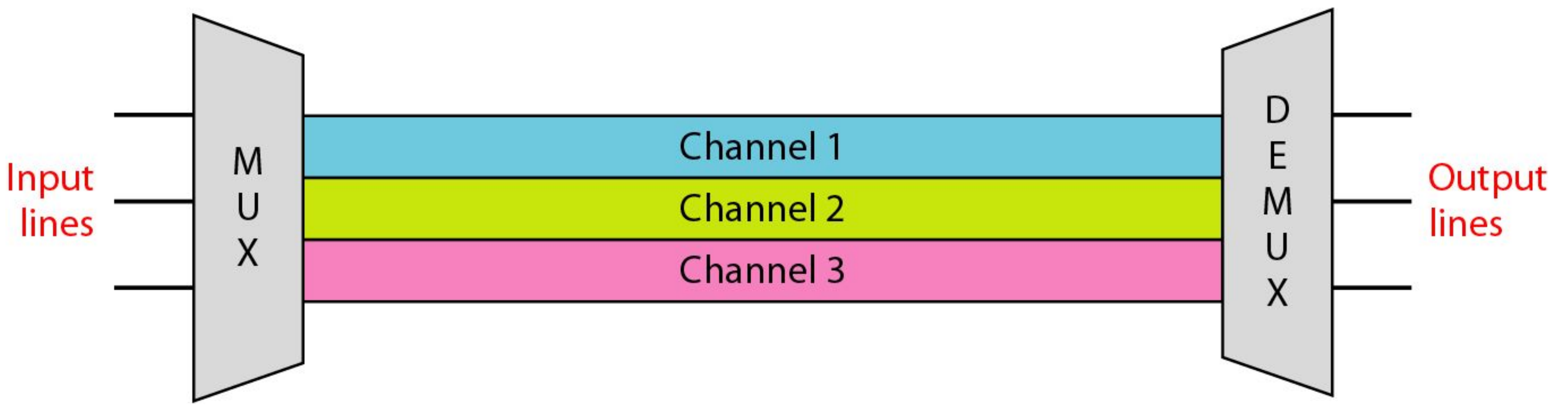


Figure 6.3 *Frequency-division multiplexing*



Note

FDM is an analog multiplexing technique that combines analog signals.

Figure 6.4 *FDM process*

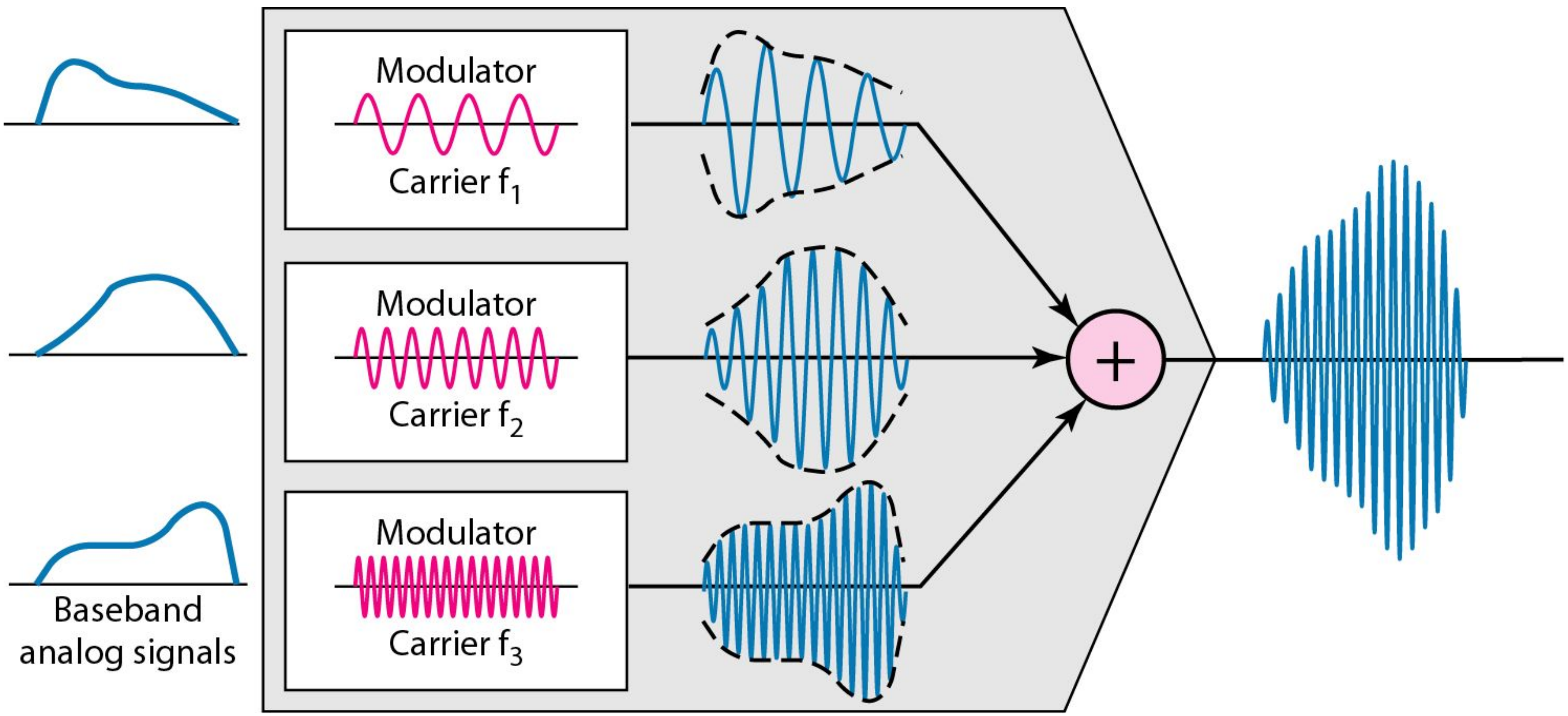
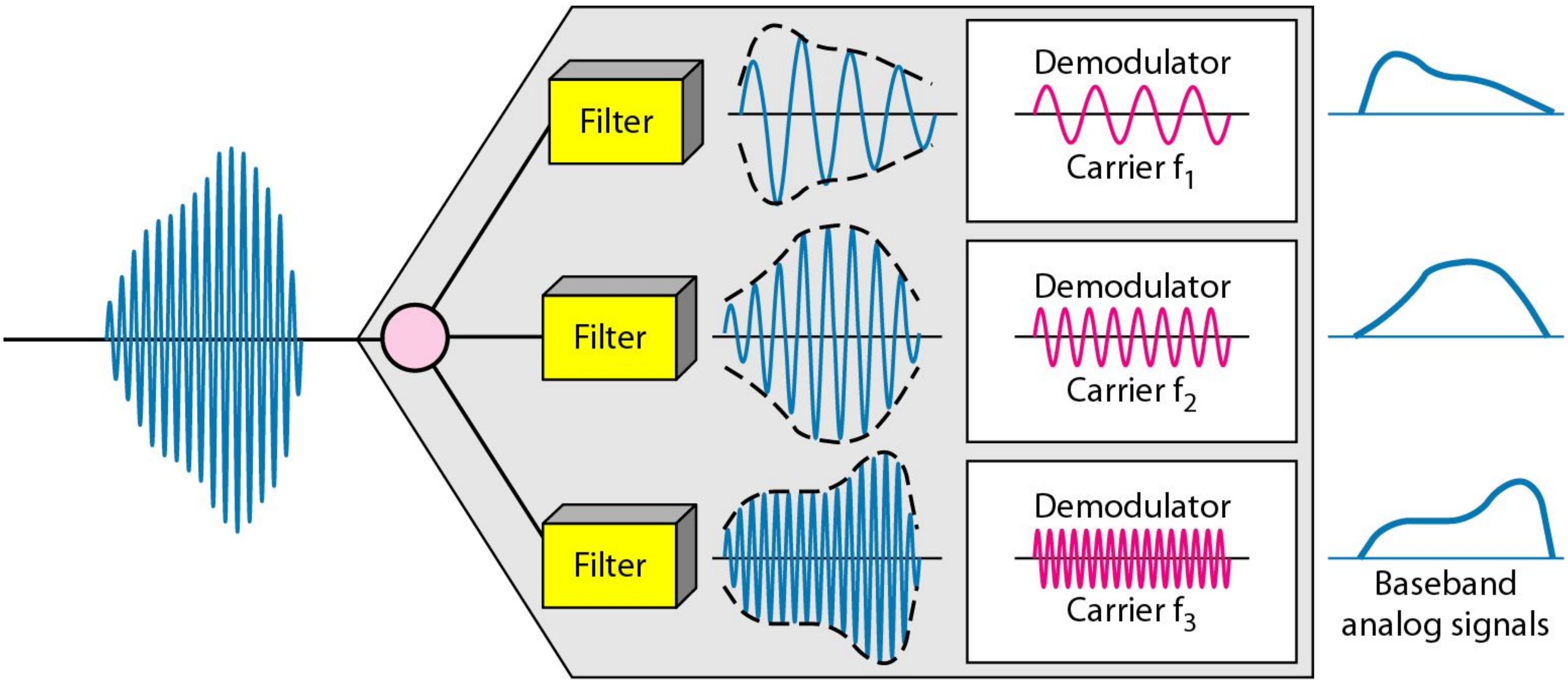


Figure 6.5 *FDM demultiplexing example*



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

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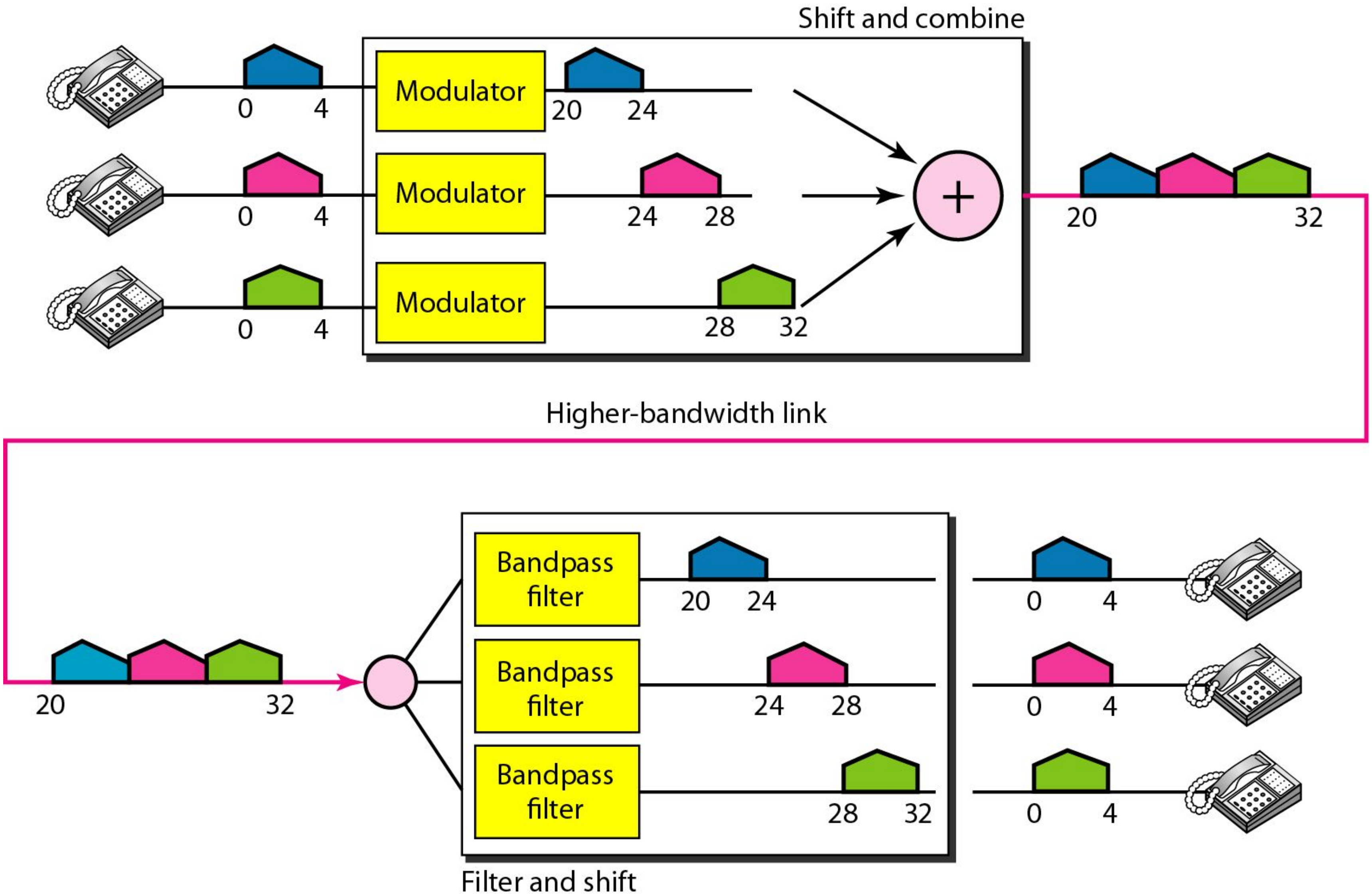
Solution

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 :

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?

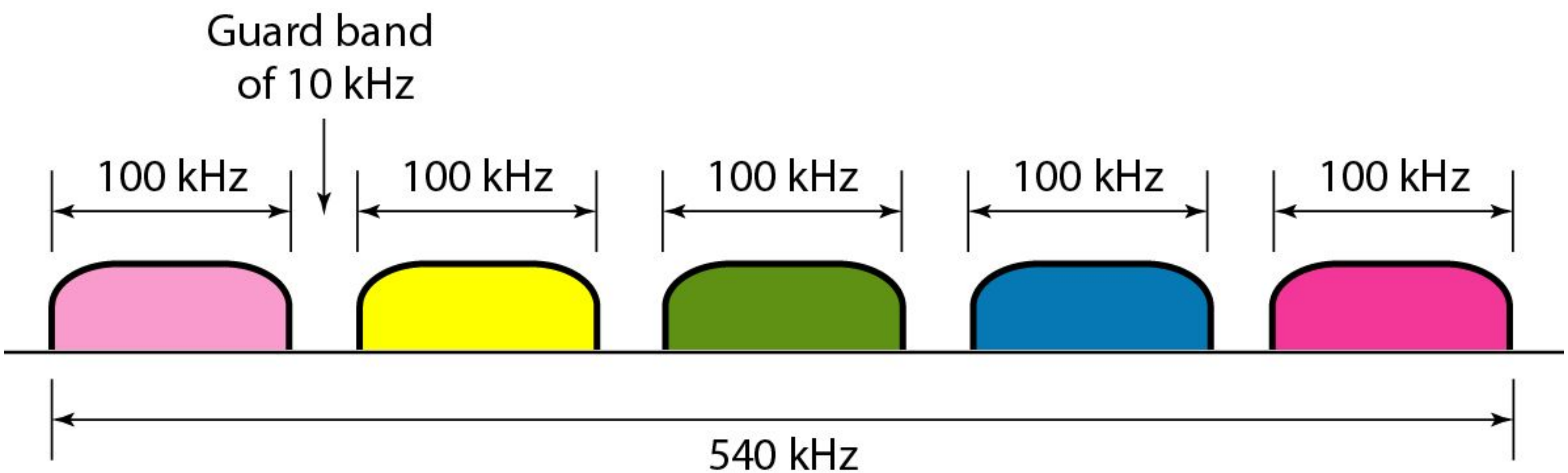
Solution

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*



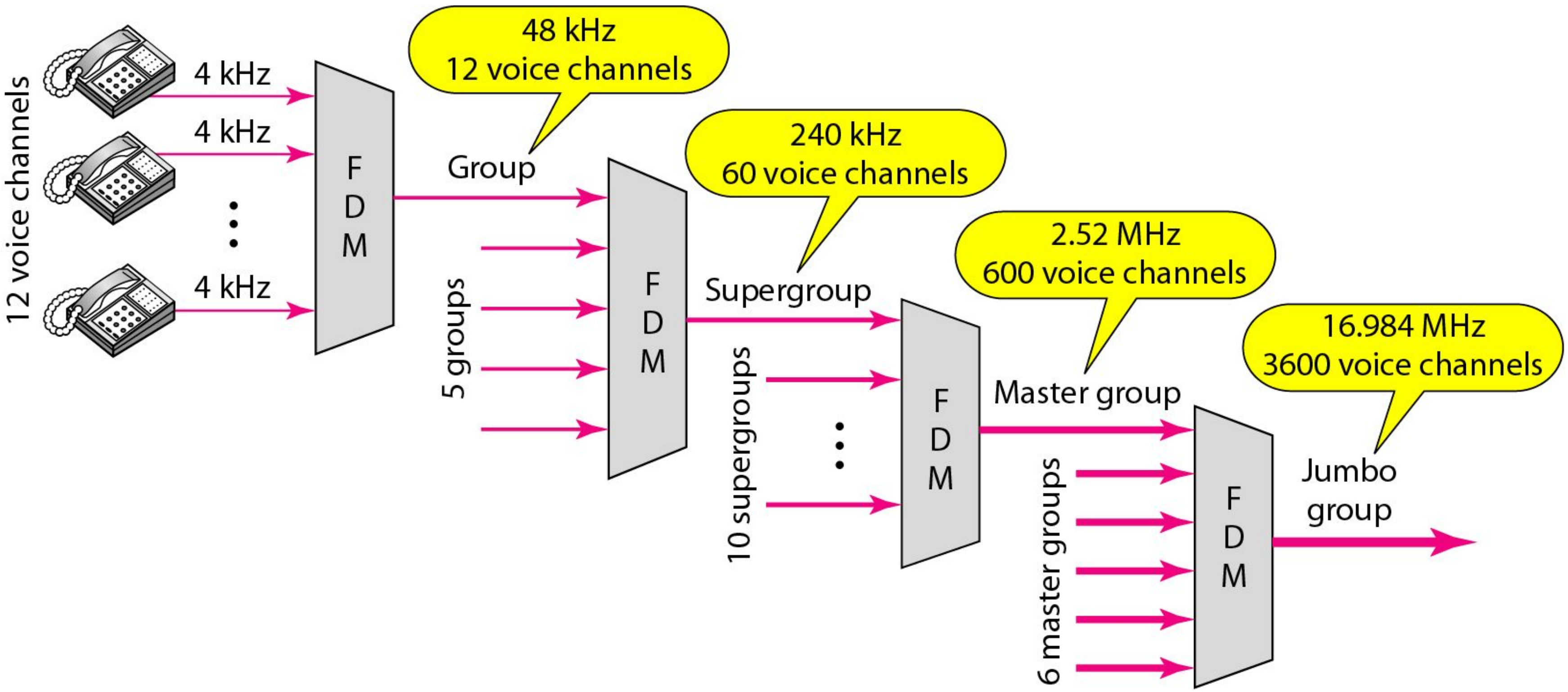
The Analog Carrier System

- To maximize the efficiency of their infrastructure, telephone companies have traditionally multiplexed signals from lower-bandwidth lines onto higher-bandwidth lines.
- In this way, many switched or leased lines can be combined into fewer but bigger channels.
- For analog lines, FDM is used.
- One of these hierarchical systems used by telephone companies is made up of groups, supergroups, master groups, and jumbo groups (see Figure 6.9)

The Analog Carrier System

- **Analog hierarchy,** 12 voice channels are multiplexed onto a higher-bandwidth line to create a **group.**
- A group has 48 kHz of bandwidth and supports 12 voice channels.
- At the next level, up to five **groups** can be multiplexed to create a composite signal called a **supergroup.**
- A **supergroup** has a bandwidth of 240 kHz and supports up to 60 voice channels.
- **Supergroups** can be made up of either five groups or 60 independent voice channels.
- At the next level, 10 supergroups are multiplexed to create a **master group.**
- A master group must have 2.40 MHz of bandwidth, but the need for guard bands between the supergroups increases the necessary bandwidth to 2.52 MHz.
- Master groups support up to 600 voice channels.
- Finally, six master groups can be combined into a **jumbo group.** A jumbo group must have 15.12 MHz (6 × 2.52 MHz) but is augmented to 16.984 MHz to allow for guard bands between the master groups.

Figure 6.9 *Analog hierarchy*



Wavelength-Division Multiplexing (WDM)

Note

WDM is an analog multiplexing technique to combine optical signals.

Figure 6.10 *Wavelength-division multiplexing*

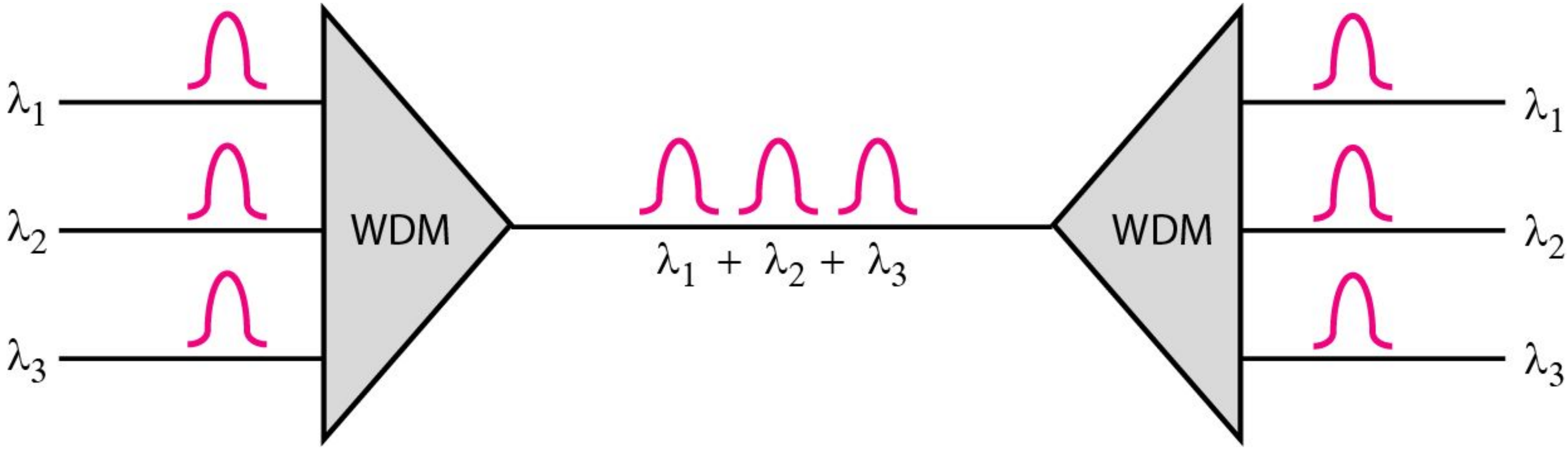


Figure 6.11 *Prisms in wavelength-division multiplexing and demultiplexing*

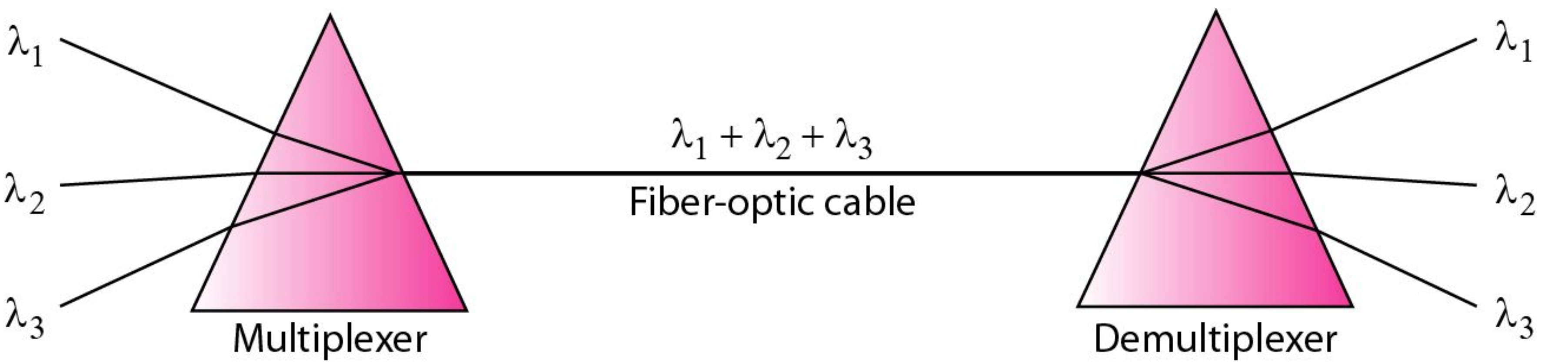
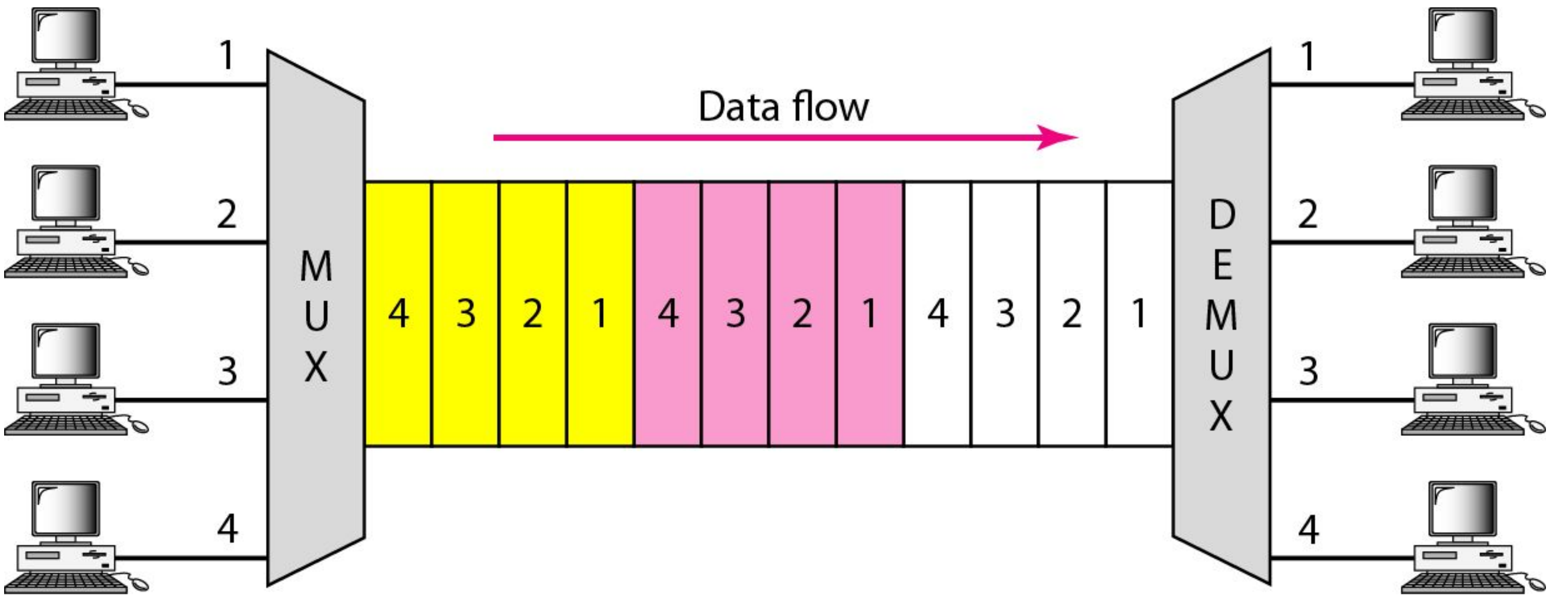


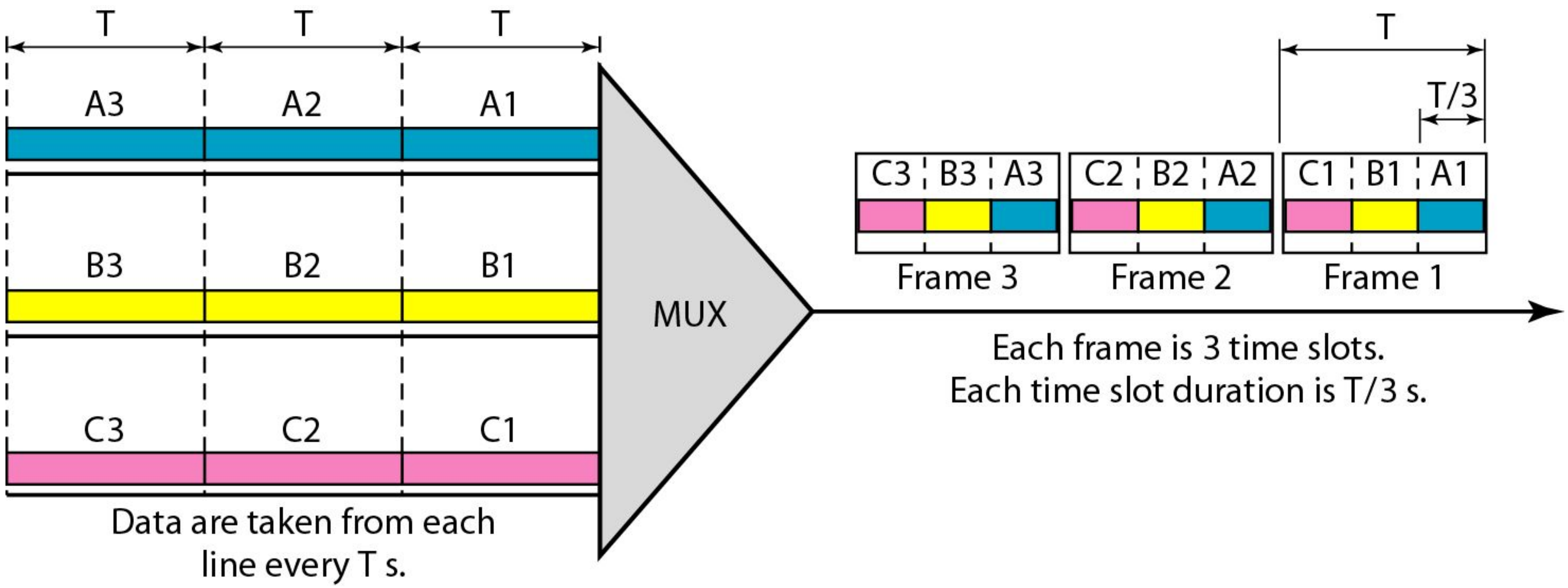
Figure 6.12 Time-Division Multiplexing (*TDM)*



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 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

We can answer the questions as follows:

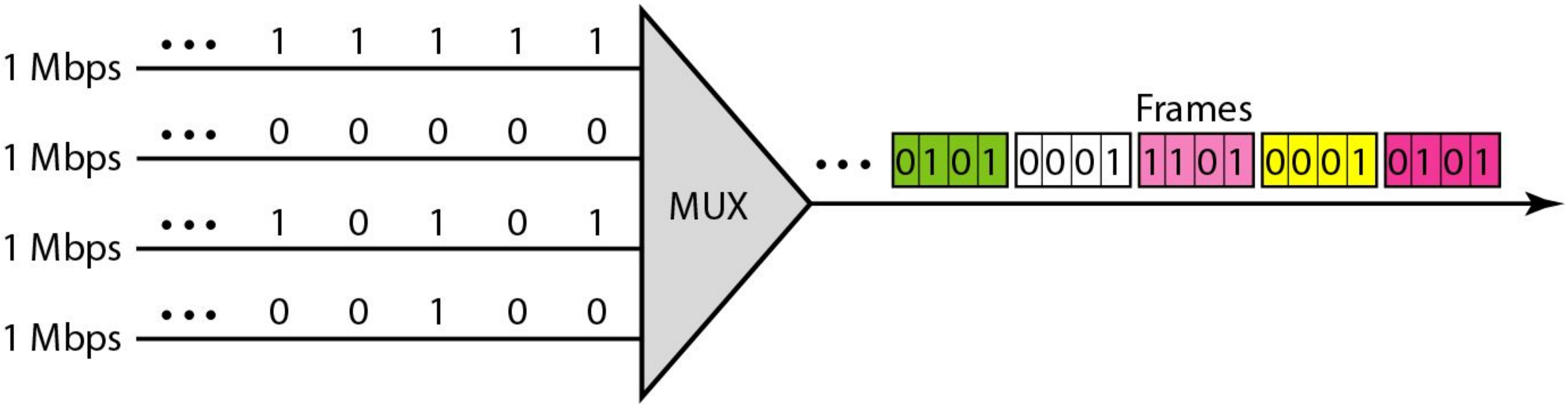
a. *The data rate of each input connection is 1 kbps. This means that the bit duration is 1/1000 s or 1 ms. The duration of the input time slot is 1 ms (same as bit duration).*

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 × 1/3 ms, or 1 ms. The duration of a frame is the same as the duration of an input unit.

Figure 6.14 *Example 6.6*



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 Mbps = 1 μs.

b. The output bit duration is one-fourth of the input bit duration, or ¼ μs.

Example 6.6 (continued)

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.*

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)

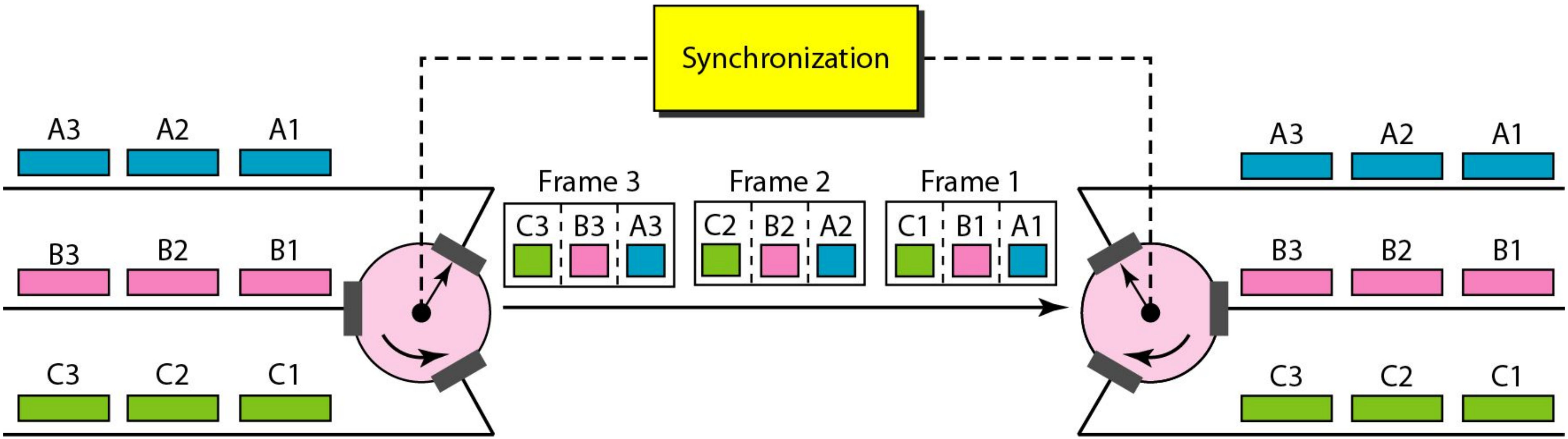
c. The duration of each time slot is one-fourth of the duration of each bit before multiplexing, or 1/4 ms or 250 μs. Note that we can also calculate this from the data rate of the link, 4 kbps. The bit duration is the inverse of the data rate, or 1/4 kbps or 250 μs.

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 multiplexing side and the other on the demultiplexing side.
- The **switches** 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 <u>send a unit onto the path.</u> This process is called **interleaving.**
- On the demultiplexing side, as the switch opens in front of a connection, that connection has the opportunity to <u>receive a unit from the path</u>.

Figure 6.15 *Interleaving*



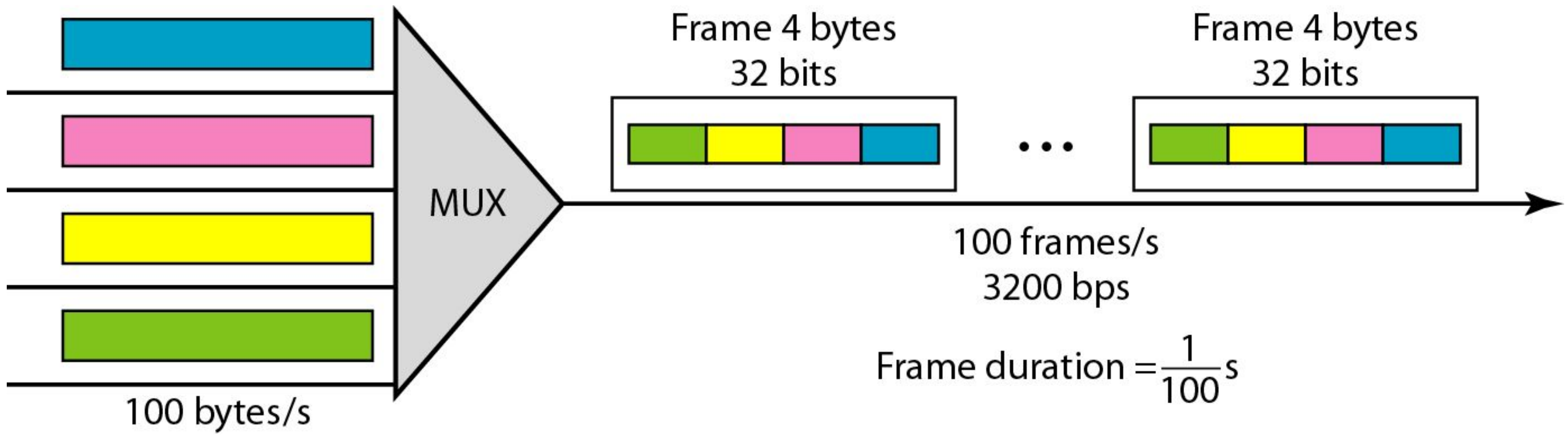
Example 6.8

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*



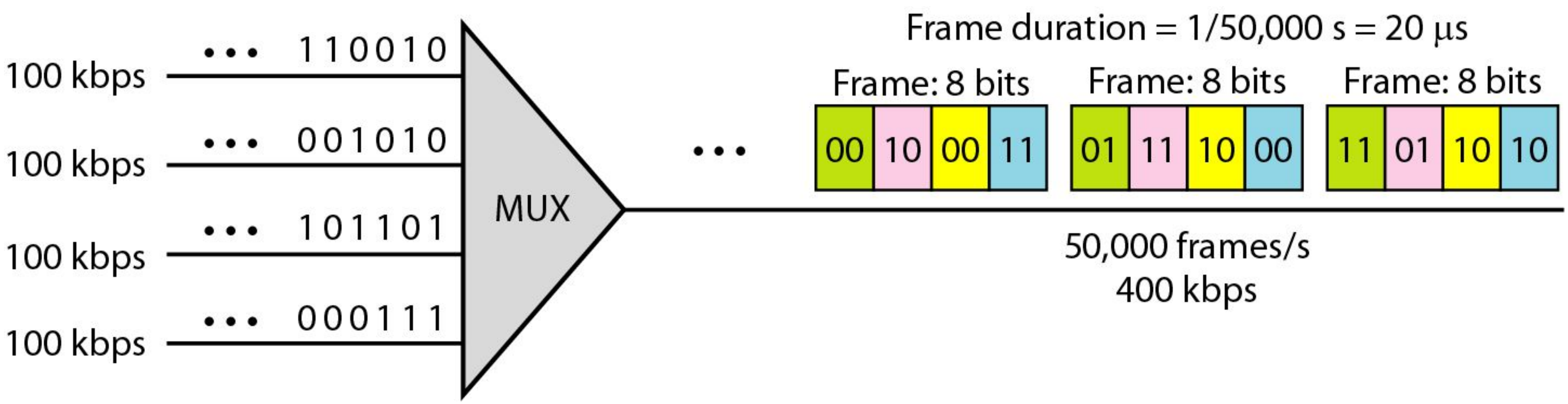
Example 6.9

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 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.

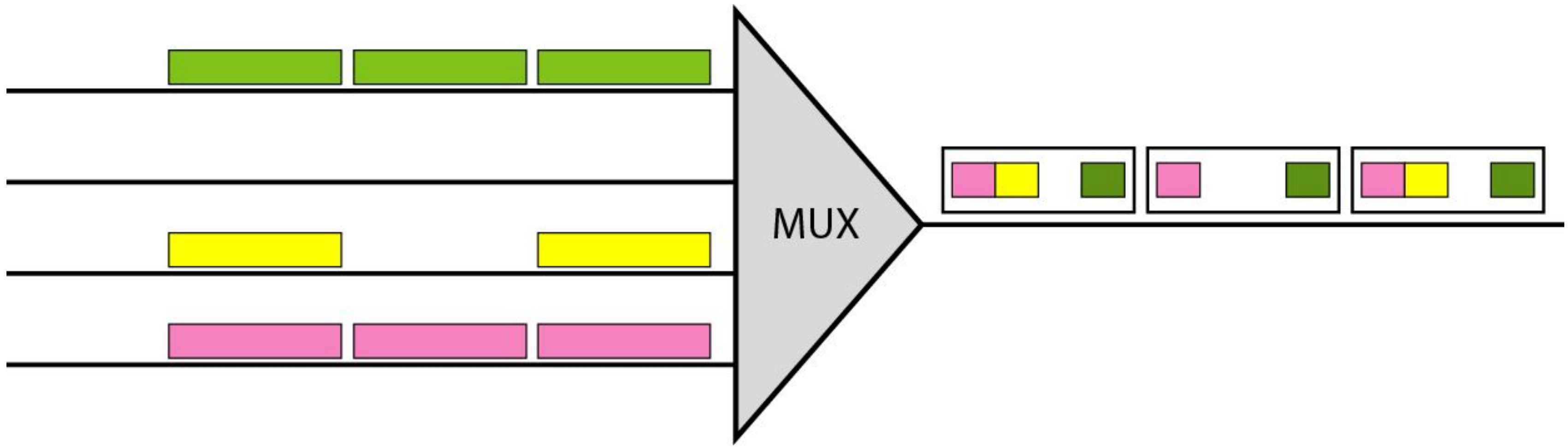
Figure 6.17 *Example 6.9*



Empty Slots & Statistical TDM

- Synchronous TDM is not as efficient as it could be.
- If a source does not have data to send, the corresponding slot in the output frame is empty.
- See next figure, the first output frame has three slots filled, the second frame has two slots filled, and the third frame has three slots filled.
- No frame is full.
- Problem.
- Solution?
- Statistical TDM can improve the efficiency by removing the empty slots from the frame.

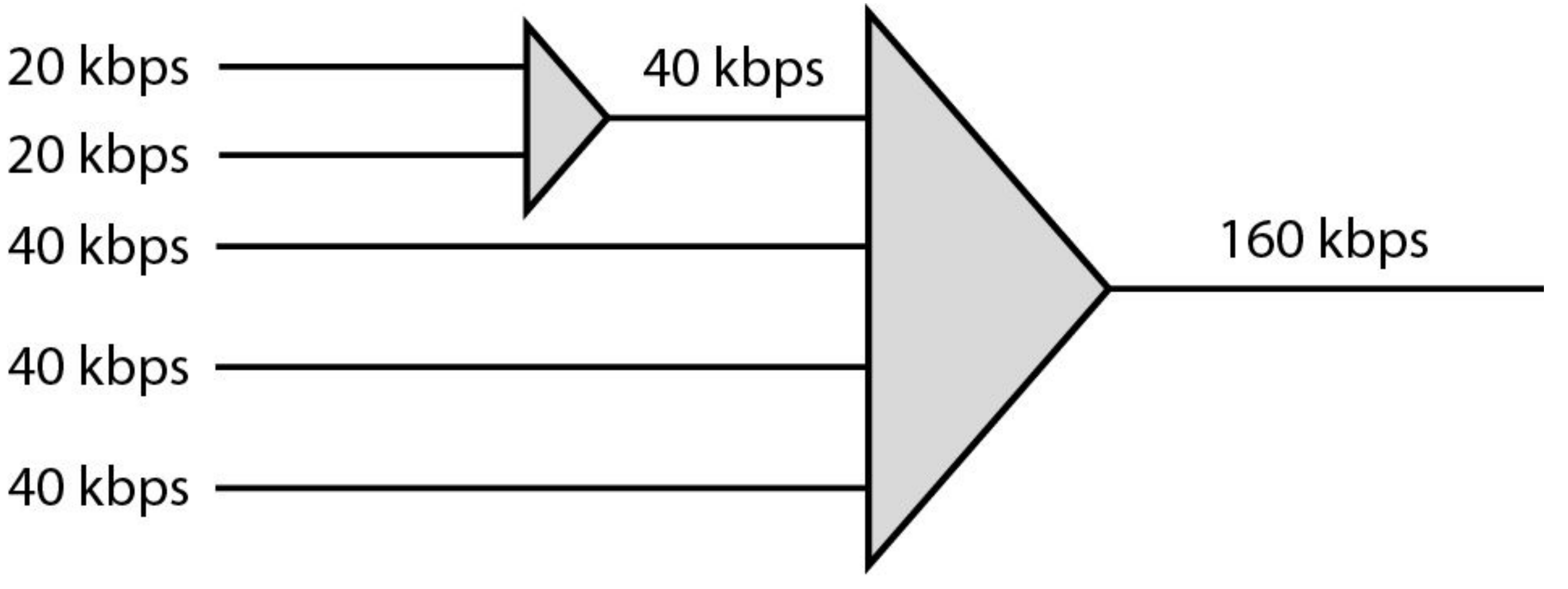
Figure 6.18 *Empty slots*



Multilevel Multiplexing

- Multilevel multiplexing is a technique used when the data rate of an input line is a multiple of others.
- For example, in Figure 6.19, we have two inputs of 20 kbps and three inputs of 40 kbps.
- The first two input lines can be multiplexed together to provide a data rate equal to the last three.
- A second level of multiplexing can create an output of 160 kbps.

Figure 6.19 *Multilevel multiplexing*



Multiple-Slot Allocation

- Sometimes it is more efficient to allot more than one slot in a frame to a single input line.
- For example, we might have an input line that has a data rate that is a multiple of another input.
- We insert a **demultiplexer** in the line to make two inputs out of one.

Figure 6.20 *Multiple-slot multiplexing*

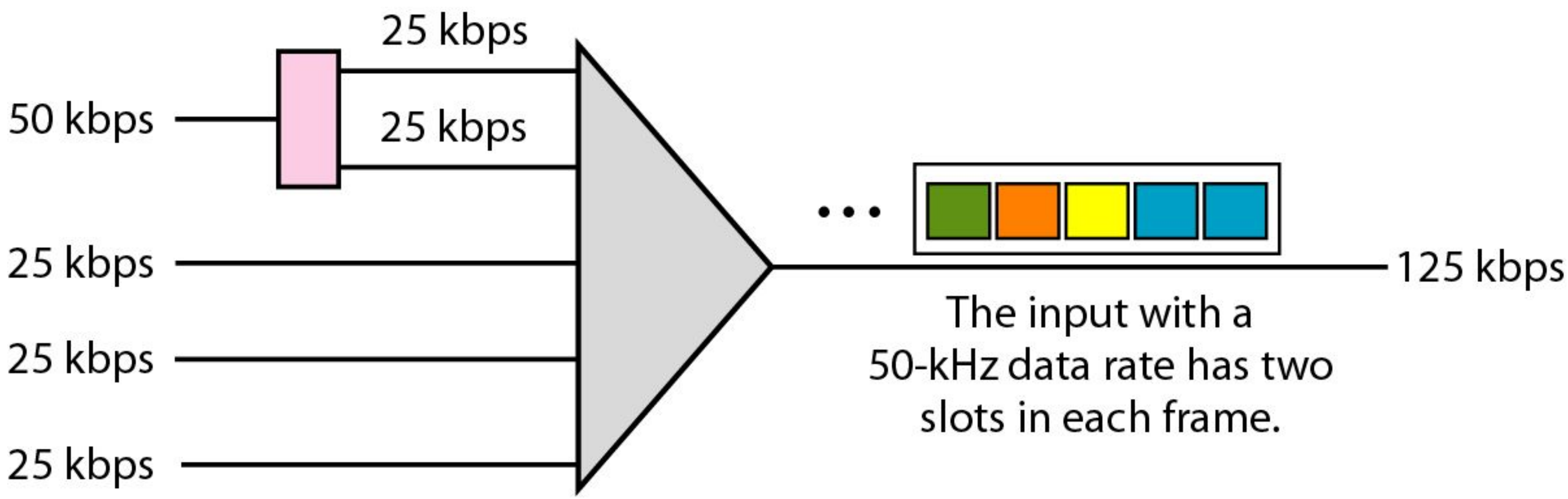
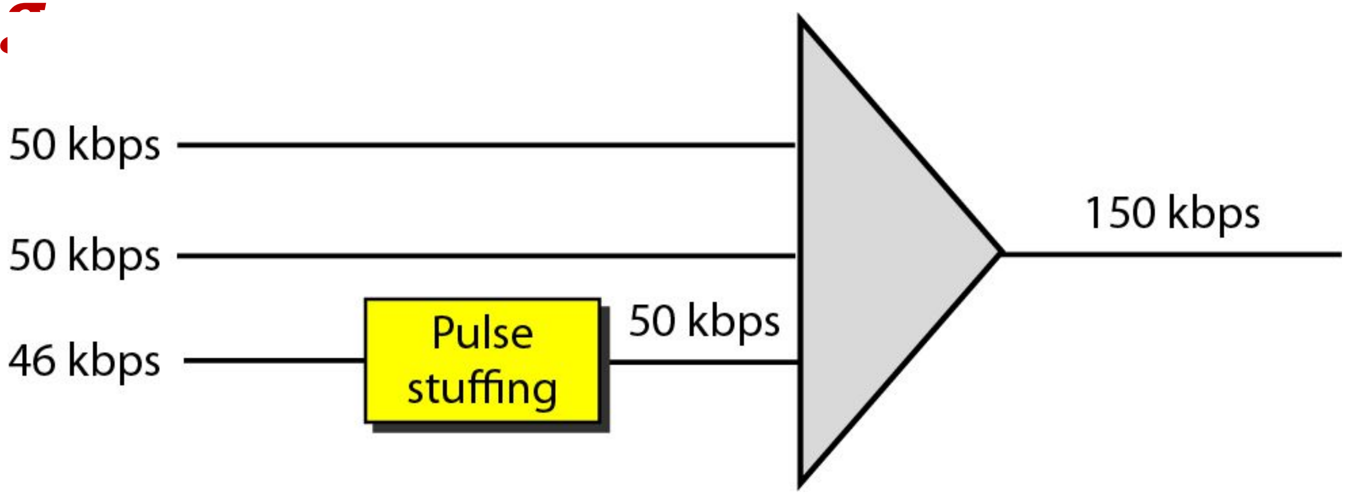
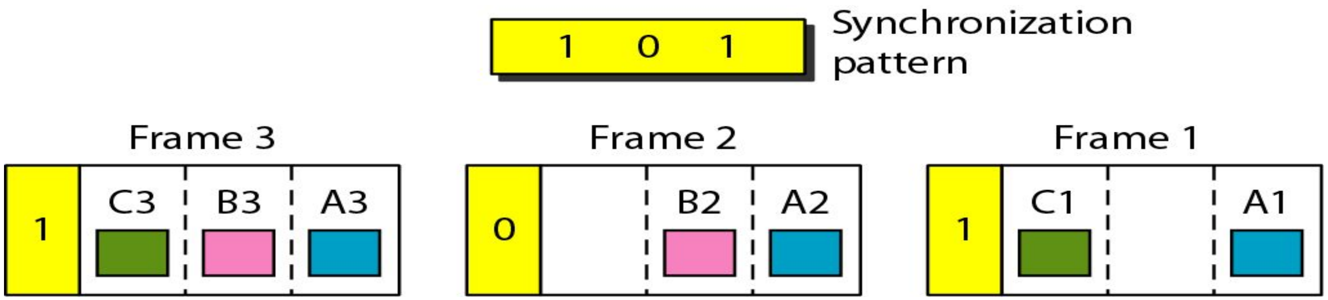


Figure 6.21 *Pulse stuffing*



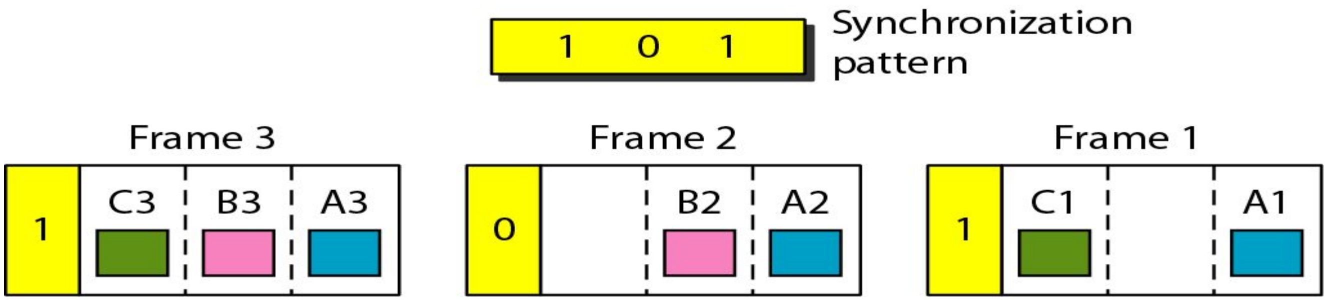
- Sometimes the bit rates of sources are not multiple integers of each other. Therefore, neither of the above two techniques can be applied.
- One solution is to make the highest input data rate the dominant data rate and then **add dummy bits to the** input lines with lower rates. This will increase their rates.
- This technique is called ***pulse stuffing,*** *bit padding,* or *bit stuffing.*

Figure 6.22 *Framing bits*



- The implementation of TDM is not as simple as that of FDM.
- 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.

Figure 6.22 *Framing bits*



- 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 .**

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 $250 \times 8 = 2000$ bps = 2 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?

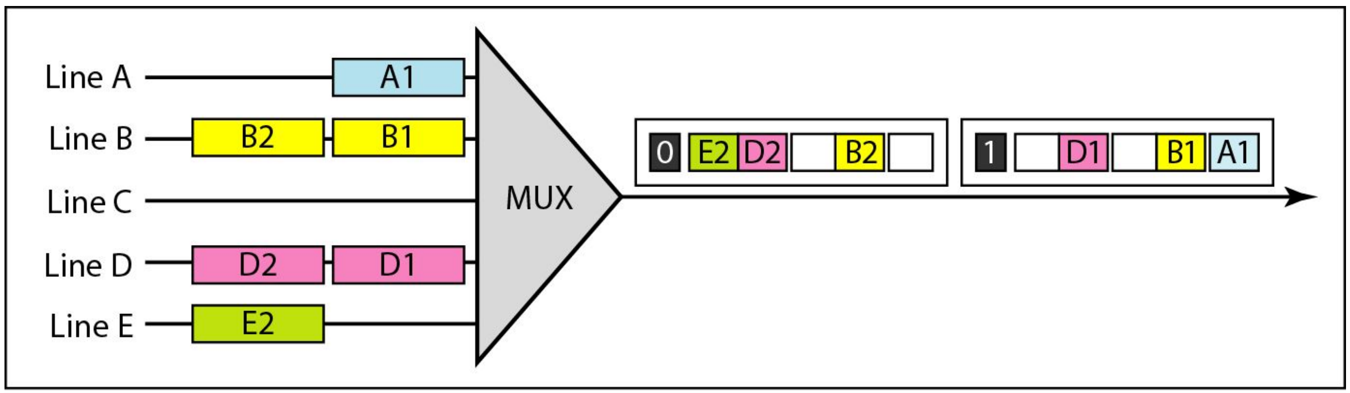
Solution

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 frames/s × 3 bits per frame, or 300 kbps.

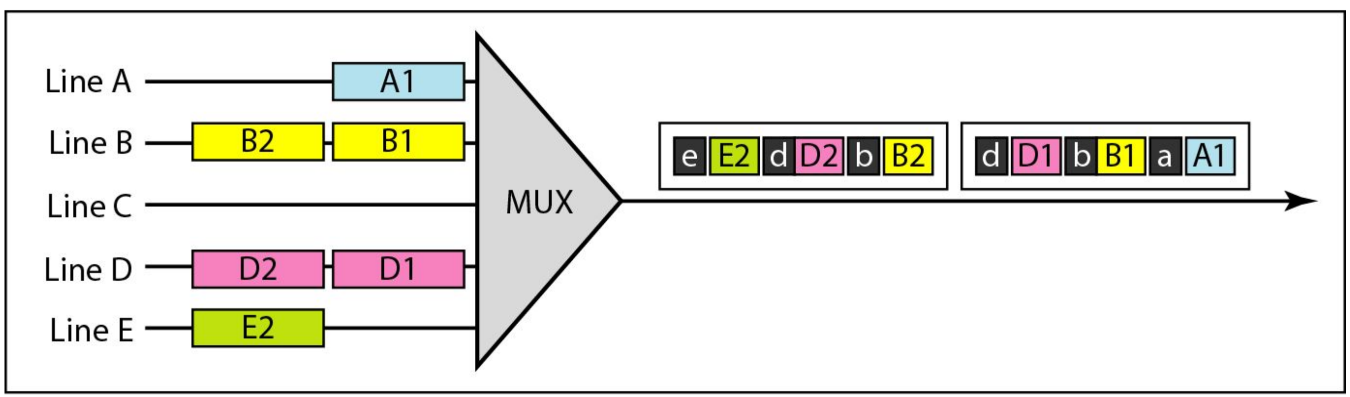
Statistical Time-Division Multiplexing

- As we saw in the previous section, 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.
- Figure 6.26 shows a synchronous and a statistical TDM example.

Figure 6.26 *TDM slot comparison*



a. Synchronous TDM



b. Statistical TDM

Definitions

Addressing

- In synchronous TDM, there is no need for addressing; synchronization and pre-assigned relationships between the inputs and outputs serve as an address.
- In statistical multiplexing, there is no fixed relationship between the inputs and outputs because there are no preassigned or reserved slots.
- The addressing in its simplest form can be n bits to define N different output lines with $n = \log 2\ N$.
- For example, for eight different output lines, we need a 3-bit address.

Definitions

Slot Size

- Since a slot carries both data and an address in statistical TDM, the ratio of the data size to address size must be reasonable to make transmission efficient.
- For example, it would be inefficient to send 1 bit per slot as data when the address is 3 bits.
- This would mean an overhead of 300 percent.
- In statistical TDM, a block of data is usually many bytes while the address is just a few bytes.

Definitions

No Synchronization Bit

- There is another difference between synchronous and statistical TDM, but this time it is at the frame level.
- The frames in statistical TDM need not be synchronized, so we do not need synchronization bits.

Definitions

Bandwidth

- In statistical TDM, the capacity of the link is normally less than the sum of the capacities of each channel.
- The designers of statistical TDM define the capacity of the link based on the statistics of the load for each channel.
- If on average only *x* percent of the input slots are filled, the capacity of the link reflects this. Of course, during peak times, some slots need to wait.