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; i.e., sharing of the bandwidth between multiple users.

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*

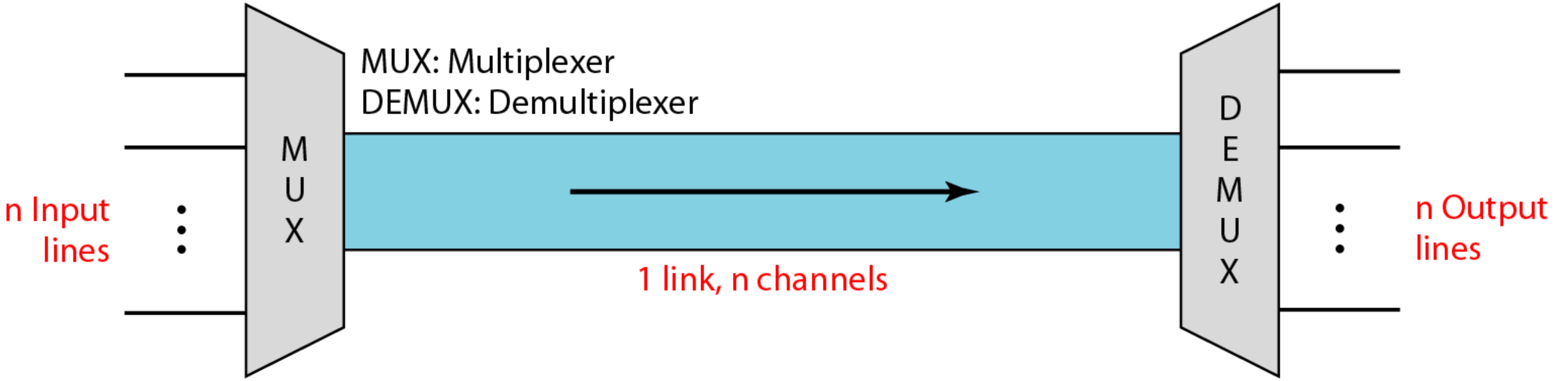


Figure 6.2 *Categories of multiplexing*

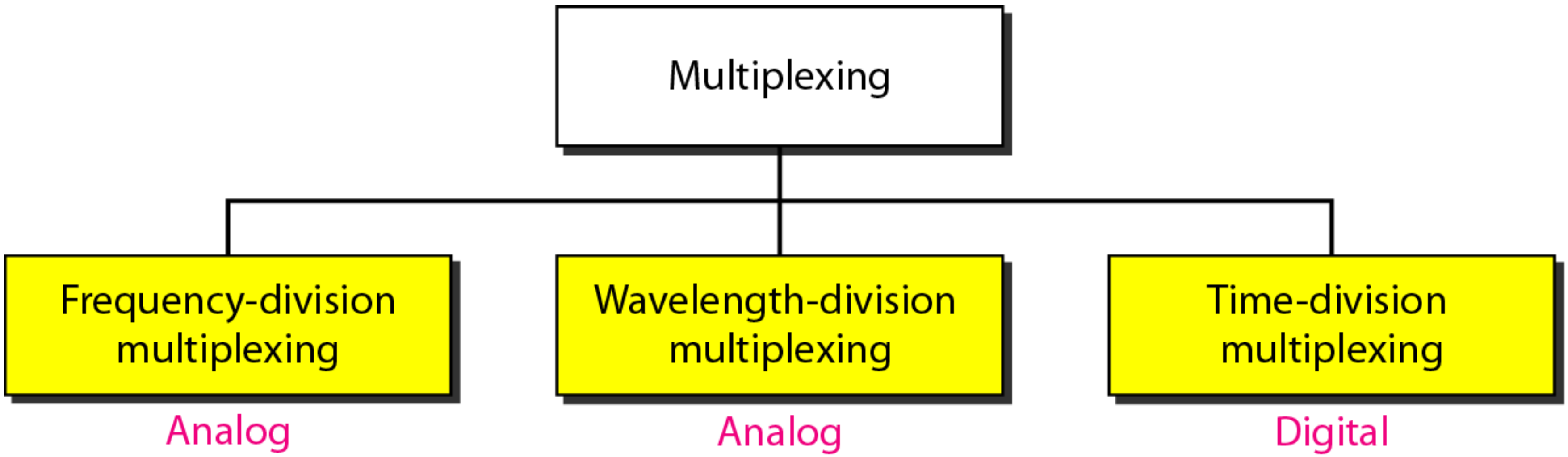


Figure 6.3 *Frequency-division multiplexing (FDM)*

Note

FDM is an analog multiplexing technique that combines analog signals.

Figure 6.4 *FDM process*

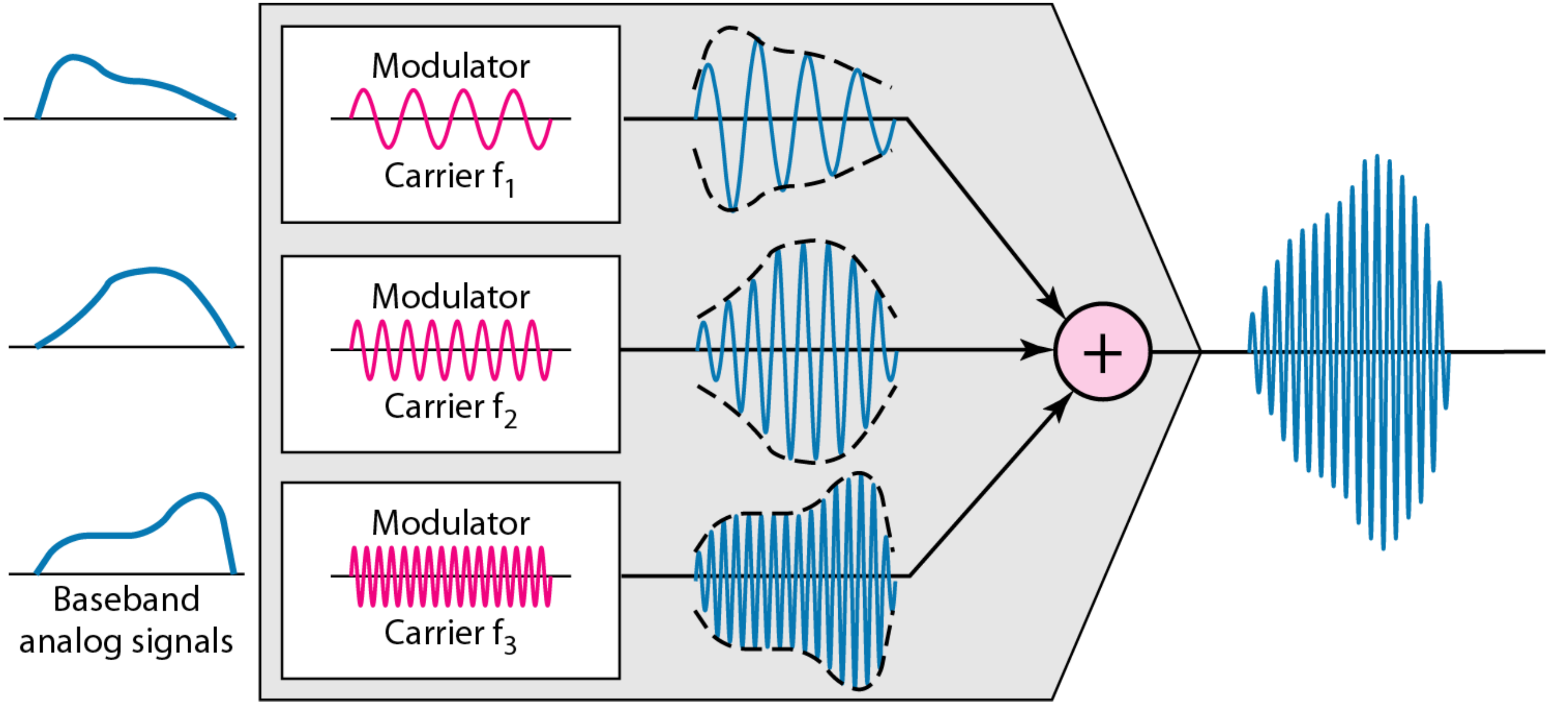
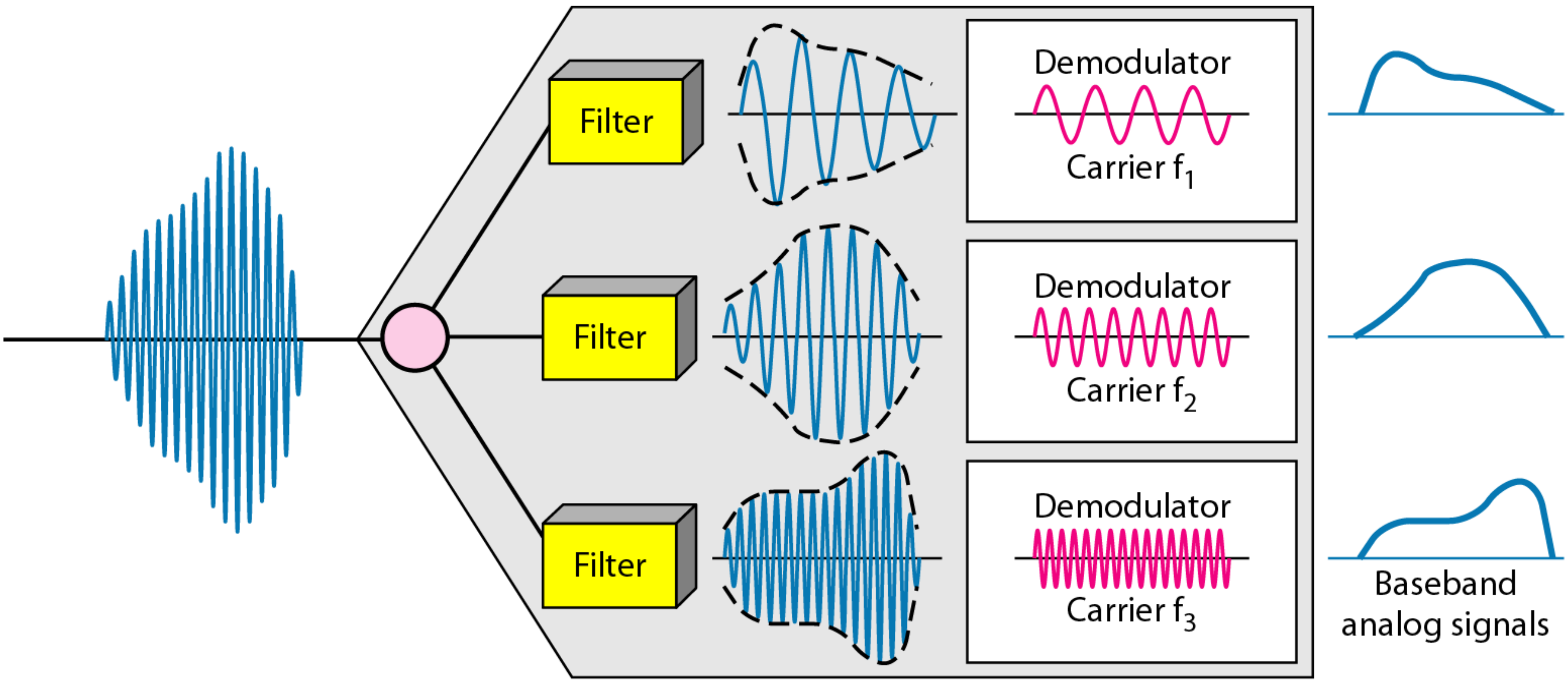


Figure 6.5 *FDM demultiplexing example*



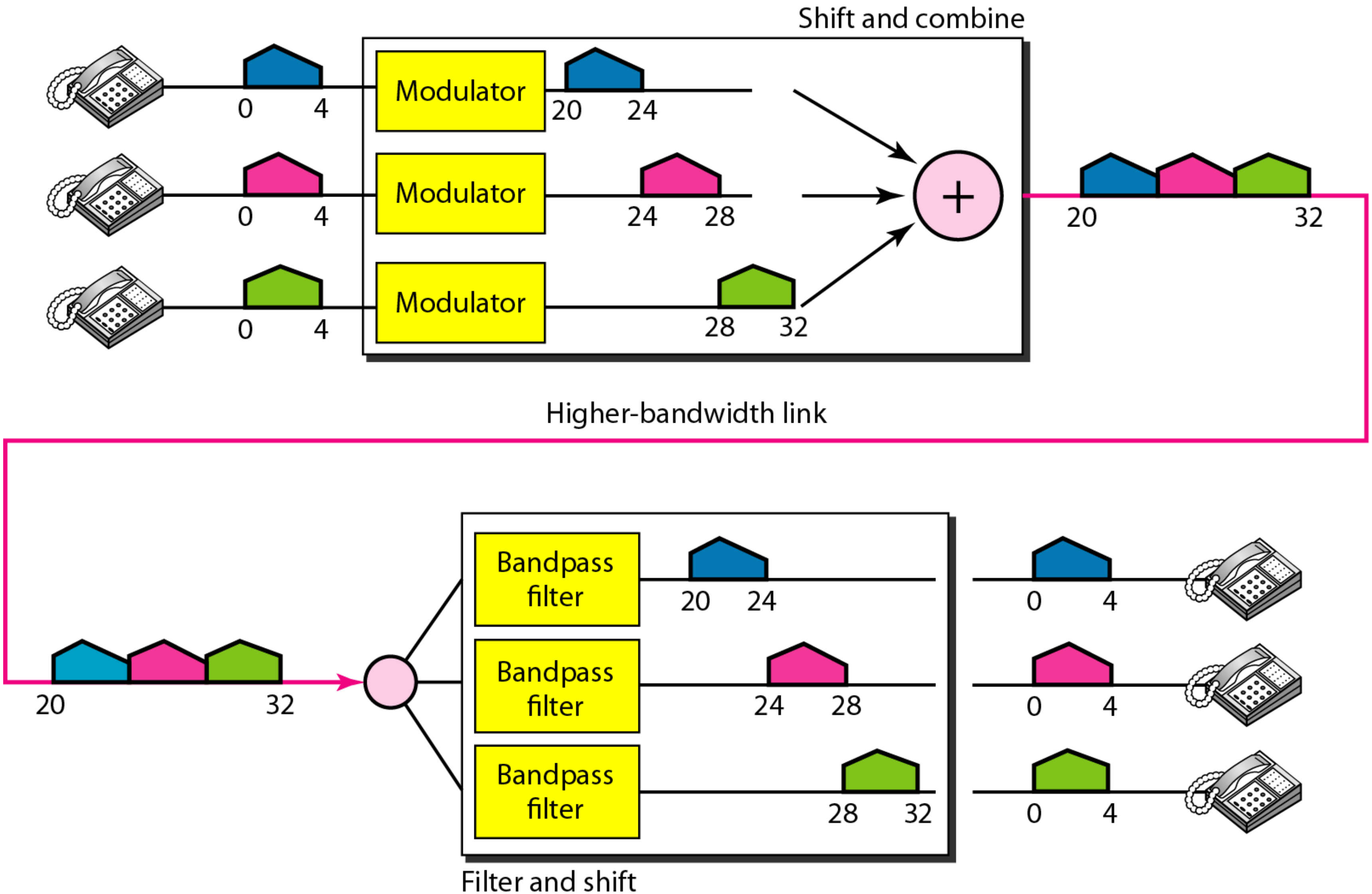
Example 6.1

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 (in next slide). 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*

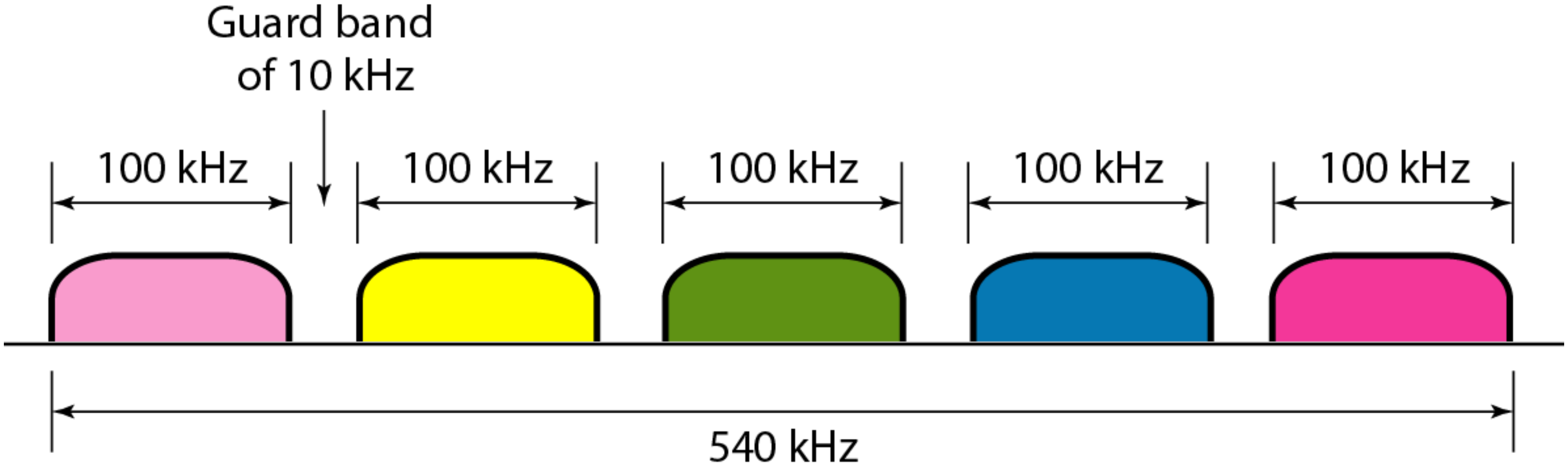


Figure 6.9 *Analog hierarchy*

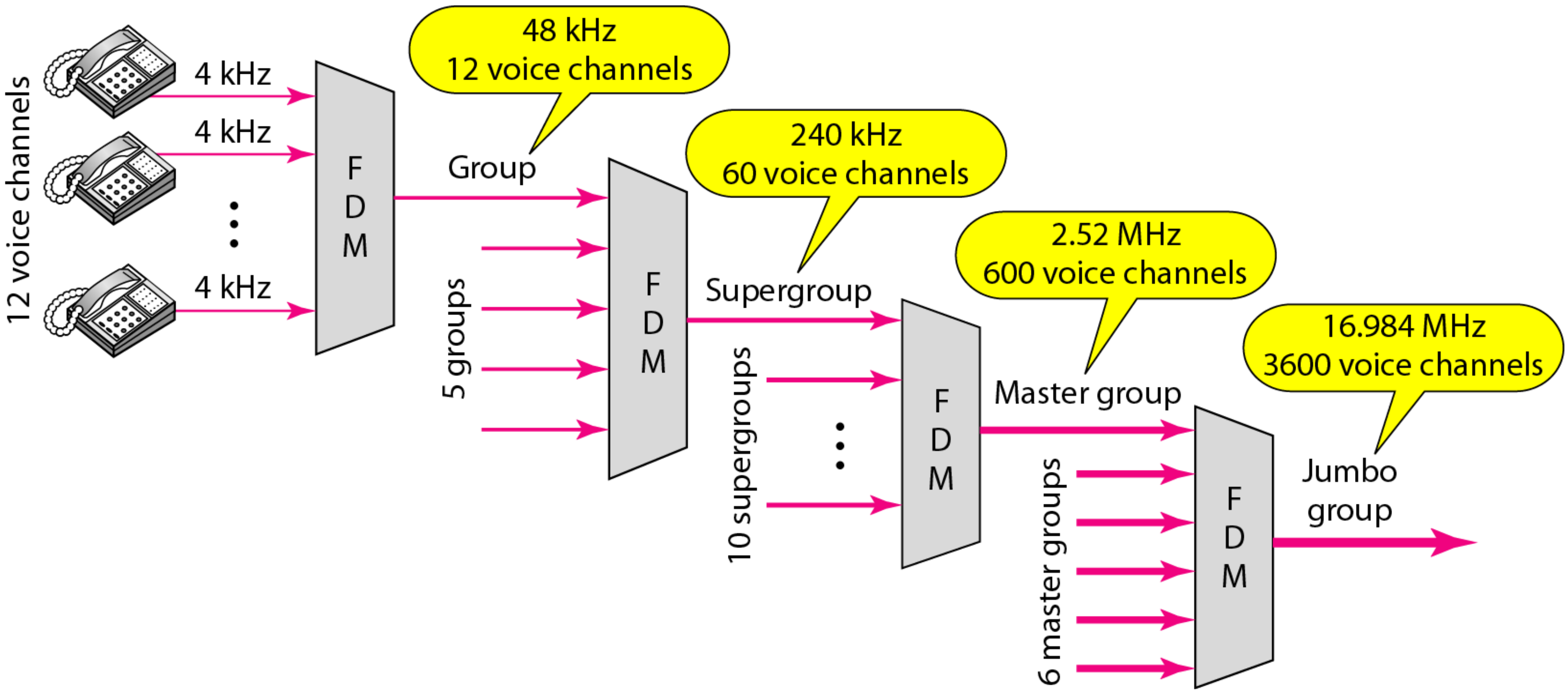
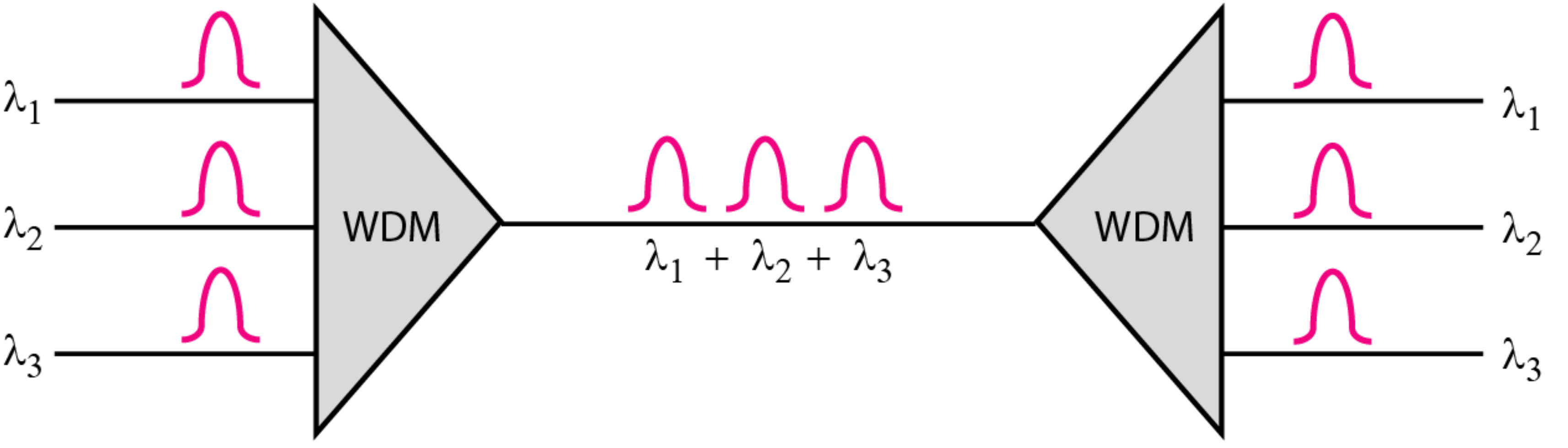


Figure 6.10 *Wavelength-division multiplexing (WDM)*



Note

WDM is an analog multiplexing technique to combine optical signals.

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

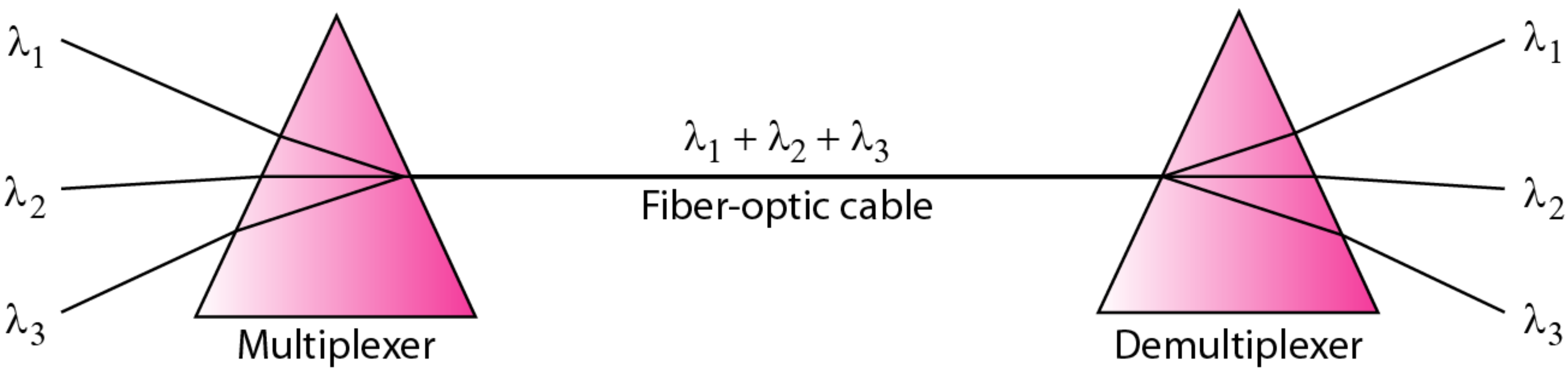
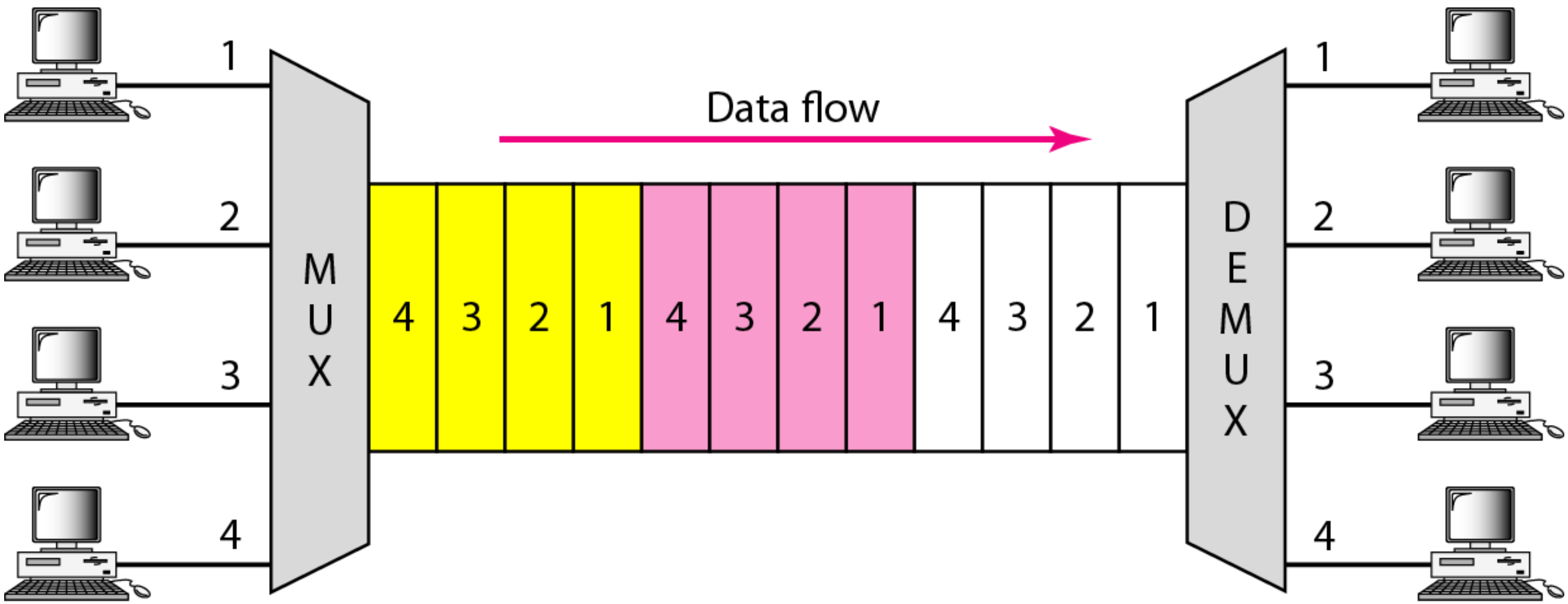


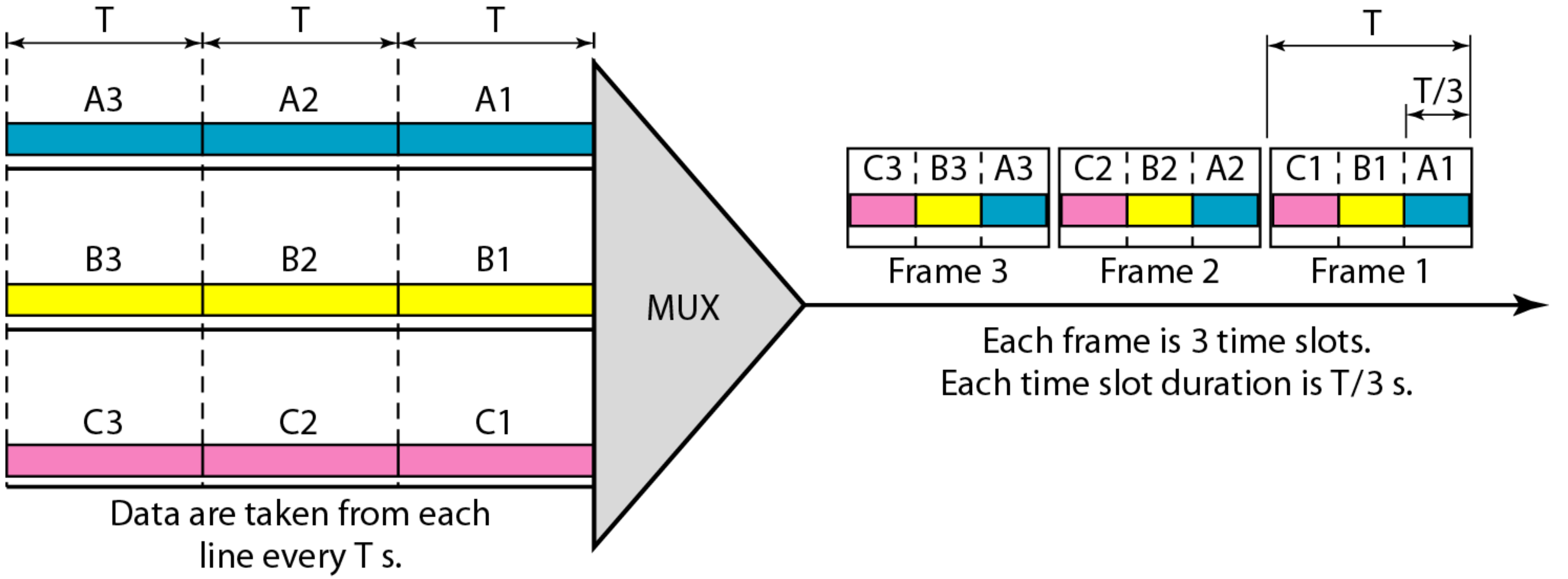
Figure 6.12 Time Division Multiplexing (*TDM*)



Note

TDM is a digital multiplexing technique for combining several low-rate digital 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 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

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.*

***Note**: 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 4 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.

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.

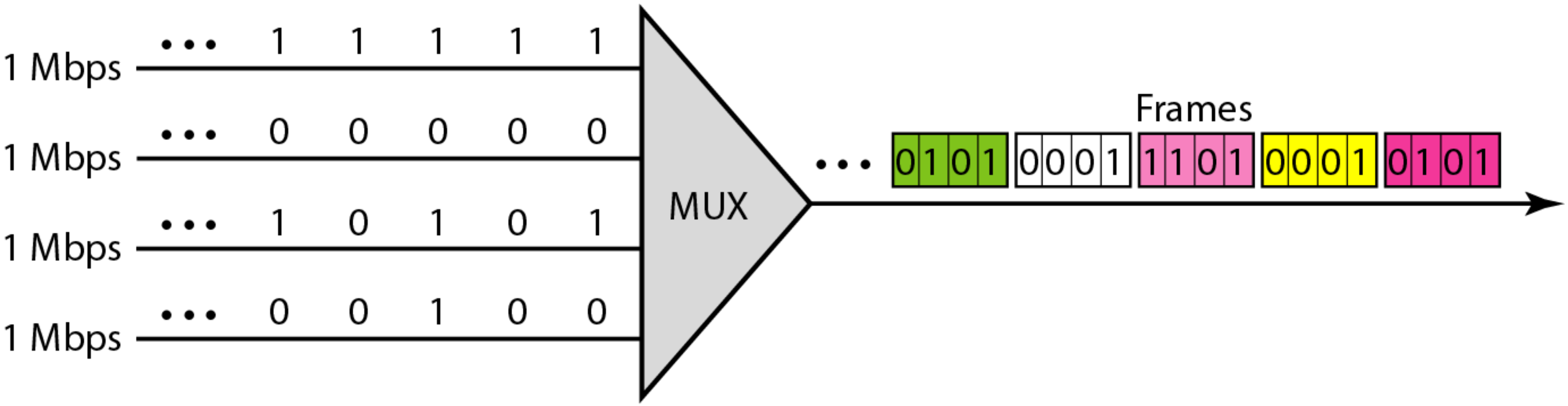
b. The output bit duration is one-fourth of the input bit duration, or ¼ μs.

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.***

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).

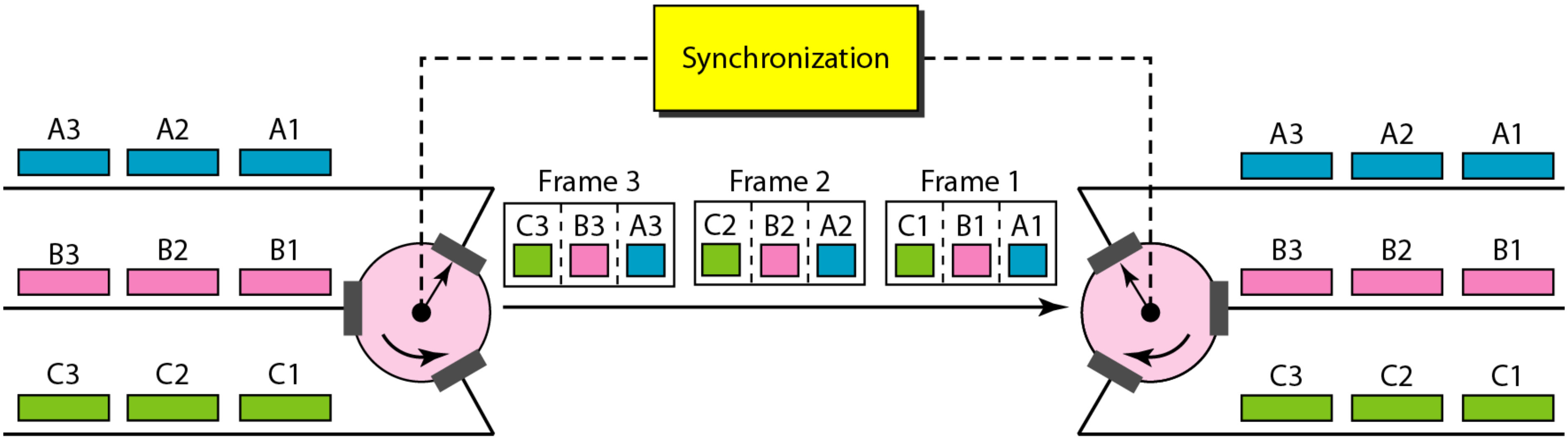
b. The rate of the link is 4 times the rate of a connection, or 4 kbps.

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 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.***

Figure 6.15 *Interleaving*



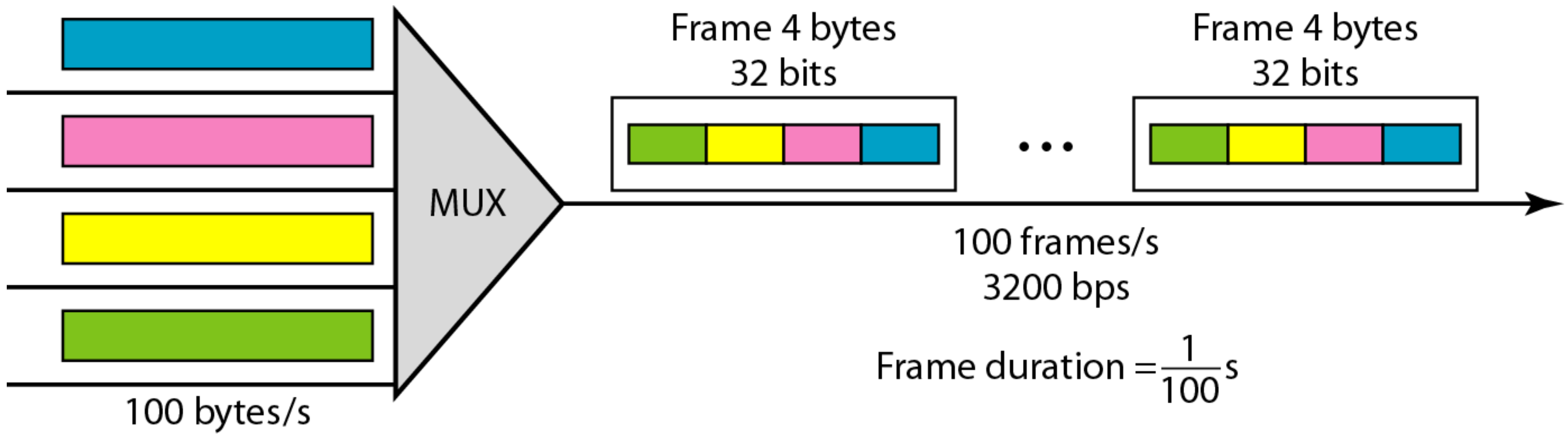
Example 6.8

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 (4x100kbps) for four arbitrary inputs. The link carries 400K/(2x4)=50,000 2x4=8bit frames per second. The frame duration is therefore 1/50,000 s or 20 μs. The bit duration on the output link is 1/400,000 s, or 2.5 μs.

Figure 6.17 *Example 6.9*

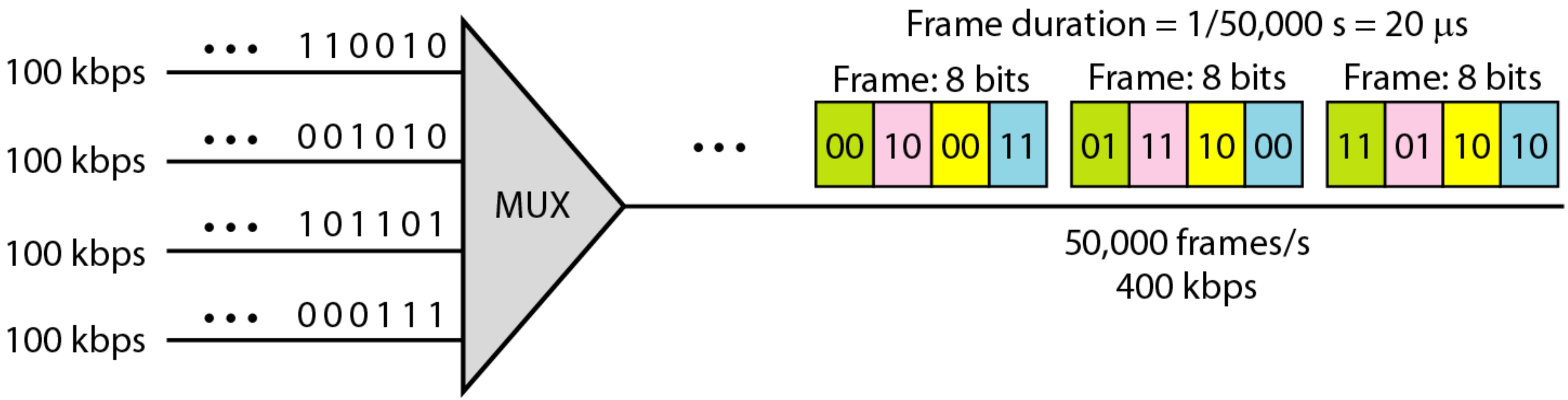
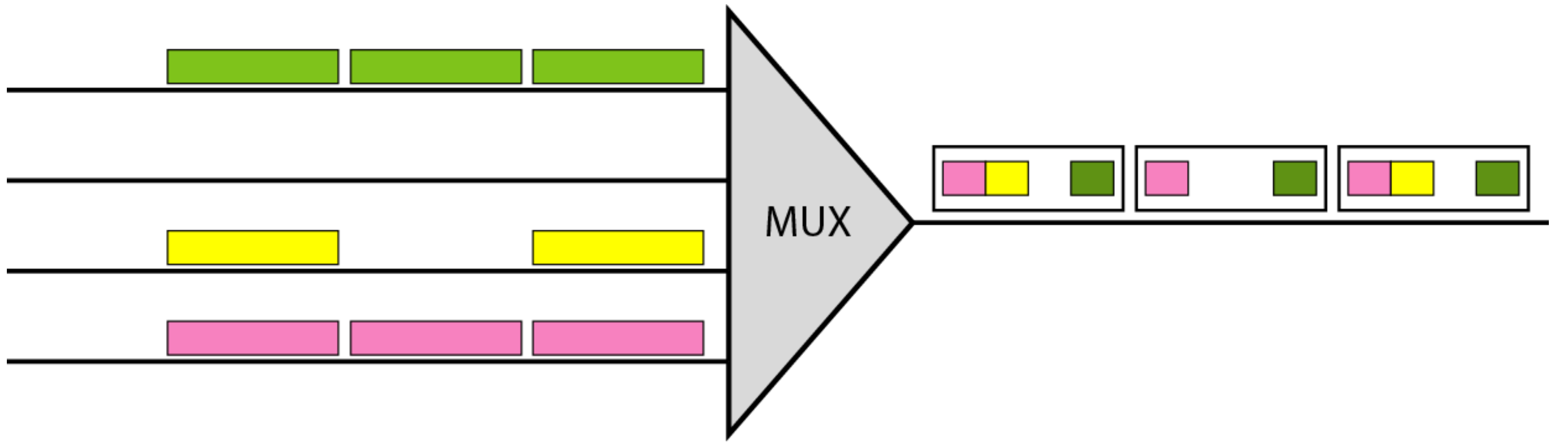


Figure 6.18 *Empty slots*



Data Rate Management

- *Not all input links 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, multiple-slot and pulse stuffing*

Figure 6.19 Multilevel Multiplexing

- ***Multilevel Multiplexing*** ***is used when the data rate of the input links are multiples of each other.***

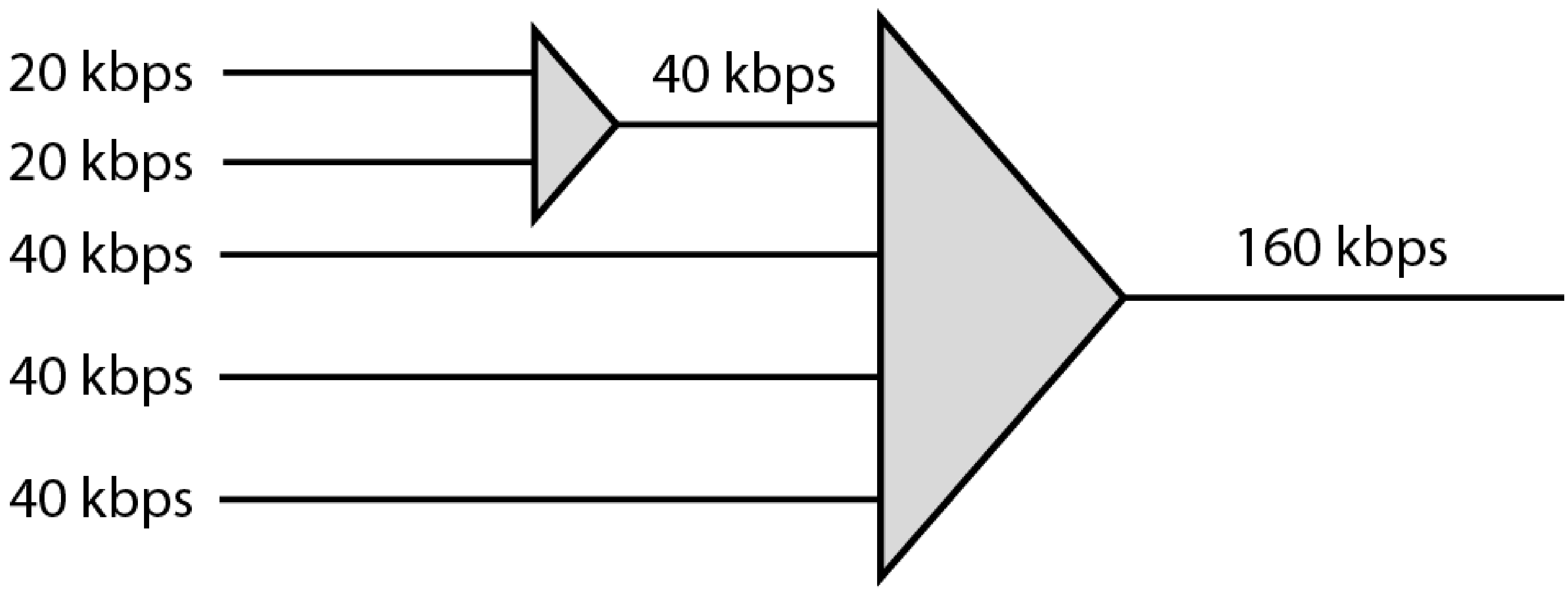


Figure 6.20 Multiple slot allocation

- ***Multiple slot allocation*** ***is used to allot more than one slot in a frame to a single input line.***

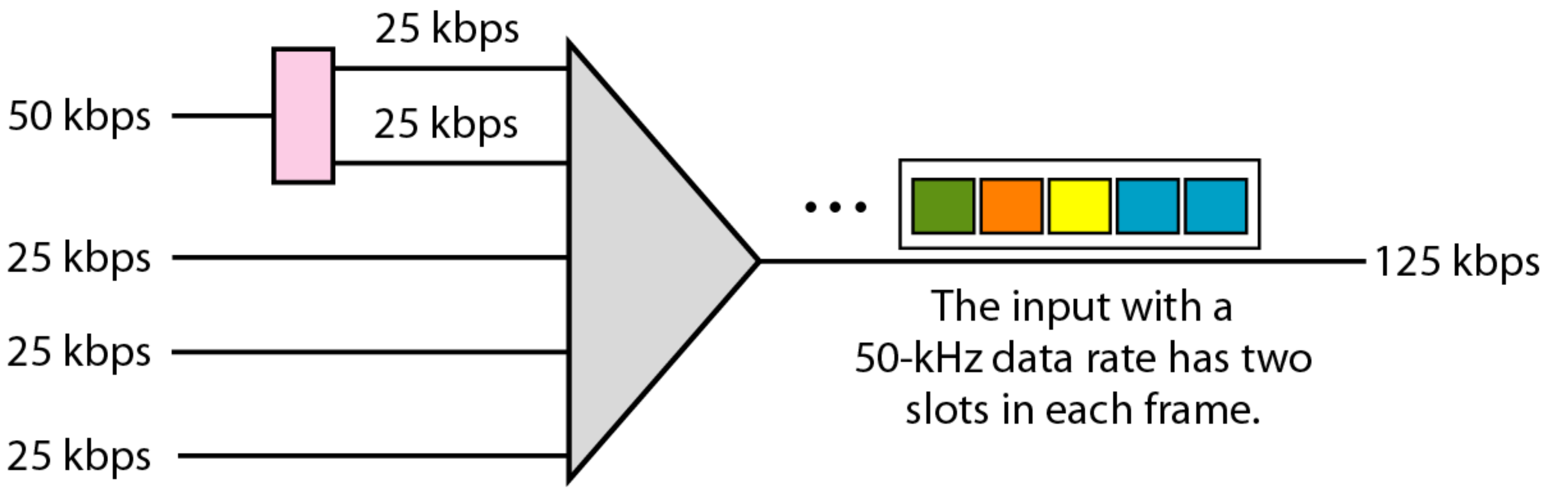
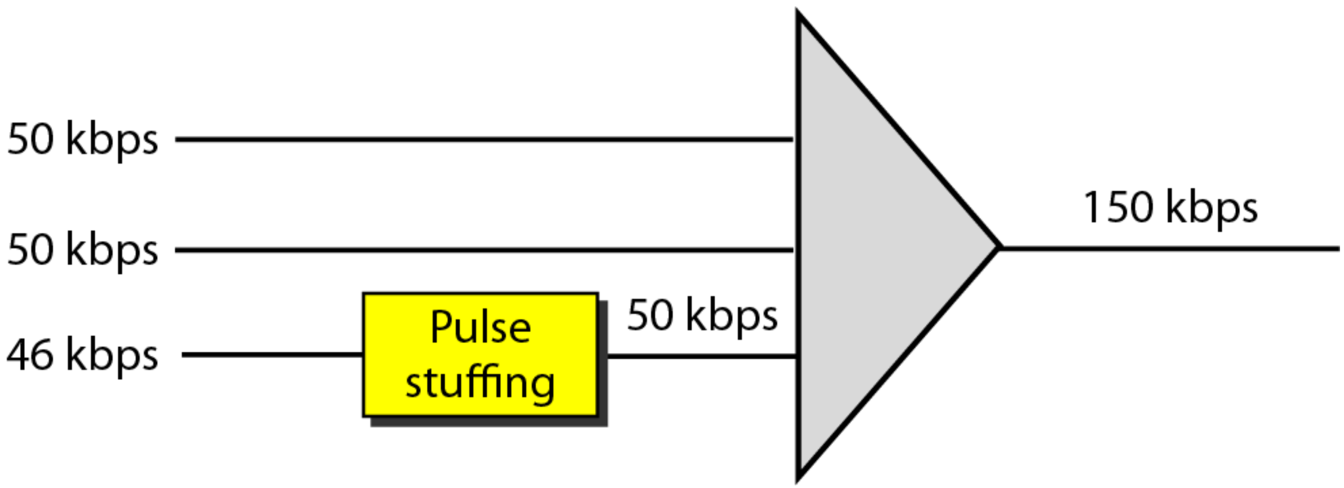


Figure 6.21 *Pulse Stuffing*

- ***Pulse Stuffing*** ***is used to make the highest input data rate the dominant data rate and then add dummy bits to the input lines with lower rates.***



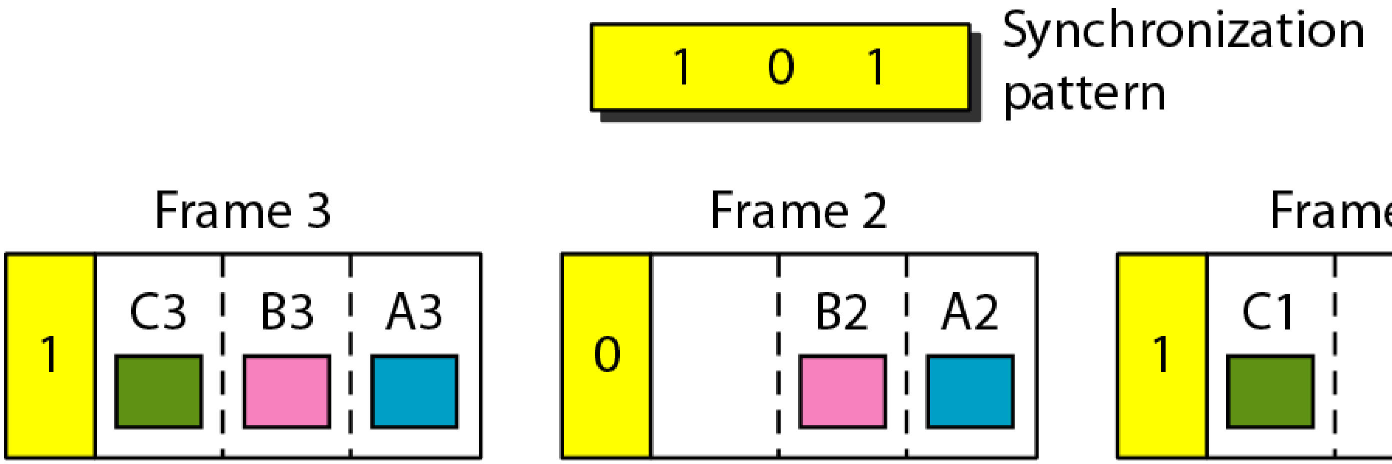
Frame Synchronization

- ***Multiplexer and demultiplexer must be synchronized***

- ***Framing bits are used to provide synchronization***

- ***They are part of the overhead of transmission.***

Figure 6.22 *Framing bits*



Example 6.10

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

We can answer the questions as follows:

a. *The data rate of each source is 250 × 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.***

Example 6.10 (continued)

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

f. The link sends 250 frames per second, and each frame contains 33 bits. This means that the data rate of the link is 250×33, or 8250 bps.

Note that the bit rate of the link is greater than the combined bit rates of the four channels. If we add the bit rates of four channels, we get 250x4x8= 8000 bps. Because 250 frames are traveling per second and each contains 1 extra bit for synchronizing, we need to add 250 to the sum to get 8250 bps.

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.

Figure 6.23 *Digital hierarchy*

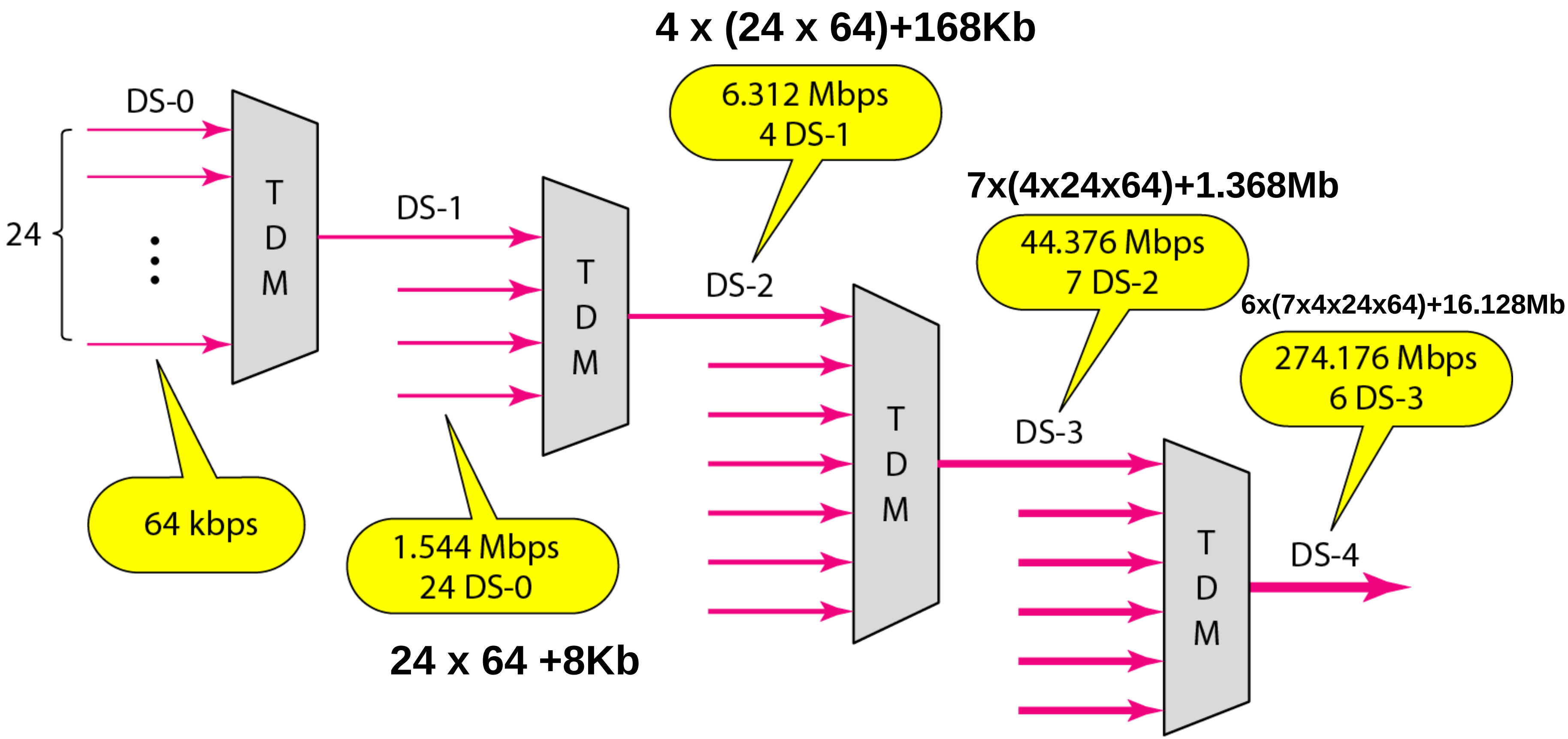


Table 6.1 ***DS and T line rates***

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

Figure 6.24 *T-1 line for multiplexing telephone lines*

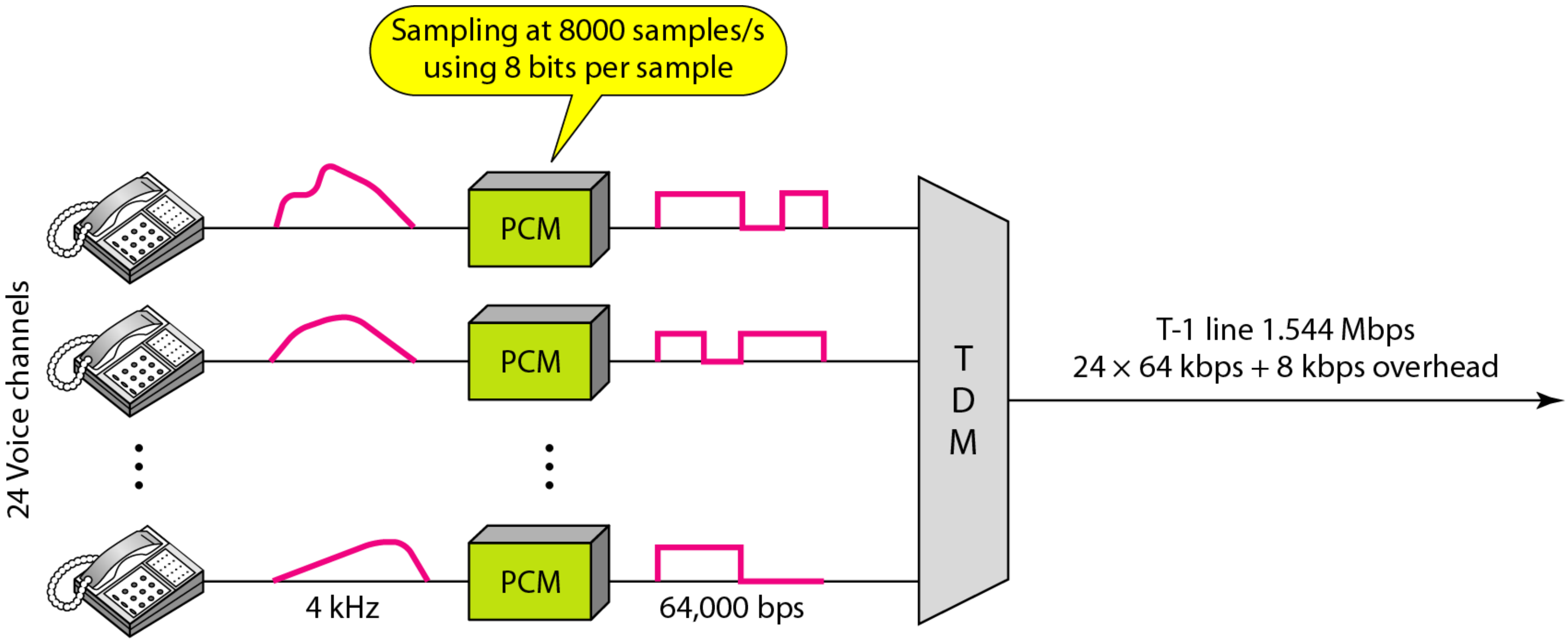


Figure 6.25 *T-1 frame structure*

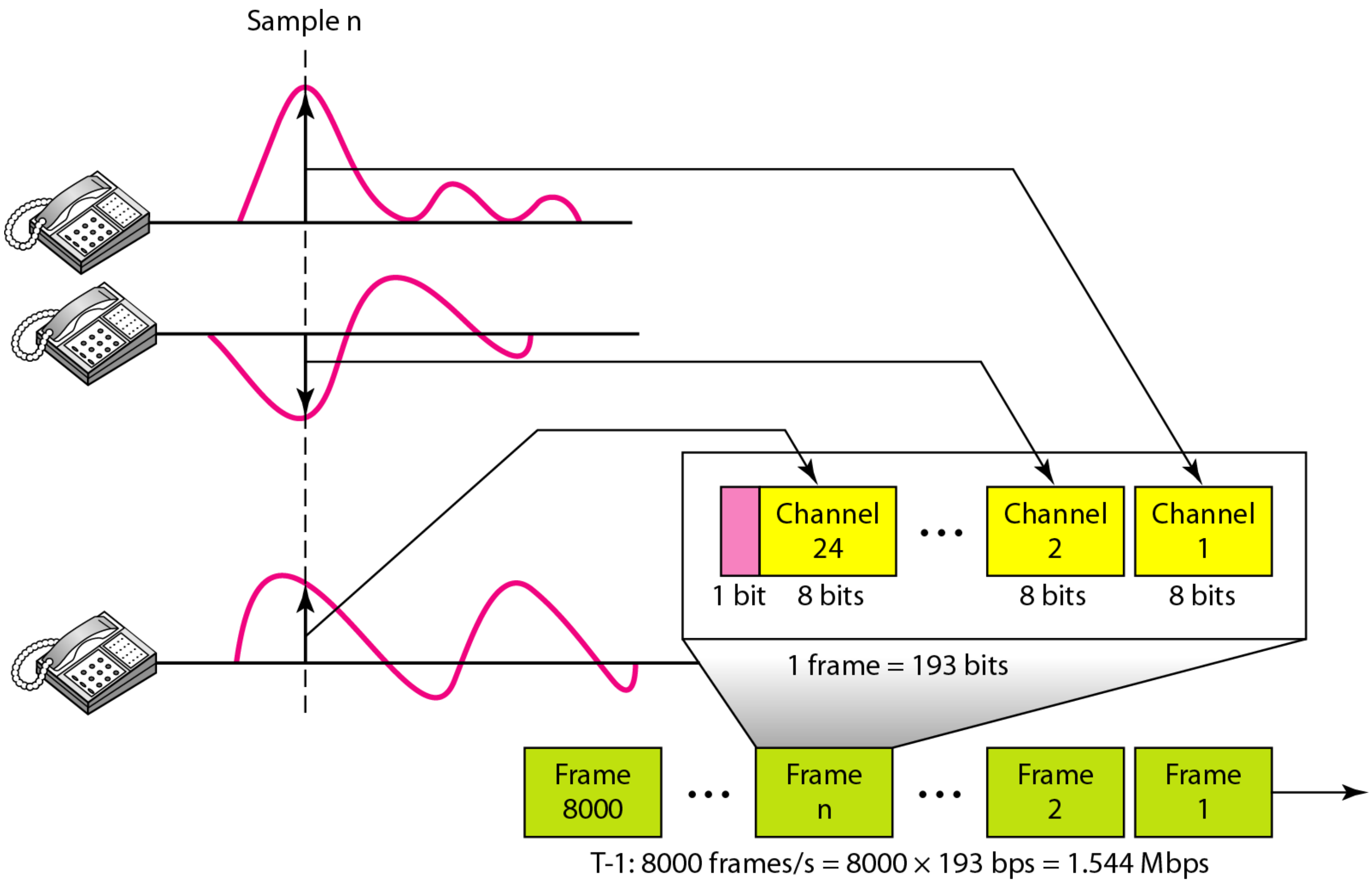
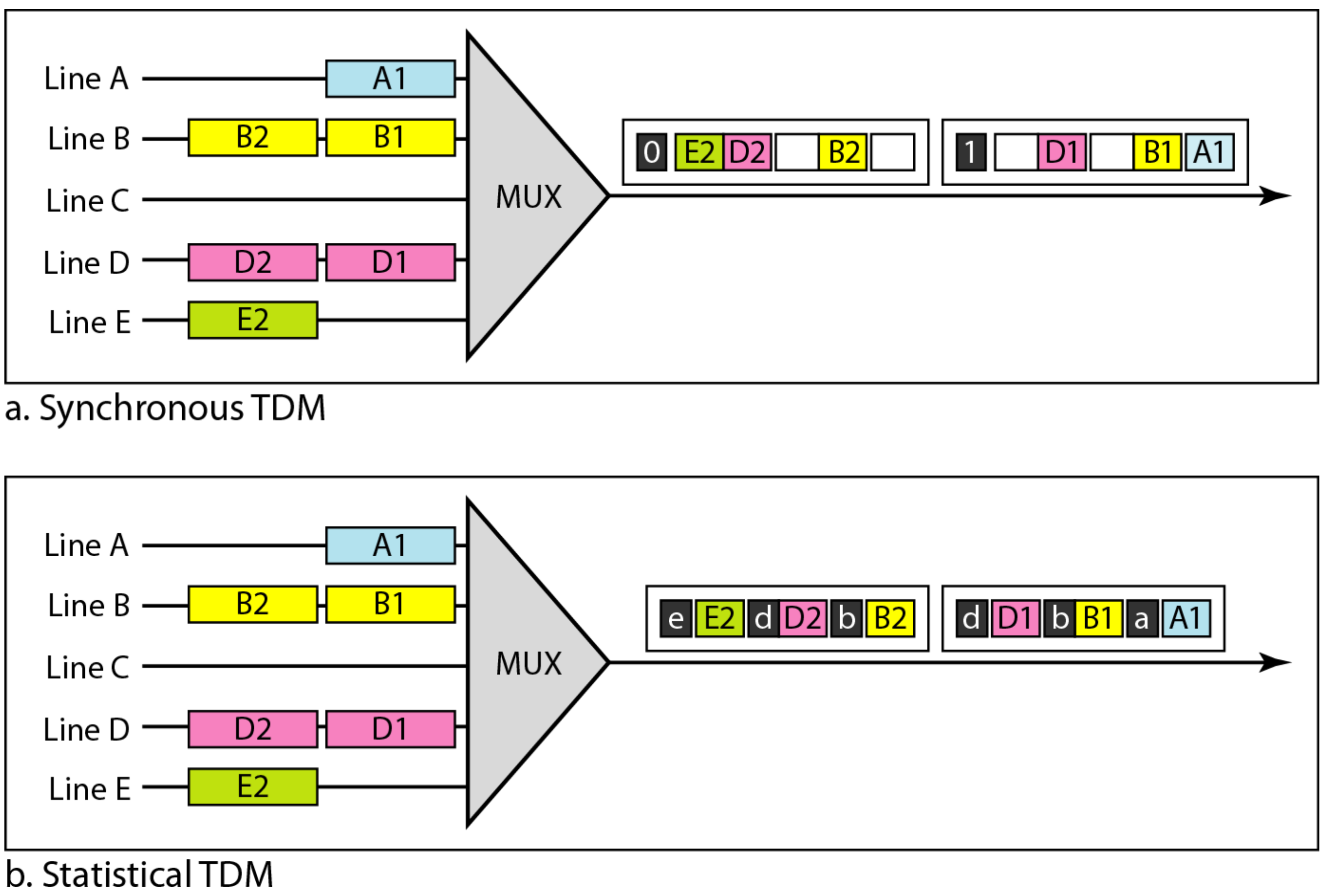


Table 6.2 ***E line rates***

Line	*Rate (Mbps)*	*Voice Channels*
E-1	2.048	30
E-2	8.448	120
E-3	34.368	480
E-4	139.264	1920

Figure 6.26 *TDM slot comparison*



6-2 SPREAD SPECTRUM

In spread spectrum (SS), we combine signals from different sources to fit into a larger bandwidth, but our goals are to prevent eavesdropping and jamming. To achieve these goals, spread spectrum techniques add redundancy.

Topics discussed in this section:

- **Frequency Hopping Spread Spectrum (FHSS)**
- **Direct Sequence Spread Spectrum (DSSS)**

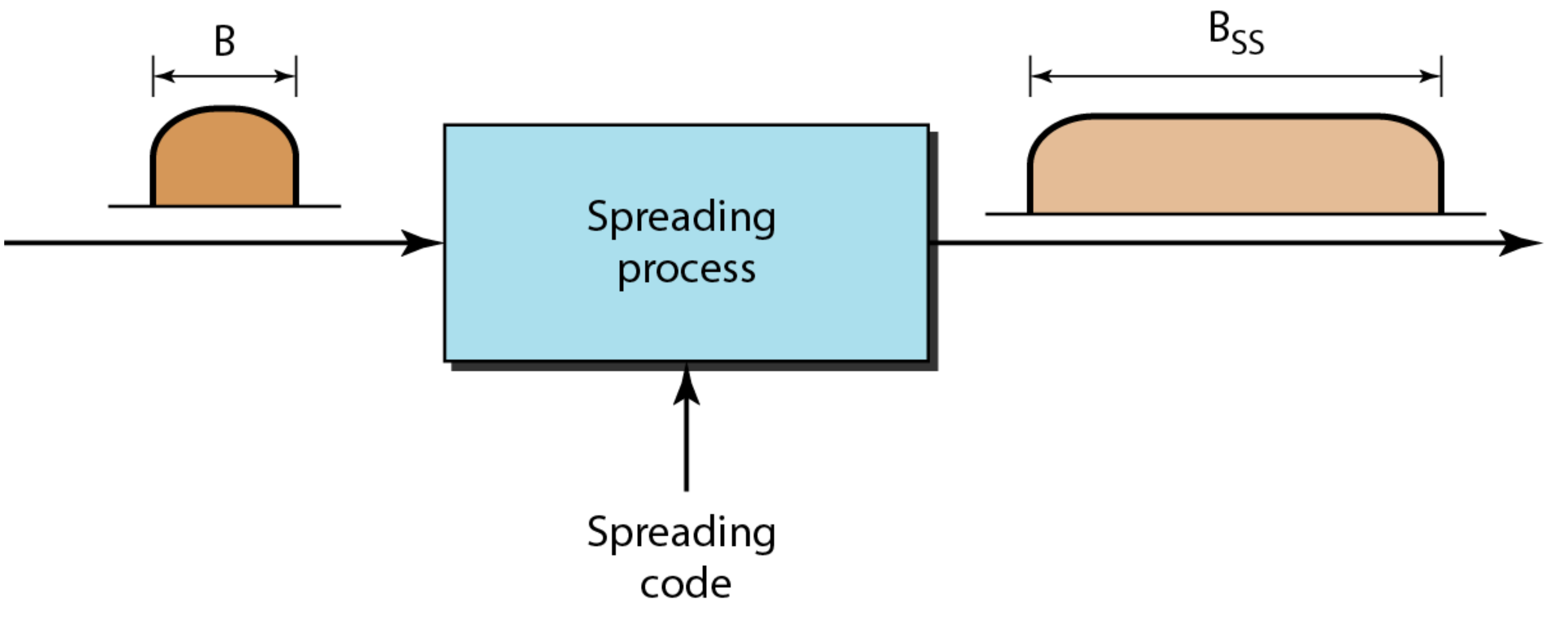
Spread Spectrum

- ***Spread signal to use larger bandwidth***
  - ***To prevent eavesdropping (privacy)***
  - ***To reduce effect from interference (anti-jamming)***
- ***If the required bandwidth for each station is B, spread spectrum expands it to B_{SS};***

$$B_{SS} >> B.$$

- ***Two principles***
  - ***Redundancy - The bandwidth allocated to each station needs to be larger than what is needed.***
  - ***Independent process - The spreading process occurs after the signal is created by the source.***

Figure 6.27 *Spread spectrum*



Frequency-Hopping Spread Spectrum (FHSS)

- ***Uses M different carrier frequencies that are modulated by the source signal.***
- ***At one moment, the signal modulates one carrier frequency; at the next moment, the signal modulates another carrier frequency.***
- ***The bandwidth occupied by a source after spreading is*** $B_{FHSS} >> B$.
- ***Used in Bluetooth technology.***

Figure 6.28 *Frequency hopping spread spectrum (FHSS)*

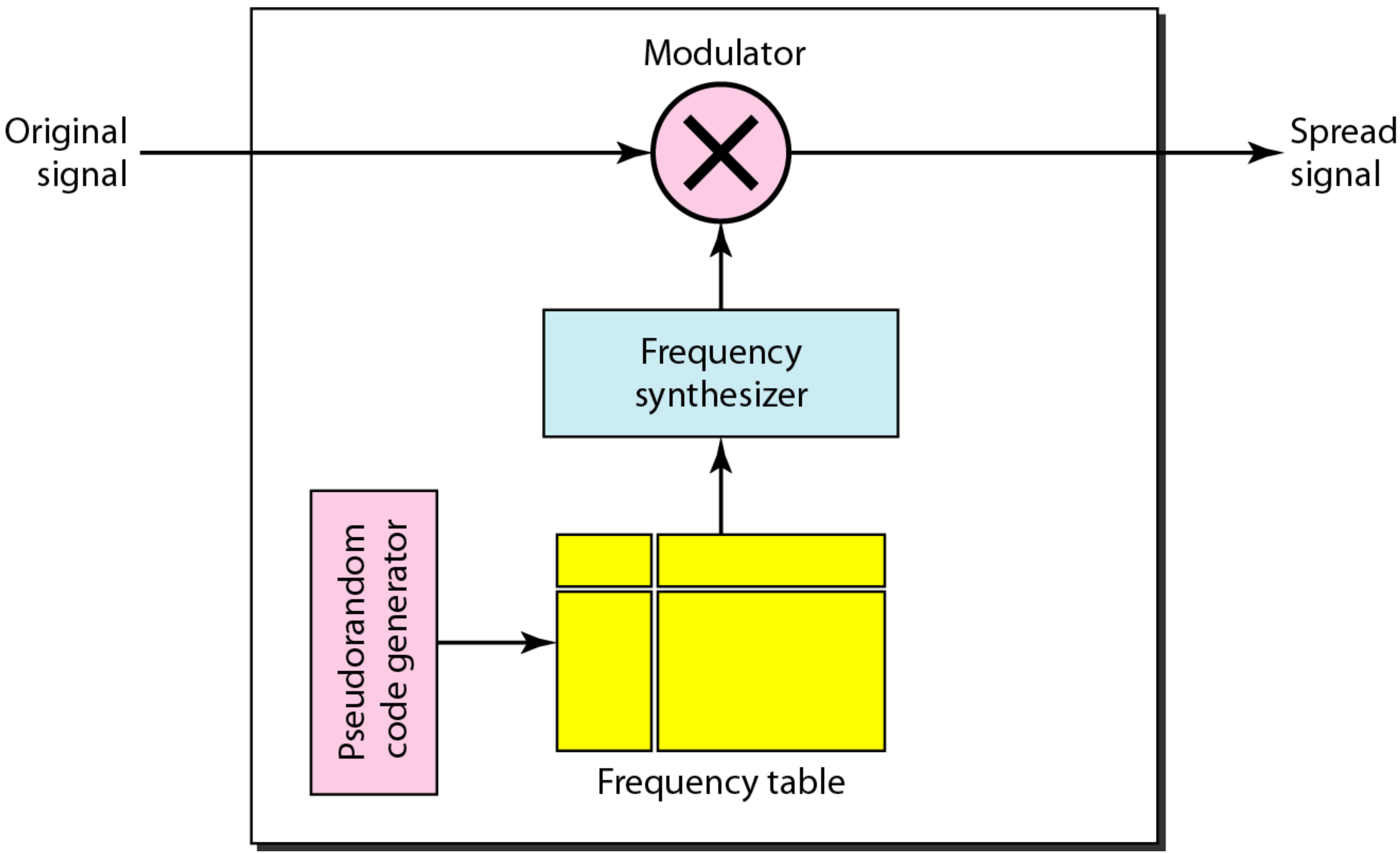


Figure 6.29 *Frequency selection in FHSS*

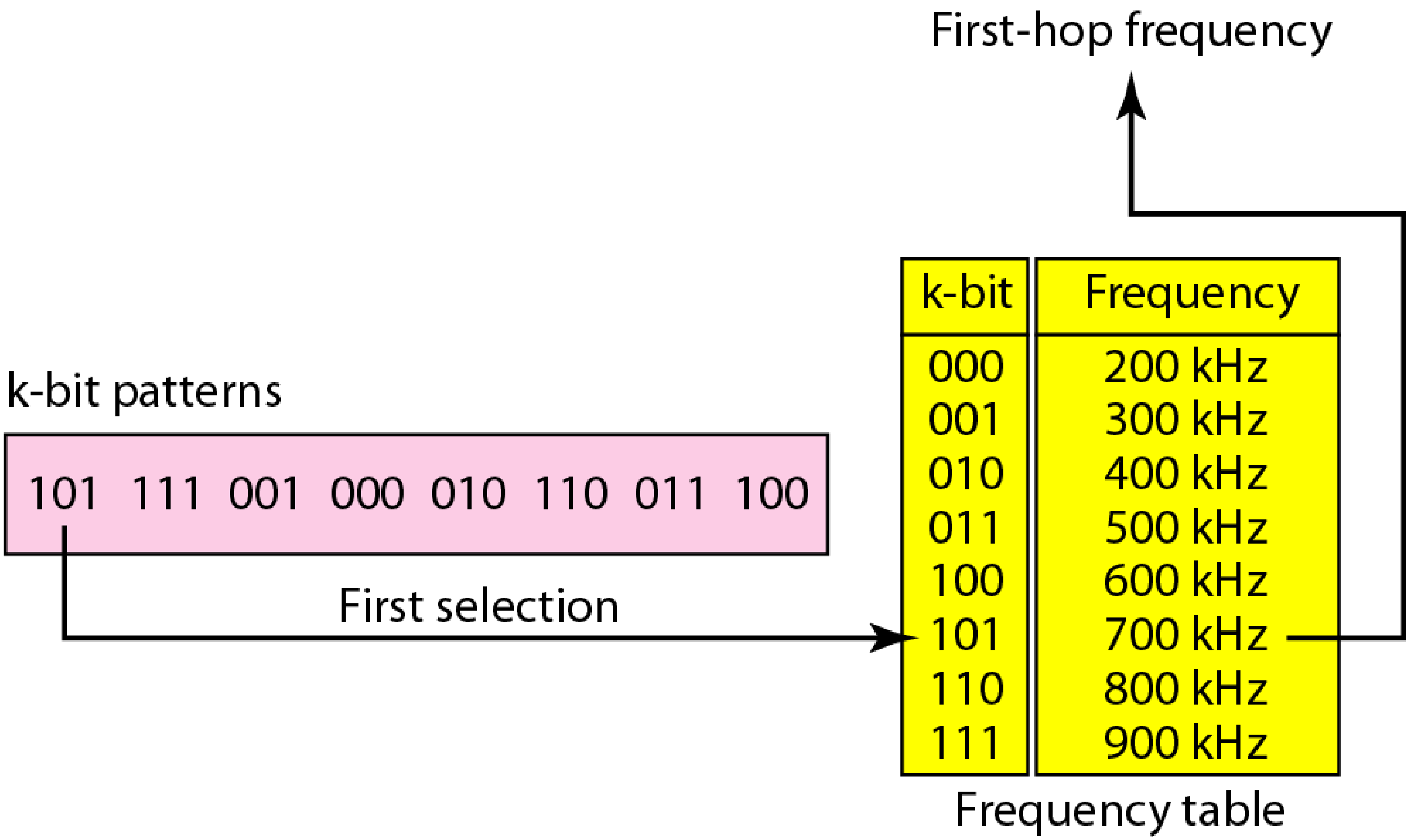
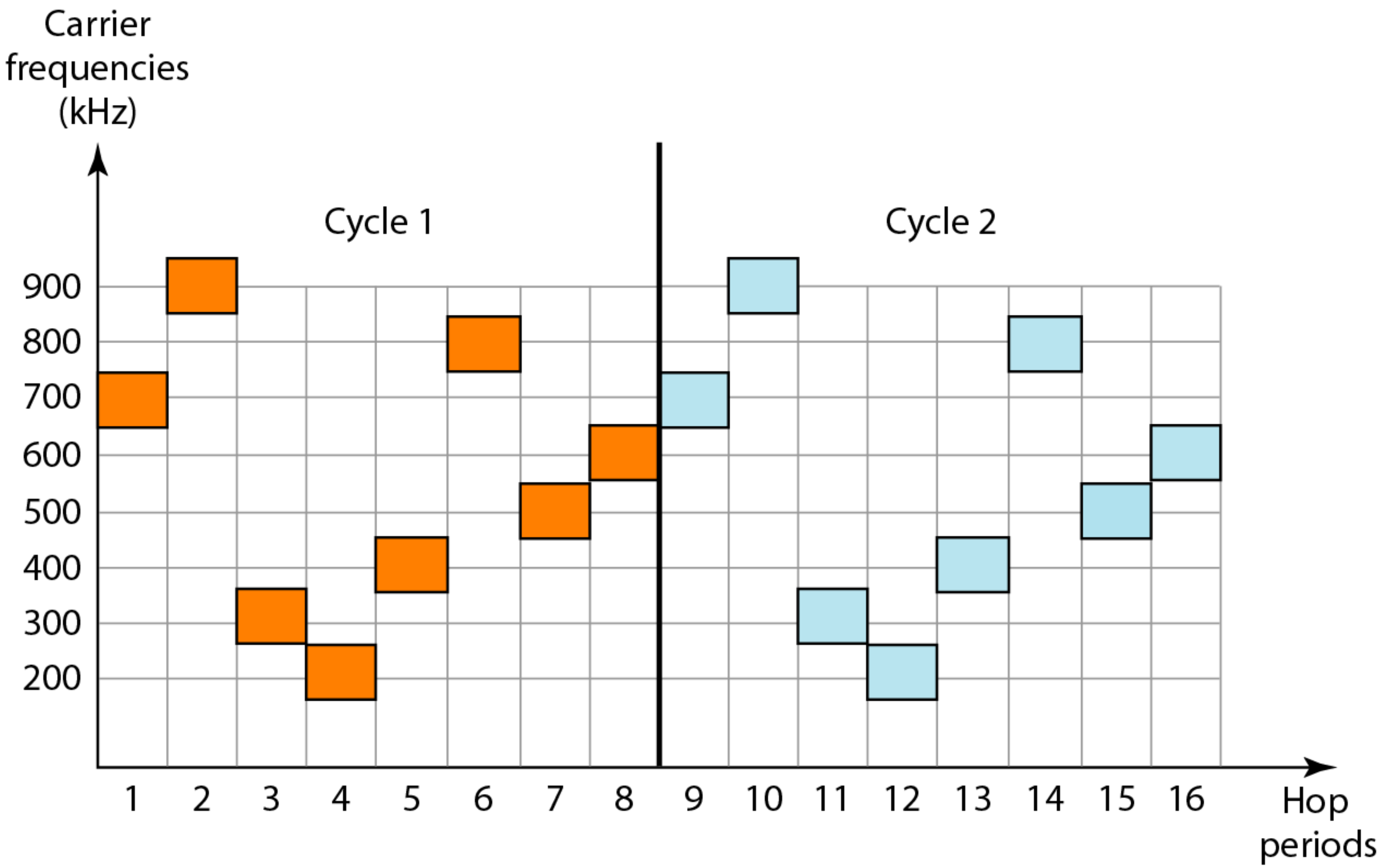


Figure 6.30 *FHSS cycles*



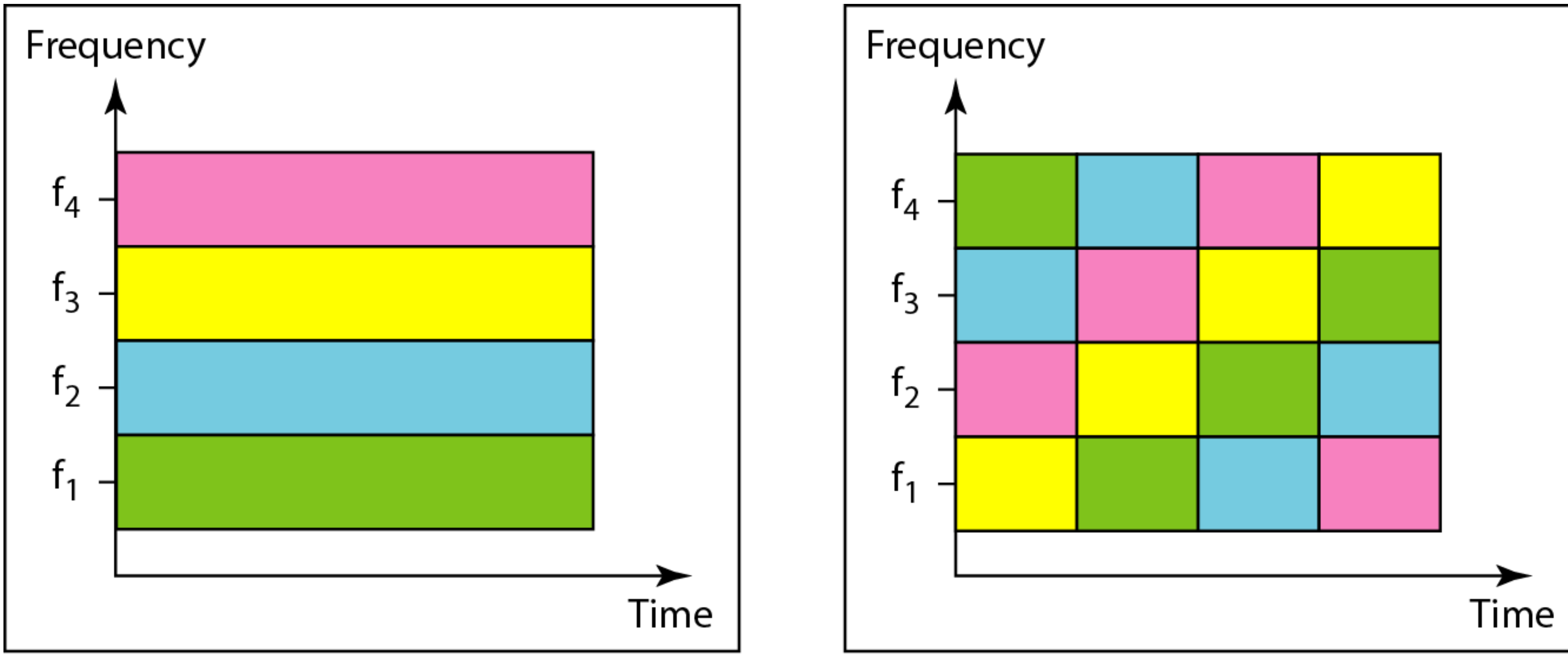
FHSS

- ***It can preserve privacy***
  - ***If an intruder tries to intercept the transmitted signal, (s)he can only access a small piece of data because (s)he does not know the spreading sequence to quickly adapt to the next hop.***
- ***Anti-jamming effect***
  - ***A malicious sender may be able to send noise to jam the signal for one hopping period (randomly), but not for the whole period.***

Bandwidth Sharing in FHSS

- ***If the number of hopping frequencies is M, we can multiplex M channels into one by using the same B_{ss} bandwidth.***
- ***This is possible because a station uses just one frequency in each hopping period; M − 1 other frequencies can be used by M − 1 other stations.***
- ***In other words, M different stations can use the same B_{ss} if an appropriate modulation technique such as multiple FSK (MFSK) is used.***

Figure 6.31 *Bandwidth sharing*



a. FDM

b. FHSS

Figure 6.32 *DSSS*

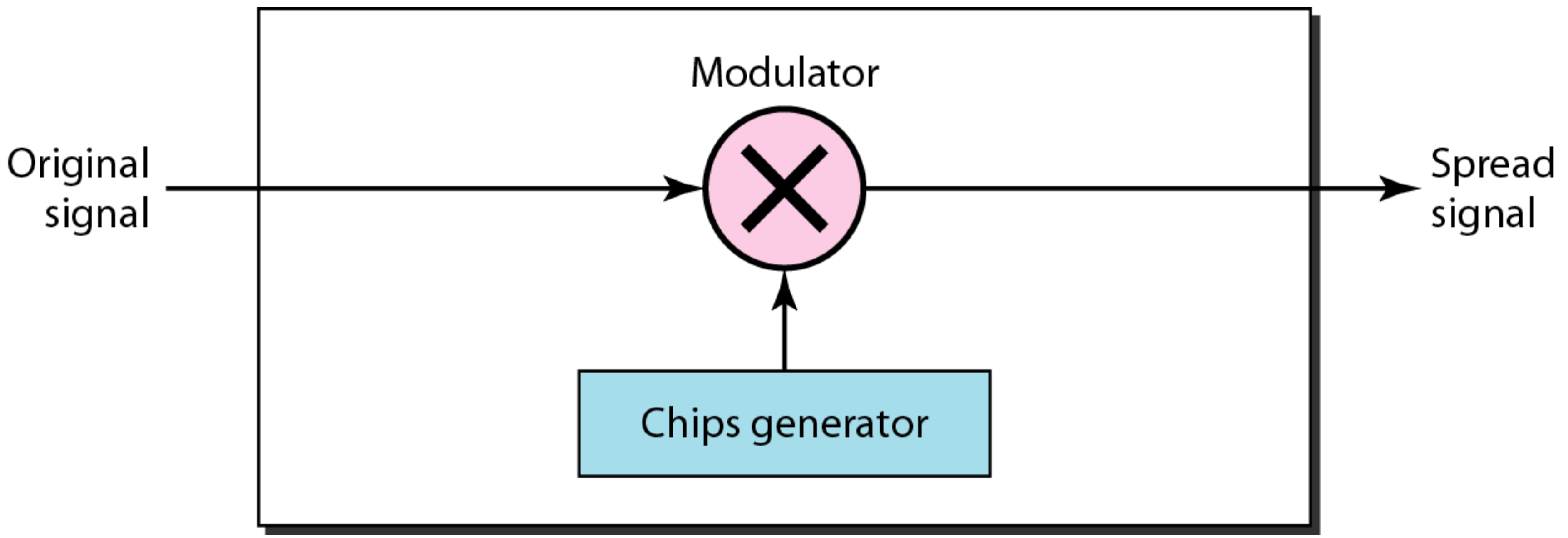
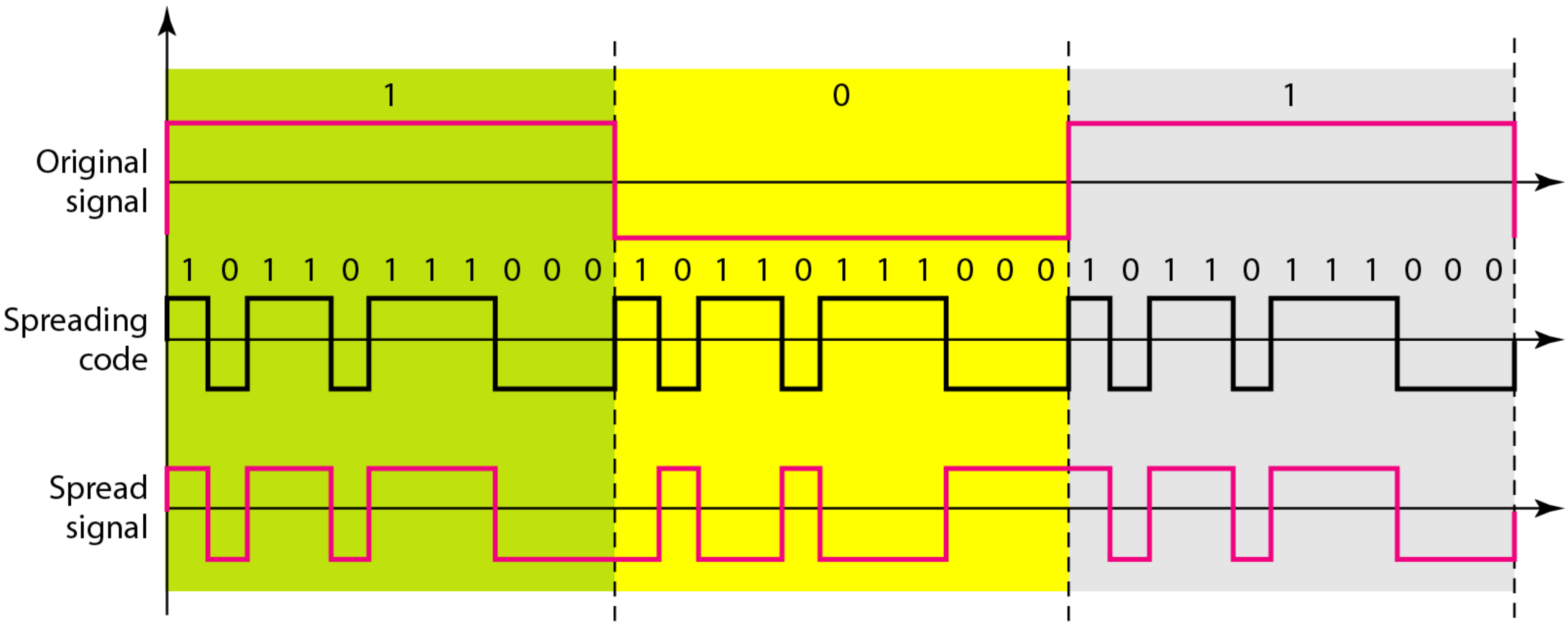


Figure 6.33 *DSSS example*



Bandwidth Sharing in DSSS

- ***Can we share a bandwidth in DSSS?***
- ***The answer is no and yes.***
- ***If we use a spreading code that spreads signals (from different stations) that cannot be combined and separated, we cannot share a bandwidth.***
- ***By using a special type of sequence code that allows the combining and separating of spread signals, we can share the bandwidth.***