Chapter 6: Bandwidth Utilization: Multiplexing and Spreading

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경매일	경매 주파수	낙찰가	1MHz 값(단가)	낙찰자
2013년 8월	1.8GHz 대역 15MHz 폭	9001억 원	600억 원	KT
2011년 8월	1.8GHz 대역 20MHz 폭	9950억 원	497.5억 원	SK텔레콤
2013년 8월	1.8GHz 대역 35MHz 폭	1조500억 원	300억 원	SK텔레콤
2011년 8월	800MHz 대역 10MHz 폭	2610억 원	261억 원	KT
2016년 5월	2.6GHz 대역 40MHz 폭	9500억 원	237.5억 원	SK텔레콤
2016년 5월	1.8GHz 대역 20MHz 폭	4513억 원	225.6억 원	KT
2011년 8월	2.1GHz 대역 20MHz 폭	4455억 원	222.7억 원	LG유플러스
2016년 5월	2.1GHz 대역 20MHz 폭	3816억 원	190.8억 원	LG유플러스
2016년 5월	2.6GHz 대역 20MHz 폭	3277억 원	163.8억 원	SK텔레콤
2013년 8월	2.6GHz 대역 40MHz 폭	4788억 원	119.7억 원	LG유플러스

Contents

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. (B/W is one of the most precious resources)

Multiplexing
Multiple Access

FDM <-> FDMA
TDM <-> TDMA
CDM <-> CDMA

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*

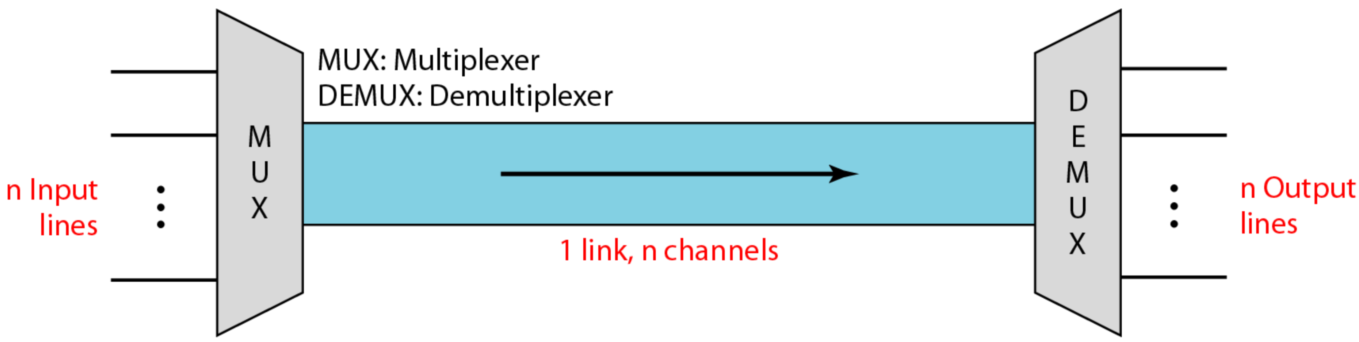
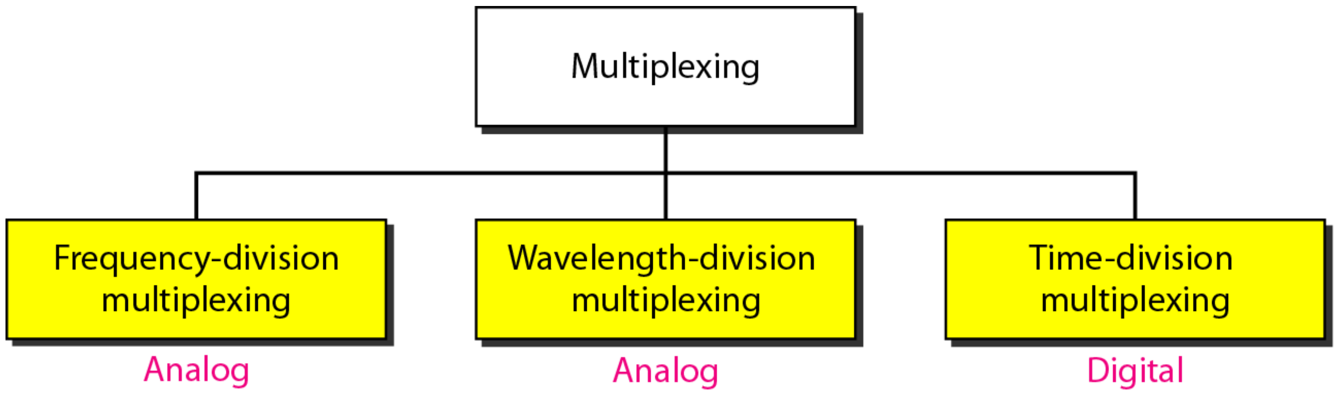


Figure 6.2 *Categories of multiplexing*



Frequency-Division Multiplexing

- FDM
  - analog technique that can be applied when the bandwidth of a link is greater than the combined bandwidths of the signals to be transmitted
  - each modulated signal which has different carrier frequencies is combined into a single composite signal
  - **channels** can be separated by **the guard band** to prevent signals from overlapping

Figure 6.3 *Frequency-division multiplexing*

Note

FDM is an analog multiplexing technique that combines analog signals.

Figure 6.4 *FDM process*

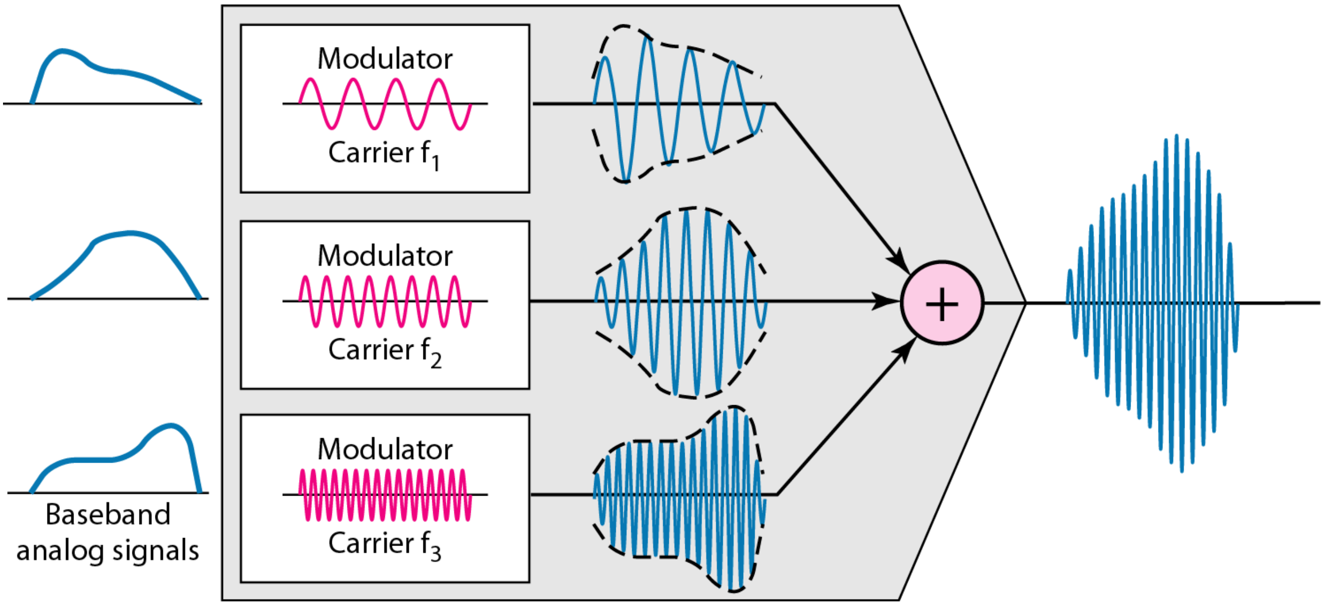
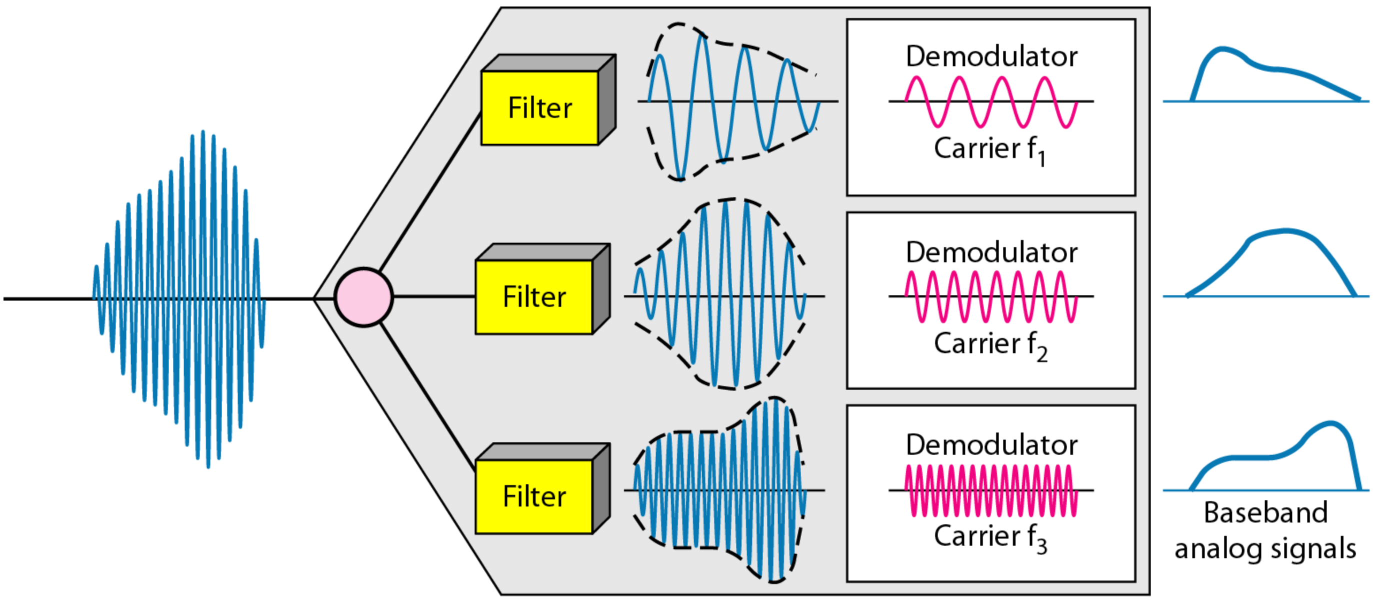


Figure 6.5 *FDM demultiplexing example*



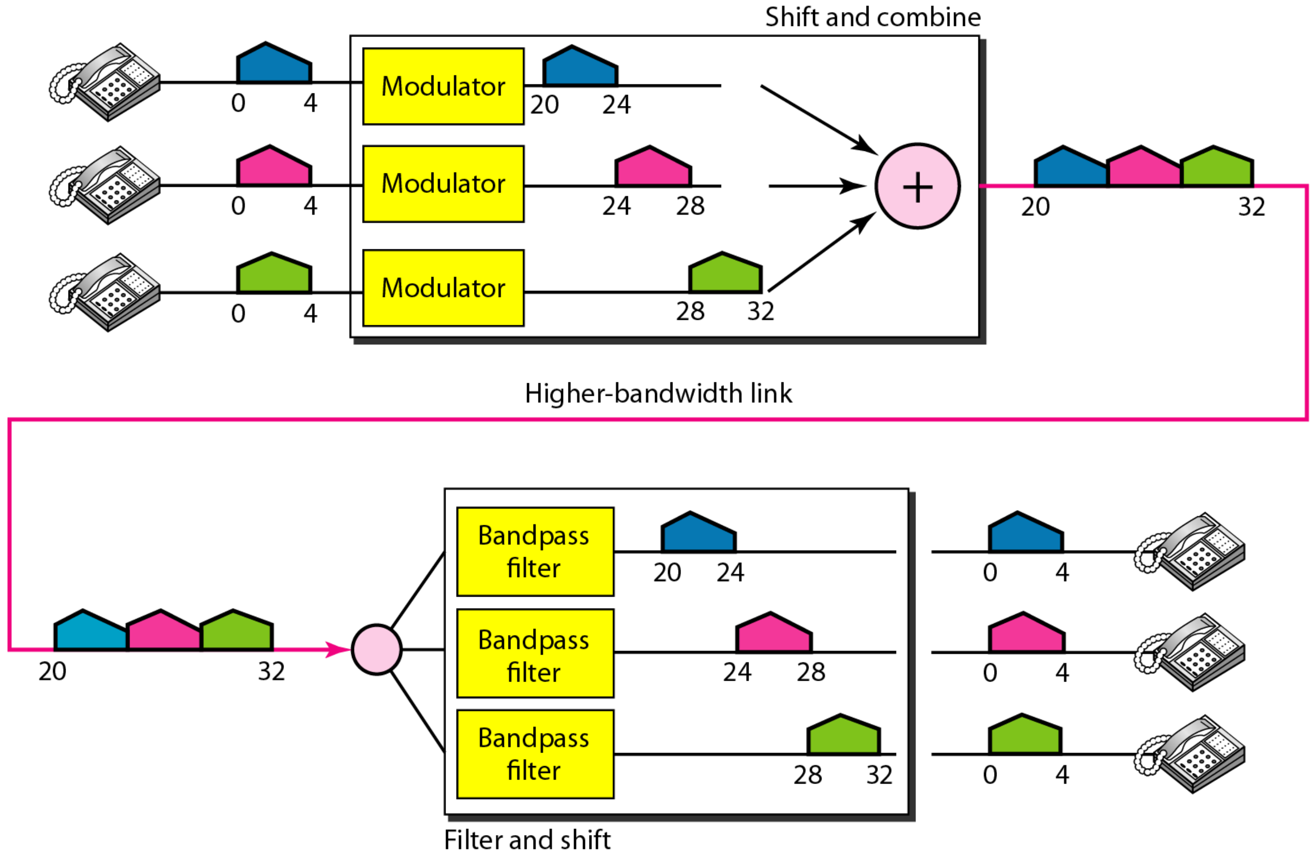
Example 6.1

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?

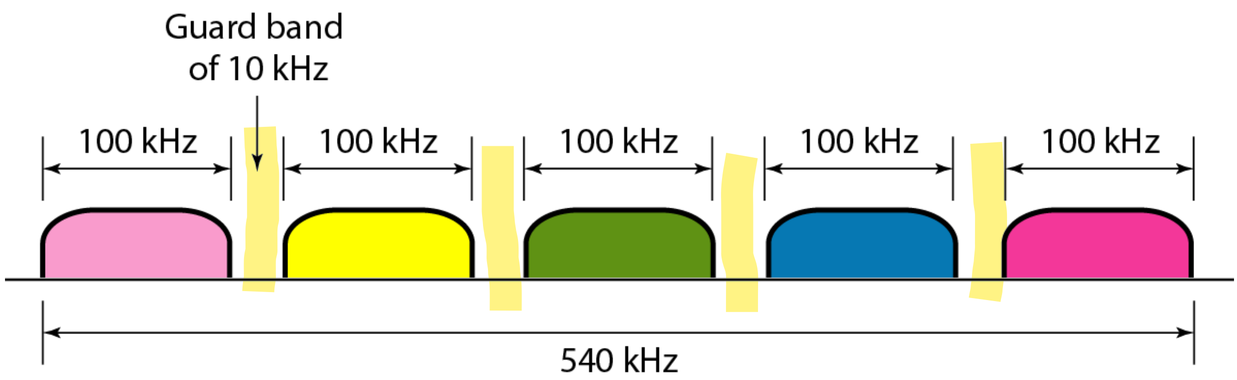
Solution

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*

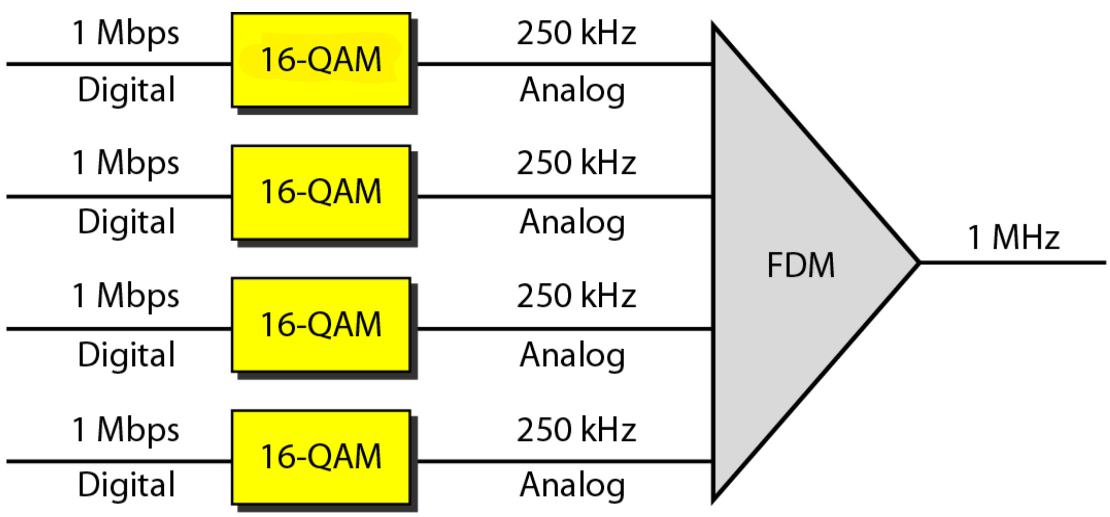
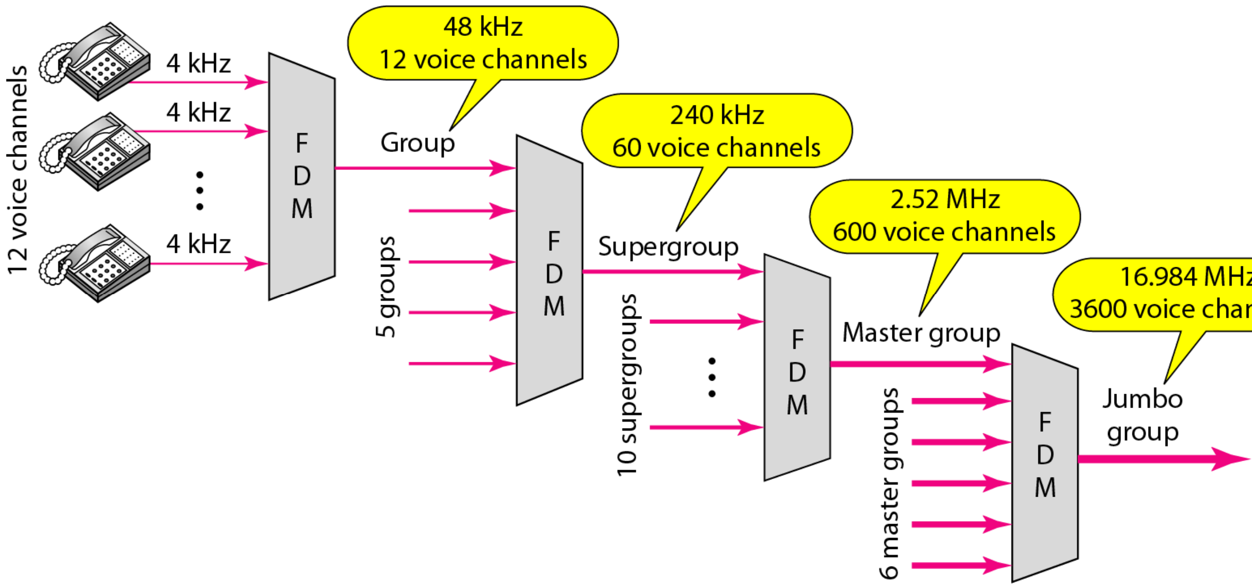
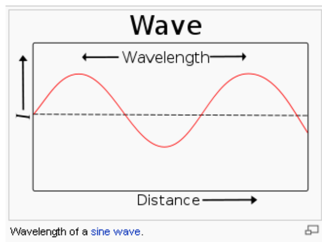


Figure 6.9 *Analog hierarchy*



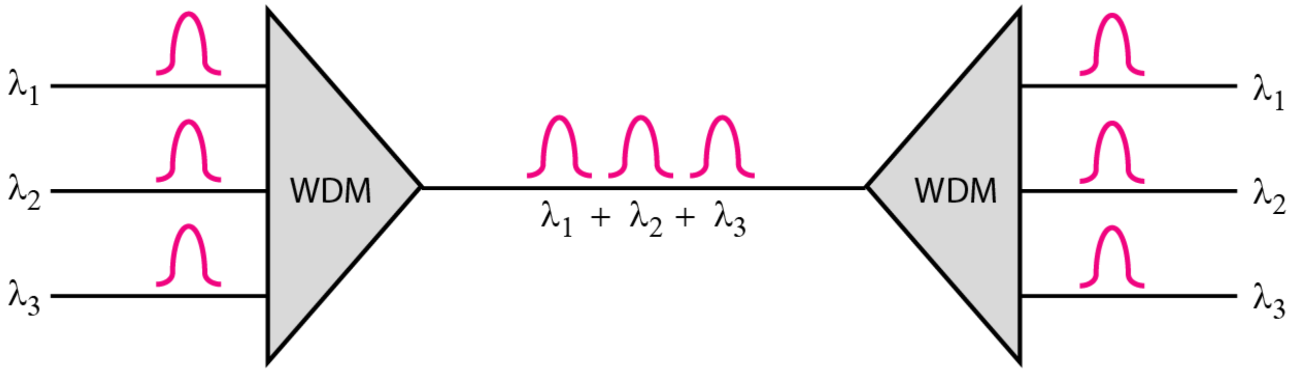
Wavelength-Division Multiplexing

- WDM
  - wavelength
    - the distance between repeating units of a propagating wave of a given frequency



  - an analog multiplexing technique to combine optical signals
    - 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
  - conceptually the same as FDM
    - combining different signals of different frequencies
    - the difference is that the frequencies are very high
      - very narrow bands of light from different sources are combined to make a wider band of light
  - one application of WDM is the SONET

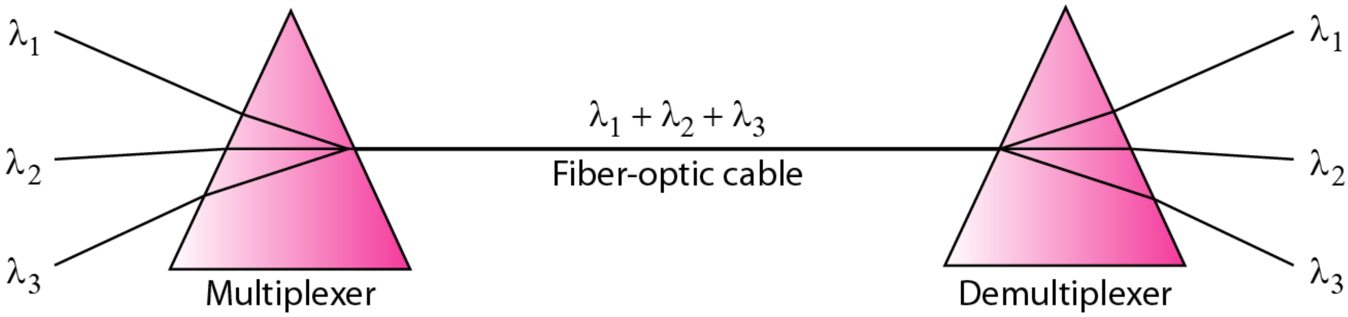
Figure 6.10 *Wavelength-division multiplexing*



Note

WDM is an analog multiplexing technique to combine optical signals.

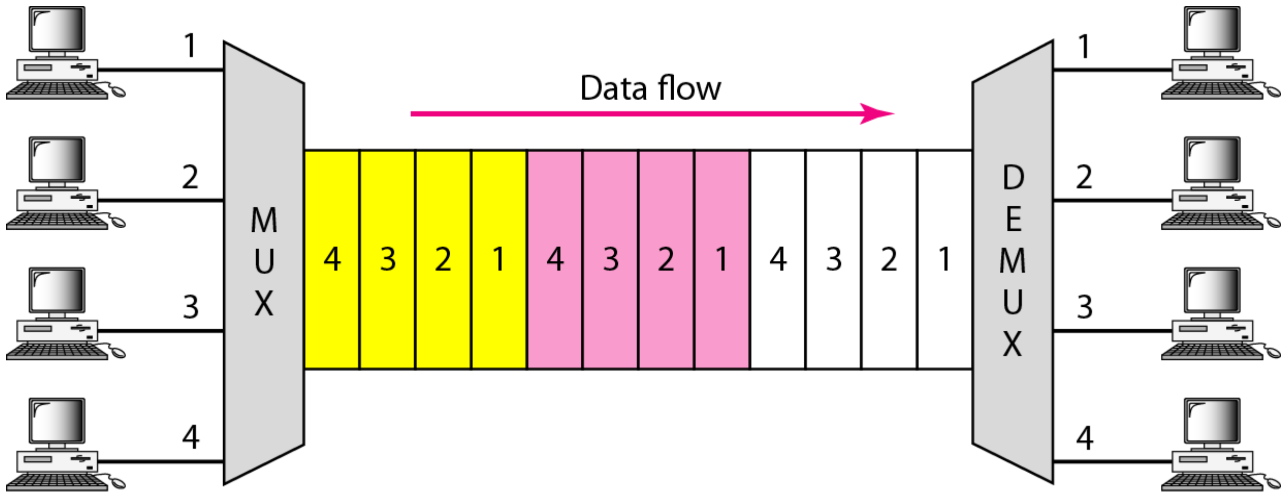
Figure 6.11 ***Prisms in wavelength-division multiplexing and demultiplexing***



Synchronous Time-Division Multiplexing

- TDM
  - a digital multiplexing technique
  - digital data from different sources are combined into one timeshared link
  - each connection occupies a portion of time in the link
- Type of TDM
  - synchronous TDM
    - each input connection has an allotment in the output even if it is not sending data
  - statistical TDM
- Time slots and frames
  - a round of data units from each input connection is collected into a frame
  - time slots are grouped into frames

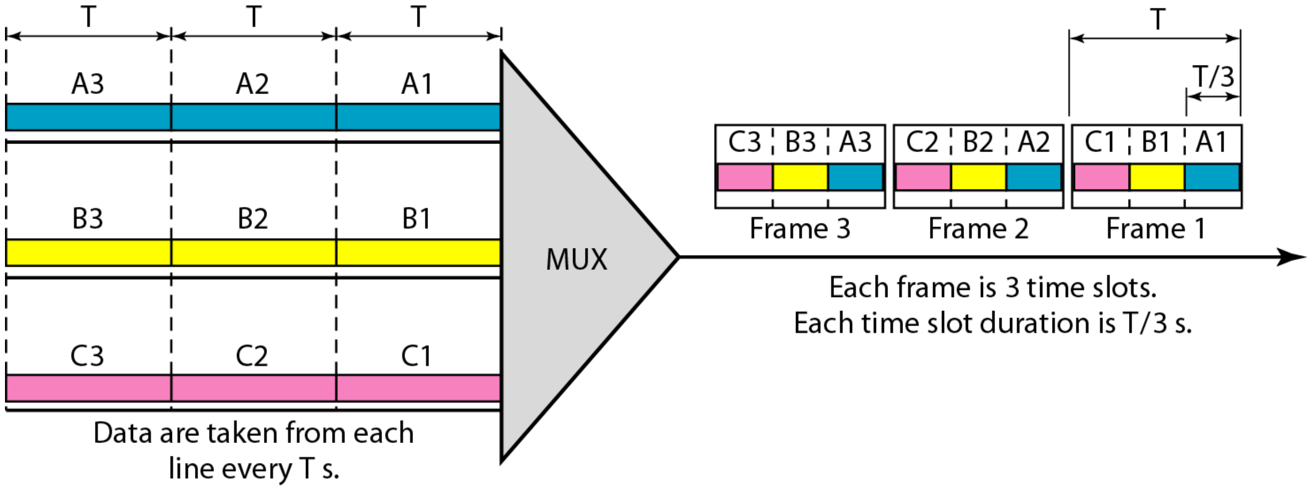
Figure 6.12 *TDM*



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.

Example 6.6 (skip – 각자풀어볼것)

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.

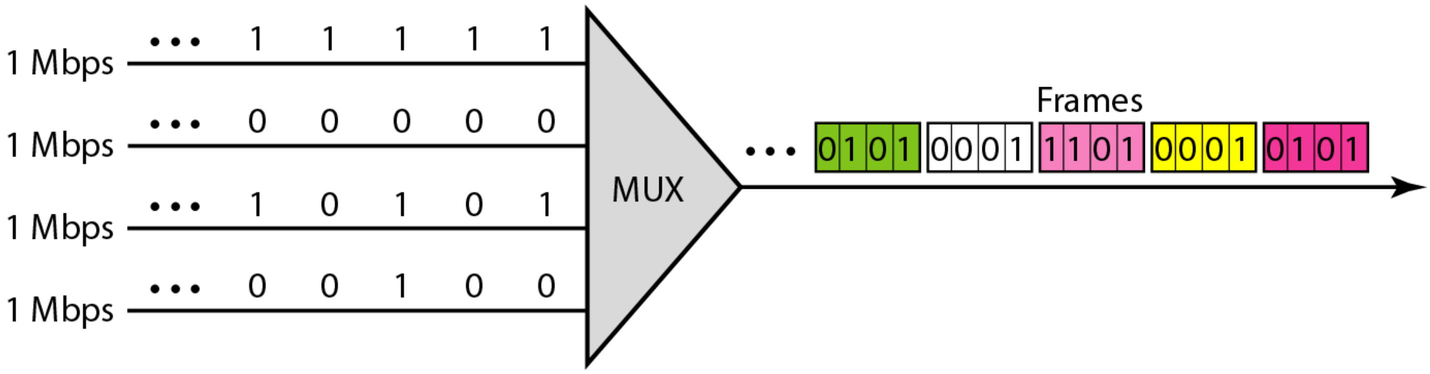
b. The output bit duration is one-fourth of the input bit duration, or ¼ μs.

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.

Figure 6.14 *Example 6.6*



Example 6.7 (skip)

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).

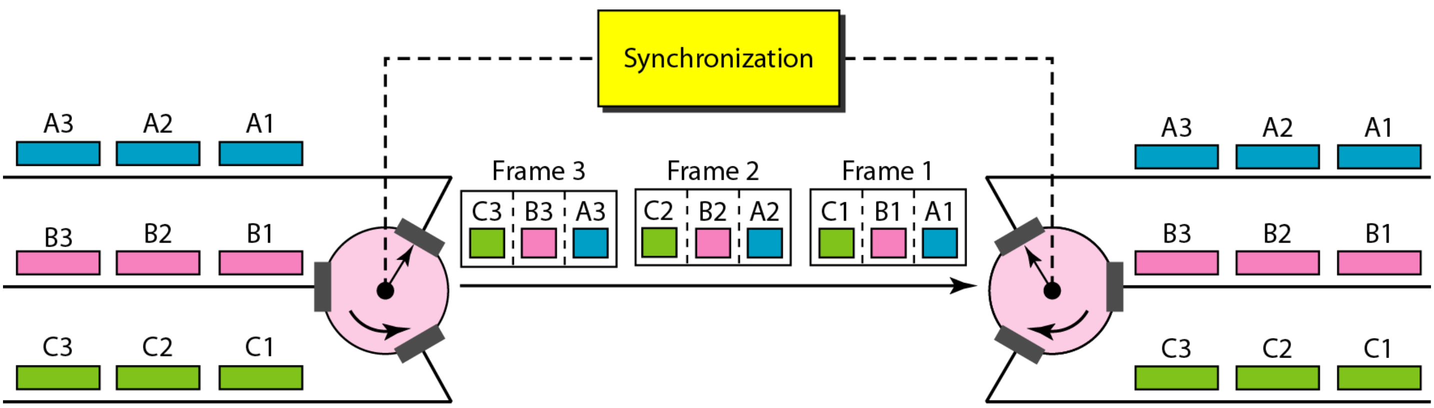
b. The rate of the link is 4 times the rate of a connection, or 4 kbps.

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*



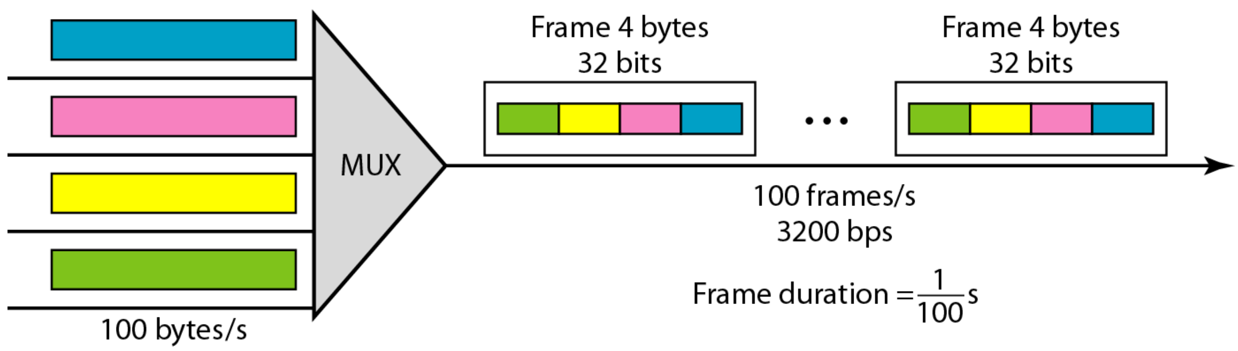
Example 6.8 (각자풀어볼것)

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 (skip)

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*

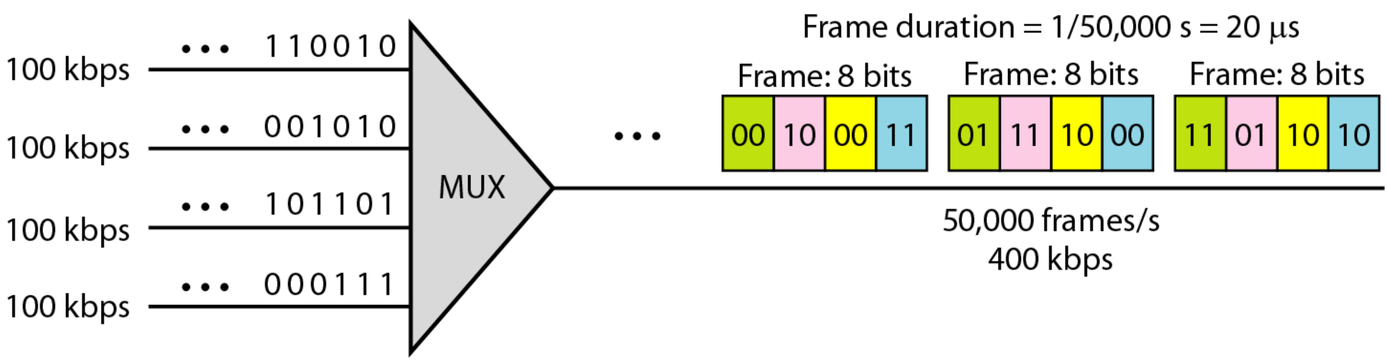
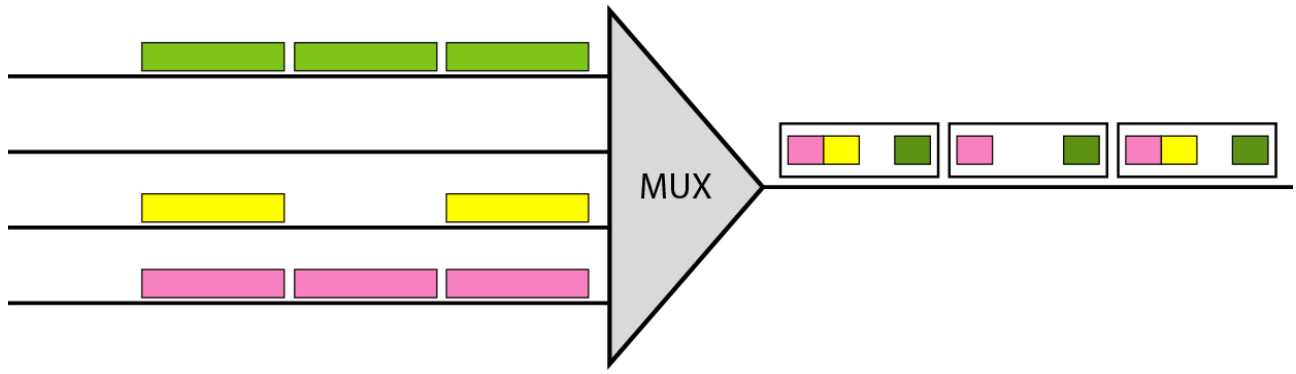


Figure 6.18 *Empty slots*



Data Rate Management in TDM

- How to handle a disparity in the input data rate?
- Solutions
  - Multilevel Multiplexing
  - Multiple-Slot Allocation
  - Pulse Stuffing

Figure 6.19 *Multilevel multiplexing*

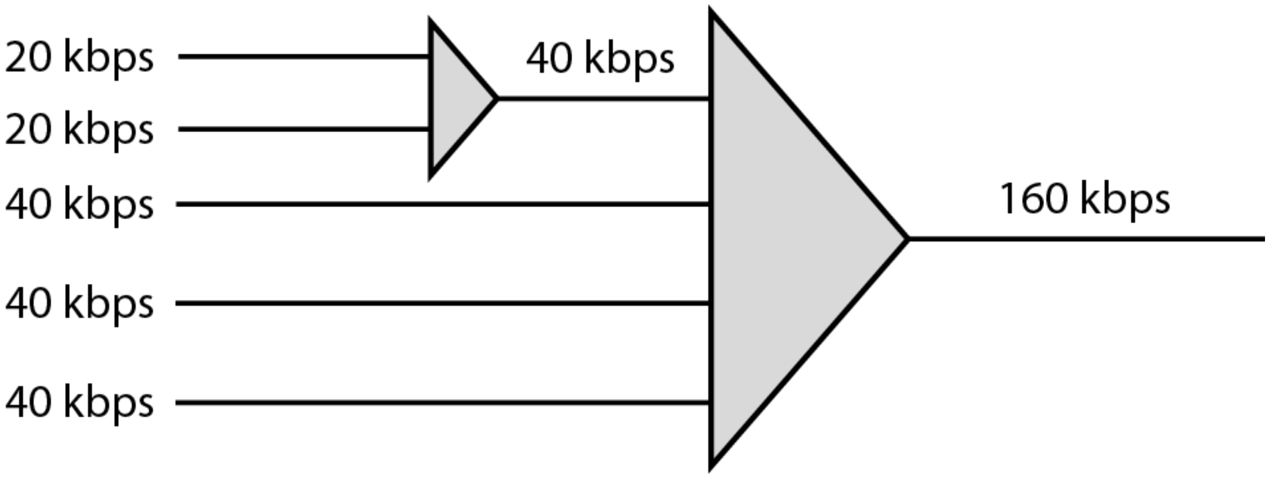


Figure 6.20 *Multiple-slot multiplexing*

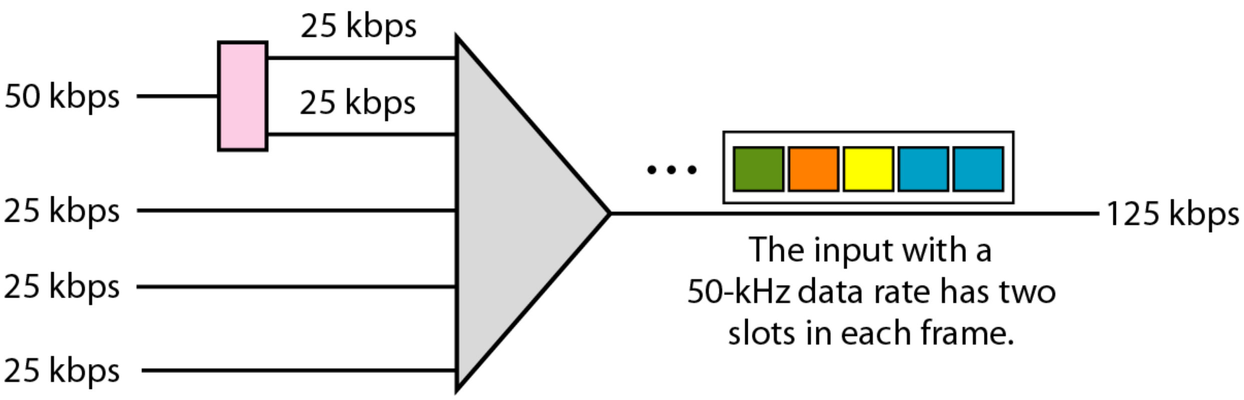
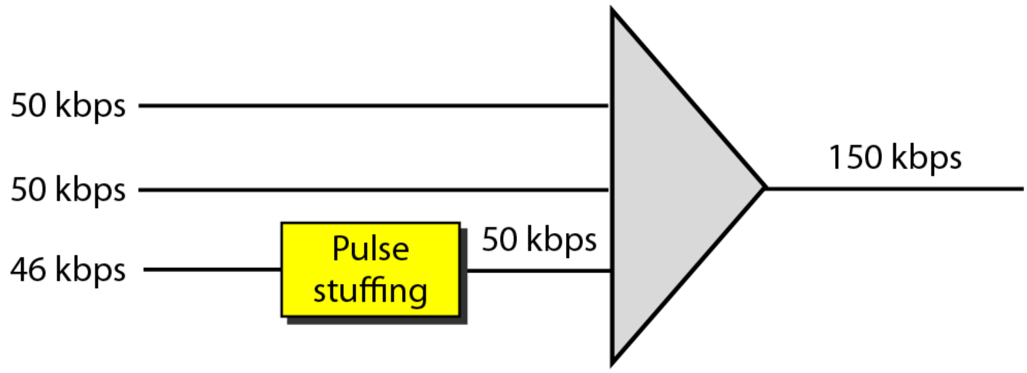


Figure 6.21 *Pulse stuffing*

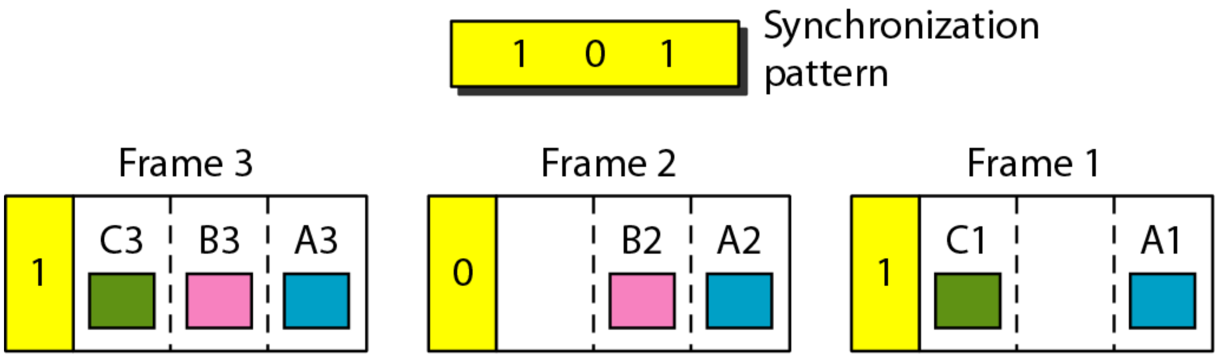


Frame Synchronization

- Synchronization between the multiplexer and demultiplexer

- Solution
  - framing bits
  - one or more sync. bits are usually added to the beginning of each frame

Figure 6.22 *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 × 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.*

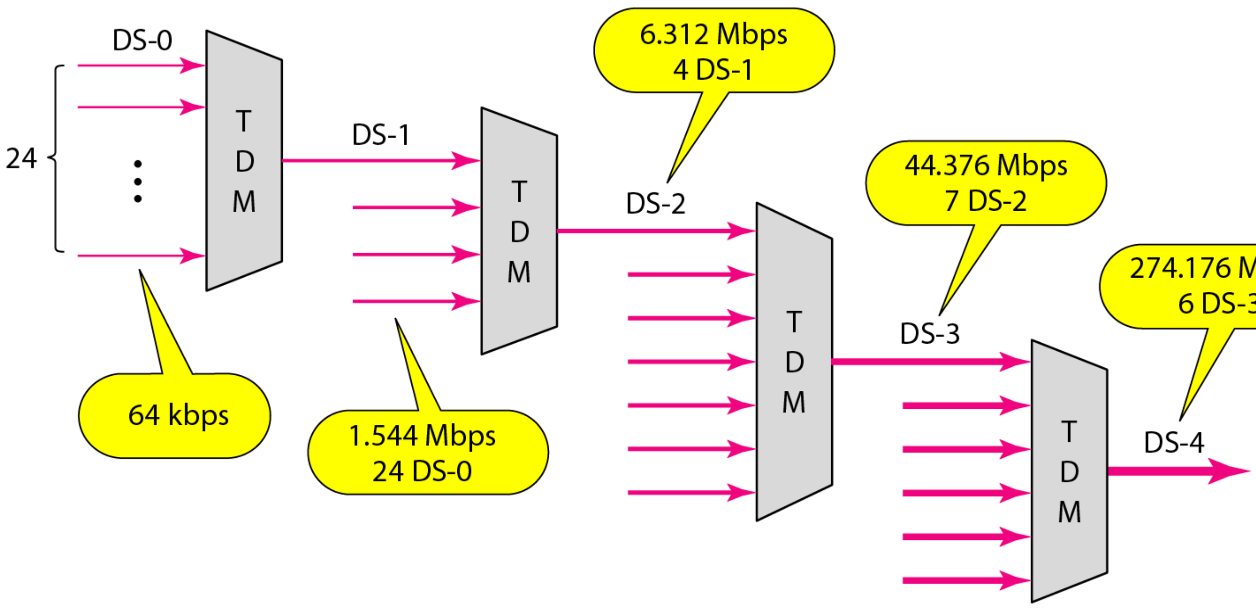
Example 6.11 (skip)

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 $\times$ *3 bits per frame, or 300 kbps.*

Figure 6.23 *Digital hierarchy*



*DS: Digital Signal

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*

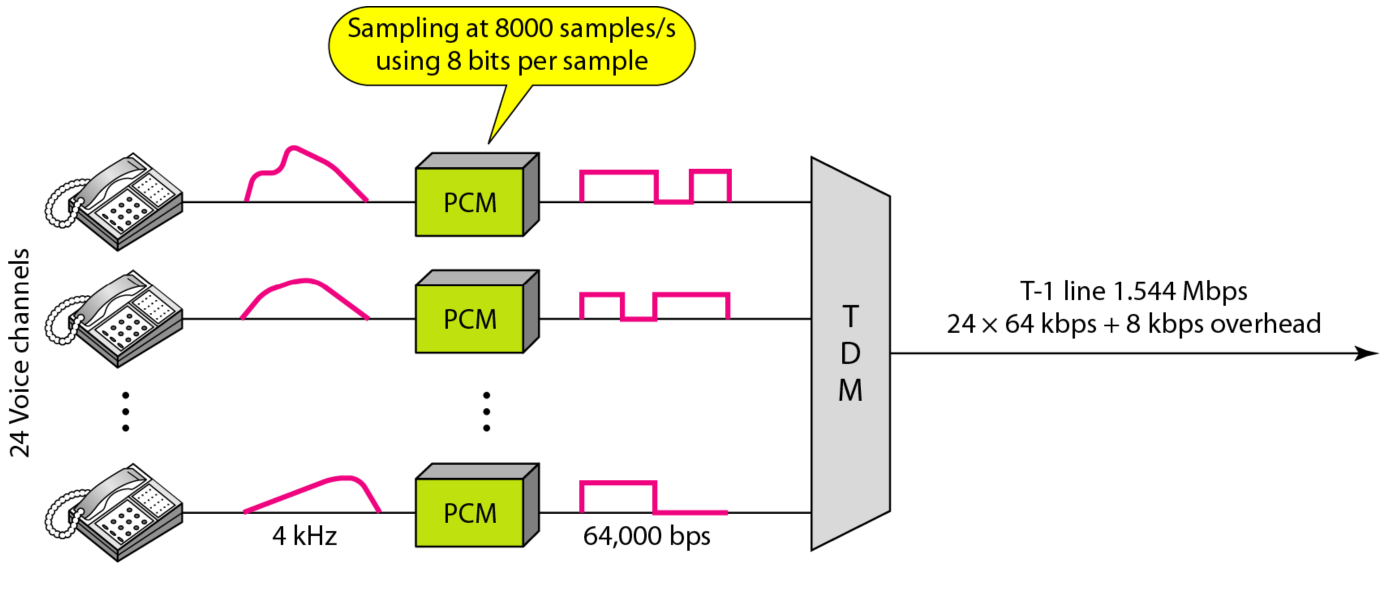


Figure 6.25 *T-1 frame structure*

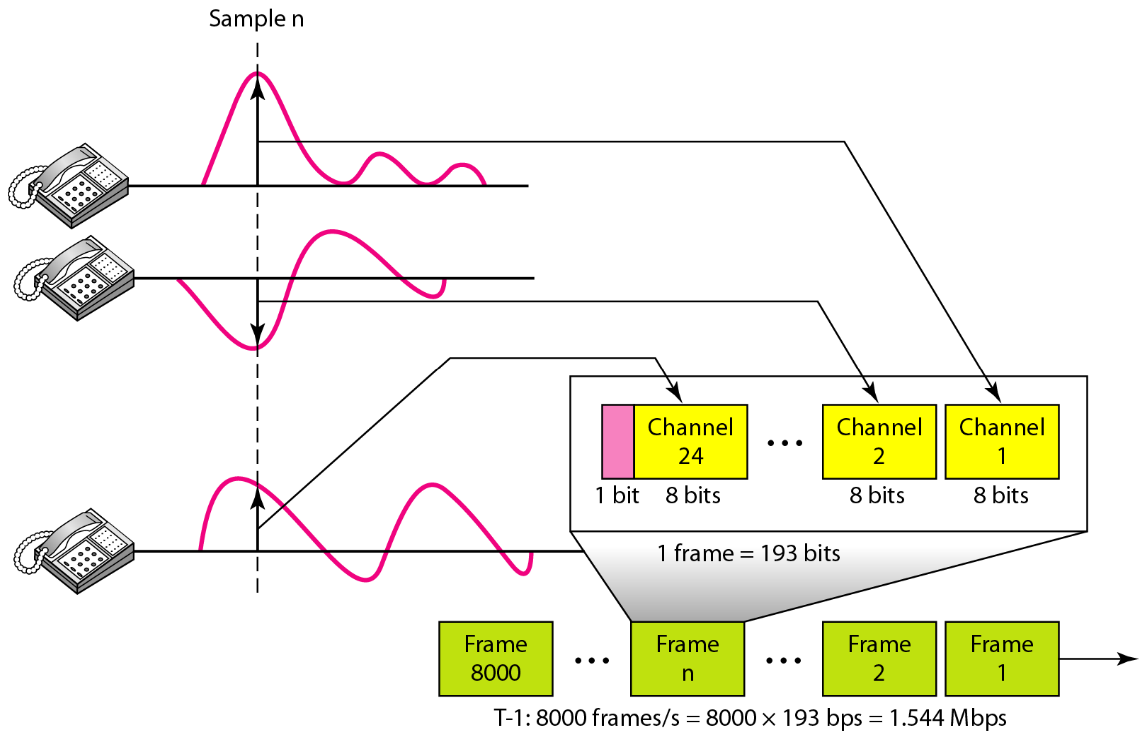
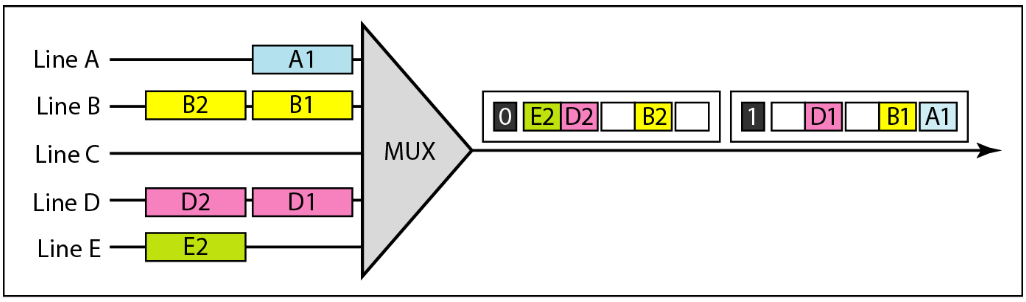


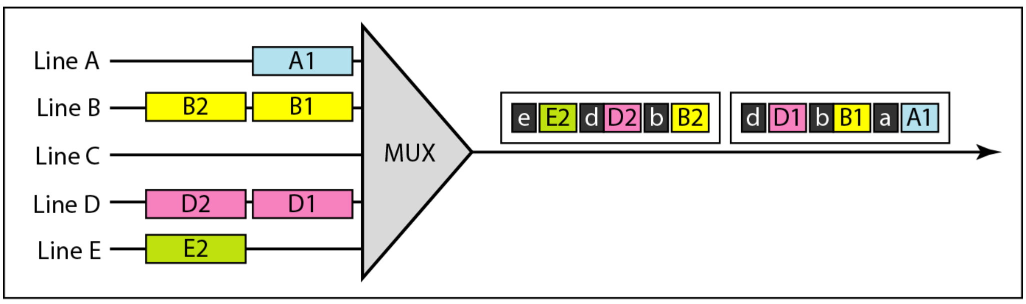
Table 6.2 *E line rates*

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*



a. Synchronous TDM



b. Statistical TDM

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

- Multiplexing Technique? or Modulation??
- Designed for wireless applications
- Two principles
  - the bandwidth allocated to each station needs to be larger than what is needed
  - the expanding of the original bandwidth B to the bandwidth B_{ss} must be done by a process that is independent of the original signal
    - after the signal is created by the source, the spreading process uses a spreading code and spreads the bandwidth
    - the spreading code is a series of numbers that look random, but are actually a pattern
- Types
  - FHSS, DSSS

Figure 6.27 *Spread spectrum*

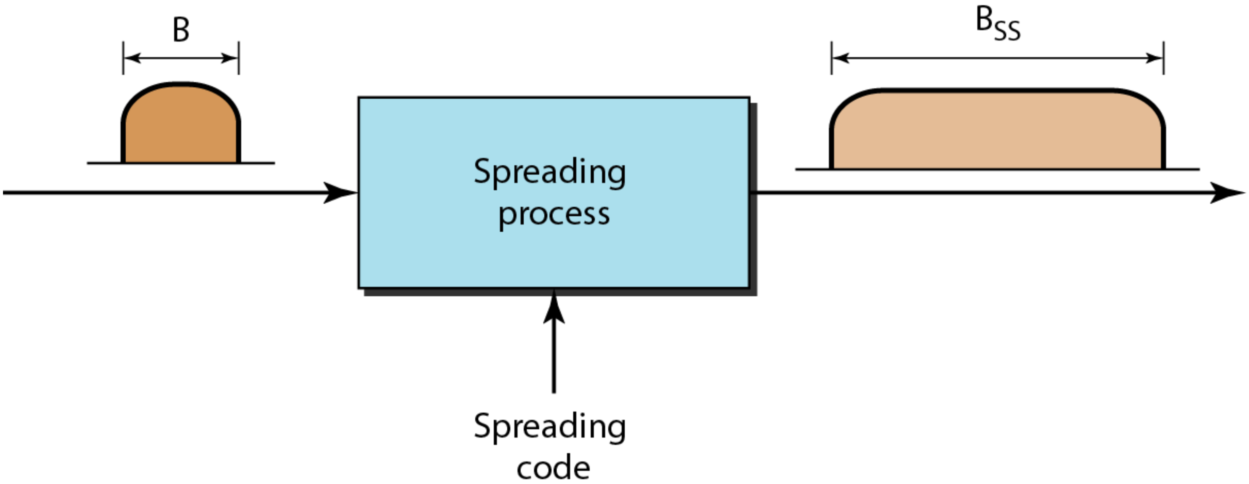


Figure 6.28 *Frequency hopping spread spectrum (FHSS)*

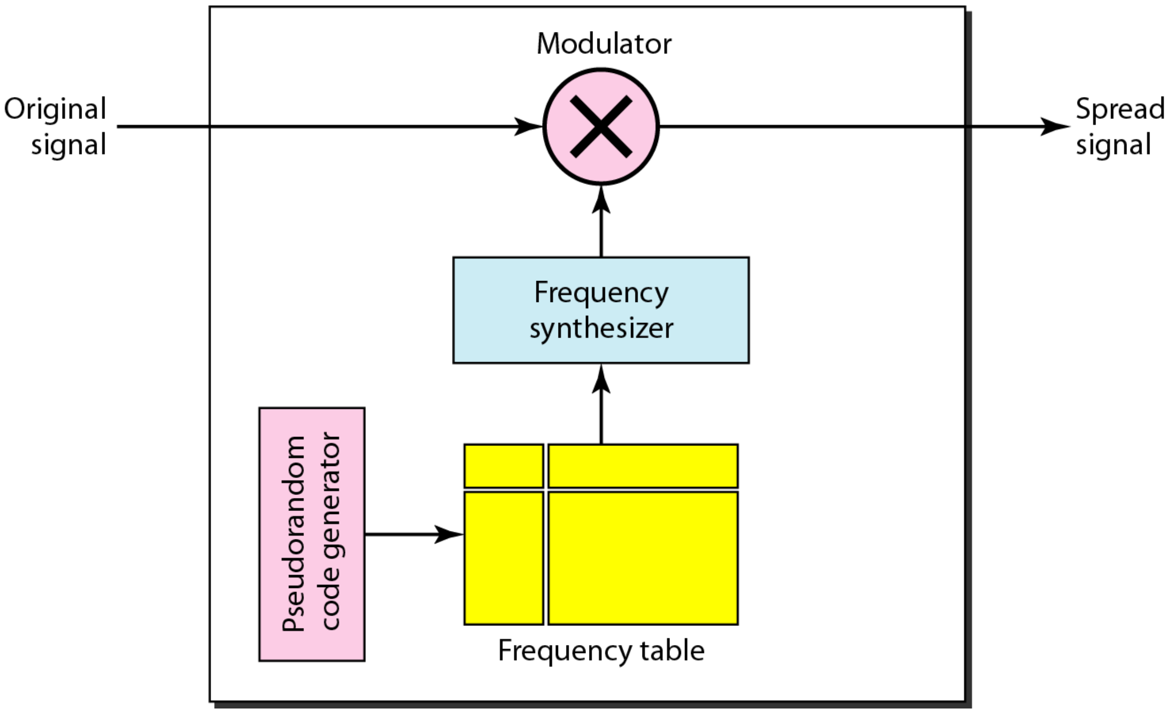


Figure 6.29 *Frequency selection in FHSS*

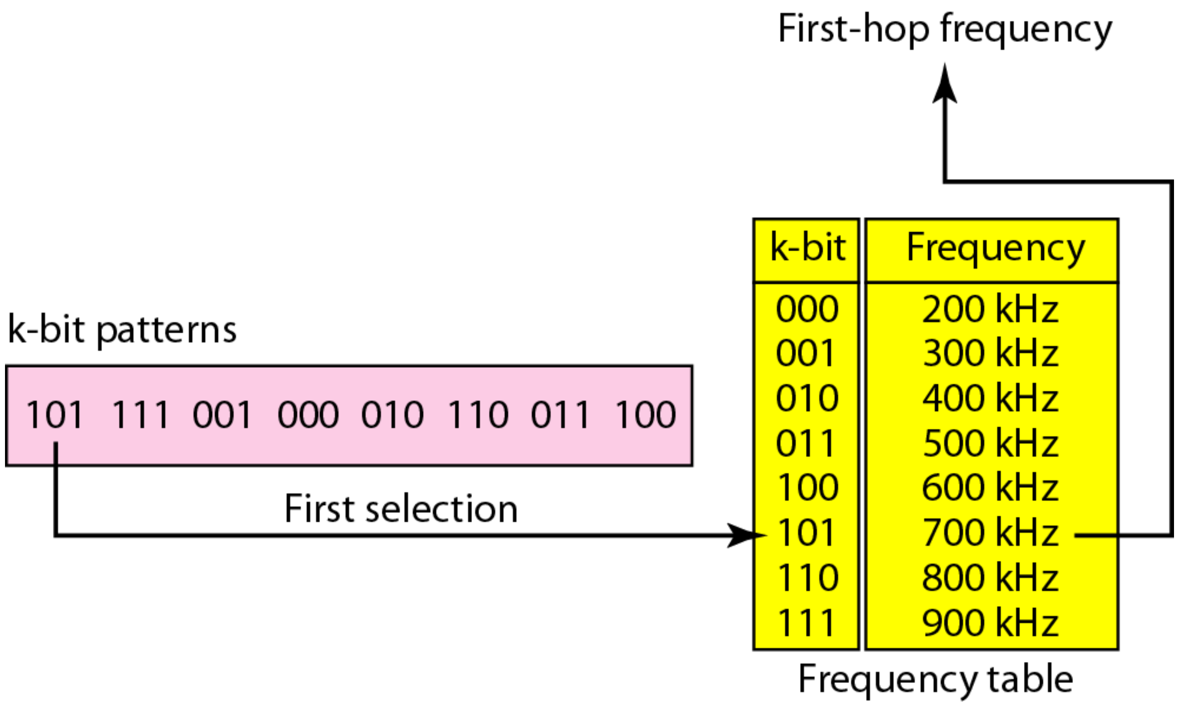


Figure 6.30 *FHSS cycles*

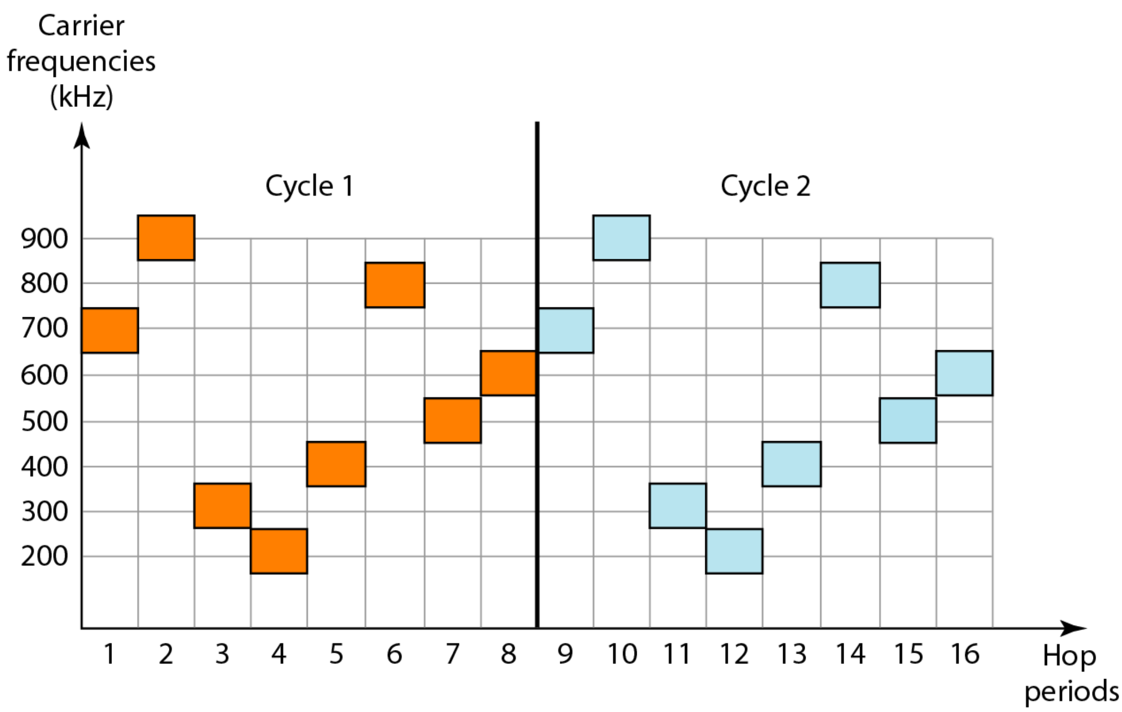


Figure 6.31 *Bandwidth sharing*

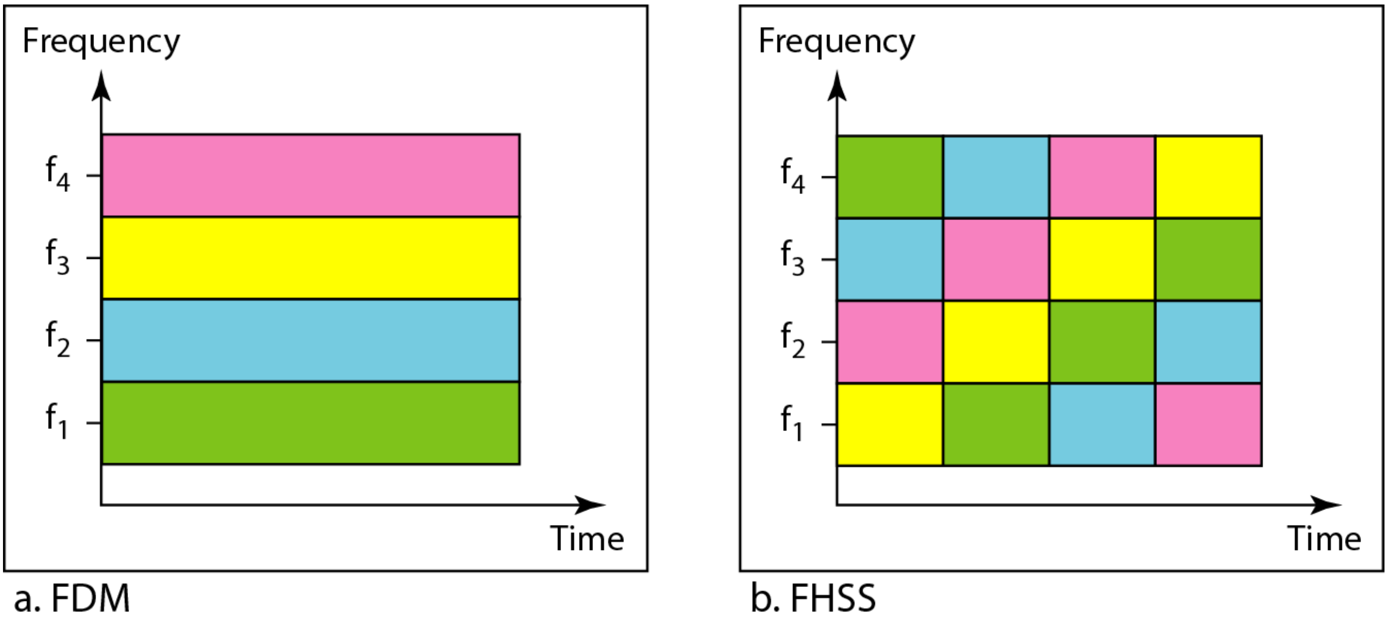


Figure 6.32 *DSSS*

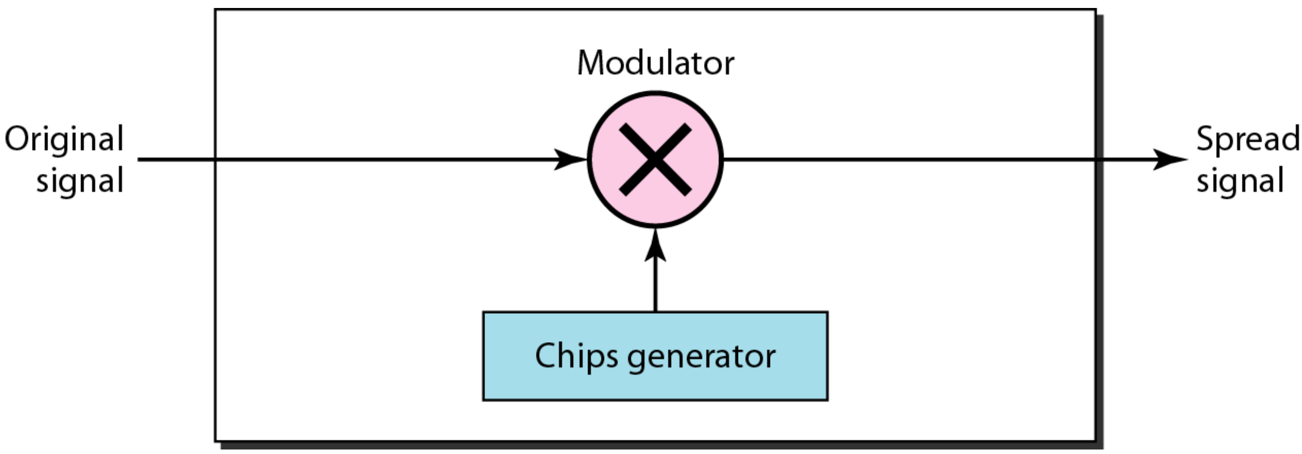
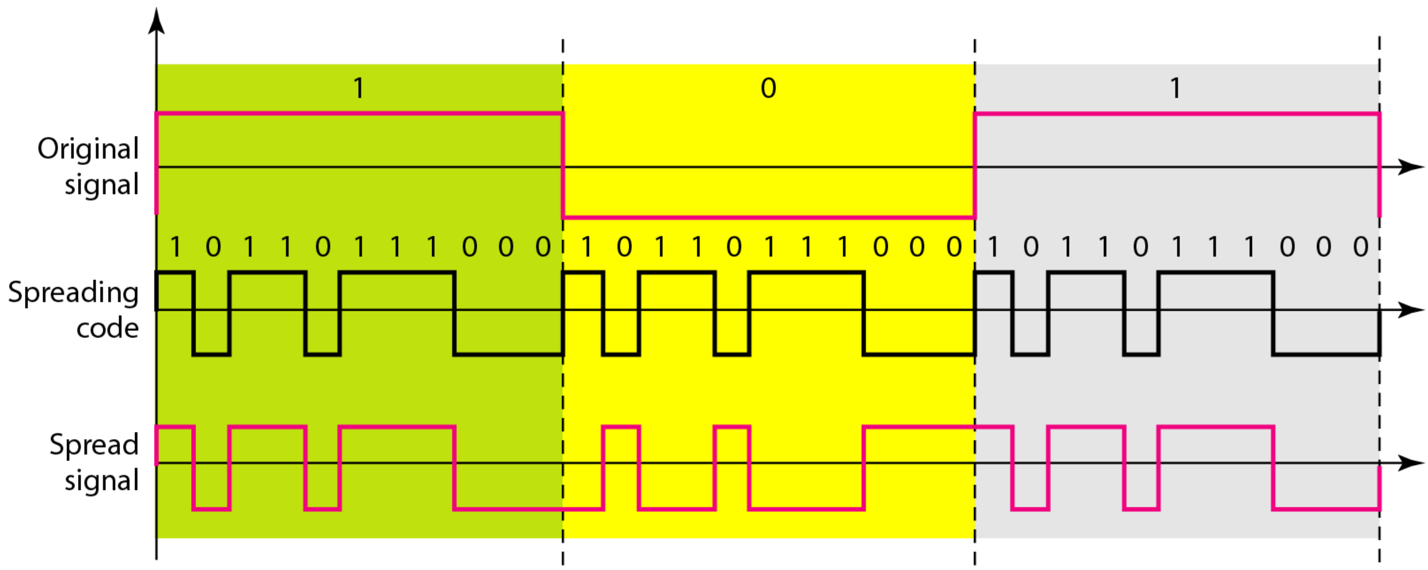


Figure 6.33 *DSSS example*



Bandwidth Sharing in DSSS

- Can we share a bandwidth in DSSS as we did in FHSS?
  - NO
    - if we use a spreading code that spreads signals (from different stations) that cannot be combined and separated, we cannot share a bandwidth
    - example: wireless LANs
  - YES
    - if we use a special type of sequence code that allows the combining and separating of spread signals, we can share the bandwidth → orthogonal code
    - example: cellular systems