



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

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. We can accommodate this increase by continuing to add individual links each time a new channel is needed; or we can install higher-bandwidth links and use each to carry multiple signals.

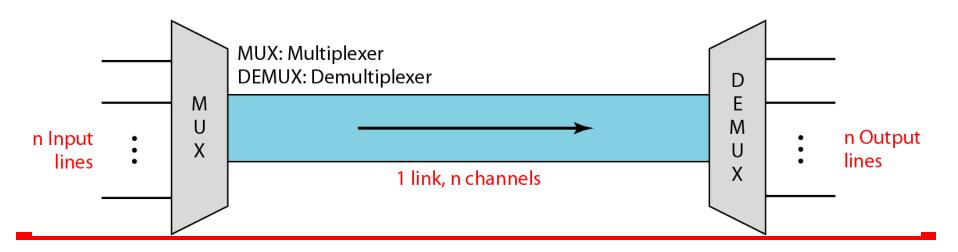


Figure 6.2 Categories of multiplexing

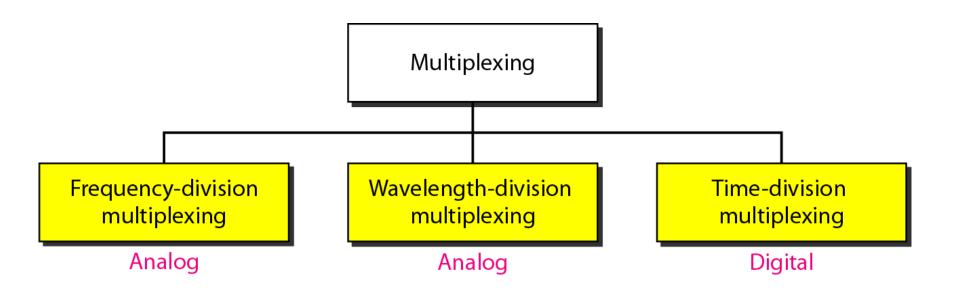


Figure 6.3 Frequency-division multiplexing

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





Note

FDM is an analog multiplexing technique that combines analog signals.

Figure 6.4 FDM process

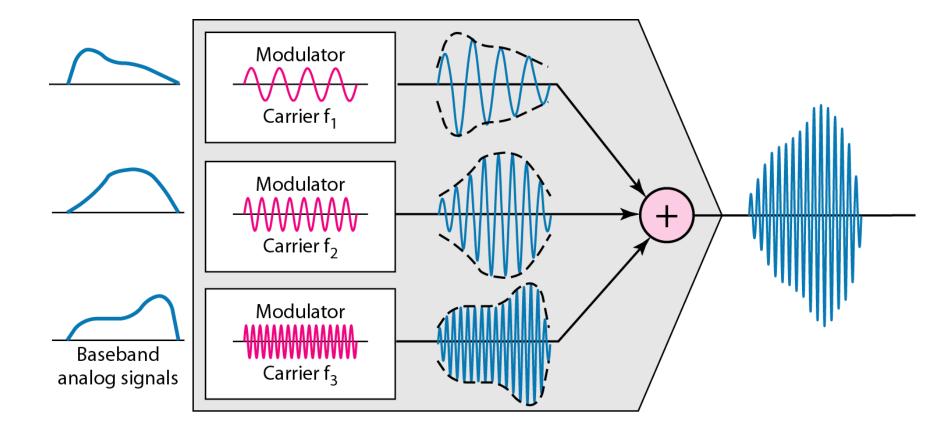
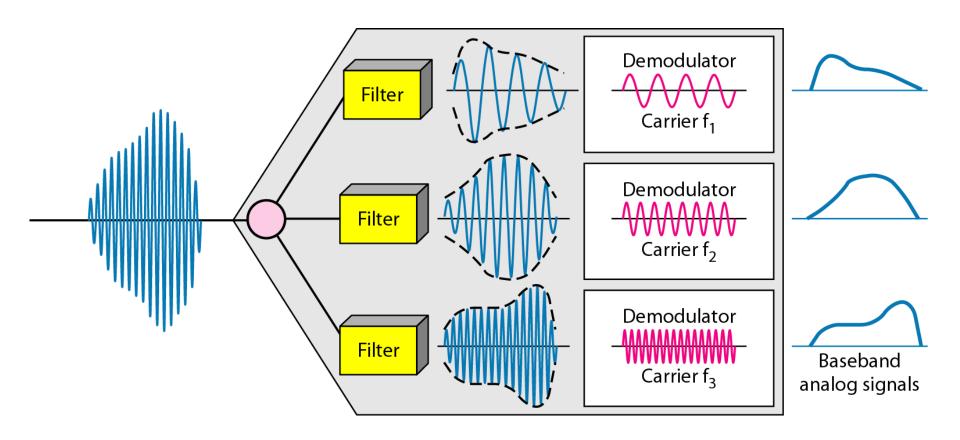


Figure 6.5 FDM demultiplexing example

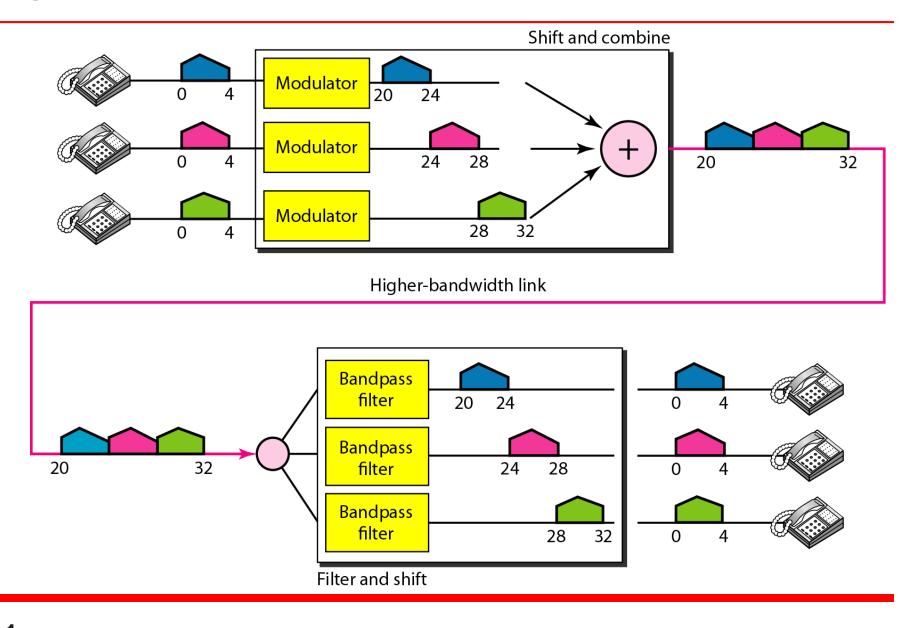


Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.

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



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

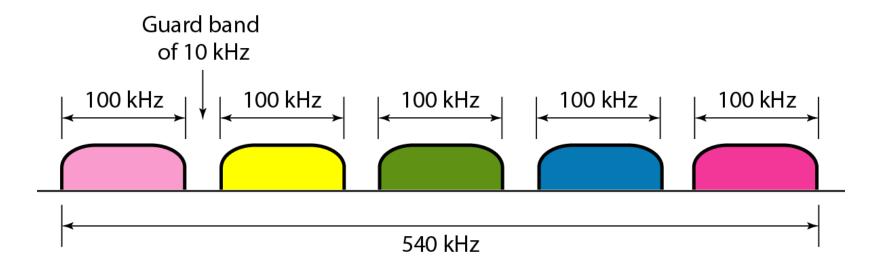
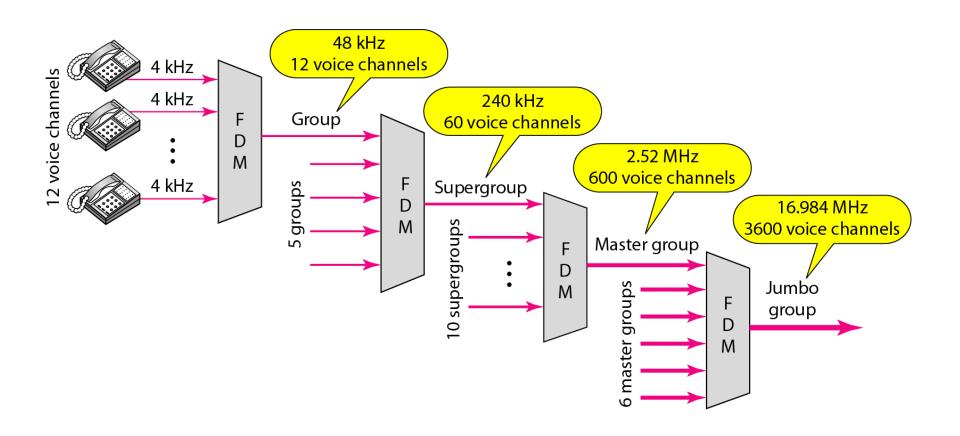


Figure 6.9 Analog hierarchy



Application of FDM

A very common application of FDM is AM and FM radio broadcasting. Radio uses the air as the transmission medium. A special band from 530 to 1700 kHz is assigned to AM radio. All radio stations need to share this band. Each AM station needs 10kHz of bandwidth. Each station uses a different carrier frequency, which means it is shifting its signal and multiplexing. The situation is similar in FM broadcasting. However, FM has a wider band of 88 to 108 MHz because each station needs a bandwidth of 200 kHz.

Application of FDM

Another common use of FDM is in television broadcasting. Each TV channel has its own bandwidth of 6 MHz.

The first generation of cellular telephones (still in operation) also uses FDM. Each user is assigned two 30-kHz channels, one for sending voice and the other for receiving.

The Advanced Mobile Phone System (AMPS) uses two bands. The first band of 824 to 849 MHz is used for sending, and 869 to 894 MHz is used for receiving. Each user has a bandwidth of 30 kHz in each direction. How many people can use their cellular phones simultaneously?

Solution

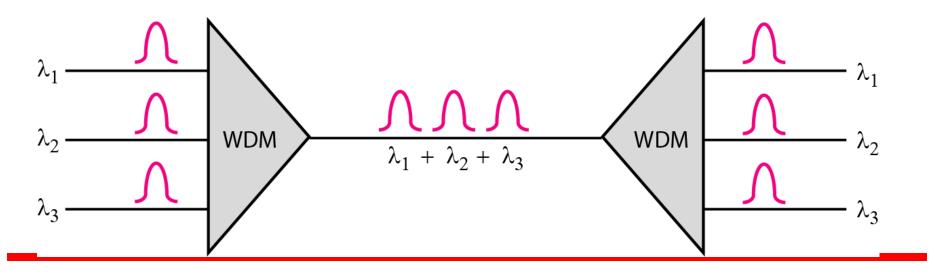
Each band is 25 MHz. If we divide 25 MHz by 30 kHz, we get 833.33. In reality, the band is divided into 832 channels. Of these, 42 channels are used for control, which means only 790 channels are available for cellular phone users.

FDM Implementation

FDM can be implemented very easily. In many cases, such as radio and television broadcasting, there is no need for a physical multiplexer or demultiplexer. As long as the stations agree to send their broadcasts to the air using different carrier frequencies, multiplexing is achieved. In other cases, such as the cellular telephone system, a base station needs to assign a carrier frequency to the telephone user. There is not enough bandwidth in a cell to permanently assign a bandwidth range to every telephone user. When a user hangs up, her or his bandwidth is assigned to another caller.

Figure 6.10 Wavelength-division multiplexing

Wavelength-division multiplexing (WDM) is designed to use the high-data-rate capability of fiber-optic cable. The optical fiber data rate is higher than the data rate of metallic transmission cable. Using a fiber-optic cable for one single line wastes the available bandwidth. Multiplexing allows us to combine several lines into one.



WDM is an analog multiplexing technique to combine optical signals.

WDM is conceptually the same as FDM, except that the multiplexing and demultiplexing involve optical signals transmitted through fiber-optic channels. 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.

Figure 6.11 Prisms in wavelength-division multiplexing and demultiplexing

WDM technology is very complex, the basic idea is very simple. We want to combine multiple light sources into one single light at the multiplexer and do the reverse at the demultiplexer. The combining and splitting of light sources are easily handled by a prism. One application of WDM is the SONET network. A new method, called dense WDM (DWDM), can multiplex a very large number of channels by spacing channels very close to one another.

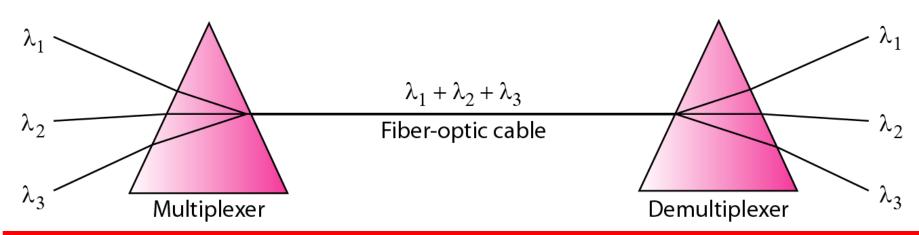
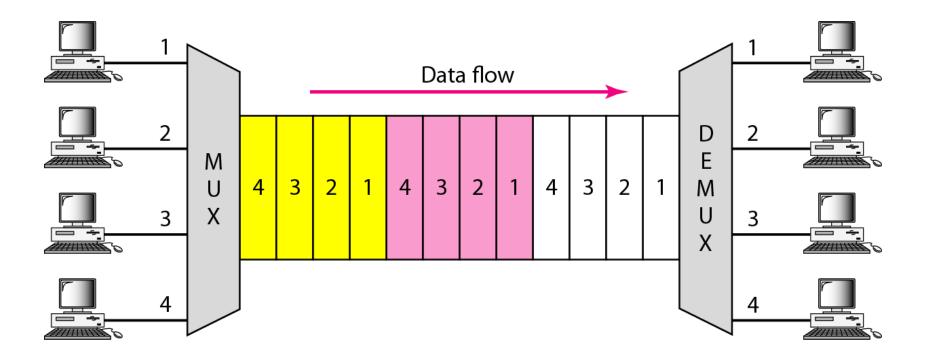


Figure 6.12 TDM



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

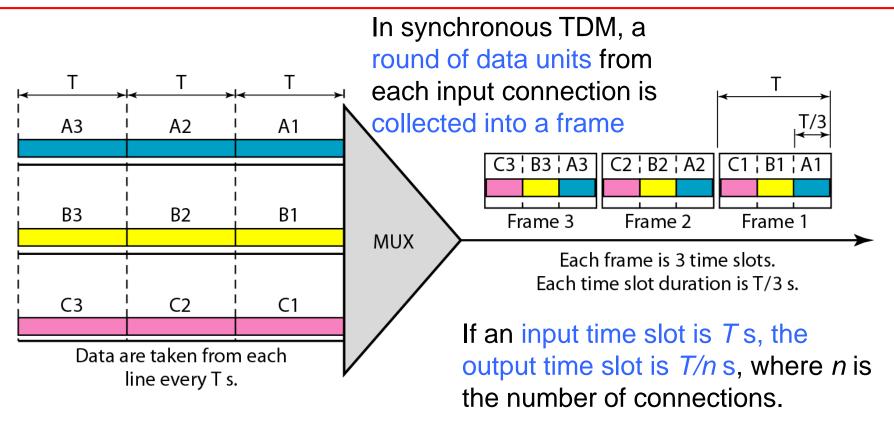
Instead of sharing a portion of the bandwidth as in FDM, time is shared. Each connection occupies a portion of time in the link.

Analog data can be sampled, changed to digital data, and then multiplexed by using TDM. We can divide TDM into two different schemes: synchronous and statistical.

In synchronous TDM, the data flow of each input connection is divided into units, where each input occupies one input time slot. A unit can be 1 bit, one character, or one block of data. Each input unit becomes one output unit and occupies one output time slot.

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

Figure 6.13 Synchronous time-division multiplexing



The data rate of the output link must be *n* times the data rate of a connection to guarantee the flow of data.

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.

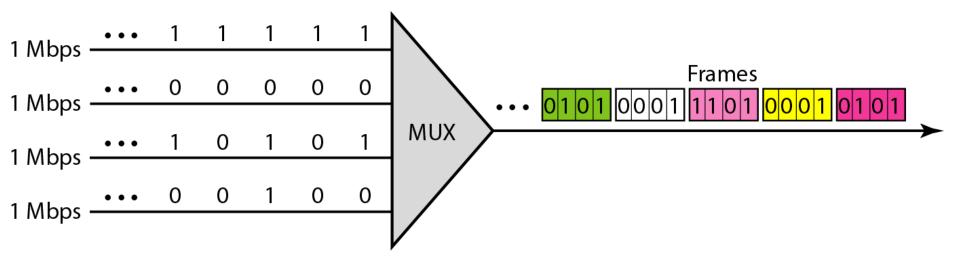
Figure 6.14 shows synchronous TDM with a data stream for each input and one data stream for the output. The unit of data is 1 bit. Find (a) the input bit duration, (b) the output bit duration, (c) the output bit rate, and (d) the output frame rate.

Solution

We can answer the questions as follows:

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

Figure 6.14 Example 6.6



Example 6.6 (continued)

- c. The output bit rate is the inverse of the output bit duration or $1/(4\mu s)$ 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 = 4×1 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.

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

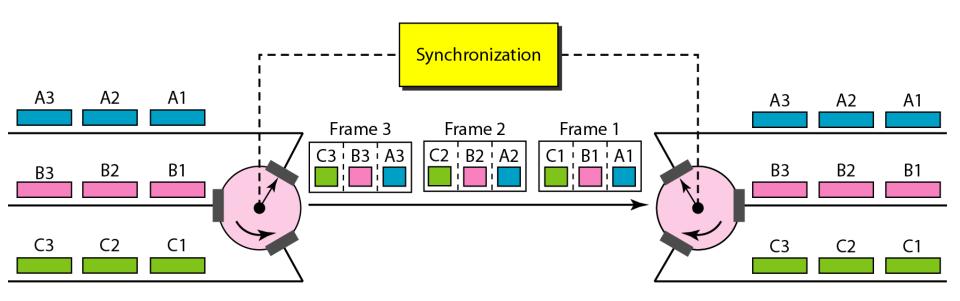
We can answer the questions as follows:

- 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

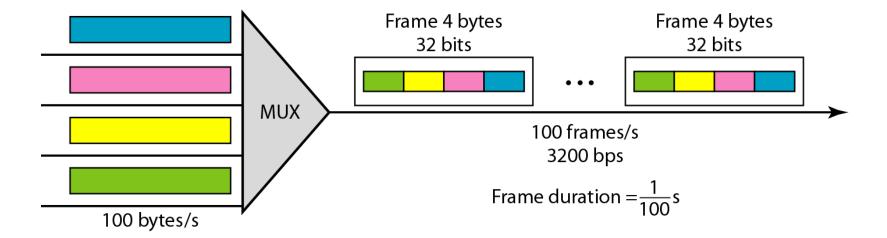


Four channels are multiplexed using TDM. If each channel sends 100 bytes /s and we multiplex 1 byte per channel, show the frame traveling on the link, the size of the frame, the duration of a frame, the frame rate, and the bit rate for the link.

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



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 $20 \mu s$. 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 $2.5 \mu s$.

Figure 6.17 Example 6.9

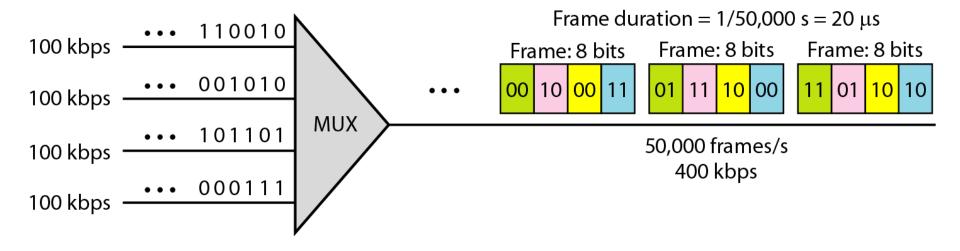
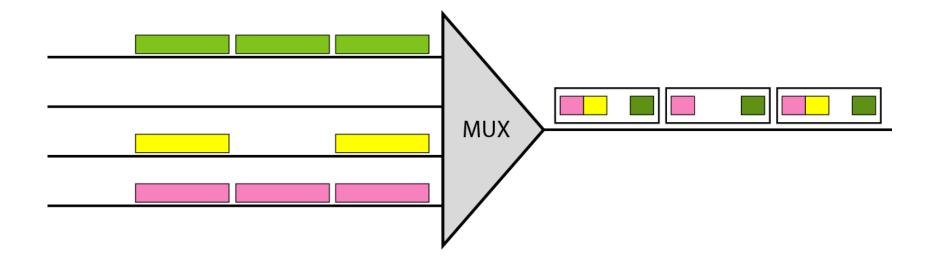


Figure 6.18 Empty slots

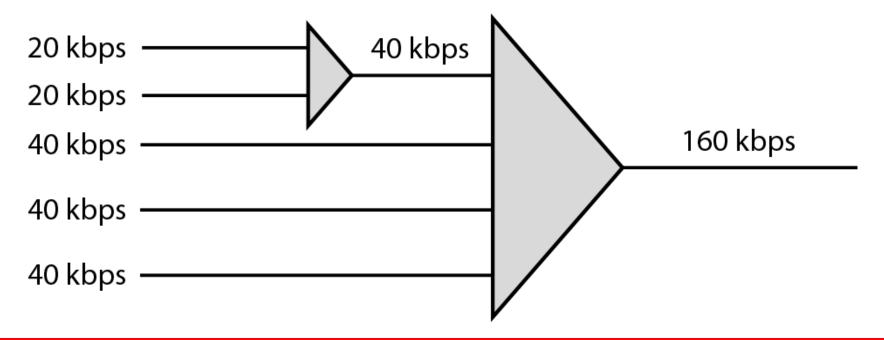
Synchronous TDM is not as efficient as it could be. If a source does not have data to send, the corresponding slot in the output frame is empty.



Data Rate Management

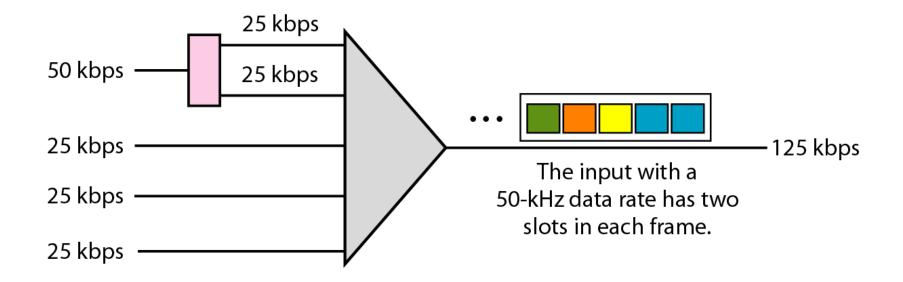
One problem with TDM is how to handle a disparity in the input data rates.

Figure 6.19 Multilevel multiplexing



Data Rate Management

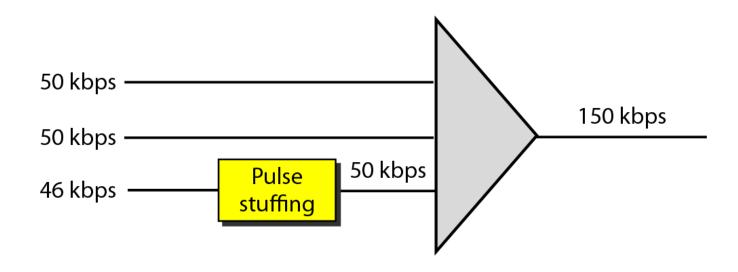
Figure 6.20 Multiple-slot multiplexing



Data Rate Management

Figure 6.21 Pulse stuffing

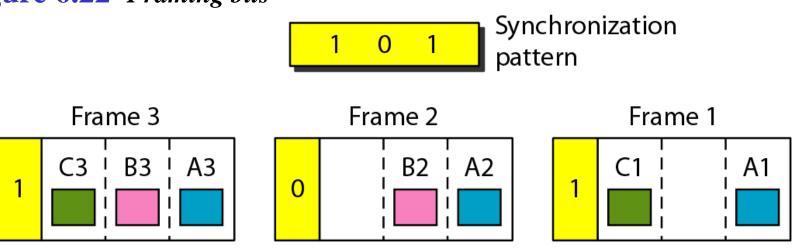
Sometimes the bit rates of sources are not multiple integers of each other. To make the highest input data rate the dominant data rate and then add dummy bits to the input lines with lower rates. This will increase the data rates.



Frame Synchronizing

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. One or more synchronization 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 $250 \times 8 = 2000 \text{ bps} = 2 \text{ kbps}$.

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

Figure 6.23 Digital hierarchy

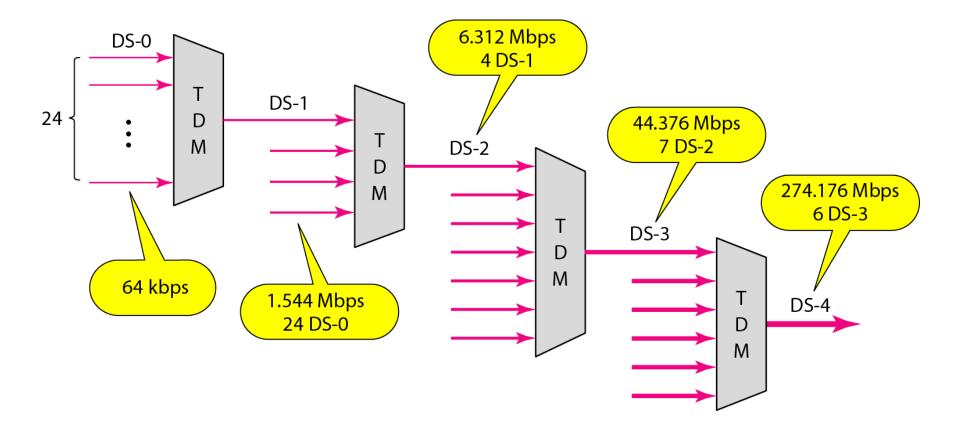


Table 6.1 DS and T line rates

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

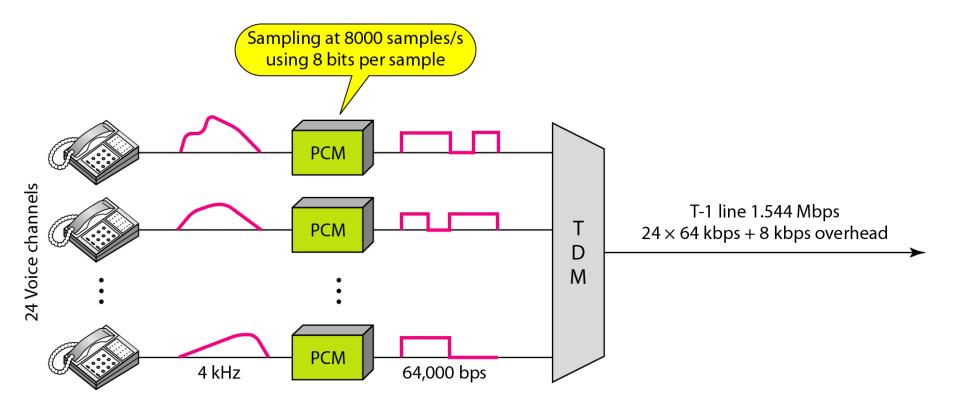


Figure 6.25 T-1 frame structure

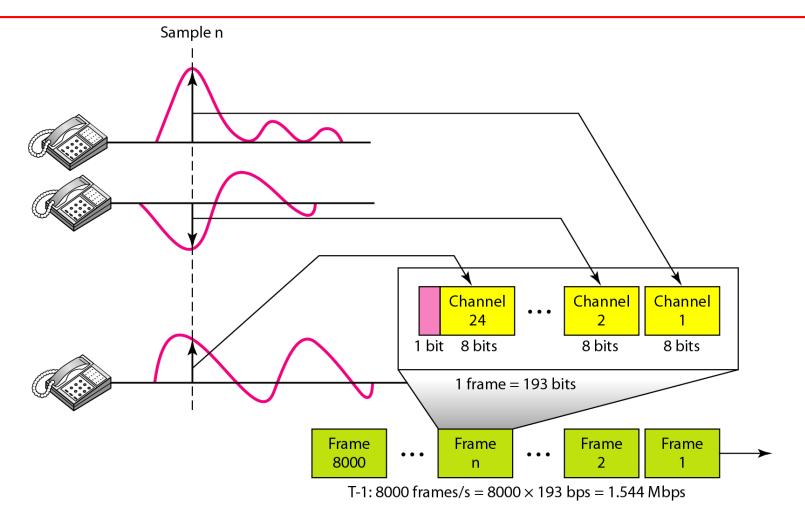
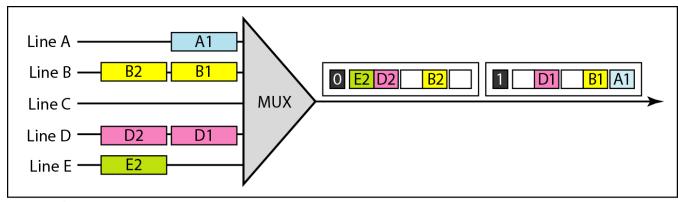


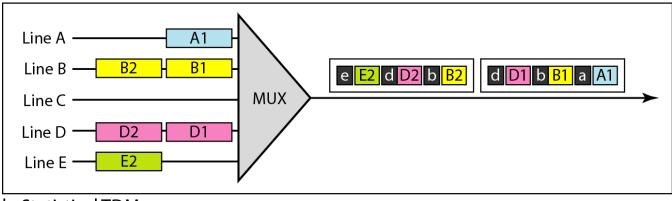
 Table 6.2
 E line rates

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



a. Synchronous TDM



b. Statistical TDM

6-1 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 Synchronous (DSSS)

Figure 6.27 Spread spectrum

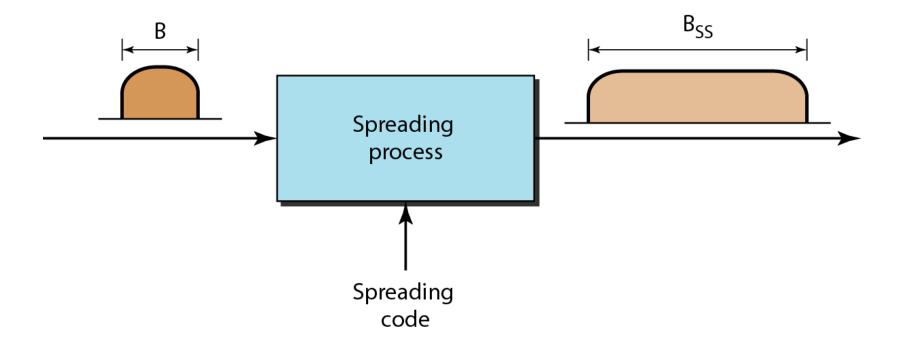


Figure 6.28 Frequency hopping spread spectrum (FHSS)

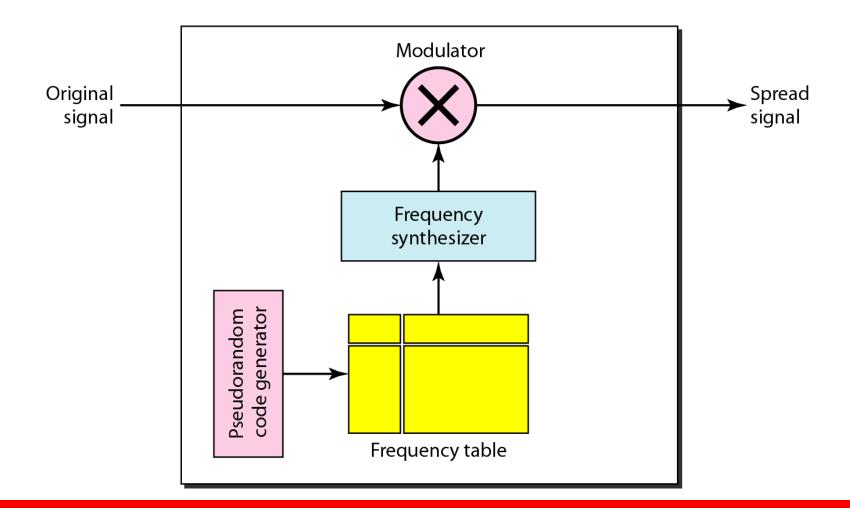


Figure 6.29 Frequency selection in FHSS

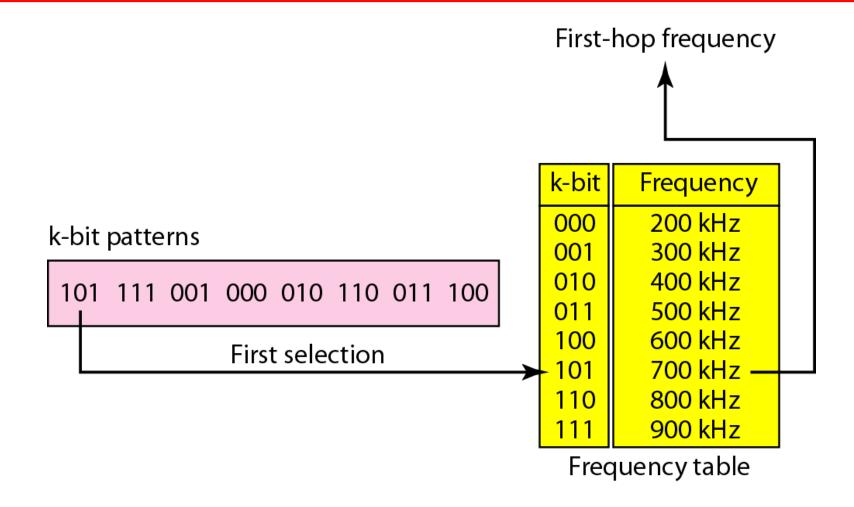


Figure 6.30 FHSS cycles

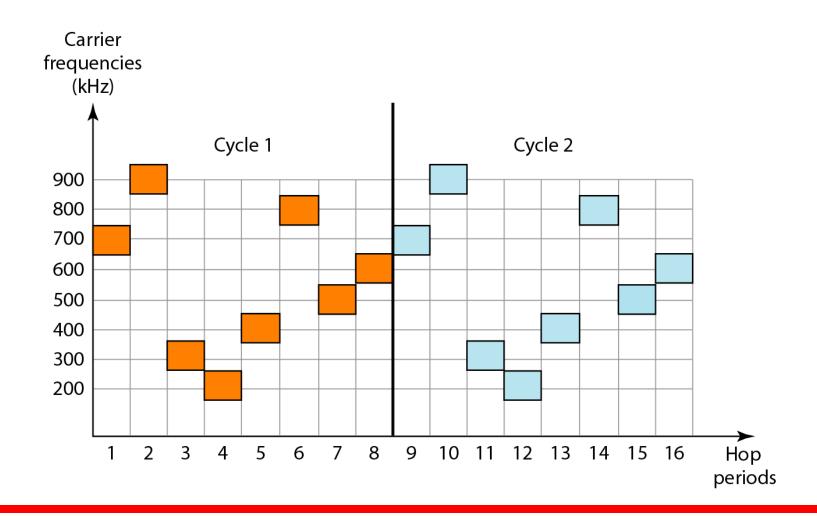
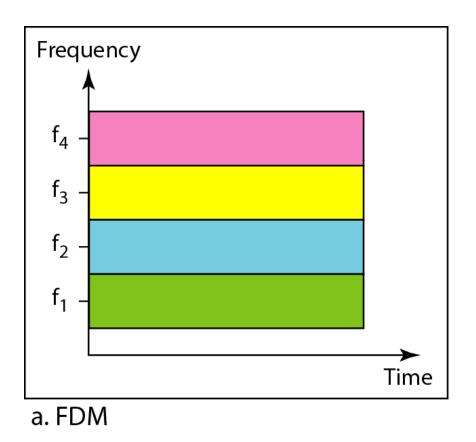


Figure 6.31 Bandwidth sharing



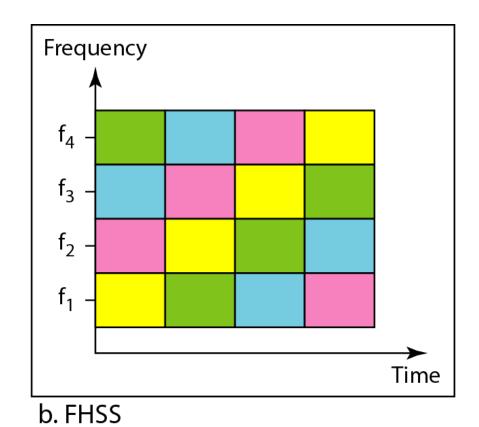


Figure 6.32 DSSS

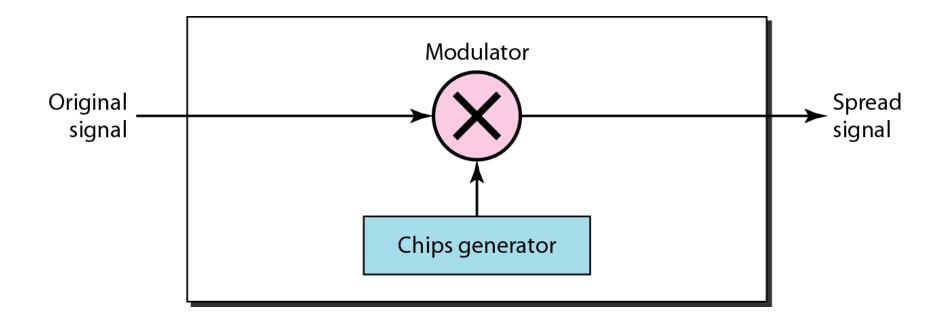


Figure 6.33 DSSS example

