Data Communications and Networking Fourth Edition

Forouzan

Chapter 6

Bandwidth Utilization: Multiplexing and Spreading

Introduction

- In real life links have limited bandwidths.
- Wise use of bandwidths has been, and will be, among the main challenges of electronic communications.
- Several low-bandwidth channels can be combined together to make one channel with larger bandwidth.
- Efficient use of the available bandwidth can be achieved by use of multiplexing.

Multiplexing

- Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, the link can be shared.
- 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
- Multiplexing is the set of techniques that allows the (simultaneous) transmission of multiple signals across a single data link.

Multiplexing (Conti…)

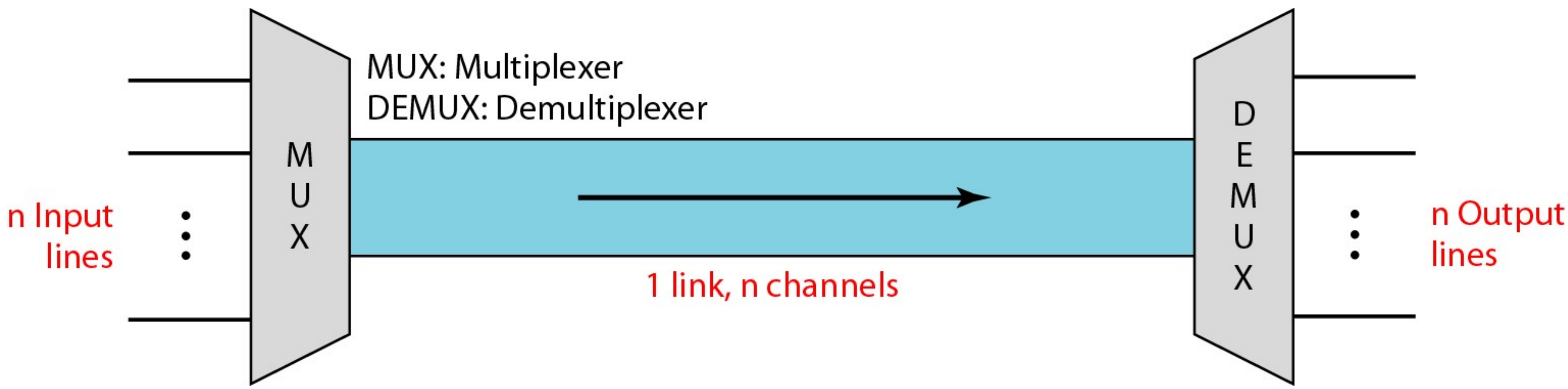


Figure 6.1 *Dividing a link into channels*

Multiplexing (Conti…)

- Figure 6.1 shows the basic format of multiplexed system.
- Sender end: Multiplexer (MUX) – Many-to-One.
- Receiving end: De-multiplexer (DEMUX) – One-to-Many.
- Link refers to the physical path.
- Channel refers to the portion of a link carries transmission between a given pair of lines.
- One link may have many (n) channels.

Multiplexing (Conti…)

- Three basic multiplexing techniques:
  - Frequency-Division Multiplexing
  - Wavelength-Division Multiplexing
  - Time-Division Multiplexing
- The first two techniques are designed for analog signals.
- The Third technique is designed for digital signals.

Multiplexing (Conti…)

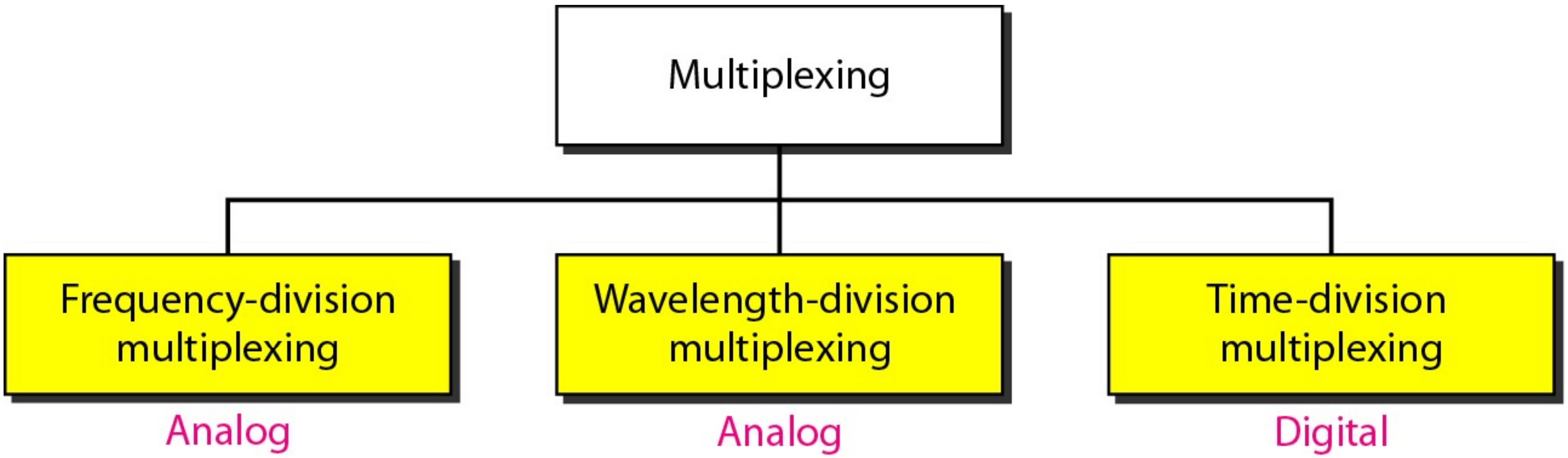


Figure 6.2 *Categories of multiplexing*

Frequency-Division Multiplexing (FDM)

- FDM is an analog technique
- Applied when bandwidth of a link (in Hz) is greater than the combined bandwidths of the signals to be transmitted.
- In FDM, different message signals are modulated at different carrier frequencies.
- The modulated signals are combined into a single composite signal to be transmitted.

FDM (Conti…)

- Carrier frequencies are separated by sufficient bandwidth
- The bandwidth ranges are the channel.
- Channels are separated by unused bandwidth known as guard bands.
- Guard bands are used to prevent signals from overlapping.
- FDM can be used to multiplex digital signals as well but the digital signal must converted to analog signal before multiplexing.

FDM (Conti…)

Figure 6.3 *Frequency-division multiplexing (FDM)*

FDM – Multiplexing Process

- Different sources generate different signals
- These generated signals modulate different carrier frequencies (f_1, f_2, f_3, and so on).
- The resulting modulated signals are then combined into a signal composite signal.
- The composite signal is sent over the link having enough bandwidth to accommodate it.

FDM – Multiplexing Process

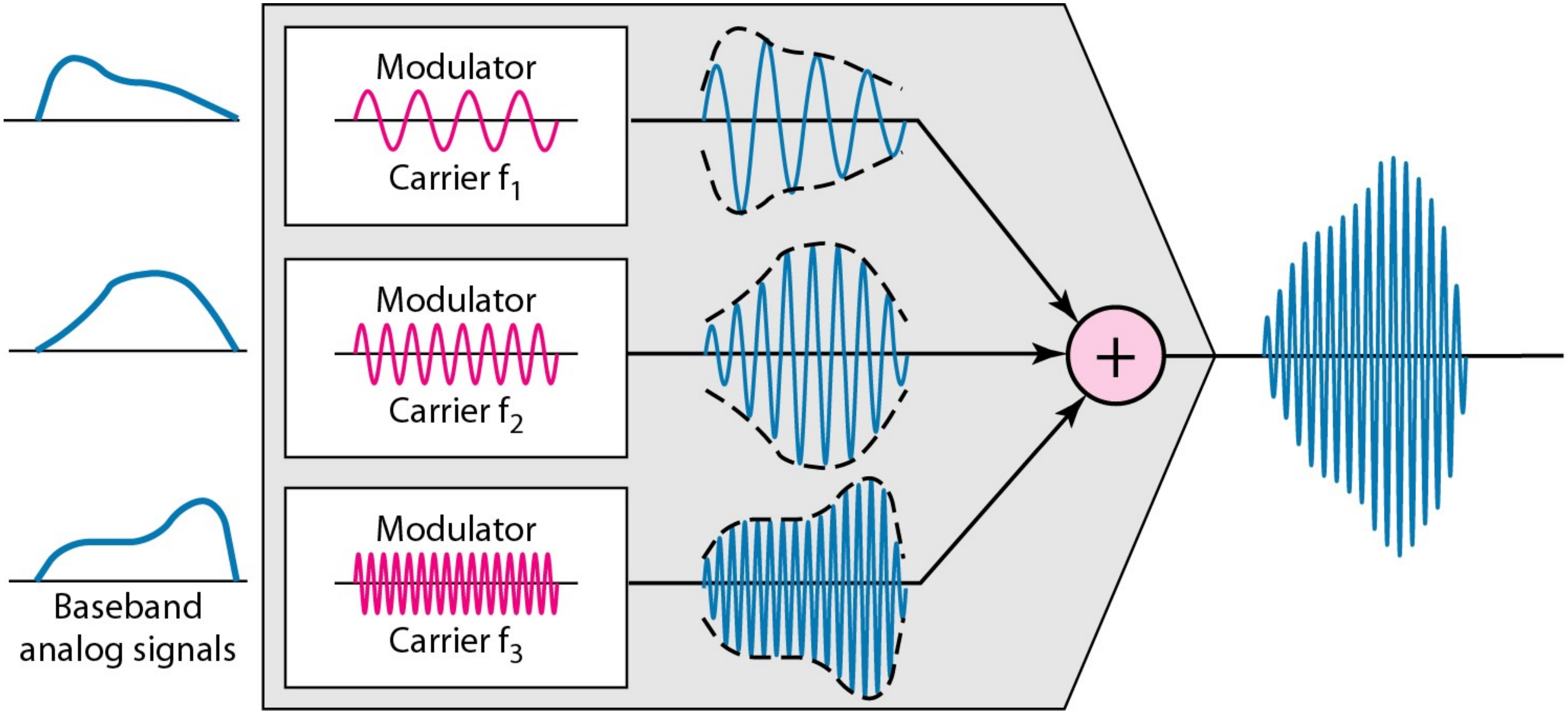


Figure 6.4 *FDM process*

FDM – Demultiplexing Process

- Demultiplexer uses a series of filters to decomposed the multiplexed signal into its component signals.
- The individual signals are then passed to a demodulator to separate them from their carriers.
- The resulting signals are then passed to the output lines.

FDM – Demultiplexing Process (Conti…)

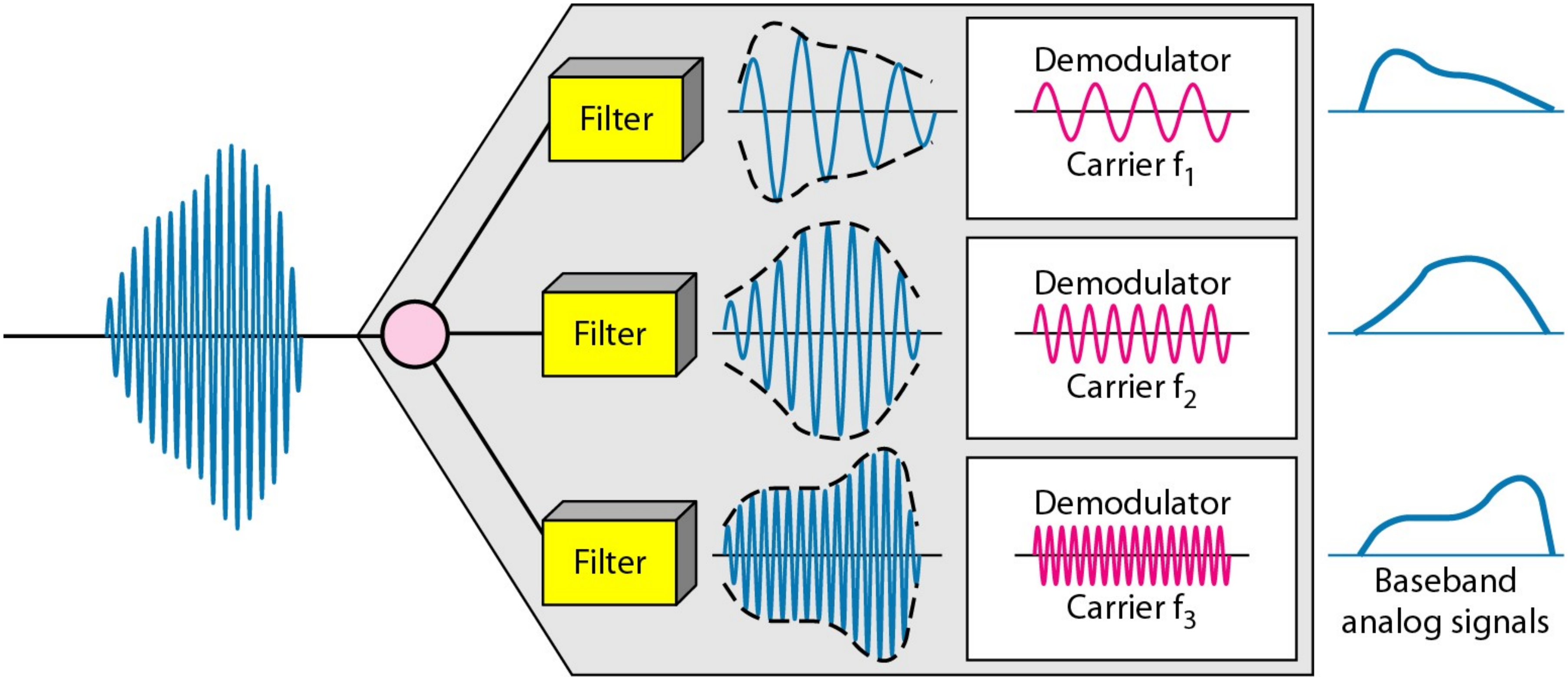


Figure 6.5 *FDM demultiplexing example*

FDM (Conti…)

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.

FDM (Conti…)

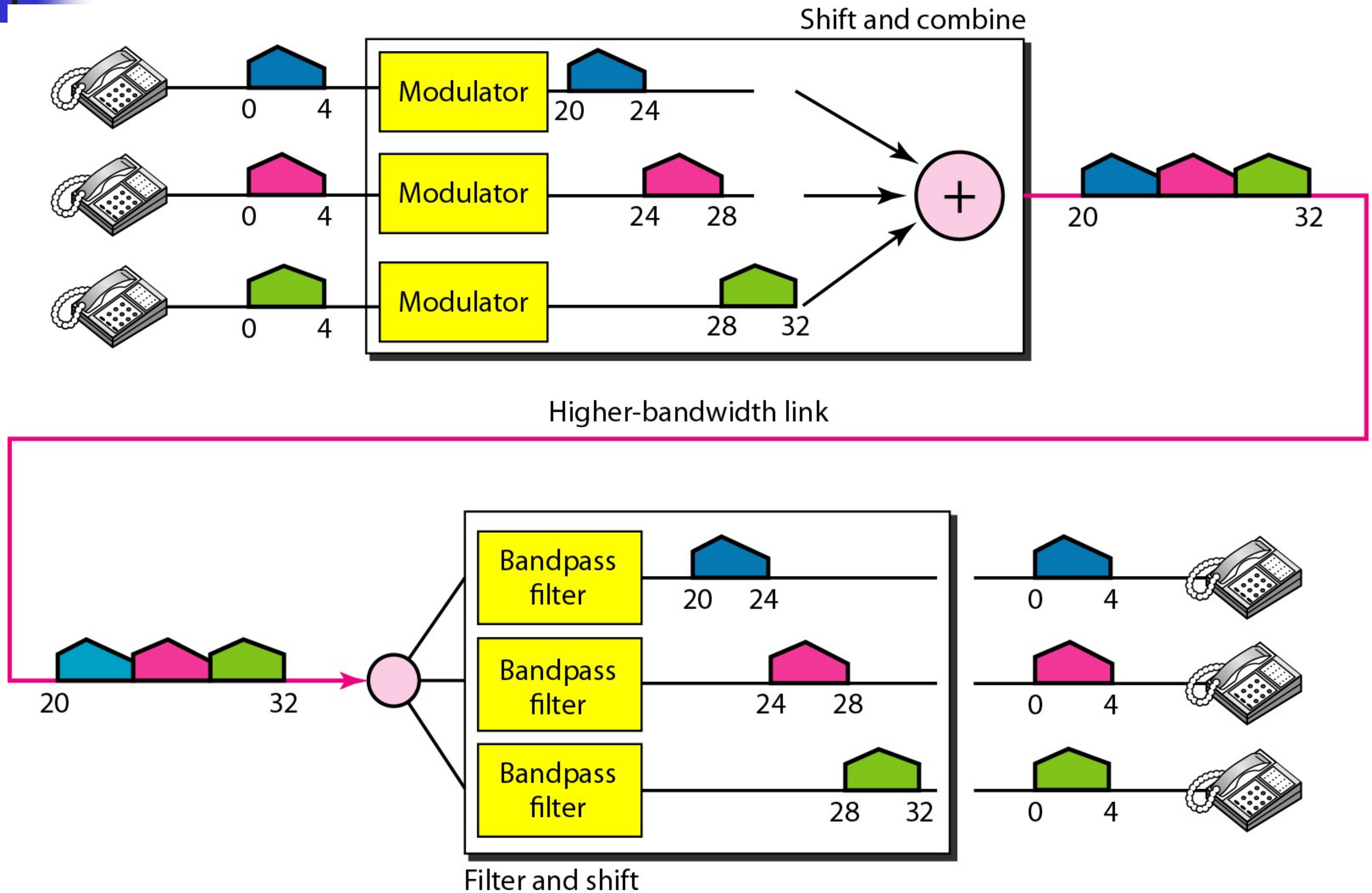


Figure 6.6 *Example 6.1*

FDM (Conti…)

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.

FDM (Conti…)

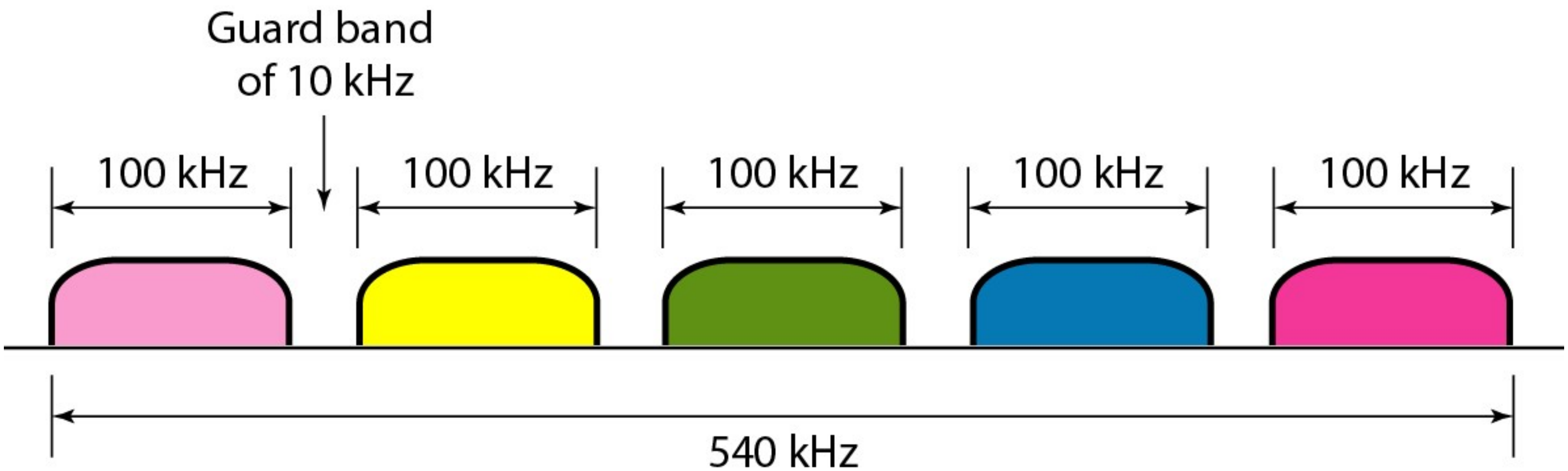


Figure 6.7 *Example 6.2*

FDM (Conti…)

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 1M/4=250-kHz bandwidth. Each digital channel of 1 Mbps must be transmitted over a 250KHz channel. Assuming no noise we can use Nyquist to get:

C = 1Mbps = 2x250K x log2 L -> L = 4 or n = 2 bits/signal element

One solution is 4-QAM modulation. In Figure 6.8 we show a possible configuration with L = 16.

FDM (Conti…)

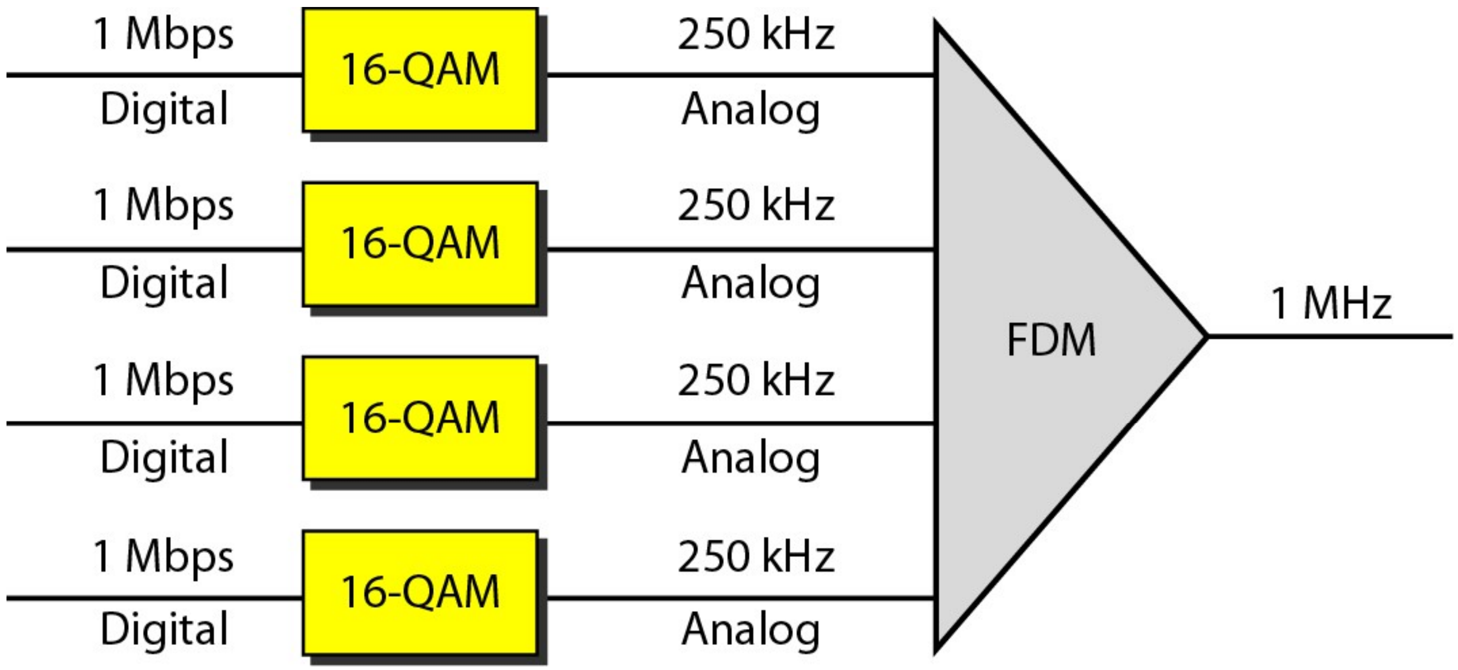


Figure 6.8 *Example 6.3*

FDM – Analog Carrier System

- To maximize the efficiency, telephone companies multiplexed signals from lower bandwidth lines onto higher bandwidth lines.
- Many switched or leased lines can be combined into fewer but bigger channels.
- One of such hierarchical system used by AT&T is made up of groups, super-groups, master groups, and jumbo groups, shown in figure 6.9.

FDM – Analog Carrier System (Conti…)

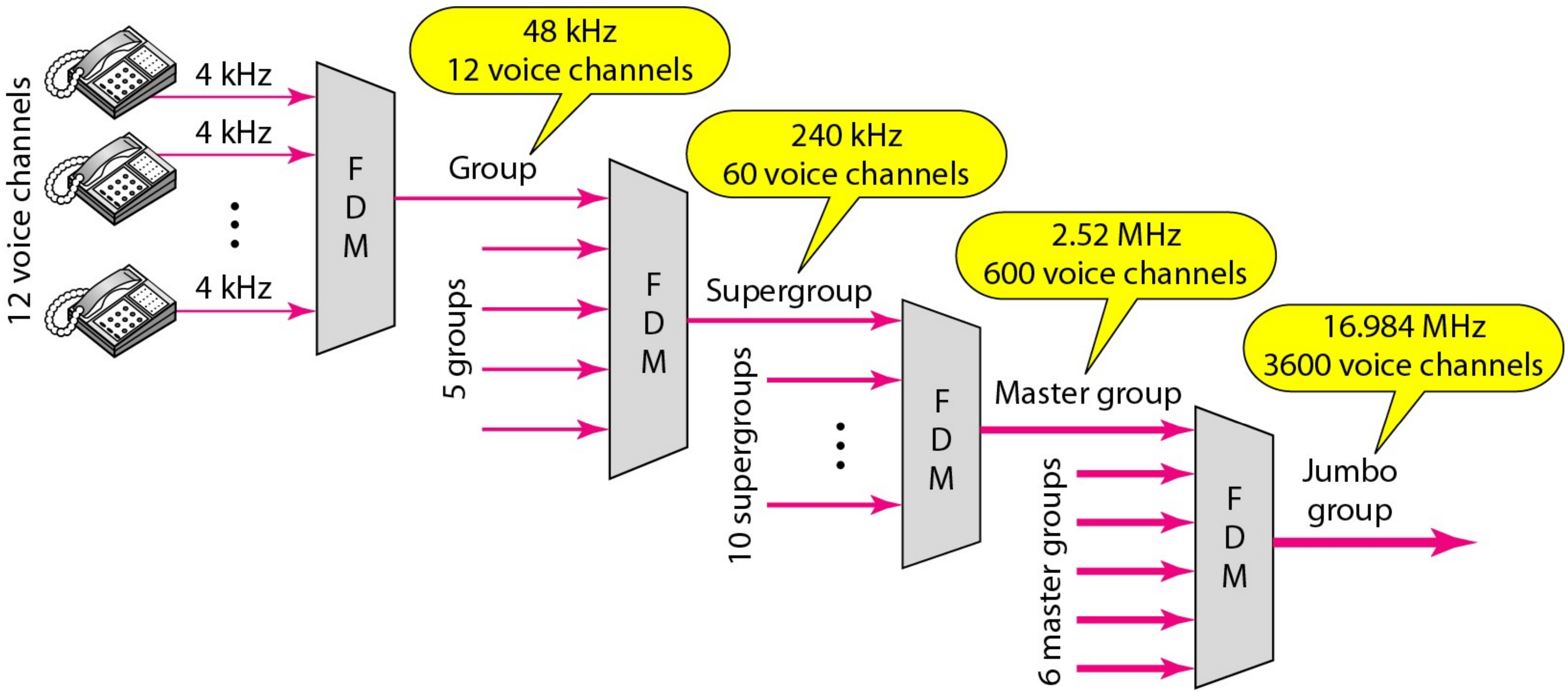


Figure 6.9 *Analog hierarchy*

Other Applications of FDM

- AM Radio Broadcasting
- FM Radio Broadcasting
- TV Broadcasting
- 1st Generation of Cellular Phones

FDM (Conti…)

Example 6.4: 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.

Wavelength-Division Multiplexing (WDM)

- 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.
- Conceptually WDM is same as FDM, except that it involves optical signals transmitted through fiber-optic channels.
- The idea is same, i.e. combining different signals of different frequencies but the frequencies are very high.

WDM (Conti…)

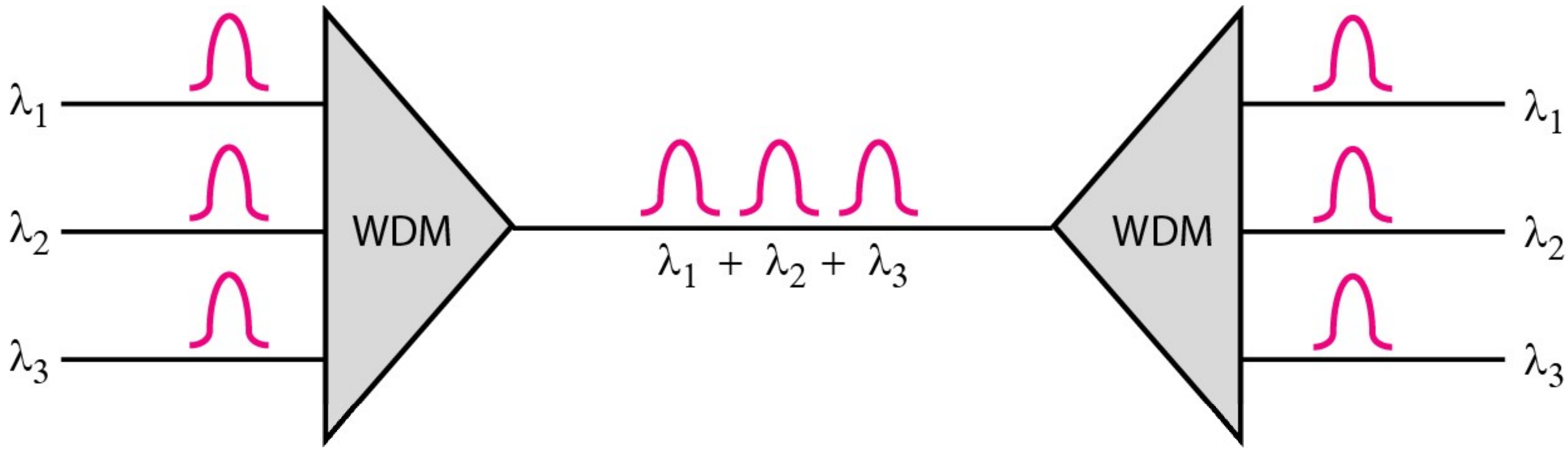


Figure 6.10 *Wavelength-division multiplexing (WDM)*

WDM (Conti…)

- WDM combines multiple light sources into a single light at the multiplexer and does reverse at the demultiplexer.
- Combining and splitting of light sources are easily handled by a prism.
- Prism bends a beam of light on the angle of incidence and frequency.
- Multiplexer - Several input beams of light of narrow band of frequencies can be combined into a single output beam of a wider band of frequencies.

WDM (Conti…)

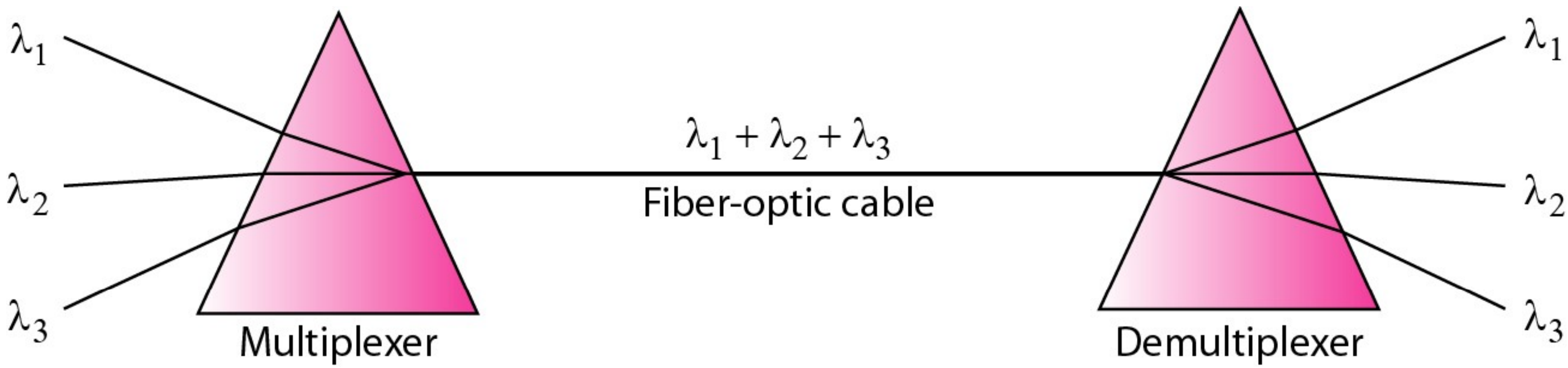


Figure 6.11 *Prisms in wavelength-division multiplexing and demultiplexing*

WDM (Conti…)

- A demultiplexer can be made to reverse the process.
- One application of WDM is the SONET network.
- A new method, known as Dense WDM (DWDM), can multiplex a very large number of spacing channels very close to one another.
- DWDM achieves even greater efficiency as compared to WDM.

Time-Division Multiplexing (TDM)

- TDM is a digital technique that allows to share the high bandwidth of a link by several lines.
- Instead of sharing a portion of the bandwidth (as in FDM), time is shared.
- Each line (connection) occupies a portion of time in the link.
- TDM is divided into:
  - Synchronous TDM
  - Statistical TDM

TDM (Conti…)

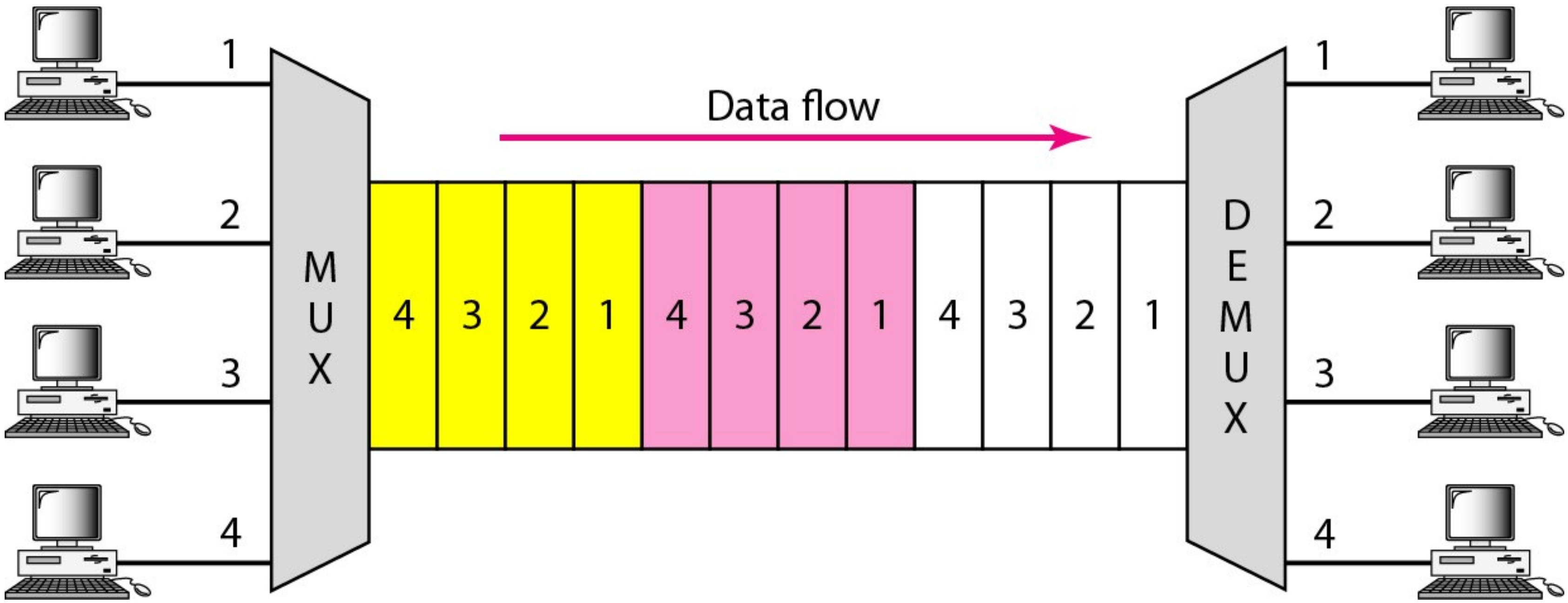


Figure 6.12 Time Division Multiplexing (*TDM)*

Synchronous TDM

- In Synchronous TDM, the data flow of each input channel is divided into units and each unit occupies one input time slot.
- A unit can be 1-bit, a character, or one block of data.
- Each input unit becomes one output unit and occupies one output time slot.
- The duration of an output time slot is shorter as compared to an input time slot.

Synchronous TDM (Conti…)

- A round of data units from each input channel is collected into a frame.
- For n channel, a frame is divided into n time slots and one slot is allocated for each unit (input channel).
- If the duration of input unit is T, then the duration of each slot (output unit) is T/n and duration of each frame is T (unless the frame carries other information).

Synchronous TDM (Conti…)

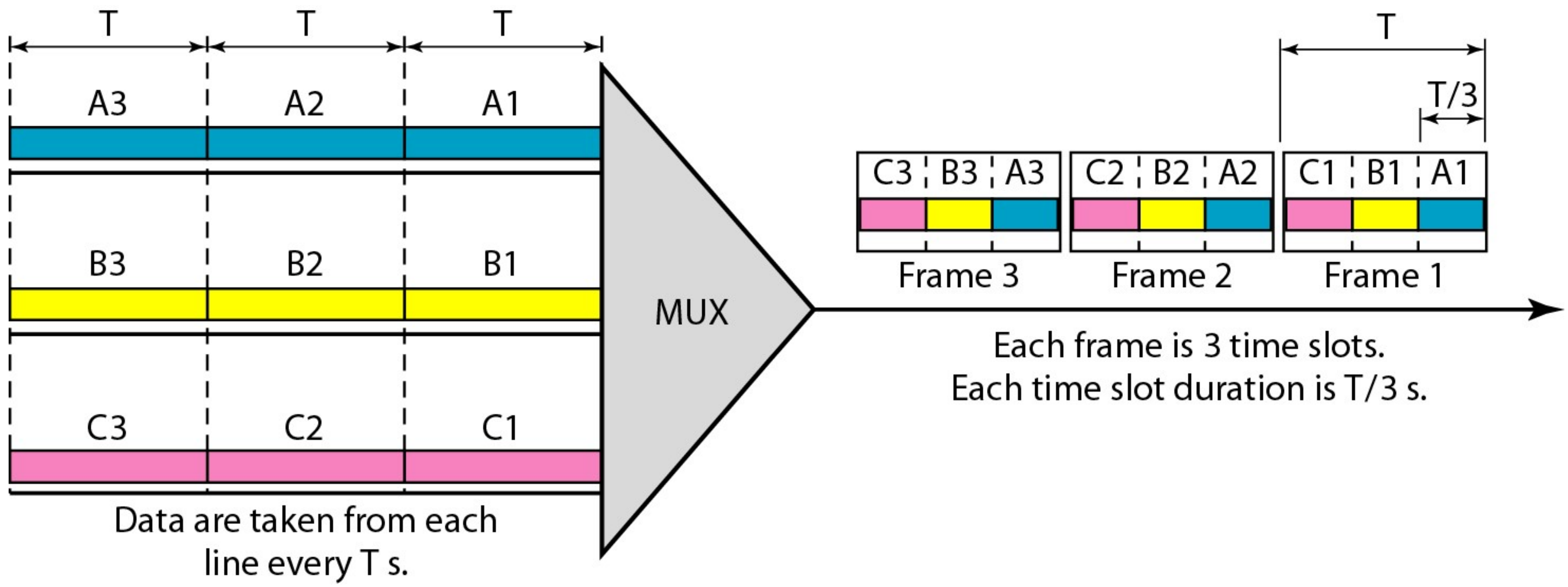


Figure 6.13 *Synchronous time-division multiplexing*

Synchronous TDM (Conti…)

- The data rate of the link is *n* time faster and the unit duration is *n* time shorter as compared to the channel.
- Time slots are grouped into frames.
- A frame is consist of one complete cycle of time slots, with one slot dedicated to each sender.
- In a system with *n* input channels, each frame has *n* slots, with each slot allocated to carrying data from a specific input channel.

Synchronous TDM (Conti…)

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).

Synchronous TDM (Conti…)

Example 6.5 (Conti…):

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.

Note: The duration of a frame is the same as the duration of an input unit.

Synchronous TDM (Conti…)

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.

Synchronous TDM (Conti…)

Example 6.6 (Conti…):

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.

Synchronous TDM (Conti…)

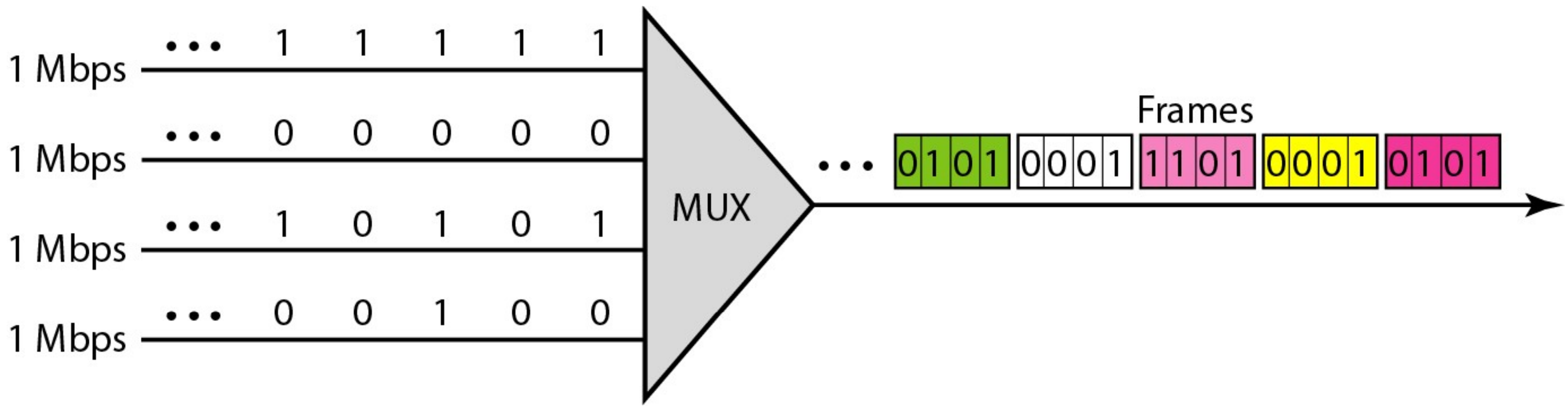


Figure 6.14 *Example 6.6*

Synchronous TDM (Conti...)

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.

Synchronous TDM (Conti…)

Example 6.7 (Conti…):

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.

Synchronous TDM – Interleaving

- TDM uses two fast-rotating switches, one on the multiplexing side and other on the de-multiplexing side.
- The switches are synchronized and rotate at the same speed but in opposite directions.
- The process of taking a group of bits from each input line for multiplexing is called interleaving.
- We interleave bits (1 - n) from each input onto one output.

Synchronous TDM – Interleaving (Conti…)

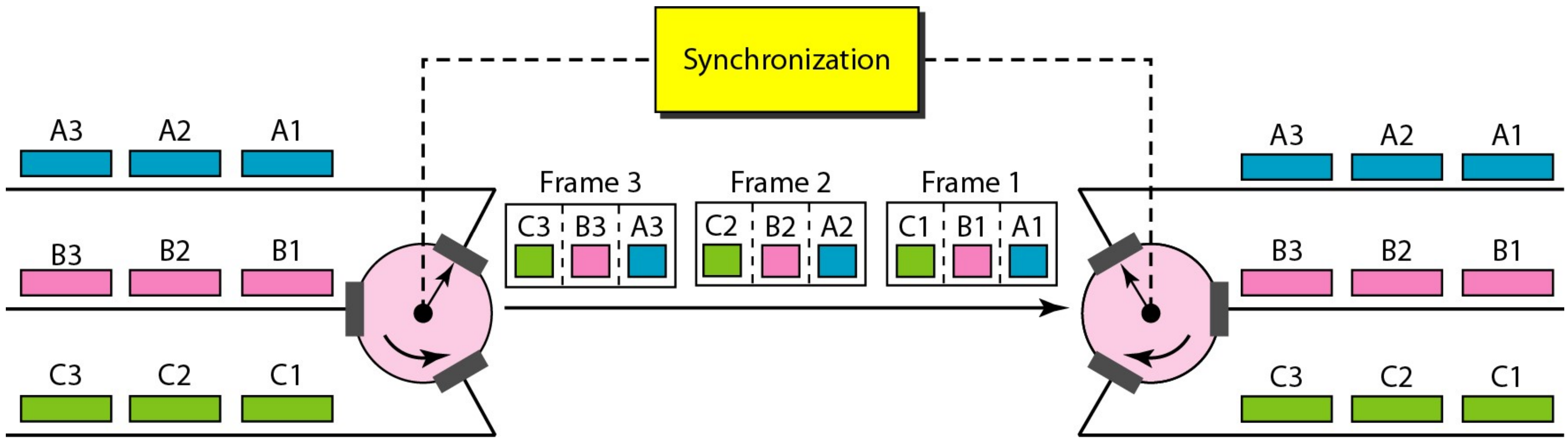


Figure 6.15 *Interleaving*

Interleaving (Conti…)

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.

Interleaving (Conti…)

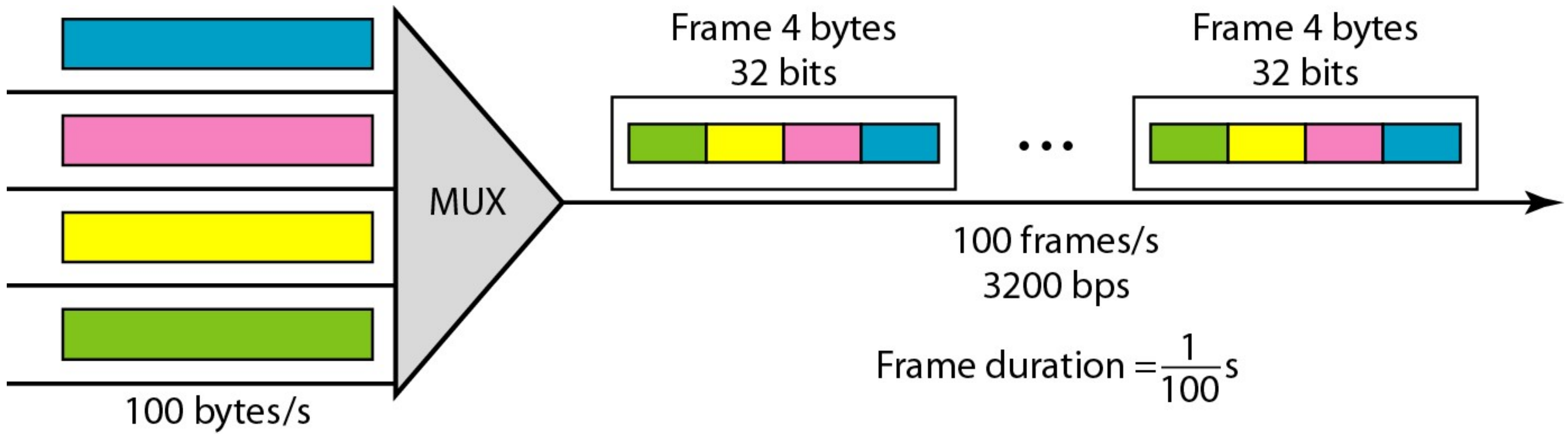


Figure 6.16 *Example 6.8*

Interleaving (Conti…)

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 (4 x100kbps = 400kbps) for four arbitrary inputs. The link carries 400,000/(2x4)=50,000 frames per second, each of 2x4=8bit. 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.

Interleaving (Conti…)

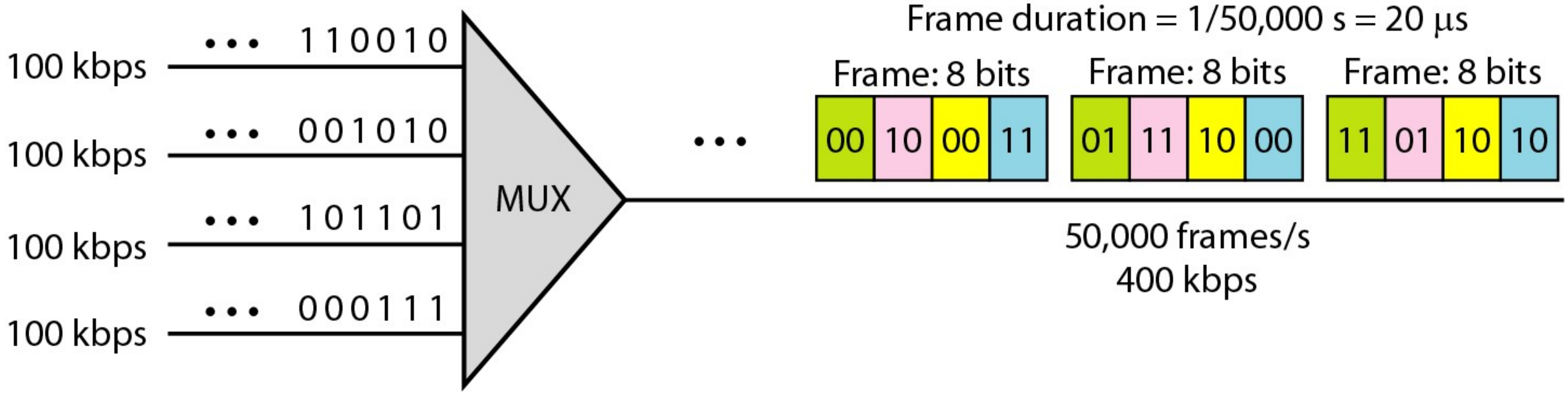


Figure 6.17 *Example 6.9*

Data Rate Management

- One problem with TDM is how to handle a disparity in the input data rates.
- Not all input links maybe 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, multislot and pulse stuffing.

Data Rate Management (Conti…)

- Multilevel: used when the data rate of the input line multiple of others.
- Multislot: used when there is a GCD (Greatest Common Divisor) between the data rates. The higher bit rate channels are allocated more slots per frame.
- Pulse Stuffing: used when there is no GCD between the links. The slowest speed link will be brought up to the speed of the other links by bit insertion, this is called pulse stuffing.

Data Rate Management (Conti…)

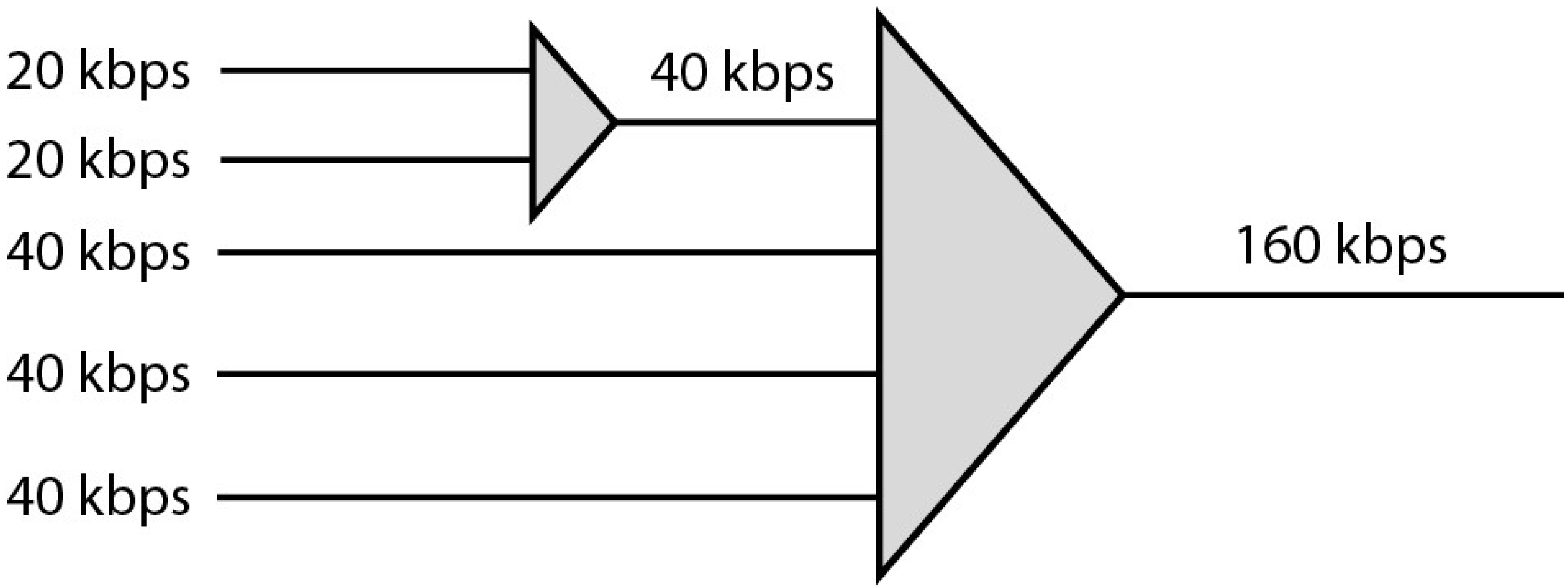


Figure 6.19 *Multilevel multiplexing*

Data Rate Management (Conti…)

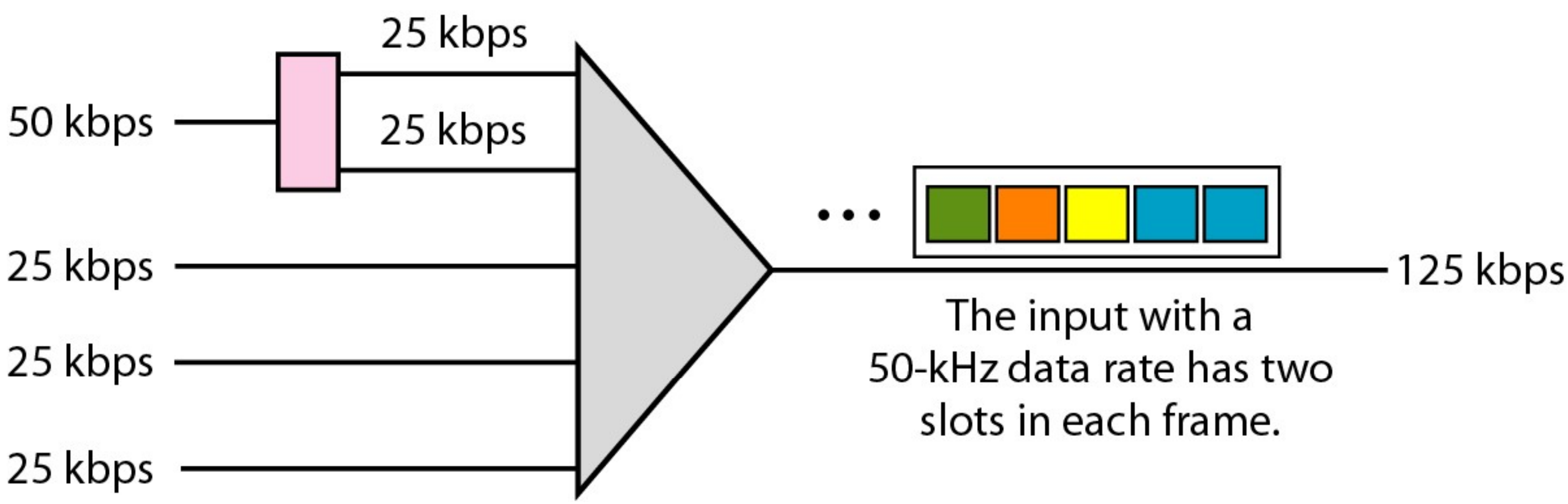


Figure 6.20 *Multiple-slot multiplexing*

Data Rate Management (Conti…)

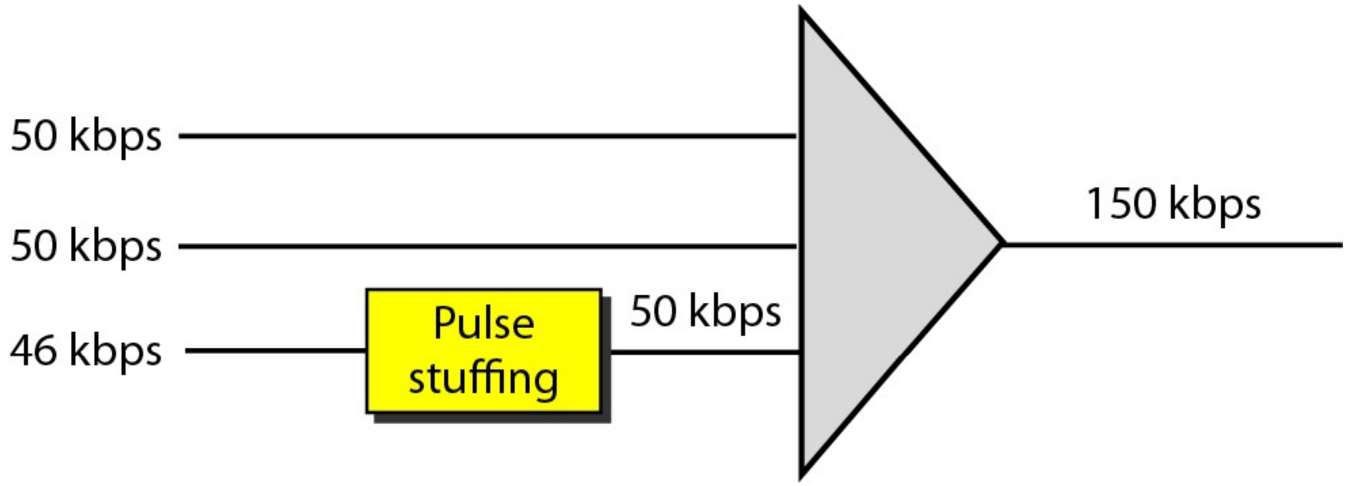


Figure 6.21 *Pulse stuffing*

Synchronization

- To ensure that the receiver correctly reads the incoming bits, i.e., knows the incoming bit boundaries to interpret a “1” and a “0”, a known bit pattern is used between the frames.
- The receiver looks for the anticipated bit and starts counting bits till the end of the frame.
- Then it starts over again with the reception of another known bit.
- These bits (or bit patterns) are called synchronization bit(s).
- They are part of the overhead of transmission.

Synchronization (Conti…)

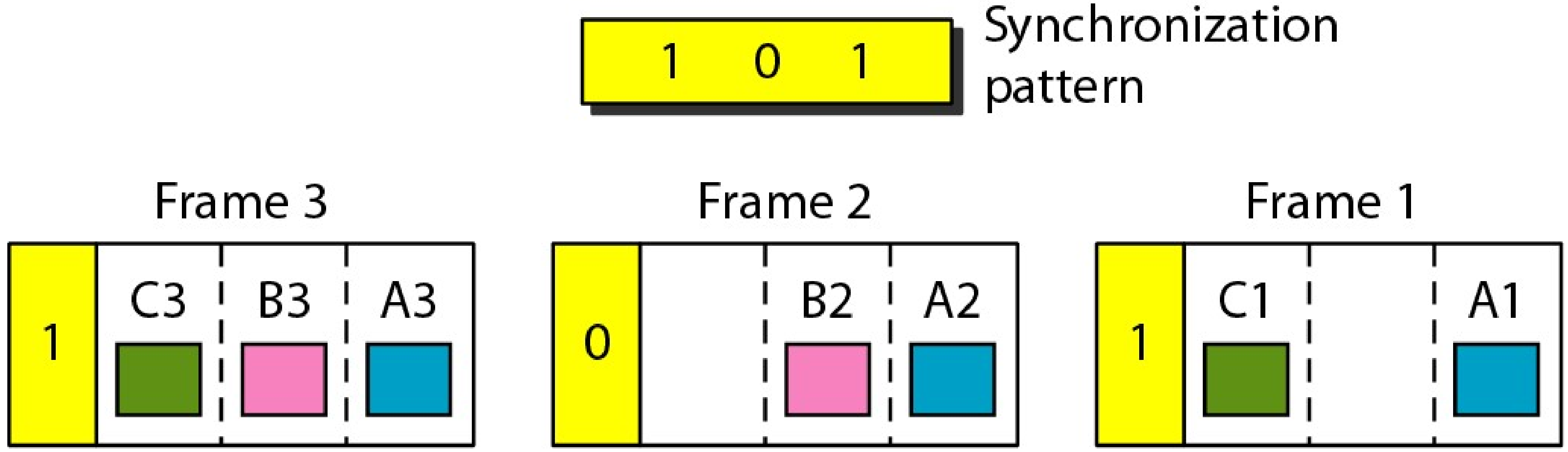


Figure 6.22 *Framing bits*

Synchronous TDM (Conti…)

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 $250 \times 8 = 2000$ bps = 2 kbps.

Synchronous TDM (Conti…)

Example 6.10 (Conti…):

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.

Synchronous TDM (Conti…)

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.

Synchronous TDM (Conti…)

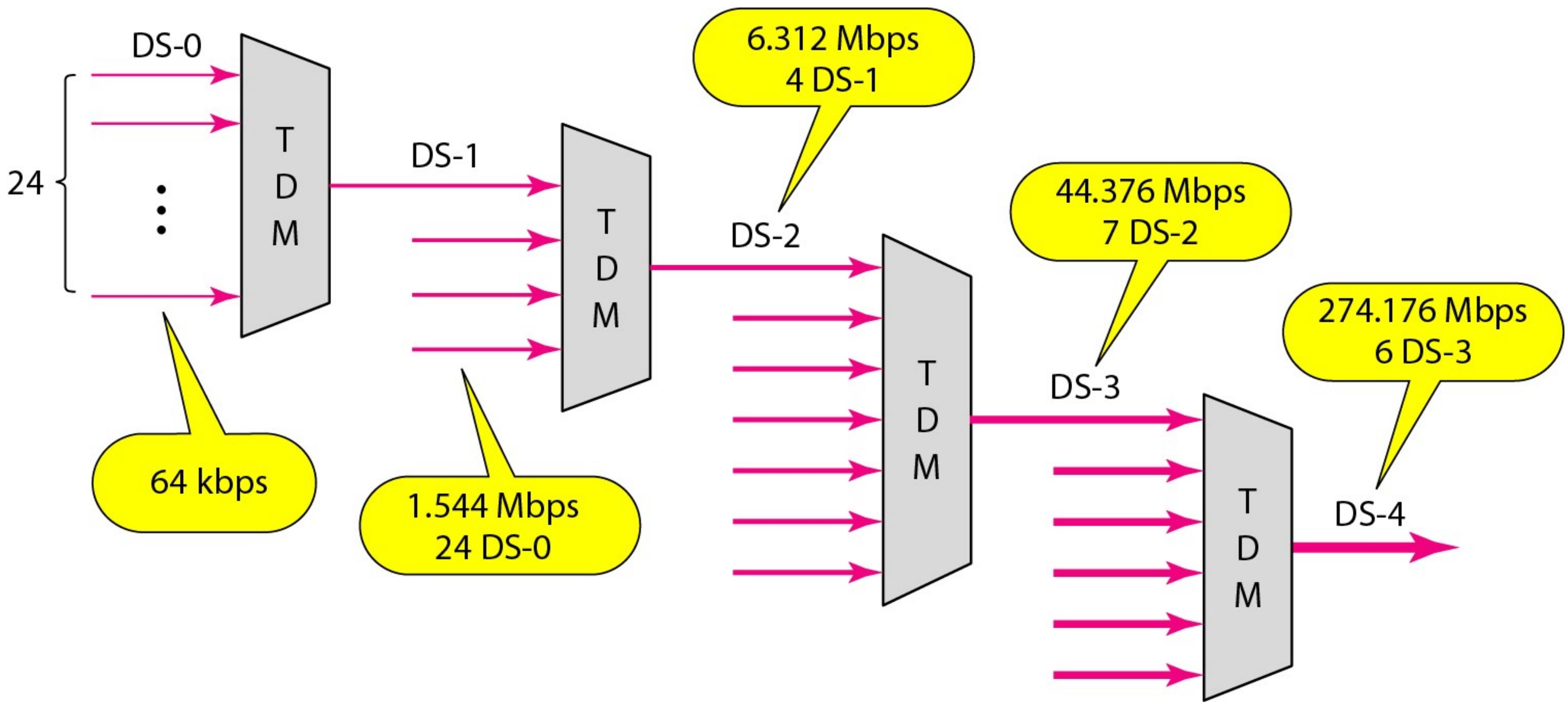


Figure 6.23 *Digital hierarchy*

Synchronous TDM (Conti…)

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

Synchronous TDM (Conti…)

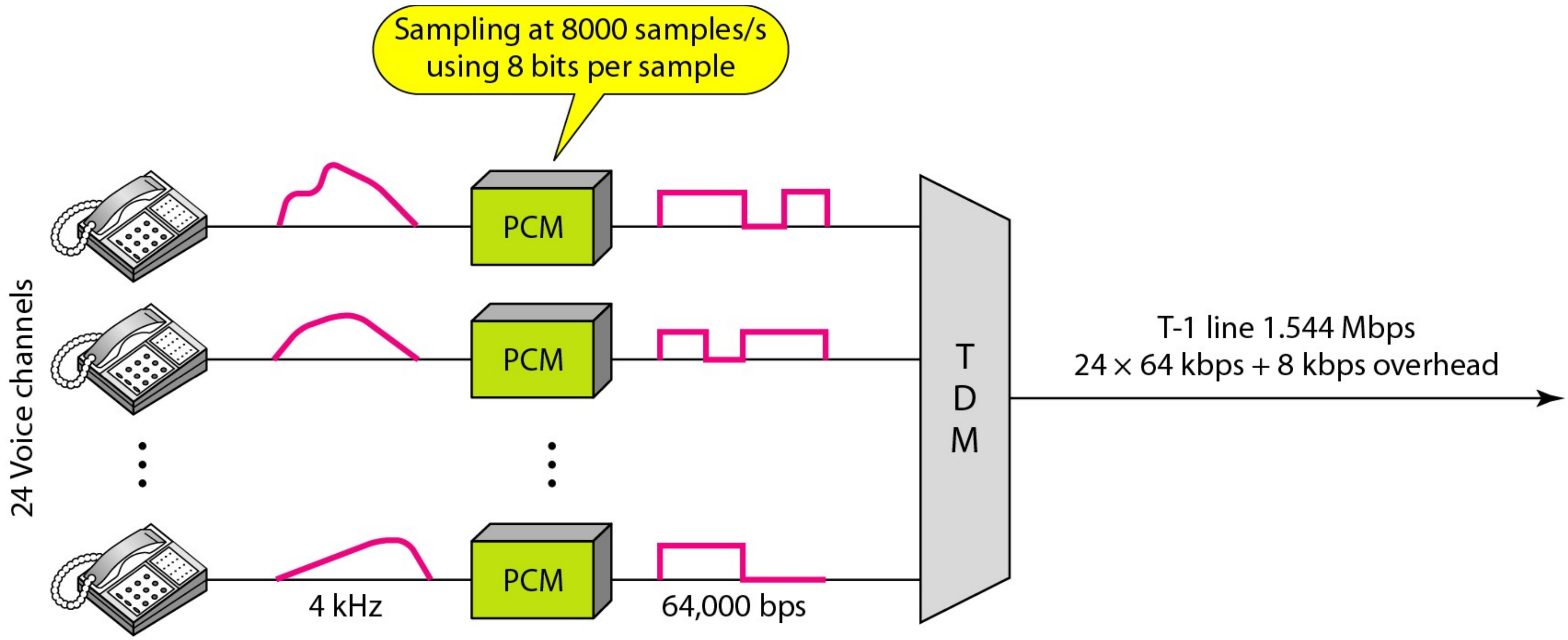


Figure 6.24 *T-1 line for multiplexing telephone lines*

Synchronous TDM (Conti…)

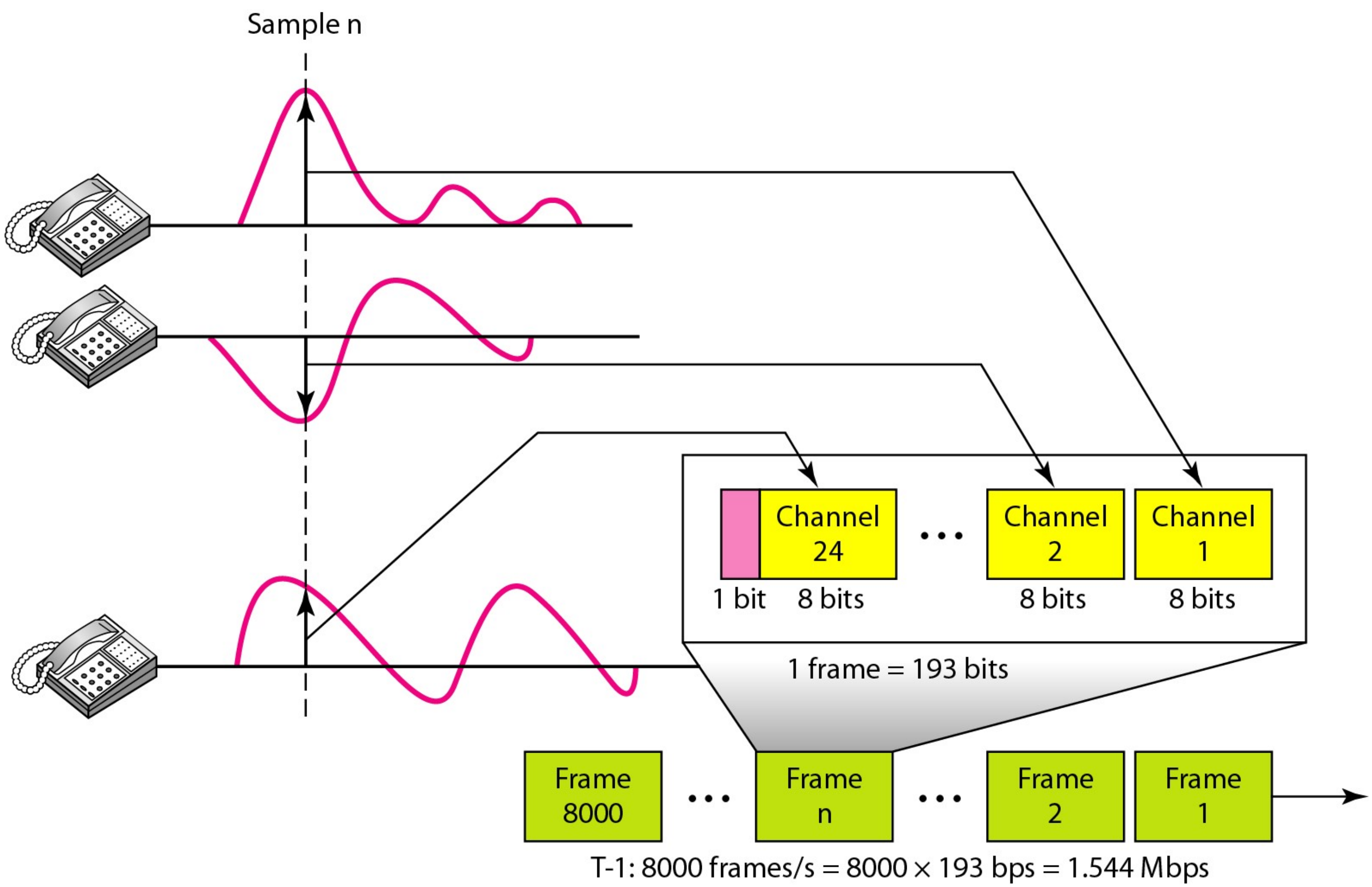


Figure 6.25 *T-1 frame structure*

Synchronous TDM (Conti...)

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

Synchronous TDM – Empty Slots

- Synchronous TDM is not as efficient as it could be.
- Sometimes an input line (source) may have no data to transmit.
- When that happens, one or more slots on the output link will go unused.
- That is wasteful of bandwidth.

Empty Slots (Conti…)

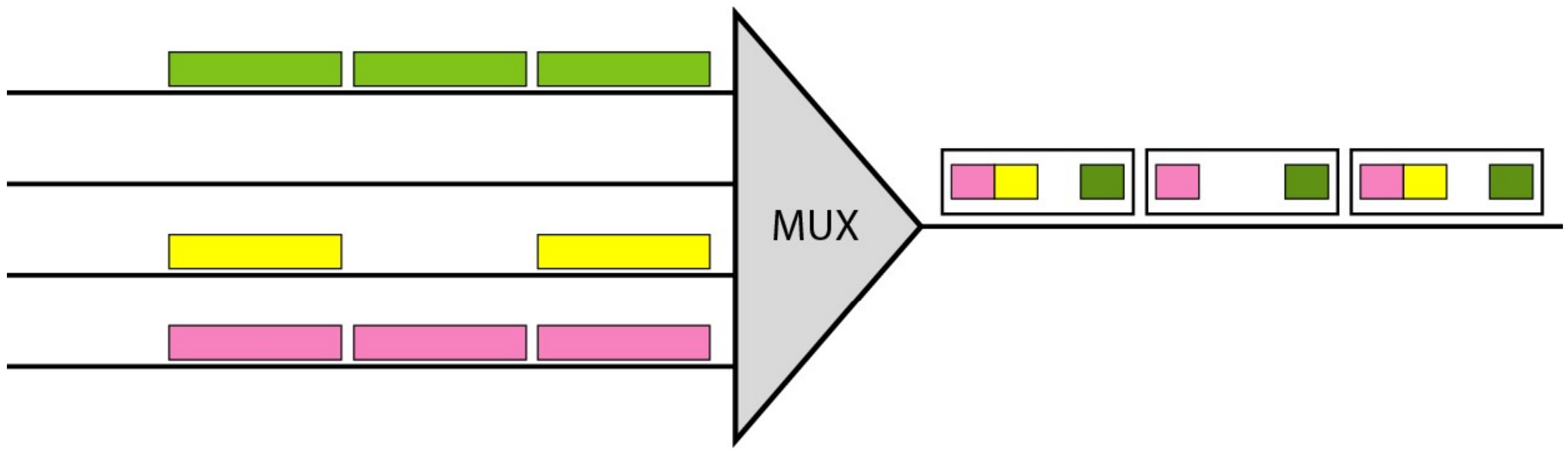


Figure 6.18 *Empty slots*

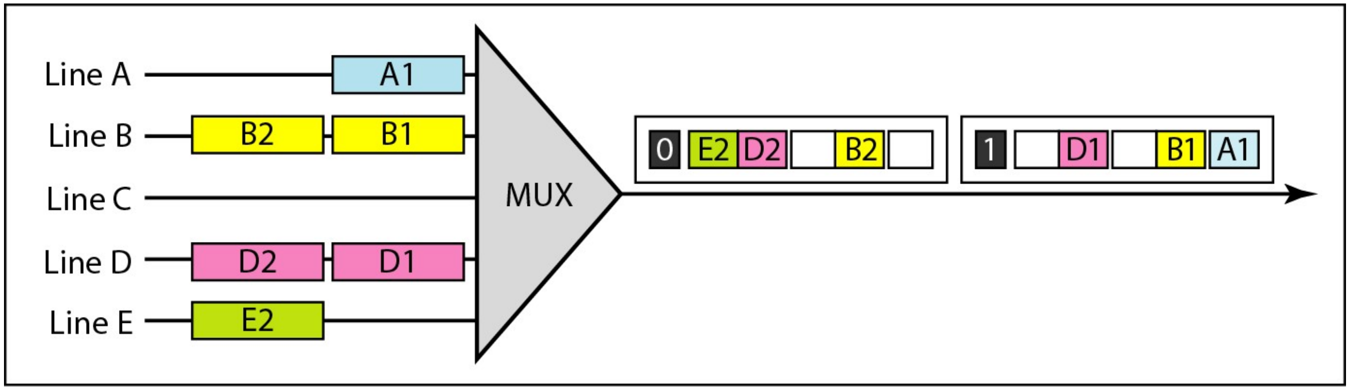
Statistical TDM

- In synchronous TDM each input channel has a reserved slot in the output frame, which may be inefficient if some input channels have no data to send.
- In statistical TDM, slots are dynamically allocated to improve bandwidth efficiency.
- Only the input channels having data will allocate slots.
- In statistical TDM, the number of slots in each frame is less than the number of input channels.

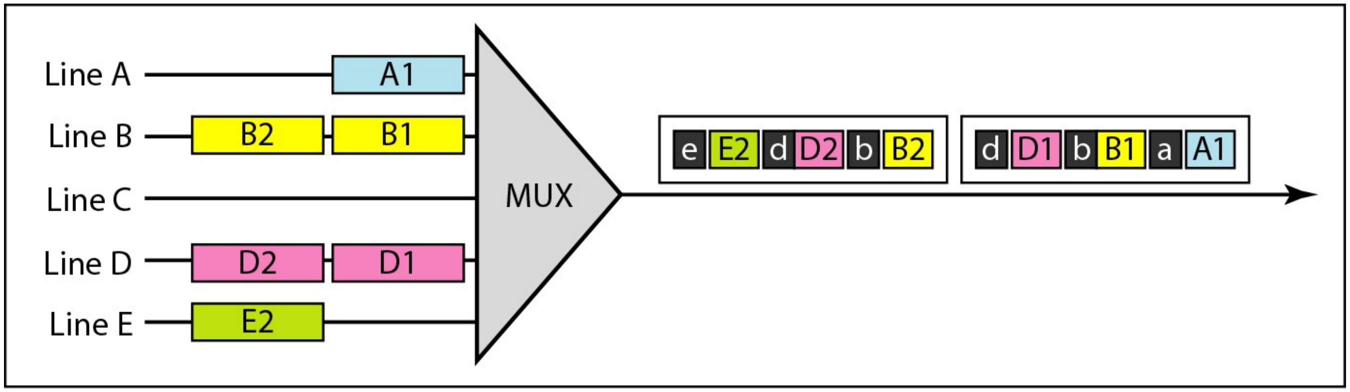
Statistical TDM (Conti…)

- The multiplexer checks each input channels in round-robin fashion.
- It allocates a slot for an input line if the channel has data to send; otherwise it skips the channel and check the next channel.
- Addressing
- Slot Size
- No Synchronization Bit
- Bandwidth

Statistical TDM (Conti…)



a. Synchronous TDM



b. Statistical TDM

Figure 6.26 *TDM slot comparison*

Spread Spectrum

- Multiplexing combines signals from several sources to achieve bandwidth efficiency; the available bandwidth of the link is divided between the sources.

- In spread spectrum (SS), signals from different sources are combined together to fit into a larger bandwidth.

- But the goals are to prevent eavesdropping and jamming.

Spread Spectrum (Conti…)

- Spread Spectrum is designed to be used in wireless applications.
- In wireless applications, all stations use air as the communication medium.
- Stations must be able to share this medium without eavesdropping and jamming.
- To achieve these goals, spread spectrum techniques add redundancy; they spread the original spectrum for each station.

Spread Spectrum (Conti…)

- A signal that occupies a bandwidth of B, is spread out to occupy a bandwidth of B_{ss}, such that $B_{ss} >> B$.
- All signals are spread to occupy the same bandwidth B_{ss}.
- Signals are spread with different codes so that they can be separated at the receivers.
- Signals can be spread in the frequency domain or in the time domain.

Spread Spectrum (Conti…)

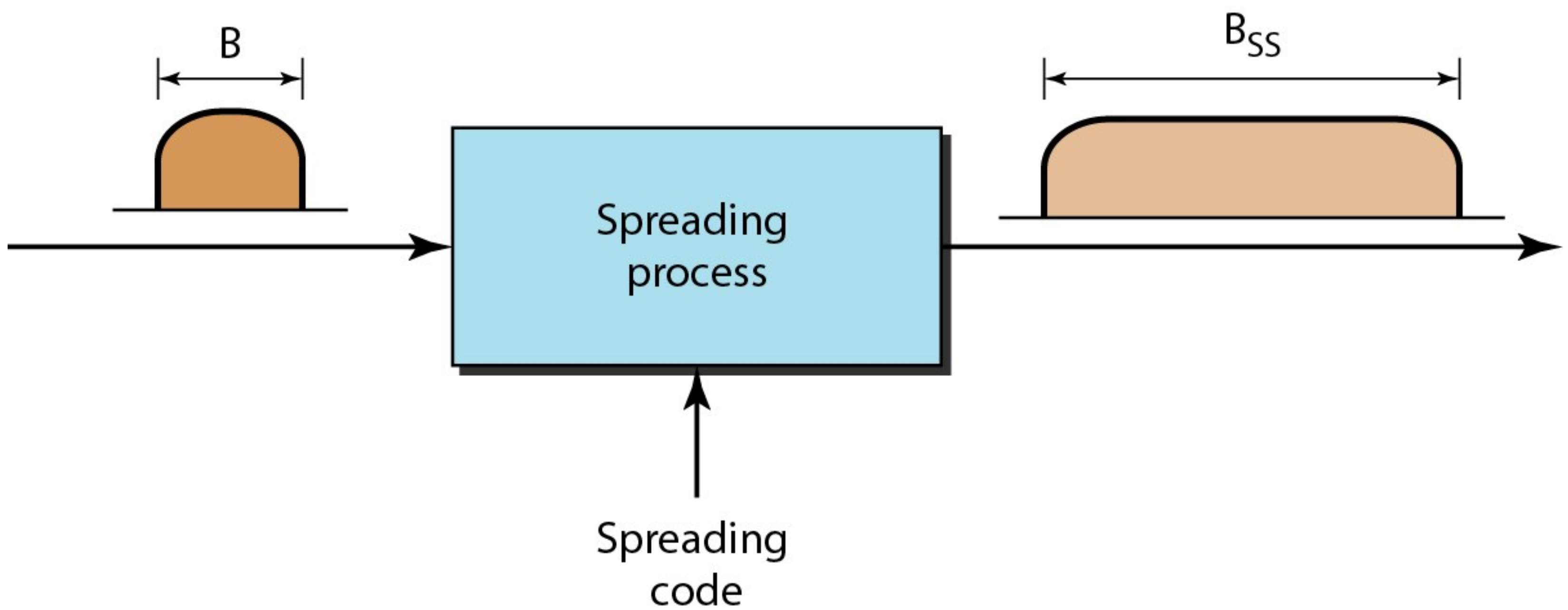


Figure 6.27 *Spread spectrum*

Spread Spectrum (Conti…)

- Spread Spectrum achieves its goals through two principles:
  - The bandwidth allocated to each station needs to be larger than needed; allows redundancy.
  - The expanding of the original bandwidth B to the bandwidth B_{ss} must be done by the process that is independent of the original signal. In other words, the spreading process occurs after the signal is created by the source

Frequency Hopping Spread Spectrum

- The Frequency Hopping Spread Spectrum (FHSS) technique uses *M* different carrier frequencies that are modulated by the source signal.
- At one moment, the signal modulated one carrier frequency, at the next moment, the signal modulates another carrier frequency.

FHSS (Conti...)

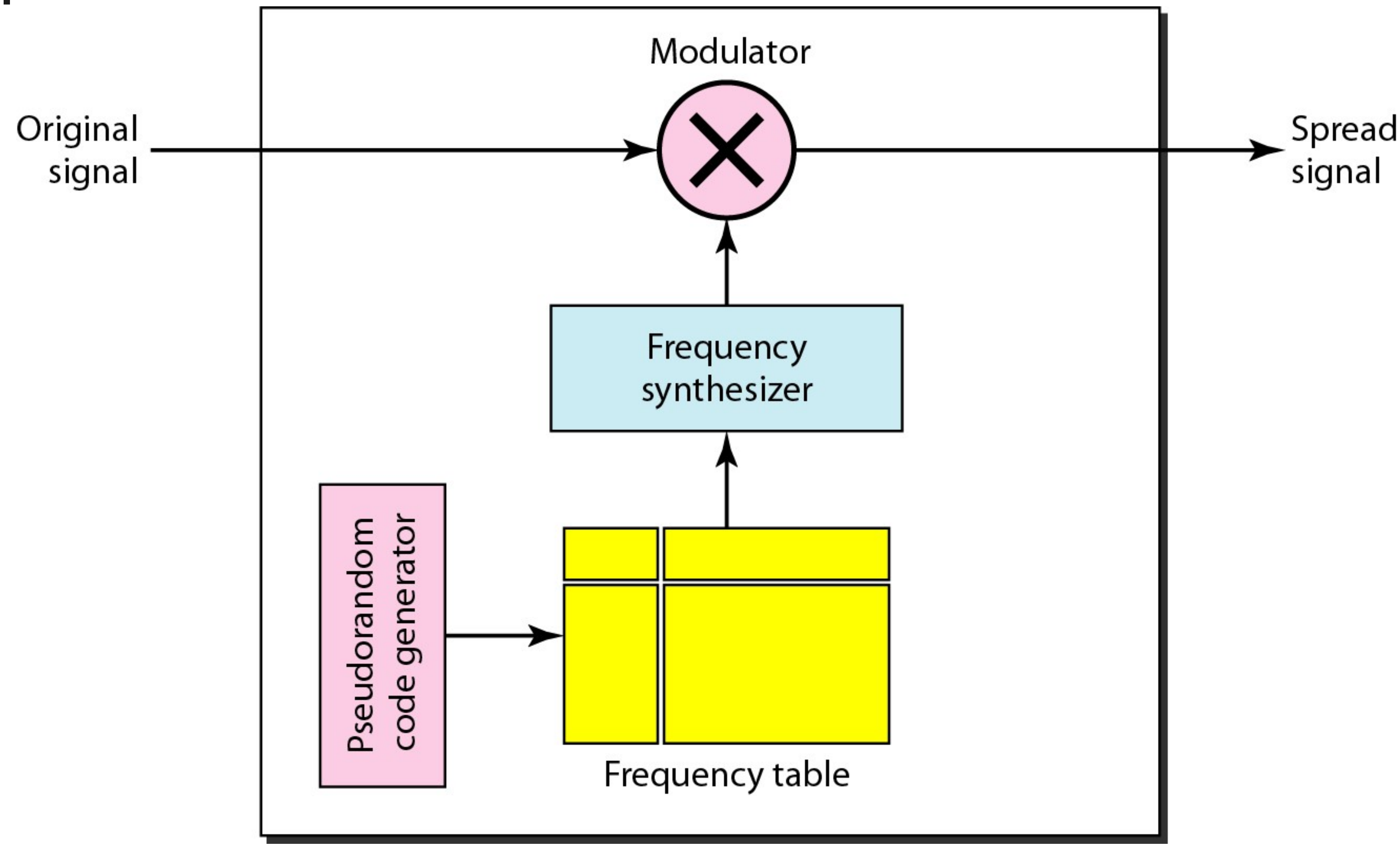


Figure 6.28 *Frequency hopping spread spectrum (FHSS)*

FHSS (Conti…)

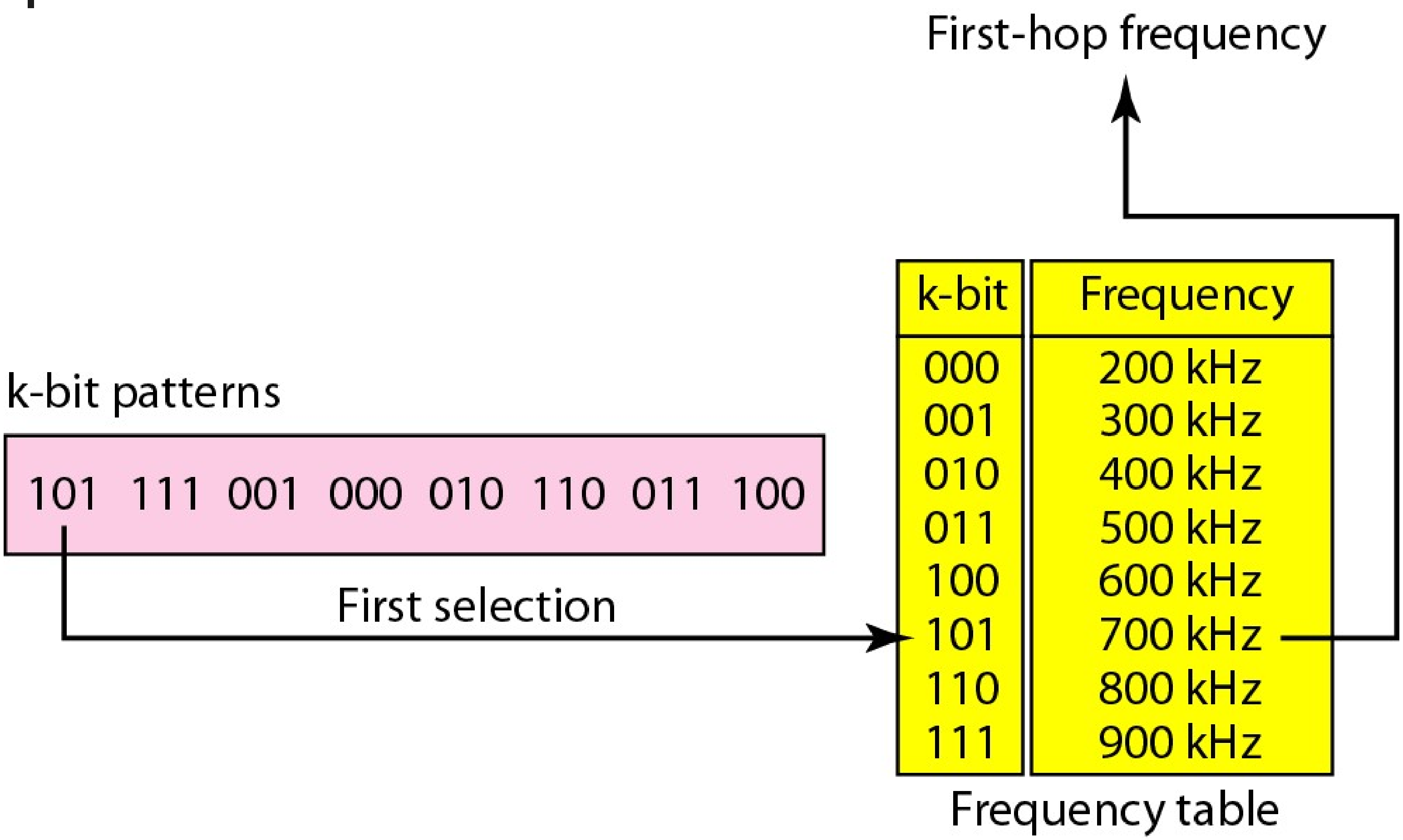


Figure 6.29 Frequency ***selection in FHSS***

FHSS (Conti…)

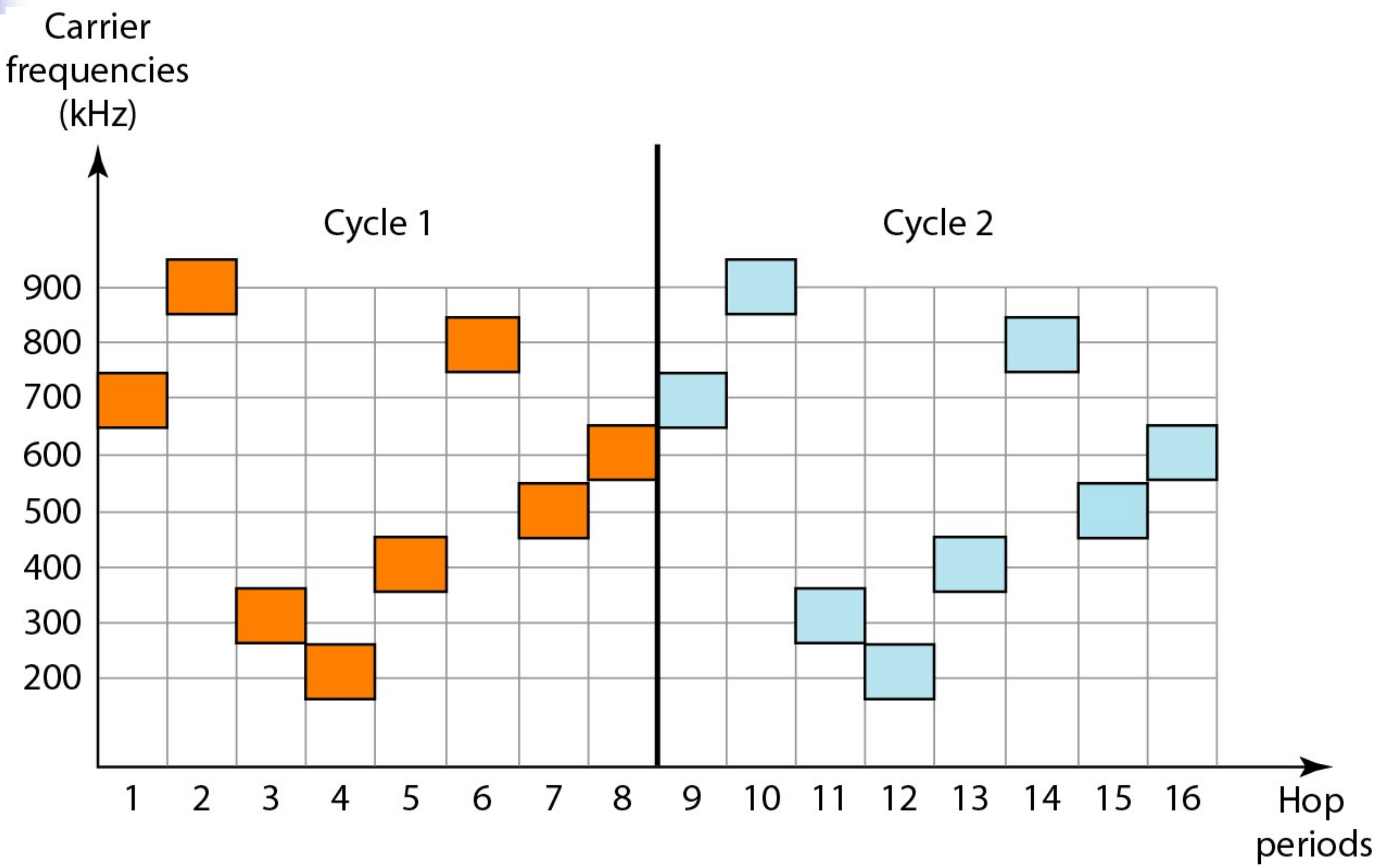


Figure 6.30 *FHSS cycles*

FHSS (Conti…)

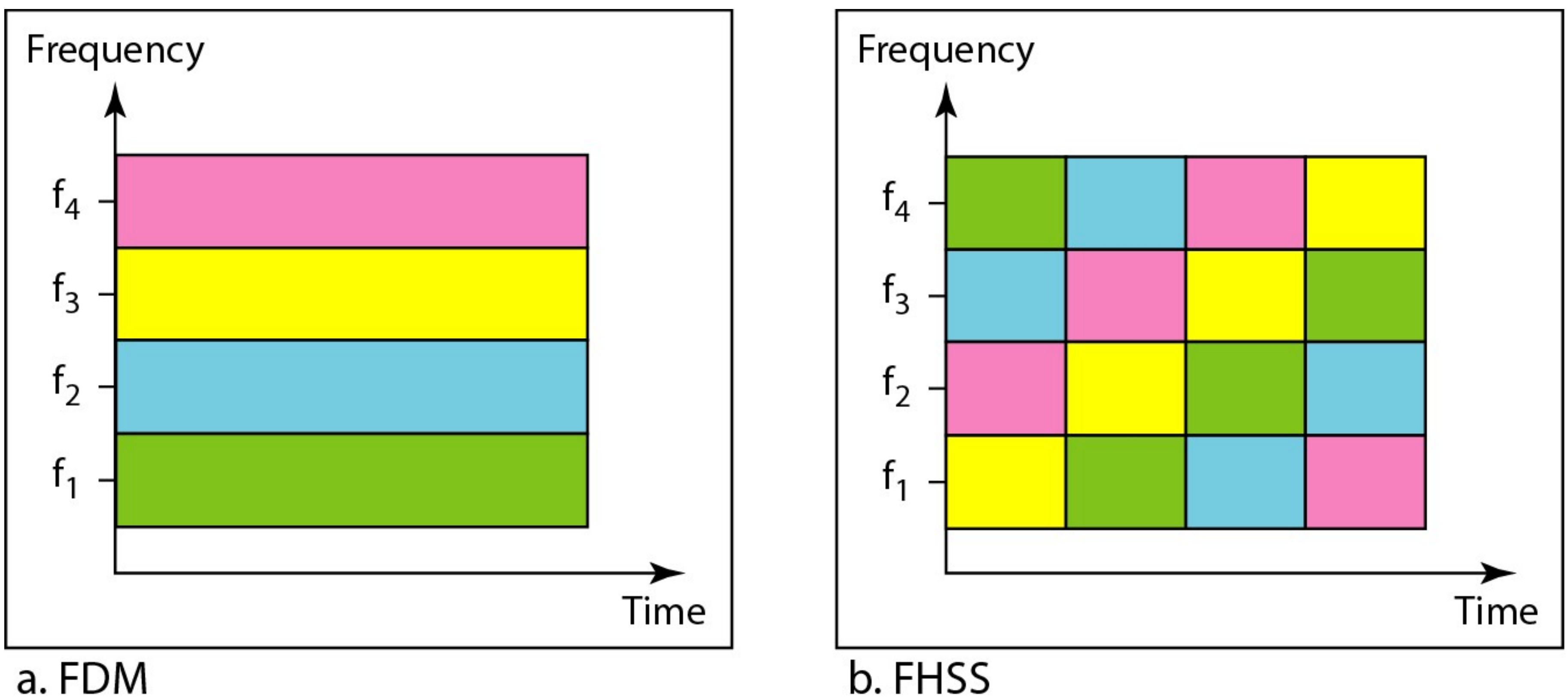


Figure 6.31 *Bandwidth sharing*

Direct Sequence Spread Spectrum

- The Direct Sequence Spread Spectrum (DSSS) technique also expands the bandwidth of the original signal, but the process is different.
- In DSSS, each data bit is replaced with *n* bits using spreading code.
- In other words, each bit is assigned a code of *n* bits called chips.
- Chip rate is *n* times of the data rate.

DSSS (Conti...)

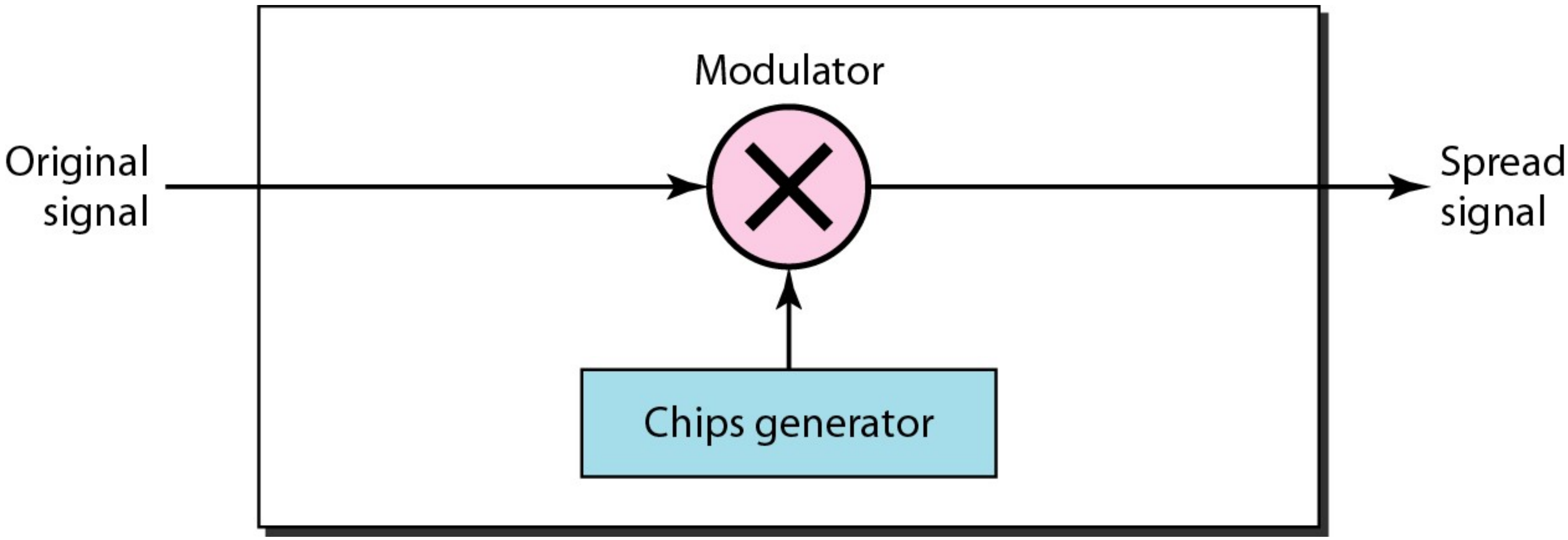


Figure 6.32 *DSSS*

DSSS (Conti…)

- For example: Let us consider the Barker Sequence used in wireless LAN, where n is equal to 11.
- Let us assume that the original signal and the chips use polar NRZ encoding.
- The spreading code is 11 chips having the pattern 10110111000 (in this case).

DSSS (Conti…)

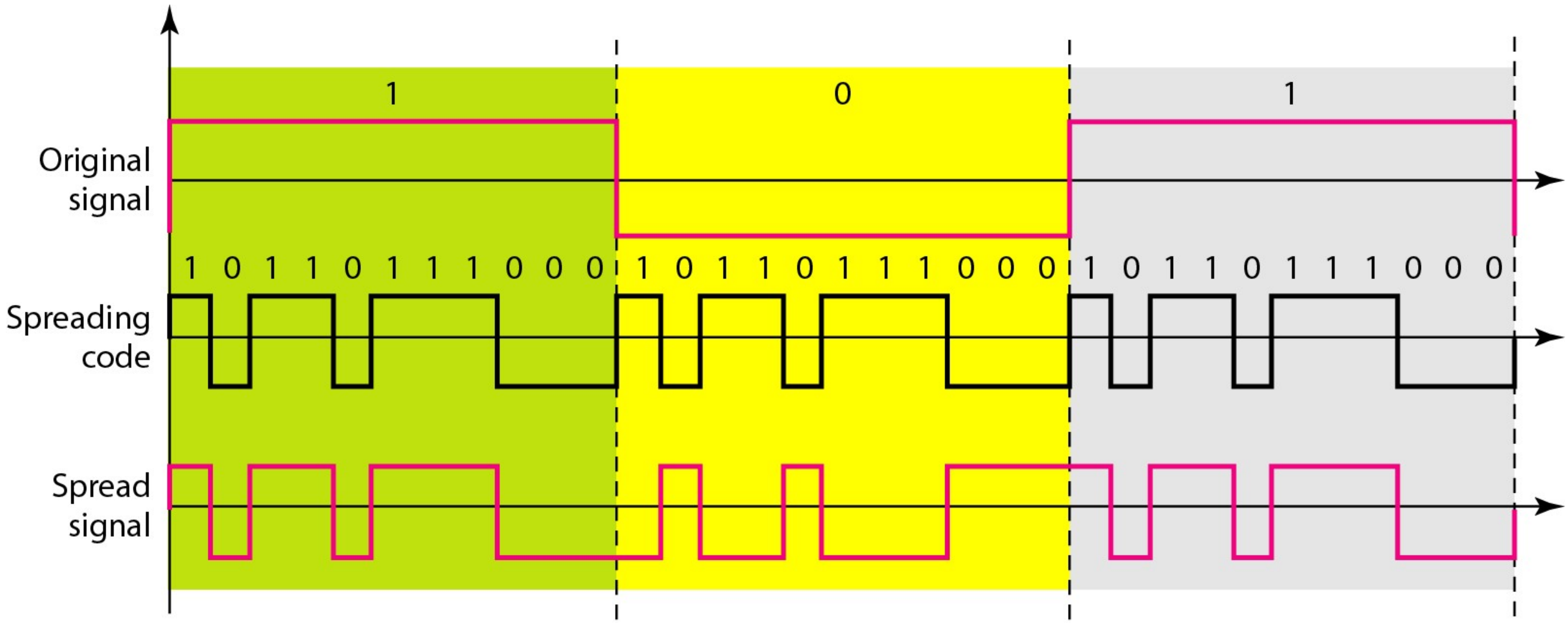


Figure 6.33 *DSSS example*