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 (BW sharing);

privacy and anti-jamming can be achieved by Spreading (BW sharing & protection).

6-1 MULTIPLEXING

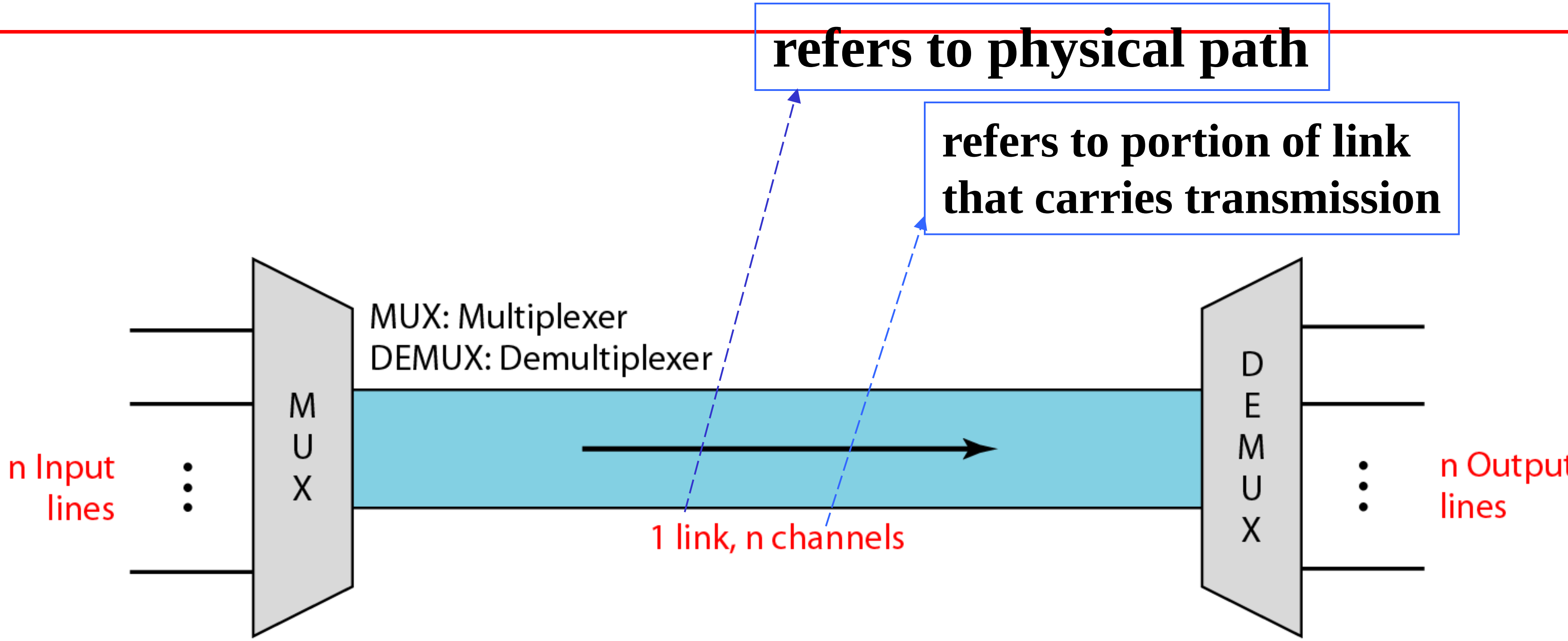
Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, the link can be shared.

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:

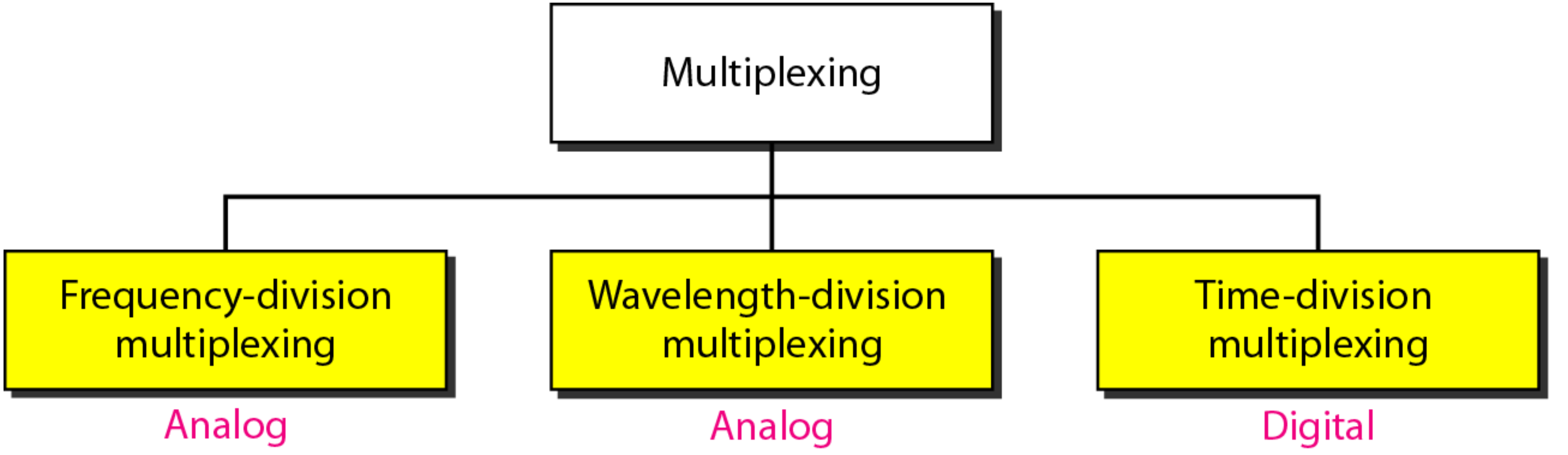
Frequency-Division Multiplexing (FDM)
Wavelength-Division Multiplexing (WDM)
Synchronous Time-Division Multiplexing (Synchronous TDM)
Statistical Time-Division Multiplexing (Statistical TDM)

Figure 6.1 *Dividing a link into channels*

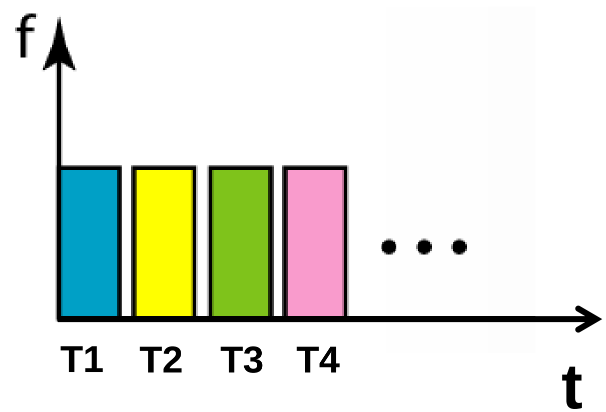


- n input lines share bandwidth of one link
- ***Multiplexer (MUX)*** combines lines on the left into a single stream (many-to-one)
- Demultiplexer (DEMUX) separates the stream back into its component transmission (one-to-many) and directs them to their corresponding lines

Figure 6.2 *Categories of multiplexing*



ใน Channel ที่มี Bandwidth จำกัด เราจะแบ่งใช้งานจาก multiple device ได้อย่างไร



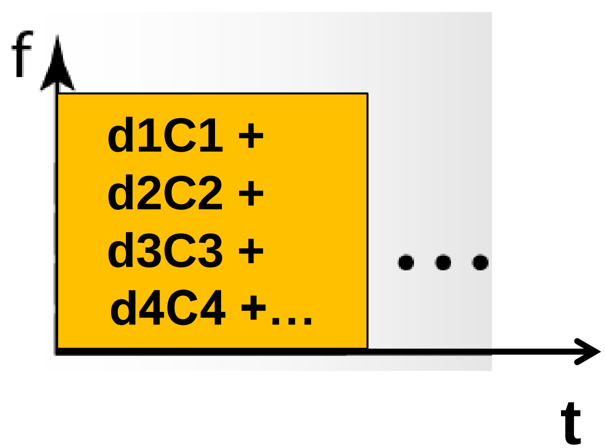
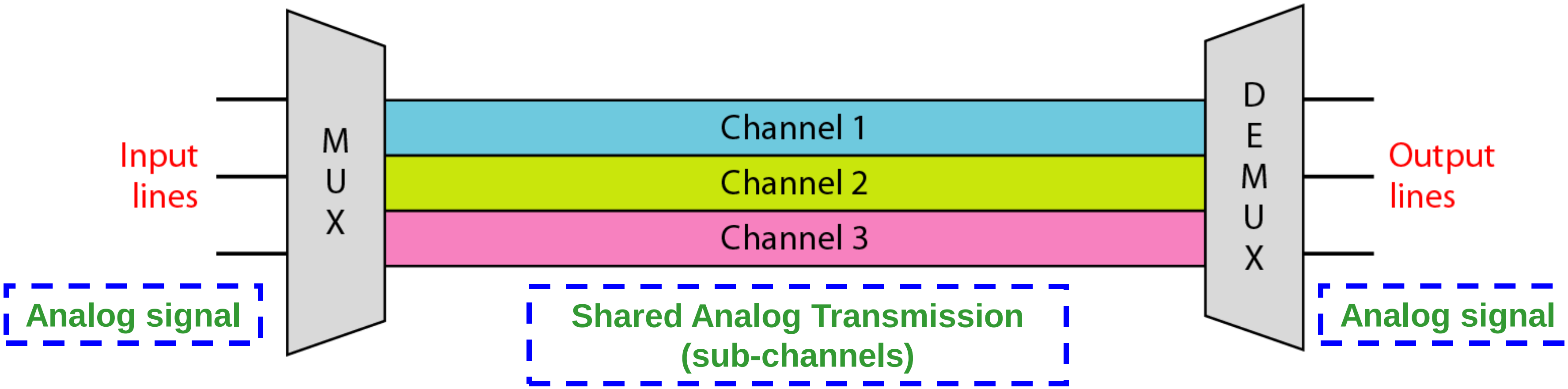


Figure 6.3 *Frequency-division multiplexing* (FDM)



- FDM can be applied when *bandwidth of link* (in hertz) is *greater than* the *combined bandwidths of signals* to be transmitted

- Signals generated by each sending device modulate different carrier frequencies and then combined into a single composite signal that can be transported by the link

- Channels can be separated by strips of unused bandwidth, called ***guard channel***, to prevent signals from overlapping

Note

FDM is an analog multiplexing technique that combines analog signals.

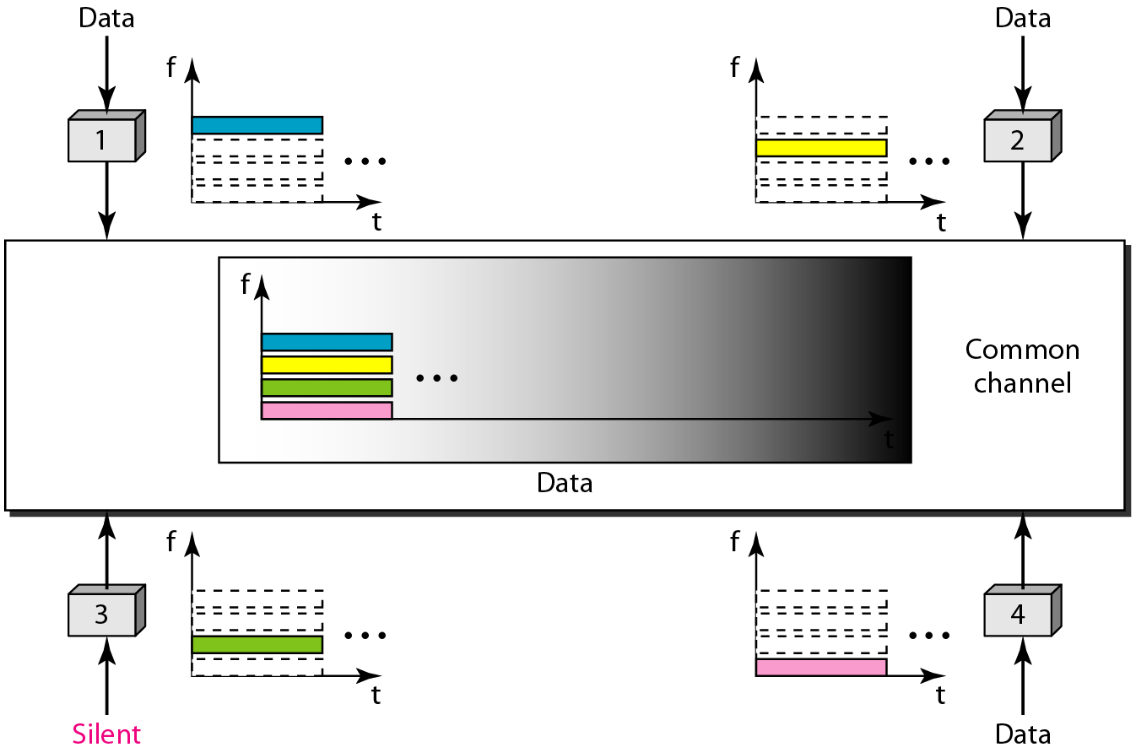


Figure 6.4 *FDM process*

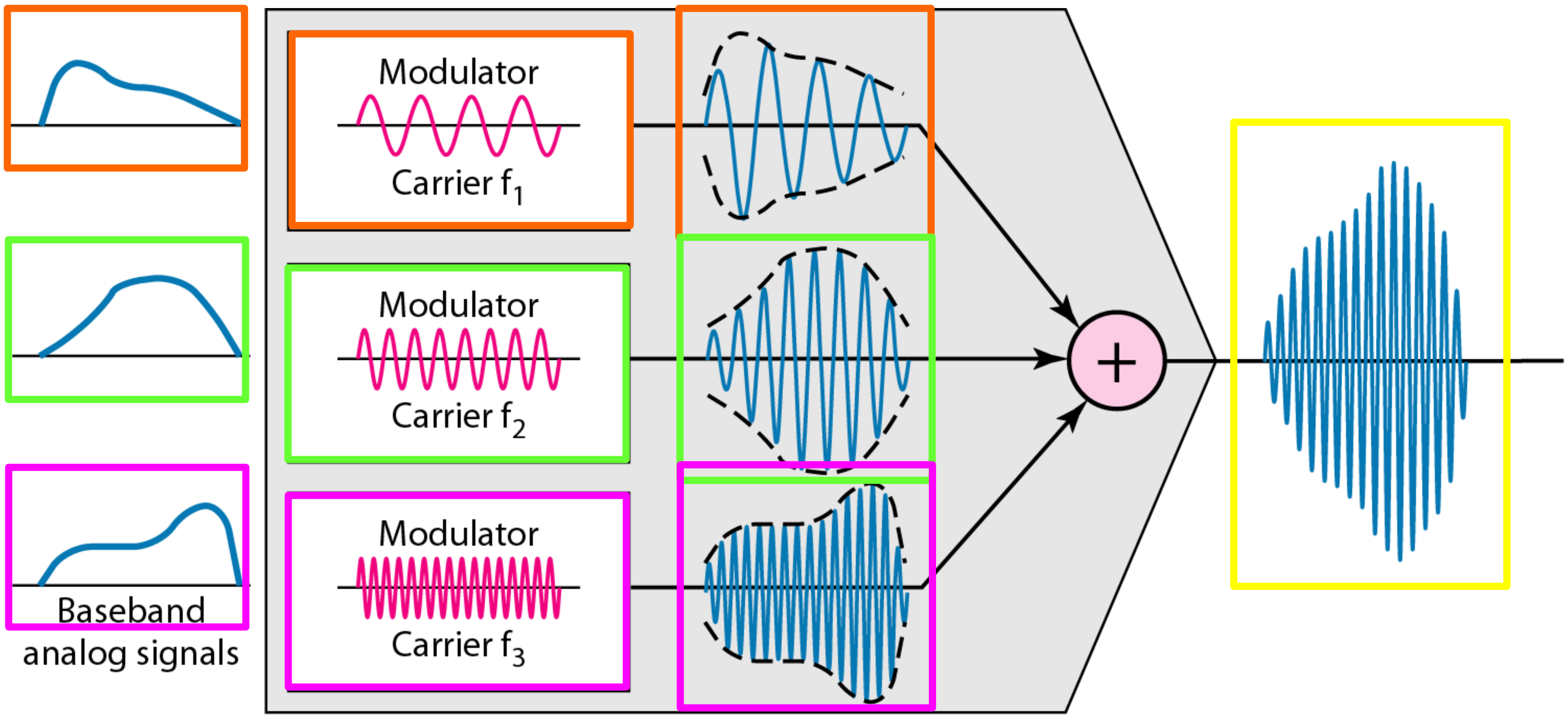
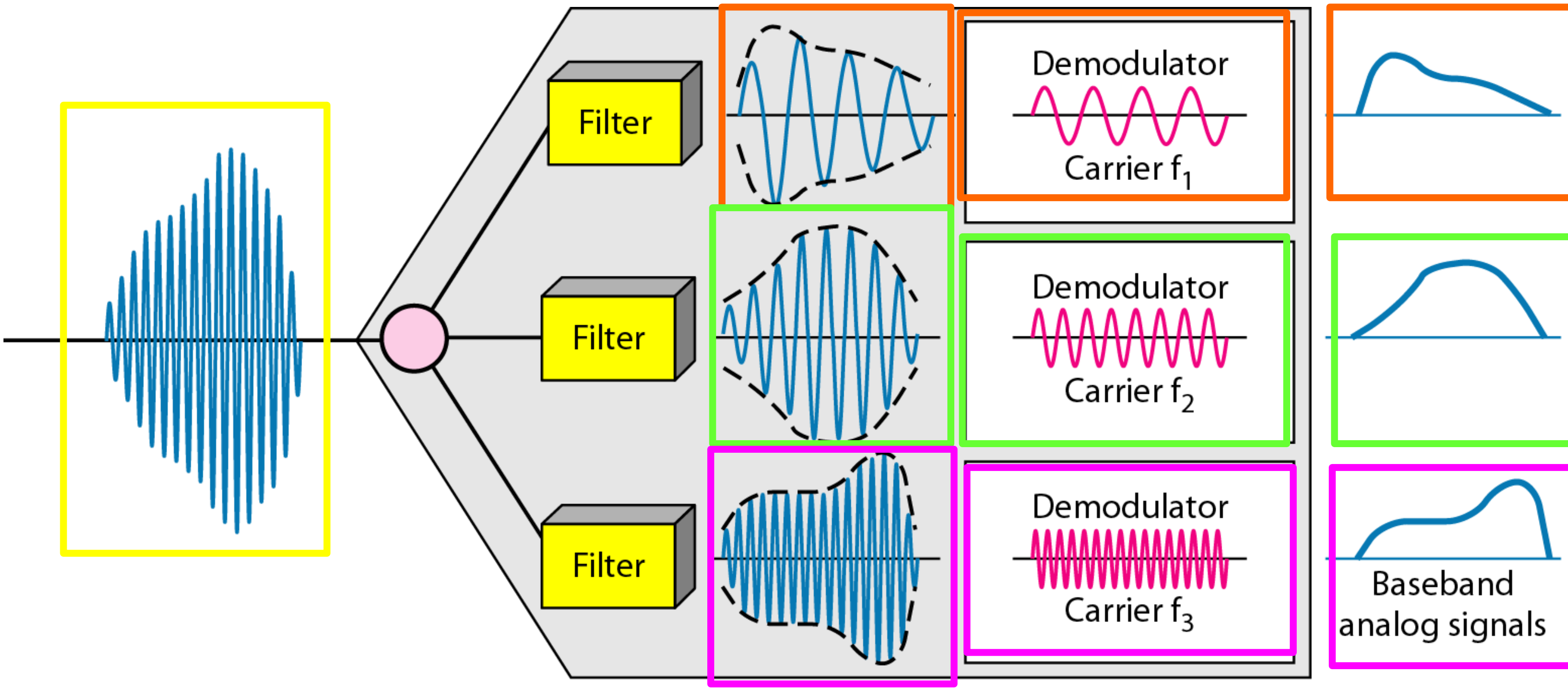


Figure 6.5 *FDM demultiplexing example*



Demultiplexing

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.

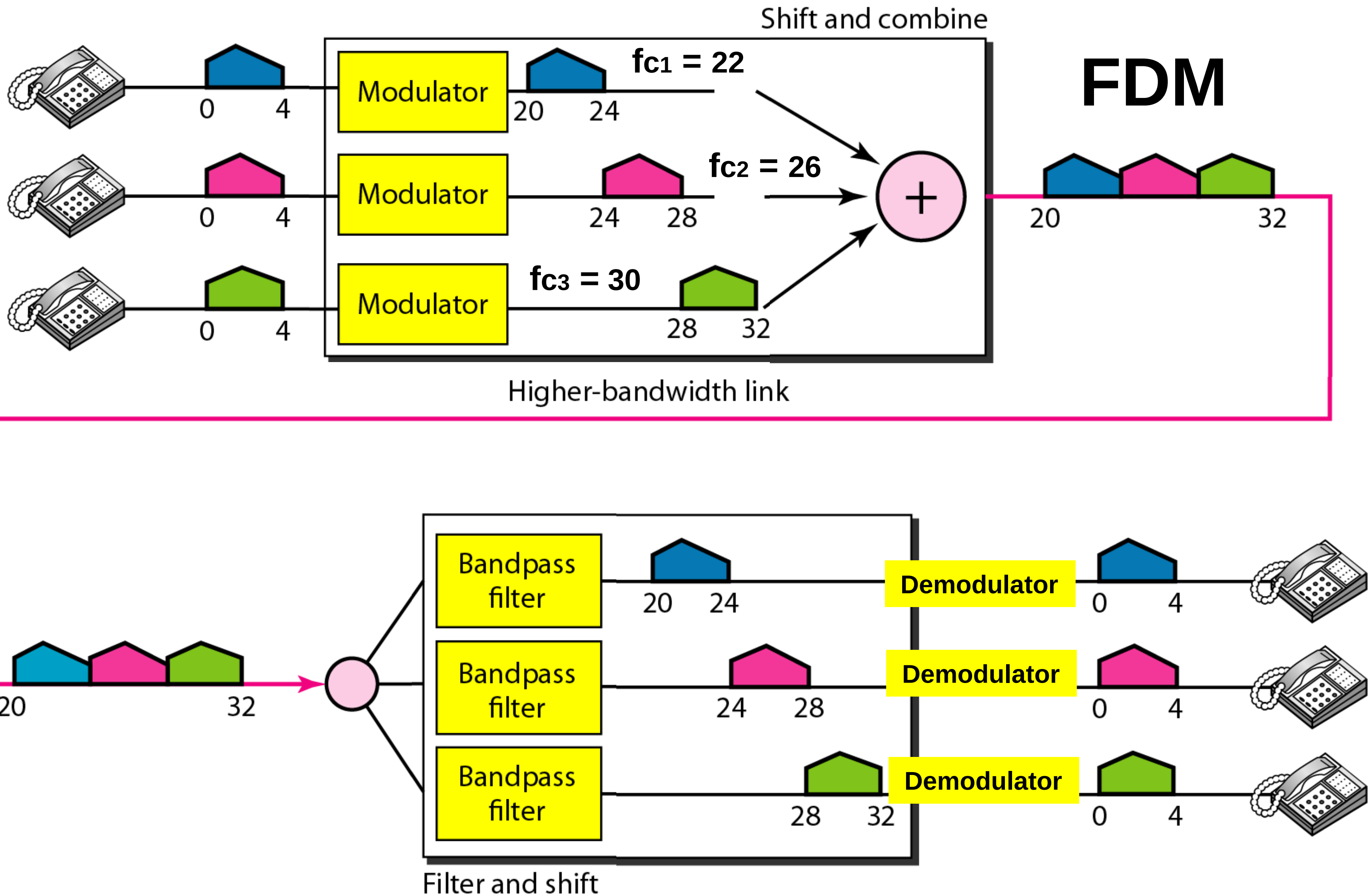
Solution

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?

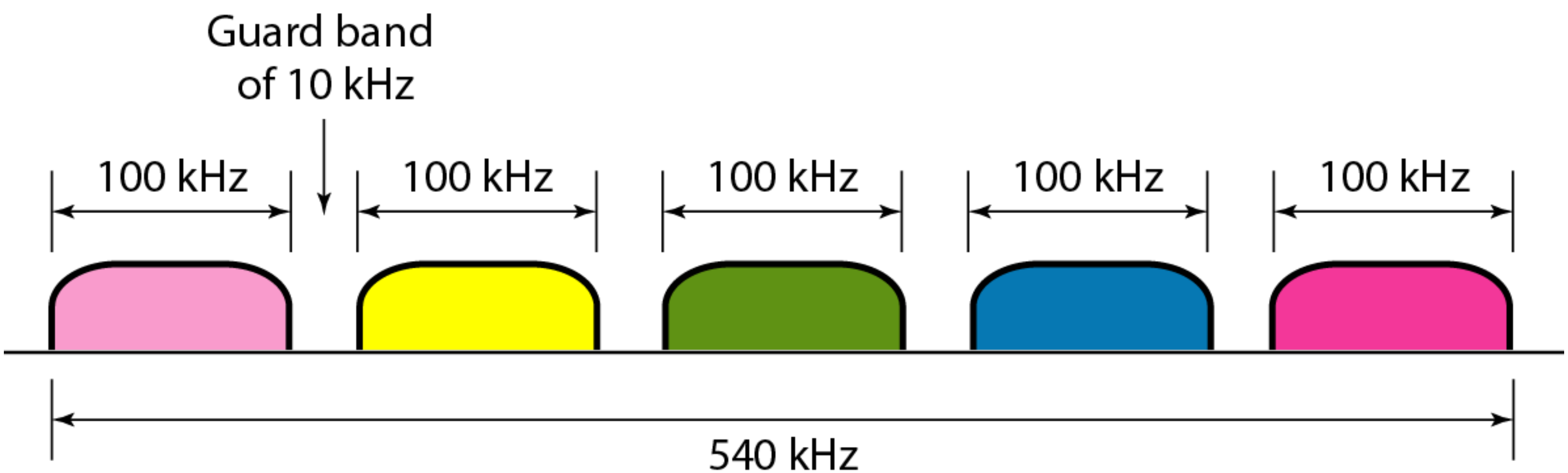
Solution

For **five channels**, we need **at least four guard bands**. This means that the required bandwidth is at least

(5 x 100) + (4 x 10) = 540 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 are modulated to 1 Hz**.
- One solution is 16-QAM modulation.
- Figure 6.8 shows one possible configuration.

Figure 6.8 *Example 6.3*

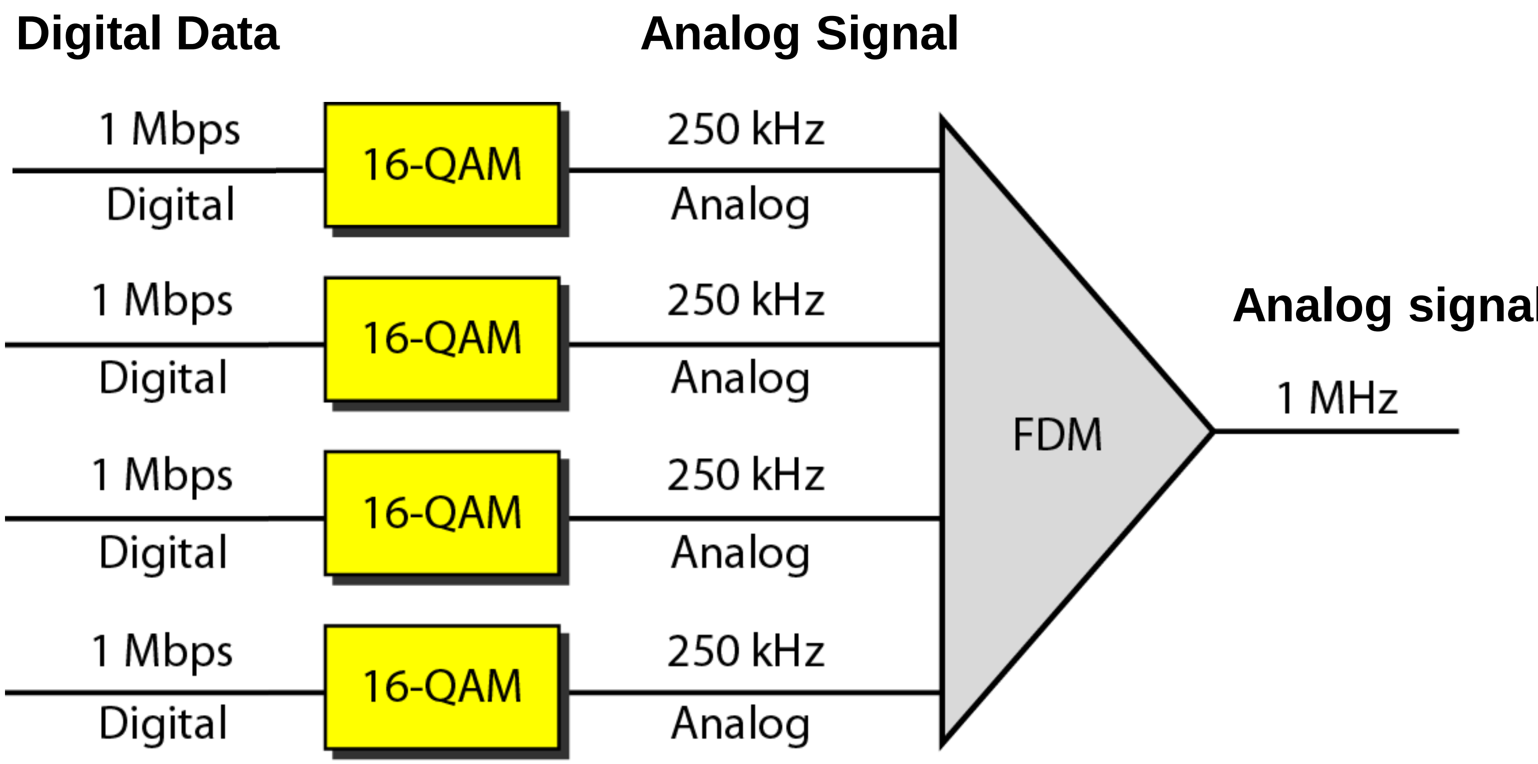
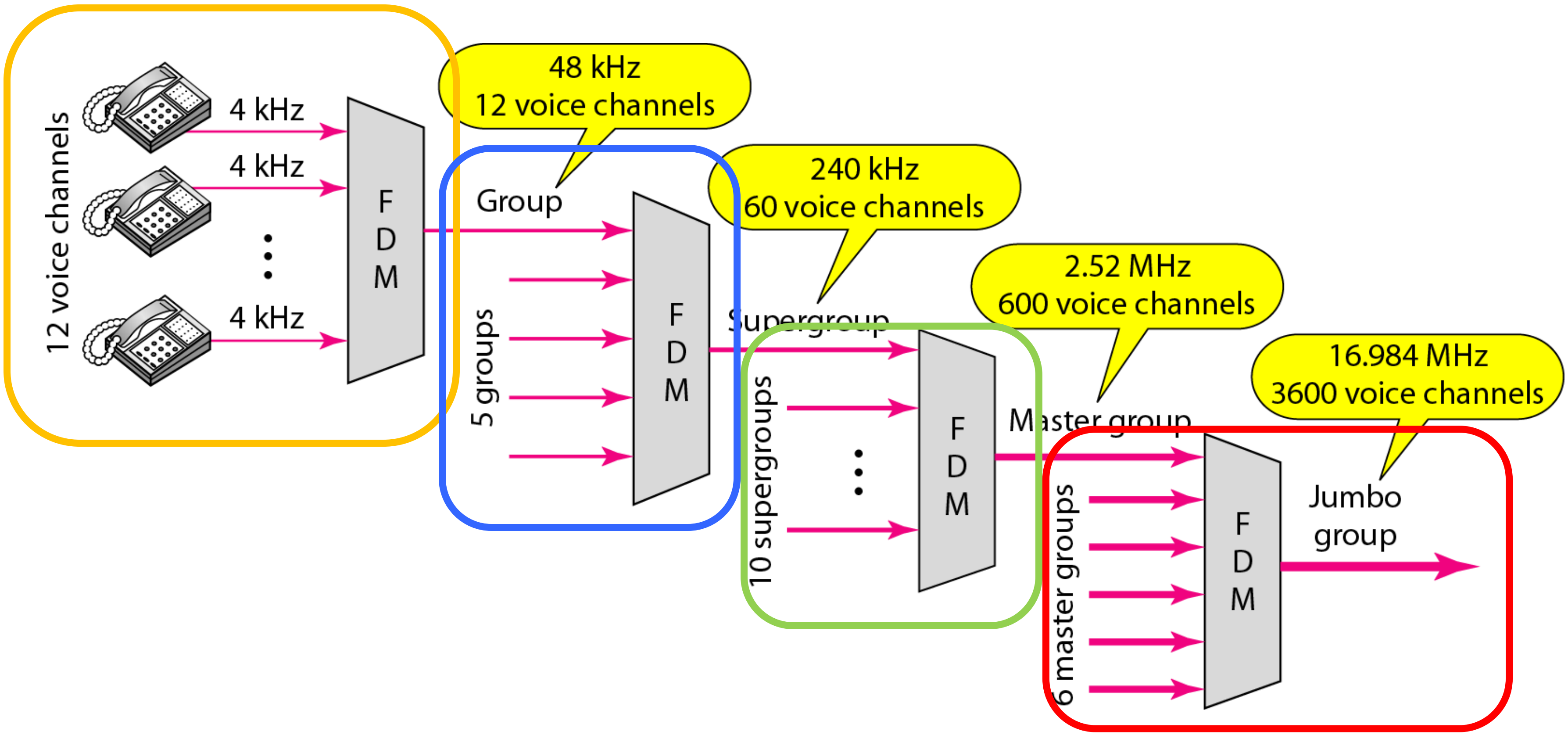


Figure 6.9 *Analog hierarchy*



Example 6.4

- The Advanced Mobile Phone System (AMPS) uses two bands.
- The first band, **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.
- The 3-KHz voice is modulated using FM, creating 30 KHz of modulated signal.
- How many people can use their cellular phones simultaneously?

Solution

Each band is 25 MHz. If we **divide 25 MHz into 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.

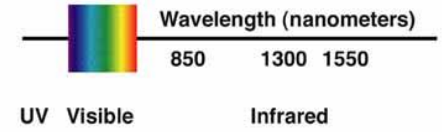
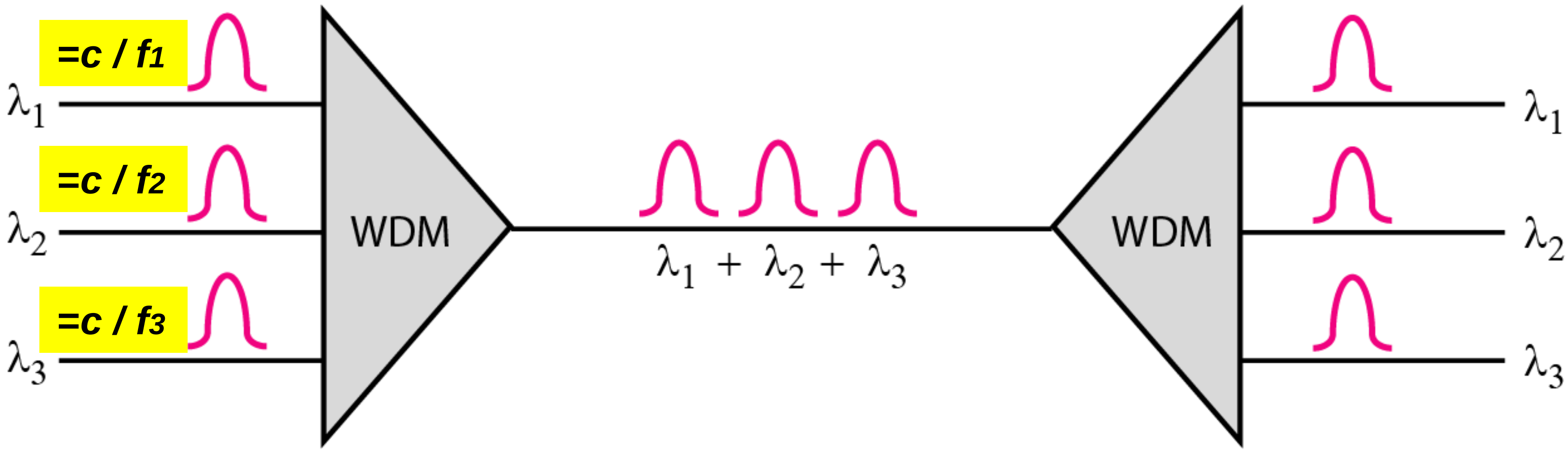


Figure 6.10 *Wavelength-division multiplexing* (WDM)



λ=*wavelength*

c = Light Speed

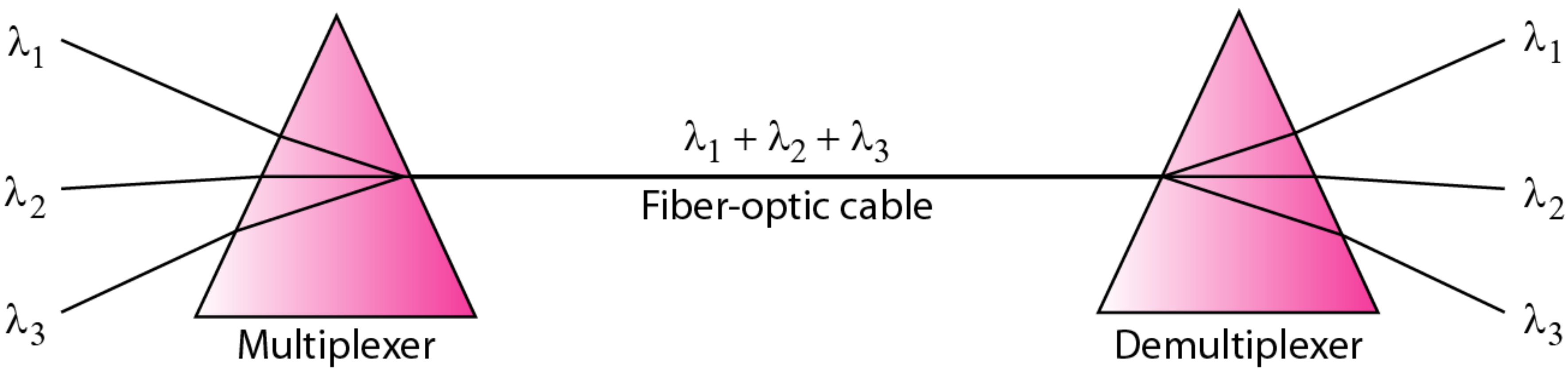
λ= c / f

- ช่วง wavelength ที่ใช้งาน 1550 nm
- Channel space:
  - SDH/SONET -> 50 GHz/ channel, 32 channels -> 2.5 Gbps x 32 = 80 Gbps
  - (1999)Bell LAB: 10 GHz/ channel, 1022 channels -> 2.5 Gbps x 1022 = 2.555 Tbps
  - (2002) NEC: 10 GHz/ channel, 273 channels -> 40 Gbps x 273 = 10.9 Tbps
  - (2011) NEC: 10 GHz/ channel, 370 channels -> 274 Gbps x 370 = 101.7 Tbps

Note

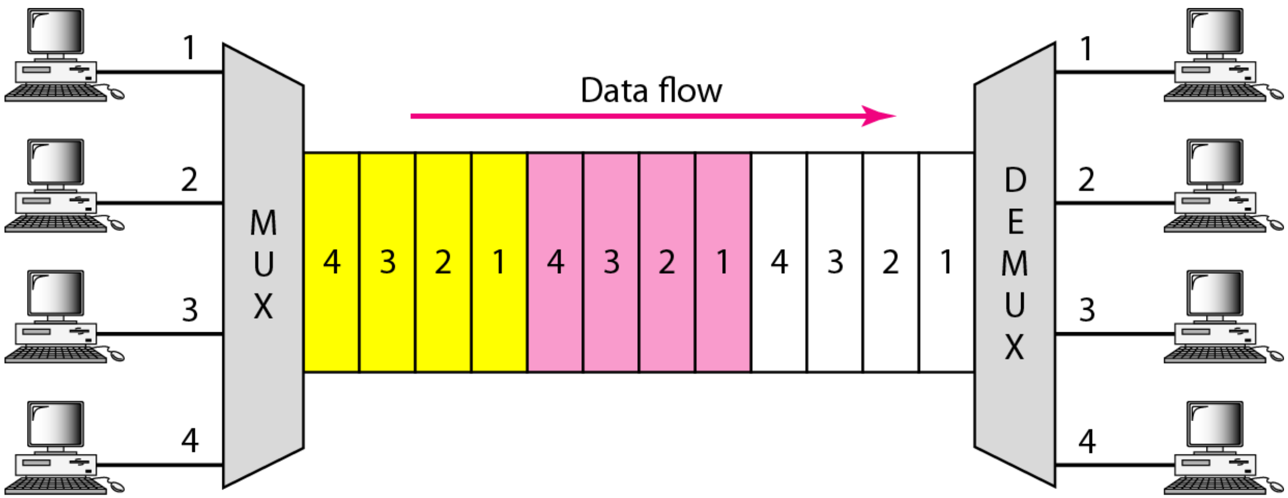
WDM is an analog multiplexing technique to combine optical signals.

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



Ex. Synchronous Optical Network (SONET)

Figure 6.12 Time Division Multiplexing (TDM)



- TDM is digital multiplexing technique for combining several low-rate channels into one high bandwidth of link by ***Sharing Time***

- TDM allows digital data from different sources are combined into one ***Timeshared Link***

- Analog data can be sampled, change to digital data, and then multiplexed by using TDM

Note

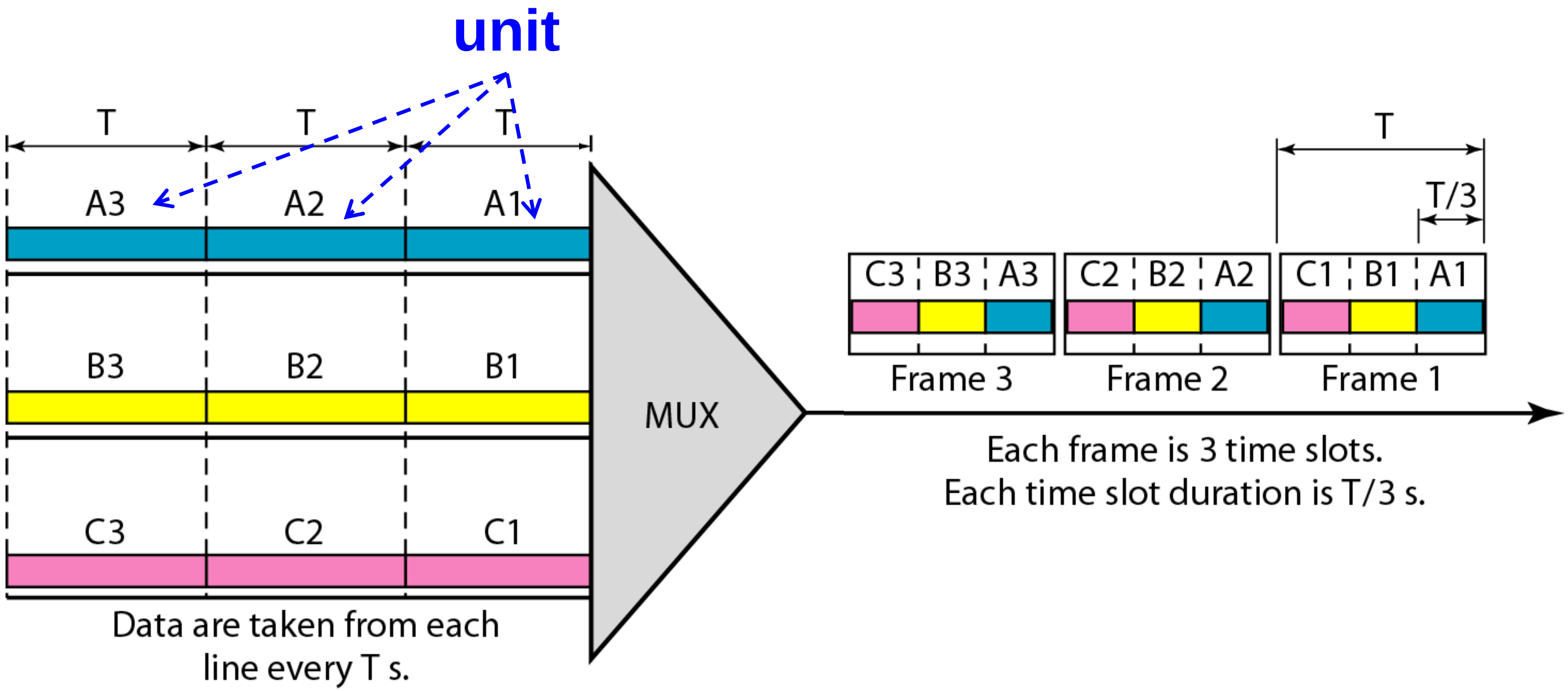
TDM is a digital multiplexing technique for combining several low-rate channels into one high-rate one.

- TDM can be divided into two different scheme

1. Synchronous TDM

2. Statistical TDM

Figure 6.13 *Synchronous Time-Division Multiplexing*



Example 5

Four 1-Kbps connections are multiplexed together. A unit is 1 bit. Find

(1) the duration of 1 bit before multiplexing,

(2) the transmission rate of the link,

(3) the duration of a time slot, and

(4) the duration of a frame?

Solution

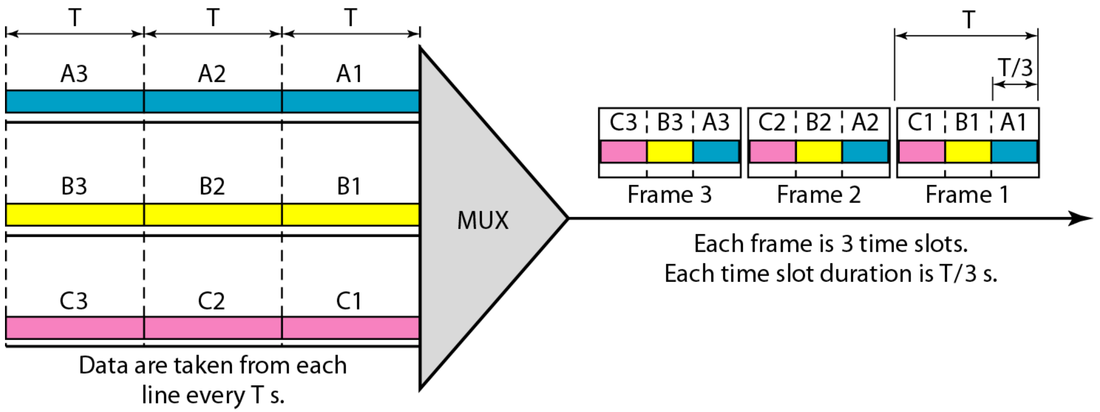
We can answer the questions as follows:

1. The duration of 1 bit is 1/1 Kbps, or 0.001 s (1 ms).
2. The rate of the link is 4 Kbps.

3. The duration of each time slot = 1/rate of Link = 1/4 ms or 250 μs.
4. The duration of a frame = 1/ frame rate = 1 ms.

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, 3 input),*



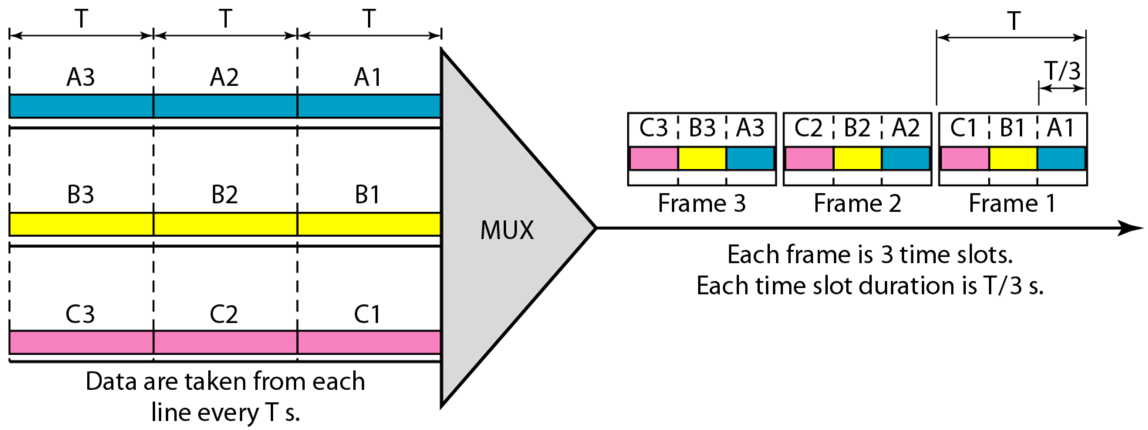
- *what is the duration of*
  - *(a) each input slot,*
  - *(b) each output slot, and*
  - *(c) each frame?*

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.

Duration of a frame is same as duration of input unit

Example 6.6

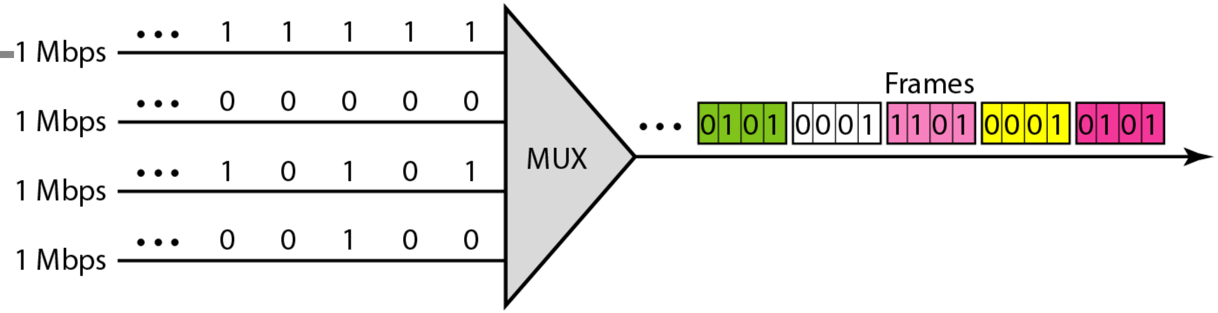


Figure 6.14 shows synchronous TDM with a data stream for each input and one data stream for the output. The unit of data is 1 bit.

Find (a) the input bit duration,
(b) the output bit duration,
(c) the output bit rate, and
(d) the output frame rate.

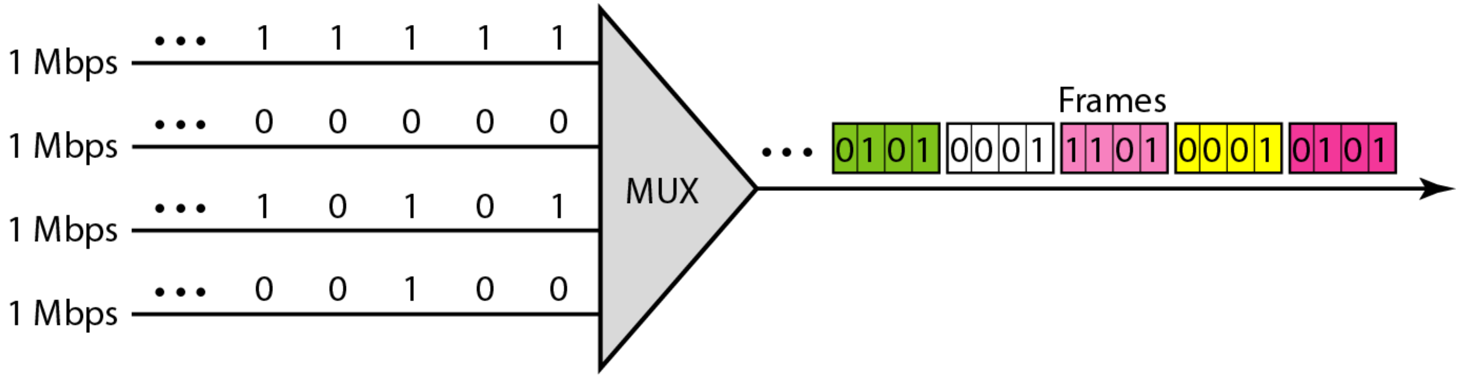
Solution

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 or 0.25 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** (1 M 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*

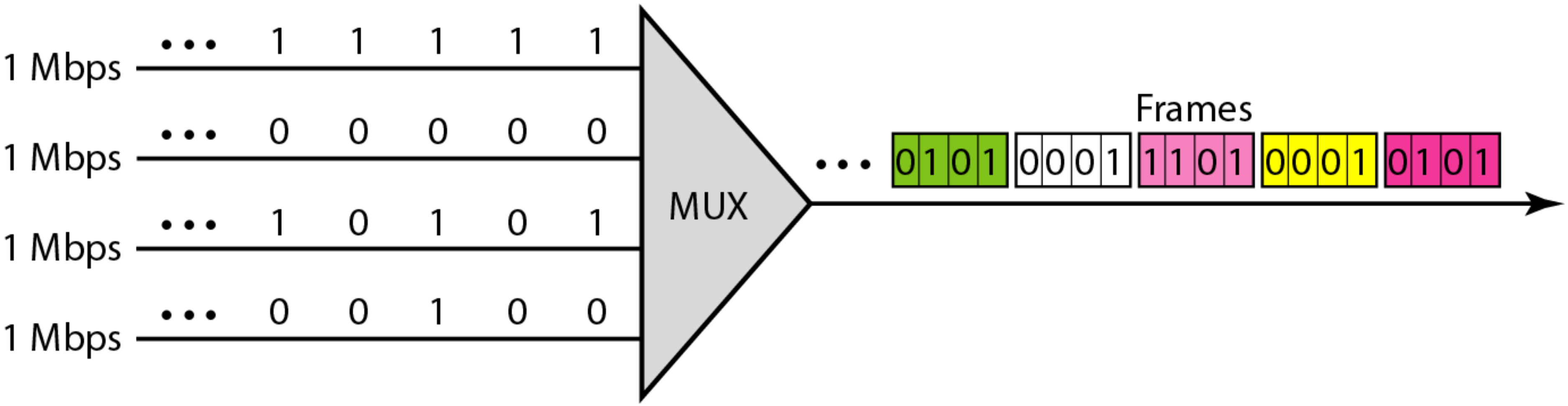
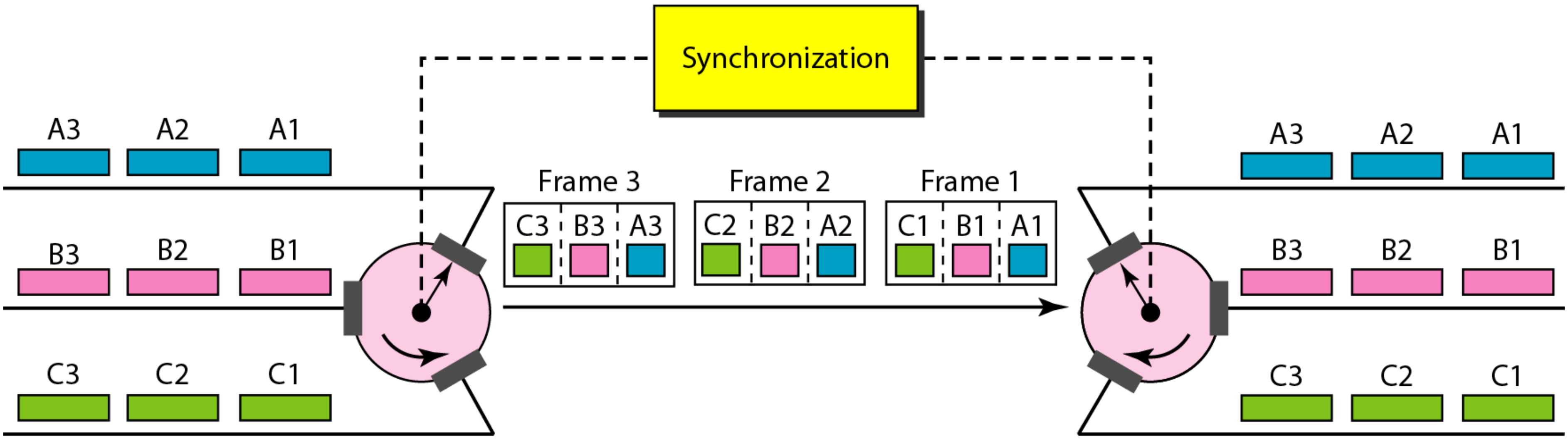


Figure 6.15 *Interleaving*



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

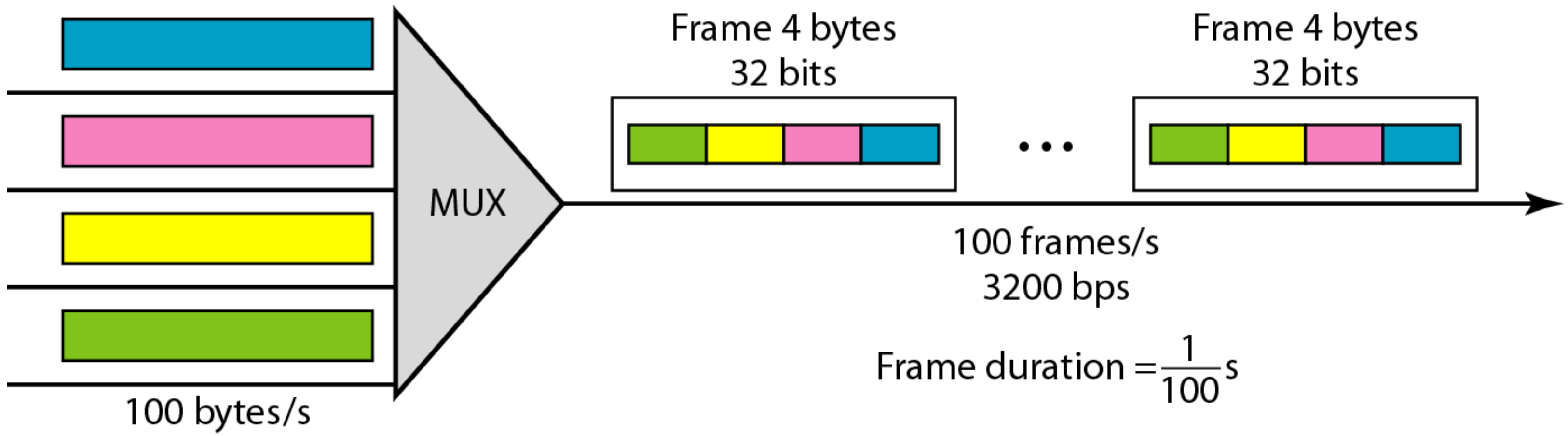
The multiplexer is shown in Figure 6.16.
1) Each frame carries 1 byte from each channel;
the size of each frame, therefore, is 4 bytes, or 32 bits.

2)) Duration of frame = 1/100 = 0.01 s

3) 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.

4) 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.

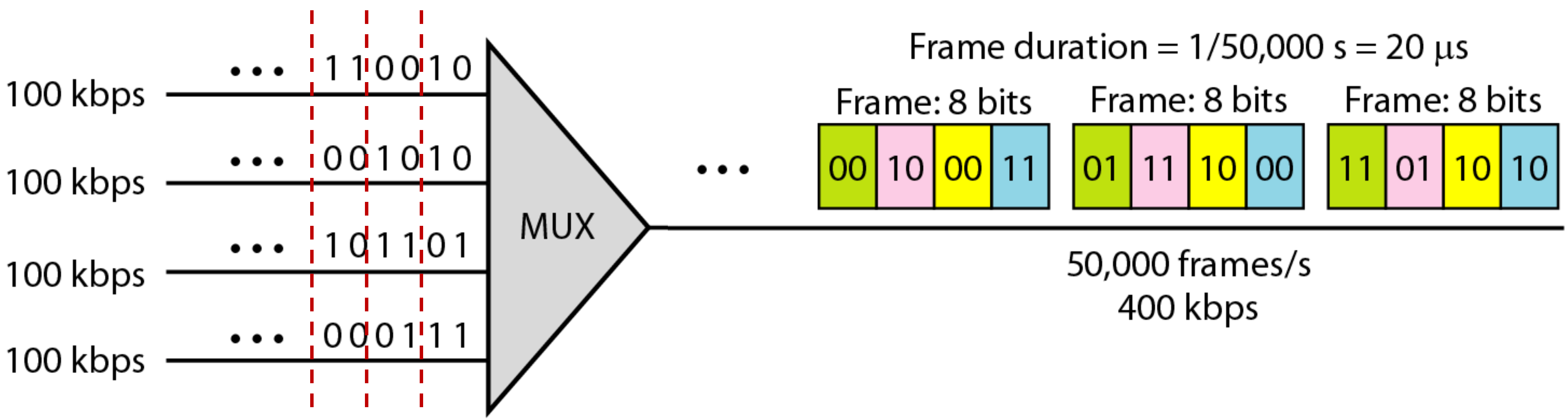
Show the output with four arbitrary inputs.
What is the frame rate?
What is the frame duration?
What is the bit rate?
What is the bit duration?

Solution
Figure 6.17 shows the output for four arbitrary inputs.
The link carries 50,000 frames per second. (Frame rate = 100 kbps / 2 bits)
1) The frame duration is therefore 1/50,000 s or 20 μs.
2) The frame rate is 50,000 frames per second, and
3) each frame carries 8 bits; the bit rate is 50,000 × 8 = 400,000 bits or 400 kbps.
4) The bit duration is 1/400,000 s, or 2.5 μs.

Figure 6.17 *Example 6.9*

Interleaving Unit = 2 bits

TDM: 2bits/slot



Frame rate = 100 kbps / 2 bits = 50 kframes / s

Figure 6.18 *Empty slots in Synchronous TDM*

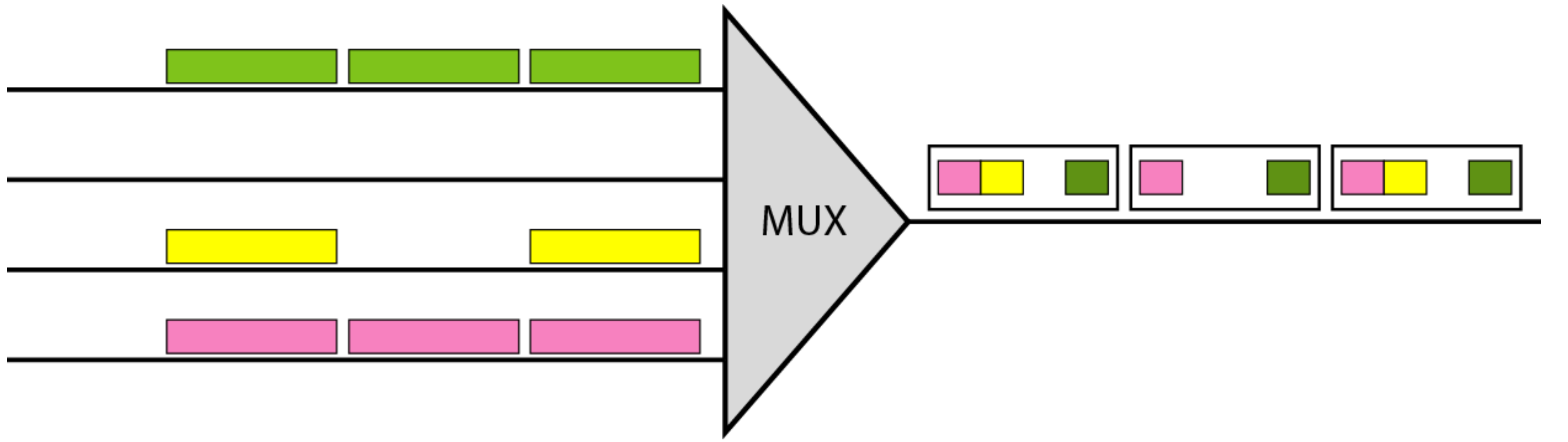


Figure 6.19 *Multilevel multiplexing*

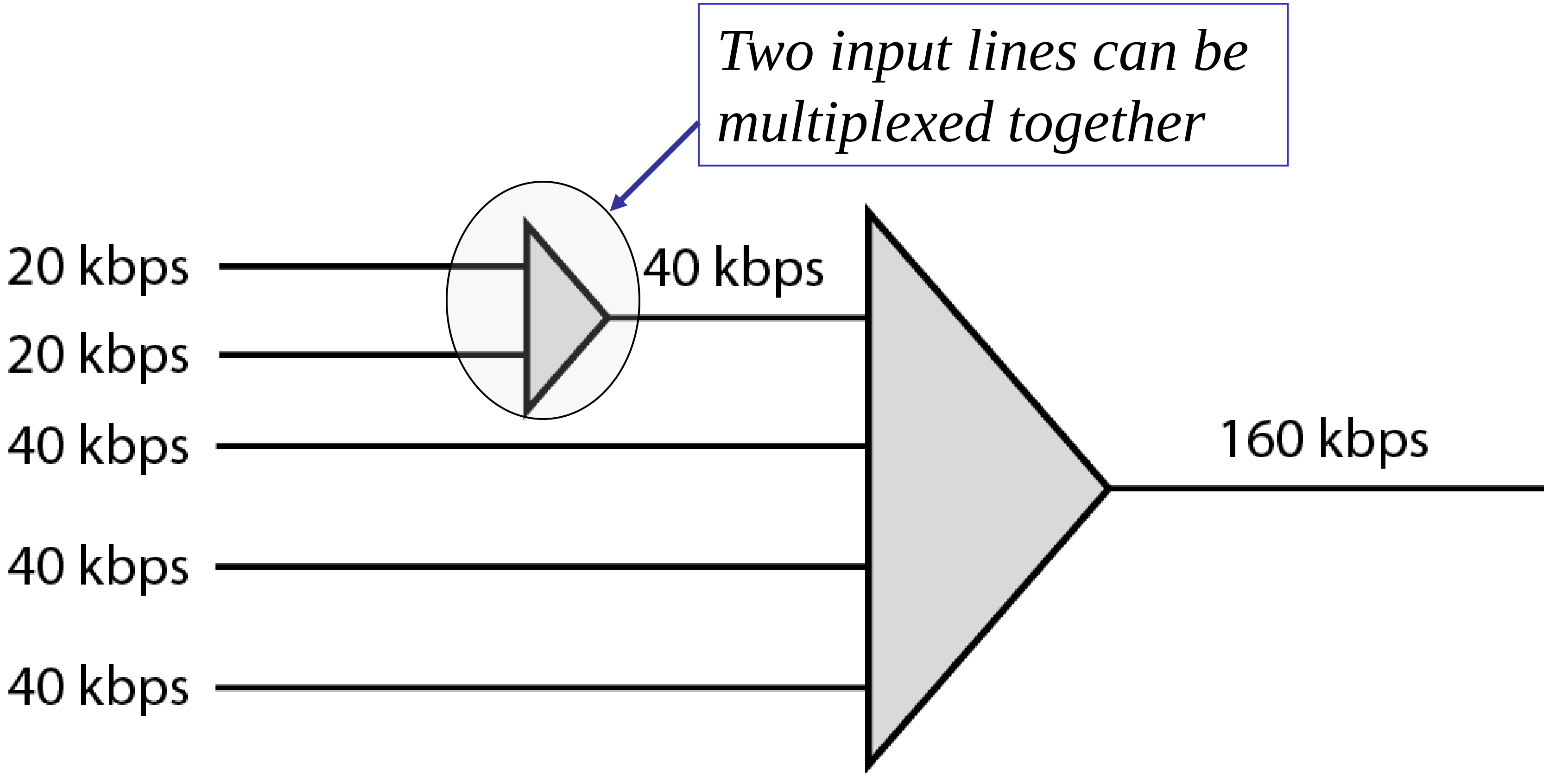


Figure 6.20 *Multiple-slot multiplexing*

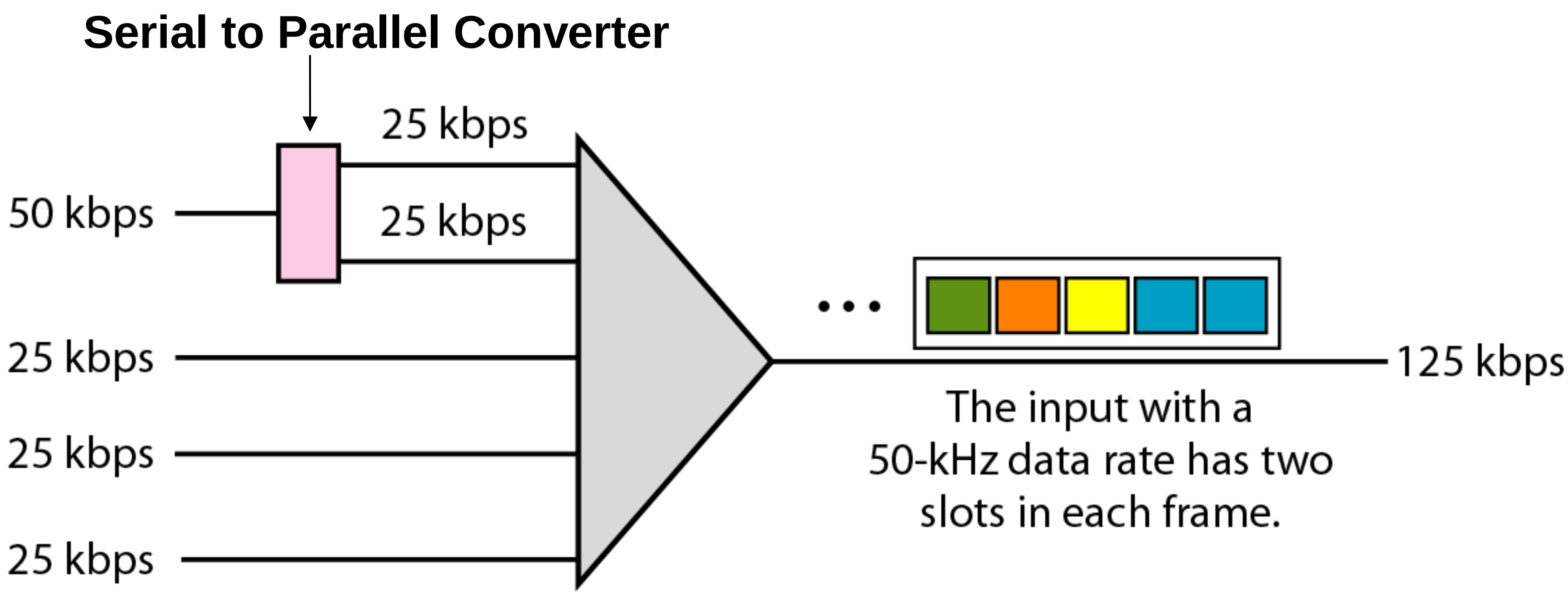


Figure 6.21 *Pulse stuffing*

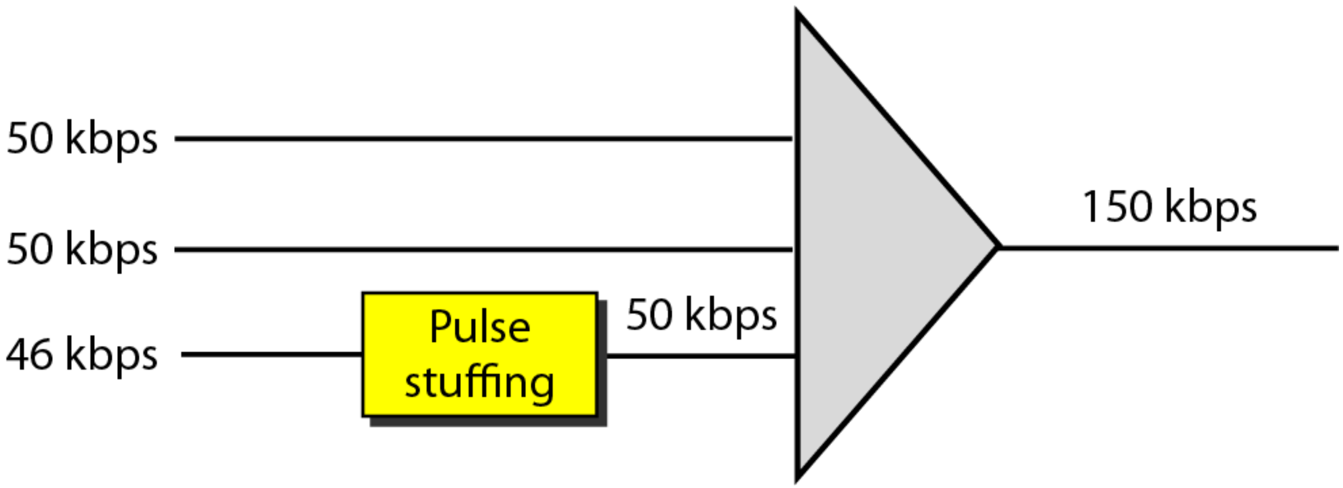
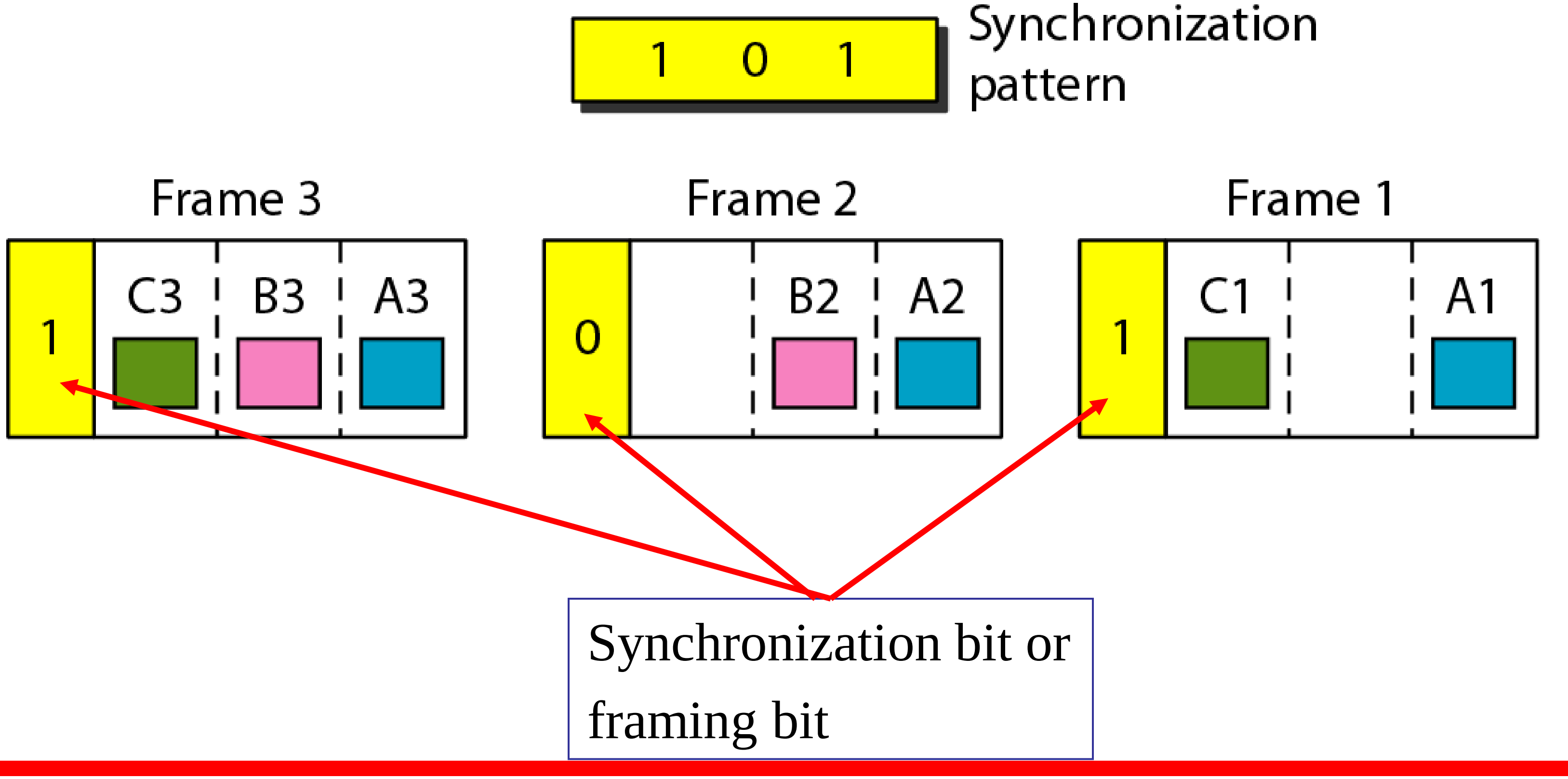


Figure 6.22 *Framing bits*



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 $250 \times 8 = 2000$ 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 × 8 + 1 = 33 bits.

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Data rate of Link = 250 frame/sec. x 33 bits = 8,250 bps

250 frame/sec. x 32 bits = 8,000 bps (No. Sync. Bit)

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. (using Serial to Parallel convertor)

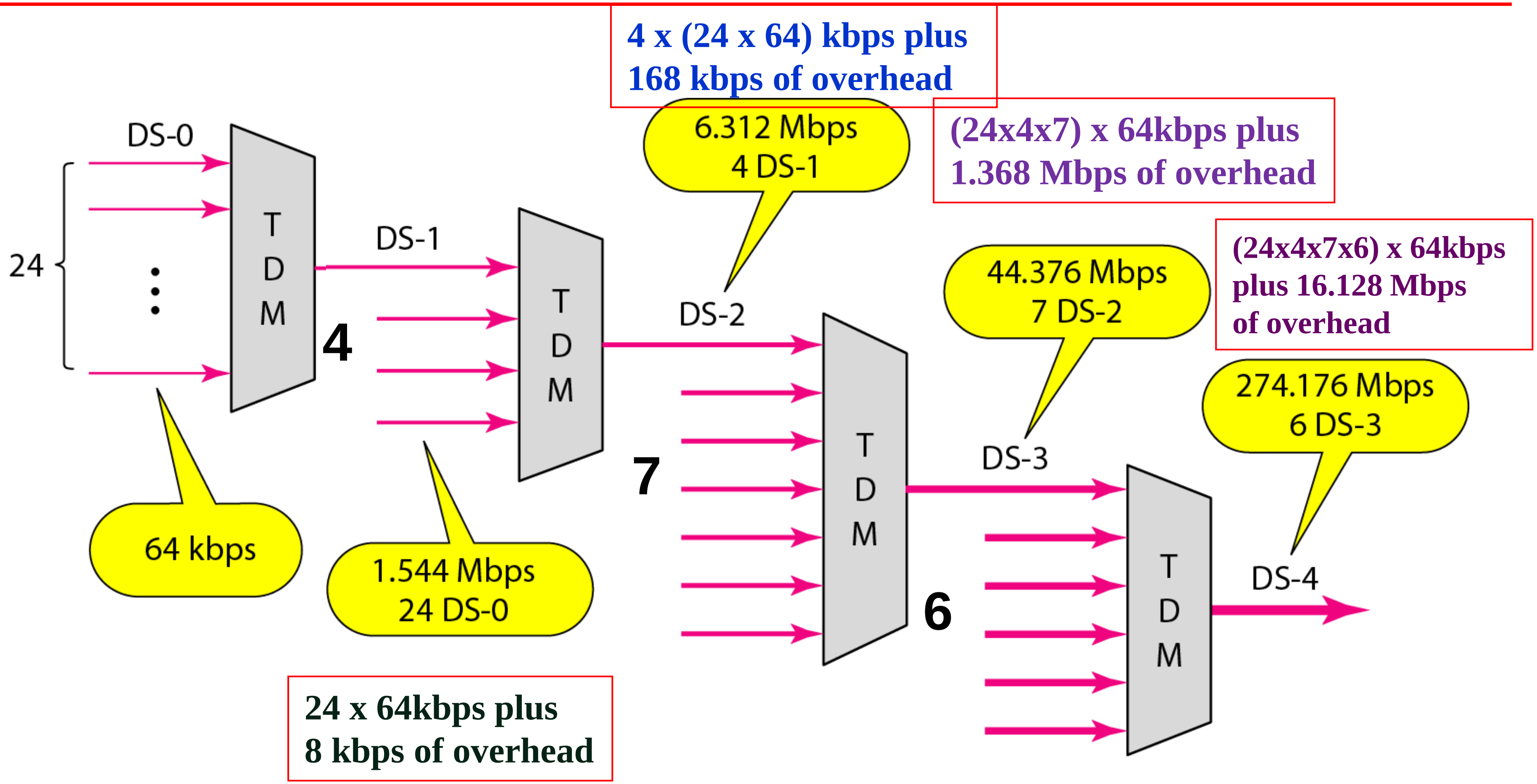
Each frame carries 3 bits.

-The frame rate is 100,000 frames per second because it carries 1 bit from the first channel.

- Frame duration = 1/100,000 sec. or 10 μs

- The bit rate is 100,000 frames/s × 3 bits per frame, or 300 kbps.

Figure 6.23 *Digital hierarchy (Digital signal service: DS)*



24x64 kbps = 1536 kbps = 1.536 Mbps

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*

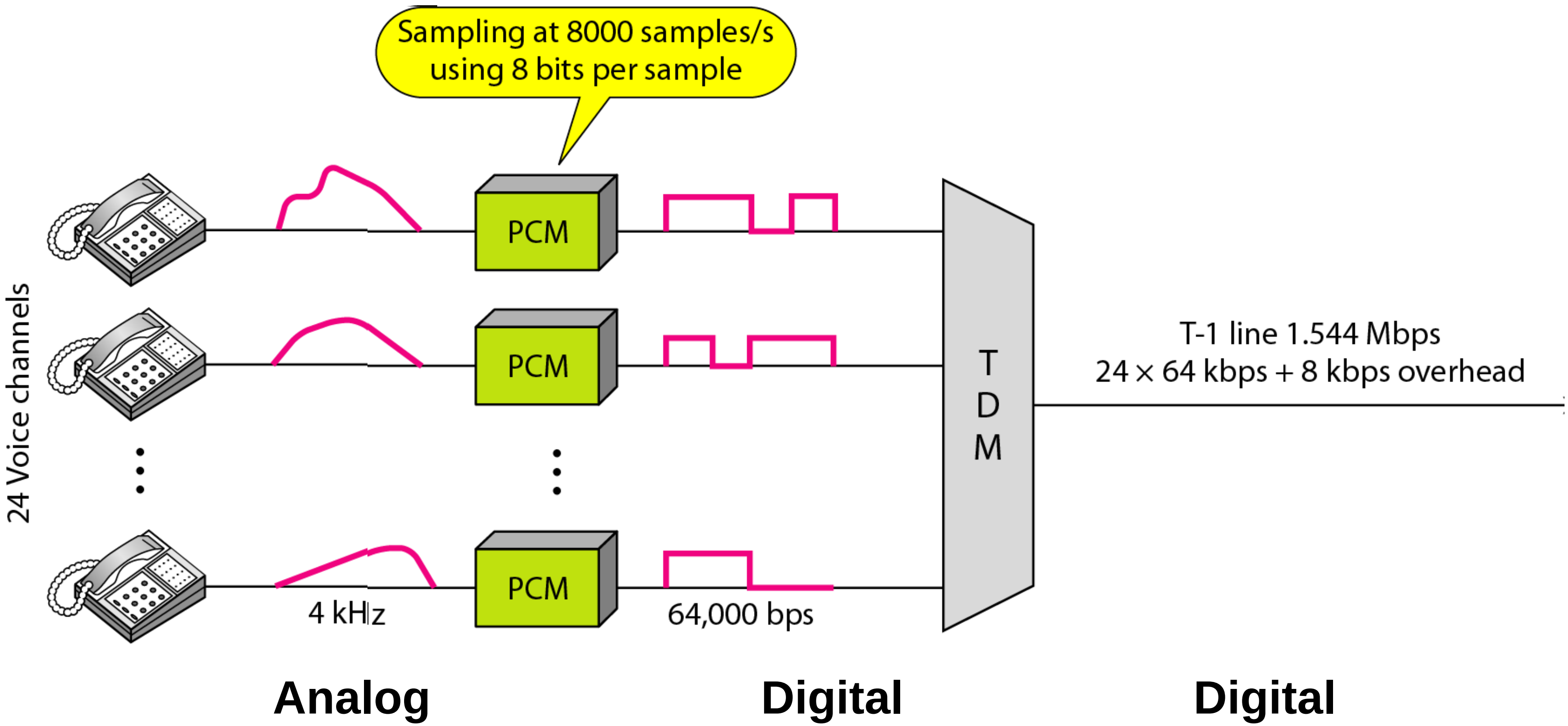


Figure 6.25 *T-1 frame structure*

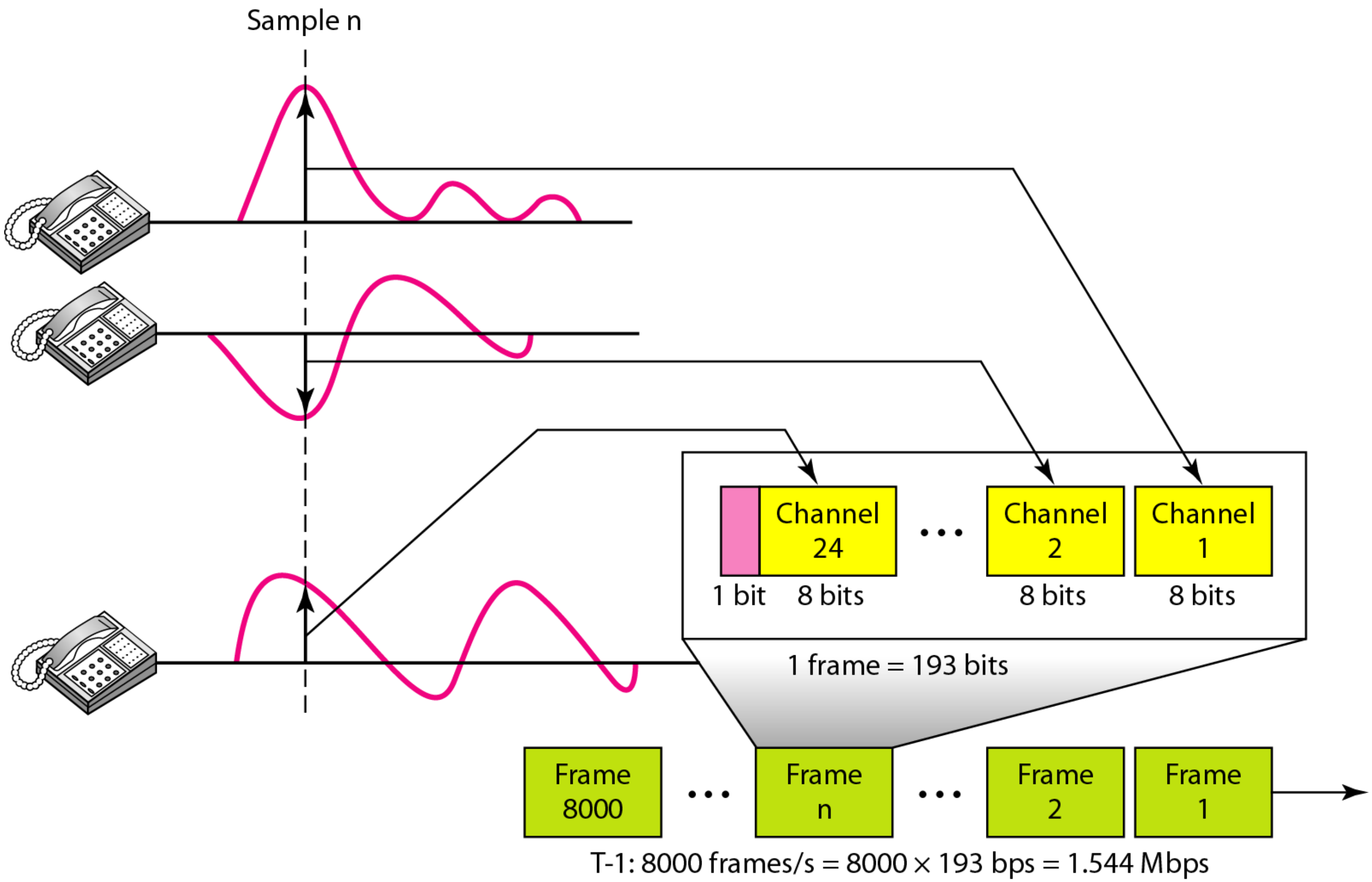
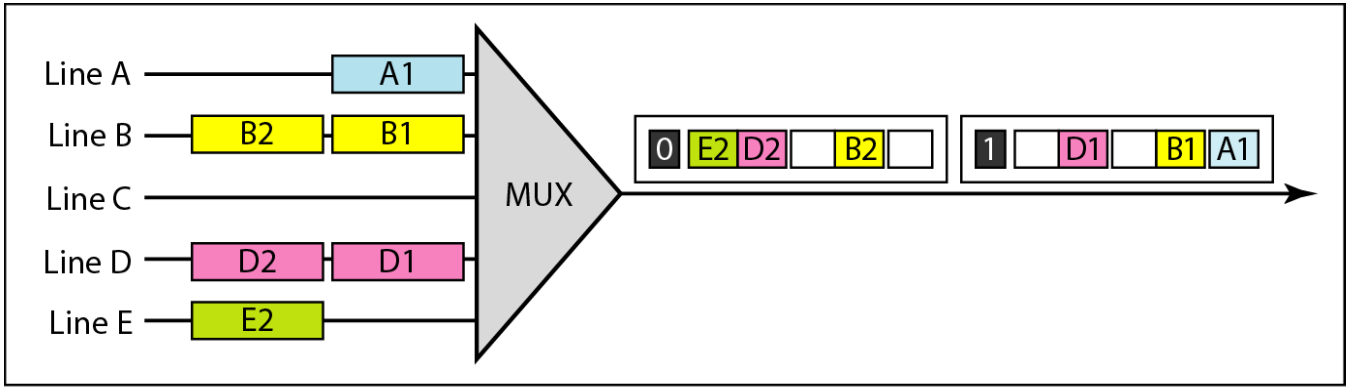


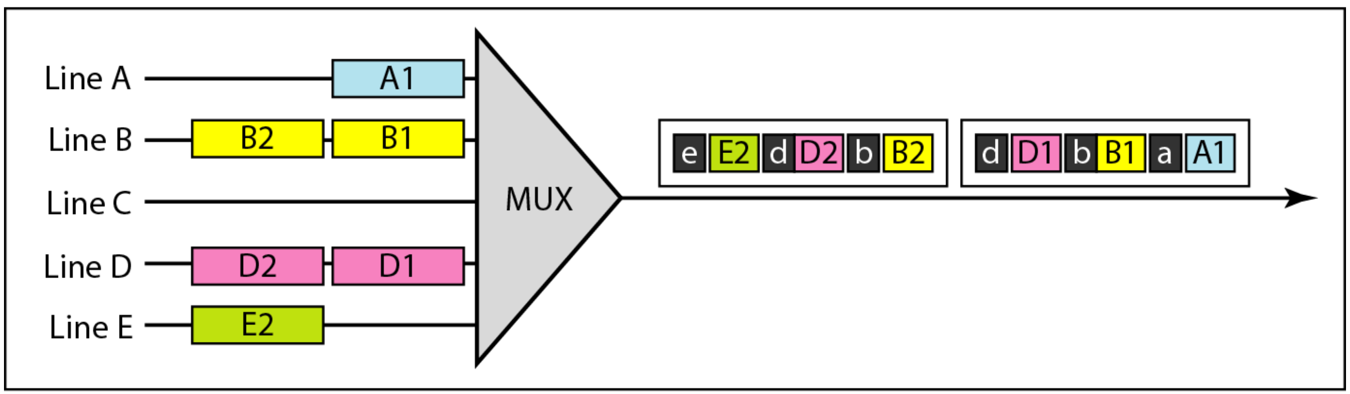
Table 6.2 ***E line rates***

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*

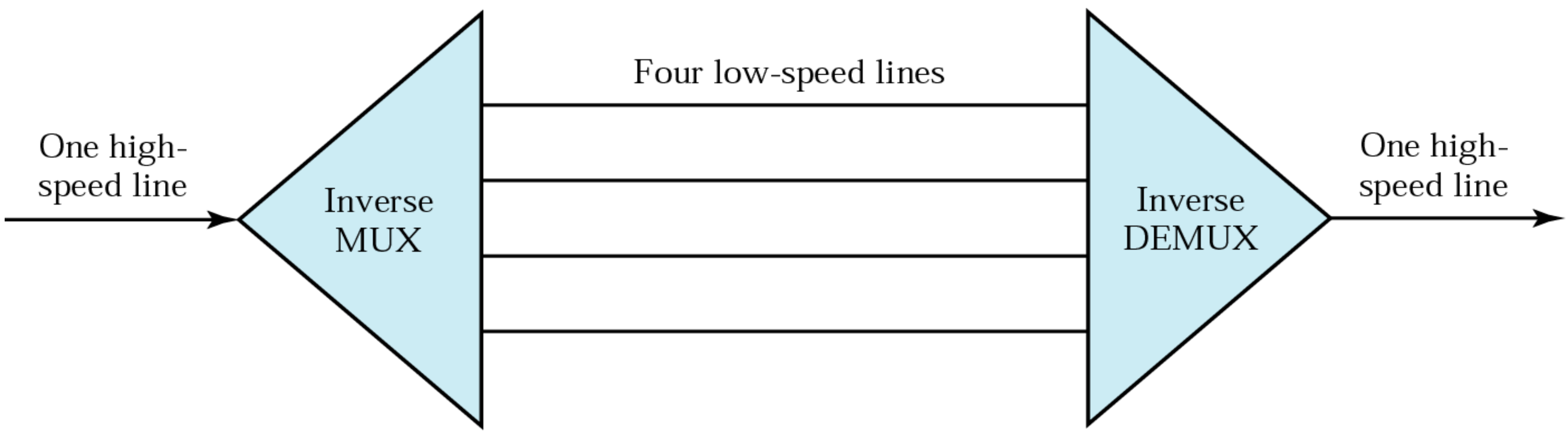


a. Synchronous TDM



b. Statistical TDM

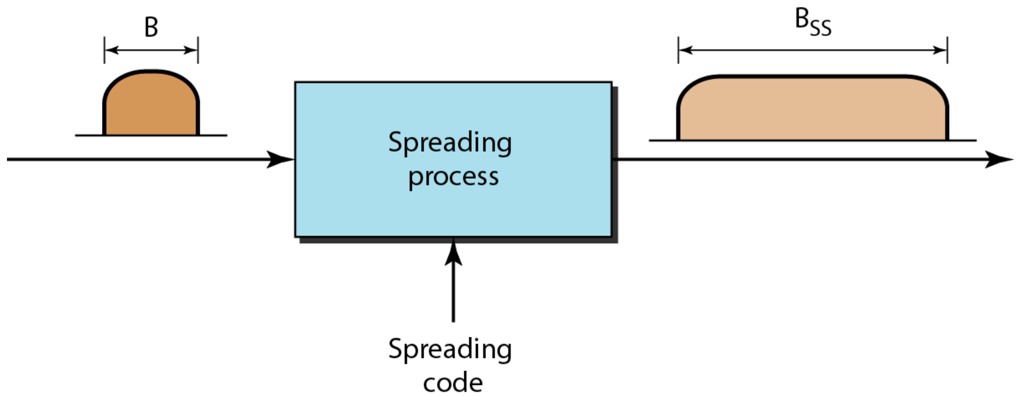
Inverse Multiplexing



6-1 SPREAD SPECTRUM (SS)

- ใช้ใน wireless communication
- วัตถุประสงค์
  - ใช้ Bandwidth ของสื่อให้คุ้มค่าที่สุด
    - โดยรวมสัญญาณจากหลาย ๆ user ส่งไปด้วยกัน
  - ป้องกันการรบกวนจากผู้ไม่หวังดี
    - *prevent eavesdropping and jamming*

6-1 SPREAD SPECTRUM



หลักการ

-combine signals from different sources to fit into a larger bandwidth

- ขยาย (spread) bandwidth ของแต่ละ user ให้เป็น Spread spectrum bandwidth (Bss)

add redundancy.

Techniques:

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

Figure 6.28 *Frequency hopping spread spectrum (FHSS)*

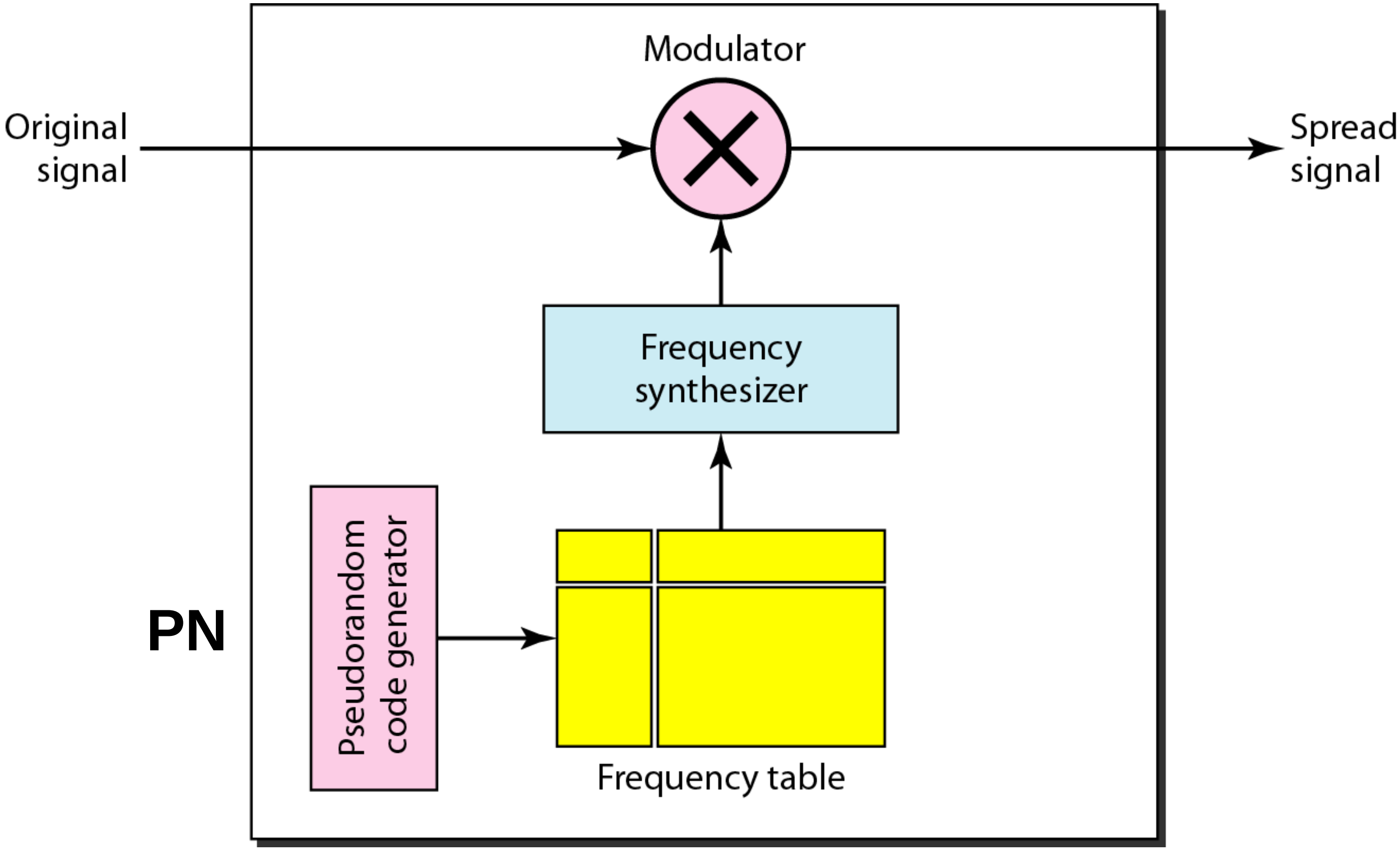


Figure 6.29 *Frequency selection in FHSS*

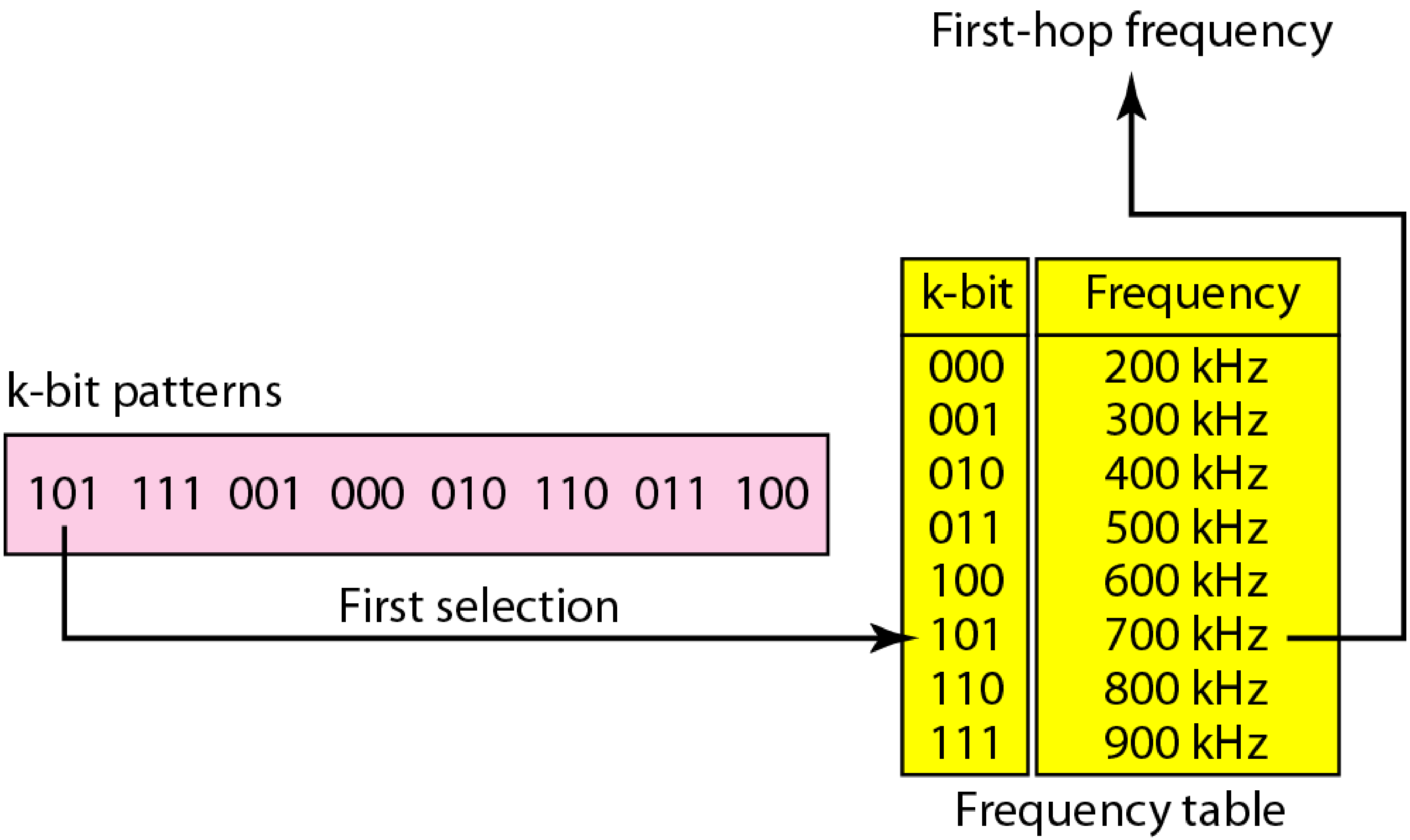


Figure 6.30 *FHSS cycles*

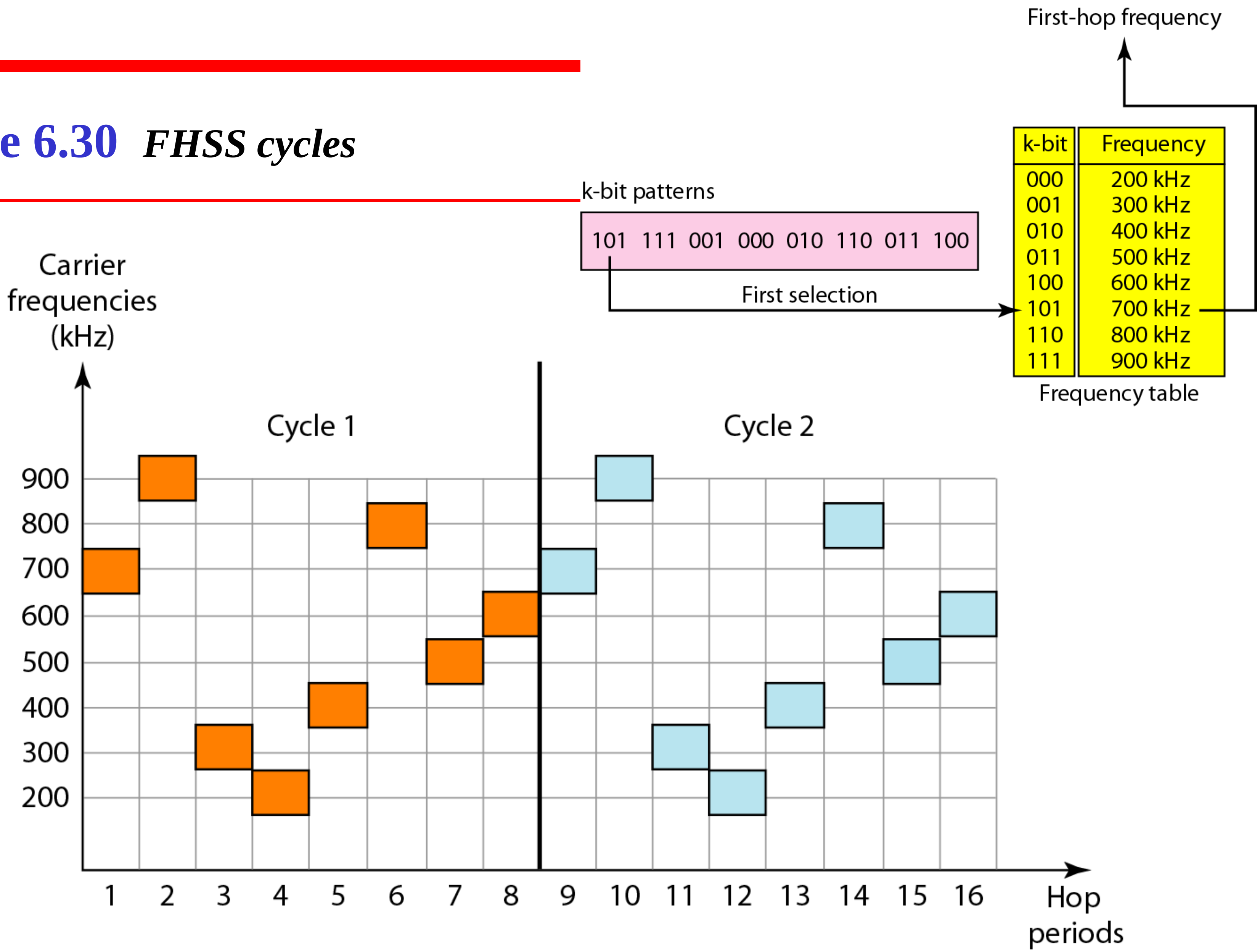


Figure 6.31 *Bandwidth sharing*

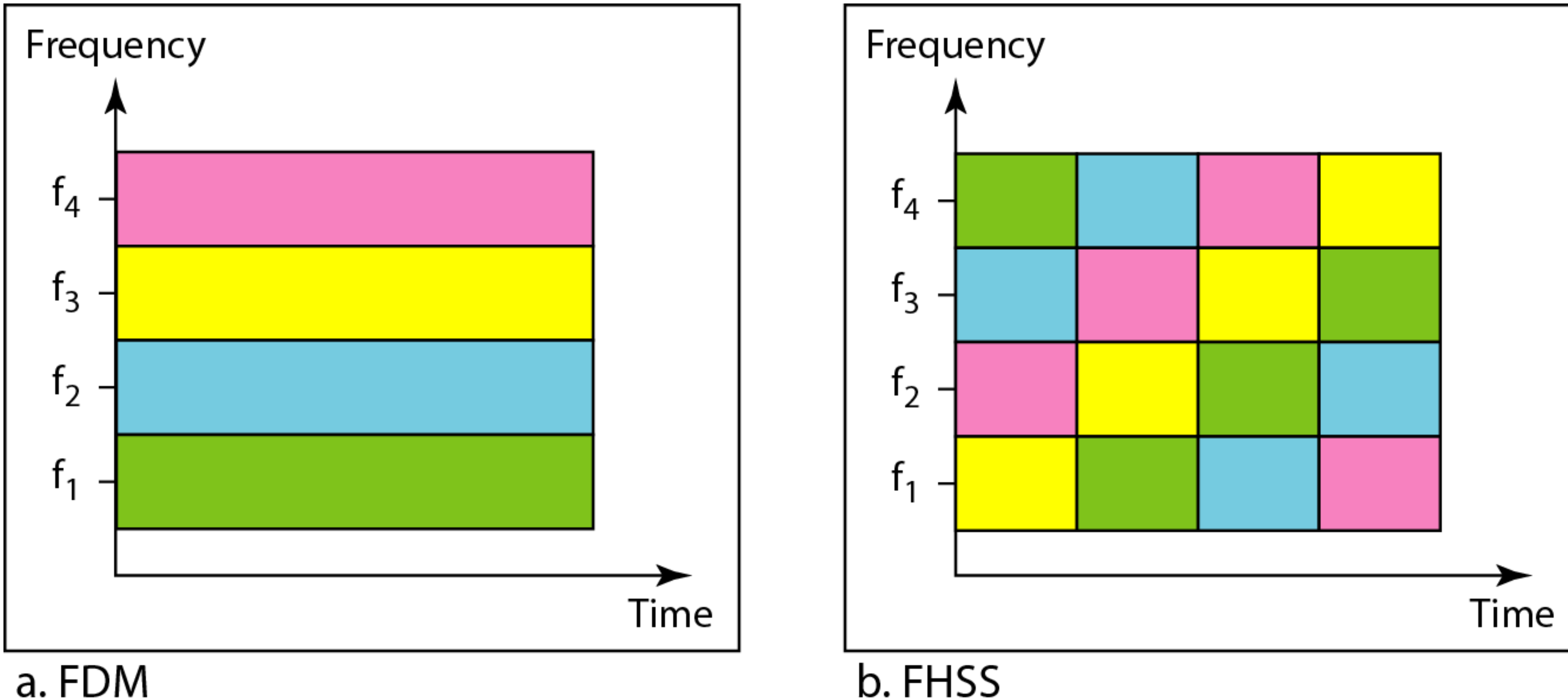
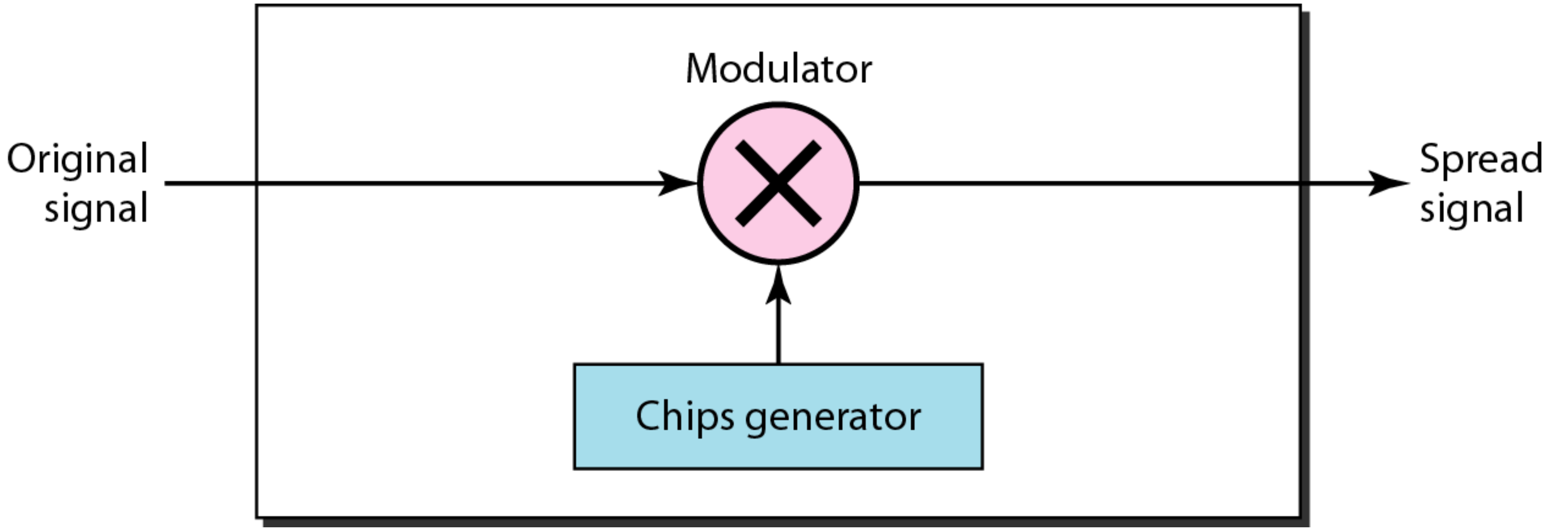


Figure 6.32 *Direct Sequence Spread Spectrum (DSSS)*



-**Spreading Code**
-**Chipping sequence**

Sequence generation

Element

$$W_1 = \begin{bmatrix} +1 \end{bmatrix}$$

$$W_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}$$

N=1

$$\begin{array}{cc} W_2 & W_2 \end{array}$$

$$W_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

$$\begin{array}{cc} W_2 & \overline{W_2} \end{array}$$

N=2

Figure 6.33 *DSSS example*