Chapter 6

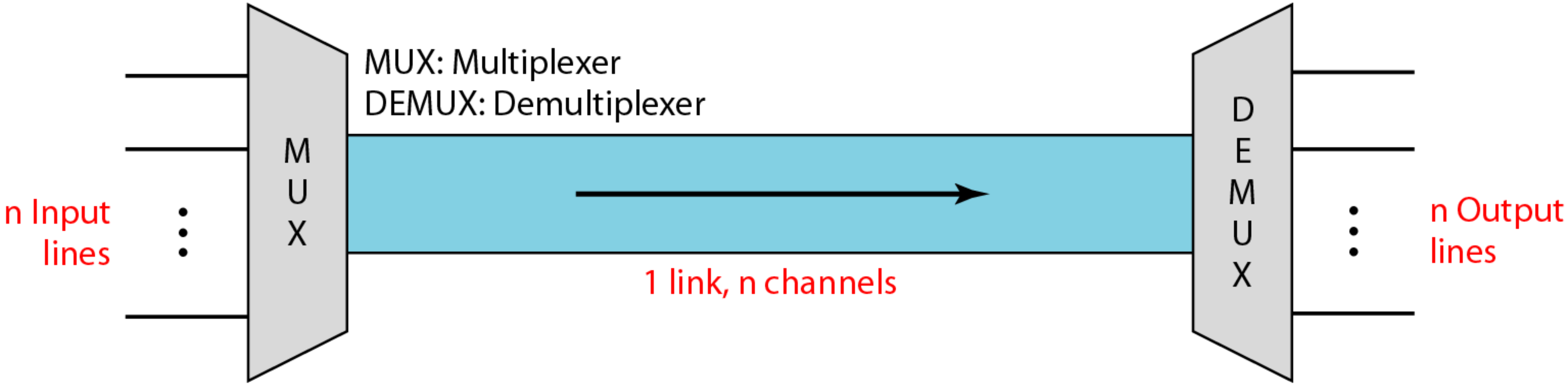
Bandwidth Utilization: Multiplexing and Spreading

6-1 Multiplexing

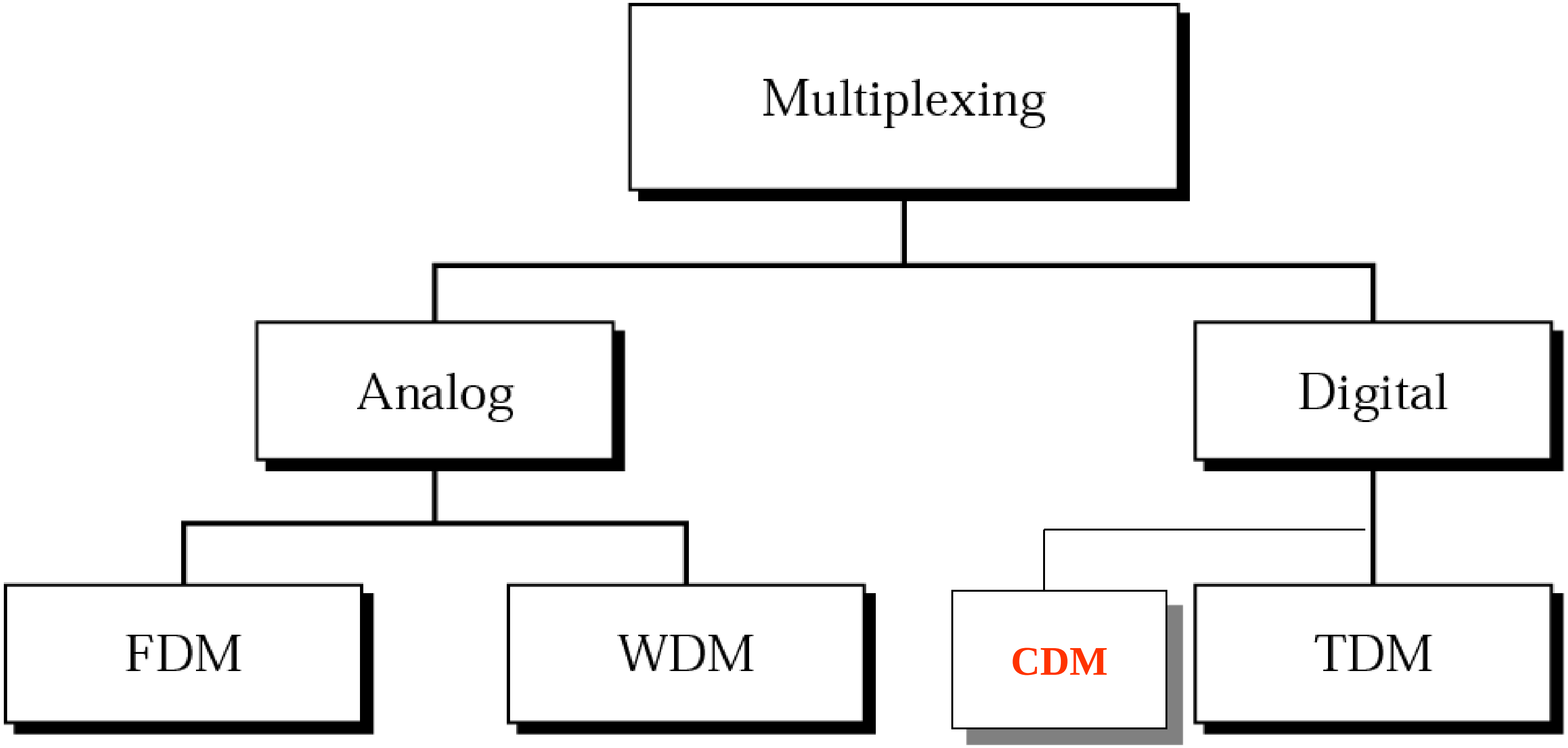
- ***Multiplexing is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link*. Multiplexing means breaking up a higher speed circuit into several slower circuits.**
- **The main advantage of multiplexing is cost; multiplexing is cheaper because fewer network circuits are needed.**
- **There are four categories of multiplexing:**
  - Time division multiplexing **(TDM)**
  - Statistical time division multiplexing **(STDM)**
  - Frequency division multiplexing **(FDM)**
  - **Code Division Mutliplexing (CDM)**
  - Wavelength division multiplexing **(WDM)**

DIVIDING A LINK INTO CHANNELS

- **Multiplexing**
  - **A set of techniques that allows the simultaneous transmission of multiple signals across a single data link.**
- **Multiplexer (MUX)**
  - **Combines multiple streams 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 correct lines.**



6-2 CATEGORIES OF MULTIPLEXING

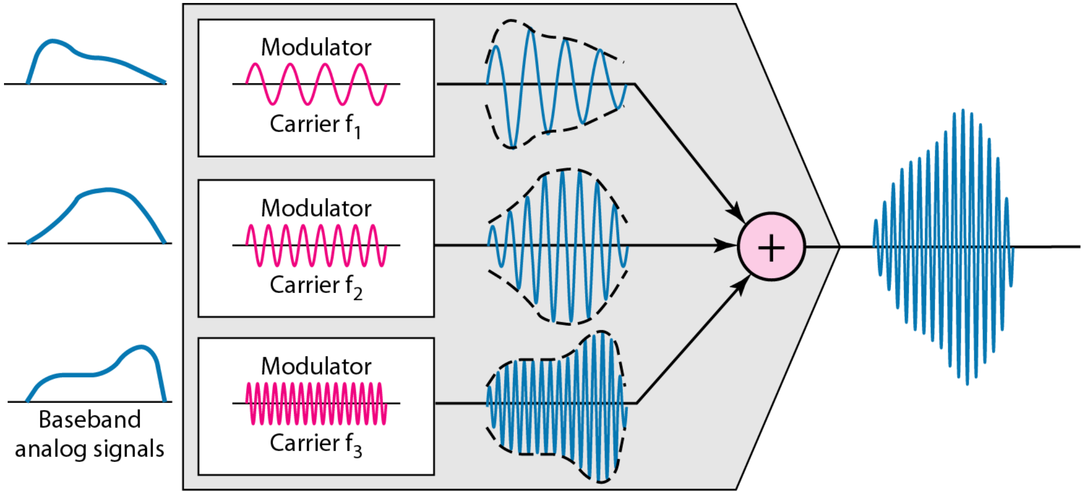


FREQUENCY DIVISION MULTIPLEXING (FDM)

- **Assigns different analog frequencies to each connected device**
- **Like Pure TDM,**
  - **mux-to-mux speed = aggregate terminal speeds**
  - **No loss of data so transparent to users and host/FEP**
- **Channels must be separated by strips of unused bandwidth - *guard bandwidth***

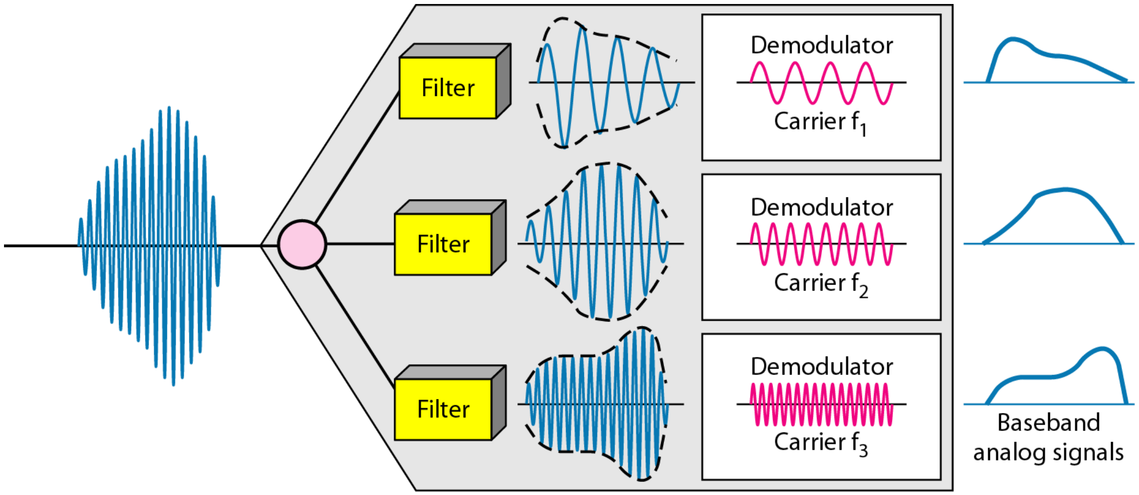
FDM PORCESS

- **Signals of each channel are modulated onto different carrier signal**
- **The resulting modulated signals are then combined into a single composite signal that is sent out over a media link**
- **The link should have enough bandwidth to accommodate it**



FDM DEMULTIPLEXING

- **Demultiplexer uses a series of filters to decompose the multiplexed signal into its constituent component signals**
- **The individual signals are then passed to a demodulator that separates them from their carriers and passes them to the waiting receivers**



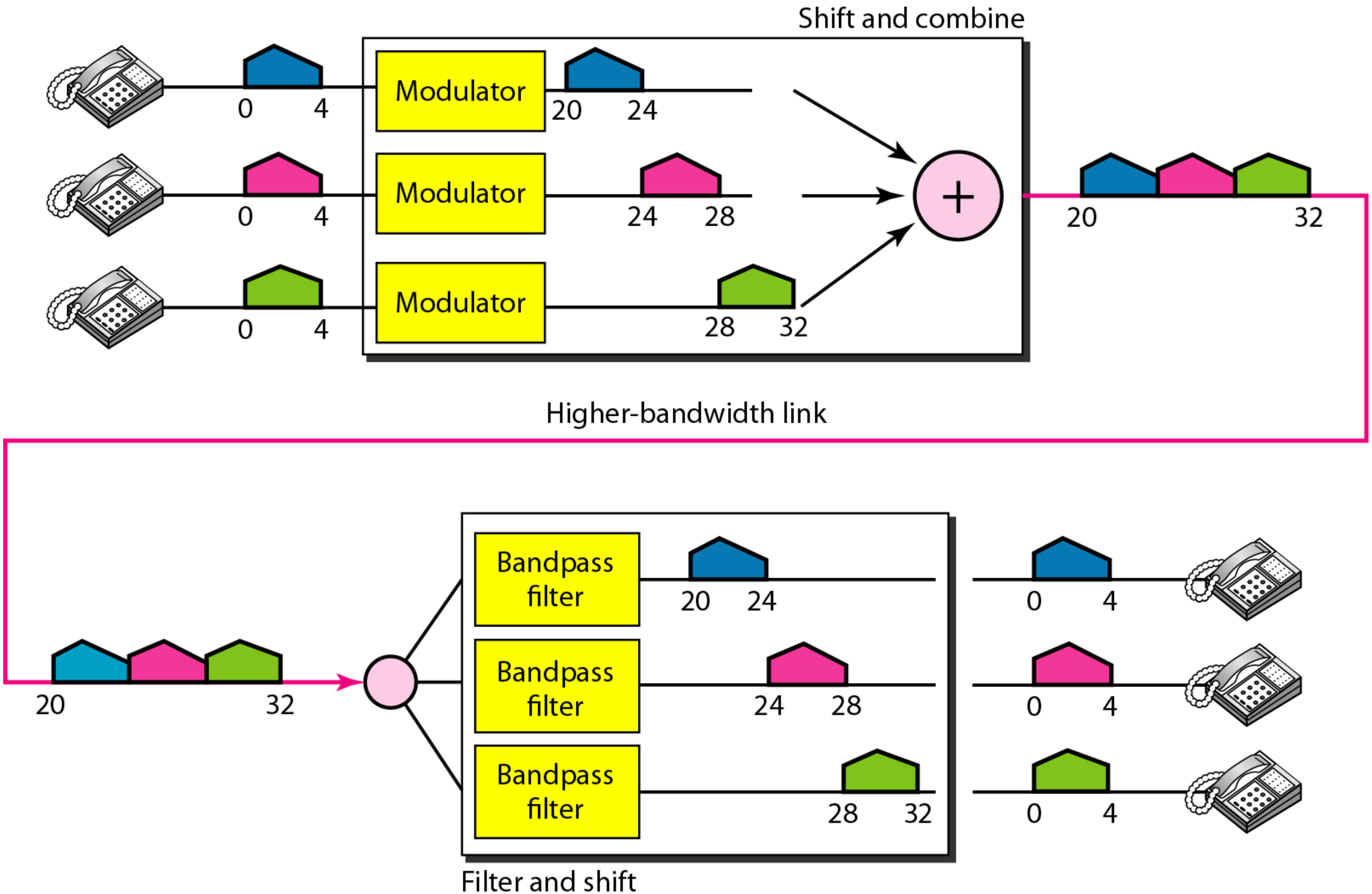
Example 6.1

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 without the use of 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

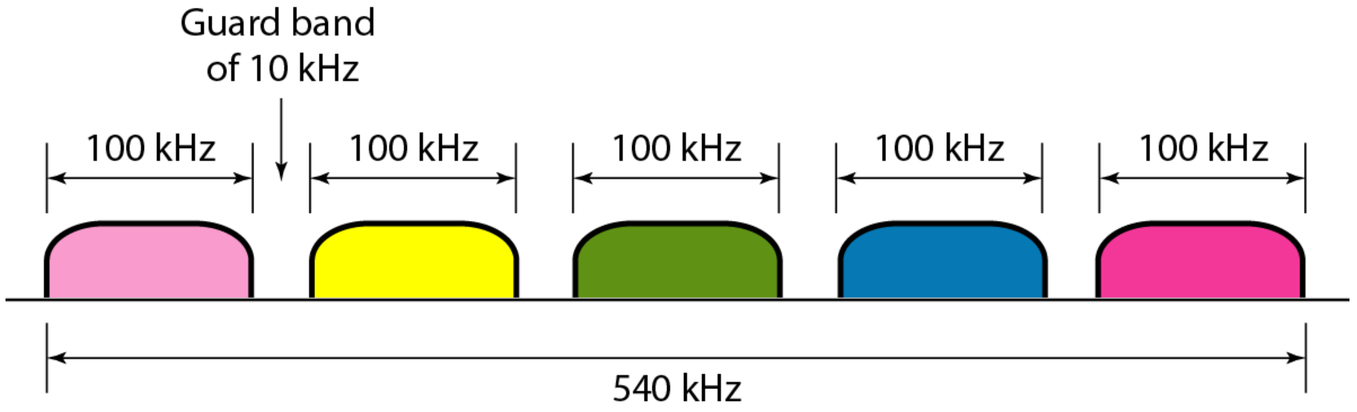
Five channels, each with a 100-KHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 KHz between the channels to prevent interference?

Solution

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

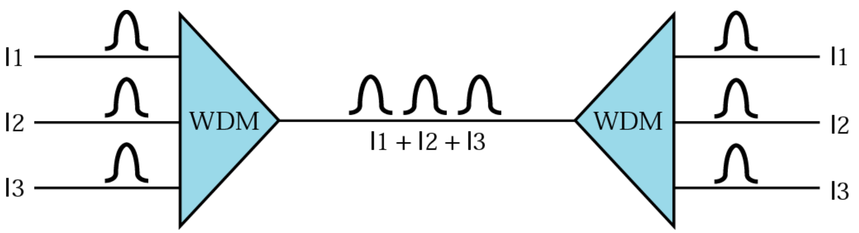
$$5 \times 100 + 4 \times 10 = 540 \text{ KHz},$$

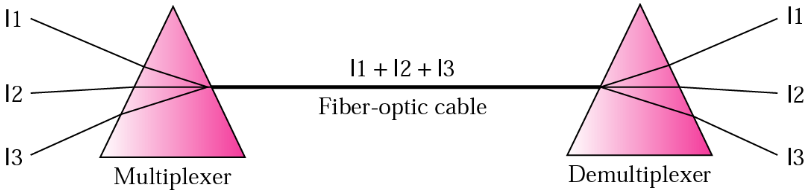
as shown in Figure of following slide.



WAVE DIVISION MULTIPLEXING (WDM)

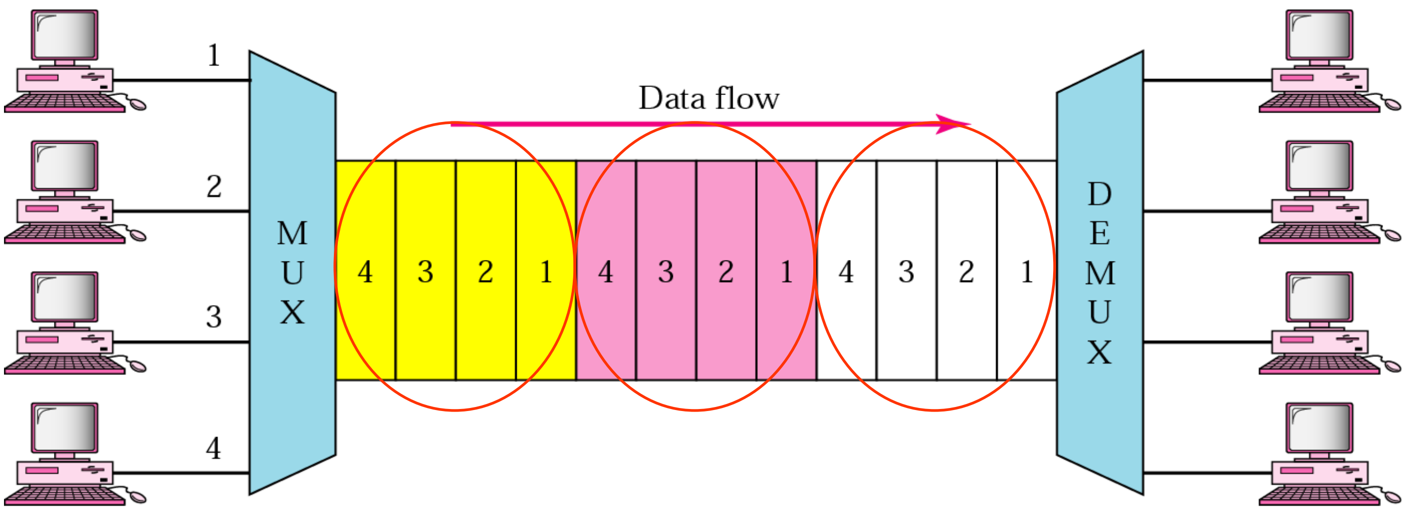
- An analog multiplexing technique to combine optical signals
- Multiple beams of light at different frequency
- Carried by optical fibber
- A form of FDM
- Each color of light (wavelength) carries separate data channel
- Commercial systems of 160 channels of 10 Gbps now available





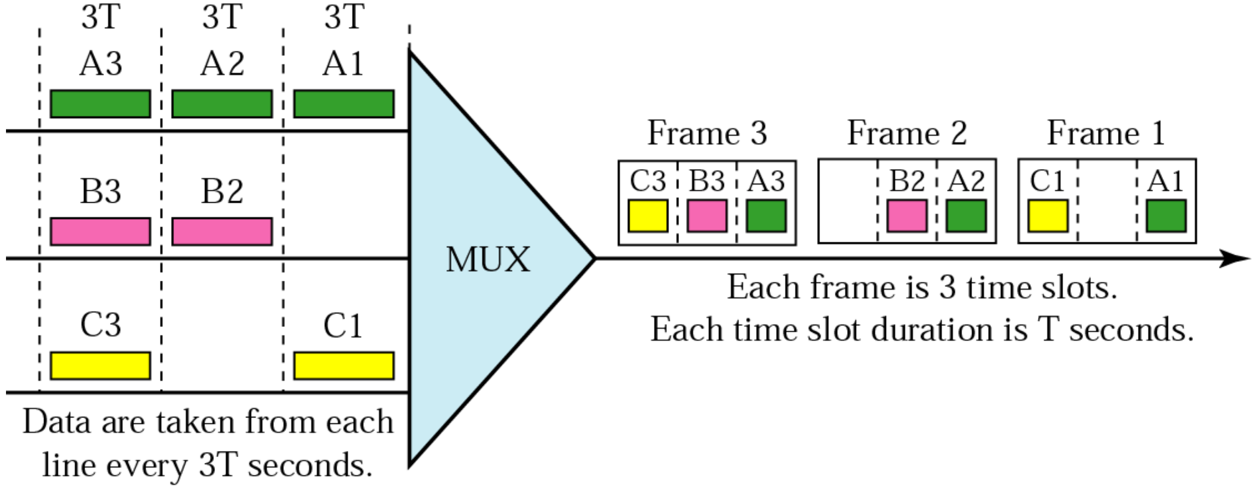
TIME DIVISION MULTIPLEXING (TDM)

- **Digital process that allows several connections to share the high bandwidth of a link**
- **Time Slots and Frames**
  - **Each terminal/host given a "slice" of time (time slot)**
  - **In TDM, a frame consists of one complete cycle of time slots, with one slot dedicated to each sending device.**



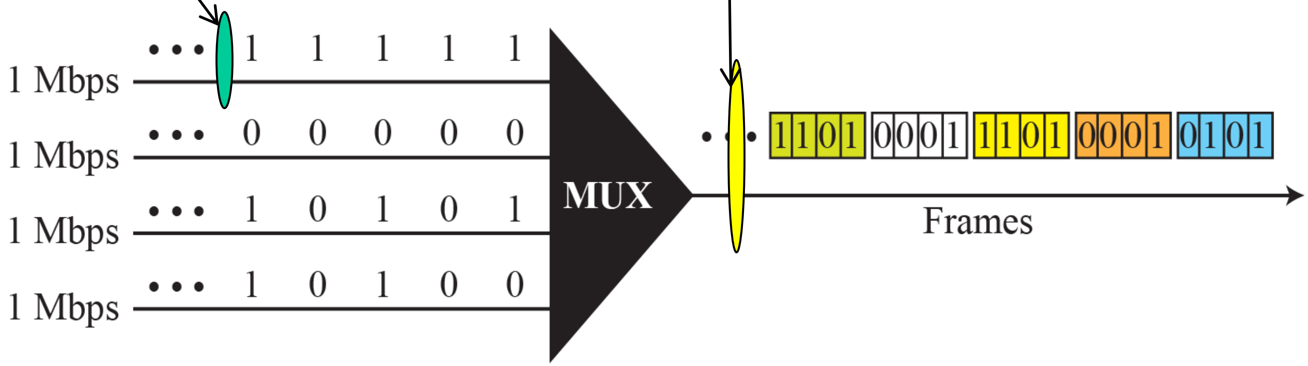
TDM FRAMES

- **Pure TDM: mux-to-mux speed = aggregate terminal speeds**
- **No loss of data (*similar to voice call multiplexing*)**



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.



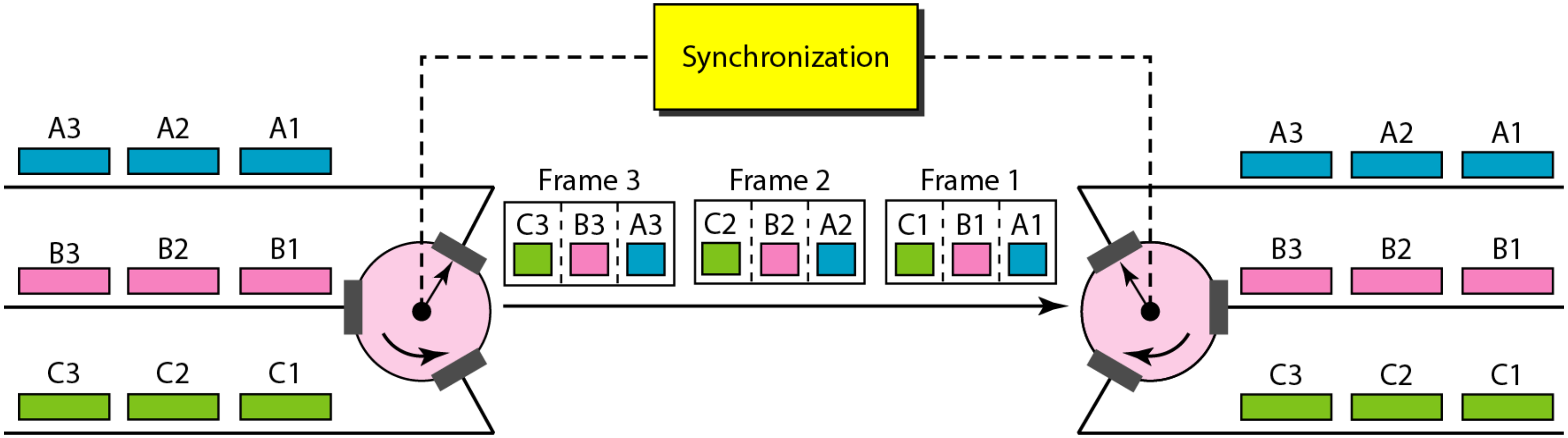
Solution

We can answer the questions as follows:

1. The input bit duration is the inverse of the bit rate: 1/1 Mbps = 1 μs.
2. The output bit duration is one-fourth of the input bit duration, or 1/4 μs.
3. The output bit rate is the inverse of the output bit duration, or 1/(1/4) μs 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.
4. 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.

INTERLEAVING

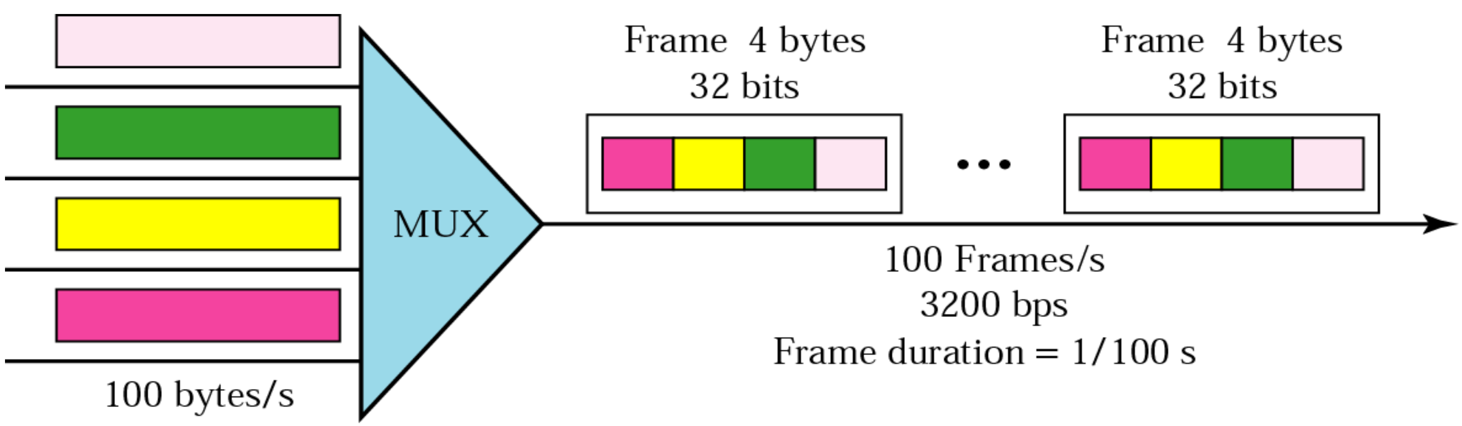
- Multiplexer/Demultiplexer process a terminal/host's unit in turn
- Character (byte) Interleaving
  - Multiplexing perform one/more character(s) or byte(s) at a time (one byte per unit)
- Bit Interleaving
  - Multiplexing perform on one bit at a time (one bit per unit)



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



Solution in detail

$$FrameSize = ChannelNumber \times UnitSize$$

$$= 4timeslot\,/\,frame \times 1byte\,/\,timeslot$$

$$= 4byte\,/\,frame = 32bit\,/\,frame$$

$$DataRate_{link} = 4 \times 100bytes\,/\sec ond$$

$$= 400 \times bytes\,/\sec ond = 3200bps$$

$$FrameRate_{link} = DataRate\,/\,FrameSize$$

$$= \frac{3200bit\,/\sec ond}{32bit\,/\,frame} = 100\,frame\,/\sec ond$$

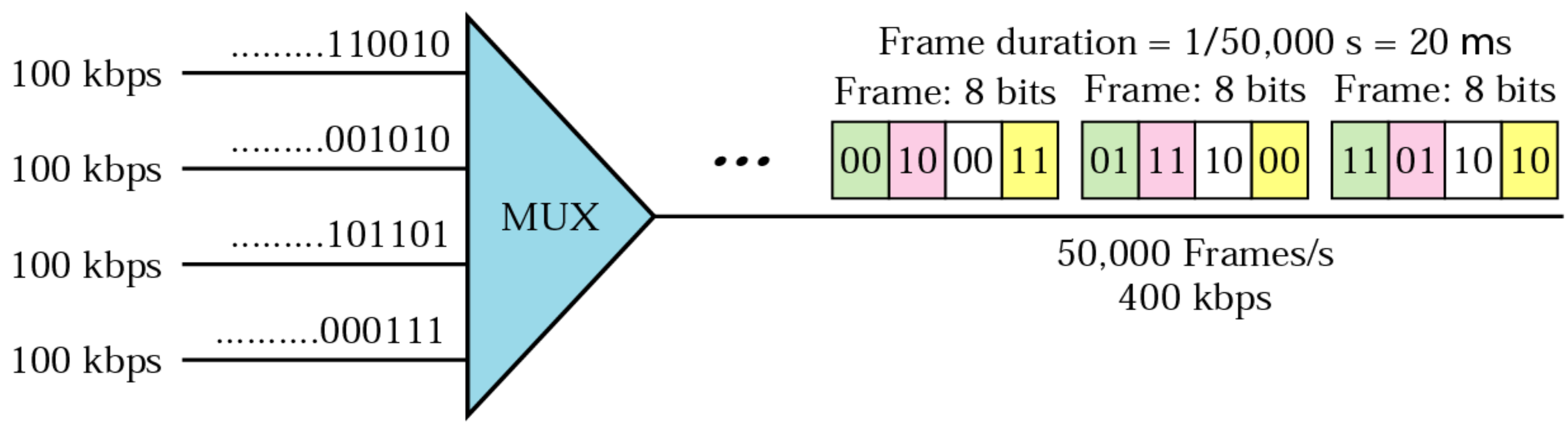
$$FrameDuration = \frac{1}{FrameRate}$$

$$= 10ms\,/\,frame$$

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



Solution in detail

$$FrameSize = ChannelNumber \times UnitSize$$
$$= 4 timeslot / frame \times 2 bit / timeslot = 8 bit / frame$$

$$DataRate_{link} = 4 \times 100 kbps = 400 kbps$$

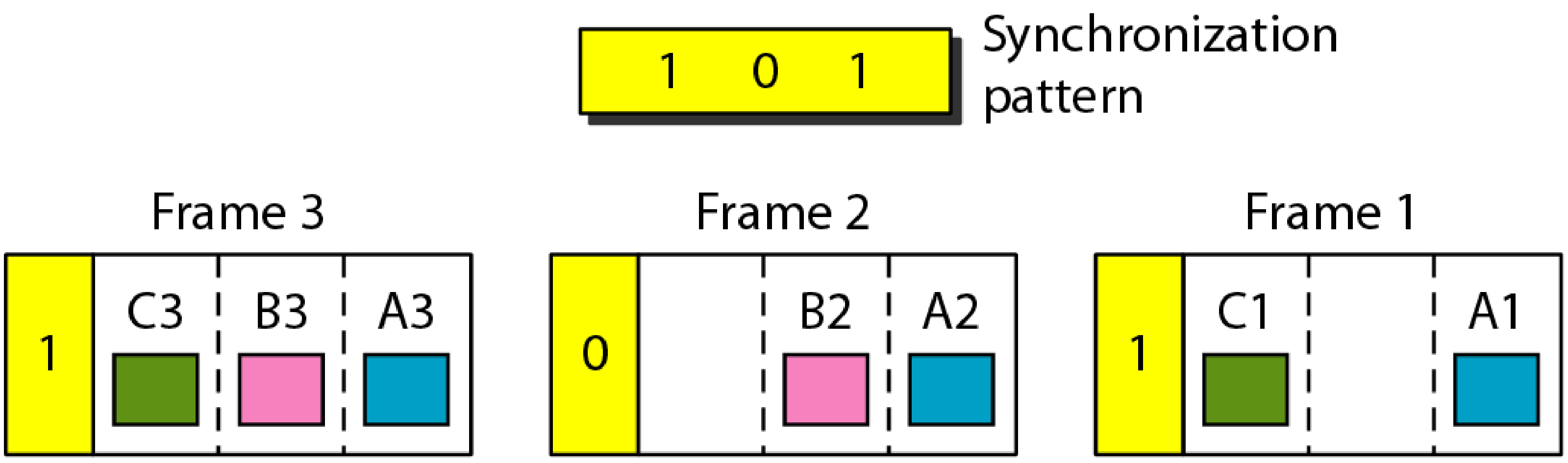
$$BitDuration_{link} = \frac{1}{BitRate} = \frac{1}{400k} \sec ond / bit$$

$$FrameRate_{link} = DataRate / FrameSize$$
$$= \frac{400 kbit / \sec ond}{8 bit / frame} = 50 kframe / \sec ond$$
$$= 50{,}000\ frame / \sec ond$$

$$FrameDuration = \frac{1}{FrameRate}$$
$$= \frac{1}{50{,}000\ frame / \sec ond} = 20 ms / frame$$

SYNCHRONIZING

- **One or more *Framing bit (s)* is (are) added to each frame for synchronization between the multiplexer and demultiplxer**
- **If 1 framing bit per frame, framing bits are alternating between 0 and 1**



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 (1) the data rate of each source, (2) the duration of each character in each source, (3) the frame rate of the multiplexed link, (4) the duration of each frame in the multiplexed link, (5) the number of bits in each frame, and (6) the data rate of the link.

Solution

See next slide.

Solution (continued)

We can answer the questions as follows:

1. The data rate of each source is 2000 bps = 2 Kbps.
2. The duration of a character is 1/250 s, or 4 ms.
3. The link needs to send 250 frames per second.
4. The duration of each frame is 1/250 s, or 4 ms.
5. Each frame is 4 x 8 + 1 = 33 bits.
6. The data rate of the link is 250 x 33, or 8250 bps.

Solution in detail

$$FrameSize = ChannelNumber \times UnitSize + Fra\min gBits$$
$$= 4timeslot\ /\ frame \times 1character\ / timeslot + 1bit\ /\ frame$$
$$= 33bits\ /\ frame$$

$$FrameRate = 250\ frame / \sec ond$$

$$DataRate = FrameRate \times FrameSize$$
$$= 250\ frame / \sec ond \times 33bits\ /\ frame$$
$$= 8250bit\ / \sec ond$$

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 frame duration is 1/100,000 s, or 10 us. The bit rate is 100,000 frames/s x 3 bits/frame, or 300 Kbps.

Solution in detail

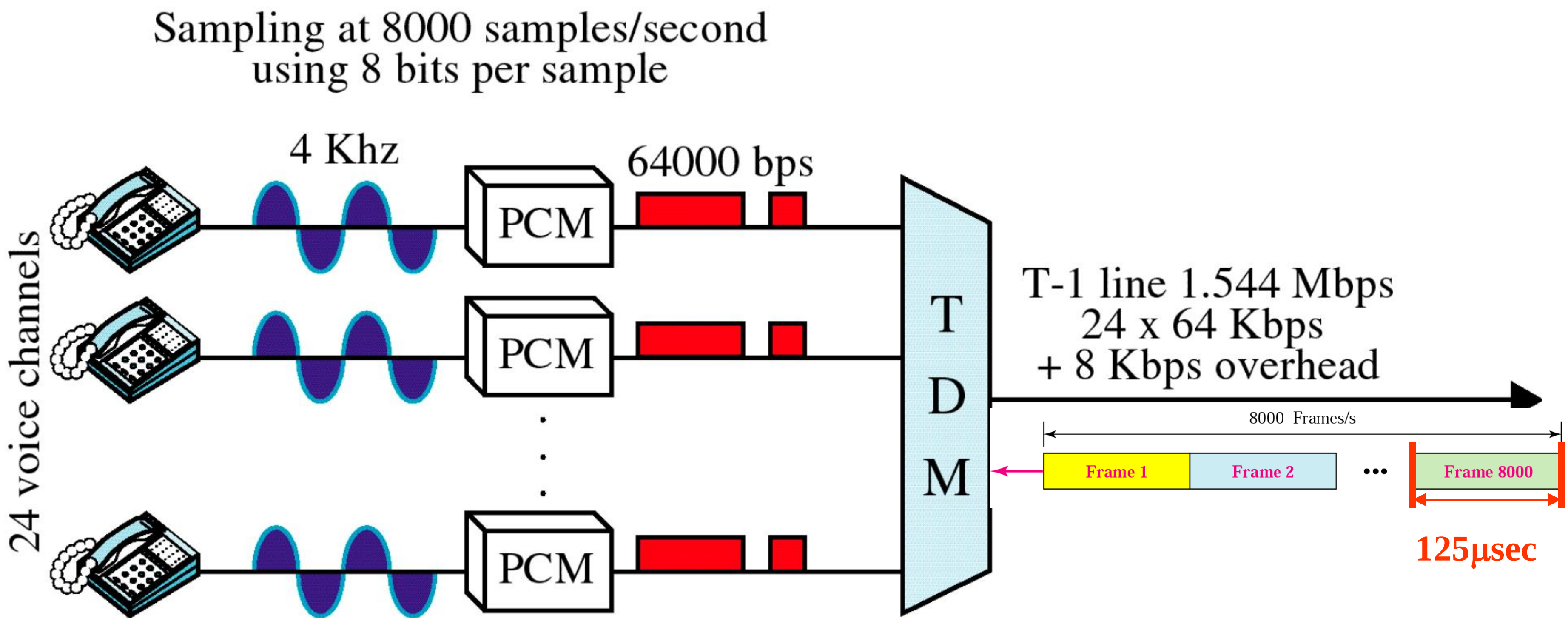
$$DataRate_{link} = 100kbps + 200kbps = 300kbps$$

$$FrameSize = UnitSize_1 + UnitSize_2$$
$$= 3bit / frame$$

$$FrameRate_{link} = DataRate / FrameSize$$
$$= \frac{300kbit / \sec ond}{3bit / frame} = 100kframe / \sec ond$$
$$= 100{,}000\ frame / \sec ond$$

$$FrameDuration = \frac{1}{FrameRate}$$
$$= \frac{1}{100{,}000\ frame / \sec ond} = 10\mu s / frame$$

Example of Multiplexing : T-1 Line



Selfwork: Check E-1 Multiplexing

Figure 6.23 *Digital hierarchy*

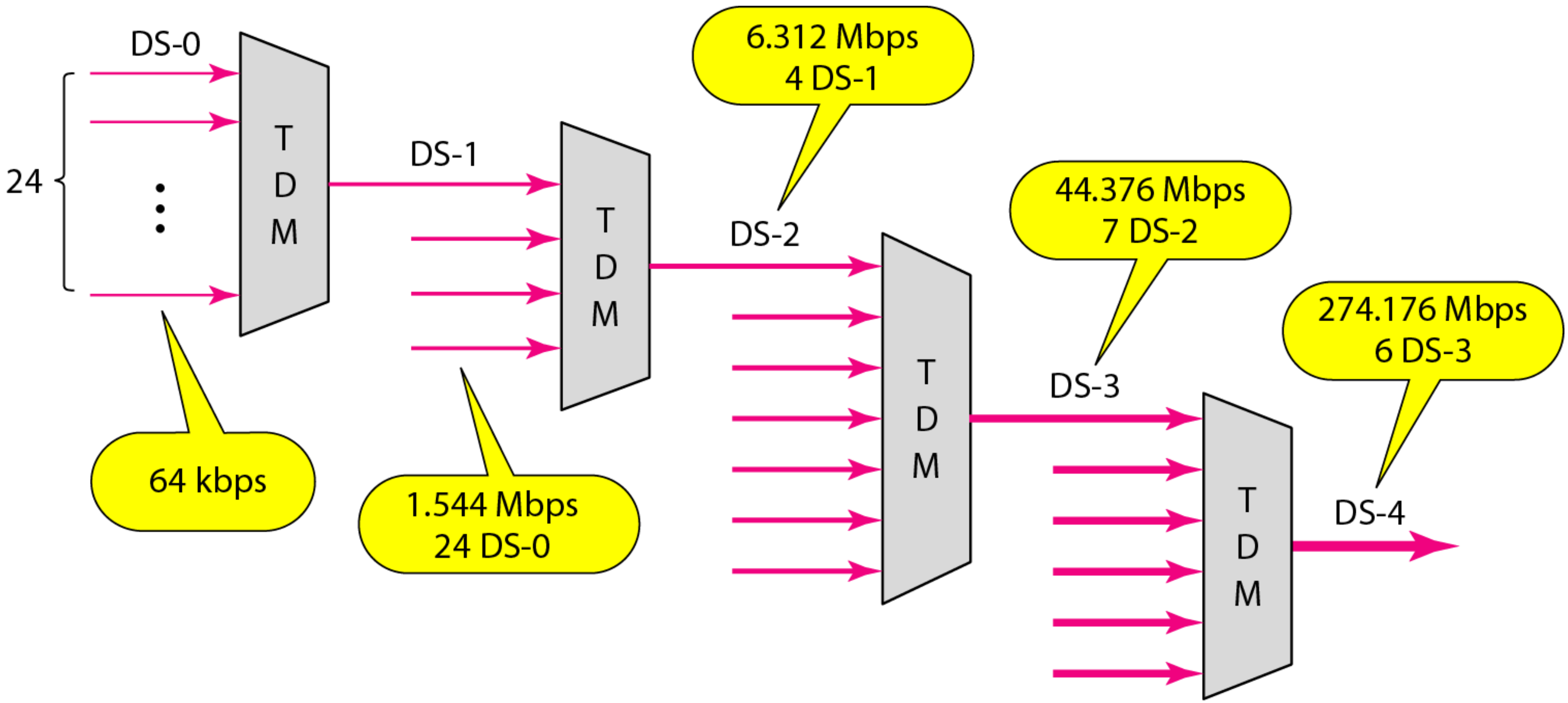


Table 6.1 ***DS and T line rates***

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*

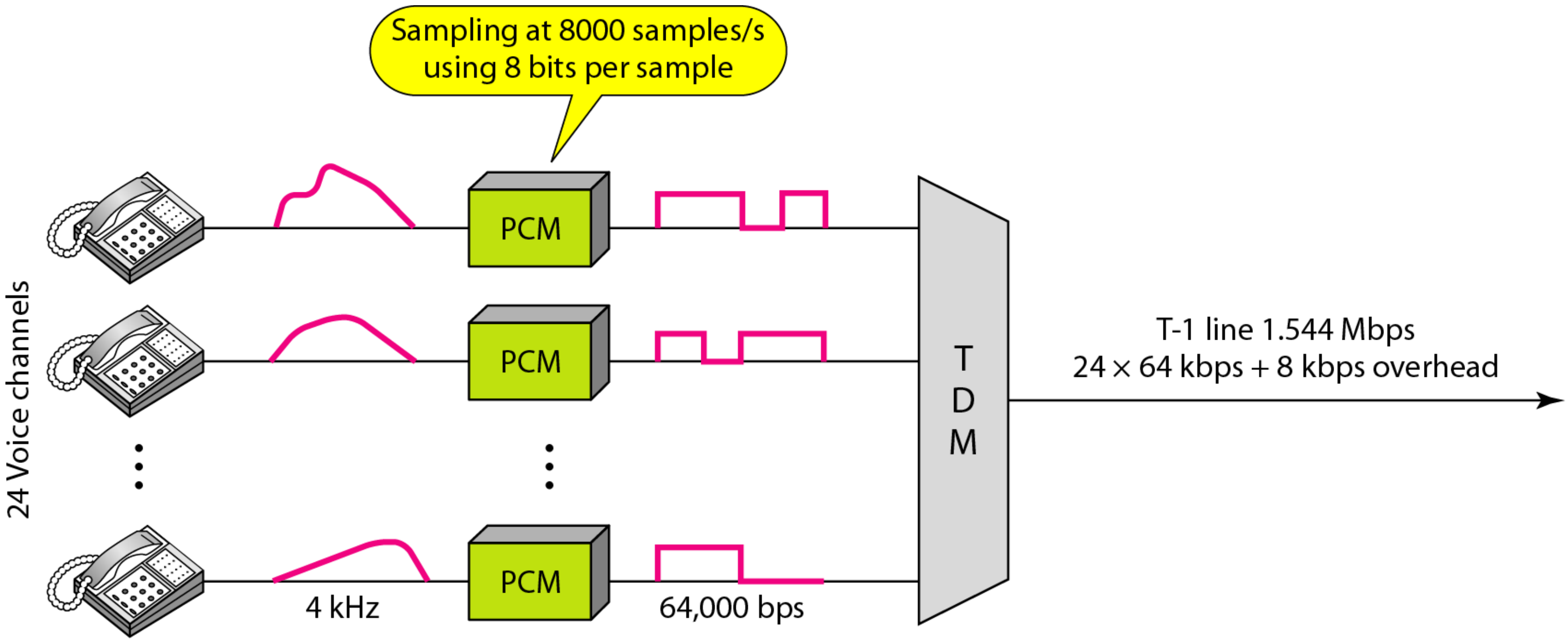
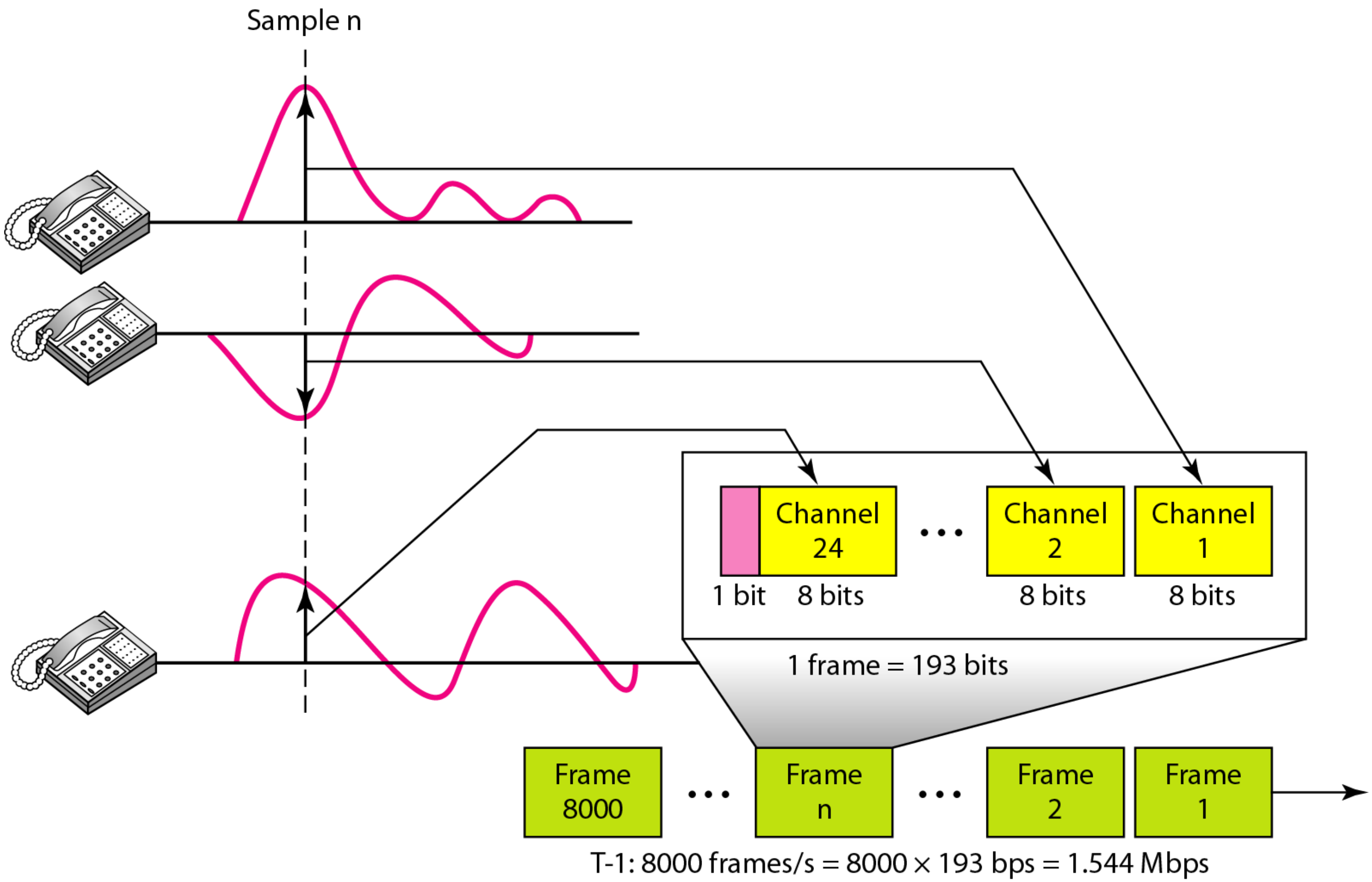
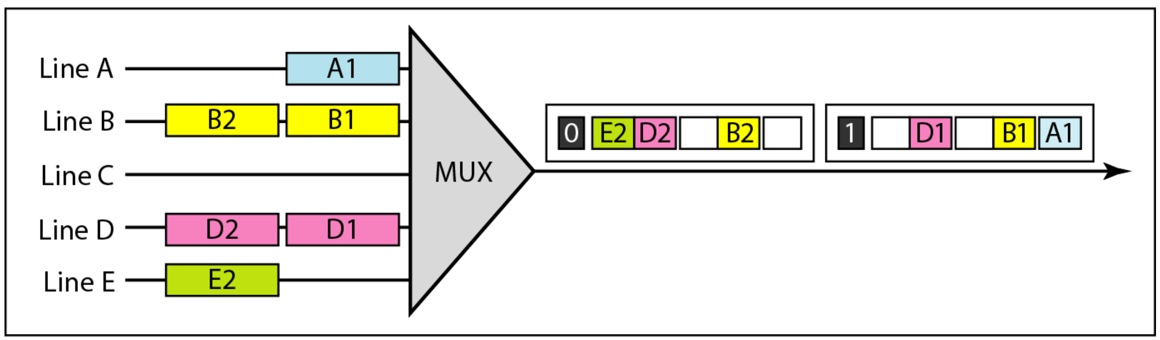


Figure 6.25 *T-1 frame structure*

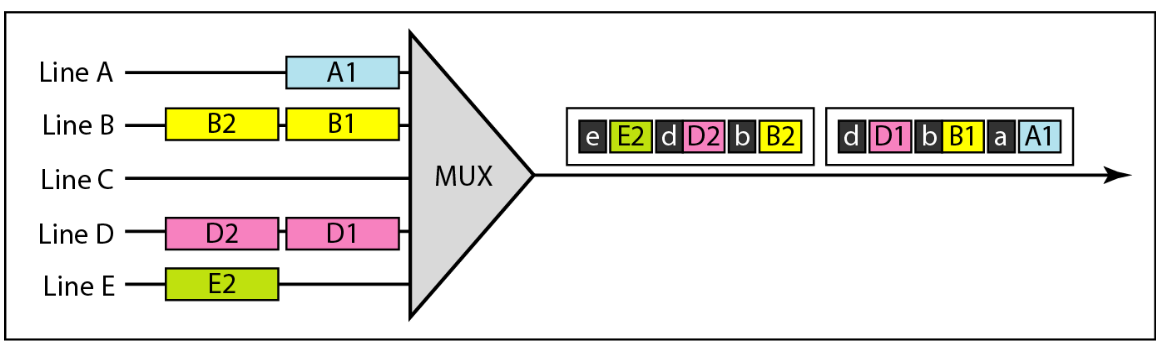


STATISTICAL TDM (STDM)

- **Mux-to-Mux speed < aggregate terminal/host speeds**
- **Time slots allocated based on traffic patterns**
  - **uses statistics to determine allocation among users**
  - **must send port address with data (takes additional time slots)**



a. Synchronous TDM



b. Statistical TDM

So why use a stat mux?

- **May Potential loss of data during peak periods**
  - **may use data buffering and/or flow control to reduce loss**
- **Not always transparent to user terminals and host/FEP**
  - **delays and data loss possible**
- **So why use a stat mux?**
  - **more economical - need fewer muxes, cheaper lines**
  - **more efficient - allows more terminals to share same line**
  - **OK to use in many situations (e.g., terminal users**

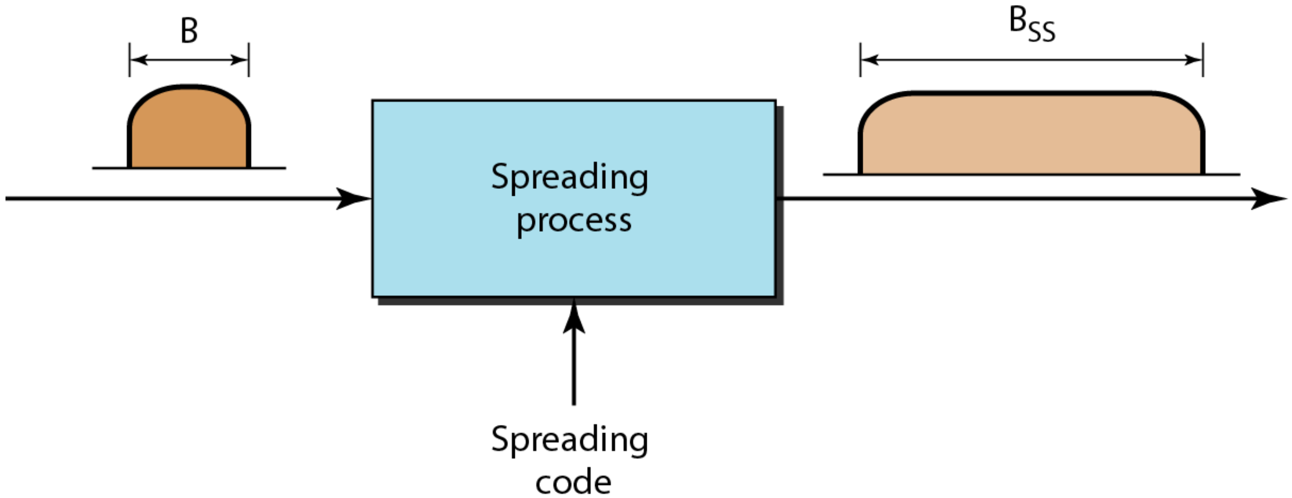
6-2 SPREAD SPECTRUM

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 Synchronous (DSSS)

Frequency Hopping Spread Spectrum (FHSS)



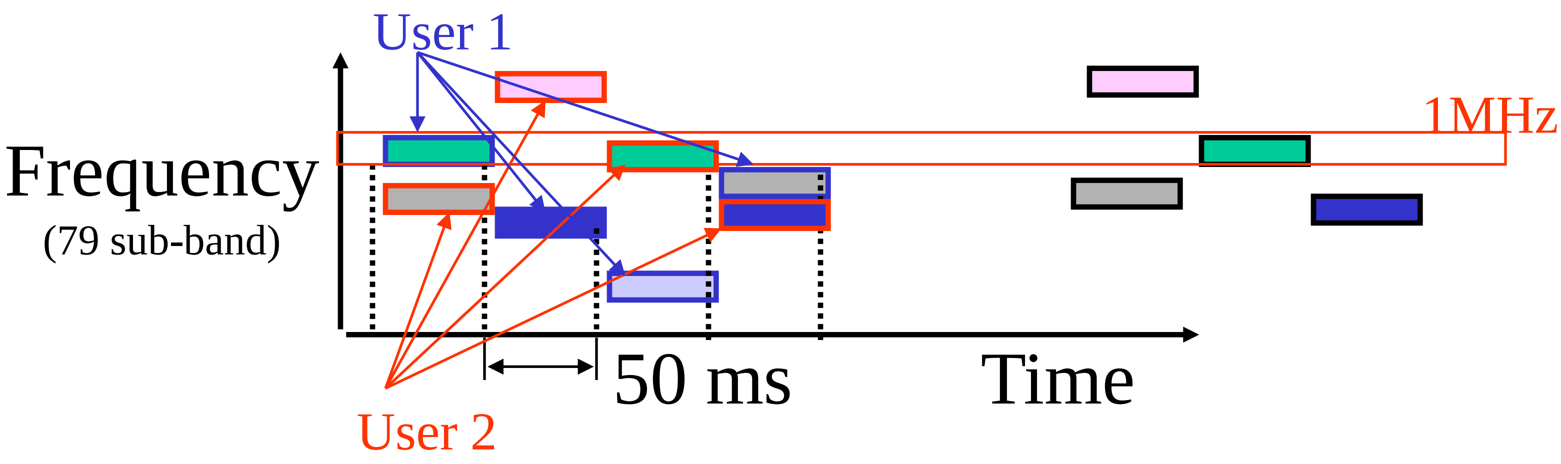


Figure 6.30 *FHSS cycles*

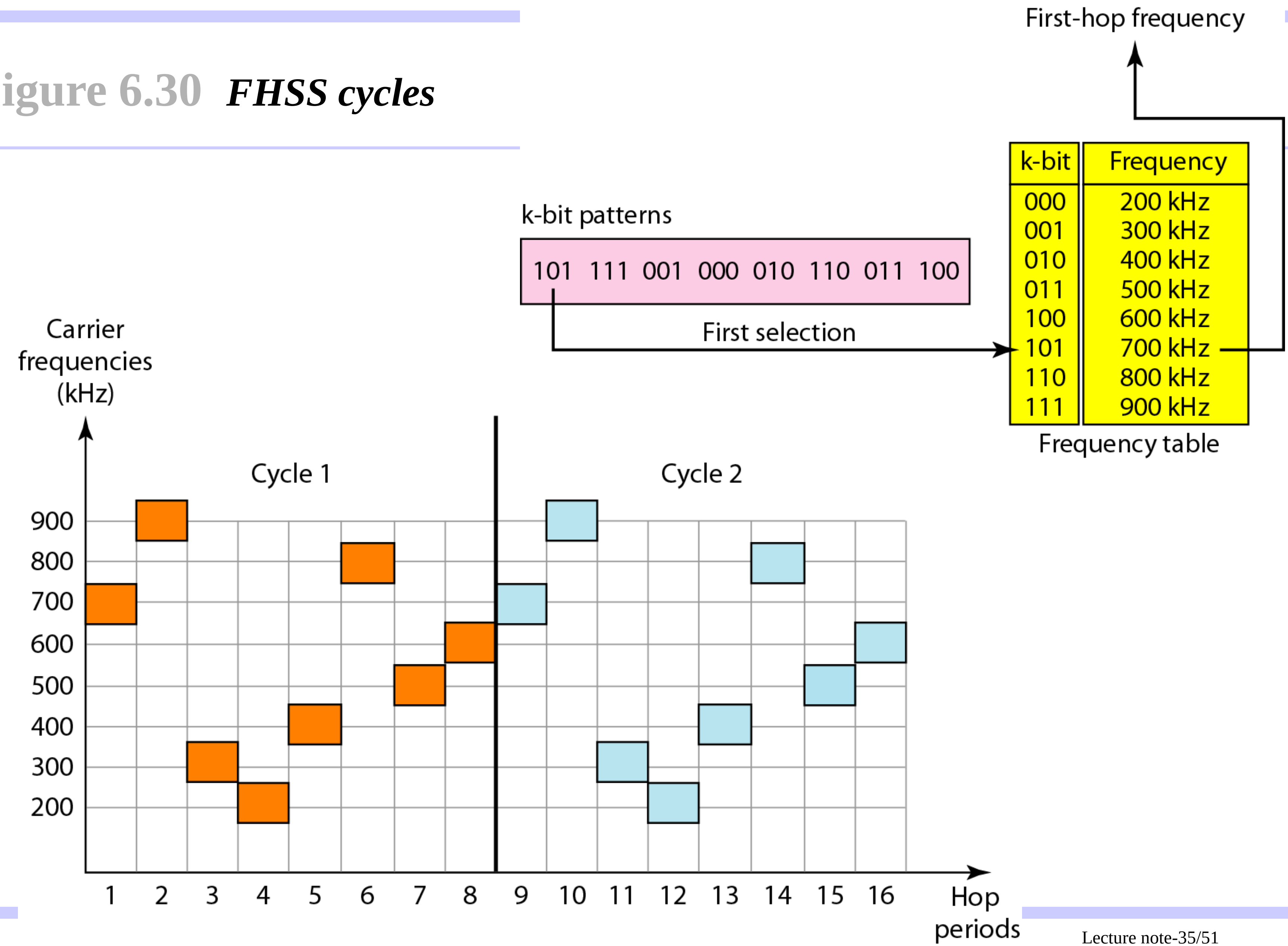
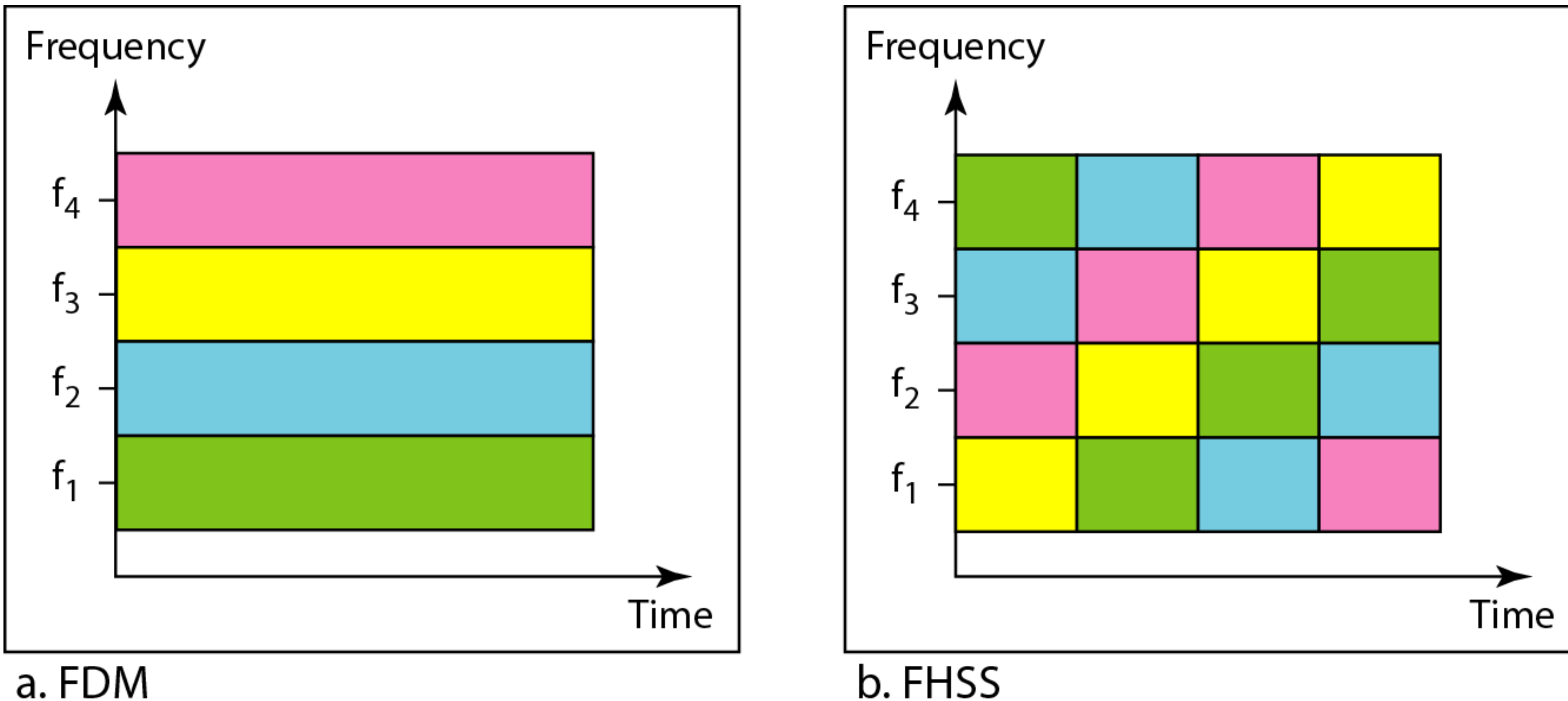
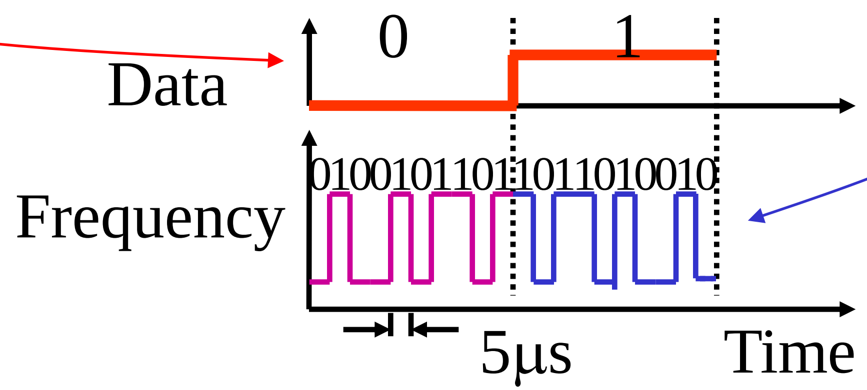


Figure 6.31 *Bandwidth sharing*



DS-SS

- Direct Sequence Spread Spectrum (DSSS)
- **Data stream is added (mod 2) to chipping (spreading) sequence of a higher rate**
- **Modulated data has much higher rate**
- **11-chip Barker sequence**
  - **+1,-1,+1,+1,-1,+1,+1,+1,-1,-1,-1**
  - **1 Mb/s data results in 11 Mb/s signal**
  - **Processing gain of 11**



Example of Encode/Decode