



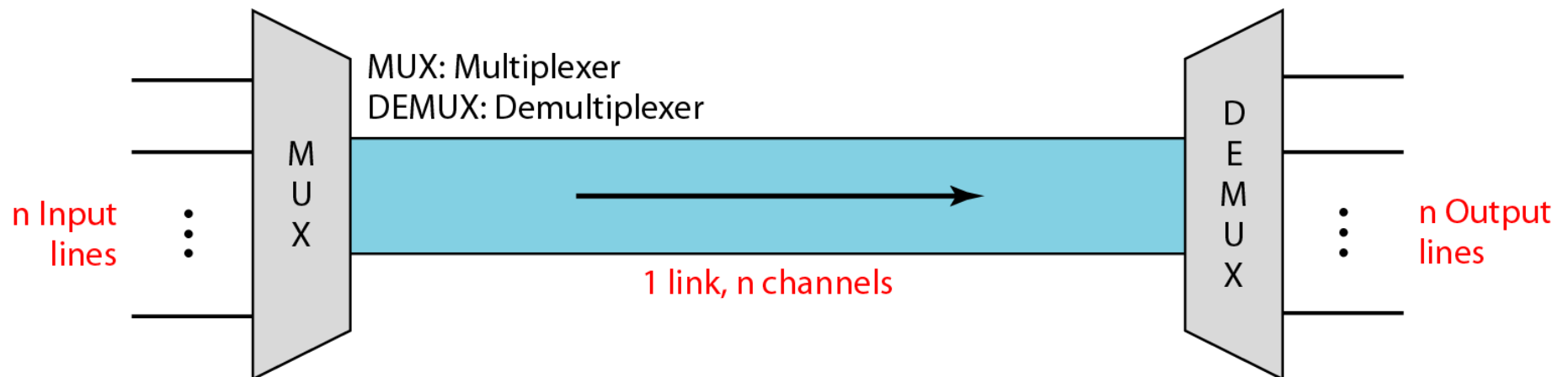
Data Communication

#10 Multiplexing

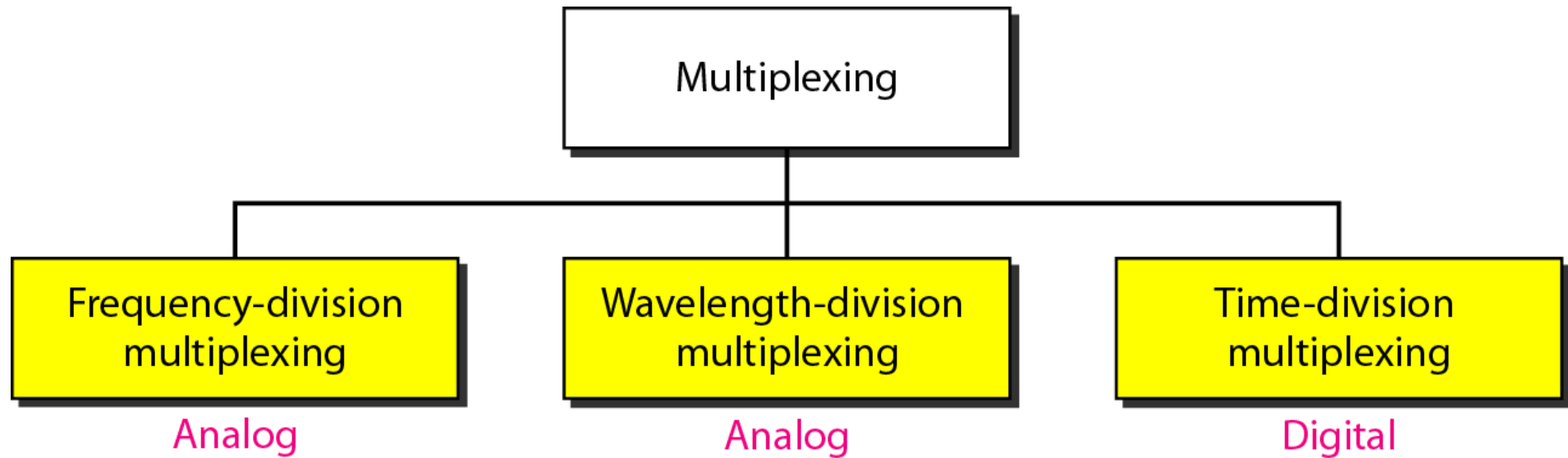
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Multiplexing

- **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.



Categories of Multiplexing

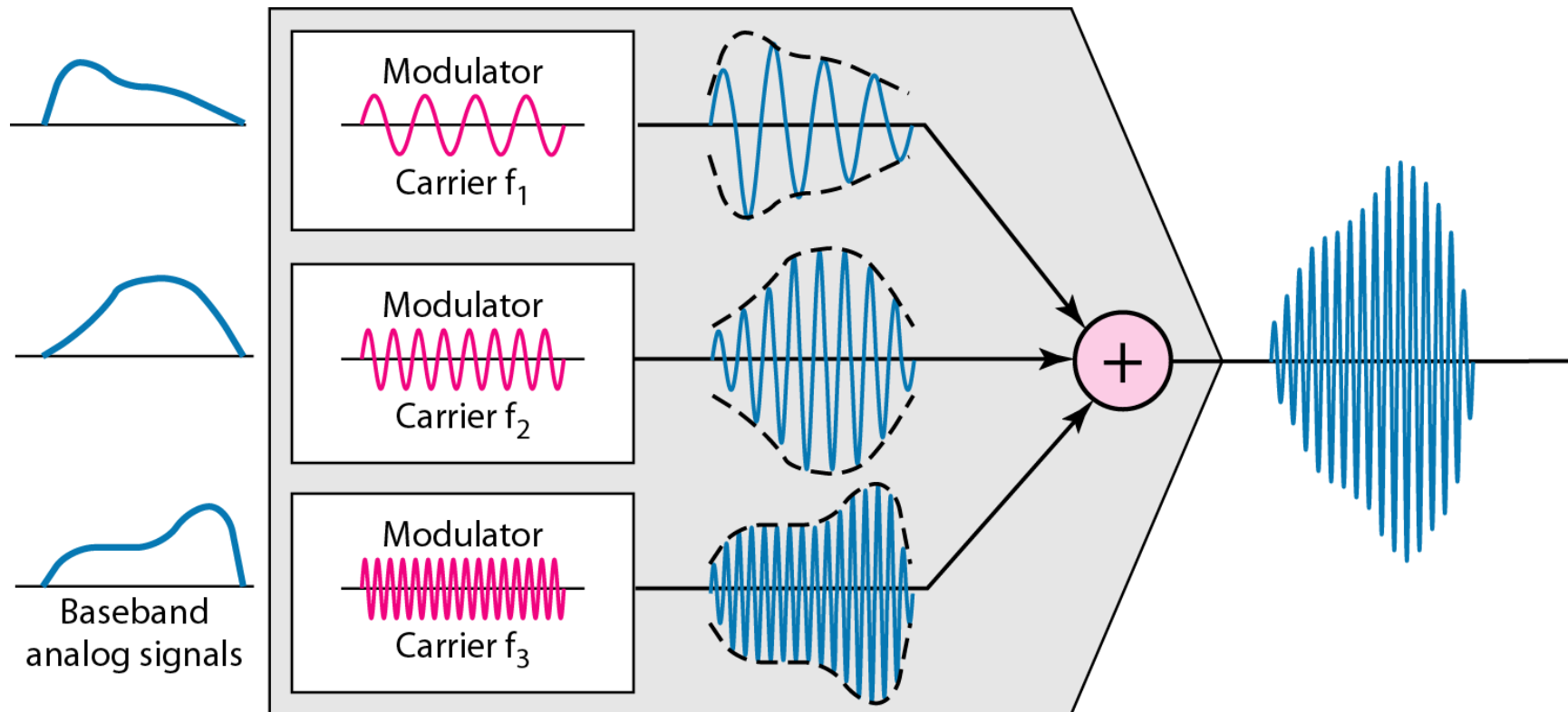


Frequency Division Multiplexing

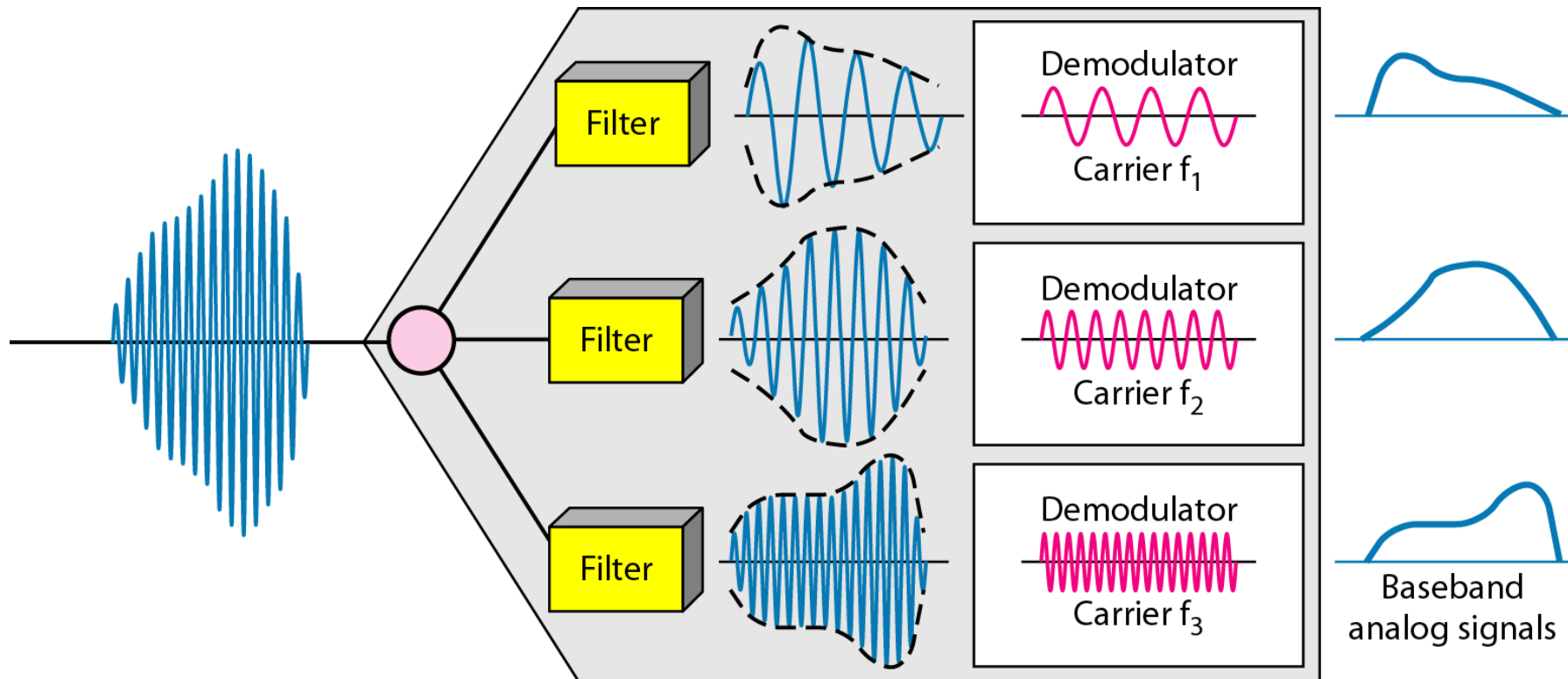


- FDM is an analog multiplexing technique that combines analog signals.

FDM Process



FDM Demultiplexing

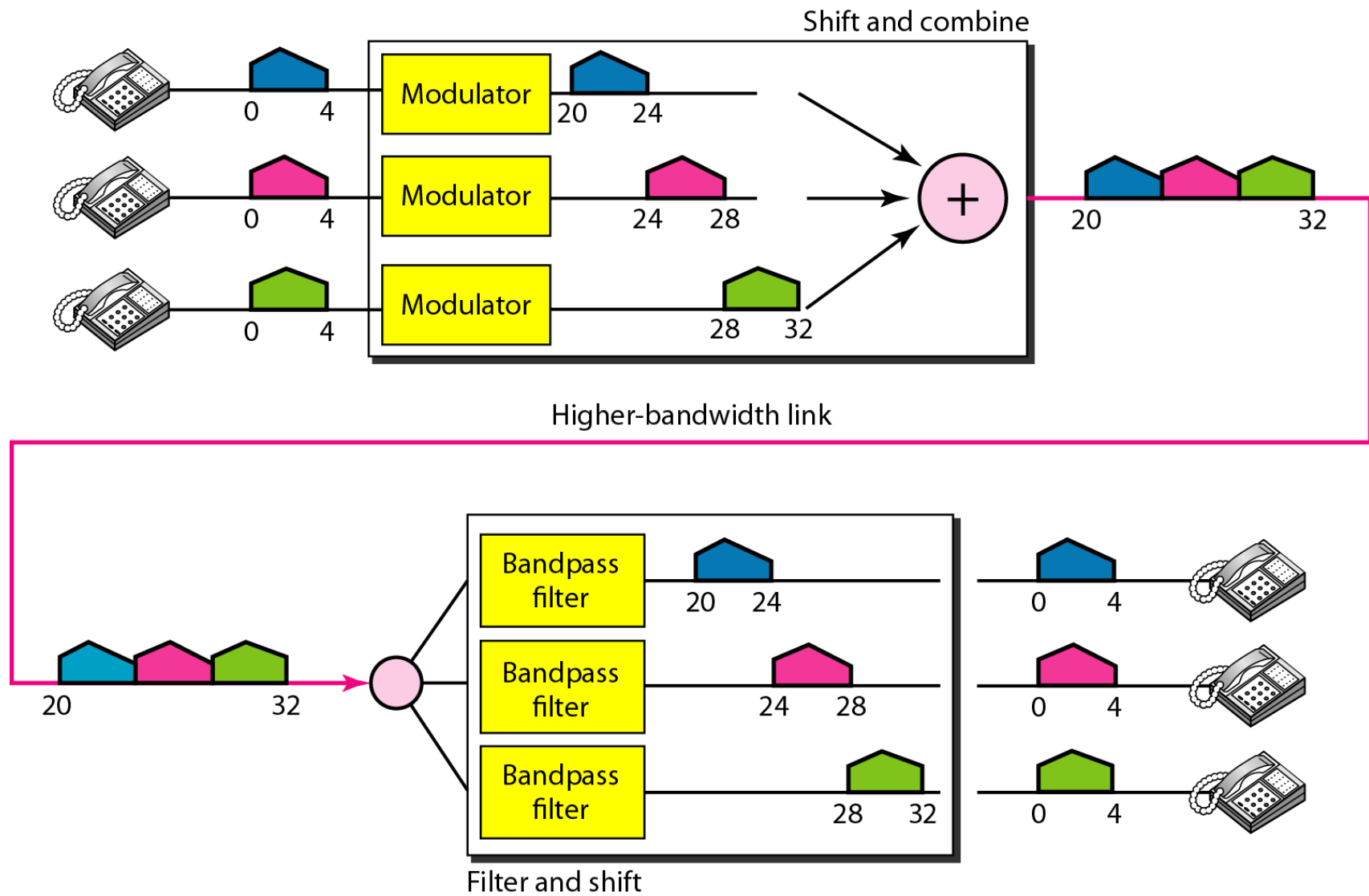


Example

- 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 below.

- 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 below.



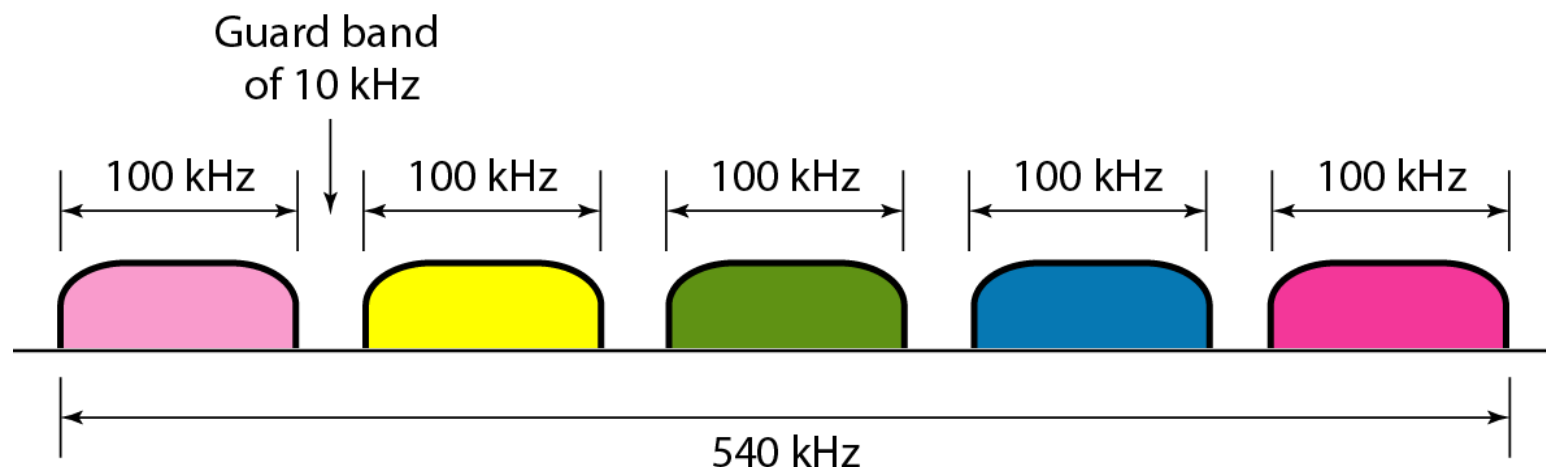
Example

- 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.

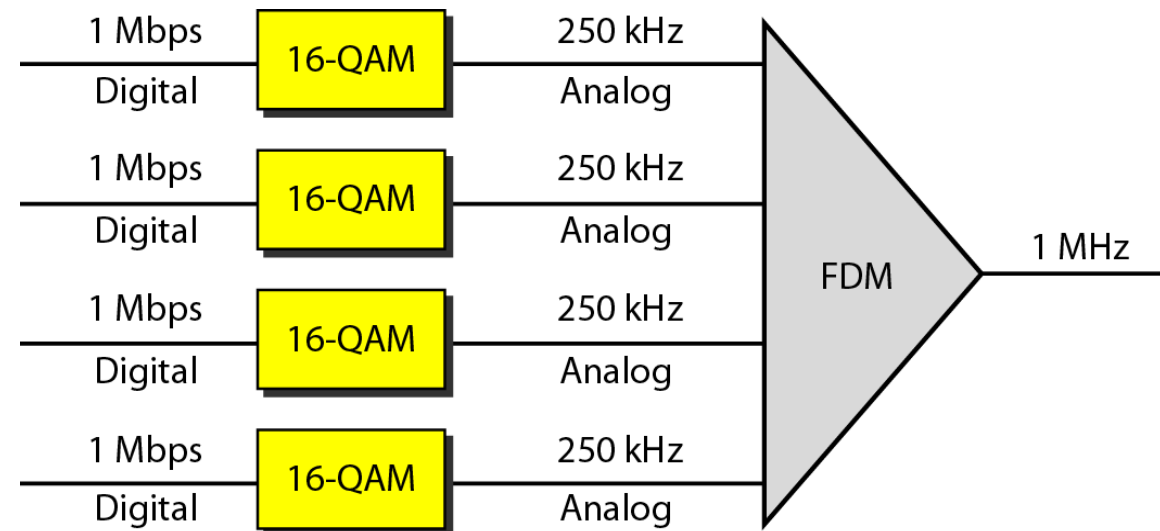


Example

- Four data channels (digital), each transmitting at 1 Mbps, use a satellite channel of 1 MHz. Design an appropriate configuration, using FDM.

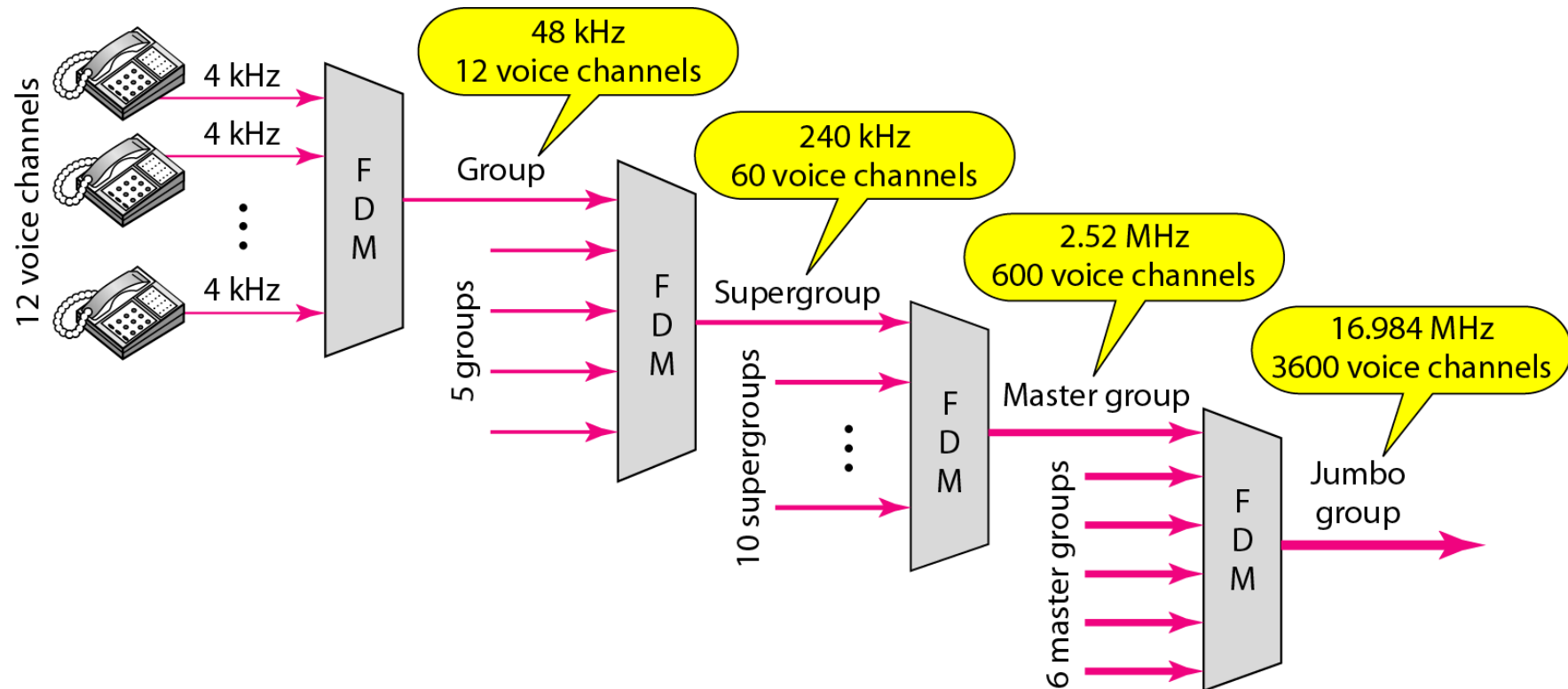
- Solution**

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.



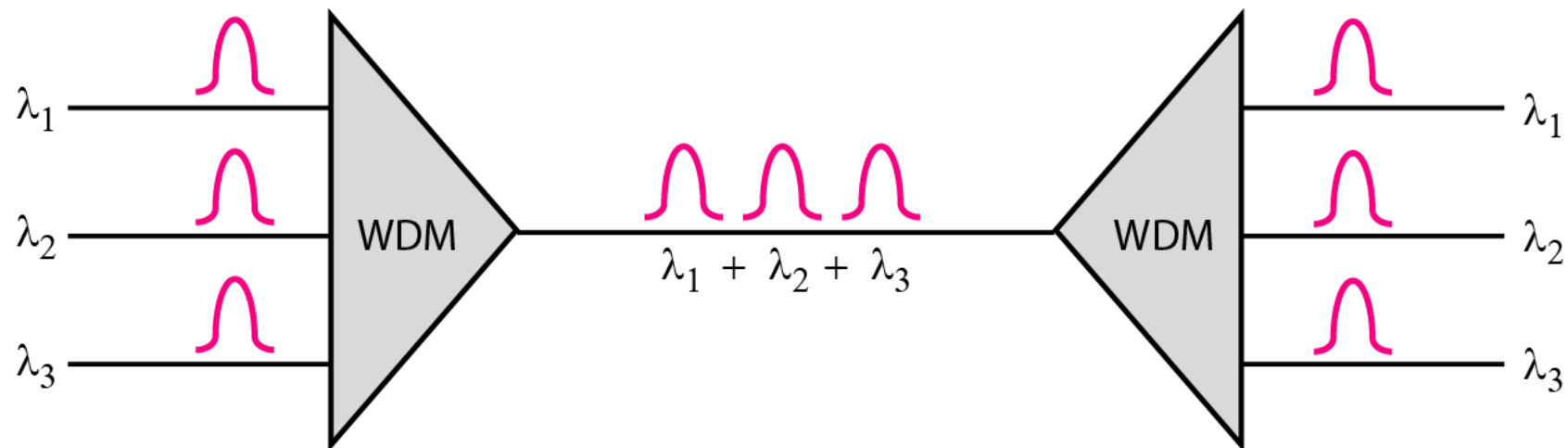
- A very common application of FDM is AM and FM radio broadcasting. Radio uses the air as the transmission medium. A special band from 530 to 1700 kHz is assigned to AM radio. All radio stations need to share this band. As discussed in Chapter 5, each AM station needs 10kHz of bandwidth. Each station uses a different carrier frequency, which means it is shifting its signal and multiplexing. The signal that goes to the air is a combination of signals. A receiver receives all these signals, but filters (by tuning) only the one which is desired. Without multiplexing, only one AM station could broadcast to the common link, the air. However, we need to know that there is physical multiplexer or demultiplexer here. 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.
- 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 voice signal, which has a bandwidth of 3 kHz (from 300 to 3300 Hz), is modulated by using FM. Remember that an FM signal has a bandwidth 10 times that of the modulating signal, which means each channel has 30 kHz (10×3) of bandwidth. Therefore, each user is given, by the base station, a 60-kHz bandwidth in a range available at the time of the call.

Analog Hierarchy

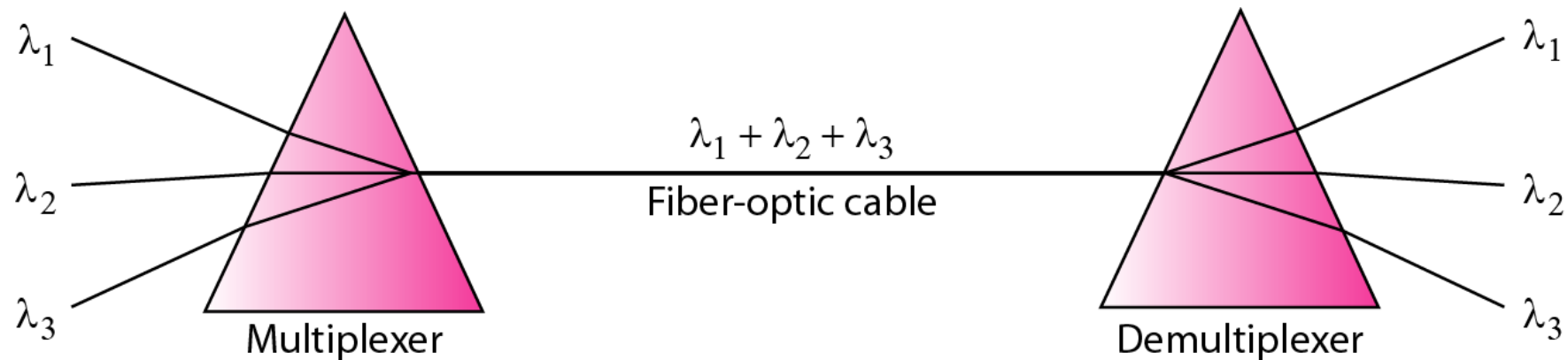


Wavelength Division Multiplexing (WDM)

- WDM is an analog multiplexing technique to combine optical signals.
- 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



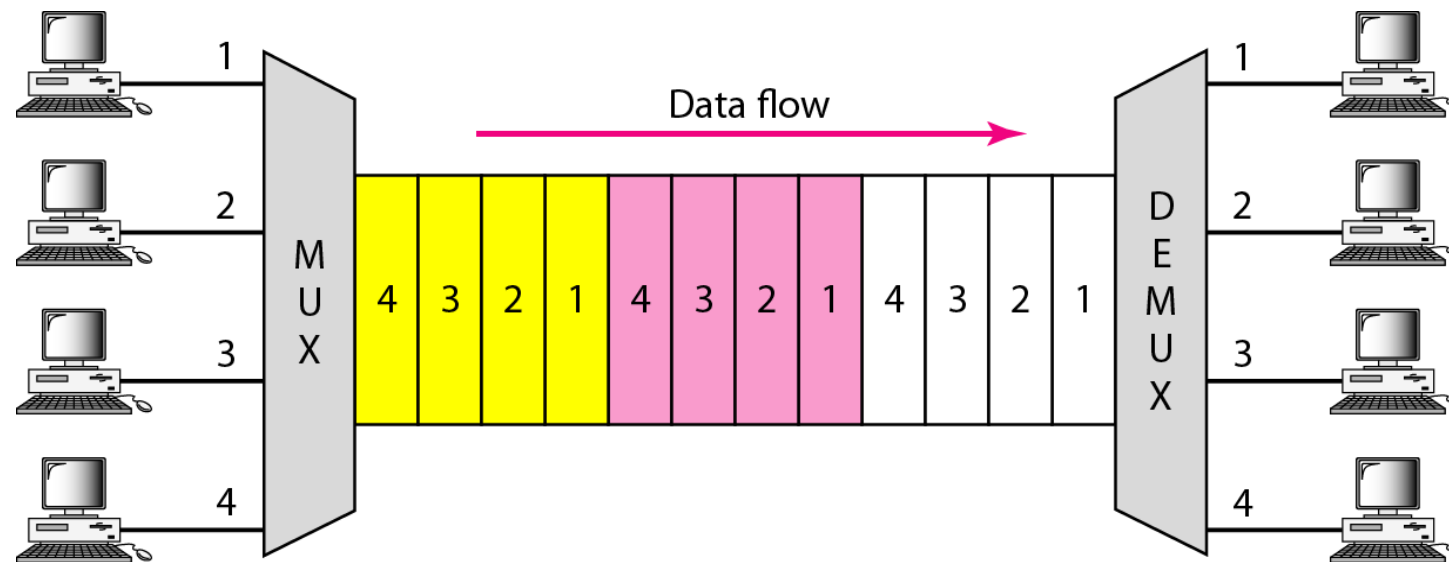
- Prism in wavelength division multiplexing



- One application of WDM is the SONET network in which multiple optical fiber lines are multiplexed and demultiplexed.
- A new method, called dense WDM (DWDM), can multiplex a very large number of channels by spacing channels very close to one another. It achieves even greater efficiency.

Time Division Multiplexing

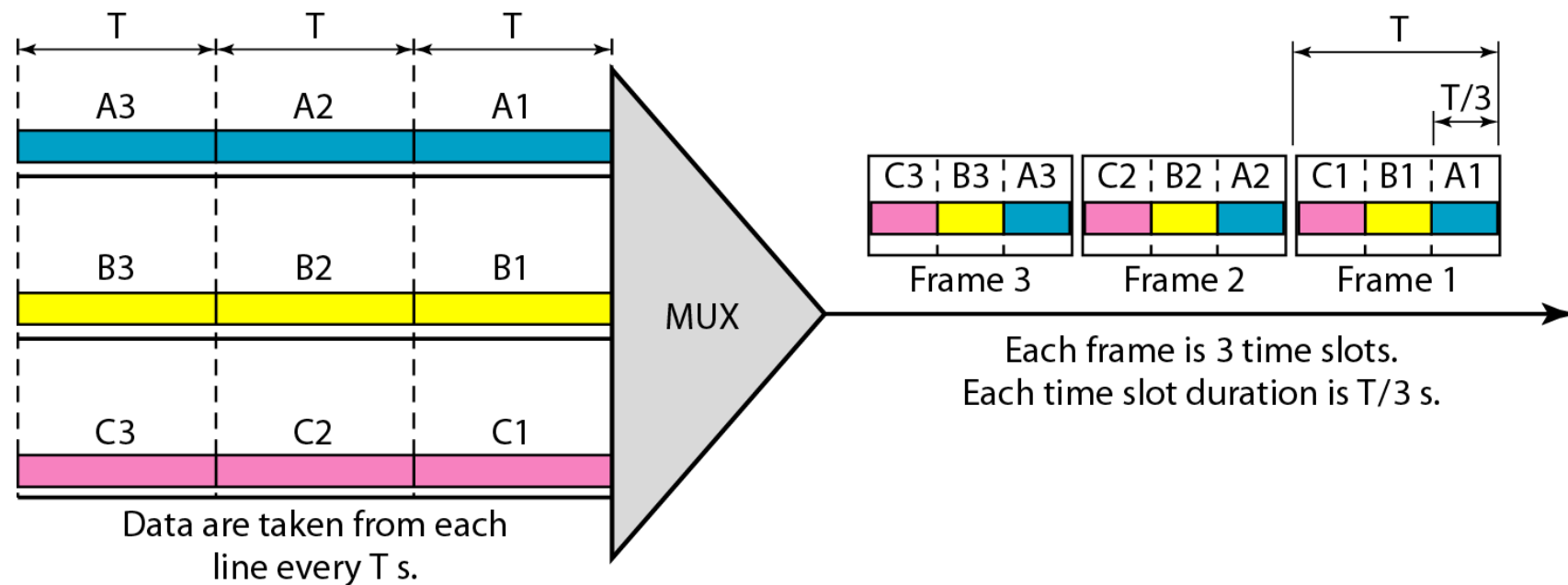
- TDM is a digital multiplexing technique for combining several low-rate channels into one high-rate one.



- We can divide TDM into two different schemes: **synchronous** and **statistical**. We first discuss synchronous TDM and then show how statistical TDM differs. In synchronous TDM, each input connection has an allotment in the output even if it is not sending data.

Synchronous Time Division Multiplexing

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



Example

- In Figure above, the data rate for each input connection is 3 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).
- 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. The duration of a frame is the same as the duration of an input unit.

Example

- Figure 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

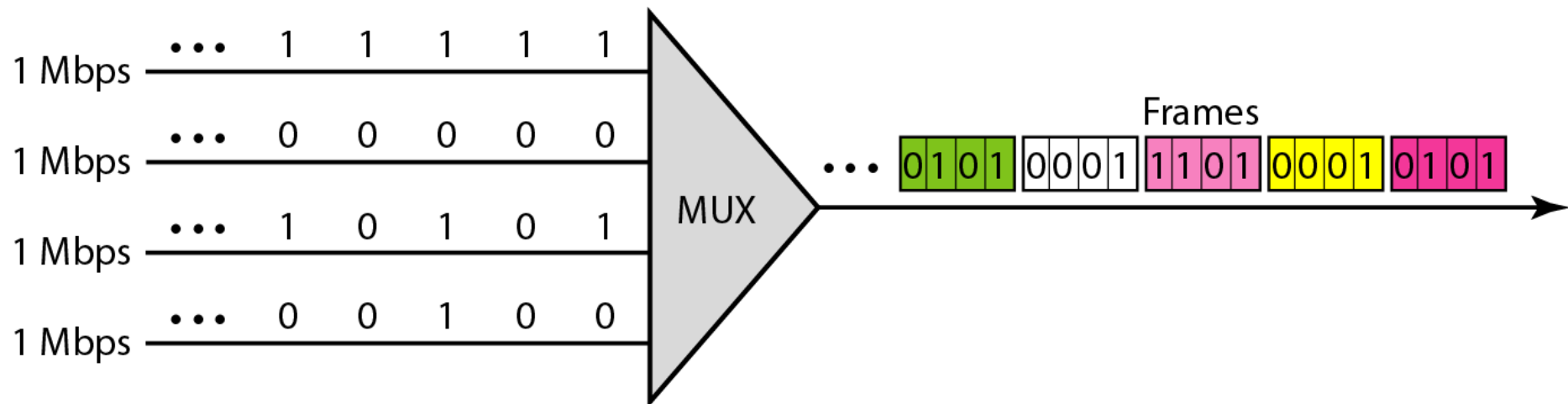
We can answer the questions as follows:

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

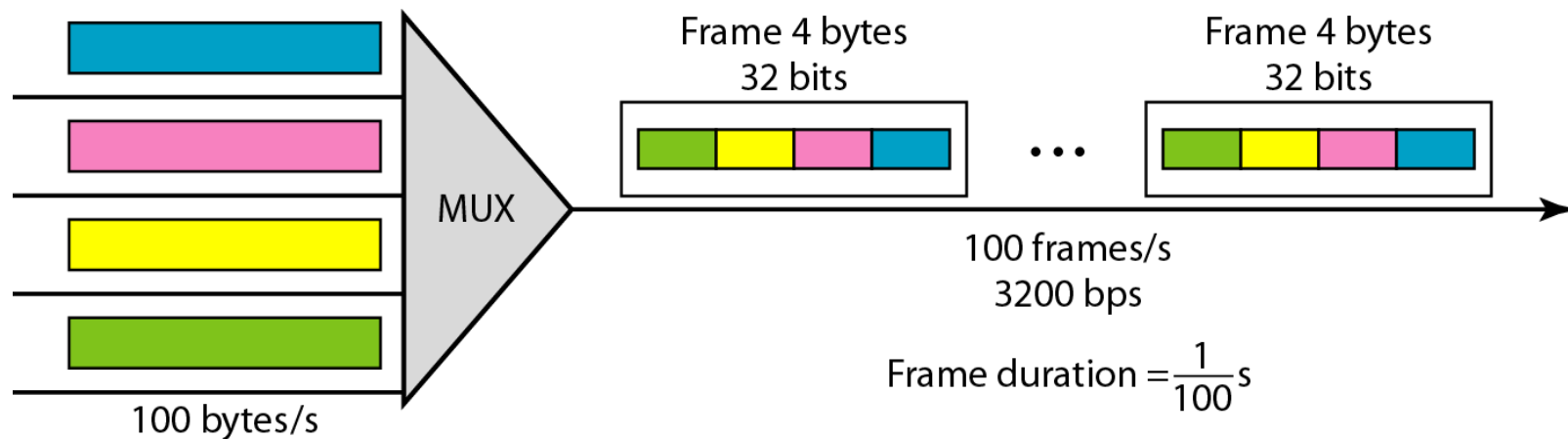
We can answer the questions as follows:

- a. The duration of 1 bit before multiplexing is $1 / 1 \text{ kbps}$, or 0.001 s (1 ms).
- b. The rate of the link is 4 times the rate of a connection, or 4 kbps.
- 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.



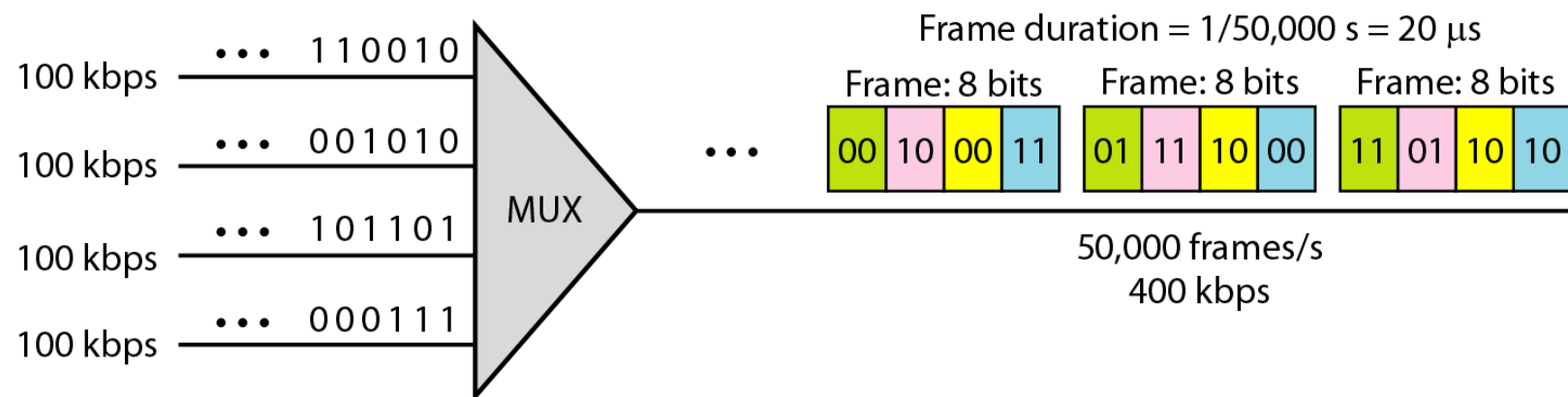
Example

- 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.

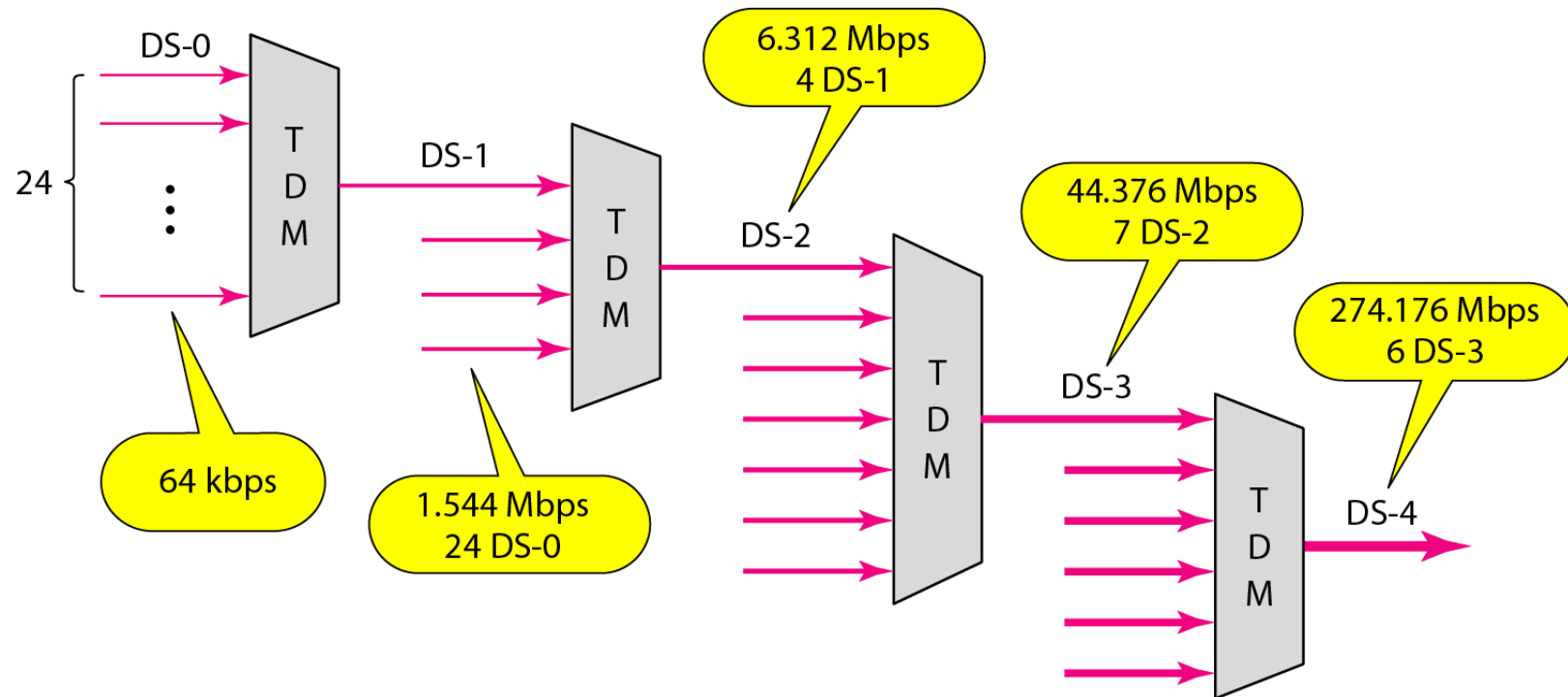


Example

- 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 below 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 $20 \mu\text{s}$. 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 $2.5 \mu\text{s}$.



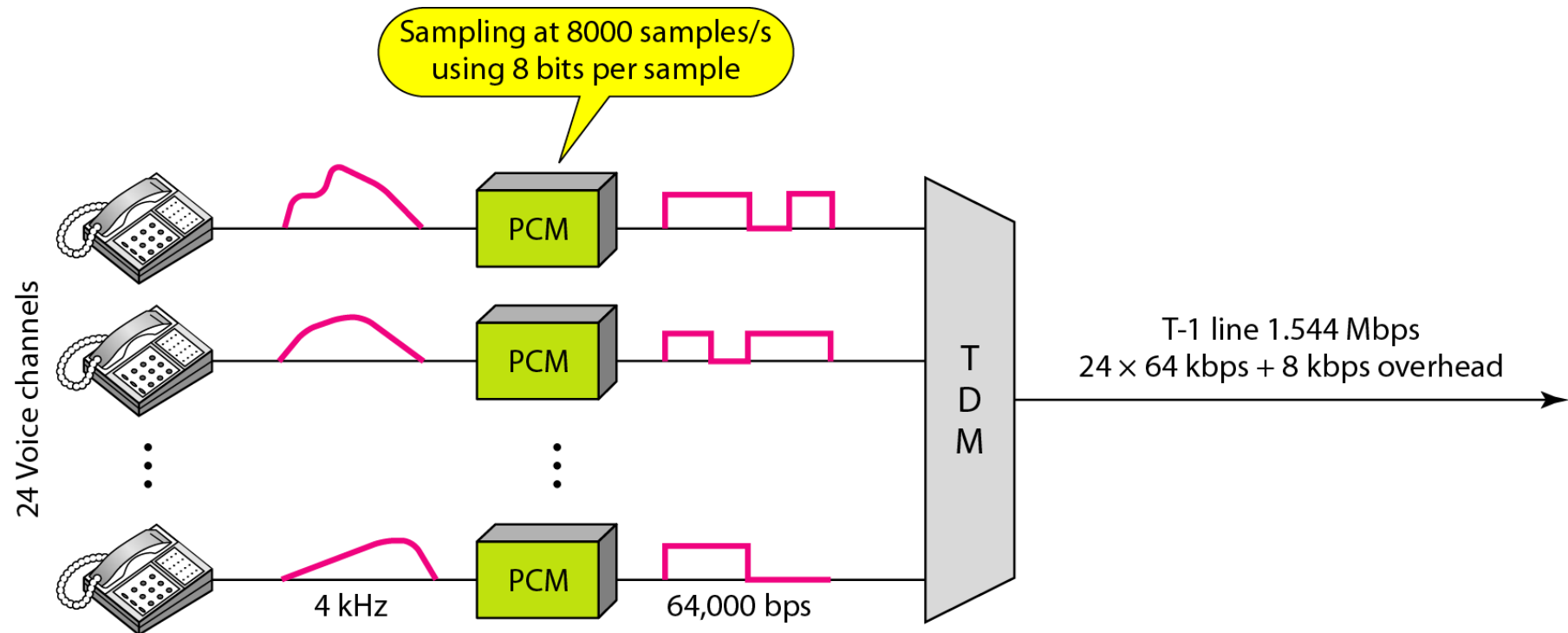
Digital Hierarchy



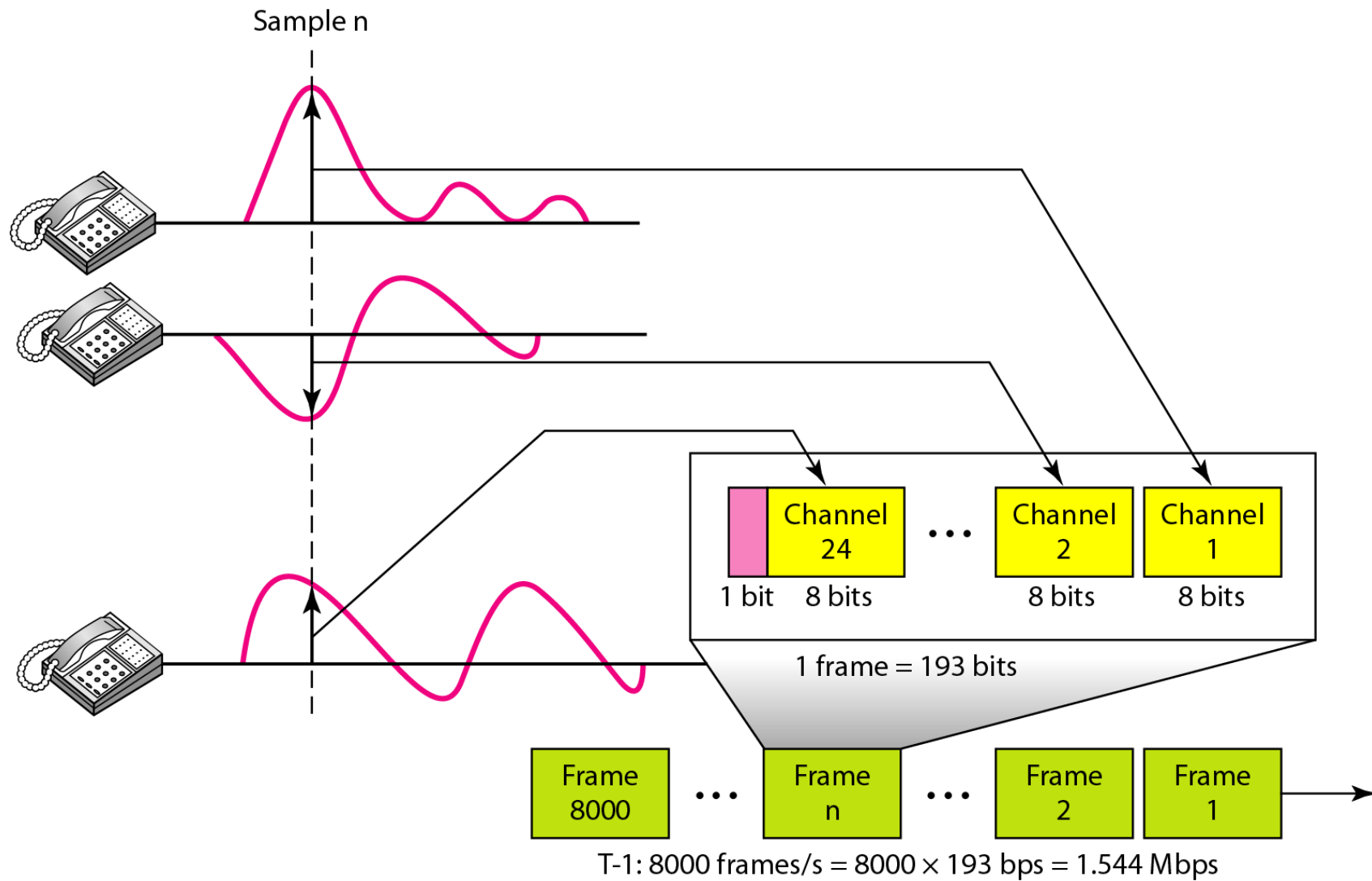
- DS-0, DS-1, and so on are the names of services. To implement those services, the telephone companies use T lines (T-1 to T-4).
- These are lines with capacities precisely matched to the data rates of the DS-1 to DS-4 services

<i>Service</i>	<i>Line</i>	<i>Rate (Mbps)</i>	<i>Voice Channels</i>
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

T-1 line for multiplexing telephone lines



T-1 Frame Structure

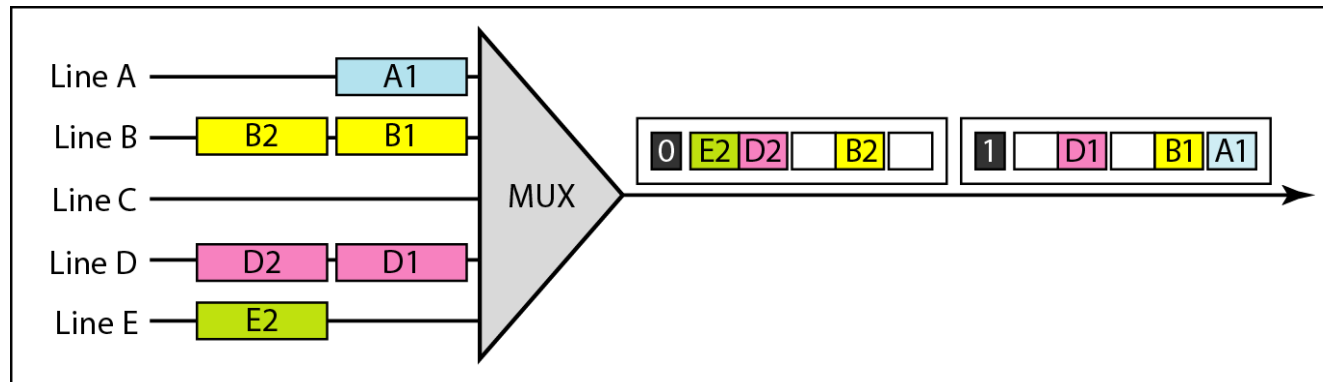


E line rates

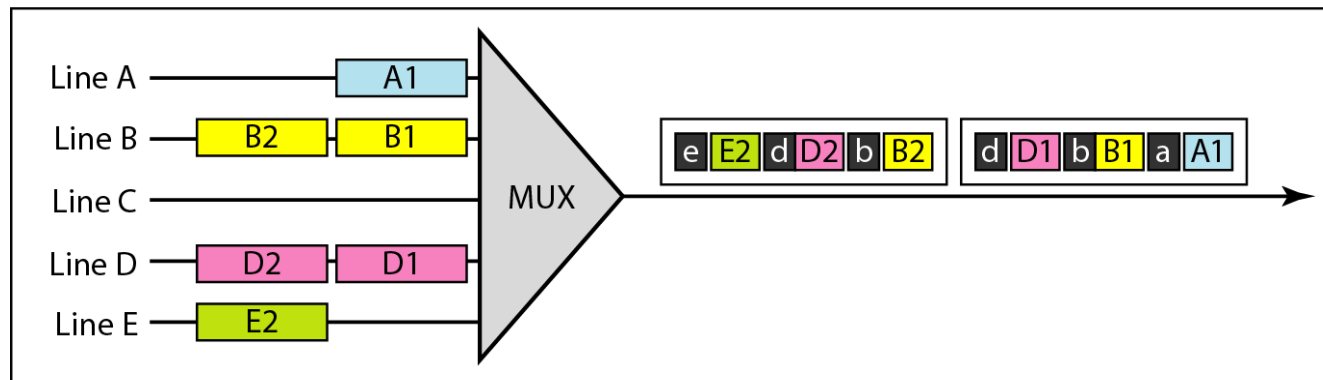
- Europeans use a version of T lines called E lines. The two systems are conceptually identical, but their capacities differ.

<i>Line</i>	<i>Rate (Mbps)</i>	<i>Voice Channels</i>
E-1	2.048	30
E-2	8.448	120
E-3	34.368	480
E-4	139.264	1920

TDM Slot Comparison



a. Synchronous TDM



b. Statistical TDM

- As we saw in the previous section, in synchronous TDM, each input has a reserved slot in the output frame. This can be inefficient if some input lines have no data to send. In statistical time-division multiplexing, slots are dynamically allocated to improve bandwidth efficiency. Only when an input line has a slot's worth of data to send is it given a slot in the output frame. In statistical multiplexing, the number of slots in each frame is less than the number of input lines. The multiplexer checks each input line in round-robin fashion; it allocates a slot for an input line if the line has data to send; otherwise, it skips the line and checks the next line.
- Figure shows a synchronous and a statistical TDM example. In the former, some slots are empty because the corresponding line does not have data to send. In the latter, however, no slot is left empty as long as there are data to be sent by any input line.

- **Addressing**

- Figure also shows a major difference between slots in synchronous TDM and statistical TDM. An output slot in synchronous TDM is totally occupied by data; in statistical TDM, a slot needs to carry data as well as the address of the destination. In synchronous TDM, there is no need for addressing; synchronization and preassigned relationships between the inputs and outputs serve as an address. We know, for example, that input 1 always goes to output 2. If the multiplexer and the demultiplexer are synchronized, this is guaranteed. In statistical multiplexing, there is no fixed relationship between the inputs and outputs because there are no preassigned or reserved slots. We need to include the address of the receiver inside each slot to show where it is to be delivered. The addressing in its simplest form can be n bits to define N different output lines with $n = \log_2 N$. For example, for eight different output lines, we need a 3-bit address.

- **Slot Size**

- Since a slot carries both data and an address in statistical TDM, the ratio of the data size to address size must be reasonable to make transmission efficient. For example, it would be inefficient to send 1 bit per slot as data when the address is 3 bits. This would mean an overhead of 300 percent. In statistical TDM, a block of data is usually many bytes while the address is just a few bytes.

- **No Synchronization Bit**

- There is another difference between synchronous and statistical TDM, but this time it is at the frame level. The frames in statistical TDM need not be synchronized, so we do not need synchronization bits.

- **Bandwidth**

- In statistical TDM, the capacity of the link is normally less than the sum of the capacities of each channel. The designers of statistical TDM define the capacity of the link based on the statistics of the load for each channel. If on average only x percent of the input slots are filled, the capacity of the link reflects this. Of course, during peak times, some slots need to wait.