Chapter 6

Bandwidth Utilization: Multiplexing and Spreading

Partially Edited and
Presented by
Dr. Md. Abir Hossain

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.
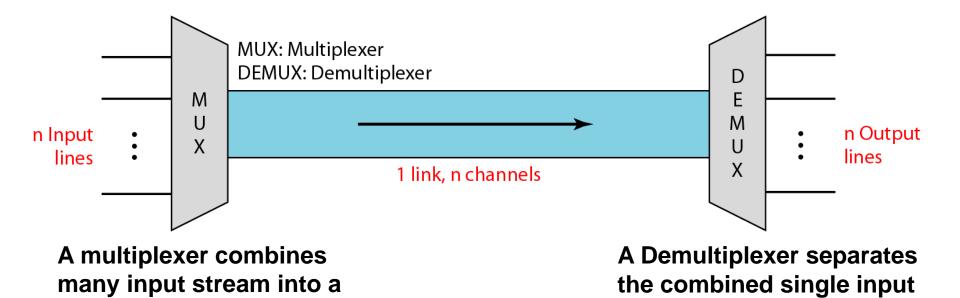
6-1   MULTIPLEXING

- **Multiplexing** is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link.

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

- In a multiplexed system, n lines share the bandwidth of one link

Topics discussed in this section:

Frequency-Division Multiplexing
Wavelength-Division Multiplexing
Synchronous Time-Division Multiplexing
Statistical Time-Division Multiplexing

6.3

Figure 6.1 *Dividing a link into channels*

MUX: Multiplexer
DEMUX: Demultiplexer

n Input
lines

1 link, n channels

n Output
lines

**A multiplexer combines
many input stream into a
single stream**

**A Demultiplexer separates
the combined single input
stream into many stream**

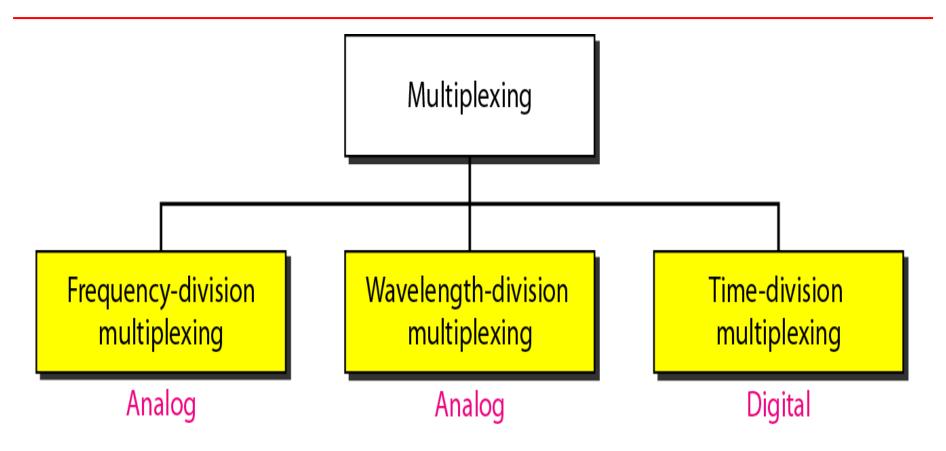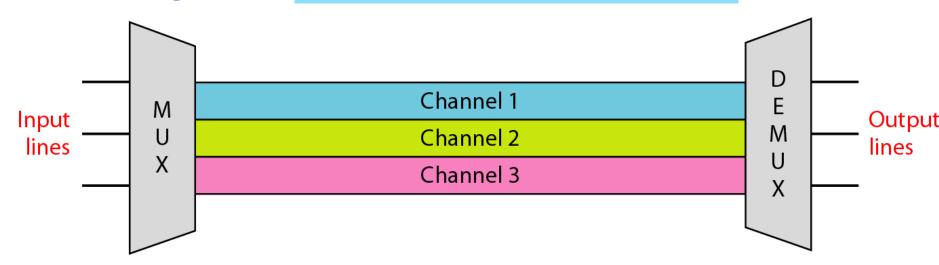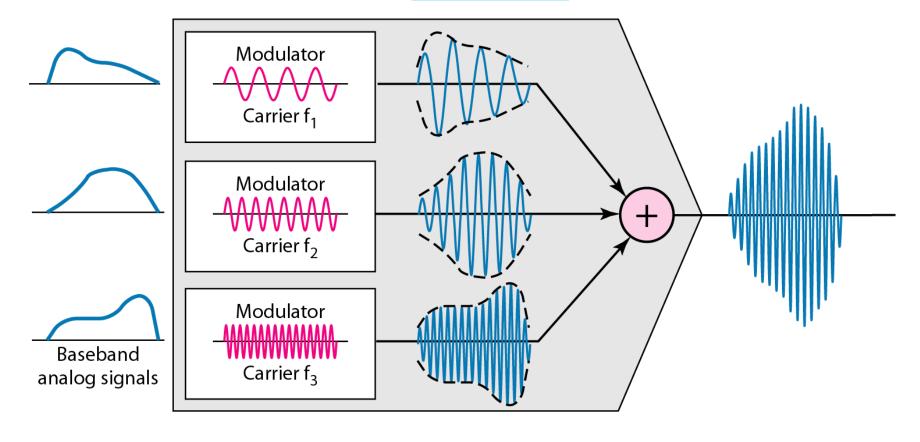# Figure 6.2 *Categories of multiplexing*

Figure 6.3 *Frequency-division multiplexing (FDM)*

- **Frequency-division multiplexing (FDM) is an analog multiplexing technique that combines analog signals**
- **In FDM, signals generated by each sending device modulate different carrier frequencies.**
- **These modulated signals are then combined into a single composite signal that can be transported by the link.**
- **Carrier frequencies are separated by sufficient bandwidth to accommodate the modulated signal.**
- **These bandwidth ranges are the channels through which the various signals travel.**
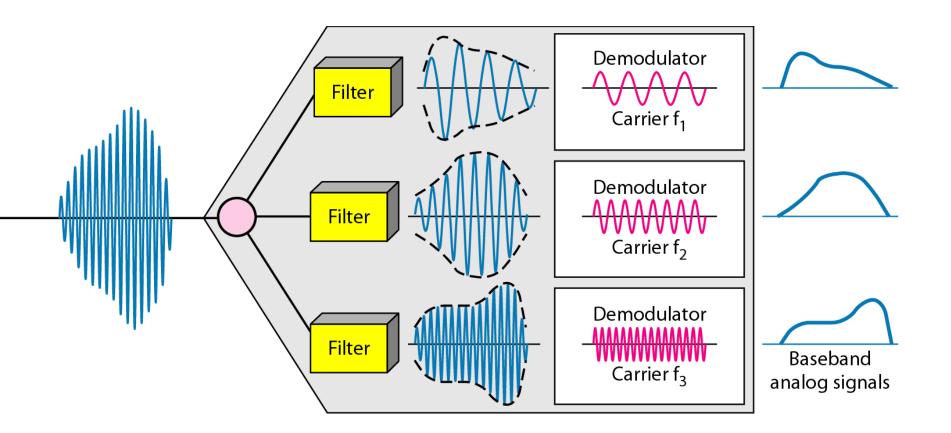- **Channels can be separated by strips of unused bandwidth—guard bands—to prevent signals from overlap- ping.**

6.6

Figure 6.4 *FDM process*

Baseband signal range 300Hz ~ 3KHz

Carrier (4G) signal frequency is about 1700/2100 MHz, 2300 MHz, and 2500 MHz

Figure 6.5 *FDM demultiplexing example*

Filter

Demodulator
Carrier f_1

Filter

Demodulator
Carrier f_2

Filter

Demodulator
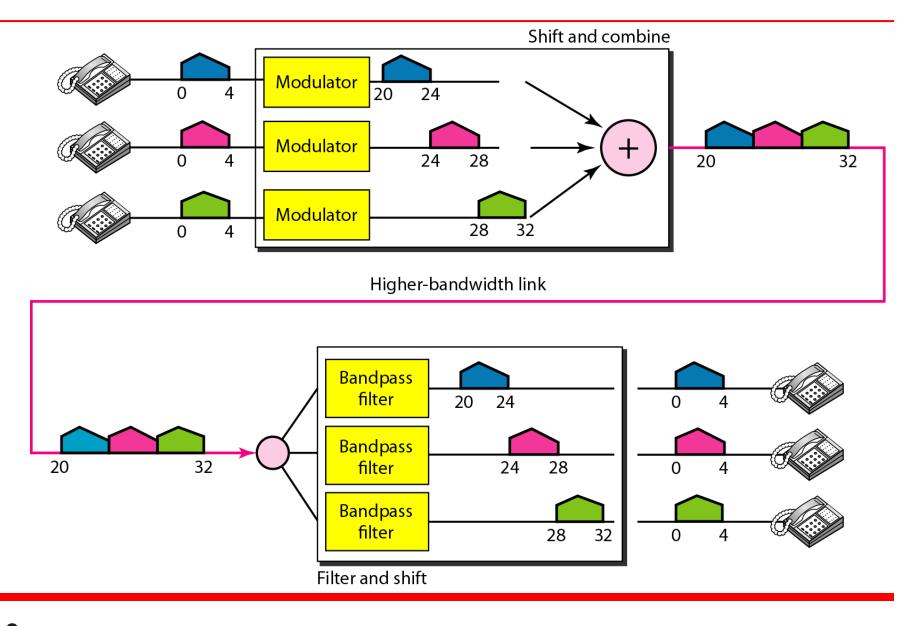Carrier f_3

Baseband
analog signals

6.8

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*

Shift and combine

Modulator

Modulator

Modulator

Higher-bandwidth link

Filter and shift

Bandpass filter

Bandpass filter

Bandpass filter

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?
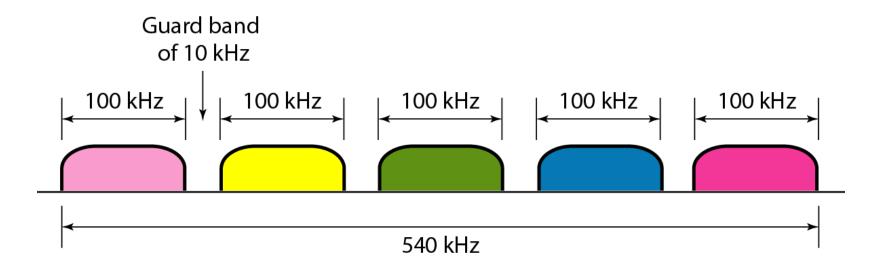
Solution

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

$$5 \times 100 + 4 \times 10 = 540 \ kHz,$$

as shown in Figure 6.7.
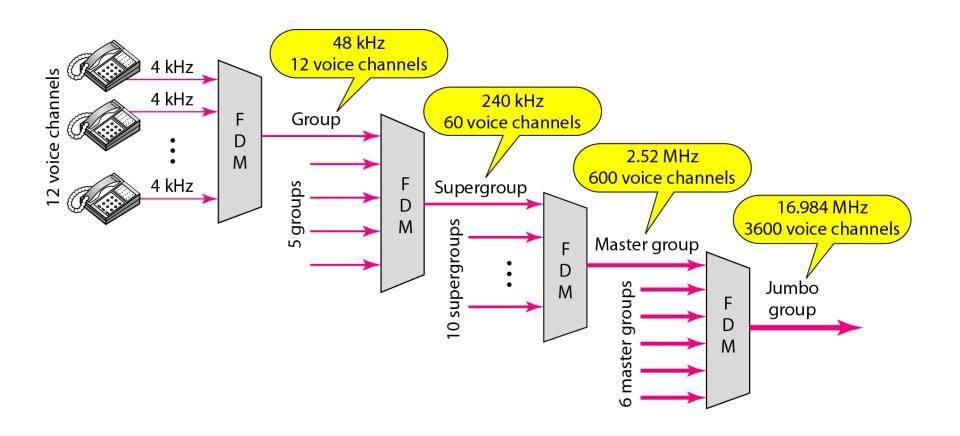
Figure 6.7 *Example 6.2*

The Analog Carrier System

- To maximize the efficiency of their infrastructure, telephone companies have traditionally multiplexed signals from lower-bandwidth lines onto higher-bandwidth lines.

- In this way, many switched or leased lines can be combined into fewer but bigger channels.

- For analog lines, FDM is used. One of these hierarchical systems used by telephone companies is made up of groups, supergroups, master groups, and jumbo groups (see Figure 6.9)

The Analog Carrier System

- In this **analog hierarchy,** 12 voice channels are multiplexed onto a higher-bandwidth line to create a **group.** A group has 48 kHz of bandwidth and supports 12 voice channels.

- At the next level, up to five **groups** can be multiplexed to create a composite signal called a **supergroup.**

- A **supergroup** has a bandwidth of 240 kHz and supports up to 60 voice channels. Supergroups can be made up of either five groups or 60 independent voice channels.

- At the next level, 10 supergroups are multiplexed to create a **master group.** A master group must have 2.40 MHz of bandwidth, but the need for guard bands between the supergroups increases the necessary bandwidth to 2.52 MHz. Master groups support up to 600 voice channels.

- Finally, six master groups can be combined into a **jumbo group.** A jumbo group must have 15.12 MHz (6 × 2.52 MHz) but is augmented to 16.984 MHz to allow for guard bands between the master groups.

6.14

Figure 6.9 *Analog hierarchy*

Wavelength Division Multiplexing

- **Wavelength-division multiplexing (WDM) is designed to use the high-data-rate capability of fiber optic cable.**

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

- **WDM combining different signals of different frequencies. The difference is that the frequencies are very high (signal range from 50 GHz ~ 800 GHz).**

- **WDM combine multiple light sources into one single light at the multiplexer and do the reverse at the demultiplexer**

- **One application of WDM is the SONET network, in which multiple optical fiber lines are multiplexed and demultiplexed.**

- **For more please visit Four types of wavelength division multiplexing(WDM) technology (fibermall.com)**

WDM is an analog multiplexing technique to combine optical signals.
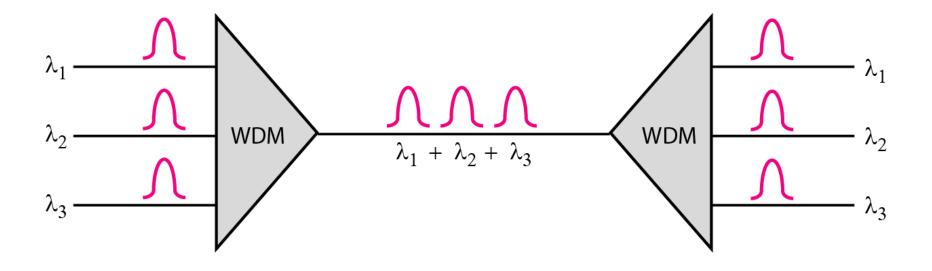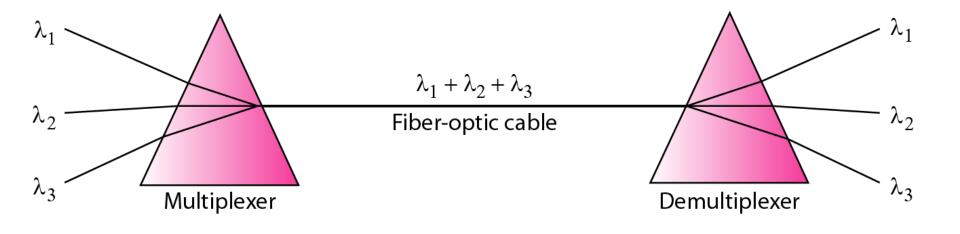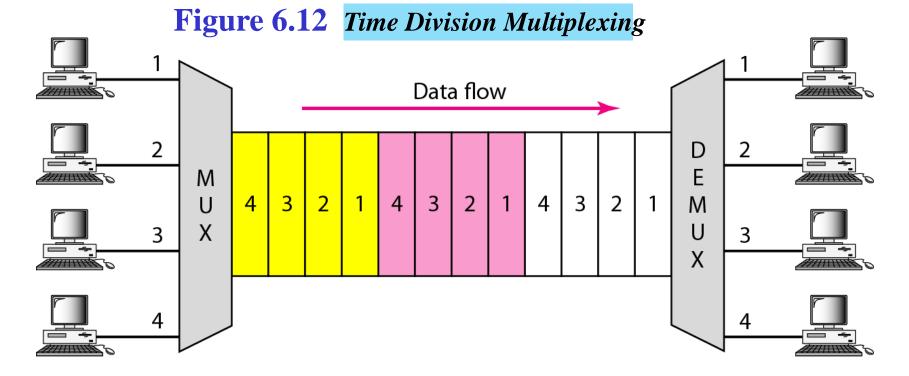
Figure 6.10 *Wavelength-division multiplexing*

λ_1

λ_2

λ_3

Multiplexer

$\lambda_1 + \lambda_2 + \lambda_3$
Fiber-optic cable

λ_1

λ_2

λ_3

Demultiplexer

Figure 6.12 *Time Division Multiplexing*

- **Time-division multiplexing (TDM) is a digital process that allows several connections to share the high bandwidth of a link**

- **Instead of sharing a portion of the bandwidth as in FDM, time is shared.**

- **Each connection occupies a portion of time in the link**

- **In the figure, portions of signals 1, 2, 3, and 4 occupy the link sequentially.**

- **We can divide TDM into two different schemes: synchronous and statistical**
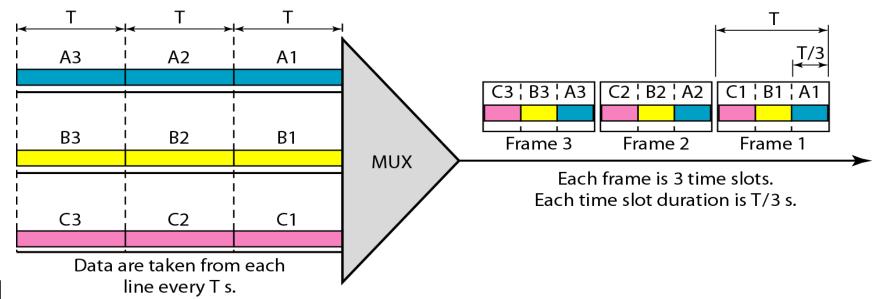
6.19

Note

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

Figure 6.13 *Synchronous time-division multiplexing*

- In synchronous TDM, each input connection has an allotment in the output even if it is not sending data.

- 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 but the duration of an output time slot is n(number of connection) times shorter than the duration of an input time slot.

- If an input time slot is T s, the output time slot is T/n s, where n is the number of connections.

6.21

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

Example 6.5

In Figure 6.13, 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).

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.*

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.*
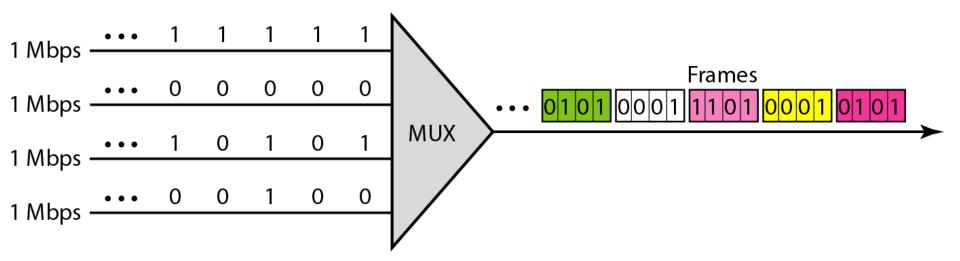
Solution

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.

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. 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*

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).

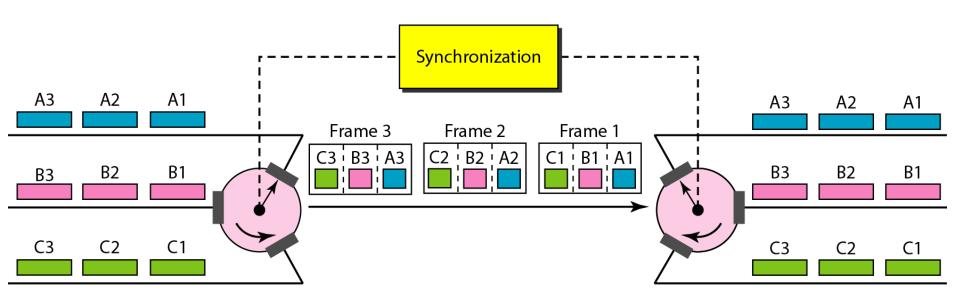*b. The rate of the link is 4 times the rate of a connection, or 4 kbps.*

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.*

Interleaving

- TDM can be visualized as two fast-rotating switches, one on the multiplexing side and the other on the demultiplexing side.
- The switches are synchronized and rotate at the same speed, but in opposite directions.
- On the multiplexing side, as the switch opens in front of a connection, that connection has the opportunity to send a unit onto the path.
- This process is called **interleaving.**
- On the demultiplexing side, as the switch opens in front of a connection, that connection has the opportunity to receive a unit from the path.
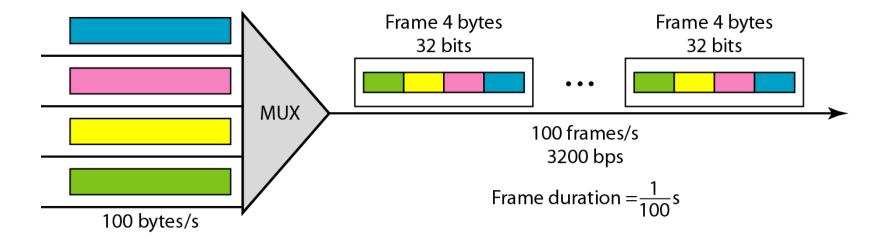
Figure 6.15 *Interleaving*

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. 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*

Frame 4 bytes
32 bits

Frame 4 bytes
32 bits

MUX

100 bytes/s

100 frames/s
3200 bps

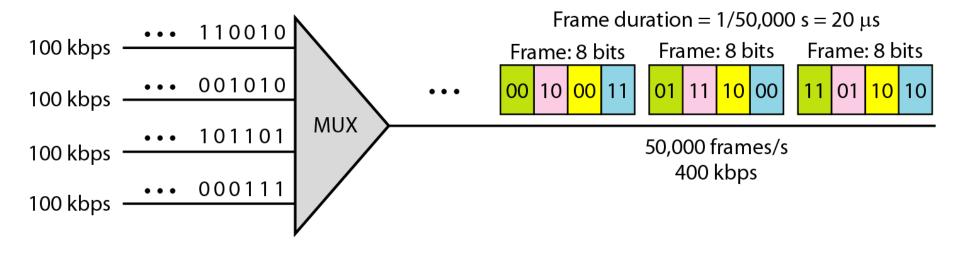$\text{Frame duration} = \dfrac{1}{100}\,\text{s}$

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. The frame duration is therefore 1/50,000 s or 20 μs. The frame rate is 50,000 frames per second, and each frame carries 8 bits; the bit rate is 50,000 × 8 = 400,000 bits or 400 kbps. The bit duration is 1/400,000 s, or 2.5 μs.
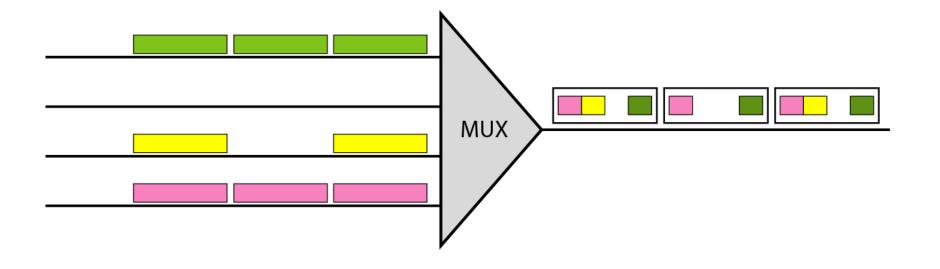
Figure 6.17 *Example 6.9*

100 kbps — • • • 1 1 0 0 1 0

100 kbps — • • • 0 0 1 0 1 0

100 kbps — • • • 1 0 1 1 0 1

100 kbps — • • • 0 0 0 1 1 1

MUX

• • •

Frame duration = 1/50,000 s = 20 μs

Frame: 8 bits   Frame: 8 bits   Frame: 8 bits

| 00 | 10 | 00 | 11 | 01 | 11 | 10 | 00 | 11 | 01 | 10 | 10 |

50,000 frames/s
400 kbps

Empty Slots & Statistical TDM

- 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.
- See next figure, the first output frame has three slots filled, the second frame has two slots filled, and the third frame has three slots filled.
- No frame is full.
- Problem.
- Solution?
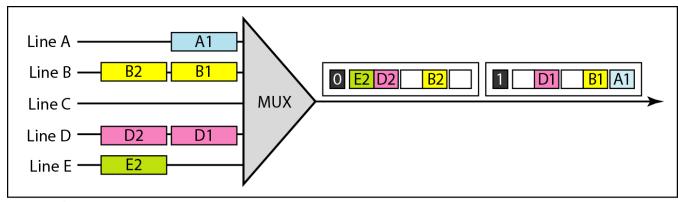- Statistical TDM can improve the efficiency by removing the empty slots from the frame.
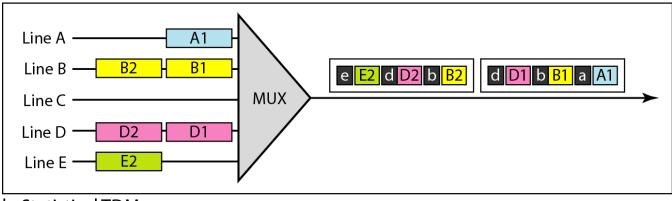
Figure 6.18 *Empty slots*

Statistical Time-Division Multiplexing

- 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.

- Figure 6.26 shows a synchronous and a statistical TDM example.

Figure 6.26 *TDM slot comparison*

a. Synchronous TDM

b. Statistical TDM

6.39

Definitions

- **Addressing**
- In synchronous TDM, there is no need for addressing; synchronization and pre-assigned relationships between the inputs and outputs serve as an address.
- In statistical multiplexing, there is no fixed relationship between the inputs and outputs because there are no preassigned or reserved slots.
- 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.

Definitions

- ***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.

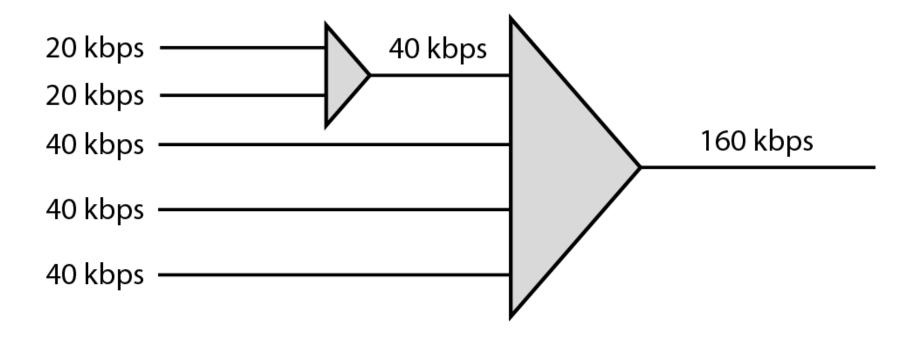- In statistical TDM, a block of data is usually many bytes while the address is just a few bytes.

Definitions

- ***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.

Definitions

- ***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.**

Multilevel Multiplexing

- Multilevel multiplexing is a technique used when the data rate of an input line is a multiple of others.

- For example, in Figure 6.19, we have two inputs of 20 kbps and three inputs of 40 kbps.

- The first two input lines can be multiplexed together to provide a data rate equal to the last three.

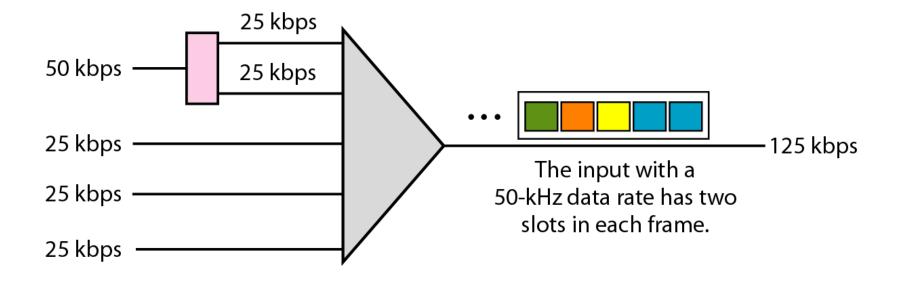- A second level of multiplexing can create an output of 160 kbps.

Figure 6.19 *Multilevel multiplexing*

Multiple-Slot Allocation

- Sometimes it is more efficient to allot more than one slot in a frame to a single input line.

- For example, we might have an input line that has a data rate that is a multiple of another input.

- We insert a demultiplexer in the line to make two inputs out of one.

Figure 6.20 *Multiple-slot multiplexing*

Please start preparation for first class Test Exam.

THANK YOU.