Q. 48 Draw the block diagram of binary PSK system and explain with signal space diagram.

Q. 49 Write an expression for the BFSK and explain the spectrum of BFSK.

Q. 50 Draw the BFSK waveform to represent the following bit stream.

00101110.

Q. 51 Explain clearly the difference between phase modulation and frequency modulation.

Q. 52 Explain the direct method of FM generation (reactance modulator).

Q. 53 Justify FM is called a constant B.W. system.

Q. 54 Compare and contrast : Frequency modulation and phase modulation.

Q. 55 Define FM and draw the necessary waveforms to explain it.

Q. 56 Derive an equation for FM wave.

Q. 57 Compare AM and FM.

Q. 58 Explain the generation of FM wave.

Q. 59 Write short note on : Frequency spectrum of FM wave.

Q. 60 Compare AM with FM with special reference to power requirements signed to noise ratio and bandwidth required.

Q. 61 Derive the formula for instantaneous value of an FM voltage and define modulation index.

Q. 62 What is angle modulation ?

❑❑❑

CHAPTER 5

Unit II

Multiplexing

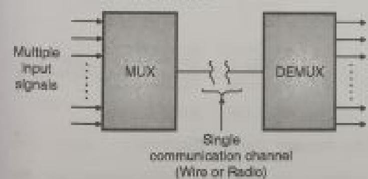
Syllabus :
Multiplexing, Frequency division multiplexing, Wavelength division multiplexing, Time division multiplexing.

5.1 Introduction to Multiplexing :

- Multiplexing is the process of simultaneously transmitting two or more individual signals over a single communication channel.
- Due to multiplexing it is possible to increase the number of communication channels so that more information can be transmitted.
- The typical applications of multiplexing are in telemetry and telephony or in the satellite communication.

5.2 Concept of Multiplexing and Demultiplexing :

- The concept of a simple multiplexer is illustrated in Fig. 5.2.1.
- The multiplexer receives a large number of different input signals.
- Multiplexer has only one output which is connected to the single communication channel.
- The multiplexer combines all input signals into a single composite signal and transmits it over the communication medium.



(L-105) **Fig. 5.2.1 : Concept of multiplexing**

- Sometimes the composite signal is used for modulating a carrier before transmission.
- At the receiving end, of communication link, a demultiplexer is used to separate out the signals into their original form.
- The operation of demultiplexer is exactly opposite to that of a multiplexer. Demultiplexing is the process which is exactly opposite to that of multiplexing.

5.2.1 Types of Multiplexing :

- There are three basic types of multiplexing. They are :
  1. Frequency Division Multiplexing (FDM).
  2. Time Division Multiplexing (TDM).
  3. Wavelength Division Multiplexing (WDM).
- The multiplexing techniques can be broadly classified into two categories namely analog and digital.
- Analog multiplexing can be either FDM or WDM and digital multiplexing is TDM.
- Fig. 5.2.2 shows the classification of multiplexing techniques.

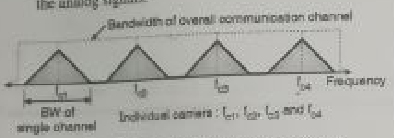
(L-106) **Fig. 5.2.2 : Classification of multiplexing techniques**

- Generally the FDM and WDM systems are used to deal with the analog information whereas the TDM systems are used to handle the digital information.
- In FDM many signals are transmitted simultaneously where each signal occupies a different frequency slot within a common bandwidth.
- In TDM the signals are not transmitted at a time, instead they are transmitted in different time slots.

5.3 Frequency Division Multiplexing (FDM) :

- The operation of FDM is based on sharing the available bandwidth of a communication channel among the signals to be transmitted.
- That means many signals are transmitted simultaneously with each signal occupying a different frequency slot within the total available bandwidth.
- Each signal to be transmitted modulates a different carrier. The modulation can be AM, SSB, FM or PM.

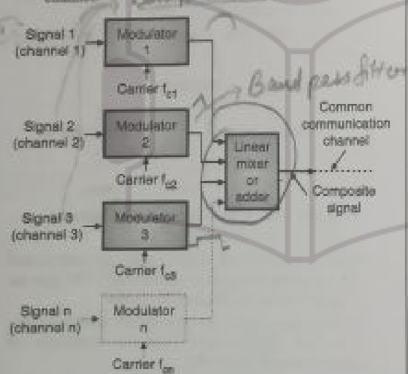
- The modulated signals are then added together to form a composite signal which is transmitted over a single channel.
- The spectrum of composite FDM signal is shown in Fig. 5.3.1(a).
- Generally the FDM systems are used for multiplexing the analog signals.



(L-107) **Fig. 5.3.1(a) : Spectrum of FDM signal**

5.3.1 FDM Transmitter (Multiplexing Process) :

- Fig. 5.3.1(b) shows the block diagram of an FDM transmitter. The signals which are to be multiplexed will each modulate a separate carrier.
- The type of modulation can be AM, SSB, FM or PM.
- The modulated signals are then added together to form a complex signal which is transmitted over a single channel.



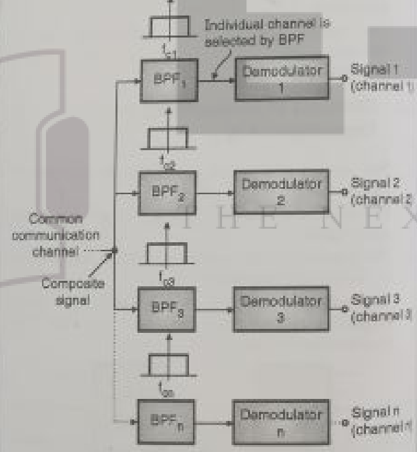
(L-108) **Fig. 5.3.1(b) : The FDM transmitter**

Operation of the FDM transmitter :

- Each signal modulates a separate carrier. The modulator outputs will contain the sidebands of the corresponding signals.
- The modulator outputs are added together in a linear mixer or adder. The linear mixer is different from the normal mixers. Here the sum and difference frequency components are not produced. But only the algebraic addition of the modulated outputs will take place.
- Different signals are thus added together in the time domain but they have their own separate identity in the frequency domain. This is as shown in the Fig. 5.3.1(a).
- The composite signal at the output of mixer is transmitted over the single communication channel as shown in Fig. 5.3.1(b). This signal can be used to modulate a radio transmitter if the FDM signal is to be transmitted through air.

5.3.2 FDM Receiver (Demultiplexing Process) :

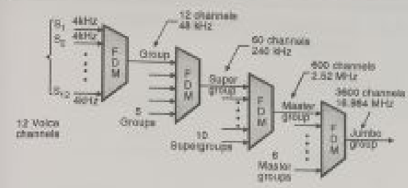
- The block diagram of an FDM receiver is as shown in Fig. 5.3.1(c). The composite signal is applied to a group of Band Pass Filters (BPF).
- Each BPF has a center frequency corresponding to one of the carriers used in the transmitter i.e. f_{c1}, f_{c2}, ... f_{cn} etc.
- The BPFs have an adequate bandwidth to pass all the channel information without any distortion.
- Each filter will pass through only its channel and rejects all the other channels. Thus all the multiplexed channels are separated out.
- The channel demodulator then removes the carrier and recovers the original signal back.



(L-109) **Fig. 5.3.1(c) : FDM receiver**

5.3.3 The Analog Carrier System :

- To maximize the efficiency of their infrastructure, the telephone companies have used multiplexing techniques for lower bandwidth lines.
- In this way it is possible to combine many switched or leased lines into fewer but bigger channels.
- One of such hierarchical system is used by AT and T. It is as shown in Fig. 5.3.2 and is made up of groups, super groups, master groups and jumbo groups.



(L-110) **Fig. 5.3.2 : FDM hierarchy**

The levels of multiplexing is also called as multiplexing hierarchy.

- The different levels of multiplexing which is also called multiplexing hierarchy is as follows :

Level (1) : Basic Group. [12 voice channels multiplexed together].

Level (2) : Super Group. [Upto 5 basic groups multiplexed together i.e. upto 60 voice channels].

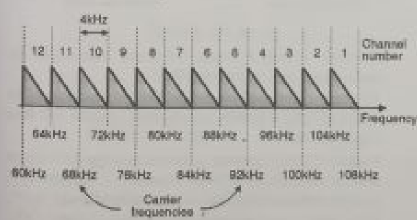
Level (3) : Master Group. [Upto 10 super groups multiplexed together i.e. upto 600 voice channels].

Level (4) : Jumbo Group. [Upto 6 master groups multiplexed together i.e upto 3600 voice channels].

- This hierarchy is used by AT and T and shown in Fig. 5.3.2.

Basic Group [12 voice channels] :

- The frequency plan for the typical basic group is as shown in Fig. 5.3.3. Here the 12 voice channels such as telephone channels modulate the carrier frequencies in the range of 60 to 108 kHz range. The carrier frequencies are spaced at 4 kHz from each other.

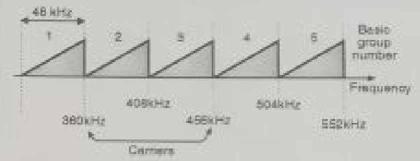


(L-111) **Fig. 5.3.3 : Frequency plan for the basic group of FDM**

- SSB modulation technique is used to save the bandwidth. Each voice channel is applied to a balanced modulator along with a carrier. The output of a balanced modulator consists of the upper and lower sidebands.
- Frequency plans of groups of FDM are nothing but the frequency spectrums.
- The frequency plan for the basic group of FDM is shown in Fig. 5.3.3.

Super group :

The frequency plan for a super group is as shown in Fig. 5.3.4. A super group consists of at the most 60 voice channels.



(L-112) **Fig. 5.3.4 : Frequency plan for a super group of FDM**

5.4 Advantages, Disadvantages and Applications of FDM :

5.4.1 Advantages of FDM :

1. A large number of signals (channels) can be transmitted simultaneously.
2. FDM does not need synchronization between its transmitter and receiver for proper operation.
3. Demodulation of FDM is easy.
4. Due to slow narrow band fading only a single channel gets affected.

5.4.2 Disadvantages of FDM :

1. The communication channel must have a very large bandwidth.
2. Intermodulation distortion takes place.
3. Large number of modulators and filters are required.
4. FDM suffers from the problem of crosstalk.
5. All the FDM channels get affected due to wideband fading.

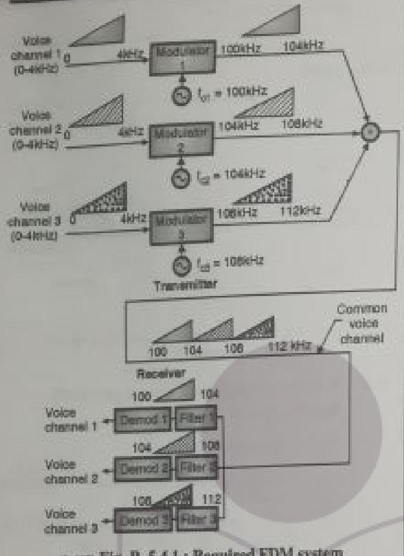
5.4.3 Applications of FDM :

Some of the important applications of FDM are :

1. Telephone systems.
2. AM (Amplitude Modulation) and FM (Frequency Modulation) radio broadcasting.
3. TV broadcasting.
4. First generation of cellular phones used FDM.

Ex. 5.4.1 : Draw the FDM system to combine three voice channels. Each voice channel occupies a bandwidth of 4 kHz. The common voice channel has a bandwidth of 12 kHz from 100 kHz to 112 kHz.

Soln. : Fig. P. 5.4.1 shows the required FDM system.

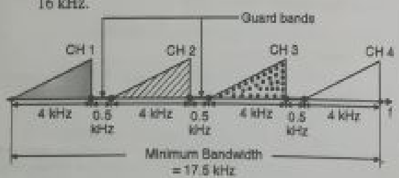


(L-117) Fig. P. 5.4.1 : Required FDM system

Ex. 5.4.2 : 4 voice channels each having a bandwidth of 4 kHz are to be multiplexed using FDM. A guardband of 500 Hz is to be inserted between the adjacent channels. Calculate the minimum bandwidth of the link.

Soln. :

- The frequency spectrum of the FDM signal is shown in Fig. P. 5.4.2.
- The minimum bandwidth is equal to 17.5 kHz as shown in Fig. P. 5.4.2.
- The bandwidth without guardbands would have been 16 kHz.



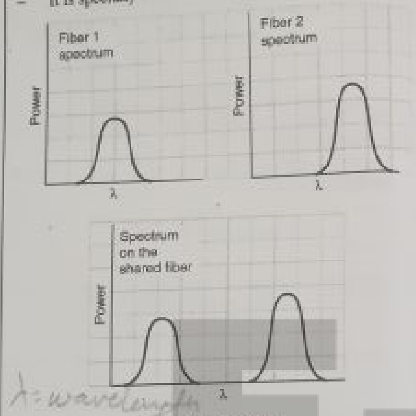
(L-118) Fig. P. 5.4.2

Conclusion :

Guardbands increase the bandwidth of FDM signal still they should be included in order to avoid interference between the adjacent channels.

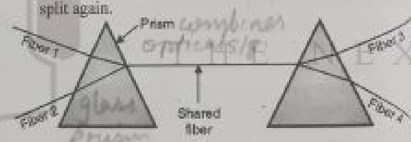
5.5 Wavelength Division Multiplexing (WDM) :

- WDM is the variation of FDM.
- It is specially used for fiber optic channels.



(L-119) Fig. 5.5.1(a)

- As shown in Figs. 5.5.1(a) and (b), 2 fibres com[illegible] together at a prism, each having energy in a differen[illegible] frequency band. After passing through the prism, beams are combined onto a single shared fiber, fo[illegible] transmission to a distant destination, where they a[illegible] split again.

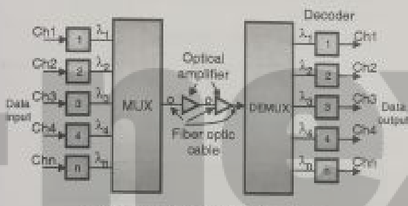


(L-120) Fig. 5.5.1(b)

- Channels having different frequency ranges can b[illegible] multiplexed on a single long fiber.
- The only difference between WDM and electrical FDM is that an optical system is completely passive and th[illegible] highly reliable.
- Reason WDM is popular, is that the energy on a sing[illegible] fiber is a few gigahertz wide because it is impossible t[illegible] convert between electrical and optical media any faste[illegible]
- Since BW of a single fiber band is about 25,000 GHz there is great potential for multiplexing many optica[illegible] channels together over long routes. Necessary condition is that incoming channels use differen[illegible] frequency bands.
- Potential application of WDM is in the FTTC (Fiber T[illegible] The Curb) systems or in SONET networks.

fibre cladding converts into light pulse

- In the Fig. 5.5.1(b) we have a fixed wavelength system bits from fiber 1 go to fiber 3 and bits from fiber 2 go to fiber 4.
- It is not possible to have bits going from fiber 1 to fiber 4. It is also possible to build WDM systems that are switched, which contain many input and output fibers, switching data among themselves.
- Although spreading energy over n outputs dilutes it by a factor n, such systems are practical for hundred of channels.
- If light from one of the incoming fibers have to go to any output fiber, all the output fibers need tunnable filters.
- Alternatively, input fibers could be tunnable and output ones fixed. Having both to be tunnable is unnecessary expense.
- A simple block diagram of WDM transmitter and receiver system with different channels is as shown in Fig. 5.5.1(c).



(L-121) Fig. 5.5.1(c) : WDM system

5.5.1 Application of WDM :

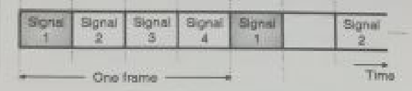
One important application of WDM is the SONET network in which a large number of optical fiber lines are multiplexed and demultiplexed.

5.5.2 DWDM (Dense WDM) :

- The long form of DWDM is dense WDM. It can multiplex a very large number of channels. The spacing between adjacent channels is small.
- Efficiency of DWDM is higher than that of WDM.

5.6 Synchronous Time Division Multiplexing :

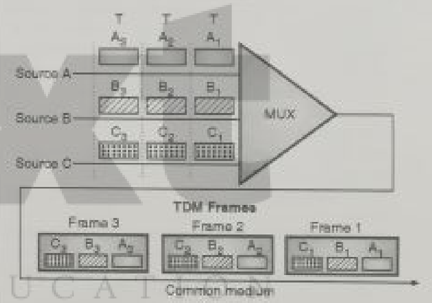
- The process called multiplexing is used in order to utilize common transmission channel or medium to transmit more than one signals simultaneously.
- TDM is a digital multiplexing process.
- In TDM all the signals to be transmitted are not transmitted simultaneously. Instead, they are transmitted one-by-one.
- Thus each signal will be transmitted for a very short time. One cycle or frame is said to be complete when all the signals are transmitted once on the transmission channel. The TDM principle is illustrated in Fig. 5.6.1.



(L-122) Fig. 5.6.1 : Principle of TDM

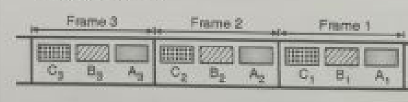
- As shown in the Fig. 5.6.1 one transmission of each channel completes one cycle of operation called as a "Frame".
- The TDM system can be used to multiplex analog or digital signals, however it is more suitable for the digital signal multiplexing.
- The concept of TDM will be more clear if you refer to Fig. 5.6.2.
- The data flow of each source (A, B or C) is divided into units (say A_1, A_2 or B_1, C_1 etc.)

  Then one unit from each source is taken and combined to form one frame. The size of each unit such as A_1, B_1 etc. can be 1 bit or several bits.



(L-123) Fig. 5.6.2 : TDM system

- Fig. 5.6.3 shows the frames of TDM signal. For 3 inputs being multiplexed, a frame of TDM will consist of 3 units i.e. one unit from each source.
- Similarly for n number of inputs, each TDM frame will consist of n units.



(L-124) Fig. 5.6.3 : TDM frames

- The TDM signal in the form of frames is transmitted on the common communication medium.

Data rate :

- For a TDM, the data rate of the multiplexed signal is always n times the data rate of individual sources, where n is the number of sources.

- So if three sources are being multiplexed, then the data rate of the TDM signal is three times higher than the individual data rate.
- Naturally the duration of every unit (A_1 or B_1 etc.) in TDM signal is n times shorter than the unit duration before multiplexing.

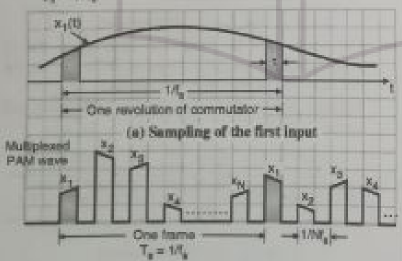
5.6.1 PAM - TDM System :

- The TDM system which is going to be discussed now, combines the concepts of PAM and TDM both. The TDM system is as shown in Fig. 5.6.4.

(L-125) **Fig. 5.6.4 : PAM/TDM system**

The operation of the system is as follows :

- The multiplexer here is a single pole rotating switch or commutator. It can be a mechanical switch or an electronic switch. It rotates at f_s rotations per second.
- As the switch arm rotates, it is going to make contact with the position 1, 2, 3 or N for a short time. To these contacts are connected the N analog signals which are to be multiplexed.
- Thus the switch arm will connect these N input signals one by one to the communication channel.
- The waveform of a TDM signal which is being transmitted is as shown in Fig. 5.6.5. It shows that the rotary switch samples each channel during each of its rotations. Each rotation corresponds to one frame. Hence 1 frame is completed in T_s seconds where $T_s = 1/f_s$.



(a) Sampling of the first input

(b) Multiplexed PAM signal, transmitted on the transmission channel

(L-126) **Fig. 5.6.5**

- At the receiver, there is one more rotating switch or commutator used for demultiplexing.
- It is important to note that this switch must rotate at the same speed as that of the commutator 1 at the transmitter and its position must be synchronized with commutator 1 in order to ensure proper demultiplexing.
- The same principle of multiplexing can be used for multiplexing more number of signals.

Interleaving :

- On the multiplexer side the commutator-1 opens in front of a connection, that connection has the opportunity to send its bit on to the channel.
- This process is called as interleaving.

Ex. 5.6.1 : 3 signals having a data rate of 2 kbps are grouped together by means of time division multiplexing. Each unit consists of 1 bit. Calculate :

1. The bit duration before multiplexing.
2. The transmission rate of TDM.
3. The duration of each time slot in TDM.
4. The duration of one TDM frame.

Soln. :

Step 1 : Duration of a bit before multiplexing :

- Each signal has a data rate of 2 kbps. That means 2000 bits per second.
- Hence the duration of each bit is,

$$T_b = \frac{1}{2000} = 0.5 \text{ mS} \quad \text{...Ans.}$$

Step 2 : Transmission rate of TDM :

- The TDM frame is shown in Fig. P. 5.6.1.

(L-127) **Fig. P. 5.6.1 : TDM frames**

- As discussed earlier the transmission rate of TDM is n times higher than the bit rate of each source.

Transmission rate of TDM $= n \times 2000$
$= 3 \times 2000$
$= 6000$ bps or 6 kbps ...Ans.

Step 3 : Duration of time slot in TDM :

$$\text{Duration of each time slot in TDM} = \frac{1}{6000} = 166.67 \quad \text{...Ans.}$$

Step 4 : Frame duration :

Duration of 1 frame $= n \times$ duration of one slot
$= 3 \times 166.67\ \mu S = 0.5$ mS ...Ans.

> **Note :** The duration of a TDM frame is always equal to the duration of one unit before multiplexing.

Ex. 5.6.2 : Three channels are to be multiplexed using TDM technique. The rate of each channel is 150 bytes per second. In TDM, one byte per channel is to be multiplexed. Calculate :

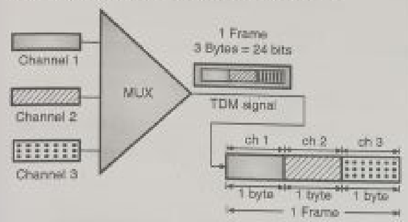
1. Frame size
2. Frame duration
3. Frame rate and
4. Bit rate of the TDM signal.

Soln. :

Given : Bit rate of each channel 150 bytes per sec, n = 3.
1 byte per channel to be multiplexed.

Step 1 : Draw the system block diagram :

Fig. P. 5.6.2(a) shows the block diagram of the TDM system and Fig. P. 5.6.2(b) shows one TDM frame.



(a) TDM system **(b) One frame of TDM**

(L-128) **Fig. P. 5.6.2**

Step 2 : Frame size :

Each frame consists of one byte from each channel. So frame size is 3 bytes or 24 bits.

Step 3 : Frame duration and frame rate :

- The duration of a TDM frame is always equal to the duration of one unit before multiplexing.
- Here one unit before multiplexing is 1 byte i.e. 8 bits.

$\therefore$ Frame duration = 1 byte duration

- But each channel transmits at 150 bytes/sec.

$$\therefore \quad \text{Frame duration} = \frac{1}{150} = 6.666 \text{ mS} \quad \text{...Ans.}$$

$$\text{Frame duration} = \frac{1}{\text{Frame duration}} = \frac{1}{6.666 \times 10^{-3}}$$
$= 150$ frames/sec. ...Ans.

Step 4 : Bit rate of TDM signal :

Bit rate of TDM = Number of bits per frame
$\times$ Number of frames per second.
$= 24 \times 150 = 3600$ bps ...Ans.

5.6.2 Signaling Rate (r) :

The signaling rate of a TDM system is defined as the number of pulses transmitted per second. It is denoted by "r". Let us now derive the expression for the signaling rate of the PAM-TDM system.

- Let W = Maximum frequency of all the input signals x_1 to x_N.
- Therefore as per Nyquist criteria, the sampling frequency $f_s \geq 2$ W. Therefore the speed of rotation of the commutators is f_s rotations per second with $f_s \geq 2W$.
- As shown in Fig. 5.6.6, one revolution of commutators corresponding to one frame contains one sample from each input signal.

$\therefore$ 1 Revolution $\Rightarrow$ 1 frame $\Rightarrow$ N pulses ...(5.6.1)

- 1 frame period is $(1/f_s)$ i.e. T_s seconds. Therefore in "T_s" seconds "N" number of pulses are transmitted.

Hence the pulse to pulse spacing within the frame is given by,

$$\text{Pulse to pulse spacing} = \frac{T_s}{N} = \frac{1}{Nf_s} \quad \text{...(5.6.2)}$$

- As the period of one pulse (ON + OFF) is $(1/Nf_s)$ seconds, the number of pulses per second is given by,

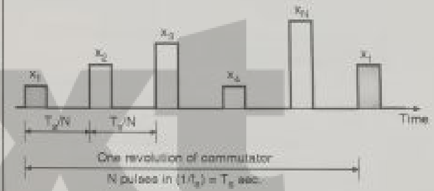
Number of pulses per second = Nf_s

- This is nothing but the signaling rate.

$\therefore$ Signaling rate of a TDM system = r
$= Nf_s$ pulses/second. But as $f_s \geq 2W$.

Signaling rate of a TDM system
$= r \geq 2NW$ pulses/second ...(5.6.3)

- A TDM system is supposed to have its signaling rate as high as possible. It is evident from the expressions above that the signaling rate can be increased by increasing the sampling rate f_s and/or the number of input signals N.



(L-129) **Fig. 5.6.6 : Calculation of number of pulses per second for PAM-TDM system**

5.6.3 Transmission Bandwidth of a TDM Channel :

- The minimum transmission bandwidth of a PAM-TDM channel is given by,

$$B_T = \frac{1}{2} \text{signaling rate}$$

$\therefore$ Minimum transmission bandwidth

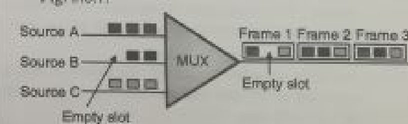
$$B_T \geq \frac{1}{2} \times 2\text{ NW}$$

$\therefore$ Minimum transmission bandwidth

$$B_T = \text{NW} \quad \text{...(5.6.4)}$$

5.6.4 Empty Slots :

- The drawback of synchronous TDM is its low efficiency. This is because if a particular source does not have any data to send, then the time slot allotted to it in the output frame will be empty, as shown in Fig. 5.6.7.



(L-765) **Fig. 5.6.7 : Empty slot**

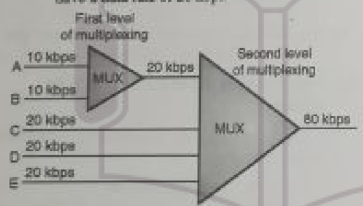
- In Fig. 5.6.7 the source B has one empty slot (due to discontinuous data).
- As shown in Fig. 5.6.7, the second and the third frame has three filled slots but the first frame has only two slots filled. Thus the first time slot is carrying less data than its maximum capacity.
- The statistical TDM system improves the efficiency by removing such empty slots.

5.6.5 Data Rate Management :

- The problem with synchronous TDM is it inability to handle the disparity in the input data rates. That means the data rates of different sources are not same but different.
- If the data rates of all the inputs are not same then three different strategies may be used. They are :
  1. Multilevel multiplexing.
  2. Multiple slot allocation.
  3. Pulse stuffing.
- We will discuss these strategies one by one.

1. Multilevel multiplexing :

- This technique is used when the data rate of an input line is exact multiple of data rates of other lines.
- For example in Fig. 5.6.8 sources A and B have data rates of 10 kbps while the remaining sources have a data rate of 20 kbps.

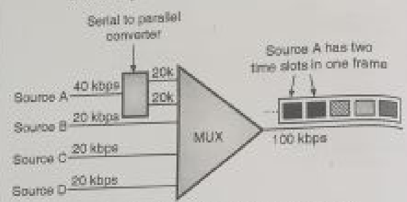


(L-766) **Fig. 5.6.8 : Multilevel multiplexing**

- As shown in Fig. 5.6.8, the input lines from sources A and B are multiplexed together to provide the data rate of 20 kbps (which is equal to the data rate of remaining three sources).
- These four inputs are given to second level of multiplexer which produces an output at 80 kbps.

2. Multiple slot allocation :

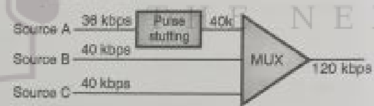
- Sometimes we can improve the efficiency by allotting more than one slot in a frame to a single source. This can be done for an input source which has a higher data rate as compared to the other input lines.
- For example refer Fig. 5.6.9 the source A has a data rate of 40 kbps and the data rate of the other sources is 20 kbps.
- So the source A is connected to a serial to parallel converter. This will give two slots for the source A.
- Thus there will be two slots for source A per frame and one slot each for sources B, C and D. The data rate of all these inputs will now be the same i.e. 20 kbps as shown in Fig. 5.6.9.



(L-767) **Fig. 5.6.9 : Multiple slot multiplexing**

3. Pulse stuffing :

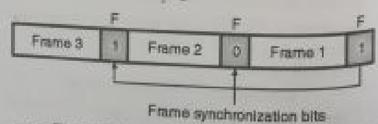
- If the bit rates of sources are not multiple integers of each other, then the two techniques discussed earlier are not useful.
- So another technique called pulse stuffing is used. Here the highest input data rate is made the dominant data rate and then dummy bits to the input lines having lower data rates.
- Pulse stuffing is also called as pulse stuffing, bit padding, or bit stuffing and it is demonstrated in Fig. 5.6.10.
- Note that the source A has a lower data rate of 36 kbps and so pulse stuffing is done to correct its rate to 40 kbps.



(L-768) **Fig. 5.6.10 : Pulse stuffing**

5.6.6 Frame Synchronization :

- The implementation of TDM is not as simple as that of FDM because in TDM, the synchronization of multiplxer and demultiplxer is essential.
- If the synchronization is not there then the bit that belongs to one channel may be received by some other channel.
- Therefore one or more synchronization bits are generally added to the beginning of each frame. They are known as the framing bits.



(L-131) **Fig. 5.6.11 : Frame synchronization in TDM**

- These bits are called frame synchronizing bits or simply framing bits.
- The framing bits will follow a pattern frame to frame. For example the pattern shown in Fig. 5.6.11 is 101.
- The framing bit pattern will allow the demux to synchronize itself to the mux.

5.6.7 Advantages of TDM :

1. Full available channel bandwidth can be utilized for each channel.
2. Intermodulation distortion is absent.
3. TDM circuitry is not very complex.
4. The problem of crosstalk is not severe.

5.6.8 Disadvantages of TDM :

1. Synchronization is essential for proper operation.
2. Due to slow narrowband fading, all the TDM channels may get wiped out.

5.6.9 Applications of TDM :

1. Multiplexing of digital signals.
2. Digital telephony.
3. Satellite communications.
4. Fiber optic communication.
5. Wireless communication applications.

5.6.10 Solved Examples on TDM / PAM :

Ex. 5.6.3 : Two analog signals m_1 (t) and m_2 (t) are to be transmitted over a common channel by means of time division multiplexing. The highest frequency of m_1 (t) is 4 kHz and that of m_2 (t) is 4.5 kHz. What is the minimum value of permissible sampling rate ?

Soln. :

The highest frequency component of the composite signal consisting of m_1 (t) and m_2 (t) is 4.5 kHz. Therefore the minimum value of permissible sampling rate is,

$$f_{s\,(min)} = 2 \times 4.5 \text{ kHz} = 9 \text{ kHz} \quad \text{...Ans.}$$

Ex. 5.6.4 : A signal x_1 (t) is bandlimited to 3 kHz. There are three more signals x_2 (t), x_3 (t) and x_4 (t) which are bandlimited to 1 kHz each. These signals are to be transmitted by a TDM system.

(a) Design a TDM scheme where each signal is sampled at its Nyquist rate.

(b) What must be the speed of the commutator ?

(c) Calculate the minimum transmission bandwidth of the channel.

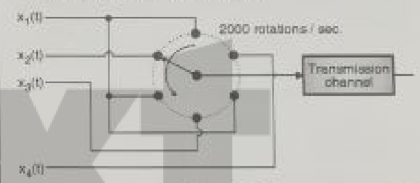
Soln. :

(a) Table P. 5.6.4 shows different message signal with corresponding Nyquist rates.

Table P. 5.6.4

Message signal	Bandwidth	Nyquist rate
x_1 (t)	3 kHz	6 kHz
x_2 (t)	1 kHz	2 kHz
x_3 (t)	1 kHz	2 kHz
x_4 (t)	1 kHz	2 kHz

- If the sampling commutator rotates at the rate of 2000 rotations per second then the signals x_2 (t), x_3 (t) and x_4 (t) will be sampled at their Nyquist rate. But we have to sample x_1 (t) also at its Nyquist rate which is three times higher than that of the other three.
- In order to achieve this we should sample x_1 (t) three times in one rotation of the commutator. Therefore the commutator must have atleast 6 poles connected to the signals as shown in Fig. P. 5.6.4.



(L-135) **Fig. P. 5.6.4**

(b) The speed of rotation of the commutator is 2000 rotations/sec.

(c) Number of samples produced per second is calculated as follows :

x_1 (t) produces 3×2000 = 6000 samples/sec.

x_2 (t), x_3 (t) and x_4 (t) produce 2000 samples/sec. each.

$\therefore$ Number of samples per second = 6000 + (3 × 2000)

= 12000 samples/sec.

$\therefore$ Signaling rate = 12000 samples/sec.

(d) The minimum channel bandwidth is,

$$B_T = \frac{1}{2} \text{ signaling rate}$$

$$= 12000/2$$

$$\therefore \quad B_T = 6000 \text{ Hz} \quad \text{...Ans.}$$

Ex. 5.6.5 : Twenty four voice signals are sampled uniformly and then time division multiplexed. The sampling operation uses flat top samples with 1 μS duration. The multiplexing operation includes provision for synchronization by adding an extra pulse of appropriate amplitude and 1 μS duration. The highest frequency component of each voice signal is 3.4 kHz.

(a) Assuming a sampling rate of 8 kHz, calculate the spacing between successive pulses of the multiplexed signal.

(b) Repeat (a), assuming the use of Nyquist rate sampling.

Soln. :

(a) It has been given that :

1. Sampling rate = 8 kHz = 8000 samples/sec.
2. There are 24 voice signals + 1 synchronizing pulse.
3. Pulse width of each voice channel and synchronizing pulse is 1 μS.

Time taken by the commutator for 1 rotation $= \frac{1}{8000}$

= 125 μsec.

Number of pulses produced in 1 rotation = 24 + 1 = 25

∴ The leading edges of the pulses are at $\frac{125}{25} = 5$ μsec. distance as shown in Fig. P. 5.6.5.

(L-136) **Fig. P. 5.6.5**

Therefore spacing between successive pulses = 5 − 1 = 4 μS ...**Ans.**

(b) Nyquist rate of sampling = 2 × 3.4 kHz = 6.8 kHz.

That means 6800 samples are produced per second. One rotation of commutator takes

1/6800 = 147 μS time.

∴ 147 μsec corresponds to 25 pulses

∴ 1 pulse corresponds to 5.88 μsec.

As the pulse width of each pulse is 1 μ sec, the spacing between adjacent pulses will be 4.88 μsec. and if we assume τ = 0 then the spacing between the adjacent pulses will be 5.88 μ sec.

Ex. 5.6.6 : Six message signals each of bandwidth 5 kHz are time division multiplexed and transmitted. Calculate the signaling rate and the minimum channel bandwidth of the PAM/TDM channel.

Soln. :

The number of channels N = 6

Bandwidth of each channel, W = 5 kHz

Minimum sampling rate = 2 × 5 kHz = 10 kHz

Signaling rate = Number of bits per second

= 6 × 10 kHz

= 60 kbits/sec. ...**Ans.**

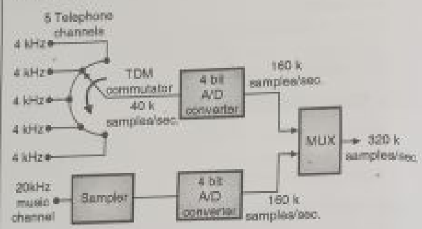
Minimum channel bandwidth to avoid cross talk in PAM/TDM is,

B_T = NW = 6 × 5 kHz = 30 kHz ...**Ans.**

Ex. 5.6.7 : Sketch a channel interleaving scheme for time division multiplexing the following PAM signals : Five 4 kHz telephone channels and one 20 kHz music channel. Find the pulse repetition rate of the multiplexed signal and estimate the minimum system bandwidth required.

Soln. :

Each telephone channel of bandwidth 4 kHz must be sampled at Nyquist rate i.e. 2 × 4 kHz = 8 kHz using a TDM commutator. The 20 kHz music channel must be sampled at 40 kHz (Nyquist rate) hence a separate sampler is required. The sampled signals are applied to two 4-bit A-D converters to obtain the equivalent digital signals. These signals are finally multiplexed using a multiplexer as shown in Fig. P. 5.6.7.



(L-769) **Fig. P. 5.6.7 : PAM-TDM system for Ex. 5.6.7**

The TDM commutator output has a pulse repetition rate of 40k samples/sec as there are 5 channel and sampling rate is 8 kHz. Similarly the output of the separate sampler has a pulse repetition rate of 40 k samples/sec. The outputs of A-D converters have pulse repetition rates of 40 × 4 = 160 k samples/sec. Therefore pulse repetition rate at the output of a multiplexer is 160 + 160 = 320 k samples/sec.

∴ Pulse repetition rate of the system = 320 kHz

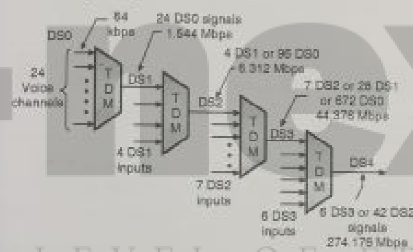
∴ Bandwidth required = Bit rate = 320 kHz ....**Ans.**

5.7 Comparison of FDM and TDM Systems :

Sr. No.	FDM	TDM
1.	The signals which are to be multiplexed are added in the time domain. But they occupy different slots in the frequency domain.	The signals which are to be multiplexed can occupy the entire bandwidth but they are isolated in the time domain.
2.	FDM is usually preferred for the analog signals.	TDM is preferred for the digital signals.
3.	Synchronization is not required.	Synchronization is required.
4.	The FDM requires a complex circuitry at the transmitter and receiver.	TDM circuitry is not very complex.
5.	FDM suffers from the problem of crosstalk due to imperfect band pass filters.	In TDM the problem of crosstalk is not severe.
6.	Due to wideband fading in the transmission medium, all the FDM channels are affected.	Due to fading only a few TDM channels will be affected.
7.	Due to slow narrowband fading taking place in the transmission channel only a single channel may be affected in FDM.	Due to slow narrowband fading all the TDM channels may get wiped out.

5.8 Digital Signal (DS) Service :

- The telephone companies implement TDM (time division multiplexing) through the hierarchy of digital signals. This is called as digital signal (DS) service or digital hierarchy.
- Fig. 5.8.1 shows the DS hierarchy and the bit rates corresponding to various levels.



(G-1311) **Fig. 5.8.1 : D.S. hierarchy**

Explanation :

- A DS0 signal is the basic input signal which is a single digital channel (usually 64 kbps PCM channel).
- 24 DS0 signals are multiplexed using TDM to produce a DS1 signal. The bit rate of DS1 is 24 × 64 kbps = 1.544 Mbps plus 8 kbps of overhead.
- 4 such DS1 signals are multiplexed at the second level of multiplexing to obtain the DS2 signal.
- One DS2 signal is equivalent to 4 DS1 or 96 DS0 signals and it has a bit rate of 6.312 Mbps.
- 7 DS2 signals are multiplexed to produce a DS3 signal. Its bit rate is 44.376 Mbps and it is equivalent to 7 DS2 or 28 DS1 or 672 DS0 signals.
- Finally 6 DS3 lines are multiplexed to obtain a DS4 signal. Its bit rate is 274.176 Mbps. It is obtained as a result of 6 DS3 or 42 DS2 channels, 168 DS1 channels and 4032 DS0 channels.

5.8.1 T Lines :

- DS0, DS1, DS2, ... etc. are the names of the services. The telephone companies use the T lines (T0, T1, T2, ... etc.) to implement these services.
- The T lines have capacities which precisely match with the bit rates of the corresponding services as shown in Table 5.8.1.

Table 5.8.1 : Relation between DS and T lines

Service	Line	Rate (Mbps)	Number of 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

- Thus T – 1 line implements DS – 1 service, T – 2 implements DS – 2 service and so on.
- DS0 is defined as the basic service.

Note : T lines are digital lines which are designed to carrying digital data, audio or video.

- But the T lines can also be used for analog communication. For example T1 line can be used for the telephone applications.

5.9 T Lines for Analog Transmission :

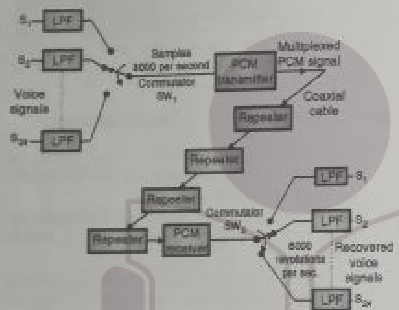
- When a large number of PCM signals are to be transmitted over a common channel, multiplexing of these PCM signals is required.
- Fig. 5.9.1 shows the basic time division multiplexing scheme for PCM voice channels called as the T_1 **digital system.**
- This system is used to convey a number of voice signals over telephone lines using wideband coaxial cable. Thus the communication medium used is a coaxial cable.

Operation of the T_1 system :

The operation of the PCM-TDM system shown in Fig. 5.9.1 is as follows :

- This system has been designed to multiplex 24 voice channels marked as S_1 to S_{24}. Each signal is bandlimited to 3.3 kHz, and the sampling is done at a standard rate of 8 kHz. This sampling rate is higher than the Nyquist rate. The sampling is done by the commutator switch SW_1.
- These voice signals are selected one by one and connected to a PCM transmitter by the commutator switch SW_1, as it completes its rotation. The commutator switch remains in contact with each voice channel for a short time. Thus it samples each of the 24 channels.
- Each sampled signal is then applied to the PCM transmitter which converts it into a digital signal by the process of A to D conversion and companding. Each sampled voice signal is converted into an 8-bit PCM word.
- The resulting digital waveform is transmitted over a co-axial cable. This waveform is called as the PCM-TDM signal.

- Periodically, after every 6000 ft., the PCM-TDM signal is regenerated by amplifiers called "Repeaters". They eliminate the distortion introduced by the channel and remove the superimposed noise and regenerate a clean noise free PCM-TDM signal at their output. This ensures that the received signal is free from the distortions and noise.
- At the destination the signal is companded, decoded and demultiplexed, using a PCM receiver. The PCM receiver output is connected to different low pass filters via the commutator switch SW_2. The LPF outputs are applied to the destination receivers (subscribers).
- Synchronization between the transmitter and receiver commutators SW_1 and SW_2 is essential in order to ensure proper communication.



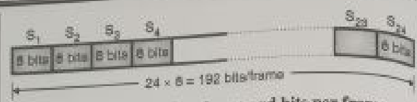
(G-1312) **Fig. 5.9.1 : Block diagram of a basic PCM-TDM system**

Bits/Frame :

- The commutators sweep continuously from S_1 to S_{24} and back to S_1 at the rate of 8000 revolutions per second (Sampling rate = 8000 samples/sec.).
- This will generate 8000 samples per second of each signal (S_1 to S_{24}). Each sample is then encoded (converted) into an eight bit digital word. One complete revolution of commutator switches corresponds to generation of one frame which consists of all 24 voice channels.
- Thus the digital signal generated during one complete sweep (revolution) of the commutator is given by :

$$\begin{aligned} 1 \text{ Frame} &= 1 \text{ revolution} \\ &= 24 \text{ channels} \\ &= 24 \times 8 \text{ bits} = 192 \text{ bits} \end{aligned}$$

- One frame of PAM-TDM is shown in Fig. 5.9.2. Each voice signal from S_1 to S_{24} is encoded into eight bits.
- One frame corresponds to one revolution which is the time taken to transmit each signal once. Hence 1-frame corresponds to one-revolution of the commutator.



(G-1313) **Fig. 5.9.2 : One frame and bits per frame**

5.9.1 Frame Synchronization :

- As we have already seen, the synchronization between the transmitter and receiver commutators is essential.
- Without such synchronization the receiver cannot know which received bits were generated by whom at the transmitter and are meant for which subscriber on the receiving side.
- To provide such synchronization, an extra bit is transmitted preceding the 192 data bits carrying the information in each frame, as shown in Fig. 5.9.3.
- This bit is called as the frame synchronizing bit "F". Thus one frame synchronizing bit is transmitted per frame.
- This makes the total number of bits per frame to be 193. The time slots for the 24 signals and the extra frame synchronizing bit is as shown in Fig. 5.9.3.

(G-1314) **Fig. 5.9.3 : The PCM T_1 frame using frame synchronization and channel associated signaling**

- Twelve successive F slots are used to transmit a 12 bit code. The code is 1101 1100 1000.
- This code is transmitted repeatedly once every 12 frames and it is used at the receiver to achieve synchronization between the transmitter and receiver commutators.

Bit rate :

- Bit rate means number of bits transmitted by a system per second. In the T1 system; as each signal is sampled 8000 times per second :

  1 frame (1 revolution of commutator) = 1/8000 = 125 μsec.

- But 1 frame consists of 193 bits.

  ∴ 193 bits are transmitted in 125μ sec.

$$\therefore \text{ Number of bits in 1 sec.} = \frac{193}{125 \times 10^{-6}} = 1.554 \times 10^6$$

$$\therefore \text{ Bit rate of } T_1 \text{ system} = 1.544 \text{ Mbits/sec.}$$

Bandwidth of T_1 system :

$$\text{Minimum bandwidth } B_T = \frac{1}{2} \text{ bit rate} = \frac{1}{2} \times 1.544 \times 10^6 = 772 \text{ kHz}$$

Duration of each bit :

$$\begin{aligned} 193 \text{ bits} &= 125\ \mu S \\ 1 \text{ bit} &= (125 / 193)\ \mu S \\ &= 0.6476\ \mu S \end{aligned}$$

5.9.2 Channel Associated Signaling :

- When the PCM-TDM system is being used for the telephony, it is expected to transmit certain control signals along with the voice information. The control information is of two types : signalling and supervisory.
- The signaling information consists of the signals such as a call is being initiated or a call is being terminated, or the address of calling party etc.
- In analog system such a signaling information is transmitted over a separate channel other than the voice channel. But in the T_1 system which is a digital system, a separate channel is not used.
- In T_1 system the signaling information is sent using the same data bit slots which are used to send the voice information. The technique used is "bit slot sharing".
- In the "bit slot sharing" method, for the first five frames, all the 24 channels are encoded into an 8 bit digital code. That means all the 8-bits in each PCM word will carry the voice information.
- However in the sixth frame, all the channels are coded into a 7 bit code and the LSB (least significant bit) of each channel is used to transmit the signaling information. This is as shown in Fig. 5.9.3. That means MSB 7-bits carry voice and the LSB bit carries the signalling information.
- This is called as "channel associated signalling". This pattern is repeated after every six frames.

5.9.3 E Lines :

- E-line is actually the European version of T lines. The T lines and E lines are conceptually identical but their capacities and number of voice channels which they can carry will be different.
- Table 5.9.1 shows the E lines, their capacities and the number of voice channels which they can carry.

Table 5.9.1 : E lines and their capacity

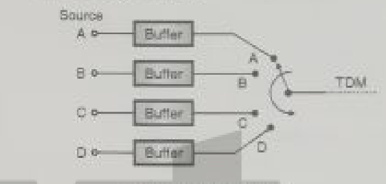
Line	Rate (Mbps)	Number of voice channels
E – 1	2.048	30
E – 2	8.448	120
E – 3	34.368	480
E – 4	139.264	1920

5.9.4 Applications of Synchronous TDM :

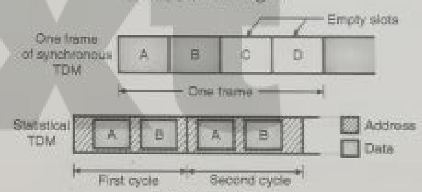
1. For analog telephone system (T – 1 system).
2. Some second generation cellular telephone companies use synchronous TDM.

5.10 Statistical TDM :

- The TDM system that we have discussed earlier is known as the synchronous TDM. This system has a major drawback. In synchronous TDM, many of the time slots in a frame are wasted due to absence of data on some of the time slots.
- Therefore an alternative system called as statistical TDM or asynchronous TDM or intelligent TDM is used.
- The block diagram of the statistical TDM system is as shown in Fig. 5.10.1(a) and its frame format is as shown in Fig. 5.10.1(b).



(L-136)(a) **Block diagram**



(b) Frame format

(L-136) **Fig. 5.10.1 : Statistical TDM**

Operating principle :

- In statistical TDM, the time slots are not permanently assigned to all the available users (like synchronous TDM). Instead, the time slots are allocated dynamically on demand only to those channels holding data for transfer.
- Each TDM channel is called as an I/O line. Thus the statistical TDM has many I/O lines and one high speed multiplexed line.
- Each I/O line has a buffer associated with it. As shown in Fig. 5.10.1, there are N number of I/O lines. Out of these only K channels are transmitted which hold data for transfer. The remaining (N – K) channels are not considered for transmission.
- In statistical TDM, the multiplexer will "scan" the input buffers of all the channels, sequentially. During the scan time, it collects the data until a frame is filled. As soon as a frame is filled, it is transmitted.
- The data is transferred on the transmission medium. The received frame is then distributed among the output buffers by the output multiplexer.

5.10.1 Data Rate of Statistical TDM :

- In statistical TDM system, all the channels are not transmitted in every frame. Hence the data rate on the multiplexed line will be less than the sum of the data rates of all the sources.
- Thus a statistical multiplexer can use a transmission medium of lower data rate to support the same number of sources as the synchronous multiplexer.
- That means if we have a synchronous and statistical TDM with equal data rates, then the statistical TDM will support more number of sources.

5.10.2 Slot Size :

- The slot carries both data and address, the ratio of the data size to address size should be reasonable to ensure high efficiency.
- In statistical TDM, the data block contains many bits while address bits are very few.

5.10.3 No Synchronization Bit :

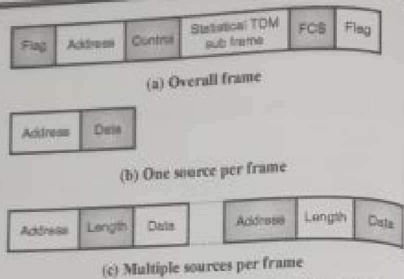
- The statistical TDM frames need not be synchronized. So it is not necessary to use the synchronizing bit.

5.10.4 Bandwidth :

- In statistical TDM, the capacity of multiplexed link is generally less than the sum of capacities of individual channels.
- Therefore the bandwidth requirement of the multiplexed link is less than that for the synchronous TDM.

5.10.5 Frame Format for Statistical TDM :

- Fig. 5.10.1(b) shows the comparison of synchronous and statistical TDM frames. It shows that there are four data sources and they are to be transmitted in four time slots t_0 to t_3.
- In the synchronous TDM, the data sources A and B only have data present whereas the data sources C and D do not have any data. Hence time slots $(t_1 - t_2)$ and $(t_2 - t_3)$ corresponding to these sources are empty.
- On the other hand, the statistical TDM system does not send the empty slots. Thus during the first cycle, data from the sources A and B only is transmitted.
- As the data from A and B only is being sent and the time slots of C and D are utilized for this purpose, the positional identity of slots is lost in statistical TDM. We cannot predict ahead of time about data from which source will be in which slot.
- Due to this unpredictability, the address information is required to be sent alongwith the data information. This address is then used for proper delivery of data.
- Thus each slot of statistical TDM carries an address as well as data. The detailed frame structure is as shown in Fig. 5.10.2.



(a) Overall frame

(b) One source per frame

(c) Multiple sources per frame

(L-146) **Fig. 5.10.2 : Frame formats of statistical TDM**

Now refer to Fig. 5.10.2.

- The frame structure for the statistical TDM should be such that it should minimize the overhead bits. This is important for improving the throughout efficiency.
- The statistical TDM system uses a synchronous protocol such as HDLC. Therefore within the HDLC frame, the data frame contains the control bits for the sake of multiplexing operation.
- Fig. 5.10.2 shows two such frame formats. Fig. 5.10.2(b) shows only one source of data per frame. This source is identified by the associated address. The length of the data field is variable and its end is identified by the end of overall frame.

  But the one source per frame scheme will work properly only for light loads. It is quite inefficient under the heavy load condition.

Improvement in efficiency :

1. The throughput efficiency can be improved by allowing the multiple data sources to be packaged in a single frame as shown in Fig. 5.10.2(c).
2. When many sources are packaged in a single frame it is necessary to specify the length of data for each source. Therefore the statistical TDM subframe consists of a sequence of data fields. Each data field is labelled with an address and a length.

5.10.6 Comparison of FDM, Synchronous TDM and Statistical TDM :

Table 5.10.1 : Comparison of data multiplexer techniques

Sr. No.	Parameter	FDM	Synchronous TDM	Statistical TDM
1.	Line utilization efficiency	Poor	Good	Very good
2.	Flexibility	Poor	Good	Very good
3.	Channel capacity	Poor	Good	Excellent
4.	Error control	Not possible	Not possible	Possible
5.	Multidrop capacity	Very good	Difficult to achieve	Possible
6.	Transmission delay	Does not exist	Low	Random
7.	Cost	High	Low	Moderate

Review Questions

Q. 1 With the help of block schematic, explain the principle of FDM.

Q. 2 Compare FDM and TDM methods of multiplexing.

Q. 3 Illustrate working of FDM used for 96 channels of telephone.

Q. 4 With the help of block diagram explain the FDM system for telephone communication.

Q. 5 Explain the principles of Time Division Multiplexing.

Q. 6 What is statistical TDM ?

Q. 7 What is the difference between synchronous and statistical TDM ?

Q. 8 What are the advantages of statistical TDM ?

Q. 9 Why is it necessary to use time division multiplexing while transmitting PAM signals ?

Q. 10 Why is synchronization needed in TDM system ?

Q. 11 Describe how transmission distortion of a TDM signal can cause cross-talk between two adjacent channels ?

Q. 12 Describe the multiplexing hierarchy for an FDM system.

Q. 13 Describe the multiplexing hierarchy for digital multiplexing.

Q. 14 Explain the PCM-TDM system.

Q. 15 What do you understand by the channel associated signaling ?

Q. 16 State the applications of PCM-TDM.

Q. 17 How is synchronization achieved in PCM-TDM system ?

Q. 18 State advantages and disadvantages of TDM system.

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