Bandwidth Utilization: Multiplexing

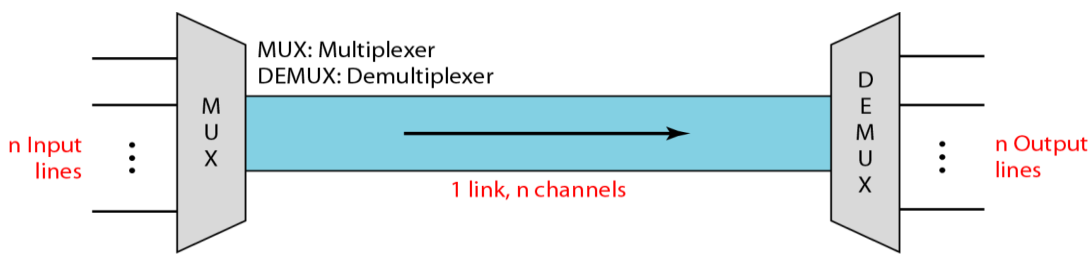
Bandwidth utilization is the wise use of available bandwidth to achieve specific goals. Efficiency can be achieved by multiplexing and privacy & anti-jamming can be achieved by spreading.

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.

If the bandwidth of a link is greater than the bandwidth needs of the devices connected to it, the bandwidth is wasted. An efficient system maximizes the utilization of all resources; bandwidth is one of the most precious resource.

Figure below shows the basic format of a multiplexed system. The lines on the left direct their transmission streams to a multiplexer (MUX), which combines them into a single stream (many-to one). At the receiving end, that stream is fed into a de-multiplexer (DEMUX), which separates the stream back into its component transmissions (one-to-many) and directs them to their corresponding lines. In the figure, the word ***link*** refers to the physical path. The word ***channel*** refers to the portion of a link that carries a transmission between a given pair of lines. One link can have many *(n)* channels.



There are three basic multiplexing techniques: **frequency-division multiplexing, wavelength-division multiplexing** and **time-division multiplexing**. The first two are techniques designed for analog signals, the third, for digital signals.

Frequency-Division Multiplexing

Frequency-division multiplexing (FDM) is an analog technique that can be applied when the bandwidth of a link (in hertz) is greater than the combined bandwidths of the signals to be transmitted. 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 overlapping.

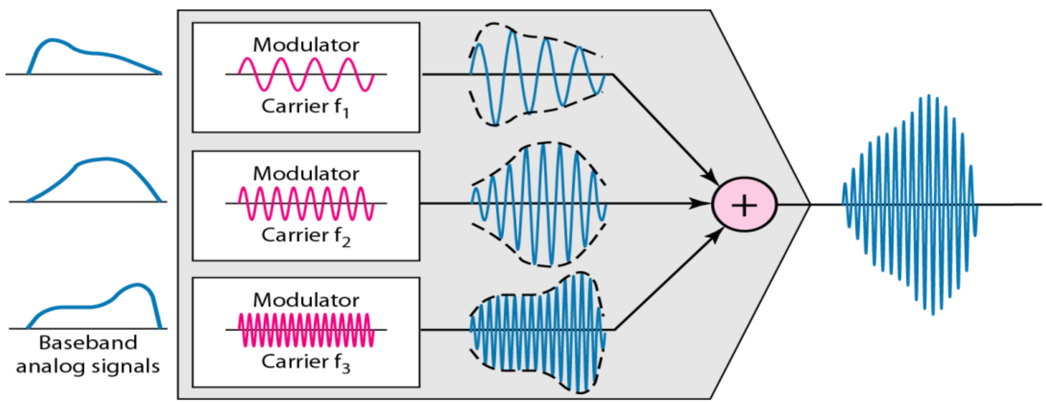
Figure below gives a conceptual view of FDM. In this illustration, the transmission path is divided into three parts, each representing a channel that carries one transmission.

 krishnaprasad@nitte.edu.in

We consider FDM to be an analog multiplexing technique; however, this does not mean that FDM cannot be used to combine sources sending digital signals. A digital signal can be converted to an analog signal before FDM is used to multiplex them.

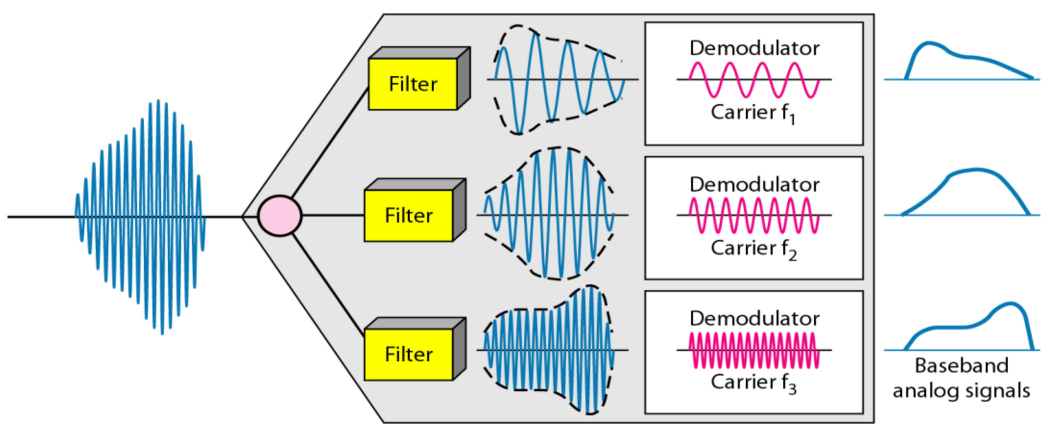
Multiplexing Process

Each source generates a signal of a similar frequency range. Inside the multiplexer, these similar signals modulates different carrier frequencies *(f_1, f_2 & f_3)*. The resulting modulated signals are then combined into a single composite signal that is sent out over a media link that has enough bandwidth to accommodate it.



De-multiplexing Process

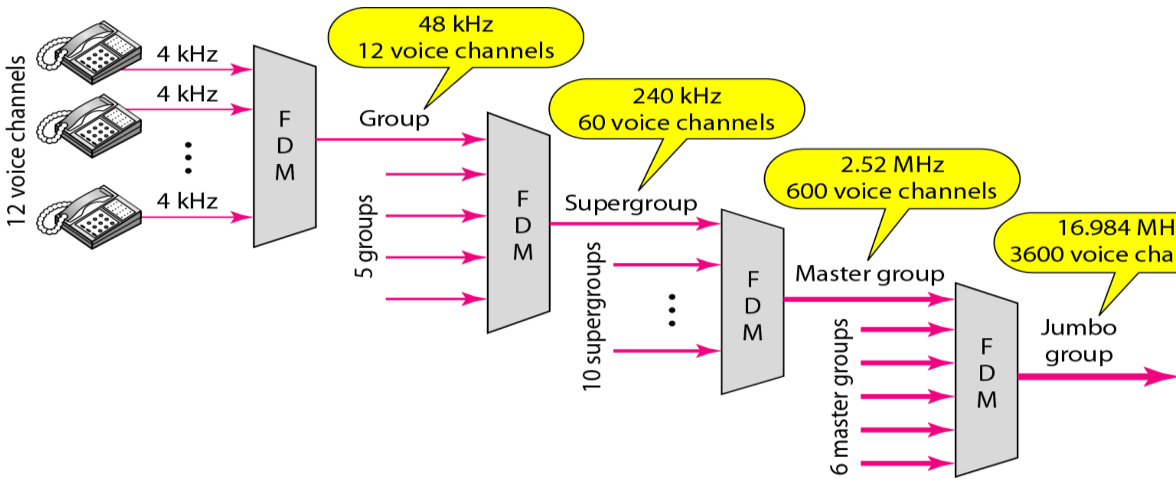
The de-multiplexer uses a series of filters to decompose the multiplexed signal into its constituent component signals. The individual signals are then passed to a demodulator that separates them from their carriers and passes them to the output lines.



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.

One of these hierarchical systems used by AT&T is made up of groups, super groups, master groups, and jumbo groups.



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 **super group**. A super group has a bandwidth of 240 kHz and supports up to 60 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. Finally, six master groups can be combined into a **jumbo group**. A jumbo group must have 15.12 MHz (6 x 2.52 MHz) but is augmented to 16.984 MHz to allow for guard bands between the master groups.

Other Applications of FDM

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. Without multiplexing, only one AM station could broadcast to the common link, the air. The situation is similar in FM broadcasting.

Another common use of FDM is in **television broadcasting**. Each TV channel has its own bandwidth of 6MHz.

Implementation

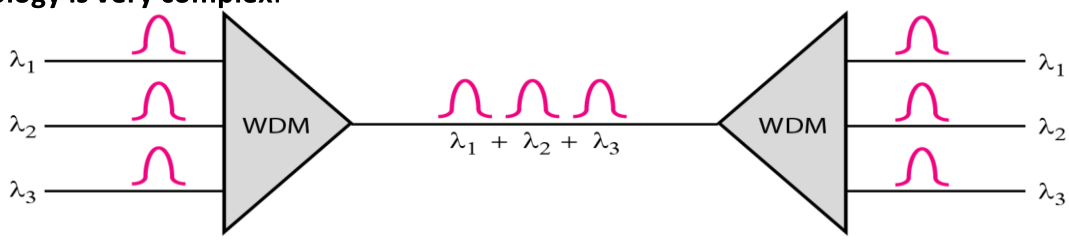
FDM is easy to implement. In **radio and television broadcasting**, there is no need for a physical multiplexer or de-multiplexer. As long as the stations agree to send their broadcasts to the air using different carrier frequencies, multiplexing is achieved.

In **cellular telephone system**, a base station needs to assign a carrier frequency to the telephone user. There is not enough bandwidth in a cell to permanently assign a bandwidth range to every telephone user. When a user hangs up, her or his bandwidth is assigned to another caller.

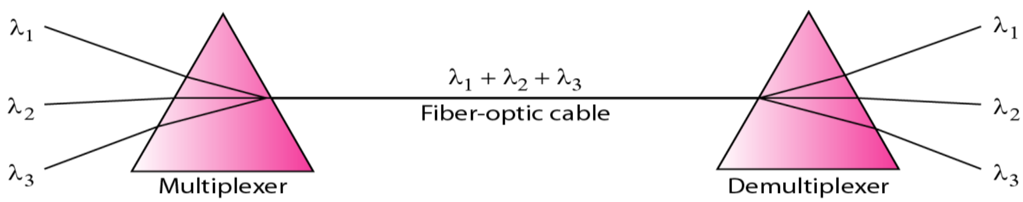
Wavelength-Division Multiplexing

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. Multiplexing allows us to combine several lines into one.

WDM is conceptually the same as FDM, except that the multiplexing and de-multiplexing involve optical signals transmitted through fiber-optic channels. The idea is the same: We are combining different signals of different frequencies. The **difference is that the frequencies are very high**. Very narrow bands of light from different sources are combined to make a wider band of light. Figure below gives a conceptual view of a WDM multiplexer and de-multiplexer. **WDM technology is very complex**.

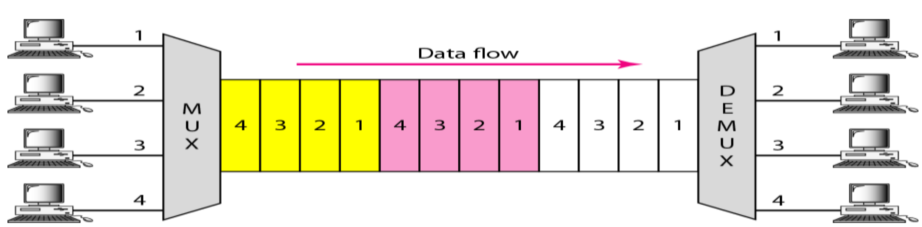


To combine multiple light sources into one single light at the multiplexer and do the reverse at the de-multiplexer, the concept of prism is used i.e. A prism bends a beam of light based on the angle of incidence and the frequency. Using this technique, a multiplexer can be made to combine several input beams of light, each containing a narrow band of frequencies, into one output beam of a wider band of frequencies. A de-multiplexer can also be made to reverse the process.



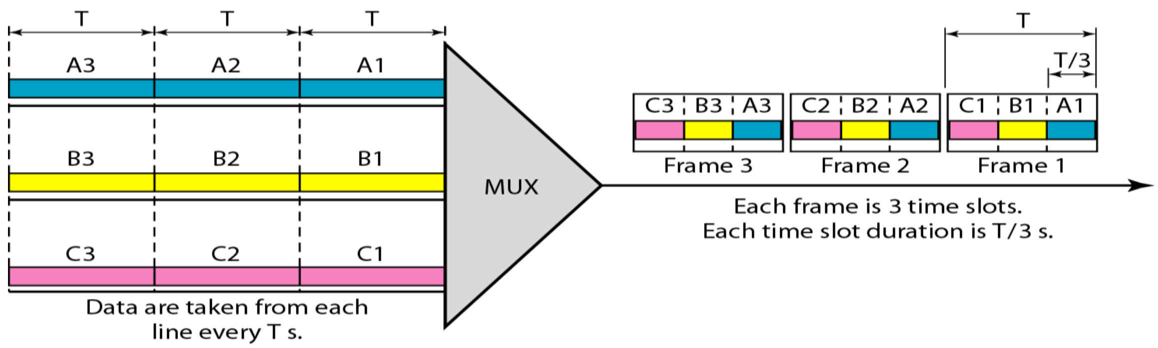
Time-Division Multiplexing

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. Figure below gives a conceptual view of TDM. (Note that in Figure, we are concerned with only multiplexing, not switching. This means that all the data in a message from source 1 always go to one specific destination, be it 1, 2, 3, or 4.)



TDM is a digital multiplexing technique. Digital data from different sources are combined into one timeshared link. Even the sources can produce analog data that can be sampled, changed to digital data, and then multiplexed by using TDM.
Two different schemes of TDM: **synchronous and statistical**.

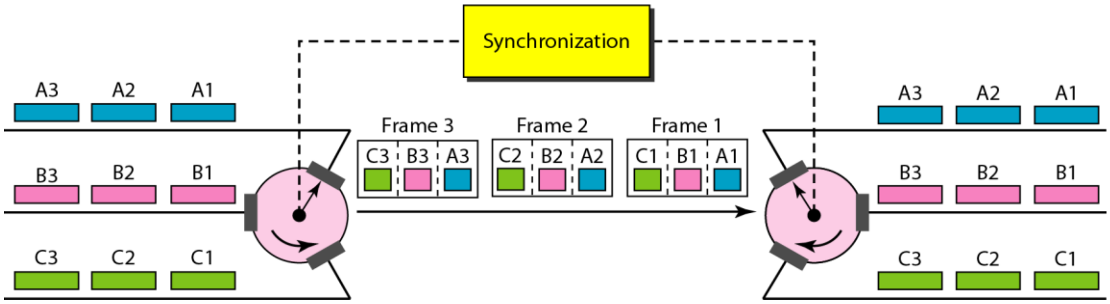
Synchronous TDM
In Synchronous TDM, each input connection has an allotment in the output even if it is not sending data.
Time Slots and Frames
In synchronous TDM, the data flow of each input connection is divided into units, where each input occupies one input time slot. A unit can be 1 bit, one character, or one block of data. Each input unit becomes one output unit and occupies one output time slot. However, the duration of an output time slot is *n* 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. In other words, a unit in the output connection has a shorter duration; it travels faster.



In synchronous TDM, a round of data units from each input connection is collected into a frame. If we have *n* connections, a frame is divided into *n* time slots and one slot is allocated for each unit, one for each input line. If the duration of the input unit is *T,* the duration of each slot is *T/n* and the duration of each frame is *T*.
The data rate of the output link must be *n* times the data rate of a connection to guarantee the flow of data. In Figure above, the data rate of the link is 3 times the data rate of a connection; likewise, the duration of a unit on a connection is 3 times that of the time slot (duration of a unit on the link). In the figure we represent the data prior to multiplexing as 3 times the size of the data after multiplexing. This is just to convey the idea that each unit is 3 times longer in duration before multiplexing than after.
Time slots are grouped into frames. A frame consists of one complete cycle of time slots, with one slot dedicated to each sending device. In a system with *n* input lines, each frame has *n* slots, with each slot allocated to carrying data from a specific input line.

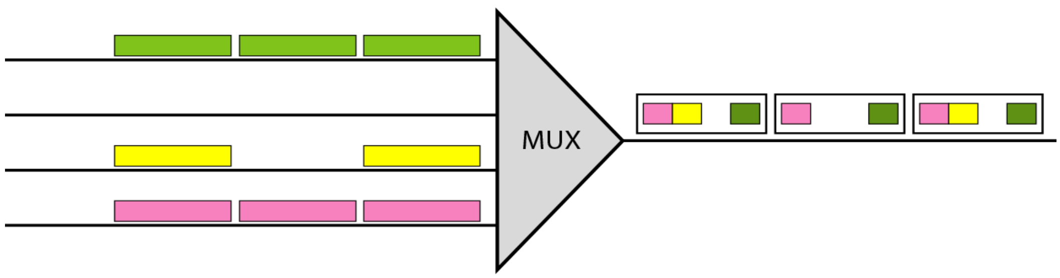
Interleaving
TDM can be visualized as two fast-rotating switches, one on the multiplexing side and the other on the de-multiplexing side. The switches are synchronized and rotate at the same speed, but in opposite directions. On the multiplexing side, as the switch opens in front of a connection, that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

On the de-multiplexing side, as the switch opens in front of a connection, that connection has the opportunity to receive a unit from the path.



Empty Slots

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. Figure below shows a case in which one of the input lines has no data to send and one slot in another input line has discontinuous data.

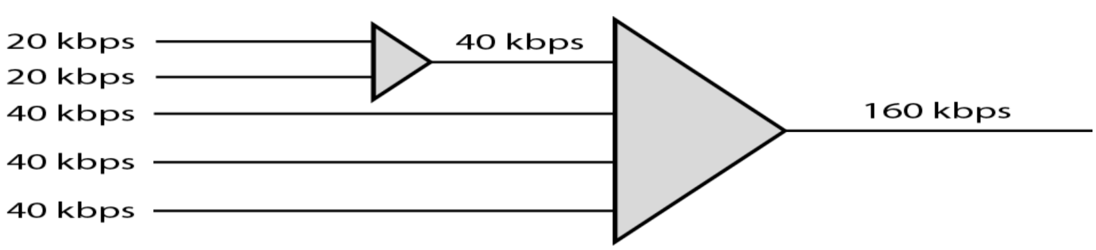


The first output frame has three slots filled, the second frame has two slots filled, and the third frame has three slots filled. No frame is full.

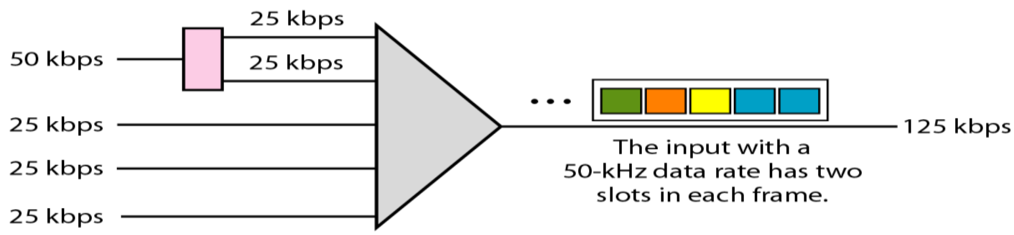
Data Rate Management

One problem with TDM is how to handle a disparity in the input data rates. In all our discussion so far, we assumed that the data rates of all input lines were the same. However, if data rates are not the same, three strategies, or a combination of them, can be used.
The three strategies are: **multilevel multiplexing, multiple-slot allocation** and **pulse stuffing.**

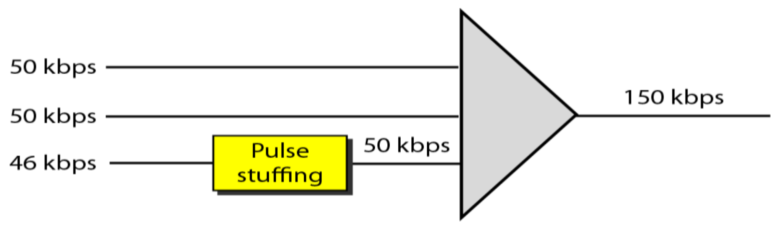
Multilevel Multiplexing: Multilevel multiplexing is a technique used when the data rate of an input line is a multiple of others. For example, in Figure, we have two inputs of 20 kbps and three inputs of 40 kbps. The first two input lines can be multiplexed together to provide a data rate equal to the last three. A second level of multiplexing can create an output of 160 kbps.



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. In Figure, the input line with a 50kbps data rate can be given two slots in the output. We insert a serial-to-parallel converter in the line to make two inputs out of one.

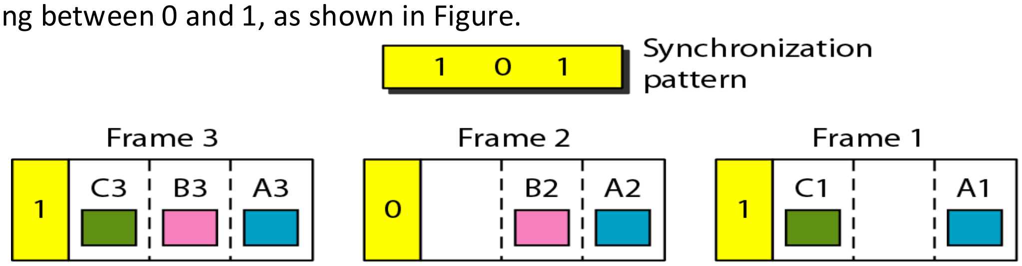


Pulse Stuffing: Sometimes the bit rates of sources are not multiple integers of each other. Therefore, neither of the above two techniques can be applied. One solution is to make the highest input data rate the dominant data rate and then add dummy bits to the input lines with lower rates. This will increase their rates. This technique is called pulse stuffing, bit padding, or bit stuffing. The input with a data rate of 46 kbps is pulse-stuffed to increase the rate to 50 kbps.



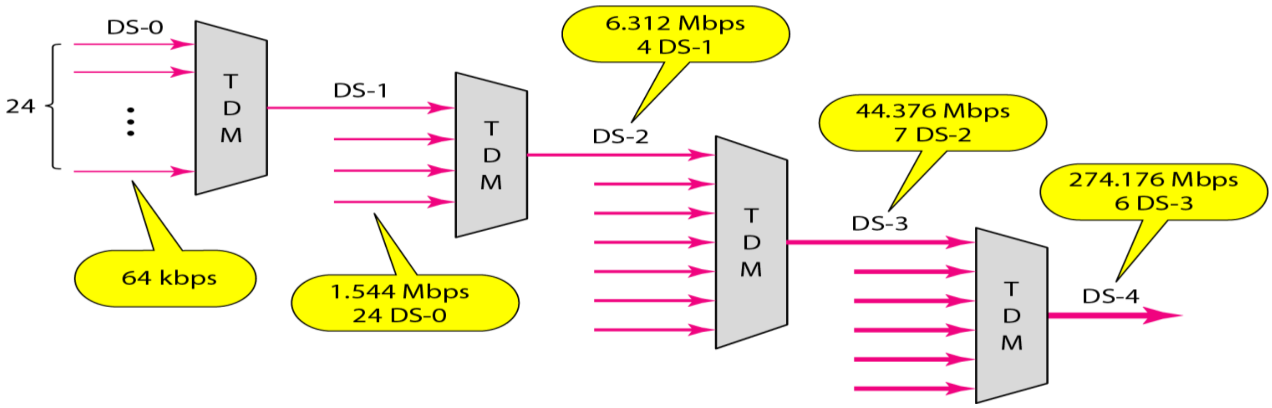
Frame Synchronizing

Synchronization between the multiplexer and de-multiplexer is a major issue. If the multiplexer and the de-multiplexer are not synchronized, a bit belonging to one channel may be received by the wrong channel. For this reason, one or more synchronization bits are usually added to the beginning of each frame. These bits, called framing bits, follow a pattern, frame to frame, that allows the de-multiplexer to synchronize with the incoming stream so that it can separate the time slots accurately. In most cases, this synchronization information consists of 1 bit per frame, alternating between 0 and 1, as shown in Figure.



Digital Signal Service

Telephone companies implement TDM through a hierarchy of digital signals, called digital signal (DS) service or digital hierarchy.



- A **DS-0** service is a single digital channel of 64 kbps.
- **DS-1** is a 1.544-Mbps service; 1.544 Mbps is 24 times 64 kbps plus 8 kbps of overhead. It can be used as a single service for 1.544-Mbps transmissions, or it can be used to multiplex 24 DS-0 channels or the combination of these service types.
- **DS-2** is a 6.312-Mbps service; 6.312 Mbps is 96 times 64 kbps plus 168 kbps of overhead. It can be used as a single service for 6.312-Mbps transmissions; or it can be used to multiplex 4 DS-1 channels, 96 DS-0 channels, or a combination of these service types.
- **DS-3** is a 44.376-Mbps service; 44.376 Mbps is 672 times 64 kbps plus 1.368 Mbps of overhead. It can be used as a single service for 44.376-Mbps transmissions; or it can be used to multiplex 7 DS-2 channels, 28 DS-l channels, 672 DS-0 channels, or a combination of these service types.
- **DS-4** is a 274. 176-Mbps service; 274.176 is 4032 times 64 kbps plus 16.128 Mbps of overhead. It can be used to multiplex 6 DS-3 channels, 42 DS-2 channels, 168 DS-1 channels, 4032 DS-0 channels, or a combination of these service types.

T Lines

To implement Digital Signal (DS) 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-l to DS-4 services.

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

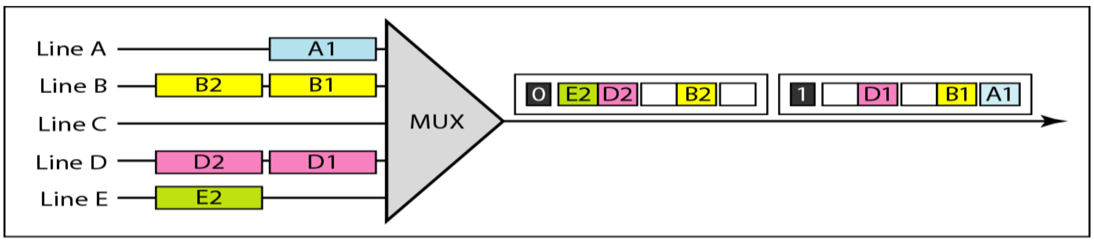
Statistical Time-Division Multiplexing

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.

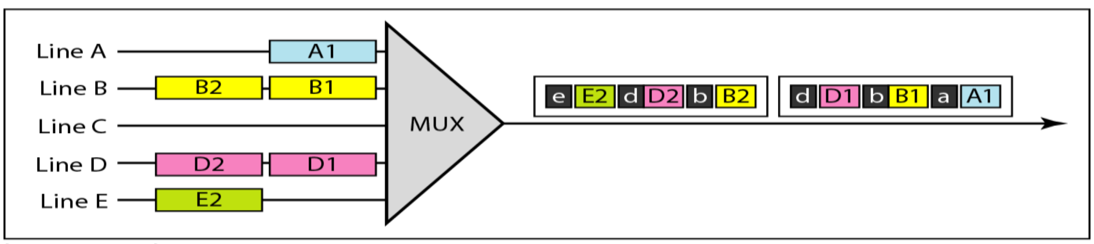
Figure below shows a synchronous and a statistical TDM example. In the former, some slots are empty because the corresponding line does not have data to send. In the latter, however, no slot is left empty as long as there are data to be sent by any input line.

Addressing

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 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 pre-assigned 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 $\mathbf{n = \log_2 N}$. For example, for eight different output lines, we need a 3-bit address.



a. Synchronous TDM



b. Statistical TDM

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

No Synchronization Bit

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. During peak times, some slots need to wait.