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2. Multiplexing

학습에 앞서

▪학습개요

- 두 개 이상의 장치가 전송 매체를 공유하여 통신하는 방법을 학습한다.

▪학습목표

- 매체 접근 제어 방식의 필요성을 설명할 수 있어야 한다.
- FDM, WDM, TDM 동작을 설명할 수 있어야 한다.

1. Multiplexing

Whenever the bandwidth of a medium linking two devices is greater than the bandwidth needs of the devices, the link can be shared. ***Multiplexing*** *is the set of techniques that allows the simultaneous transmission of multiple signals across a single data link. As data and telecommunications use increases, so does traffic.*

Topics discussed in this section:

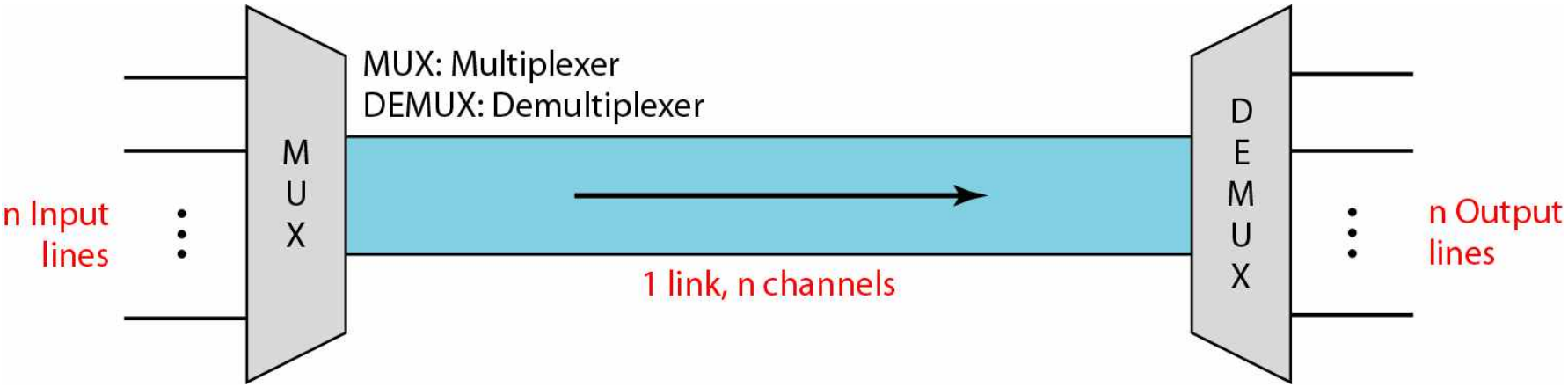
Frequency-Division Multiplexing
Wavelength-Division Multiplexing
Synchronous Time-Division Multiplexing
Statistical Time-Division Multiplexing

1. Multiplexing

- Multiplexing
  - The set of techniques that allows the simultaneous transmission of multiple signals across a single data link ➔ share the high-bandwidth of a medium
- Transmission service is the most significant cost
  - Two approaches to achieve greater efficiency in the use of transmission services
    - multiplexing: several information sources share a large transmission capacity
    - compression: reduces the number of bits required to represent a given amount of information
  - could be applied separately or, simultaneously
- Concept
  - combines many individual signals so they can be sent over one transmission medium
  - contains equipment to do multiplexing (MUX) and demultiplexing (DEMUX)

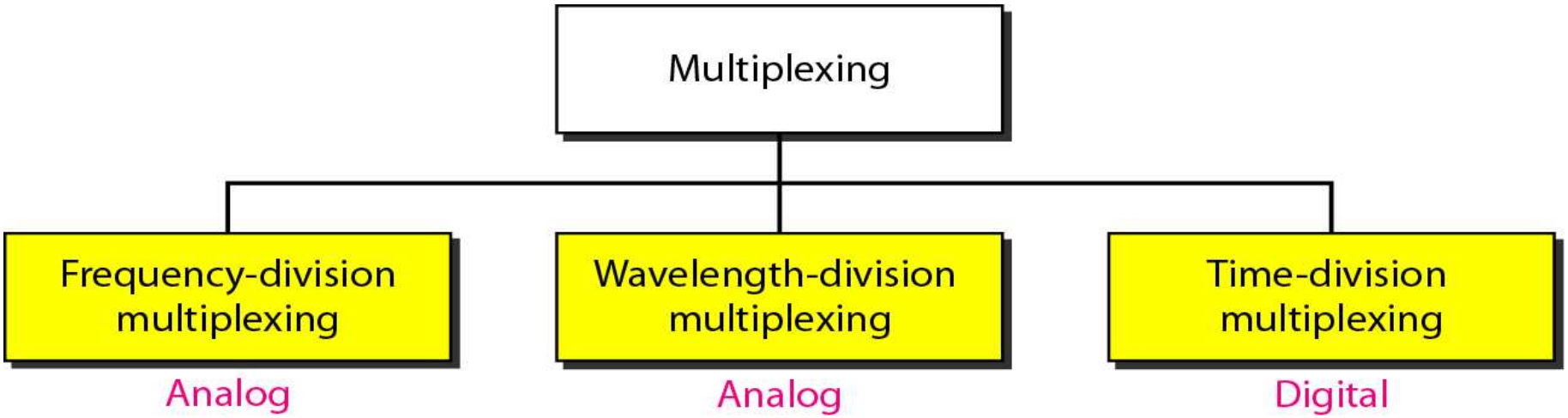
1. Multiplexing

- In a multiplexed system, n lines share the bandwidth of one link.
- Multiplexer (MUX)
  - combines multiple lines into a single stream (many-to-one)
- Demultiplexer (DEMUX)
  - separates the stream back into its component transmissions (one-to-many)
- Link
  - Physical path
- Channel
  - The portion of a link that carries a transmission between a given pair of lines.
  - One link can have many (n) channels.



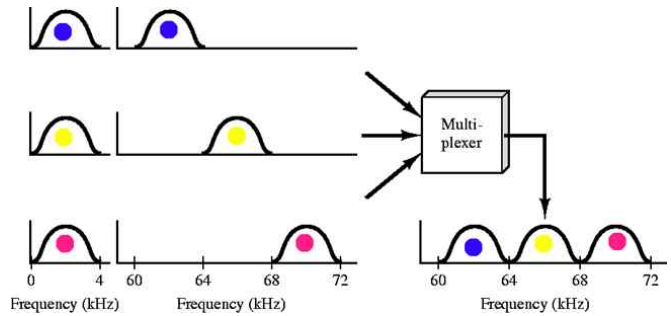
1. Multiplexing

- There are three basic multiplexing technique
  - Frequency-division multiplexing
  - Wavelength-division multiplexing
  - Time-division multiplexing



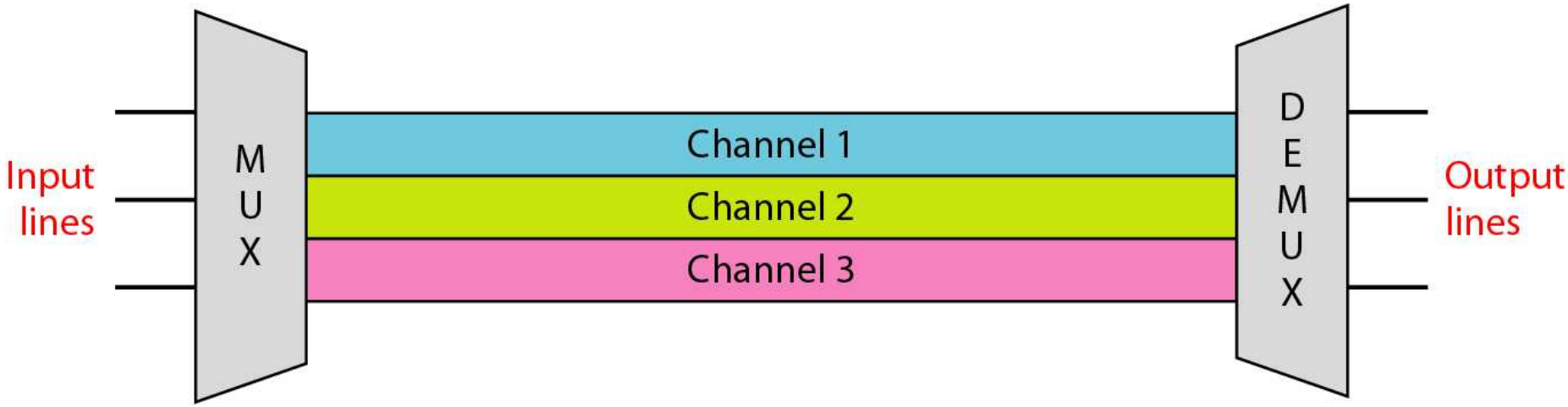
Frequency-Division Multiplexing (FDM)

- An analog technique that can be applied when the bandwidth of a link is greater than the combined bandwidth of the signals to be transmitted.
- Operation:
  - Signals generated by each device modulate different carrier frequencies.
  - These modulated signals are then combined into a single composite signal that can be transport by the link.
- Bandwidth:
  - Carrier frequencies are separated by sufficient bandwidth accommodate the modulated signal.
  - Channels can be separated by strips of unused bandwdith, guard bands, to prevent signals from overlapping.
  - Output bandwidth = sum of inputs + guard bands



Frequency-Division Multiplexing (FDM)

- Frequency-division multiplexing

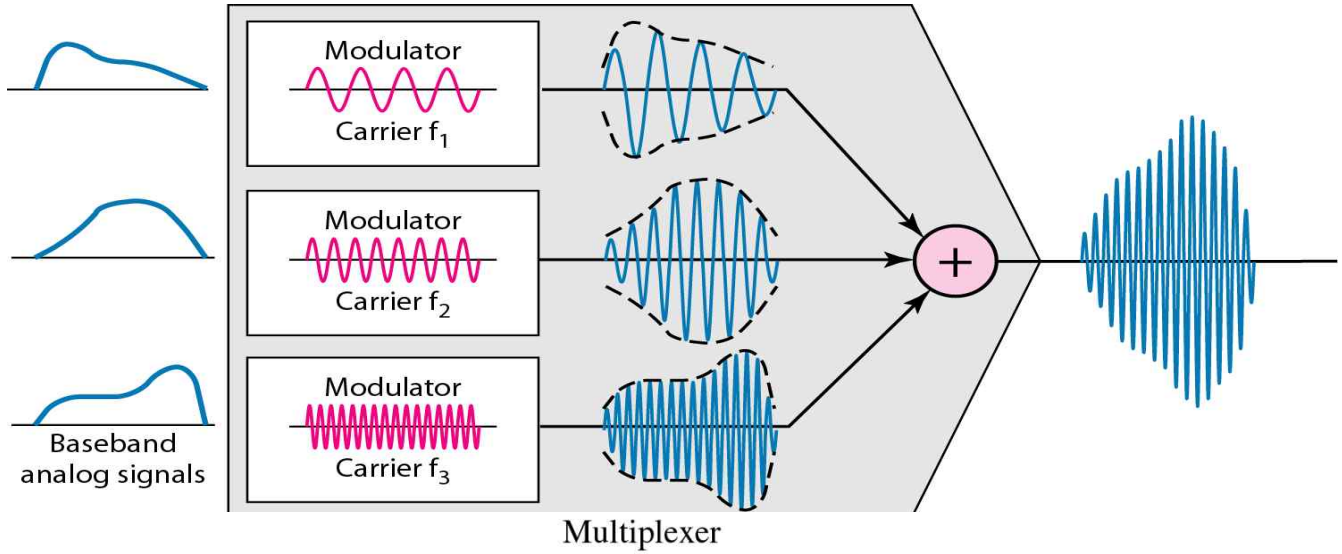


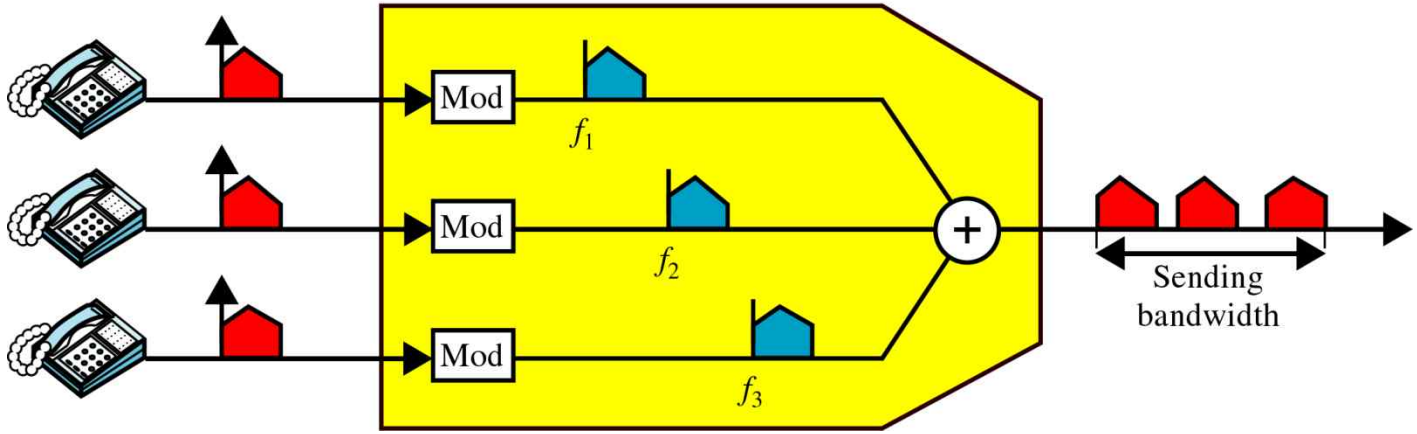
FDM is an analog multiplexing technique that combines analog signals.

1. Multiplexing

(1) Multiplexing process

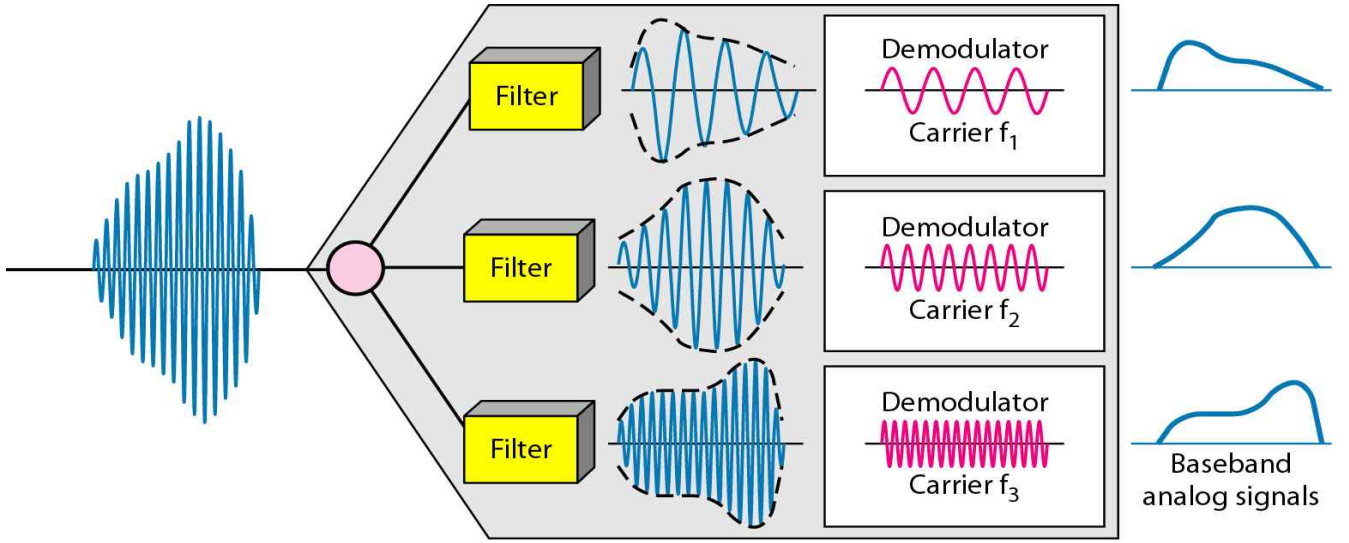
- Each source generates a signal of a similar frequency range.
- These similar signals modulates difference carrier frequencies (f_1, f_2, and f_3)

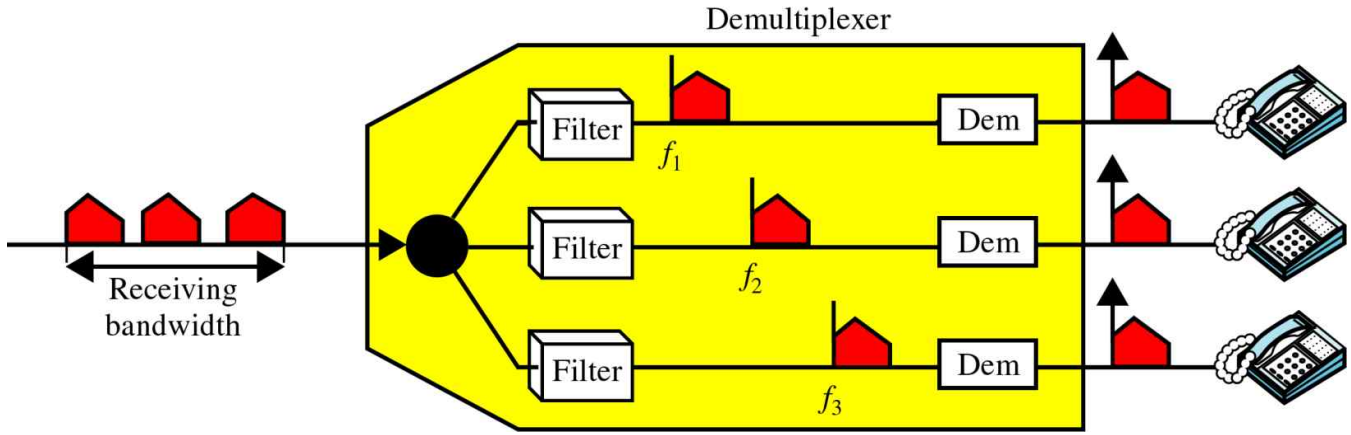




(2) Demultiplexing process

– A series of filters to decompose the multiplexed signal into its constituent component signals.





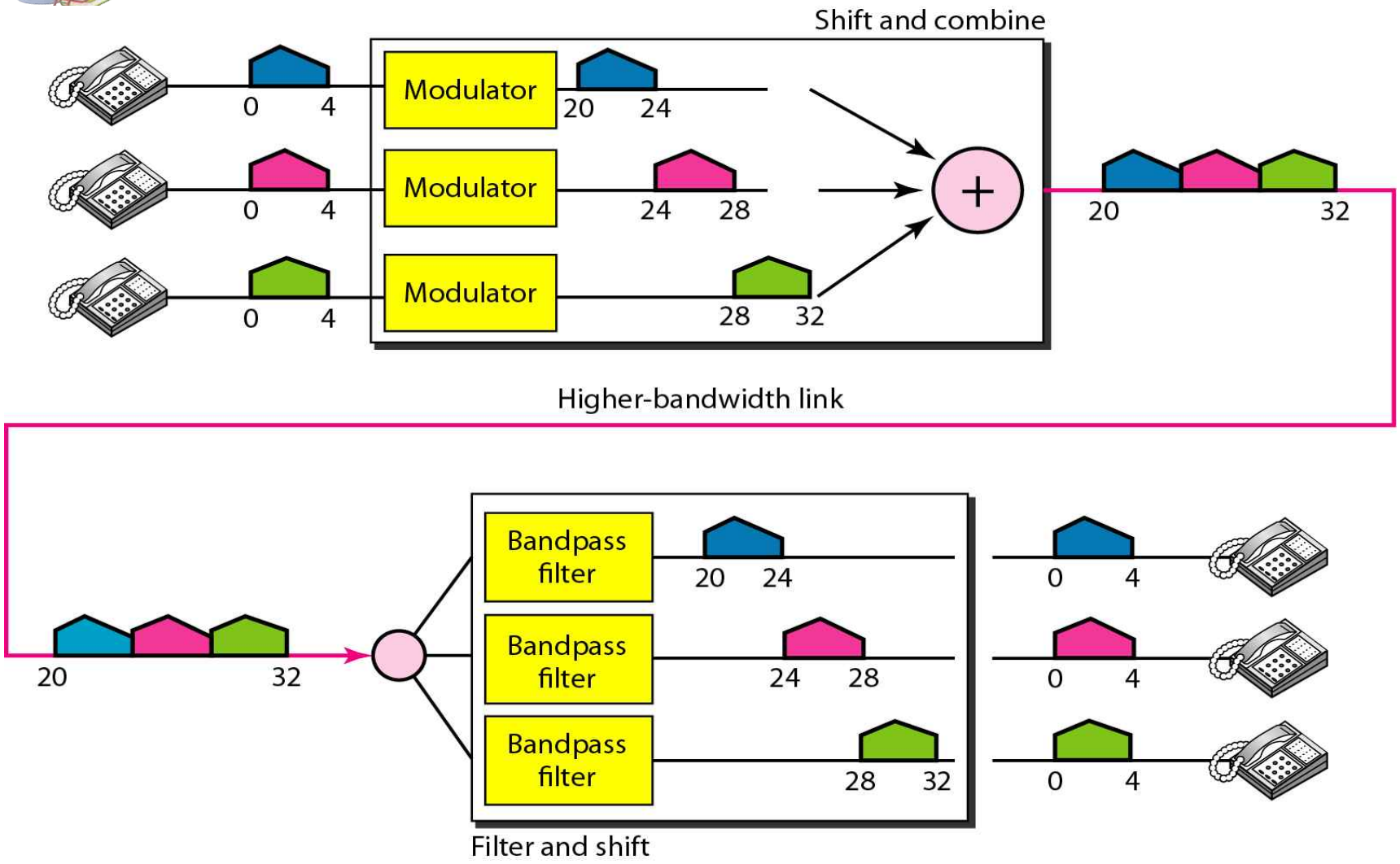
Example 6.1

*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.

Example 6.1


Shift and combine
Modulator
Modulator
Modulator
0
4
20
24
24
28
28
32
20
32
Higher-bandwidth link
20
32
Bandpass filter
Bandpass filter
Bandpass filter
Filter and shift

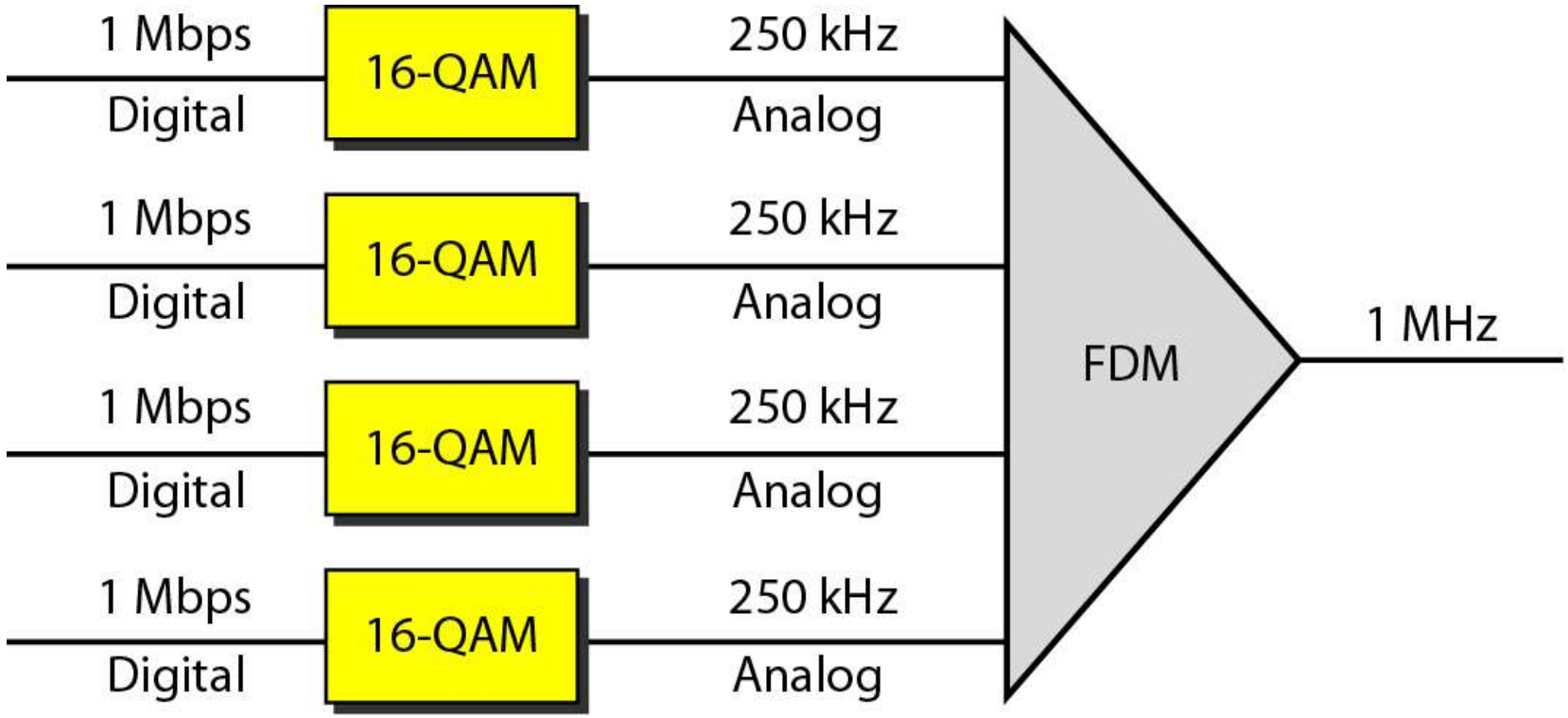
Example 6.3

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

Solution

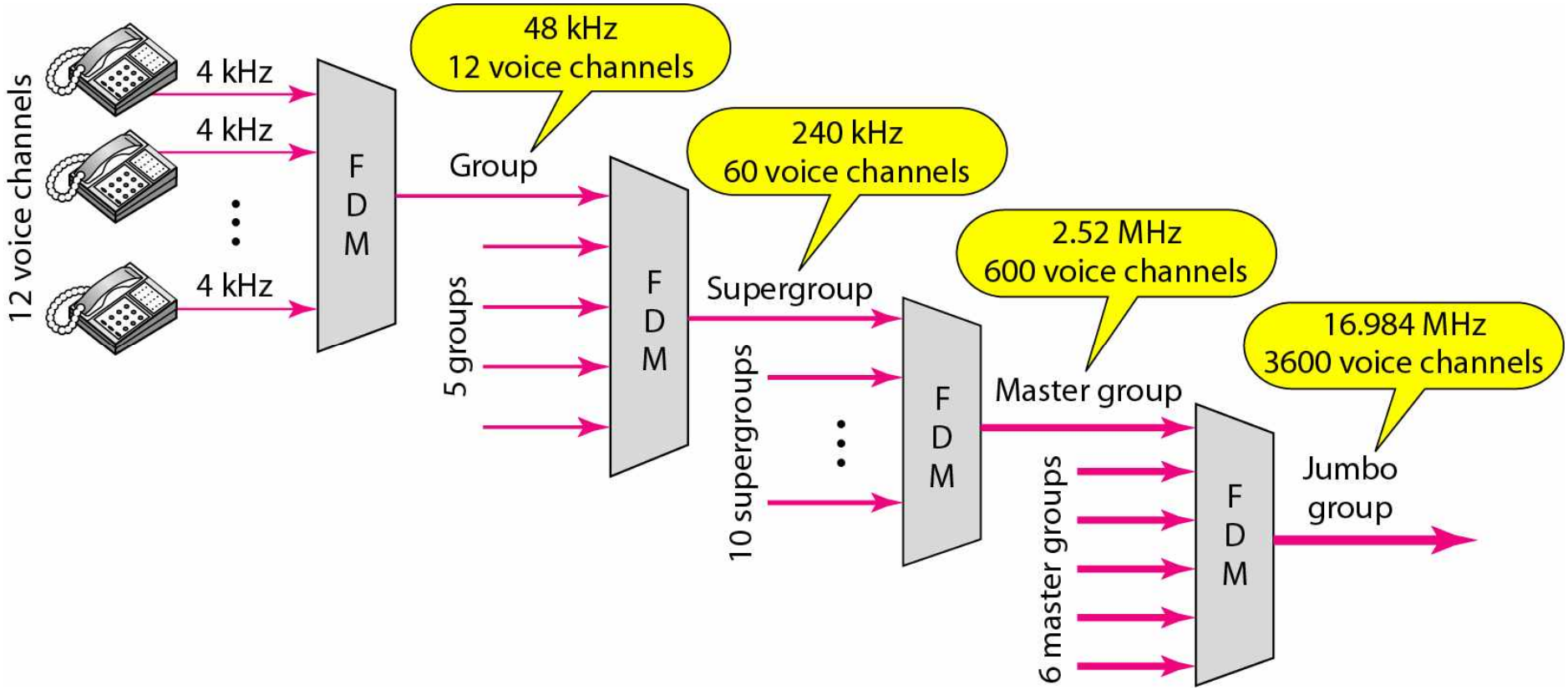
The satellite channel is analog. We divide it into four channels, each channel having a 250-kHz bandwidth. Each digital channel of 1 Mbps is modulated such that each 4 bits is modulated to 1 Hz. One solution is 16-QAM modulation. Figure 6.8 shows one possible configuration.

Example 6.3


1 Mbps
Digital
16-QAM
250 kHz
Analog
1 Mbps
Digital
16-QAM
250 kHz
Analog
1 Mbps
Digital
16-QAM
250 kHz
Analog
1 Mbps
Digital
16-QAM
250 kHz
Analog
FDM
1 MHz

(3) The analog hierarchy

- FDM is used for analog lines
- There are hierarchies of FDM structures of various capacity
- One of these hierarchical systems used by AT&T is made up of groups, supergroups, master groups, and jumbo groups.



(3) The analog hierarchy

- North American and International FDM Carrier Standards

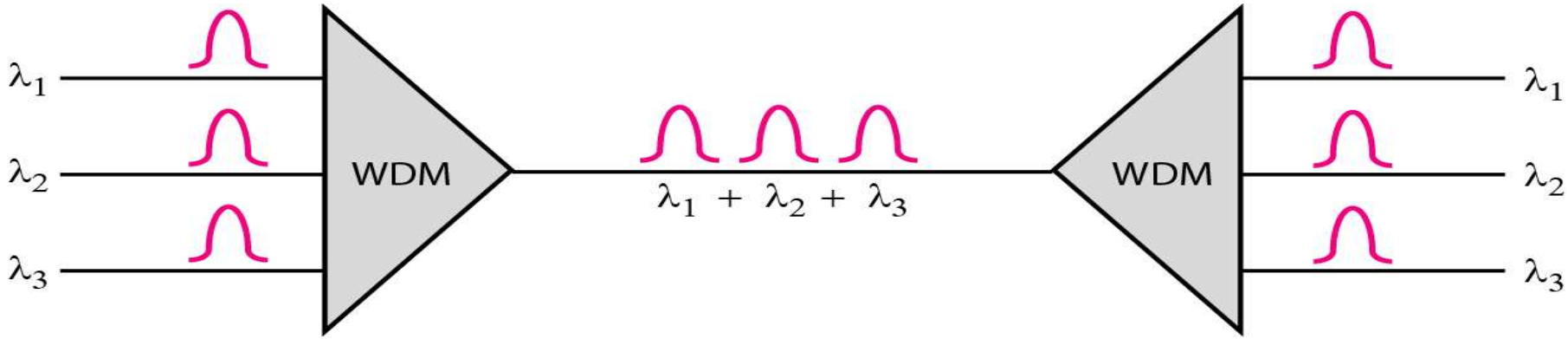
Number of Voice Channels	Bandwidth	Spectrum	AT&T	ITU-T
12	48 kHz	60–108 kHz	Group	Group
60	240 kHz	312–552 kHz	Supergroup	Supergroup
300	1.232 MHz	812–2044 kHz		Mastergroup
600	2.52 MHz	564–3084 kHz	Mastergroup	
900	3.872 MHz	8.516–12.388 MHz		Supermaster group
$N \times 600$			Mastergroup multiplex	
3,600	16.984 MHz	0.564–17.548 MHz	Jumbogroup	
10,800	57.442 MHz	3.124–60.566 MHz	Jumbogroup multiplex	

(4) Other applications of FDM

- A very common application
  - AM and FM radio broadcasting
  - AM has a special band from 530 to 1700 kHz, and each station needs a bandwidth of10 kHz.
  - FM has a wider band of 88 to 108 MHz and each station needs a bandwidth of 200 kHz.
- Another common use
  - TV broadcasting
  - each TV channel has its own bandwidth of 6 MHz
- First generation of cellular telephones
  - Each user is assigned two 30-kHz channels, one for sending voice and the other for receiving.
  - The voice signal has a bandwidth of 3 kHz (from 300 to 3300 Hz).
  - Note: Remember that an FM signal has a bandwidth 10 times that of the modulating signal.

Wavelength-Division Multiplexing (WDM)

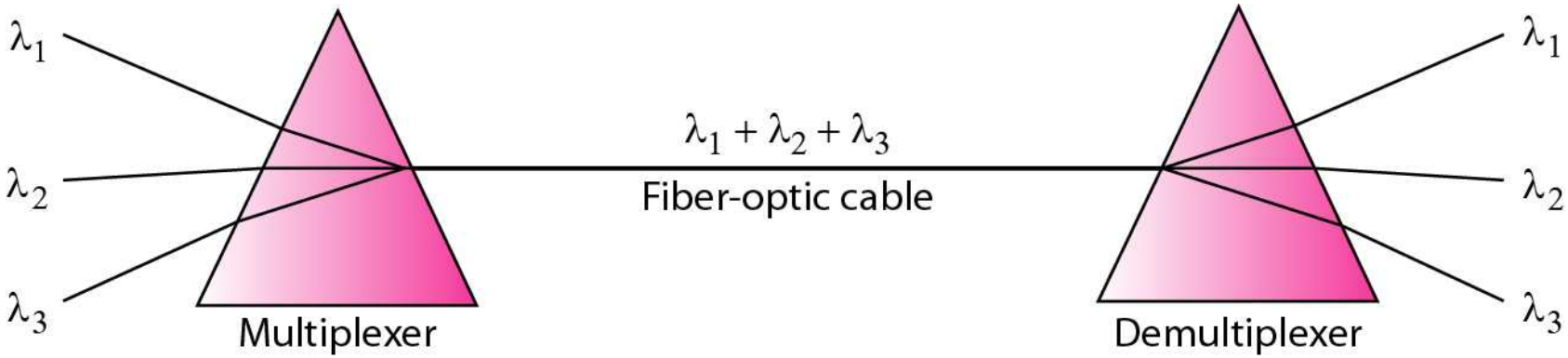
- Designed to use the high-data-rate capability of fiber-optic cable.
- Operation:
  - WDM is conceptually the same as FDM, except that the multiplexing and demultiplexing involve optical signals transmitted through fiber-optic channels.
  - Very narrow bands of light from different sources are combined to make a wider band of light.



Wavelength-Division Multiplexing (WDM)

- Combine multiple light sources into one single light at the multiplexer and do the reverse at the demultiplexer.
  - The combining and splitting of light sources are easily handled by a prism.
  - A prism bends a beam of light based on the angle of incidence and the frequency.

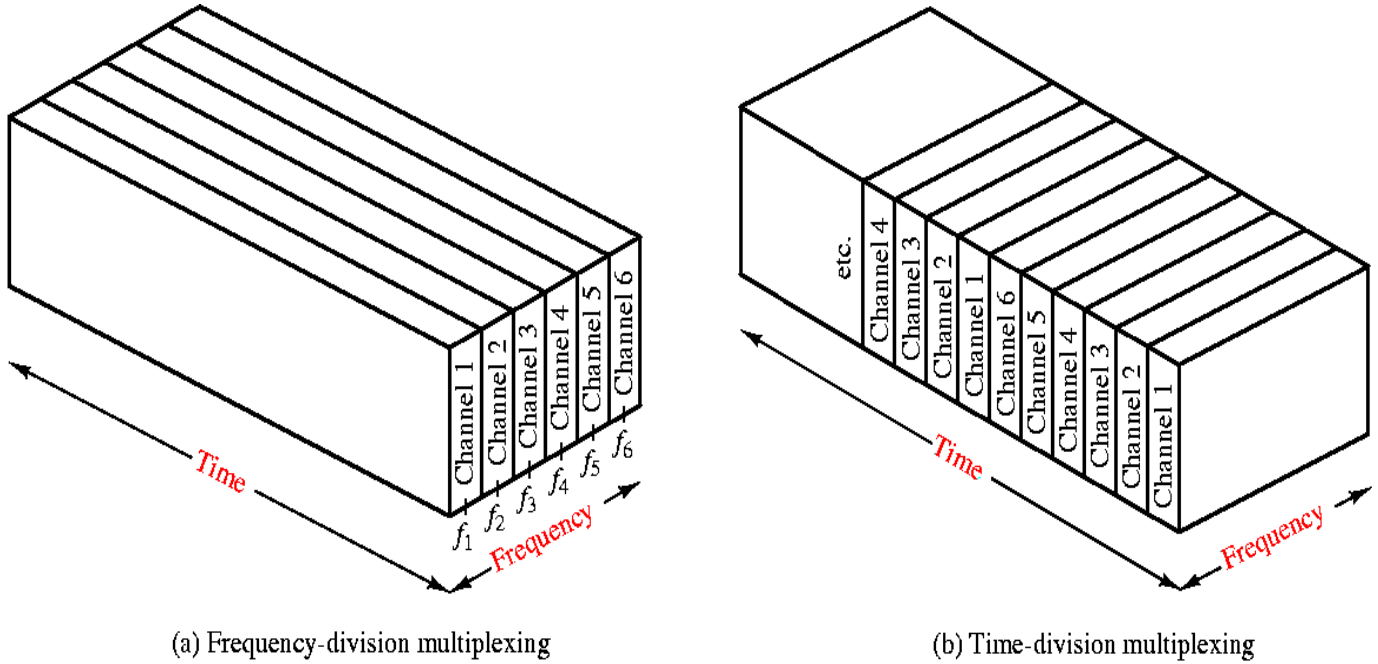
- Figure 6.11 Prisms in wavelength-division multiplexing and demultiplexing



WDM is an analog multiplexing technique to combine optical signals.

Time-Division Multiplexing (TDM)

- Instead of sharing a portion of the bandwidth as in FDM, time is shared.
  - Each connection occupies a portion of time in the link.



(a) Frequency-division multiplexing

(b) Time-division multiplexing

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

Synchronous TDM

- The data flow of each input connections 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.
- 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, where n is the number of connections.
- Frame vs slot
  - Slot: Each slot is allocated to carrying data from a specific input line.
  - Frame: A frame consists of one complete cycle of time slots.

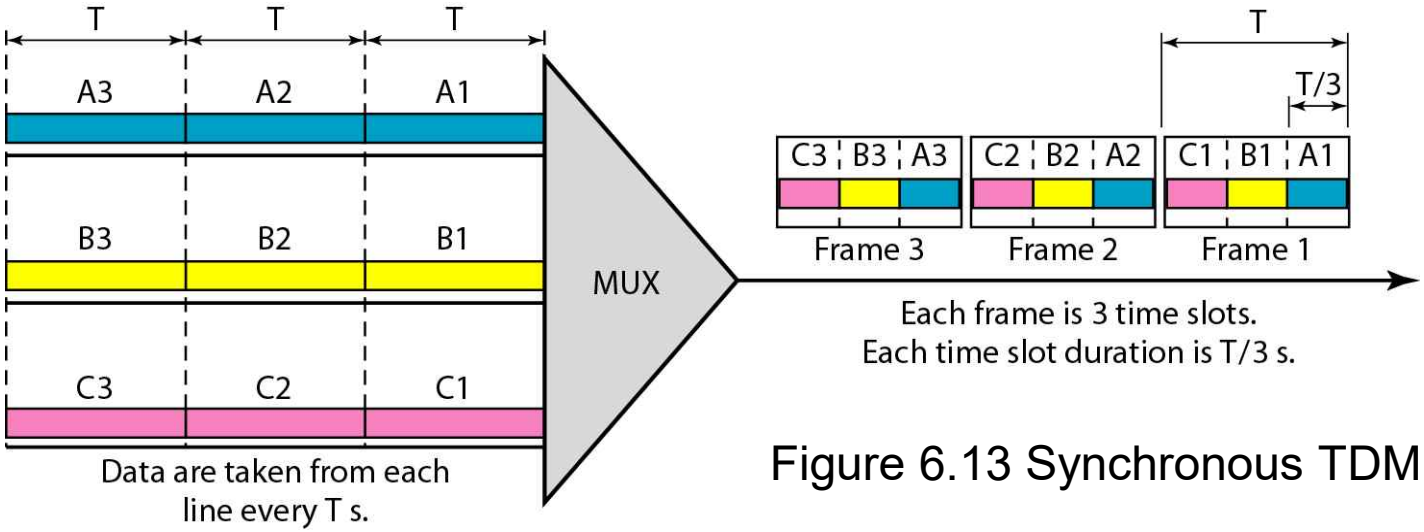
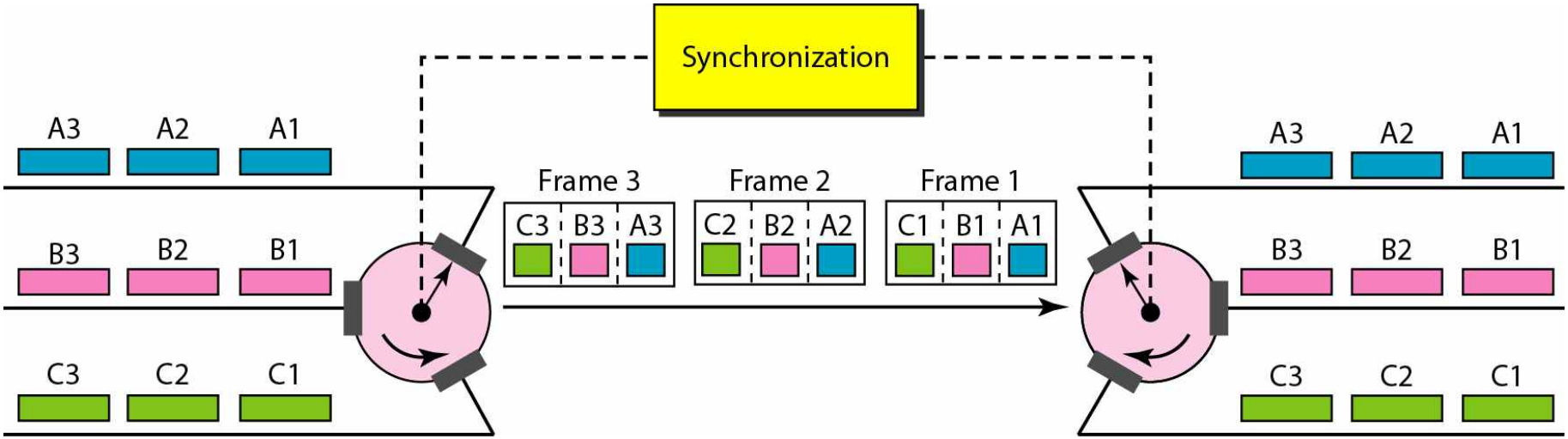


Figure 6.13 Synchronous TDM

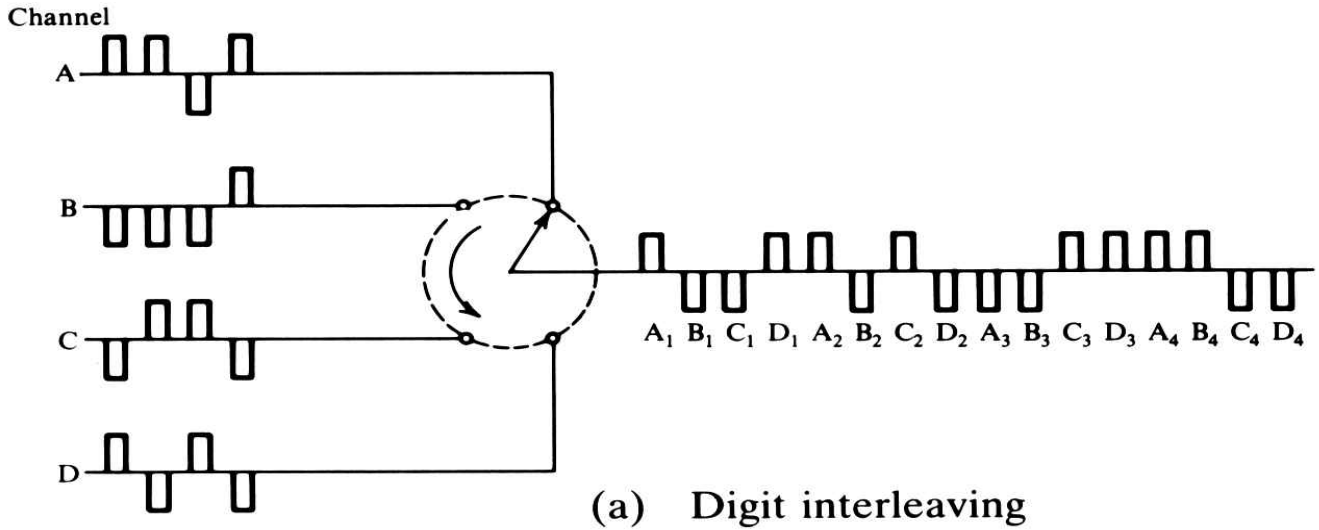
Interleaving

- Interleaving
  - A fixed time slot is assigned to a input whether it is active or not ➔ generally, many of the time slots in a frame are wasted : extremely inefficient

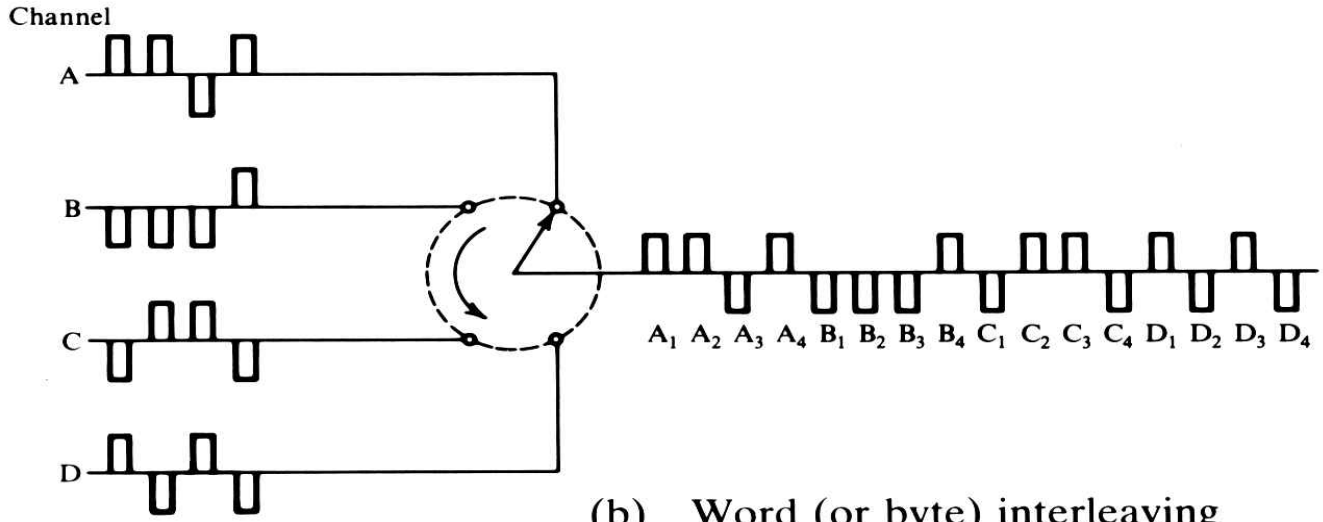


Interleaving

– bit vs. byte interleaving



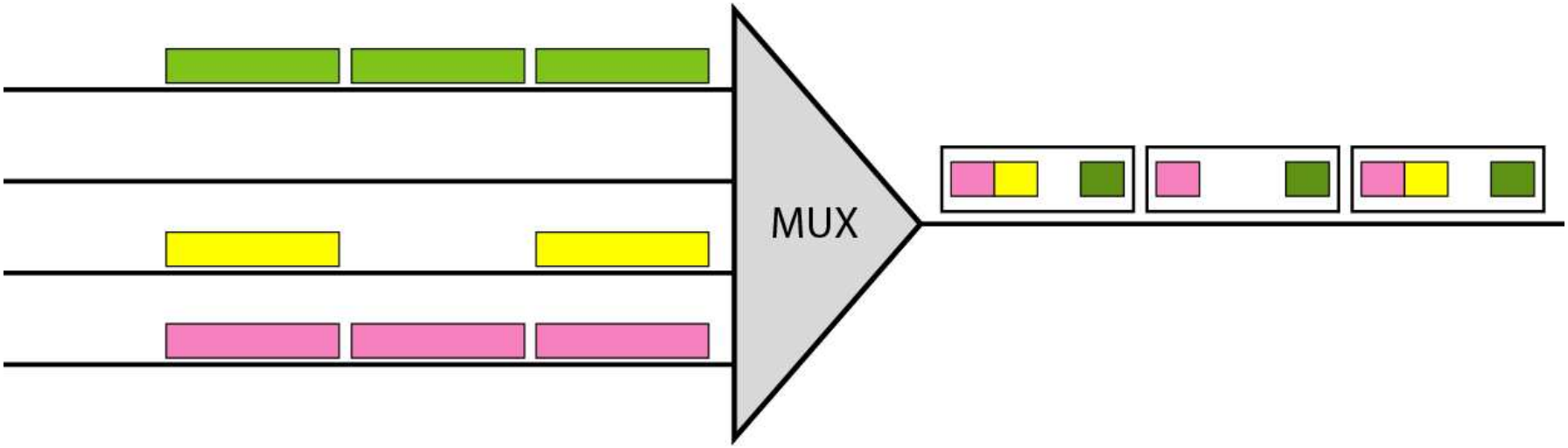
(a) Digit interleaving



(b) Word (or byte) interleaving

Interleaving

- Empty slots
  - If a source does not have data to send, the corresponding slot in the output frame is empty.



  - The first output frame has three slots filled, the second frame has two slots filled, and the third frame has three slots filled.

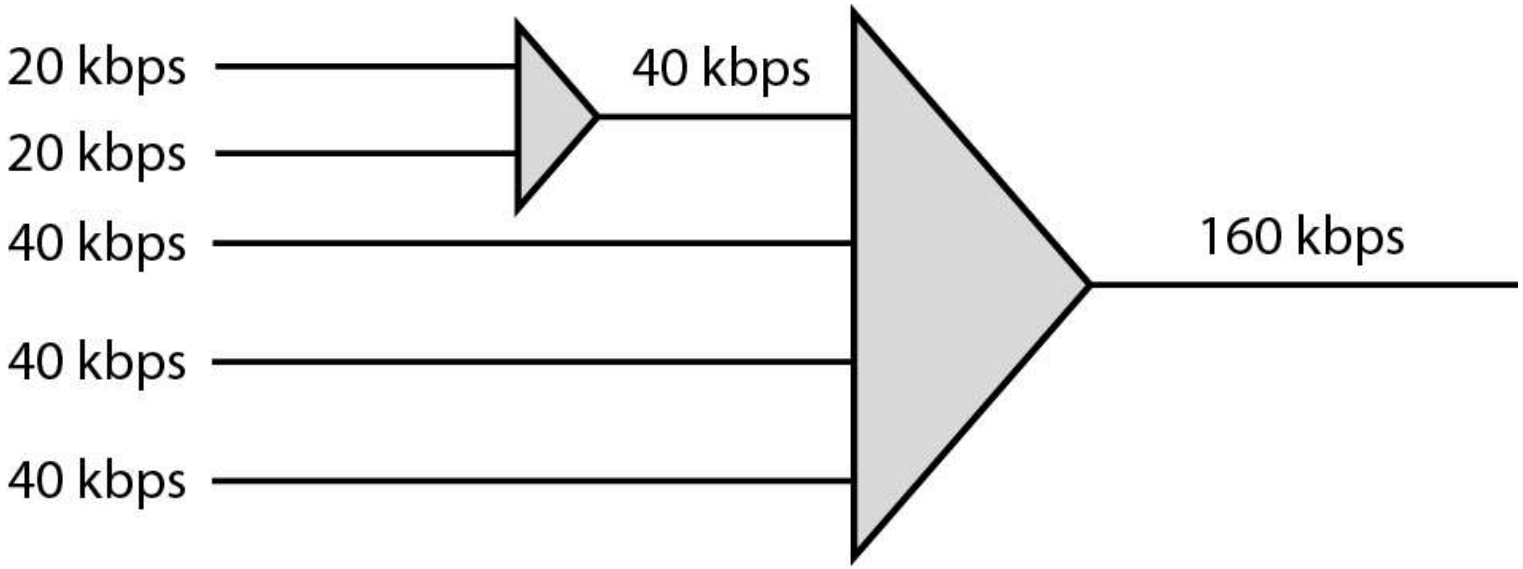
    → No frame is full.

Data Rate Management

- If the data rates of all input lines are not the same, the following three strategies can be used:
  - multilevel multiplexing, multi-slot allocation, and pulse stuffing

(1) Multilevel multiplexing

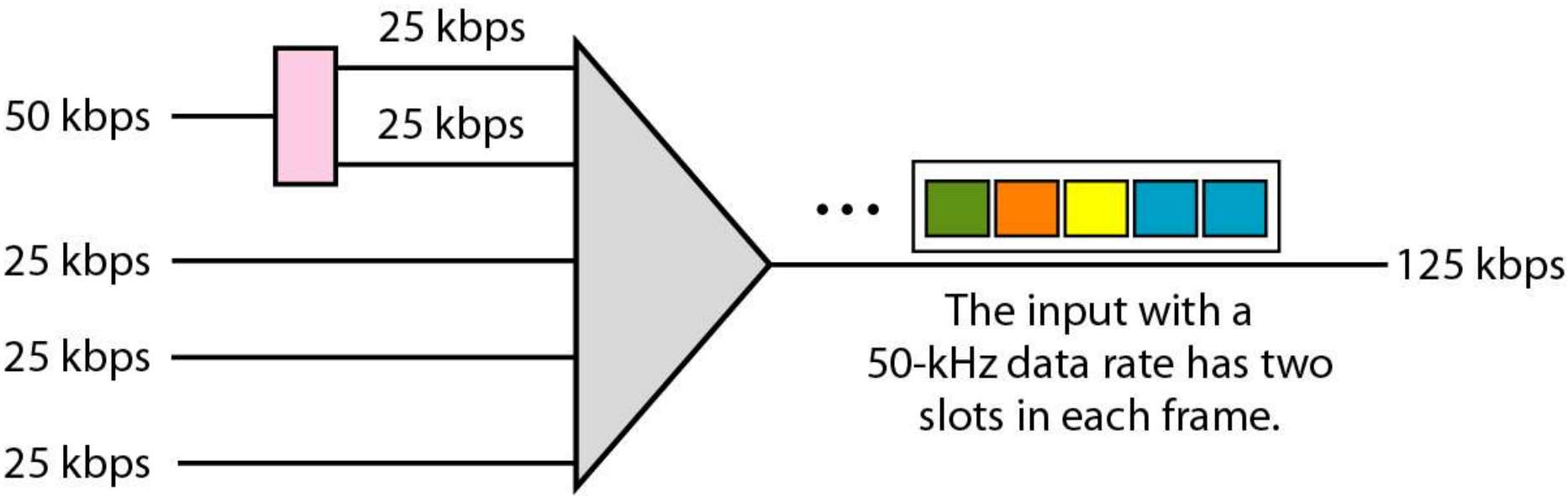
- Used when the data rate of an input line is a multiple of others.



- For example, in the above Figure, the first two input lines can be multiplexed together to provide a data rate equal to the last three.

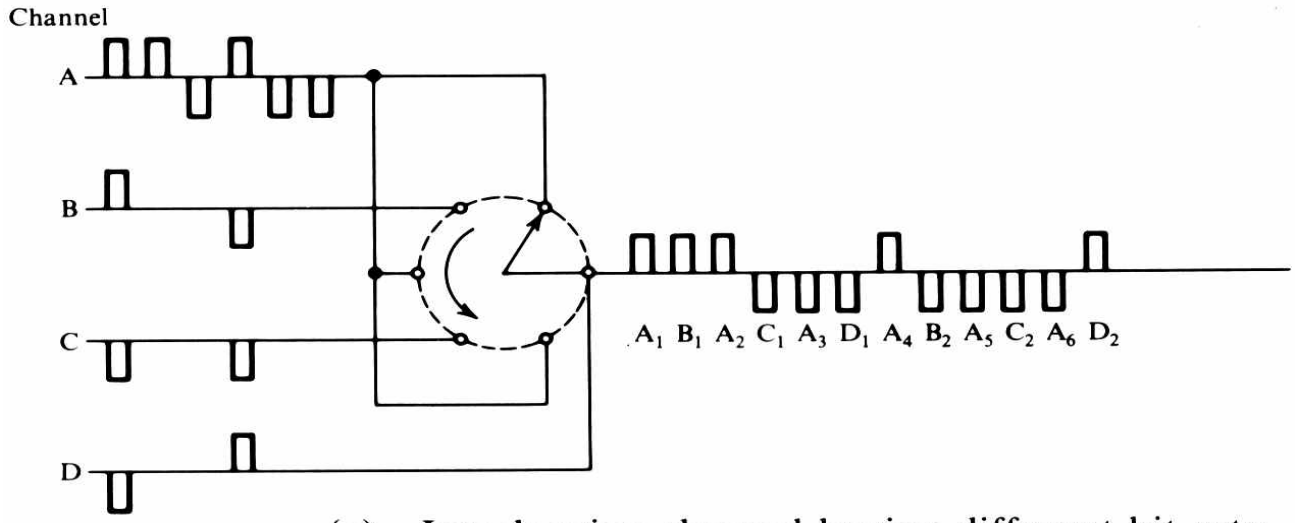
(2) Multiple-Slot Allocation

- Allocate more than one slot in a frame to a single input.

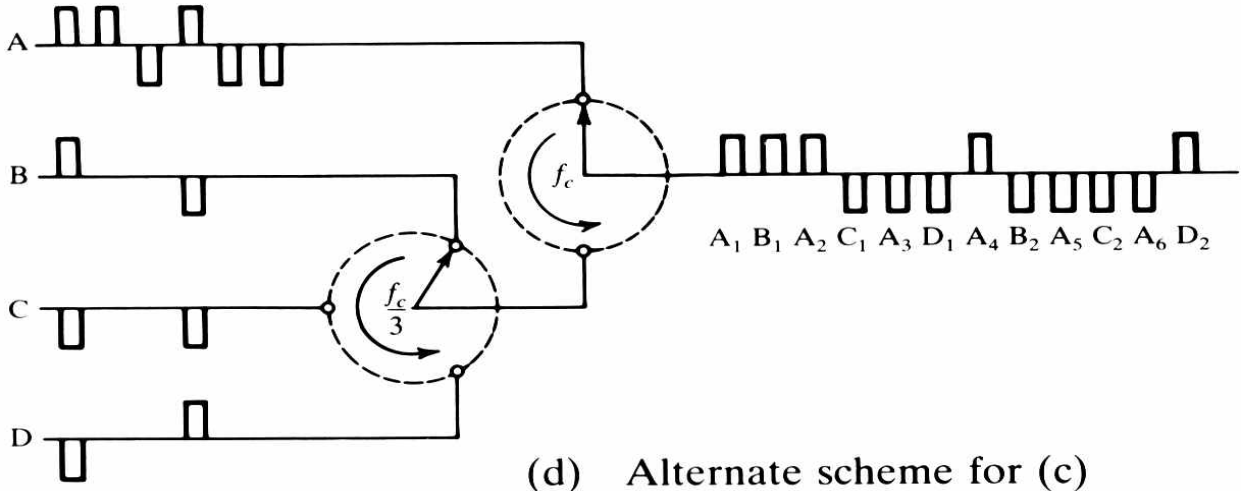


(2) Multiple-Slot Allocation

– Multiplexing of different bit rate



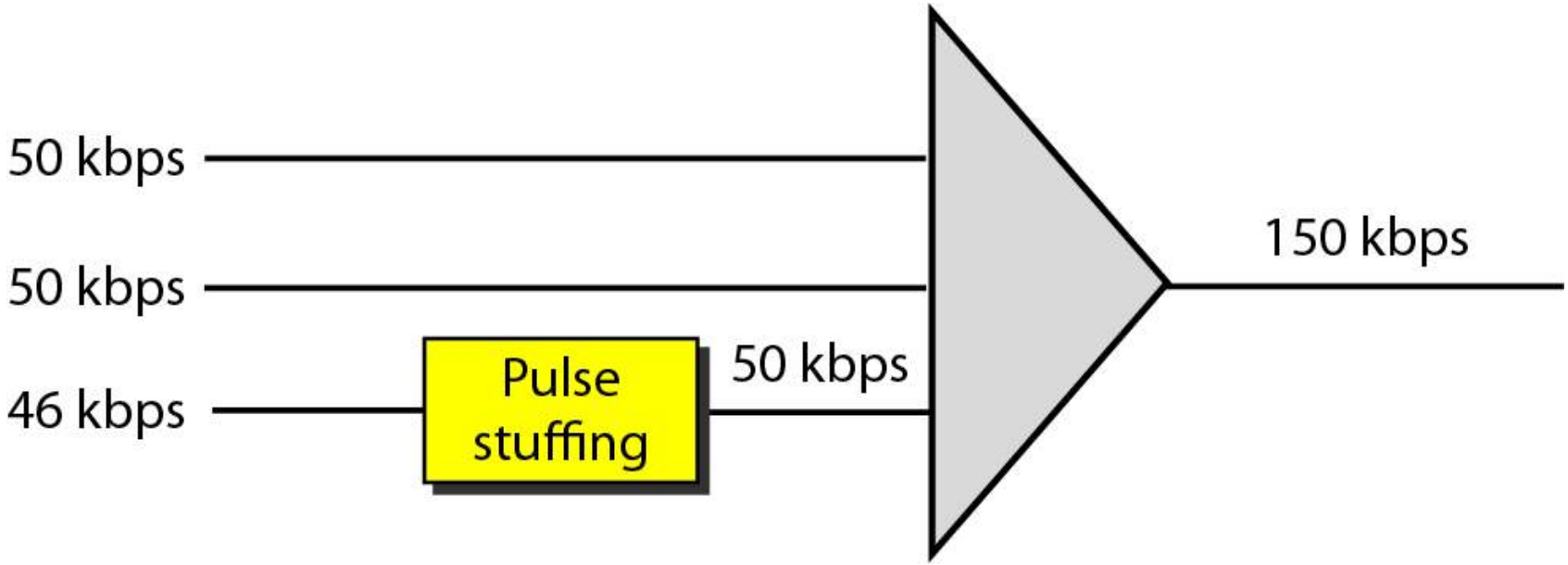
(c) Interleaving channel having different bit rate



(d) Alternate scheme for (c)

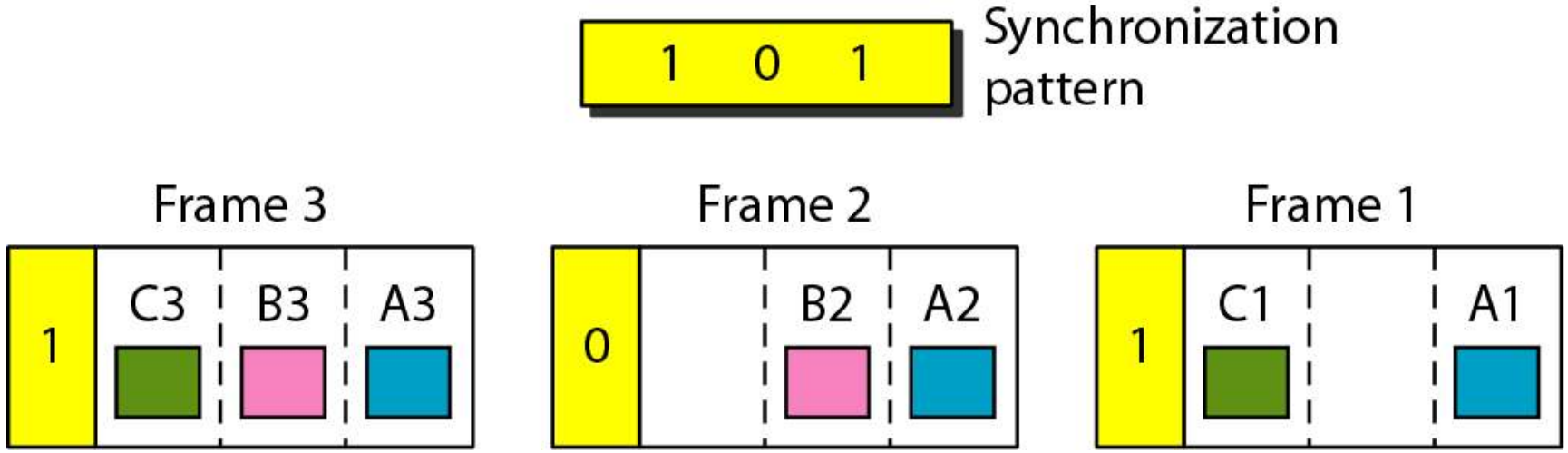
(3) Pulse Stuffing

- When the bit rates of sources are not multiple integers of each other.
- Add dummy bits to the input lines in order to make the highest input data rate or the dominant data rate



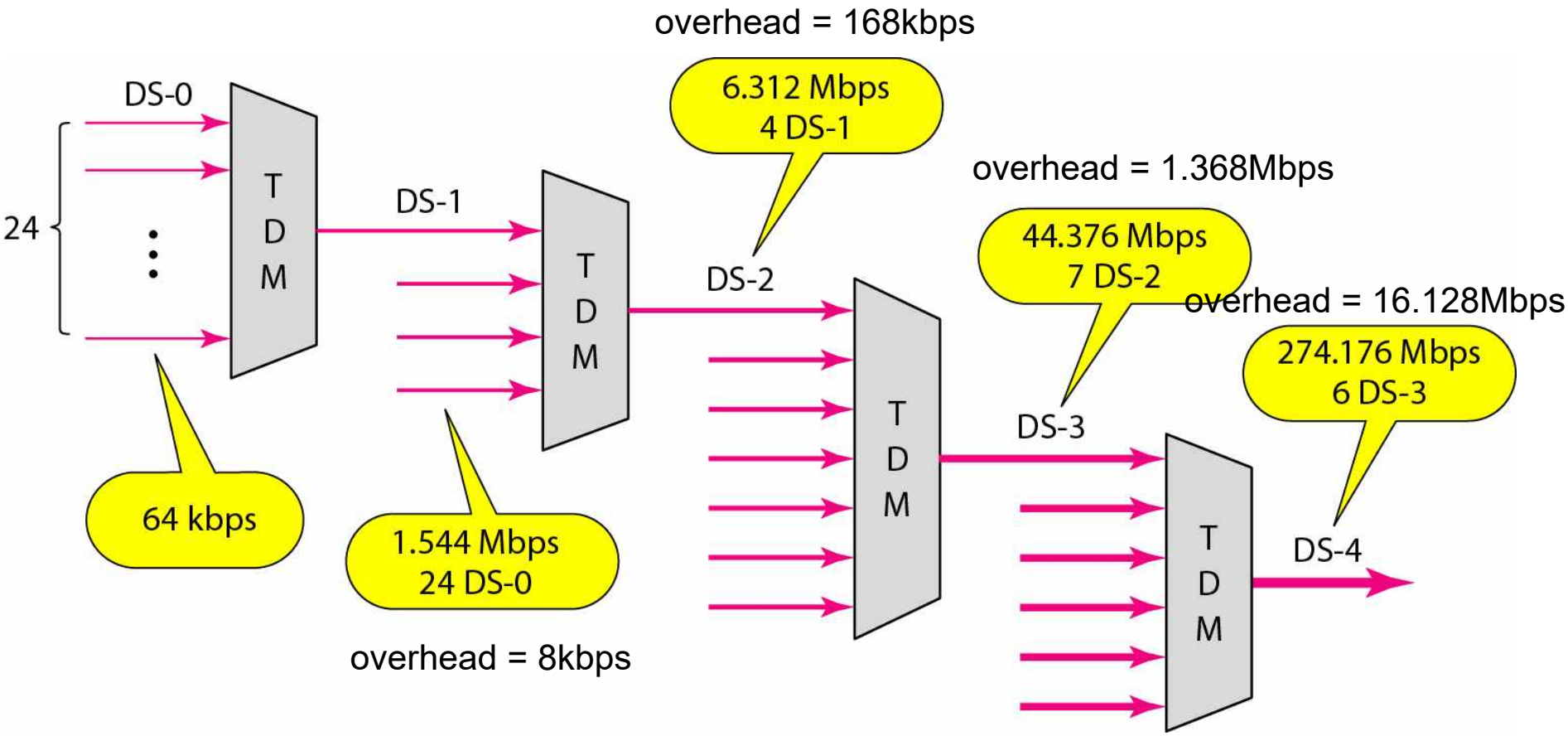
Frame Synchronizing

- Synchronization between the multiplexer and demultiplexer is a major issue.
- One or more synchronization bits, called framing bits, are usually added to the beginning of each frame.
  - allow the demultiplexer to synchronize with the incoming stream so that it can separate the time slots accurately.
  - In most cases, the synchronization information consists of 1 bit per frame, alternating between 0 and 1.



Digital Signal Service

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



Digital Signal Service

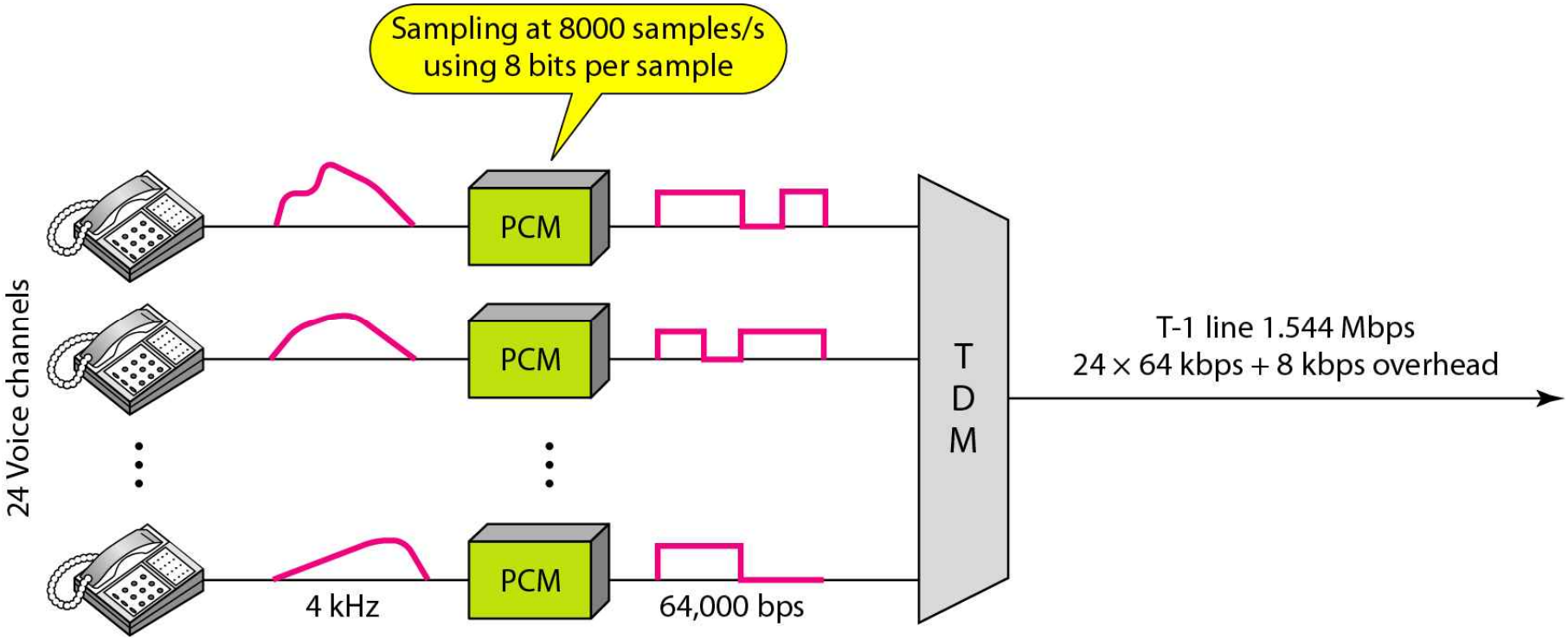
- To implement services, DS-0, DS-1, …, the telephone companies uses T lines in North America and E lines in Europeans

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

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

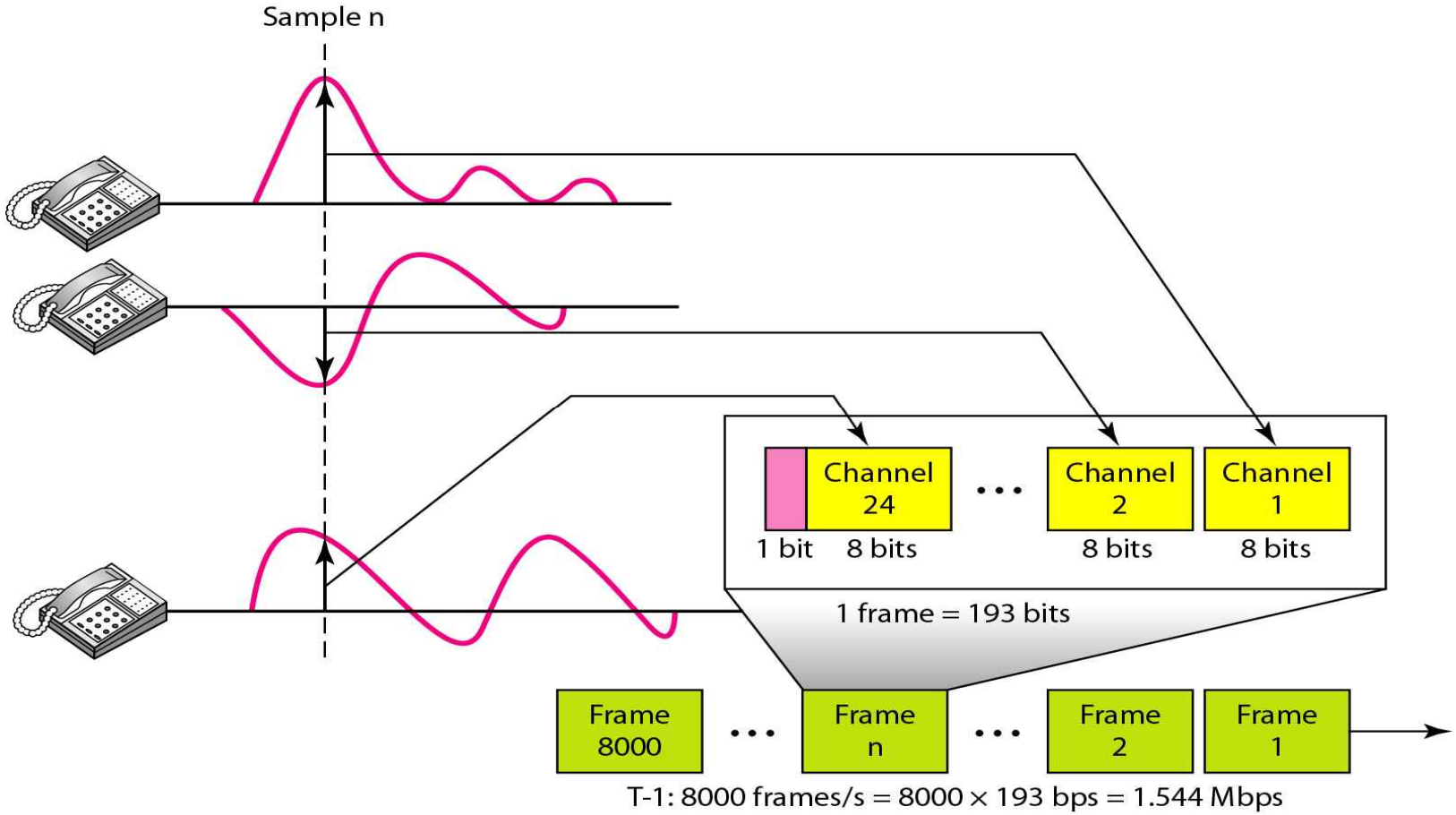
Digital Signal Service

- T lines are digital lines designed for the transmission of digital data, audio or video, but they also can be used for analog transmission.



Digital Signal Service

- T-1 frame structure
  - 1 frame = 24 voice channel frame + 1 extra bit = 24 X 8 + 1 = 193 bit
  - T-1 = 8000 frames / sec * 193 bit / frame = 1.544 Mbps



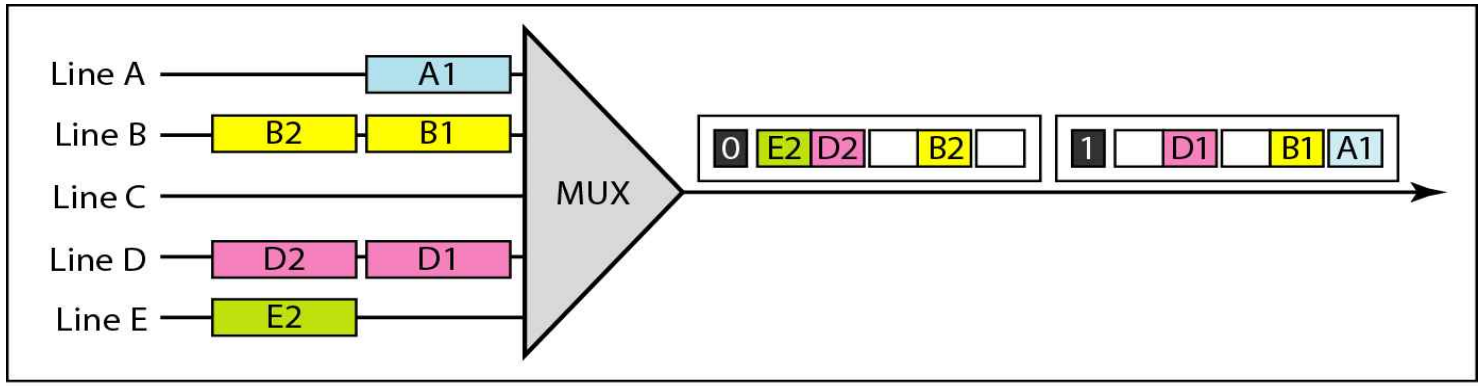
Digital Signal Service

- TDM Applications
  - Some second-generation cellular telephone
  - The each band has 30-kHz band.
  - Six users share the band → The each band consists of six time slots.
  - 6 times greater capacity compared with the first-generation FDM

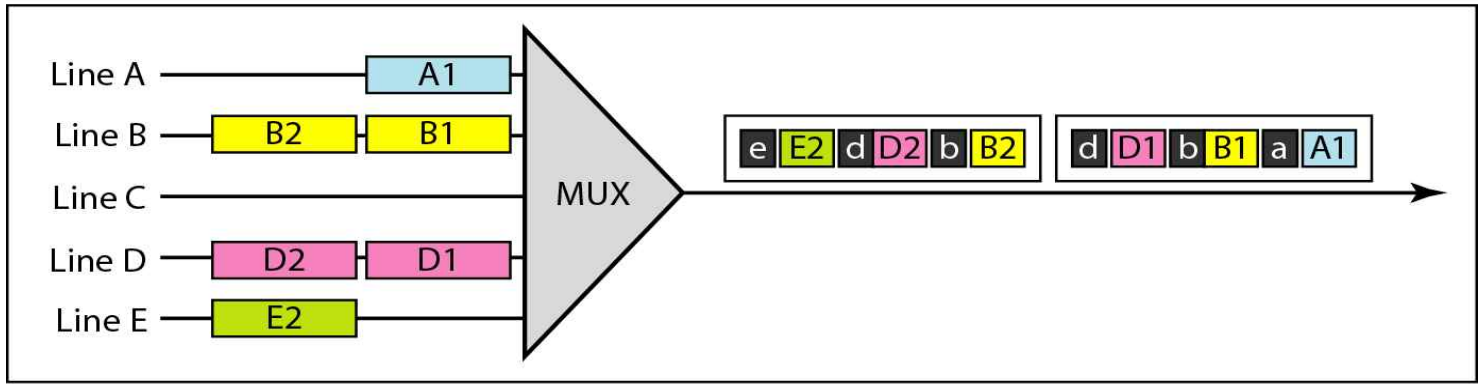
  Cf . In the first-generation FDM cellular telephone, each user is assigned two 30-kHz channels

Statistical Time-Division Multiplexing

- Sync. TDM vs Statistical TDM
  - If some input lines have no data to send, the synchronous TDM is inefficient.
  - In statistical TDM, slots are dynamically allocated to improve bandwidth efficiency.



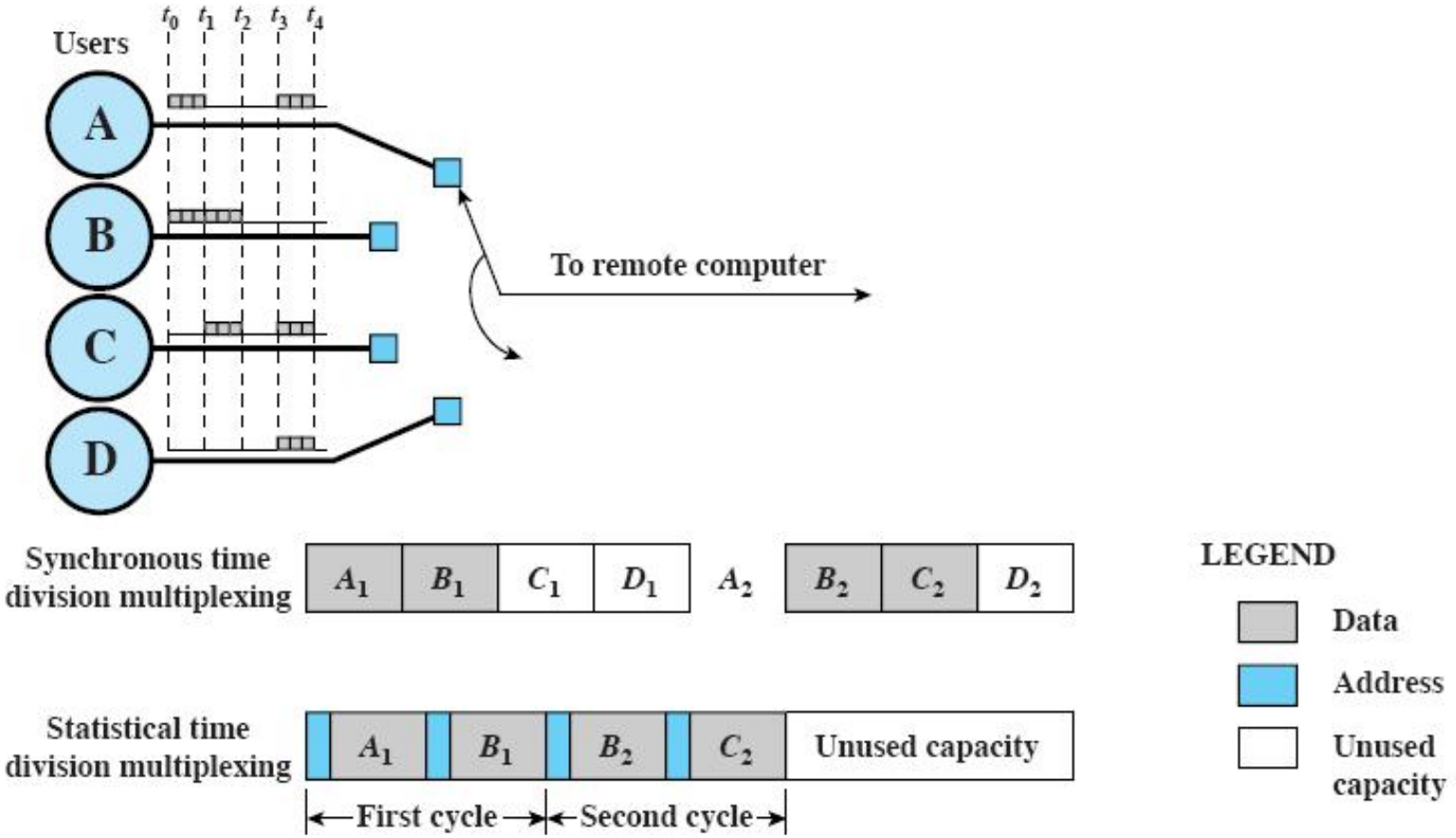
a. Synchronous TDM



b. Statistical TDM

Statistical Time-Division Multiplexing

- Addressing
  - Include the address to show where it is to be delivered.
  - For example, to define N different lines, we needs n = $\log_2 N$ bits.
  - Adding address increases the overhead of statistical TDM system



Summary

- Multiplexing is the simultaneous transmission of multiple signals across a single data link.
- Frequency-division multiplexing (FDM) and wave-division multiplexing (WDM) are techniques for analog signals, while time-division multiplexing (TDM) is for digital signals.
- In FDM, each signal modulates a different carrier frequency. The modulated carriers are combined to form a new signal that is then sent across the link.
- WDM is similar in concept to FDM. The signals being multiplexed, however, are light waves.
- In TDM, digital signals from n devices are interleaved with one another, forming a frame of data (bits, bytes, or any other data unit).