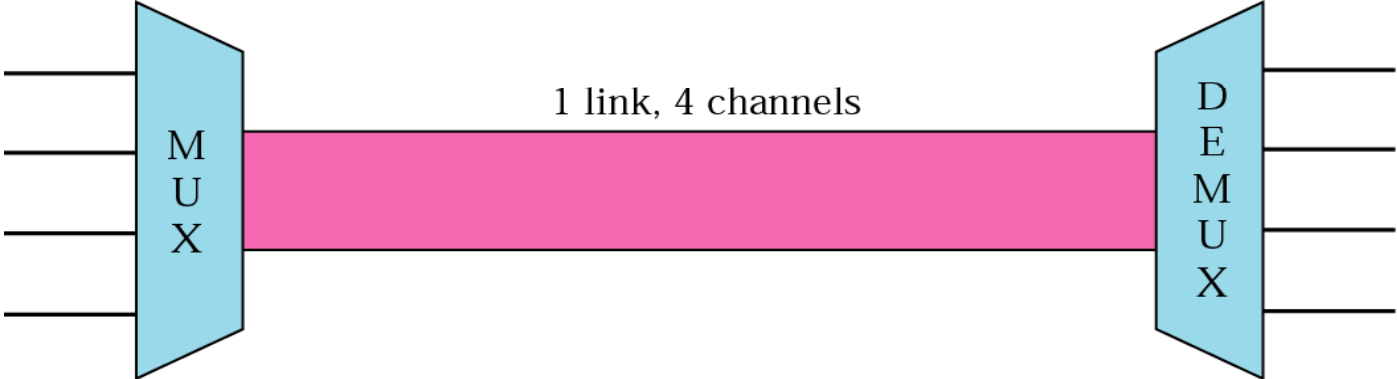
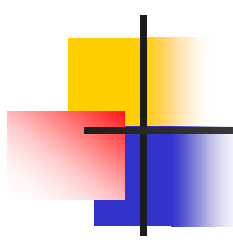


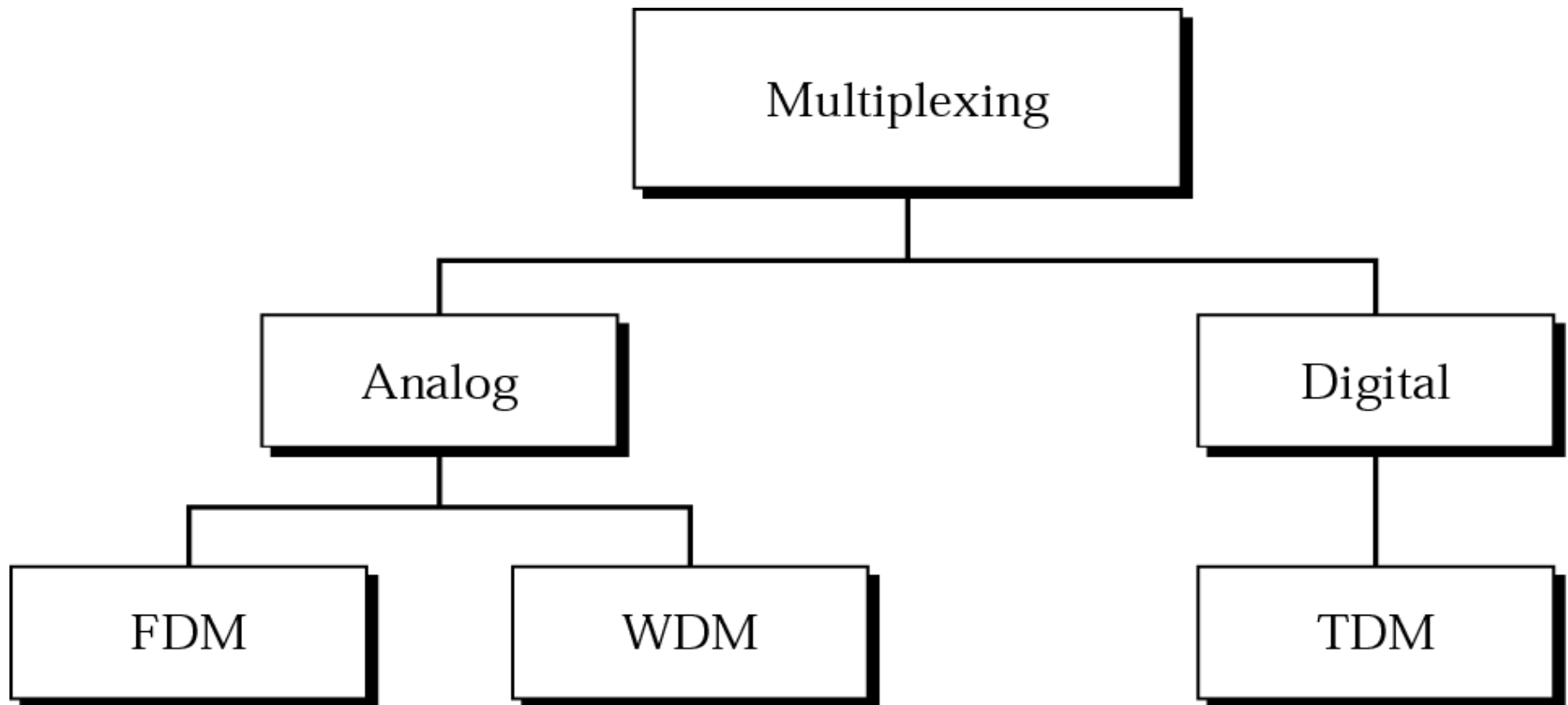
# *Multiplexing*

*Dividing a link into channels*





*Categories of multiplexing*



# FDM

*Multiplexing Process*

*Demultiplexing Process*

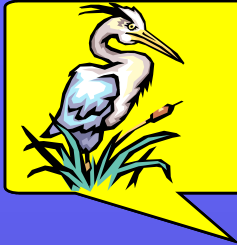
*The Analog Hierarchy*

*Other Applications of FDM*

*Implementation*

*FDM*

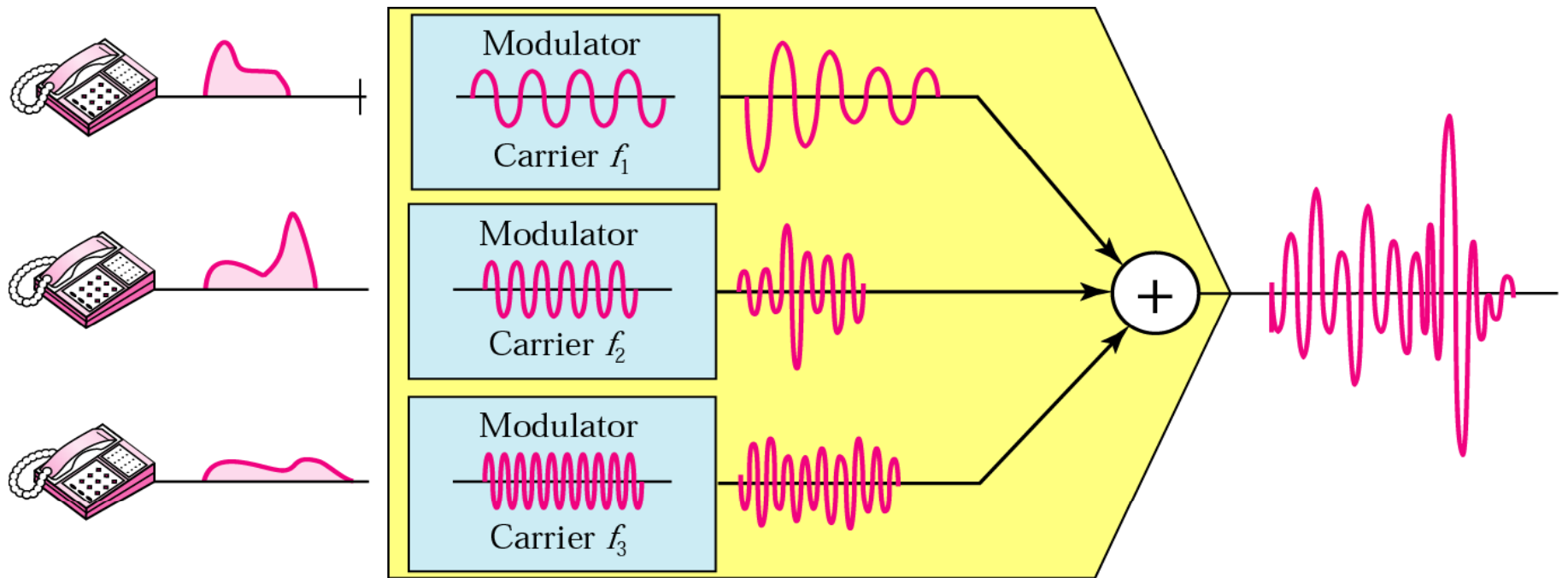




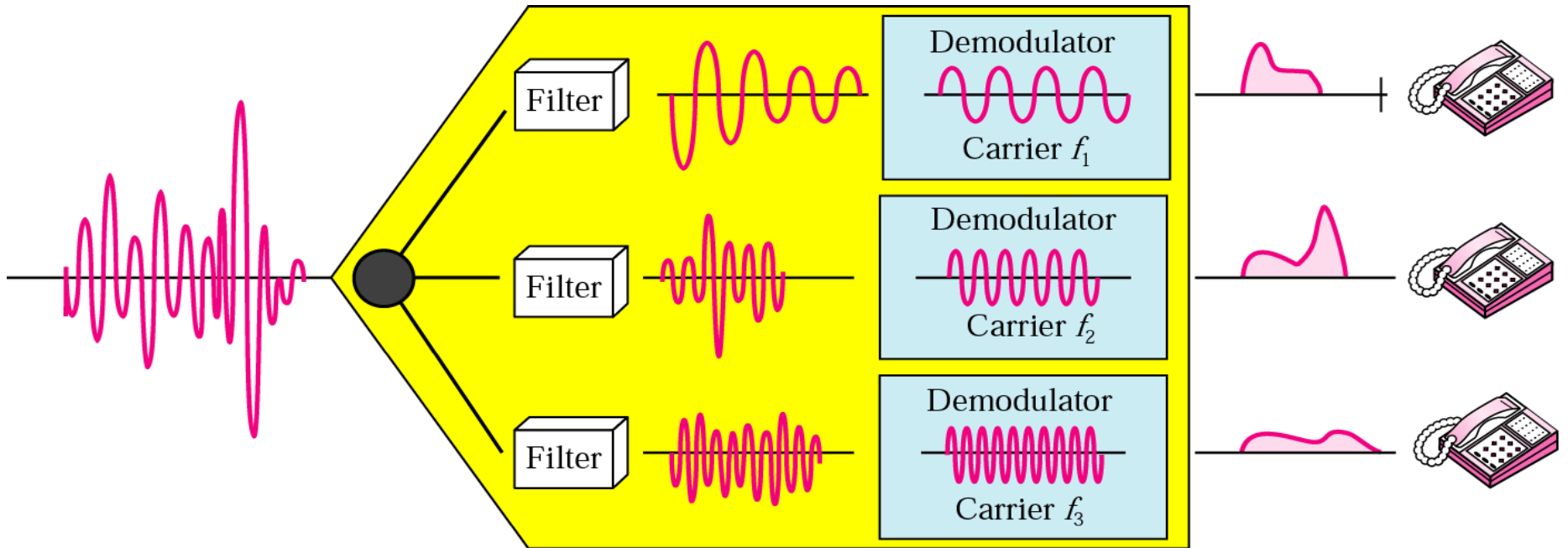
**Note:**

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

# FDM process



# FDM demultiplexing example





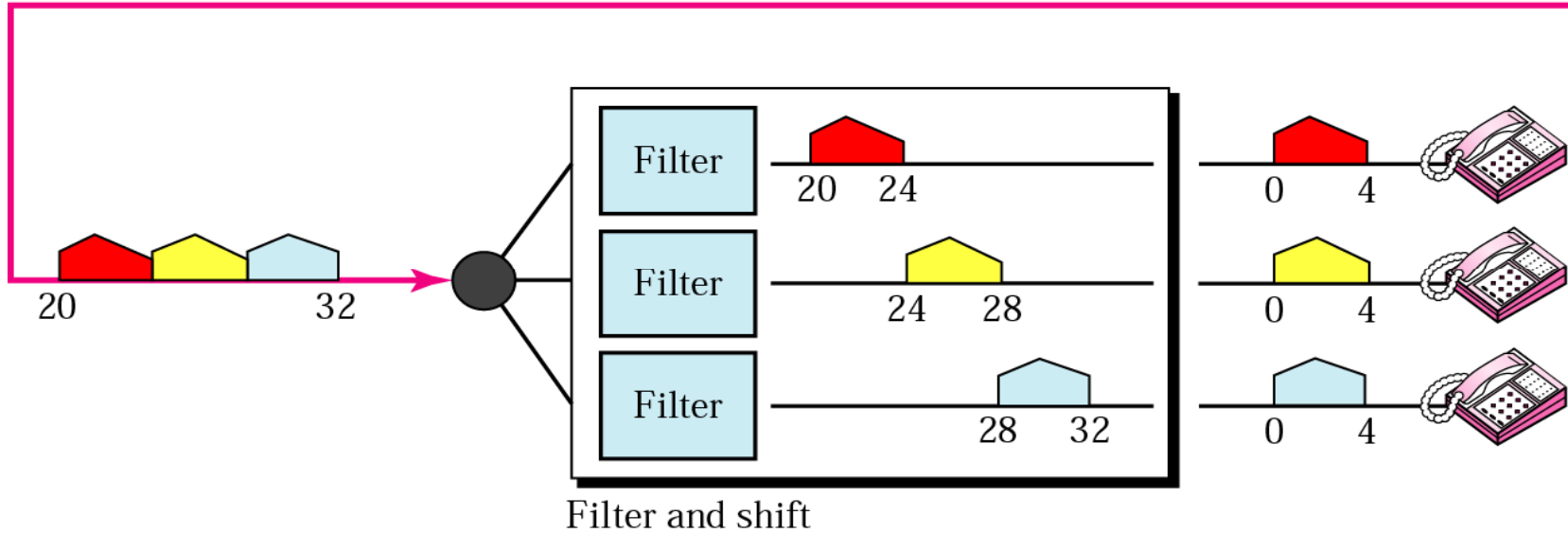
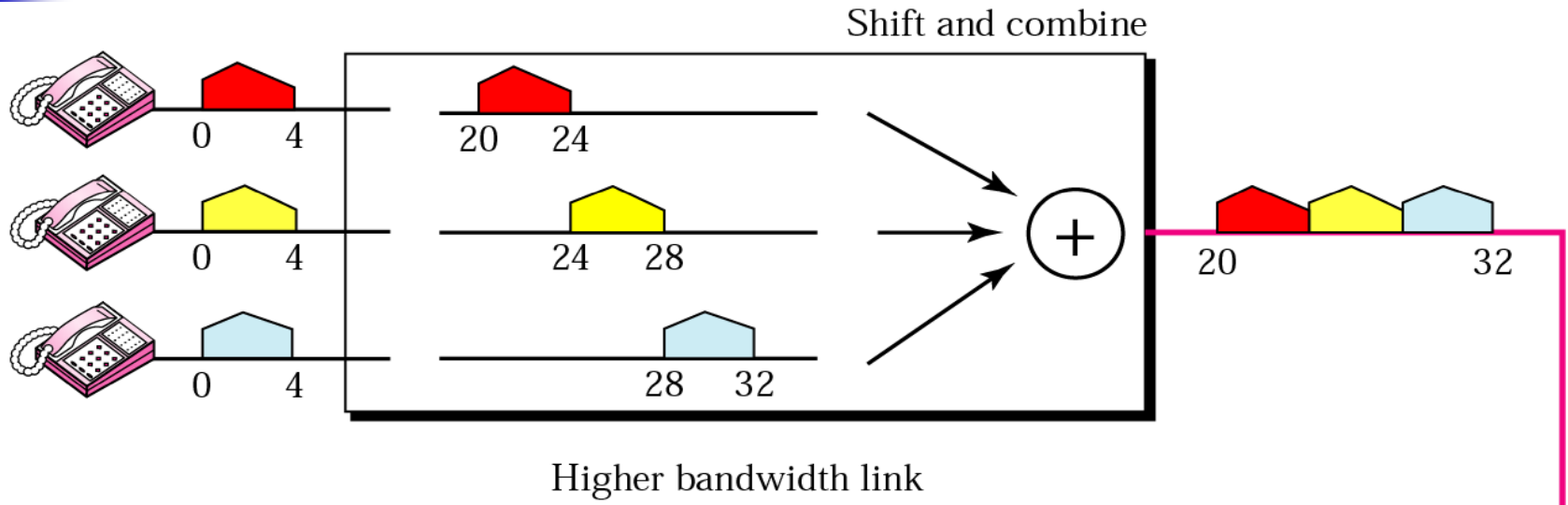
## ***Example 1***

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 without the use of guard bands.

## ***Solution***

Shift (modulate) each of the three voice channels to a different bandwidth, as shown in Figure

# Example 1



## *Example 2*

Five channels, each with a 100-KHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 KHz between the channels to prevent interference?

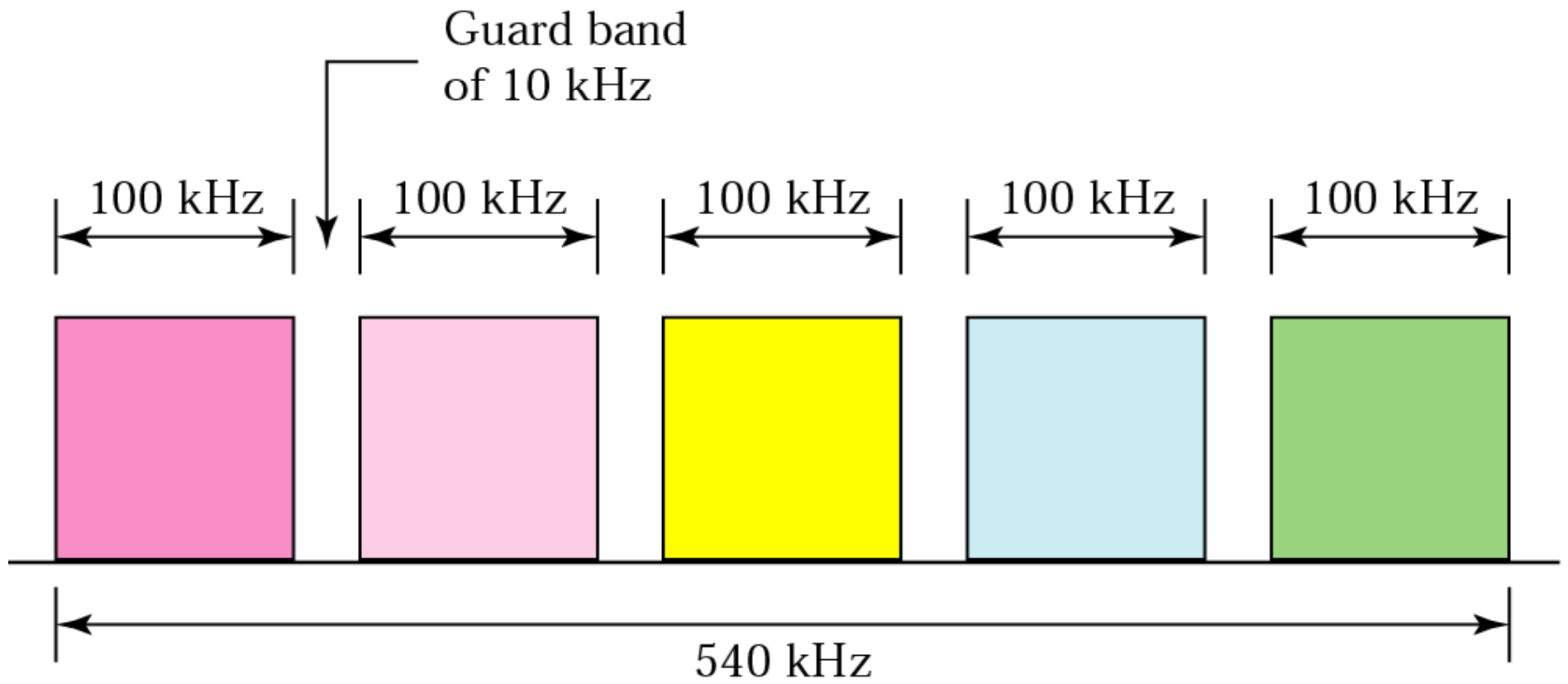
## *Solution*

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

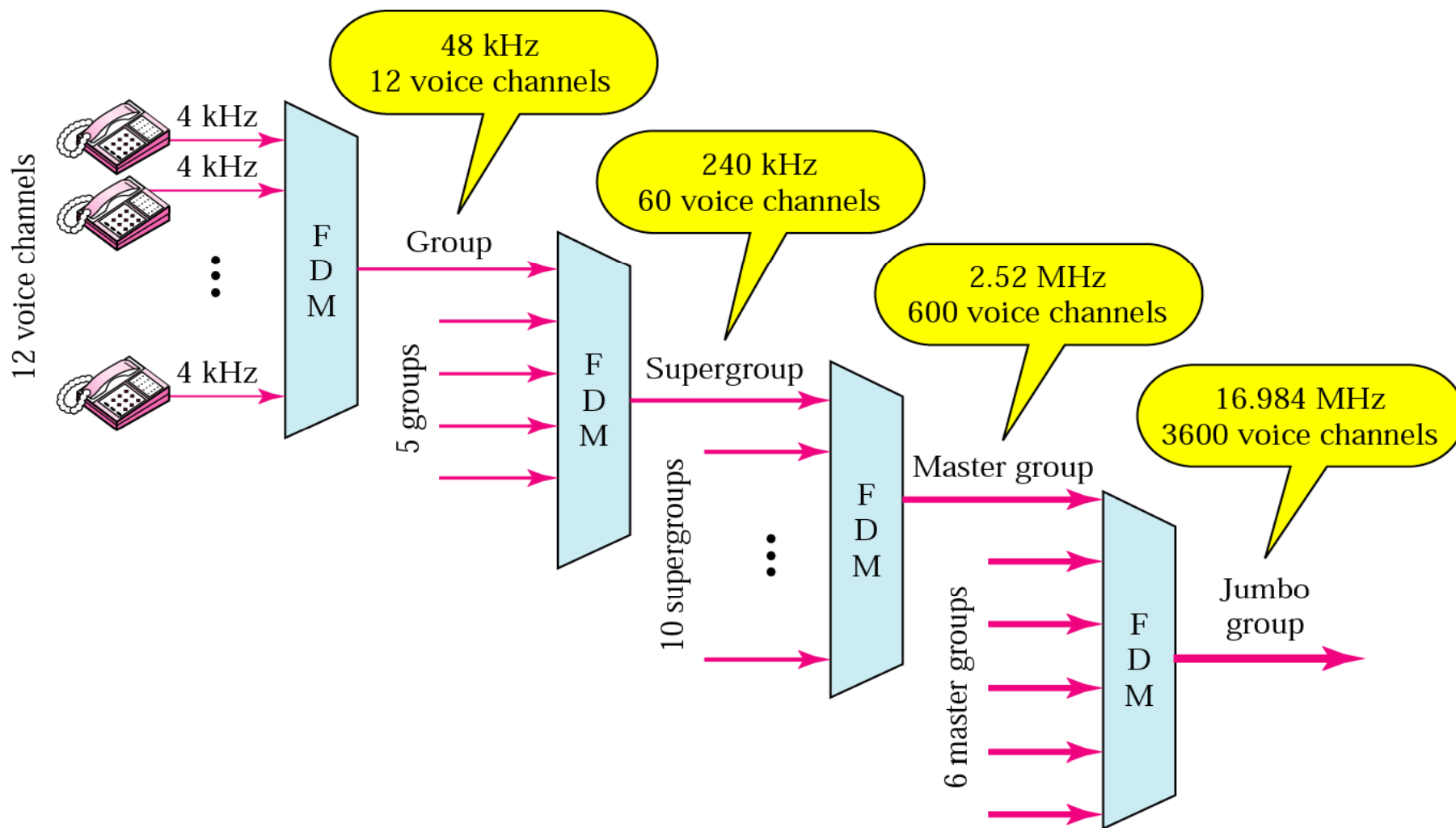
$$5 \times 100 + 4 \times 10 = 540 \text{ KHz,}$$

as shown in Figure 6.7.

## Example 2

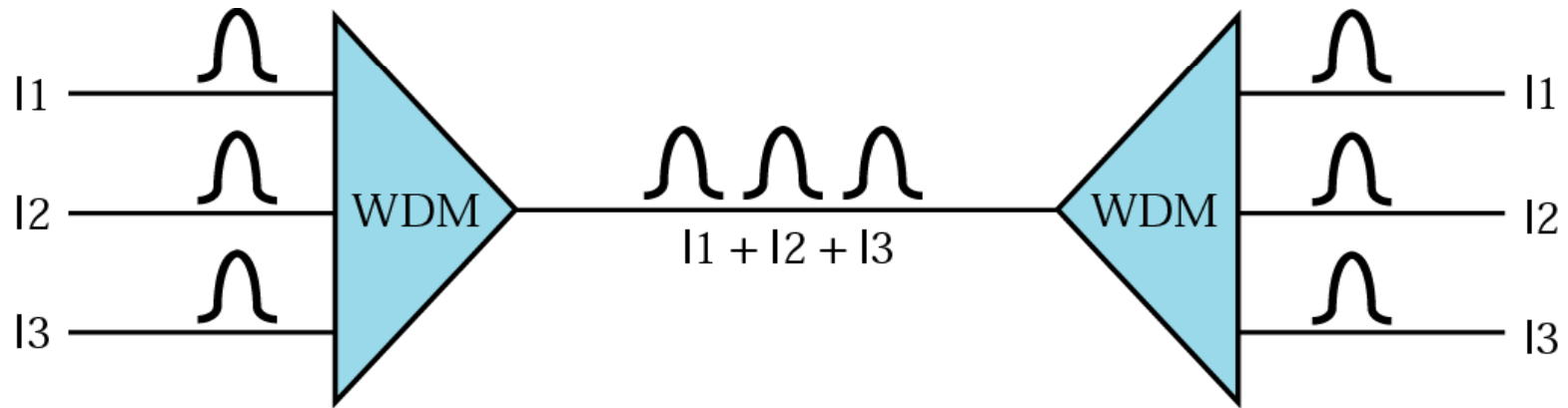


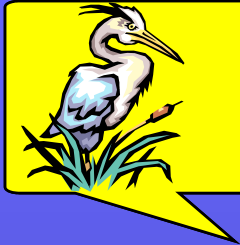
# Analog hierarchy



**WDM**

*Wave Division Multiplexing*





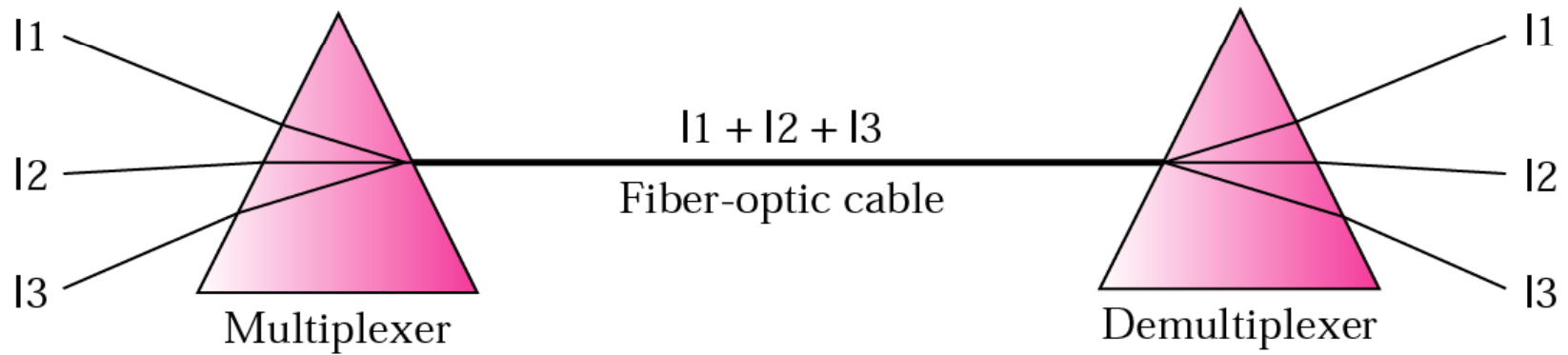
Note:

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



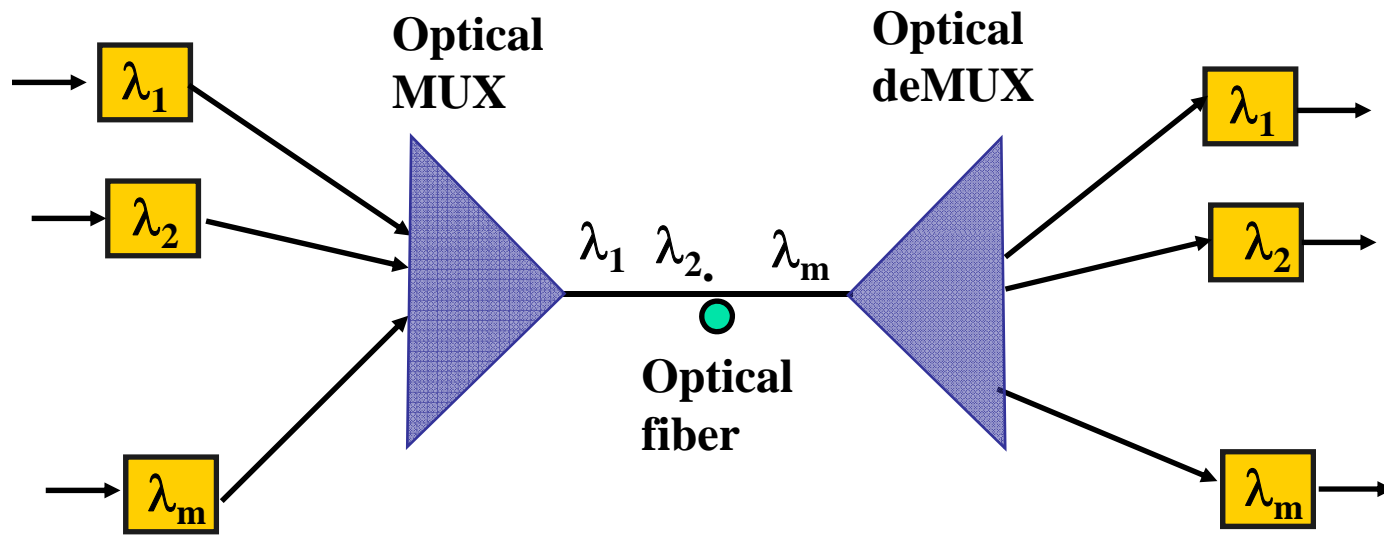


## *Prisms in WDM multiplexing and demultiplexing*



# Wavelength-Division Multiplexing

- Optical fiber link carries several wavelengths
  - From few (4-8) to many (64-160) wavelengths per fiber
- Imagine prism combining different colors into single beam
- Each wavelength carries a high-speed stream
  - Each wavelength can carry different format signal
  - e.g., 1 Gbps, 2.5 Gbps, or 10 Gbps



# TDM

*Time Slots and Frames*

*Interleaving*

*Synchronizing*

*Bit Padding*

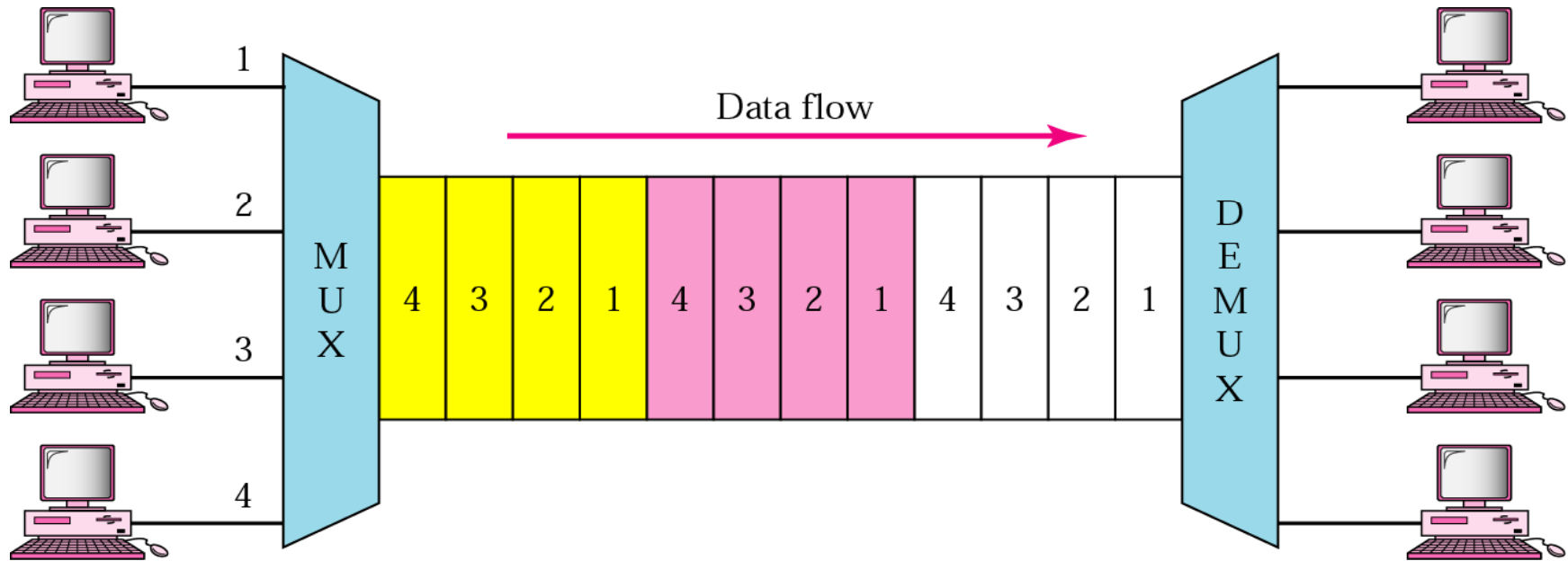
*Digital Signal (DS) Service*

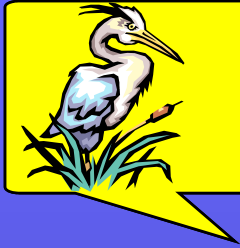
*T Lines*

*Inverse TDM*

*More TDM Applications*

# TDM

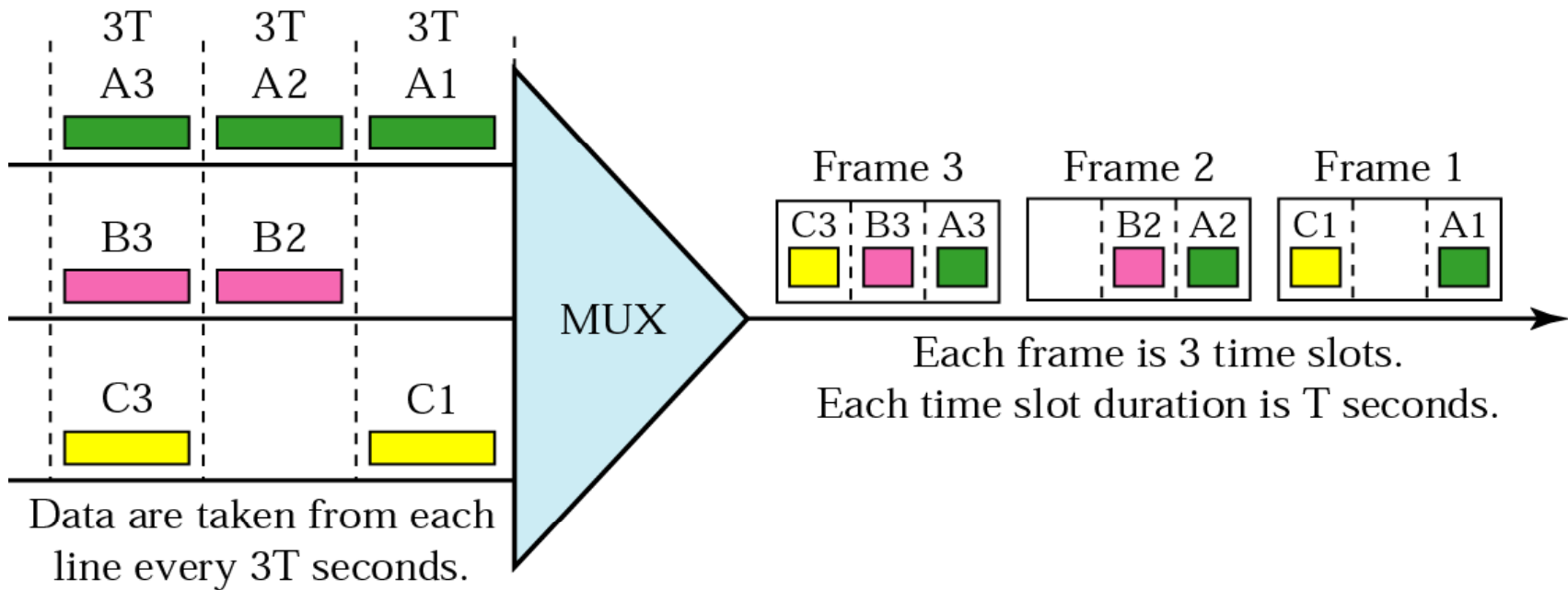


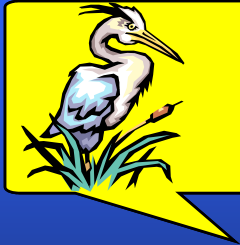


Note:

*TDM is a digital multiplexing technique to combine data.*

# TDM frames

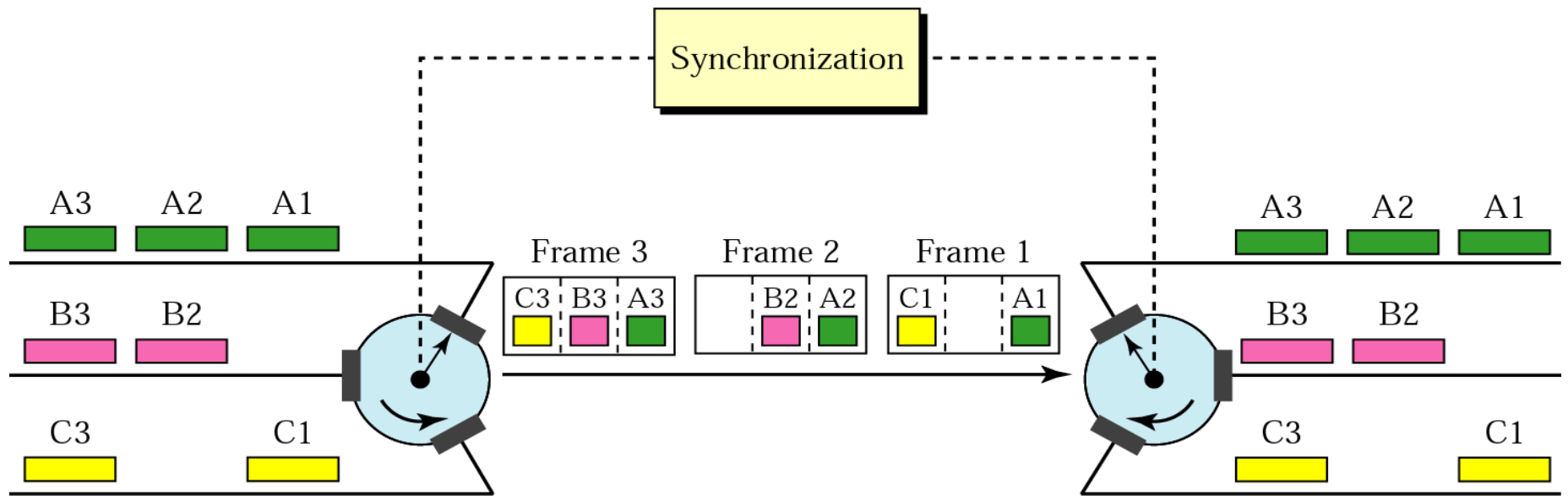




Note:

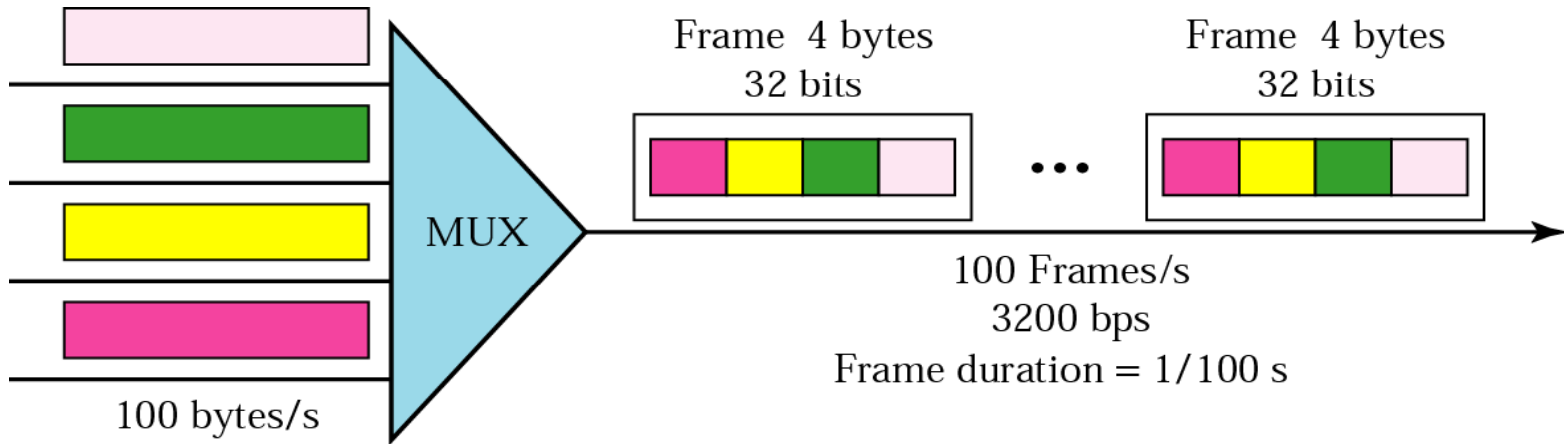
*In a TDM, the data rate of the link is  $n$  times faster, and the unit duration is  $n$  times shorter.*

# Interleaving





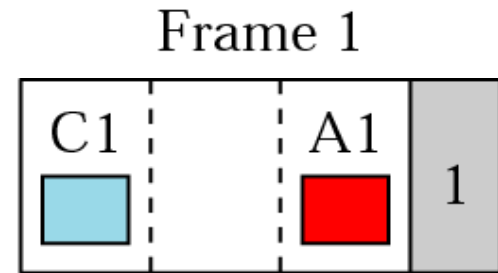
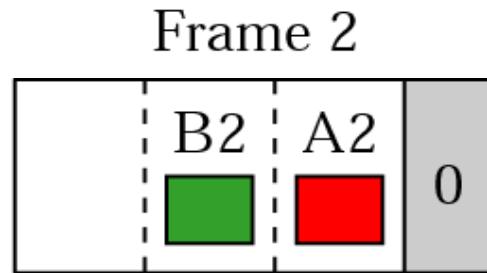
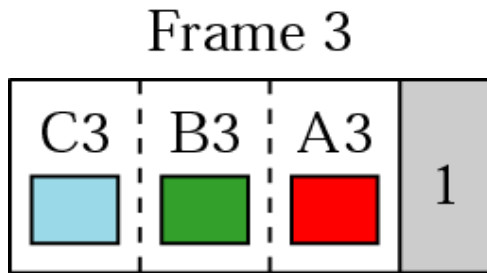
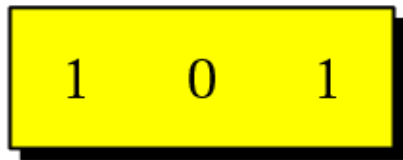
*Example*



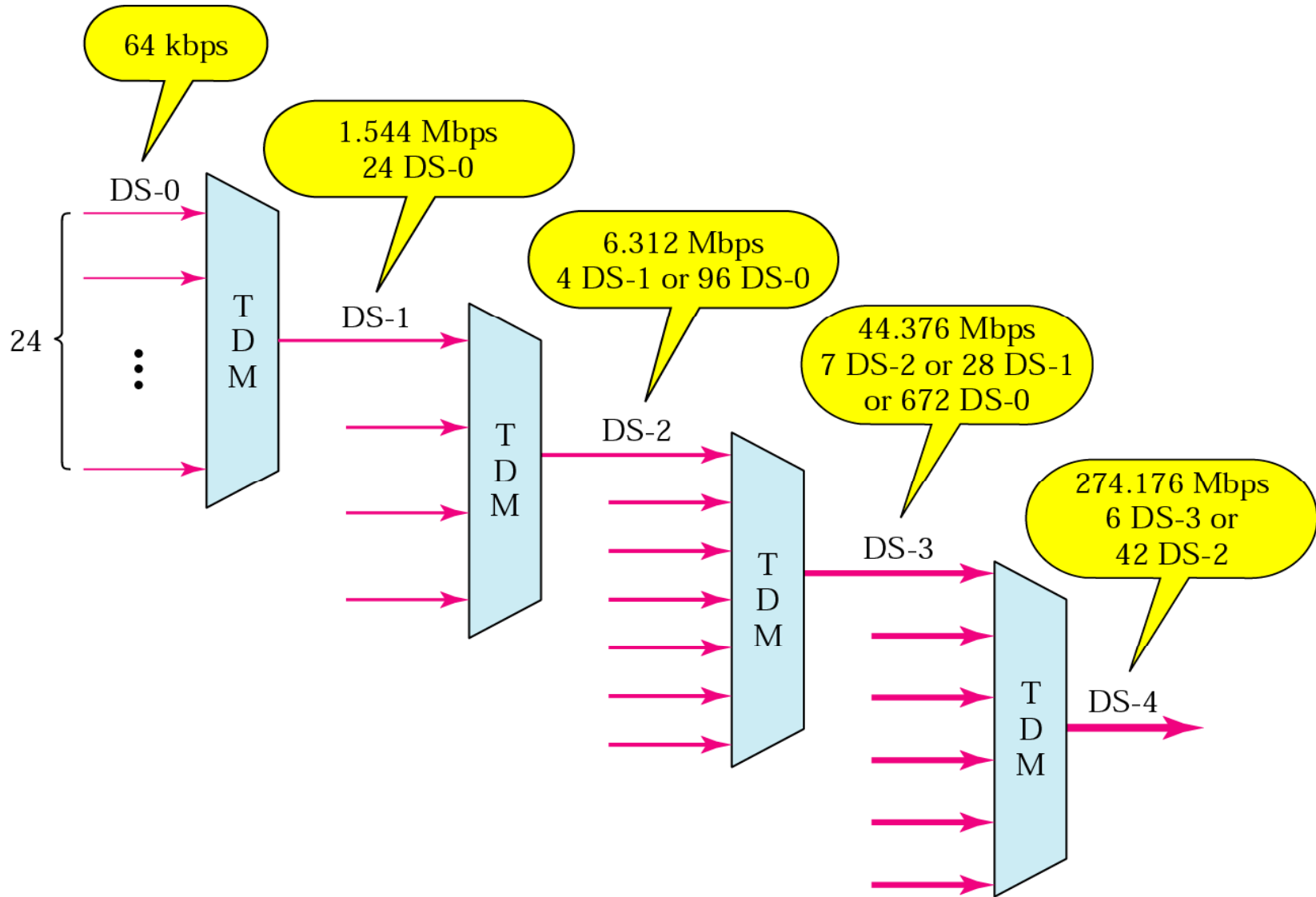


*Framing bits*

Synchronization pattern



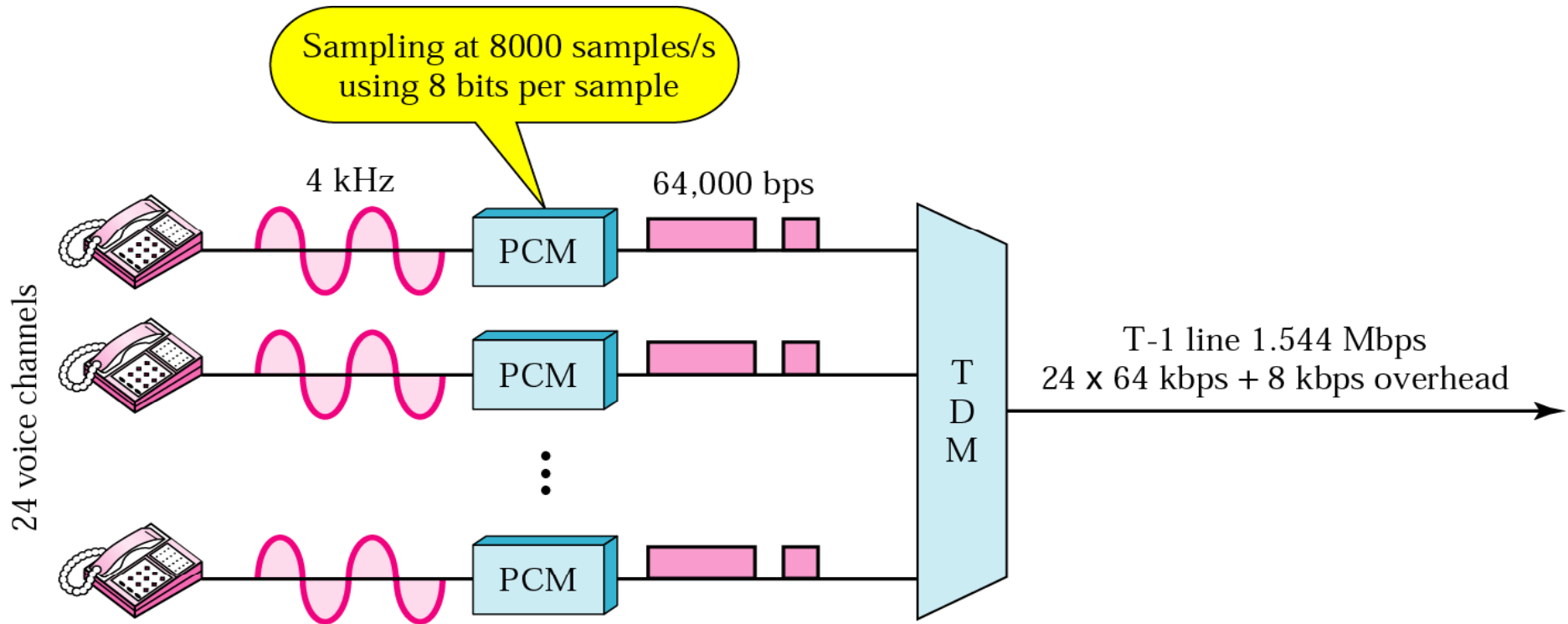
# DS hierarchy



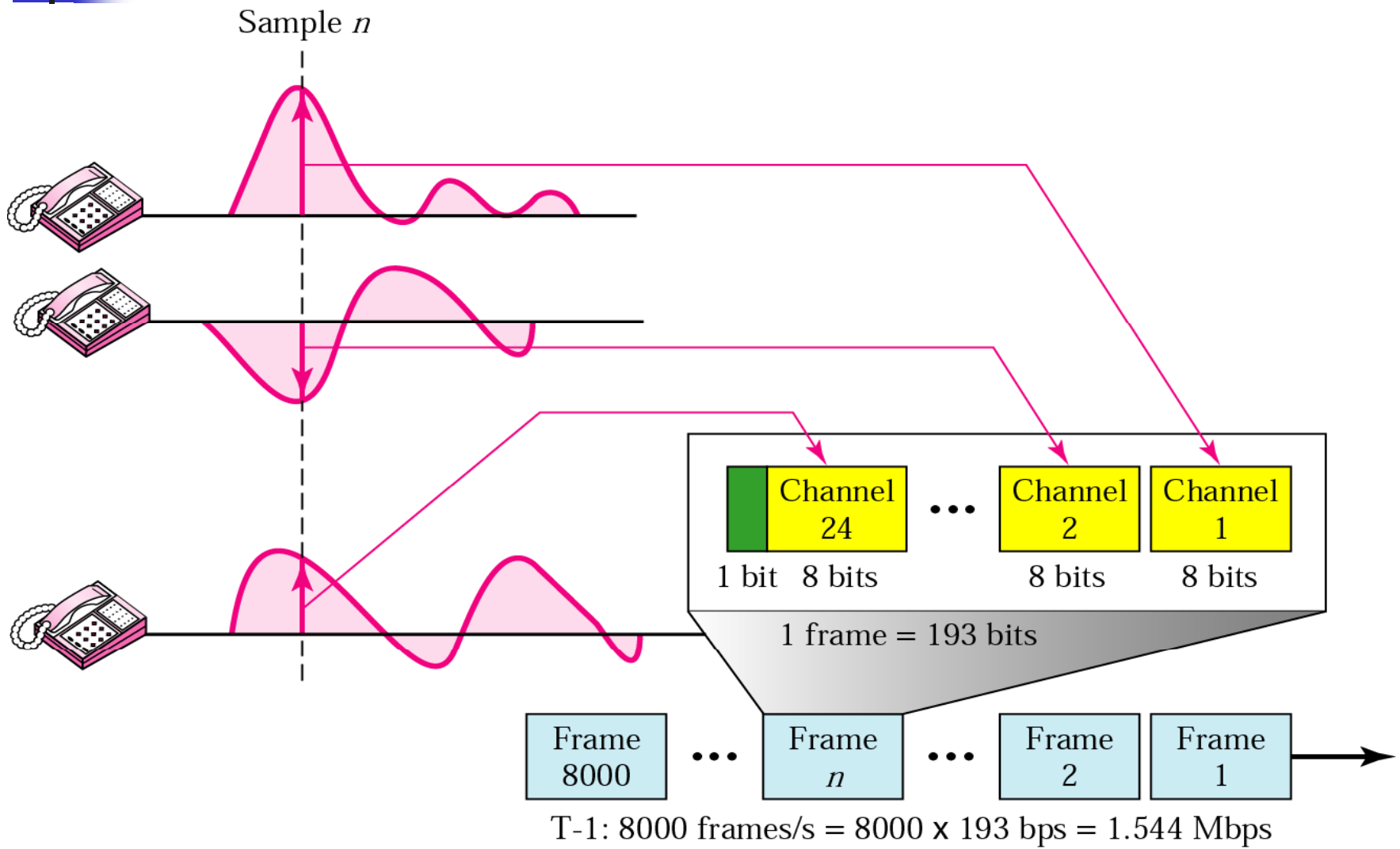
*Table 6.1 DS and T lines rates*

<b>Service</b>	<b>Line</b>	<b>Rate (Mbps)</b>	<b>Voice Channels</b>
<b>DS-1</b>	<b>T-1</b>	<b>1.544</b>	<b>24</b>
<b>DS-2</b>	<b>T-2</b>	<b>6.312</b>	<b>96</b>
<b>DS-3</b>	<b>T-3</b>	<b>44.736</b>	<b>672</b>
<b>DS-4</b>	<b>T-4</b>	<b>274.176</b>	<b>4032</b>

# T-1 line for multiplexing telephone lines



# T-1 frame structure

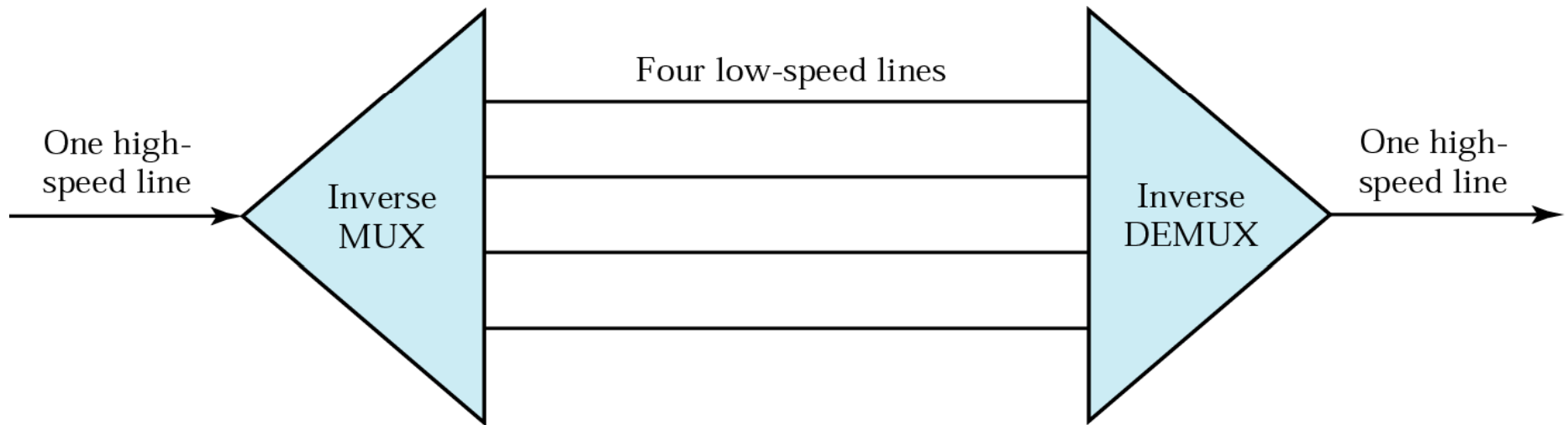


*Table 6.2 E line rates*

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



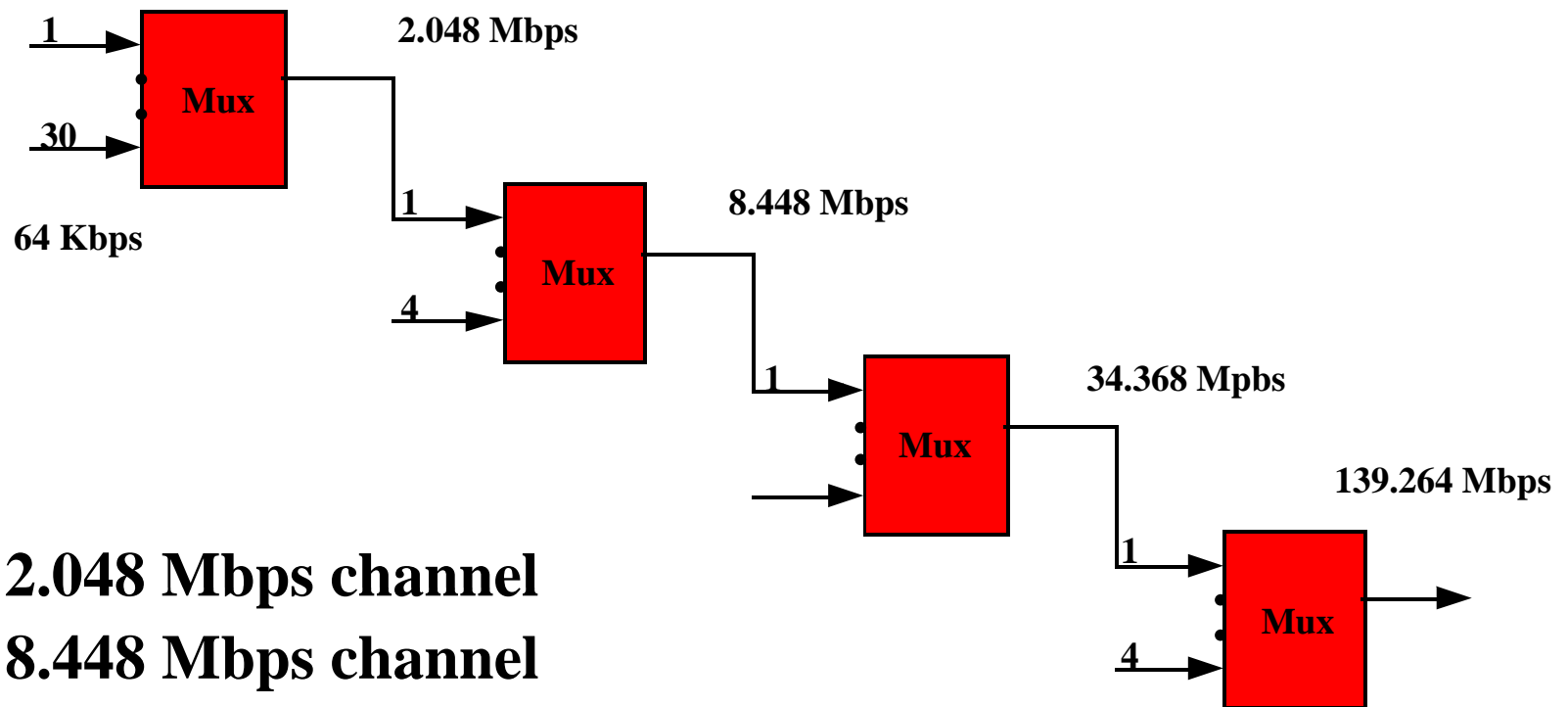
## *Multiplexing and inverse multiplexing*





# CCITT Digital Hierarchy

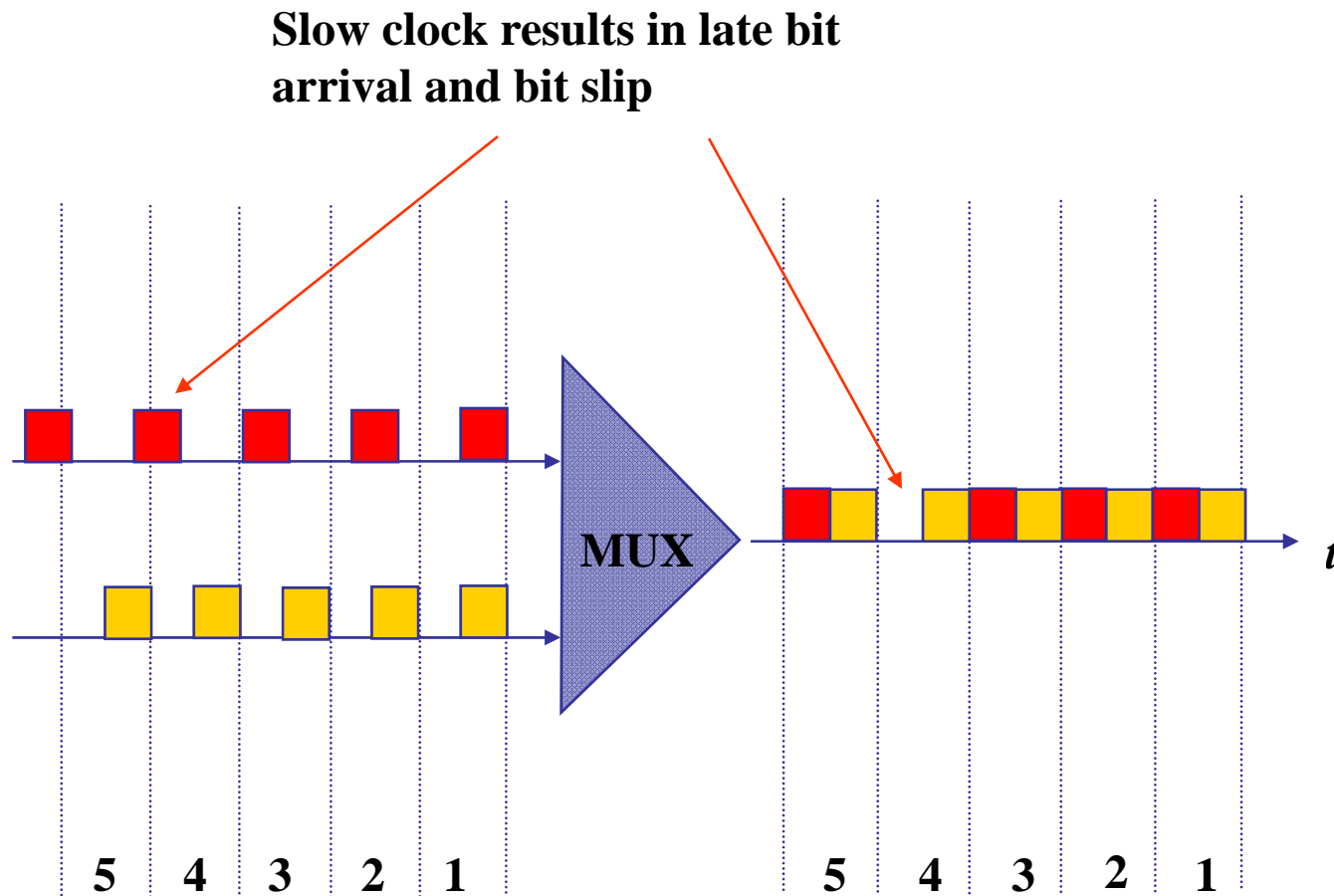
- CCITT digital hierarchy based on 30 PCM channels



- E1, 2.048 Mbps channel
- E2, 8.448 Mbps channel
- E3, 34.368 Mbps channel
- E4, 139.264 Mbps channel

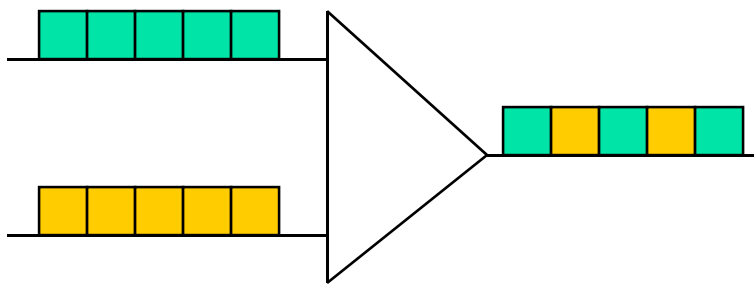
# Clock Synch & Bit Slips

- Digital streams cannot be kept perfectly synchronized
- Bit slips can occur in multiplexers

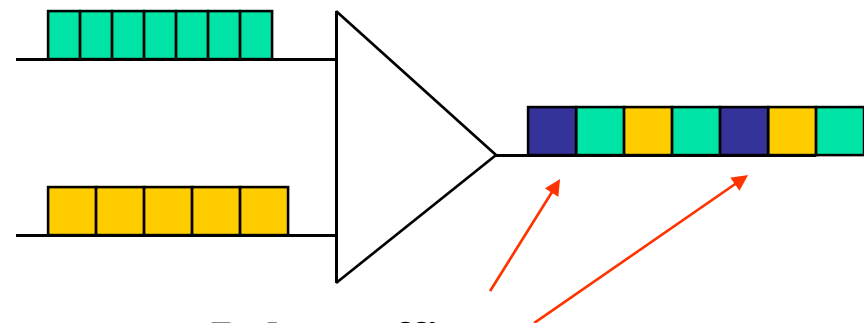


# Pulse Stuffing

- Pulse Stuffing: synchronization to avoid data loss due to bit slips
- Output rate  $> R1+R2$ 
  - i.e. DS2, 6.312Mbps = 4x1.544Mbps + 136 Kbps
- Pulse stuffing format
  - Fixed-length master frames with each channel allowed to stuff or not to stuff a single bit in the master frame.
  - Redundant stuffing specifications
  - signaling or specification bits (other than data bits) are distributed across a master frame.



**Muxing of equal-rate signals  
requires perfect synch**



**Pulse stuffing**