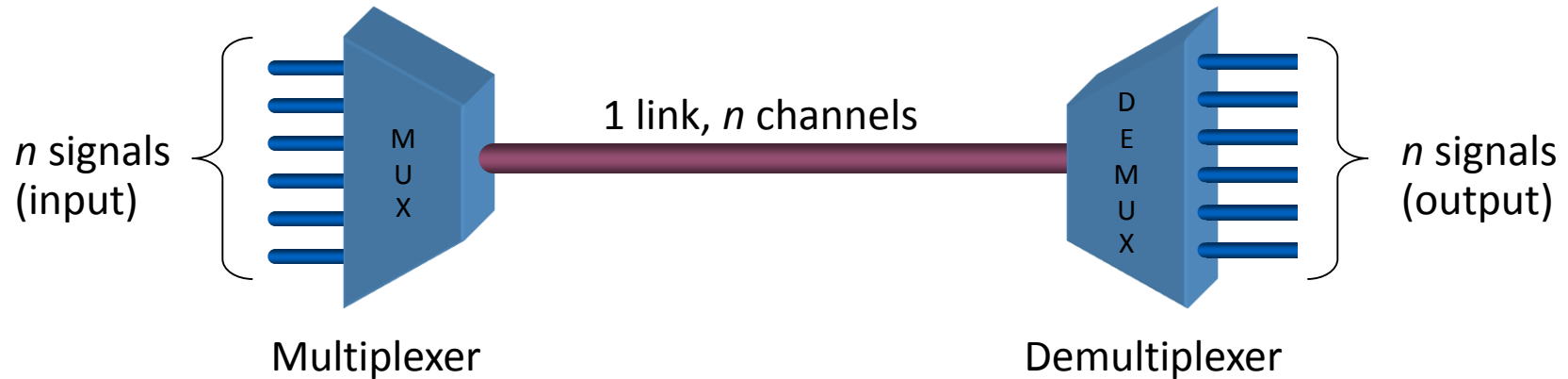


# Multiplexing

# Sharing Medium

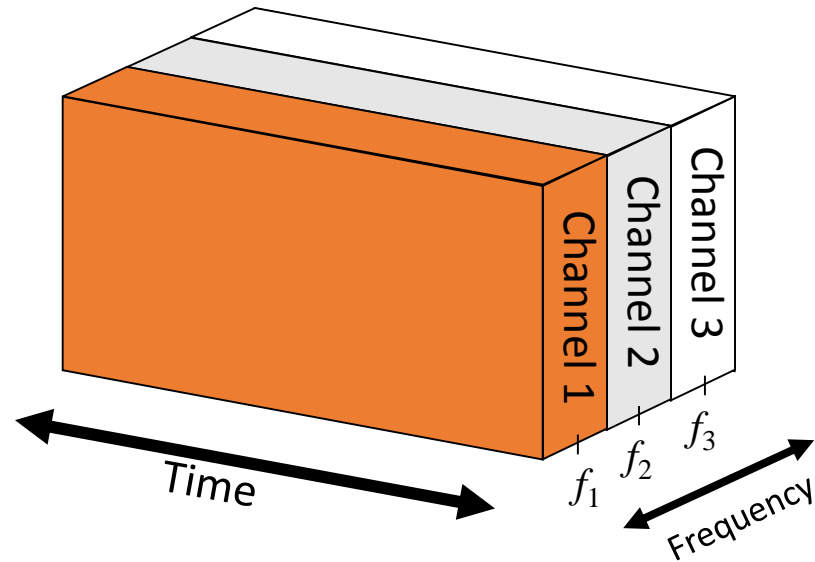
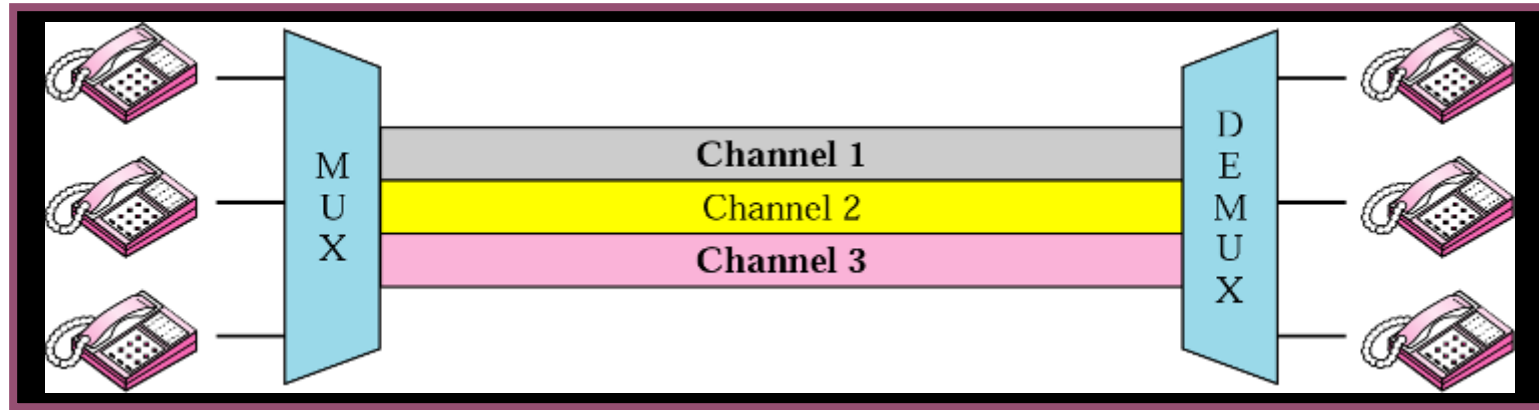
- A link is divided into channels

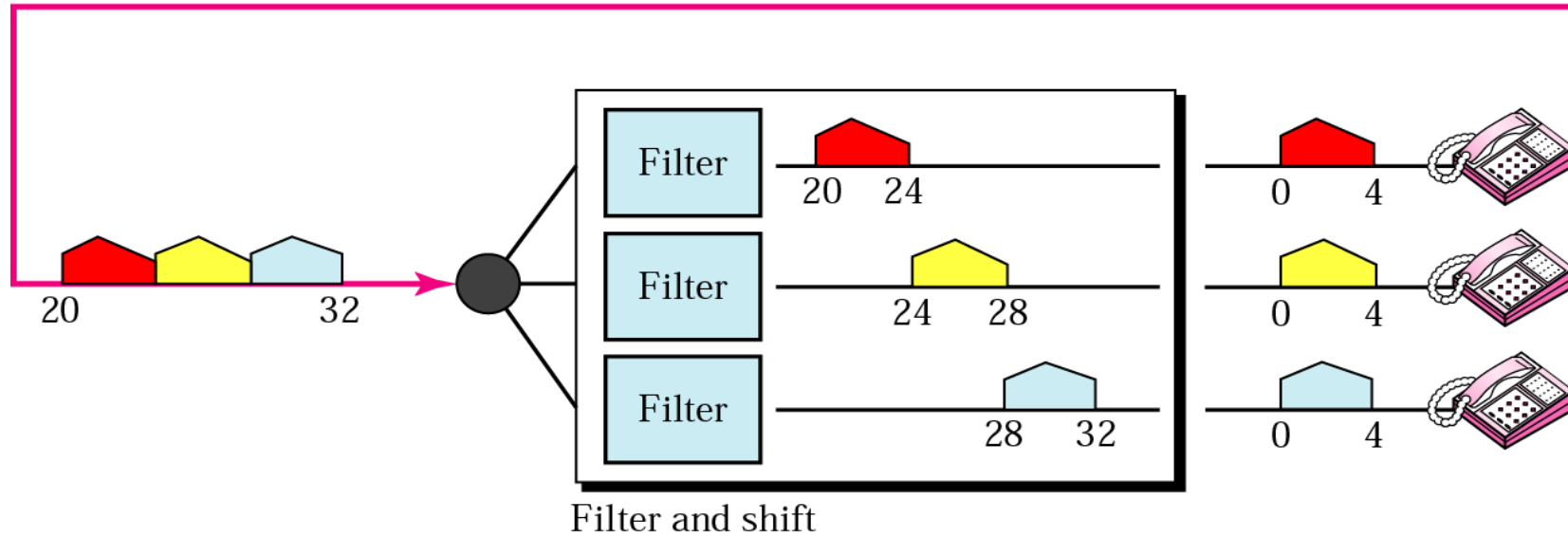
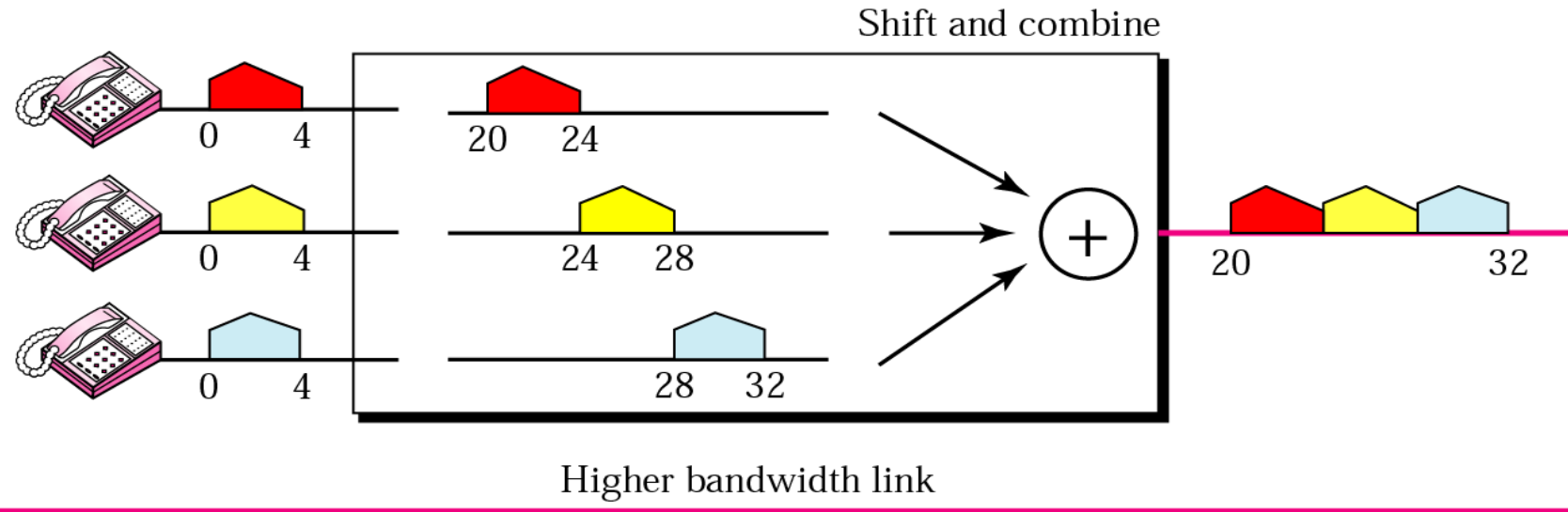


# Frequency Division Multiplexing (FDM)

- An analog multiplexing technique to combine signals
- Medium BW > Channel BW
- Each signal is modulated to a different carrier frequency
- E.g., broadcast radio
- Channel allocated even if no data

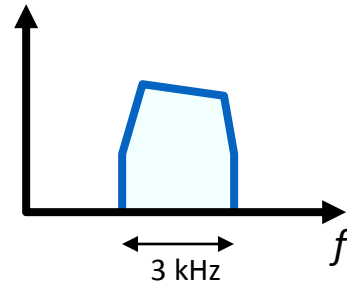
# Conceptual View of FDM



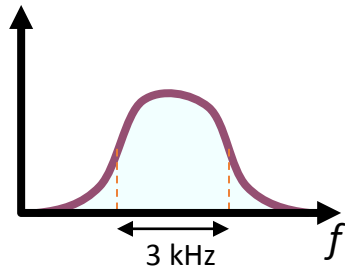
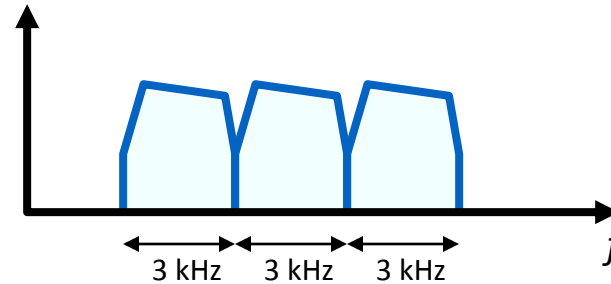


# Guard Bands

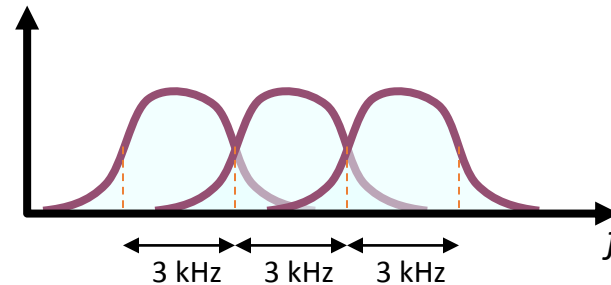
- Strips of unused bandwidth to prevent signals from overlapping



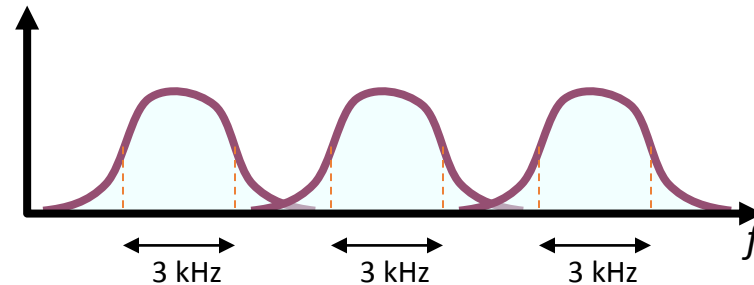
FDM



FDM  
(no guard band)



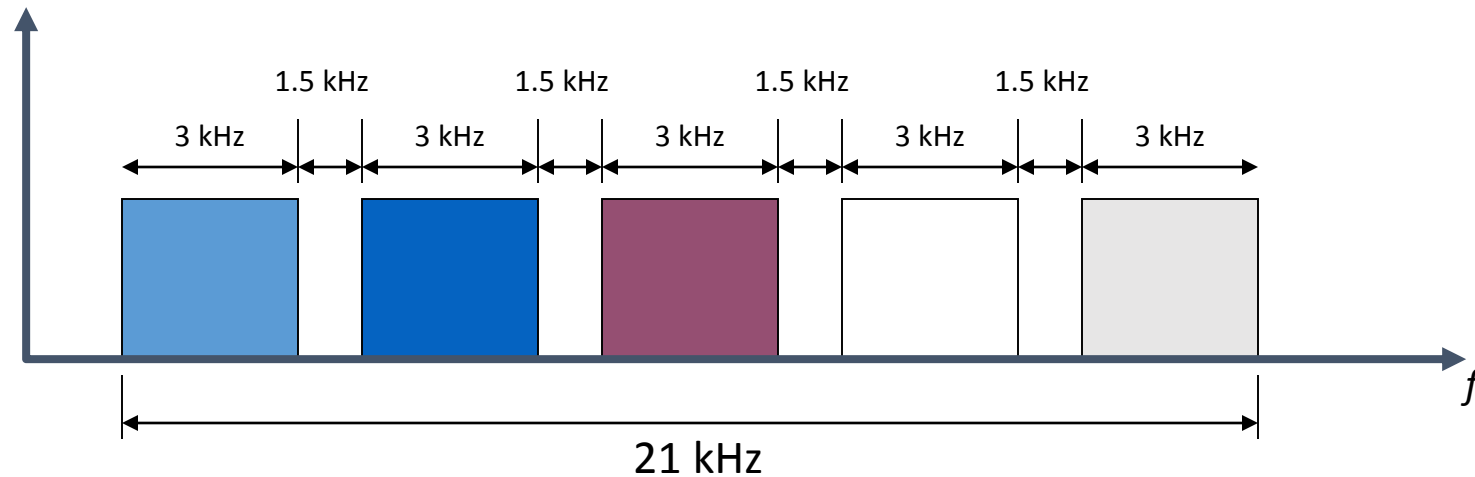
FDM  
(with guard band)



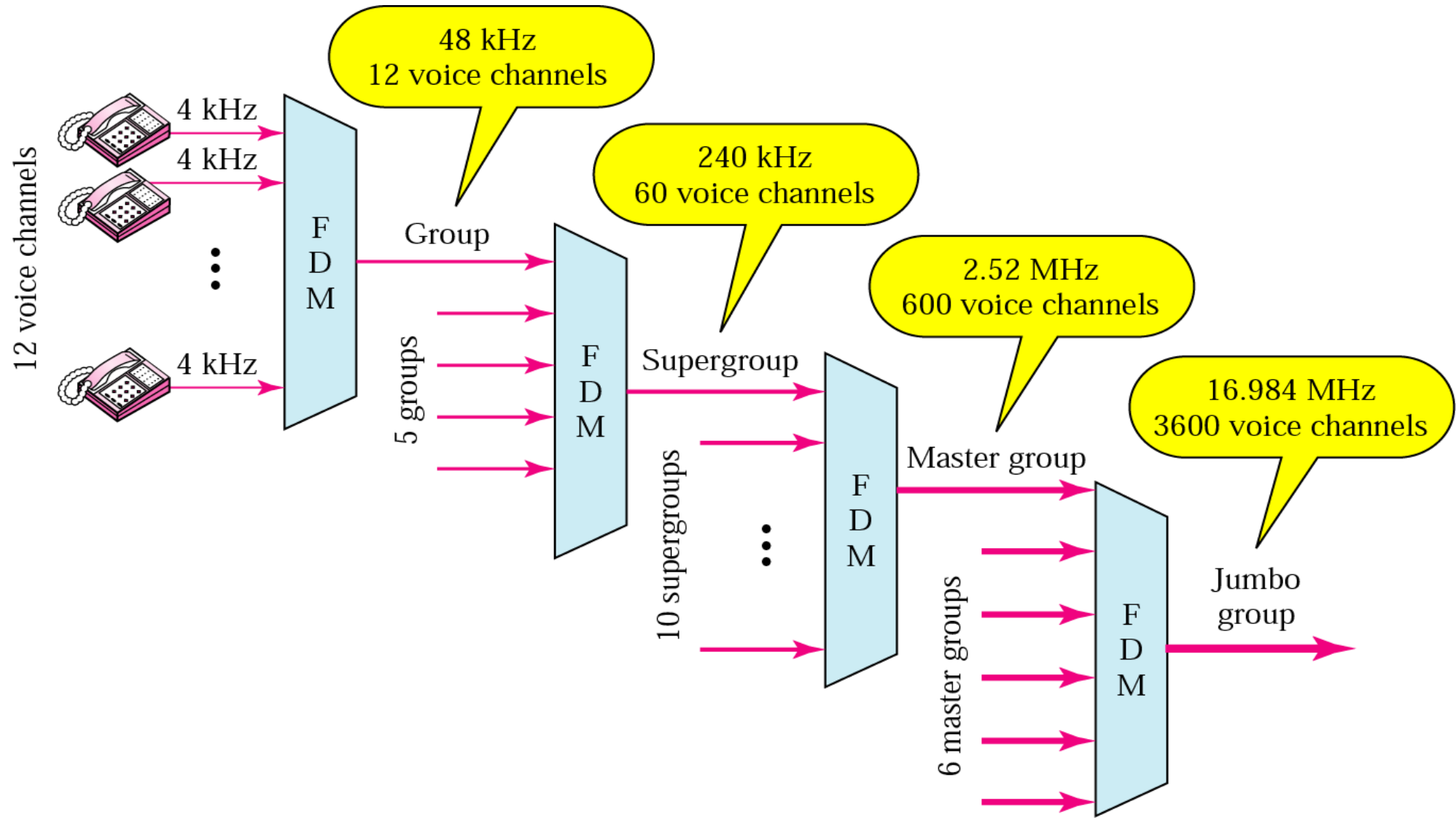
## FDM: *Example 1*

Five voice channels, each with 3-kHz bandwidth, are to be multiplexed together.

If there is a need for a guard band of 1.5 kHz, what is the minimum bandwidth of the link?



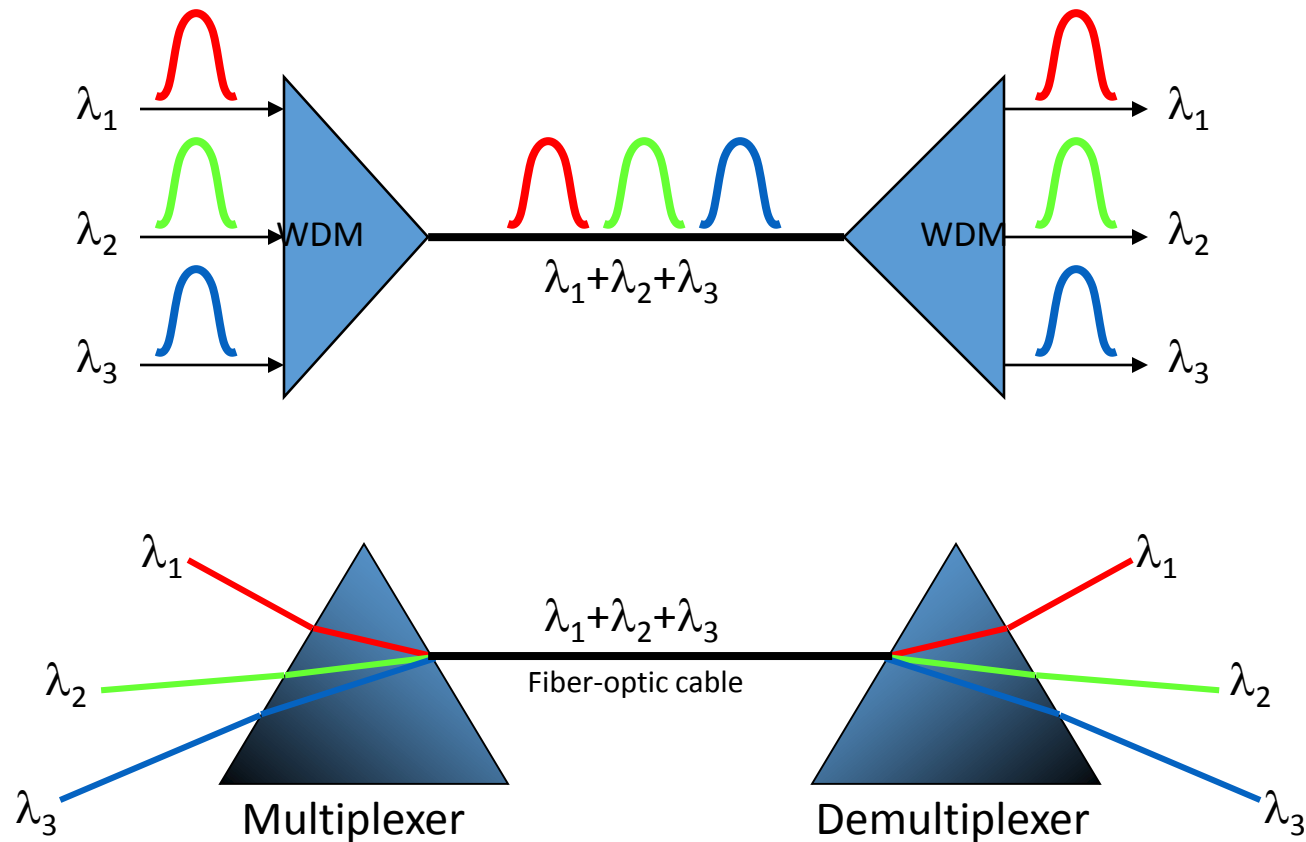
# FDM Carrier Standards in Telephone Network





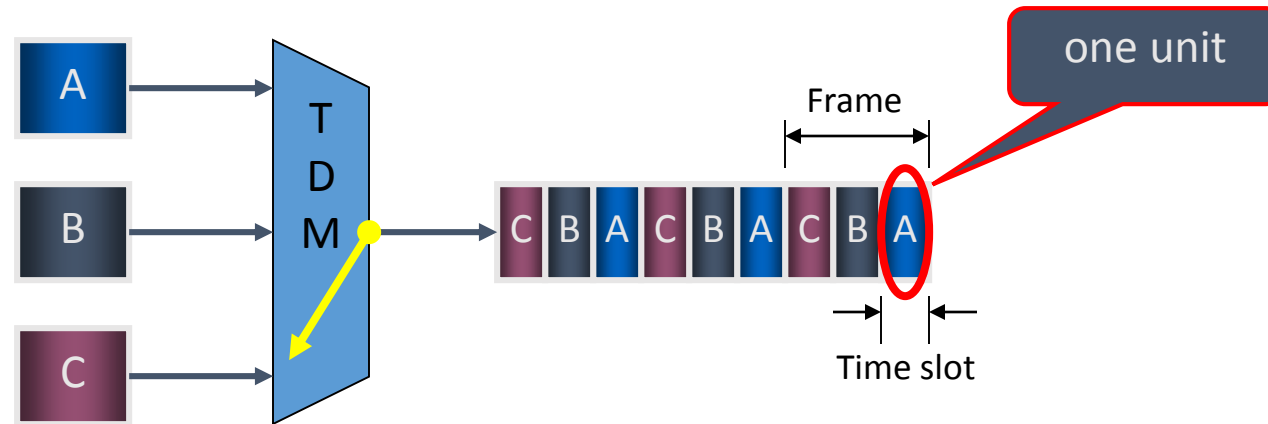
# Wavelength Division Multiplexing (WDM)

- WDM is a special case of FDM used for optical signals



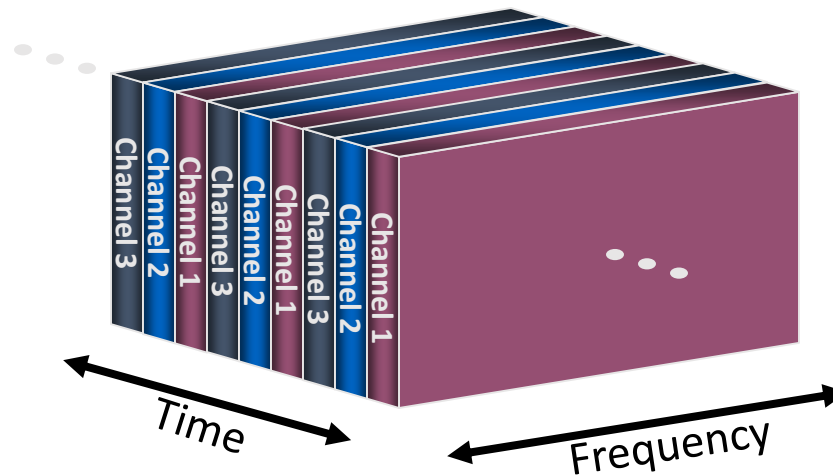
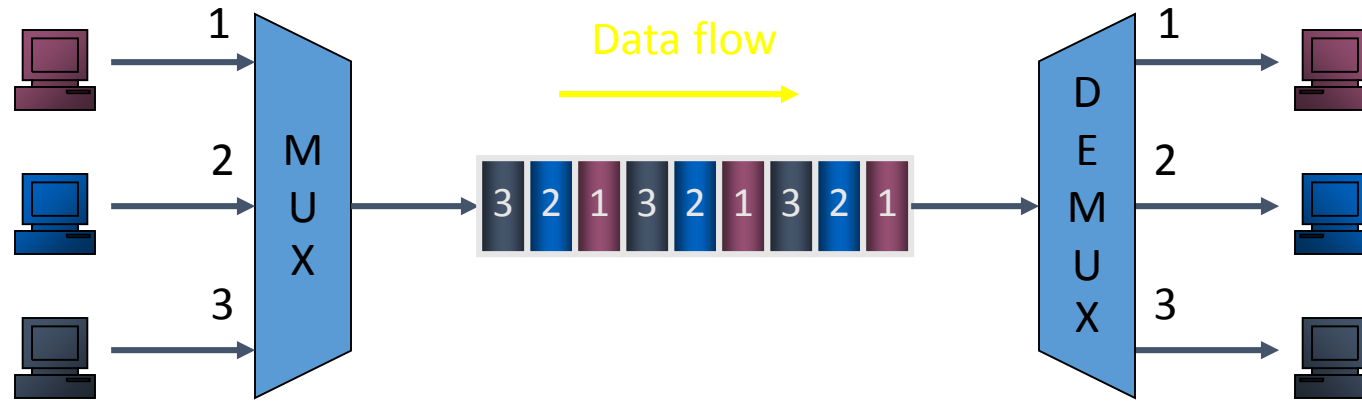
# Time Division Multiplexing (TDM)

- A Digital multiplexing technique to combine data
- Medium Data Rate > Signal Data Rate
- Multiple digital signals interleaved in time



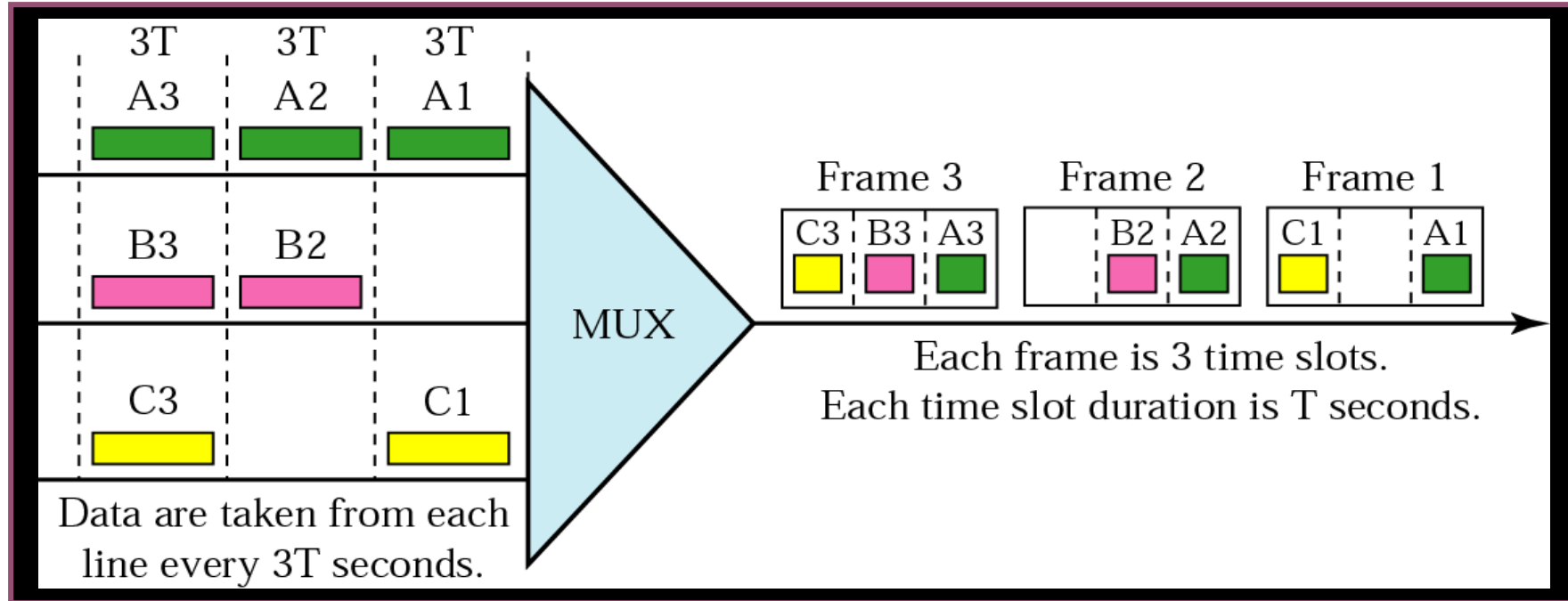
- Time slots
  - are preassigned to sources and fixed
  - are allocated even if no data
  - do not have to be evenly distributed among sources

# Conceptual View of TDM

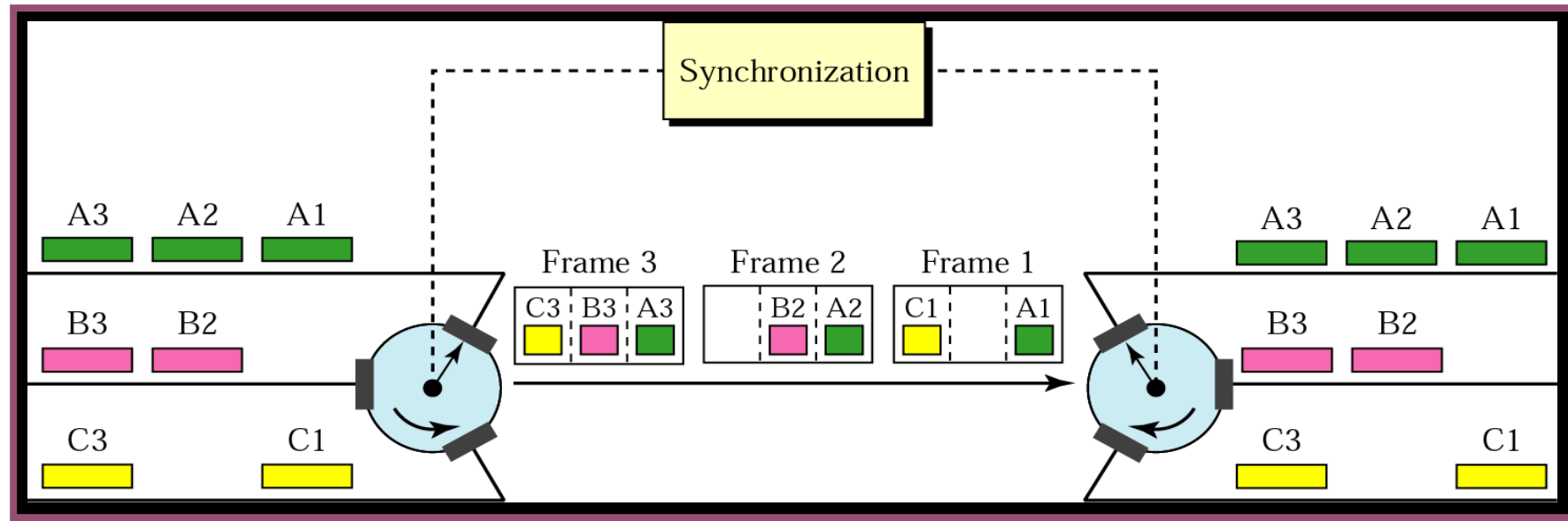


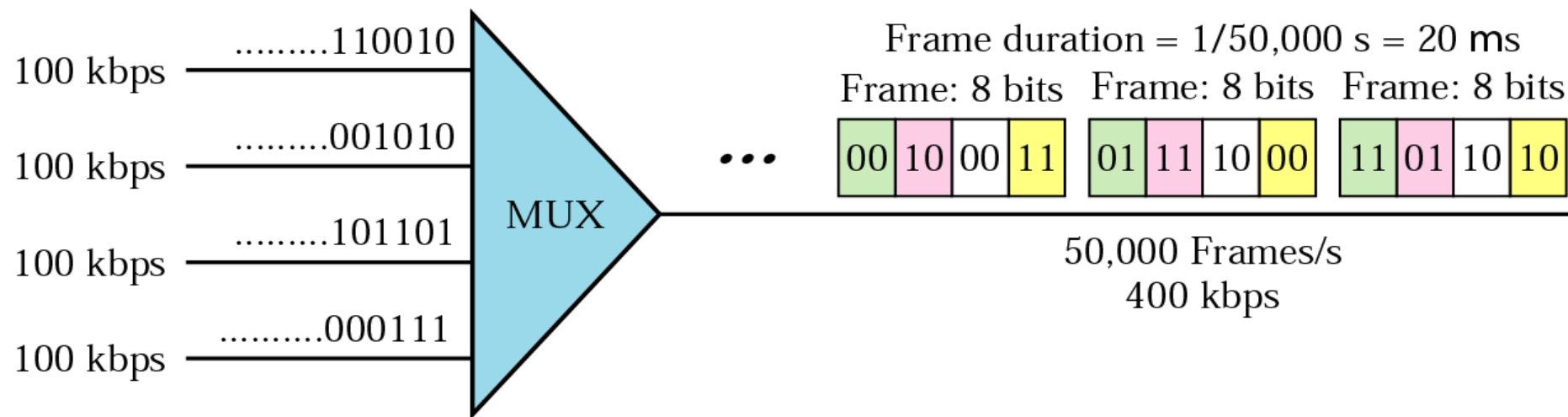
# TDM Frames

- A frame consists of one complete cycle of time slots



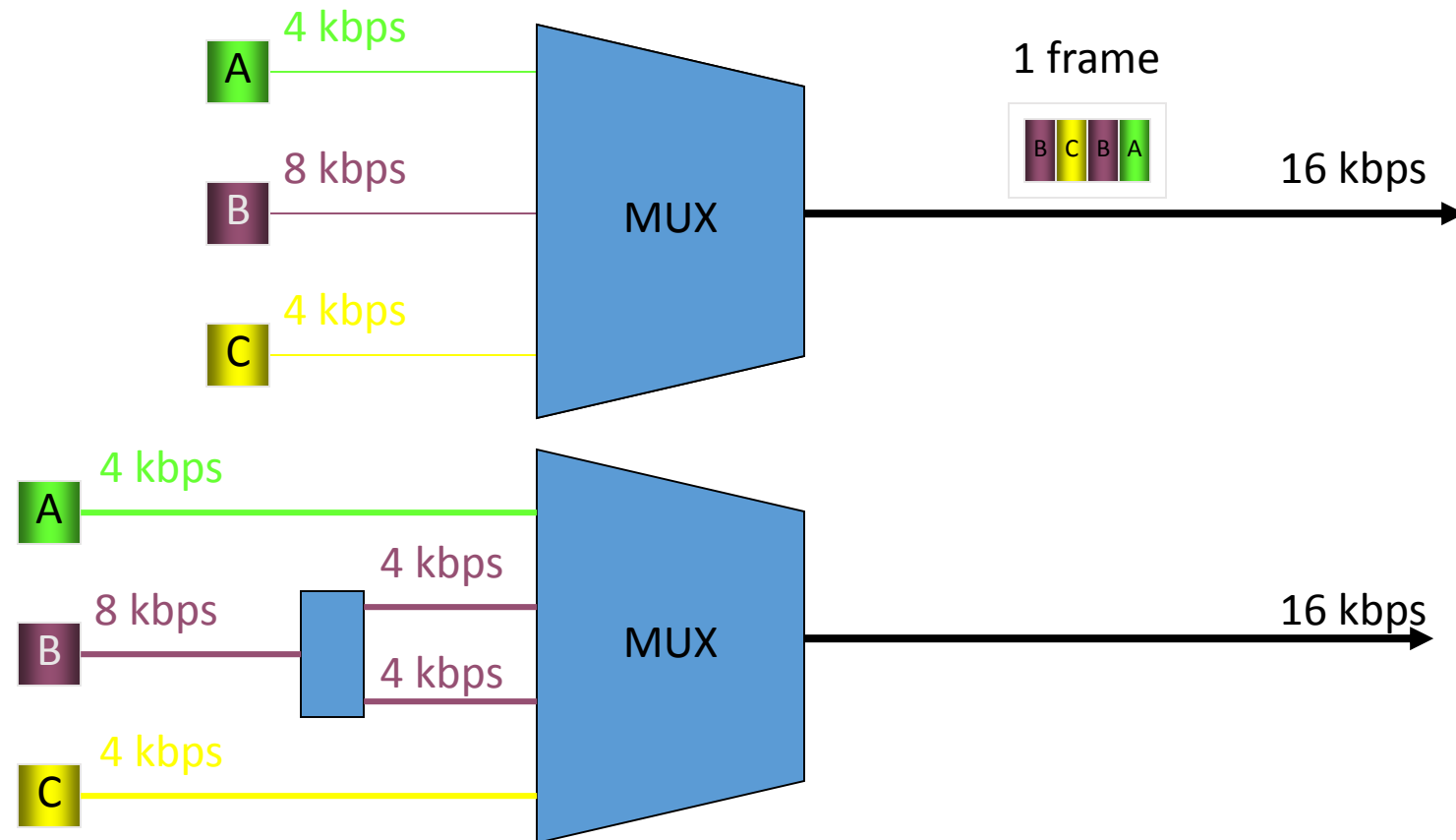
# Empty Slot





# TDM of Different Data Rates

- Data rate from one source may be faster than the others
- More than one time slot can be assigned to certain sources



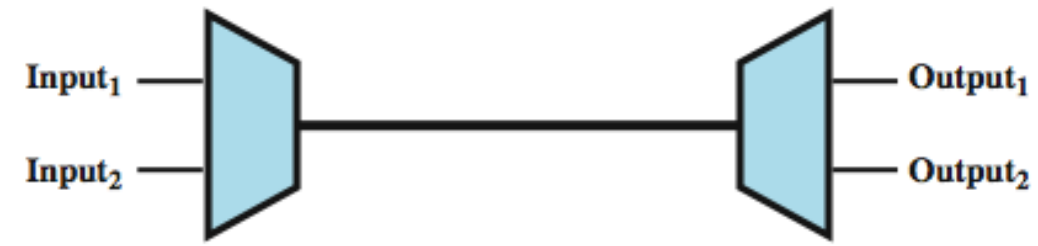
Note: assume 1 unit = 1 bit

# TDM Link Control

- no headers and trailers
- data link control protocols not needed
- flow control
  - data rate of multiplexed line is fixed
  - if one channel receiver can not receive data, the others must carry on
  - corresponding source must be quenched
- error control
  - errors detected & handled on individual channel



# Data Link Control on TDM



(a) Configuration

Input<sub>1</sub>..... F<sub>1</sub> f<sub>1</sub> f<sub>1</sub> d<sub>1</sub> d<sub>1</sub> d<sub>1</sub> C<sub>1</sub> A<sub>1</sub> F<sub>1</sub> f<sub>1</sub> f<sub>1</sub> d<sub>1</sub> d<sub>1</sub> d<sub>1</sub> C<sub>1</sub> A<sub>1</sub> F<sub>1</sub>  
 Input<sub>2</sub>... F<sub>2</sub> f<sub>2</sub> f<sub>2</sub> d<sub>2</sub> d<sub>2</sub> d<sub>2</sub> d<sub>2</sub> C<sub>2</sub> A<sub>2</sub> F<sub>2</sub> f<sub>2</sub> f<sub>2</sub> d<sub>2</sub> d<sub>2</sub> d<sub>2</sub> d<sub>2</sub> C<sub>2</sub> A<sub>2</sub> F<sub>2</sub>

(b) Input data streams

... f<sub>2</sub> F<sub>1</sub> d<sub>2</sub> f<sub>1</sub> d<sub>2</sub> f<sub>1</sub> d<sub>2</sub> d<sub>1</sub> d<sub>2</sub> d<sub>1</sub> C<sub>2</sub> d<sub>1</sub> A<sub>2</sub> C<sub>1</sub> F<sub>2</sub> A<sub>1</sub> f<sub>2</sub> F<sub>1</sub> f<sub>2</sub> f<sub>1</sub> d<sub>2</sub> f<sub>1</sub> d<sub>2</sub> d<sub>1</sub> d<sub>2</sub> d<sub>1</sub> d<sub>2</sub> d<sub>1</sub> C<sub>2</sub> C<sub>1</sub> A<sub>2</sub> A<sub>1</sub> F<sub>2</sub> F<sub>1</sub>

(c) Multiplexed data stream

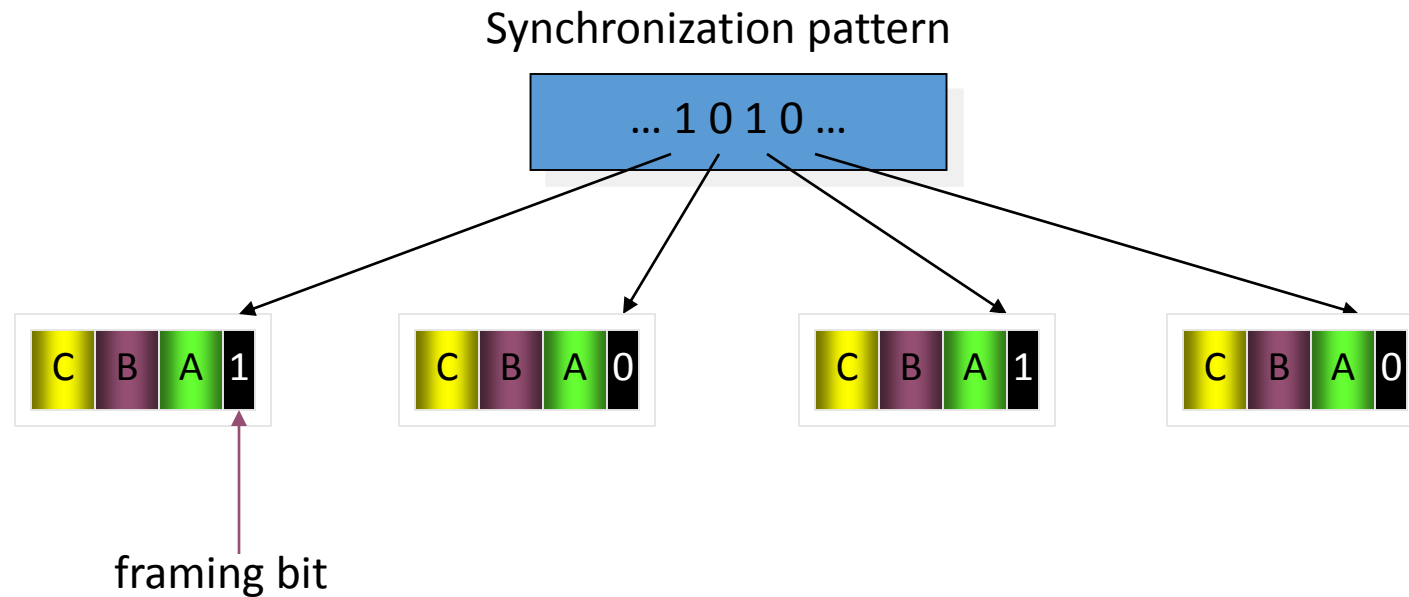
Legend: F = flag field      d = one octet of data field  
 A = address field    f = one octet of FCS field  
 C = control field

# Framing

- no flag or SYNC chars bracketing TDM frames
- must still provide synchronizing mechanism between src and dest clocks
- added digit framing
  - one control bit added to each TDM frame
  - identifiable bit pattern used on control channel
  - eg. alternating 01010101...unlikely on a data channel
- frame search mode
  - compare incoming bit patterns on each channel with known sync pattern

# Synchronization

- Multiplexer and demultiplexer must be synchronized
- Framing bits are used to provide synchronization



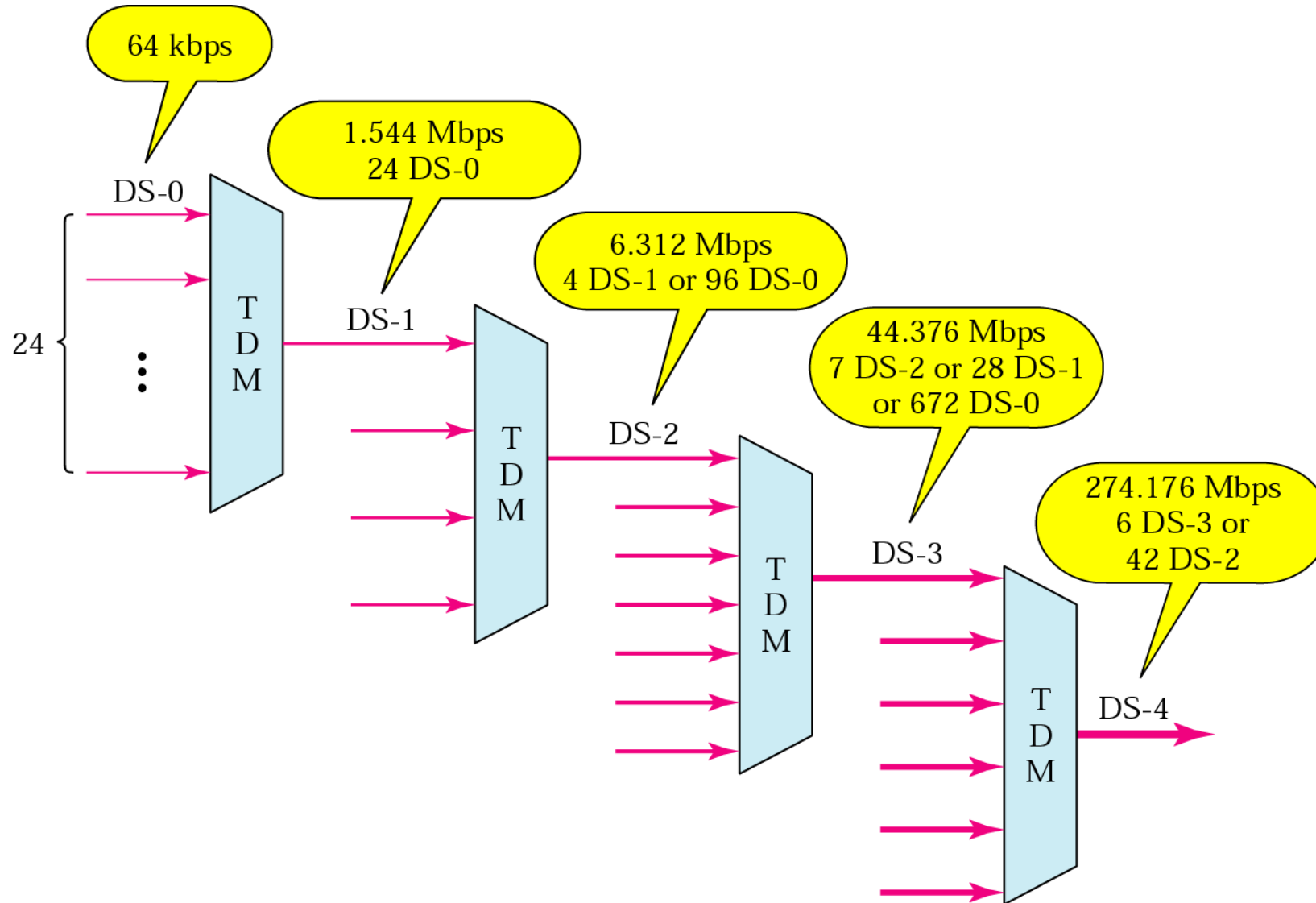
# Pulse Stuffing

- have problem of synchronizing data sources
- also issue of data rates from different sources not related by simple rational number
- Pulse Stuffing a common solution
  - stuff extra dummy bits or pulses into each incoming signal until it matches local clock
  - stuffed pulses inserted at fixed locations in frame and removed at demultiplexer

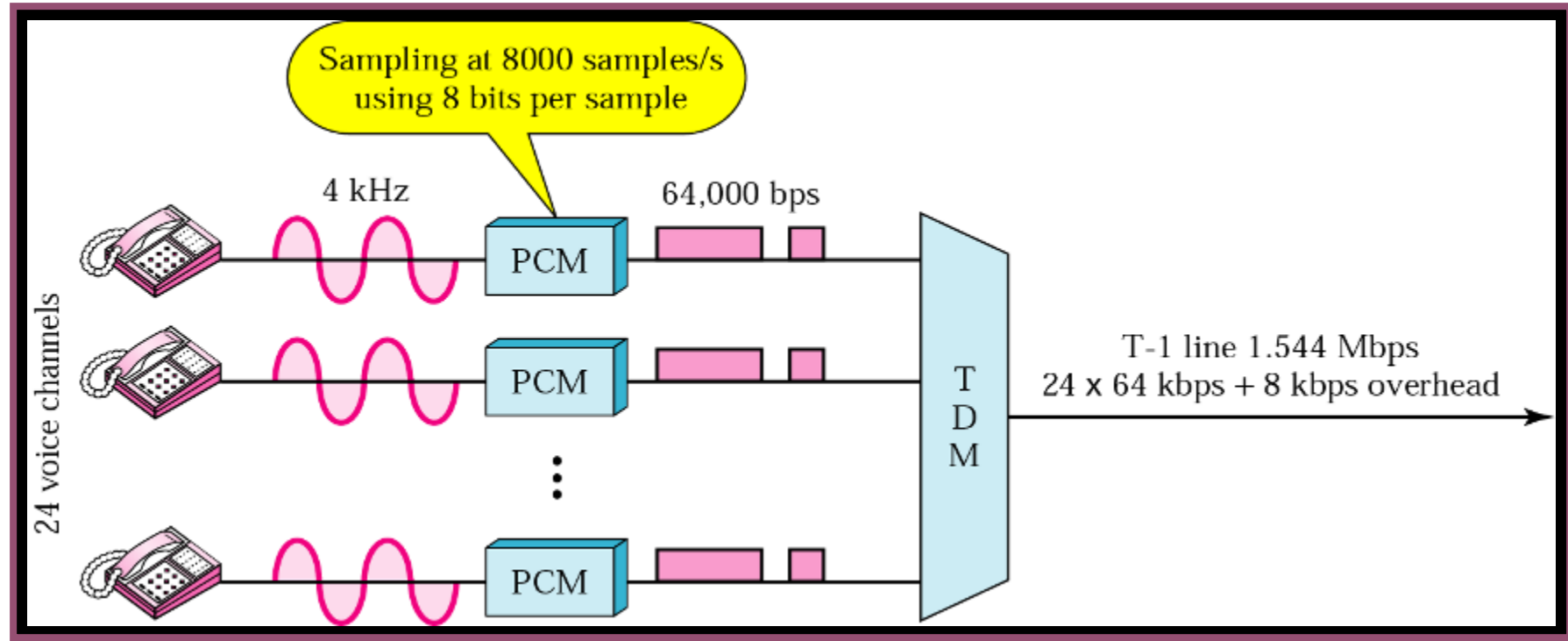
# Digital Carrier Systems

- long-distance links use an TDM hierarchy
- AT&T (USA) and ITU-T (International) variants
- US system based on DS-1 format
- can carry mixed voice and data signals
- 24 channels used for total data rate 1.544Mbps
- each voice channel contains one word of digitized data (PCM, 8000 samples per sec)
- same format for 56kbps digital data
- can interleave DS-1 channels for higher rates
  - DS-2 is four DS-1 at 6.312Mbps

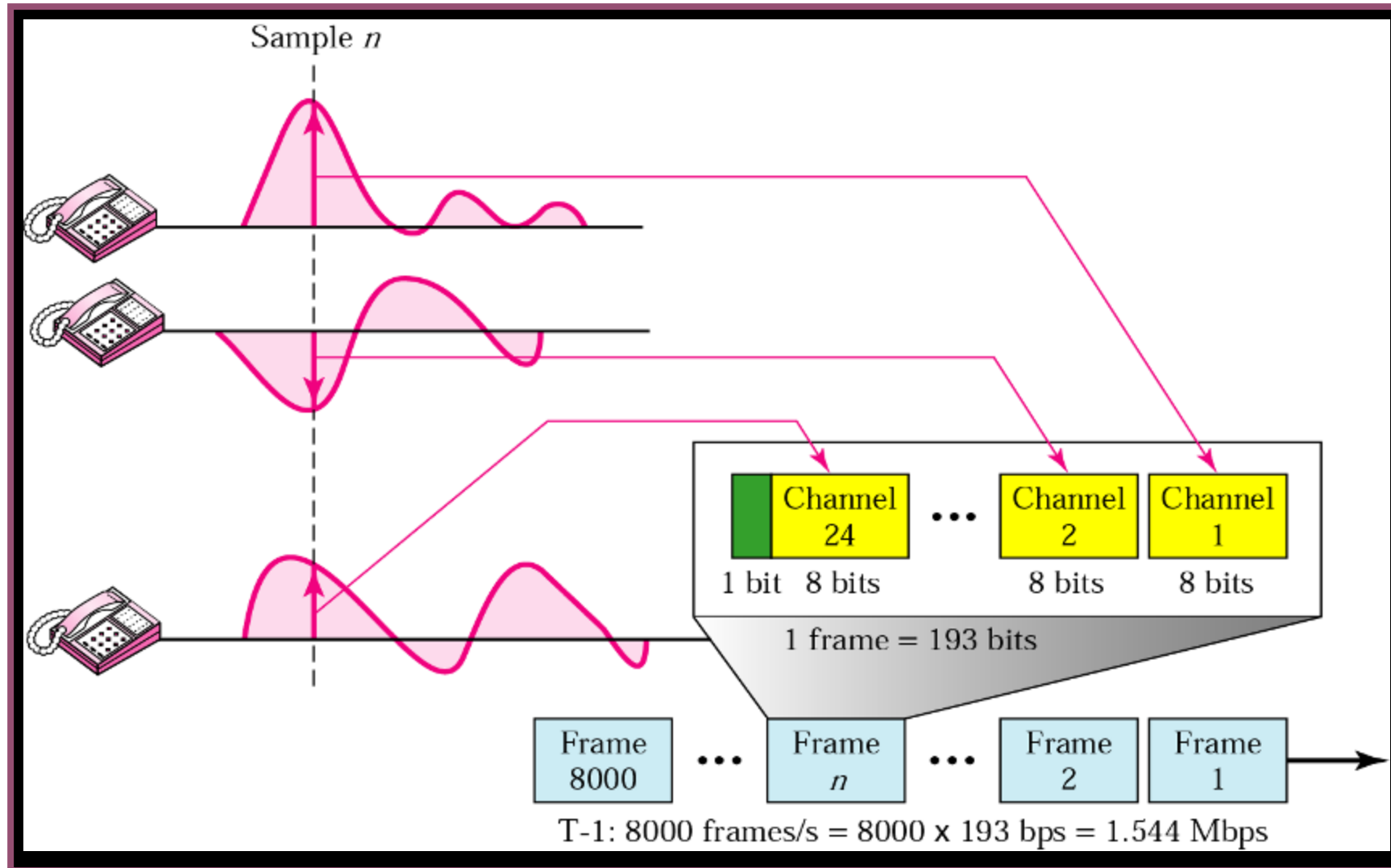
# Digital Signal (DS) Hierarchy



# T Lines and Analog Signals



# T-1 Frame Structure

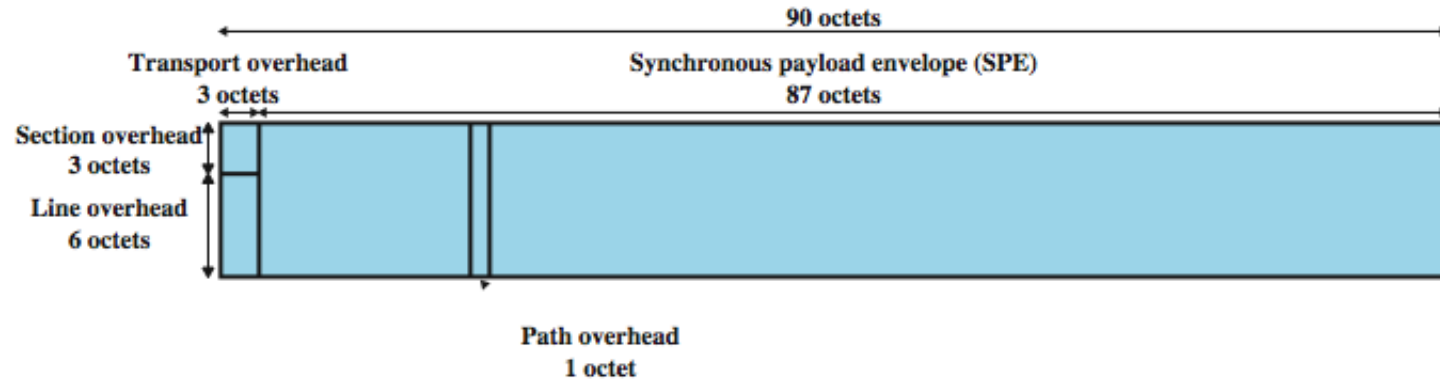




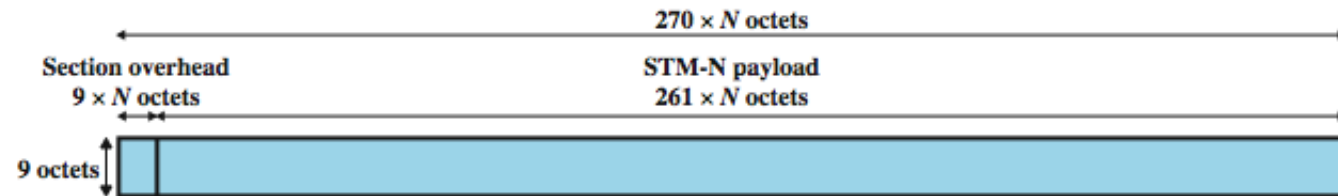
# SONET/SDH

- Synchronous Optical Network (ANSI)
- Synchronous Digital Hierarchy (ITU-T)
- have hierarchy of signal rates
  - Synchronous Transport Signal level 1 (STS-1) or Optical Carrier level 1 (OC-1) is 51.84Mbps
  - carries one DS-3 or multiple (DS1 DS1C DS2) plus ITU-T rates (eg. 2.048Mbps)
  - multiple STS-1 combine into STS-N signal
- Each frame of 810 bytes sent every 125 microsec.
- 9 rows of 90 octets
  - 27 octets reserved for overhead

# SONET Frame Format



(a) STS-1 frame format



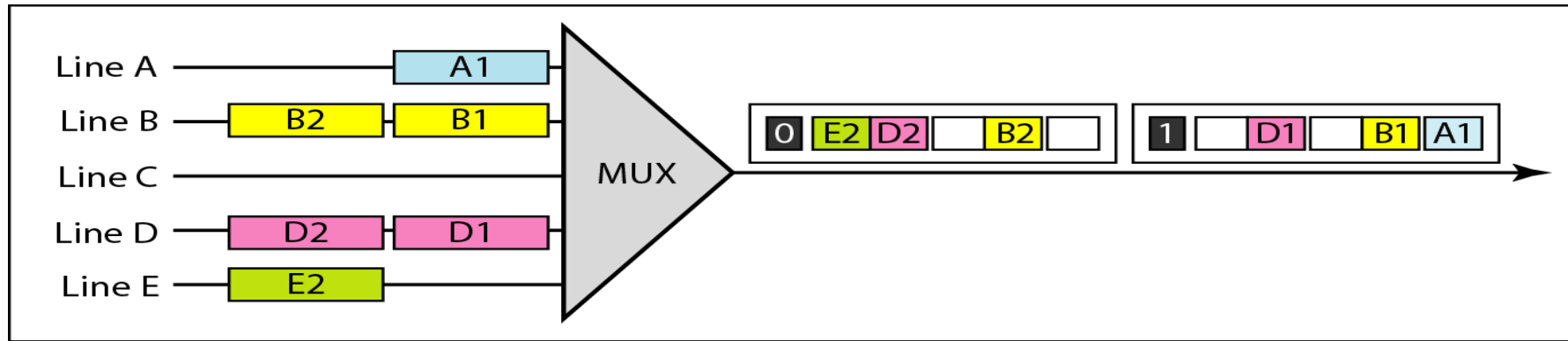
(b) STM-N frame format

Section: Between regenerators; Line: Between Mux and Demux; Path: Between SONET terminals

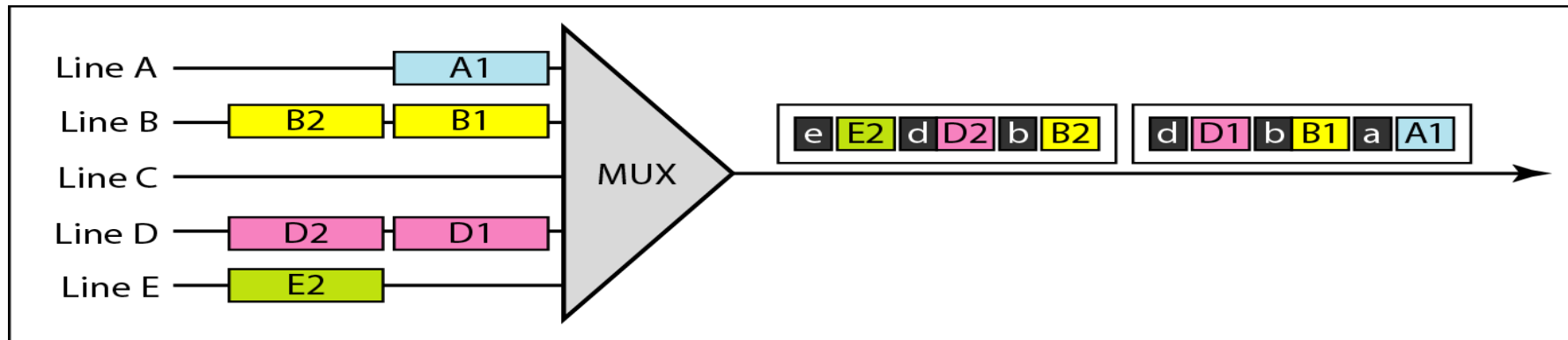
# Statistical TDM

- synch TDM many slots are wasted
- statistical TDM allocates time slots dynamically based on demand
- multiplexer scans input lines and collects data until frame full
- multiplexed line data rate lower than aggregate input line rates
- can support more users than sync TDM
- may have problems during peak periods
  - must buffer inputs

# Synchronous vs Statistical TDM



a. Synchronous TDM

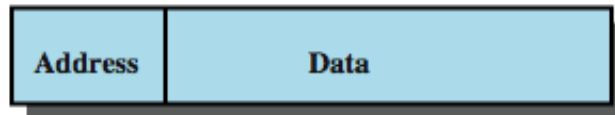


b. Statistical TDM

# Statistical TDM Frame Format



(a) Overall frame



(b) Subframe with one source per frame

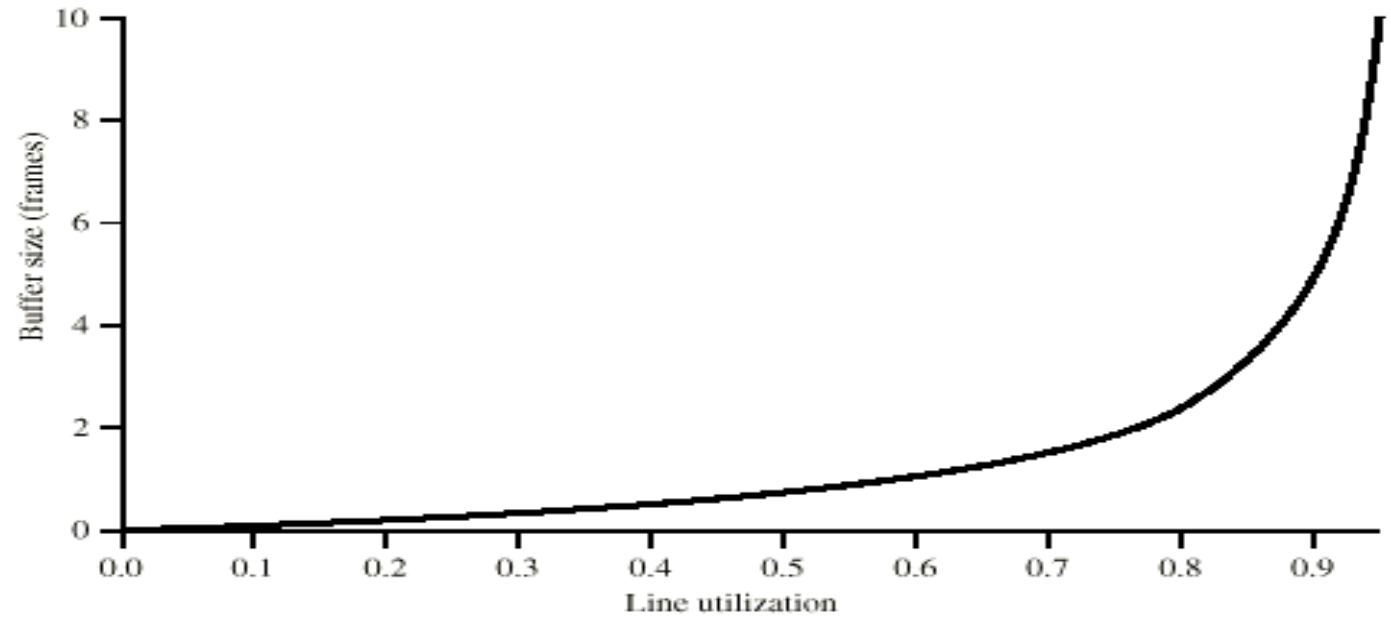


(c) Subframe with multiple sources per frame

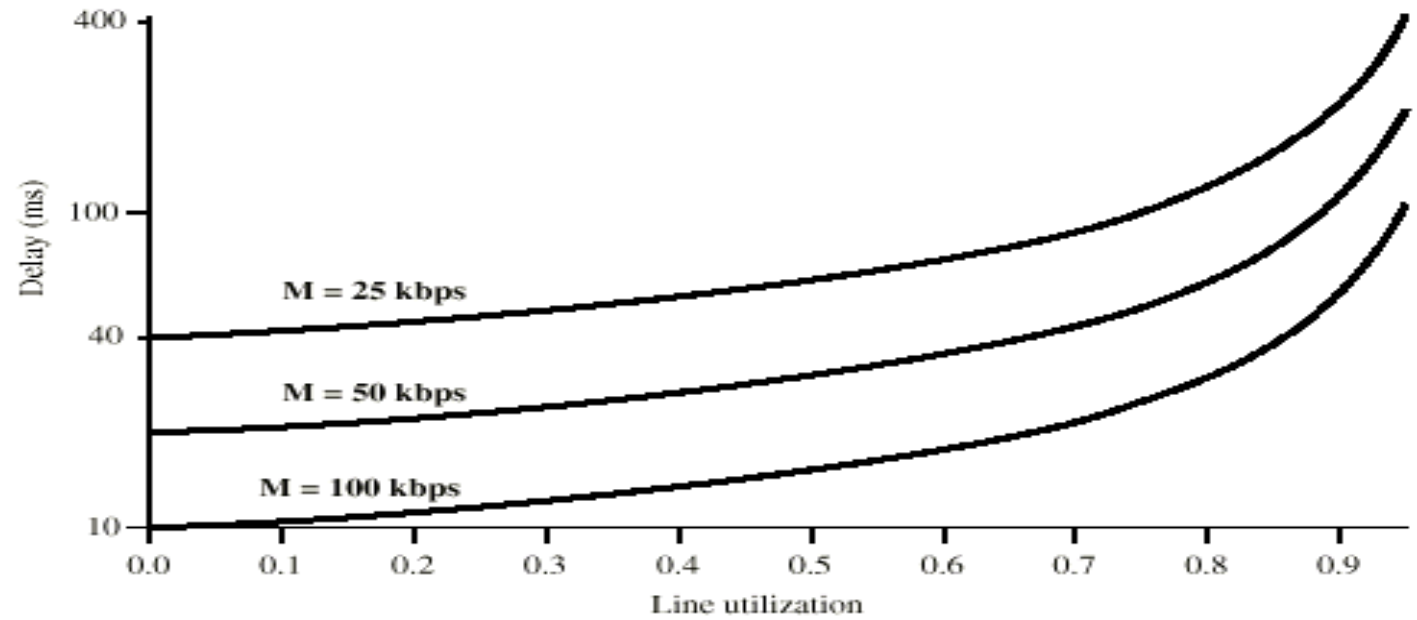
# Performance

- Output data rate less than aggregate input rates
- May cause problems during peak periods
  - Buffer inputs
  - Keep buffer size to minimum to reduce delay
  - Queueing delay is random and makes end-to-end delay unpredictable
  - Packet losses occur when buffer is full

# Buffer Size and Delay




(a) Mean buffer size versus utilization



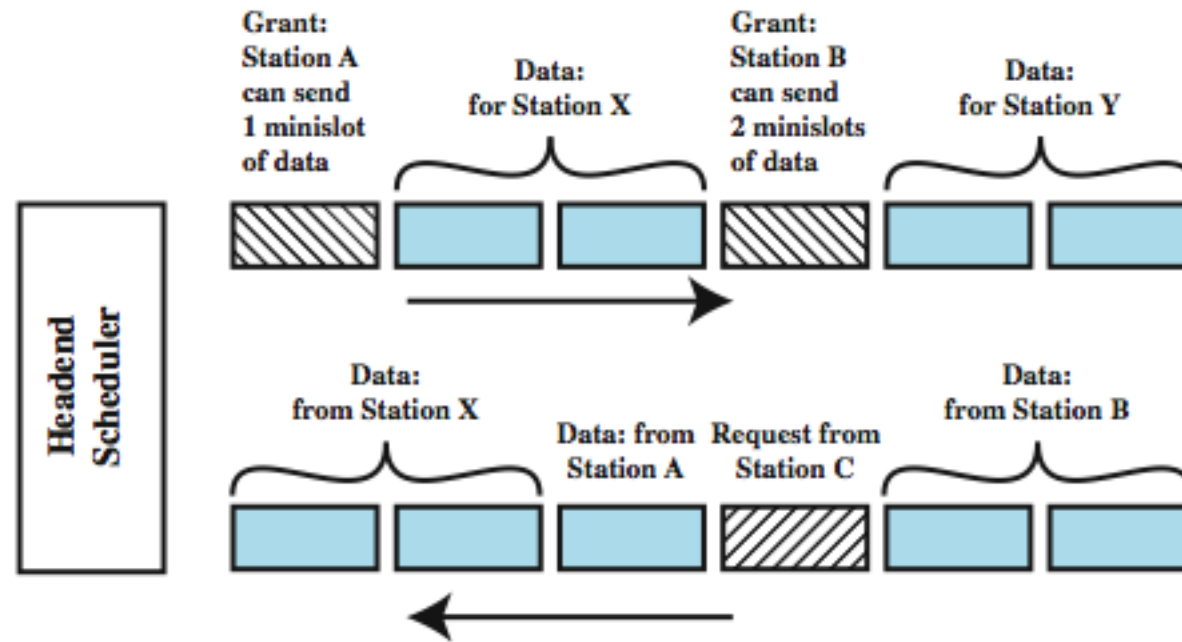
(a) Mean delay versus utilization

# Cable Modems

- dedicate two cable TV channels to data transfer
- each channel shared by number of subscribers, using statistical TDM
- Downstream
  - cable scheduler delivers data in small packets
  - active subscribers share downstream capacity
  - also allocates upstream time slots to subscribers
- Upstream
  - user requests timeslots on shared upstream channel
  -  • Headend scheduler notifies subscriber of slots to use



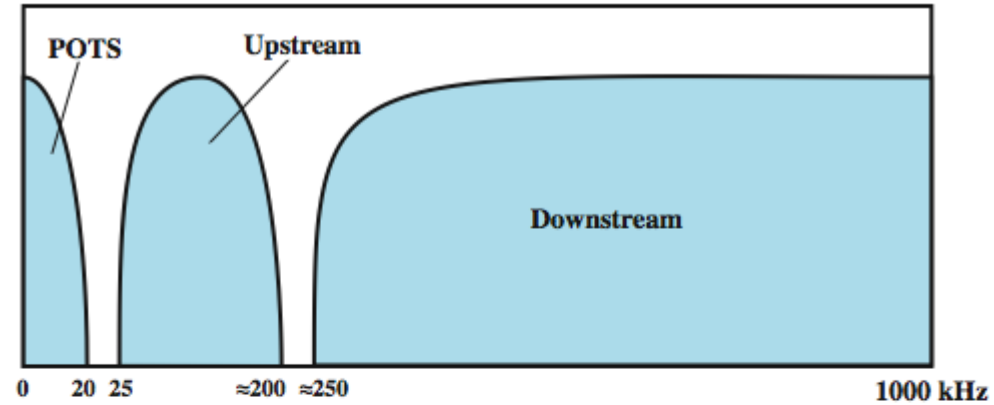
# Cable Modem Scheme



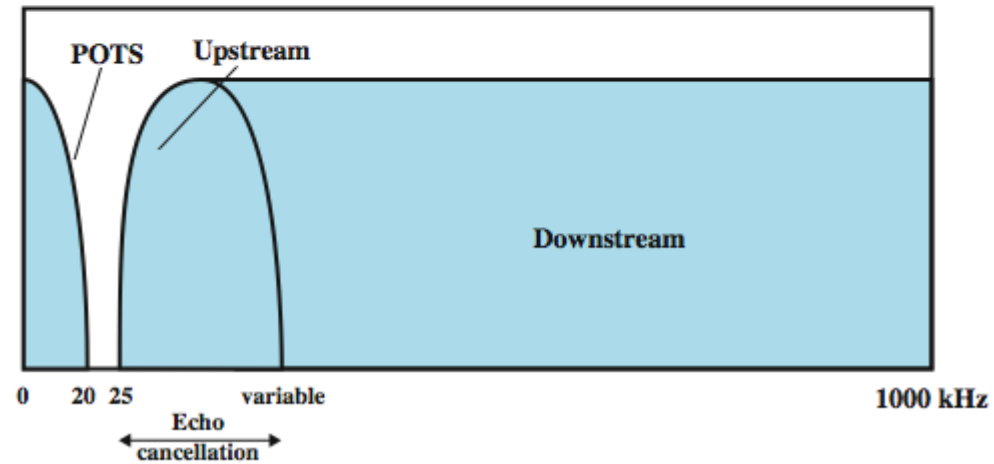
# Asymmetrical Digital Subscriber Line (ADSL)

- link between subscriber and network
- uses currently installed twisted pair cable
- is asymmetric - bigger downstream than up
- uses frequency division multiplexing
  - reserve lowest 25kHz for voice (POTS)
  - uses echo cancellation or FDM to give two bands
- has a range of up to 5.5km

# ADSL Channel Configuration



(a) Frequency-division multiplexing



(b) Echo cancellation

# Discrete Multitone (DMT)

- multiple carrier signals at different frequencies
- divide into 4kHz subchannels
- test and use subchannels with better SNR
- 256 downstream subchannels at 4kHz (60kbps)
  - in theory 15.36Mbps, in practice 1.5-9Mbps

