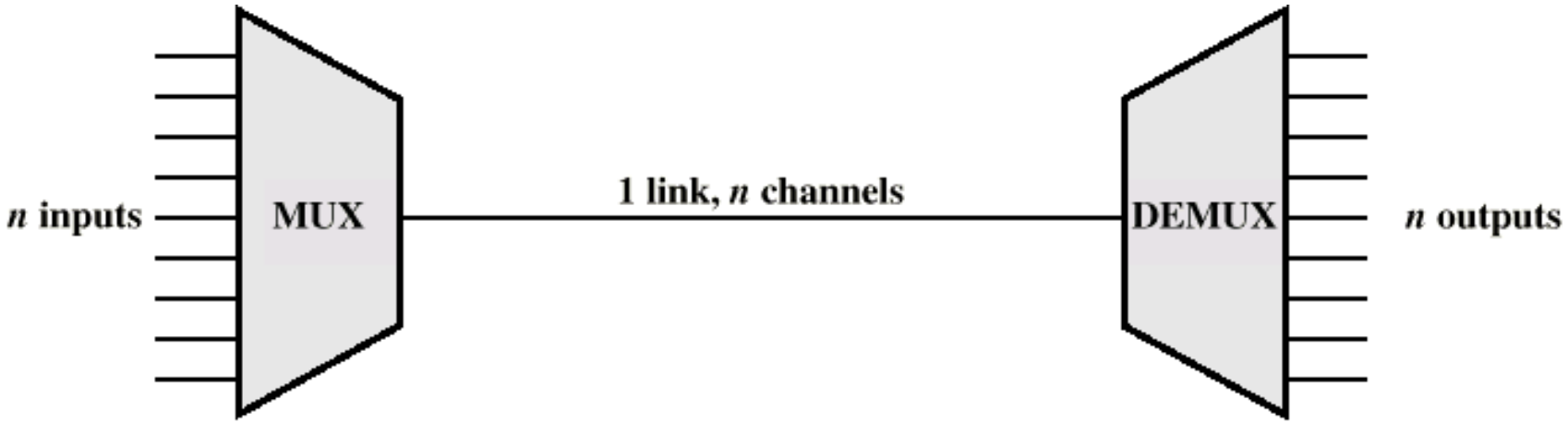
William Stallings
Data and Computer Communications
7th Edition

Chapter 8
Multiplexing

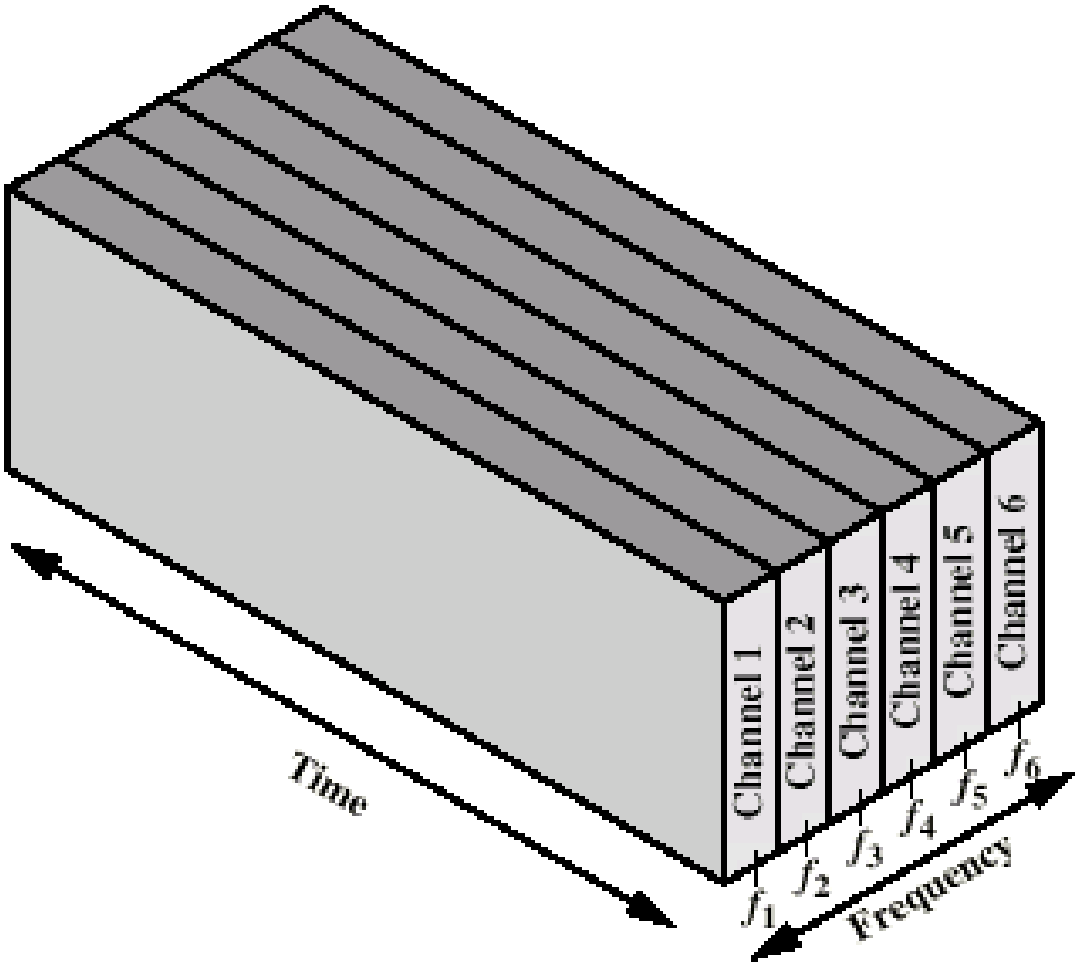
Multiplexing



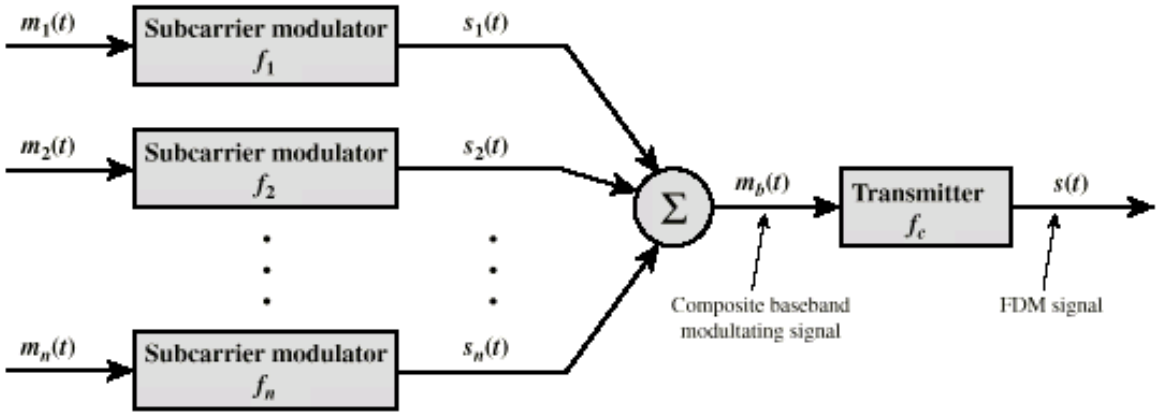
Frequency Division Multiplexing

- FDM
- Useful bandwidth of medium exceeds required bandwidth of channel
- Each signal is modulated to a different carrier frequency
- Carrier frequencies separated so signals do not overlap (guard bands)
- e.g. broadcast radio
- Channel allocated even if no data

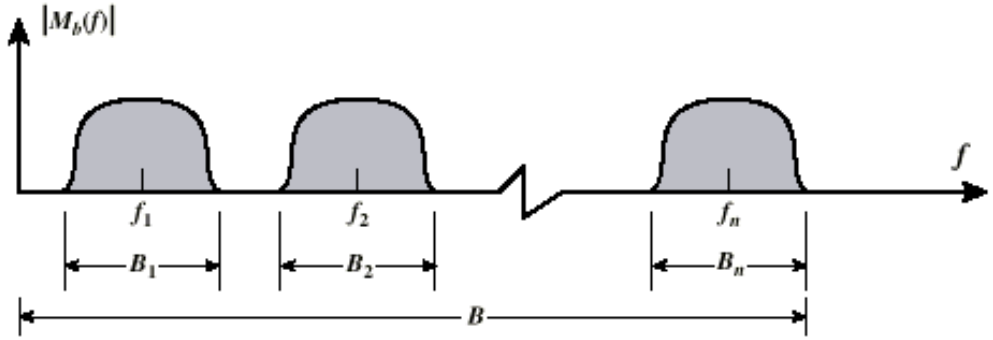
Frequency Division Multiplexing Diagram



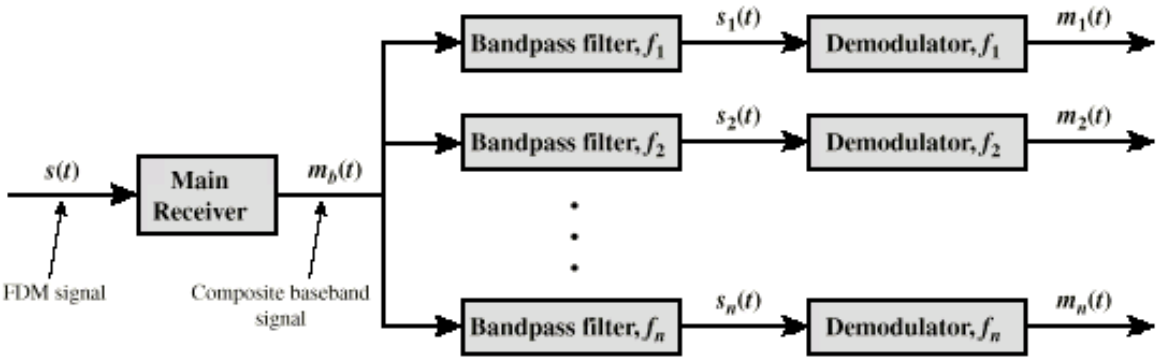
FDM System



(a) Transmitter

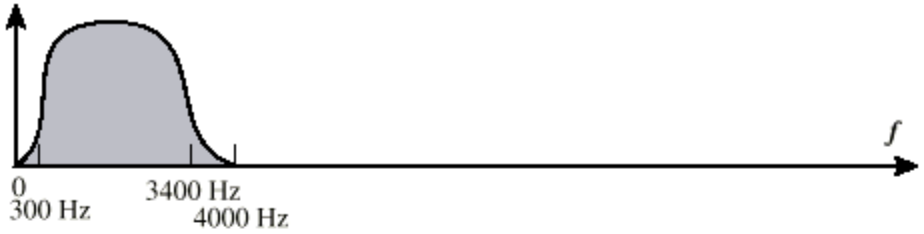


(b) Spectrum of composite baseband modulating signal

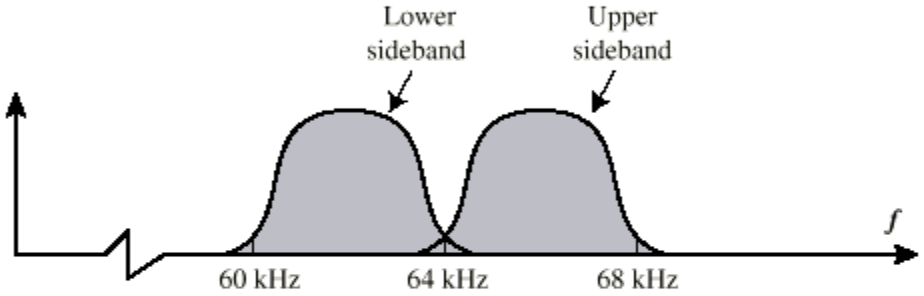


(c) Receiver

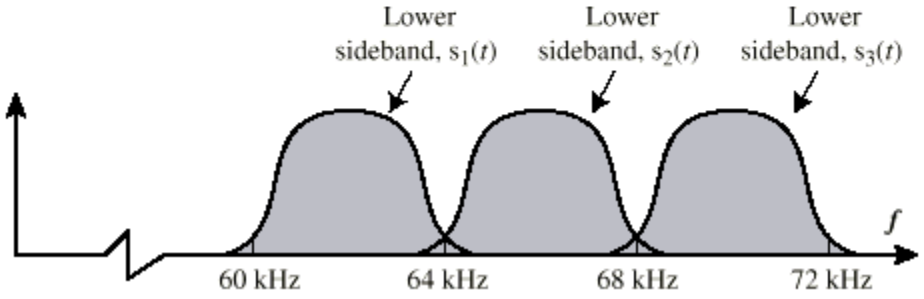
FDM of Three Voiceband Signals



(a) Spectrum of $m_1(t)$, positive f



(b) Spectrum of $s_1(t)$ for $f_1 = 64$ kHz



(c) Spectrum of composite signal using subcarriers at 64 kHz, 68 kHz, and 72 kHz

Analog Carrier Systems

- AT&T (USA)
- Hierarchy of FDM schemes
- Group
  - 12 voice channels (4kHz each) = 48kHz
  - Range 60kHz to 108kHz
- Supergroup
  - 60 channel
  - FDM of 5 group signals on carriers between 420kHz and 612 kHz
- Mastergroup
  - 10 supergroups

Wavelength Division Multiplexing

- Multiple beams of light at different frequency
- Carried by optical fiber
- A form of FDM
- Each color of light (wavelength) carries separate data channel
- 1997 Bell Labs
  - 100 beams
  - Each at 10 Gbps
  - Giving 1 terabit per second (Tbps)
- Commercial systems of 160 channels of 10 Gbps now available
- Lab systems (Alcatel) 256 channels at 39.8 Gbps each
  - 10.1 Tbps
  - Over 100km

WDM Operation

- Same general architecture as other FDM
- Number of sources generating laser beams at different frequencies
- Multiplexer consolidates sources for transmission over single fiber
- Optical amplifiers amplify all wavelengths
  - Typically tens of km apart
- Demux separates channels at the destination
- Mostly 1550nm wavelength range
- Was 200MHz per channel
- Now 50GHz

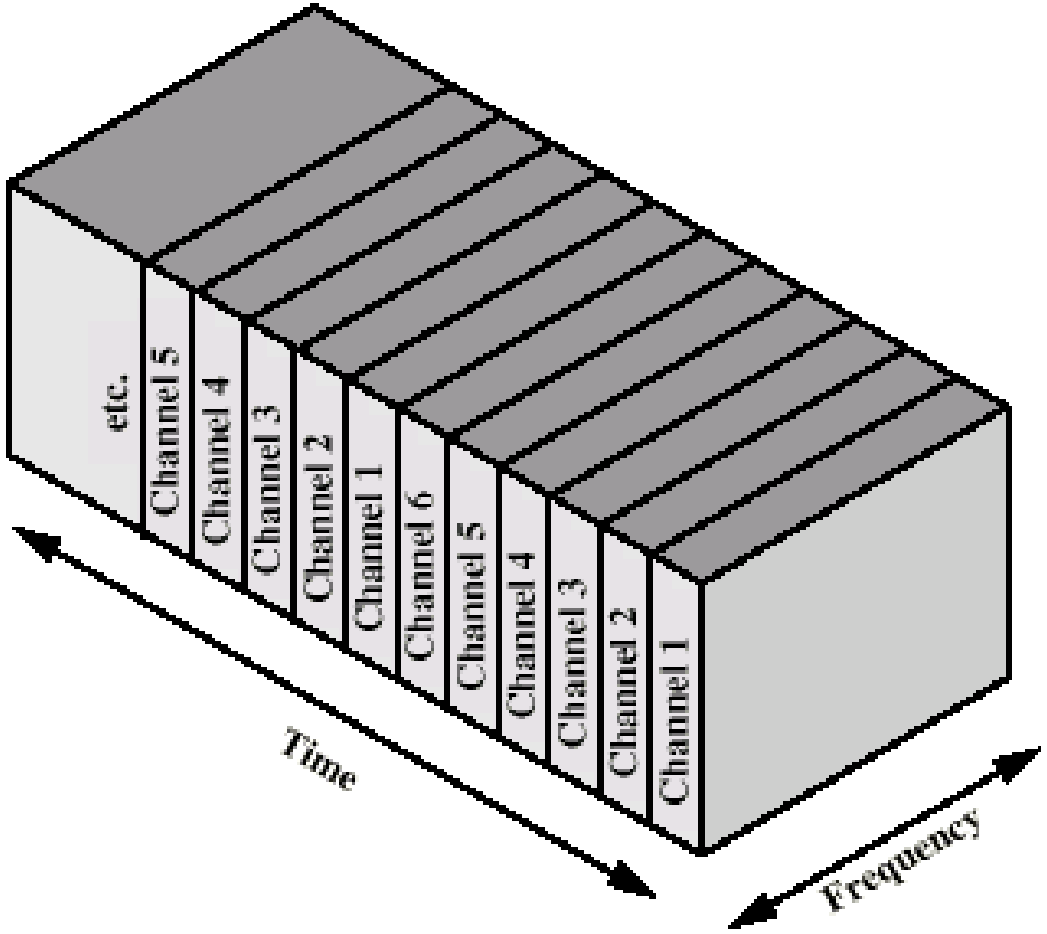
Dense Wavelength Division Multiplexing

- DWDM
- No official or standard definition
- Implies more channels more closely spaced that WDM
- 200GHz or less

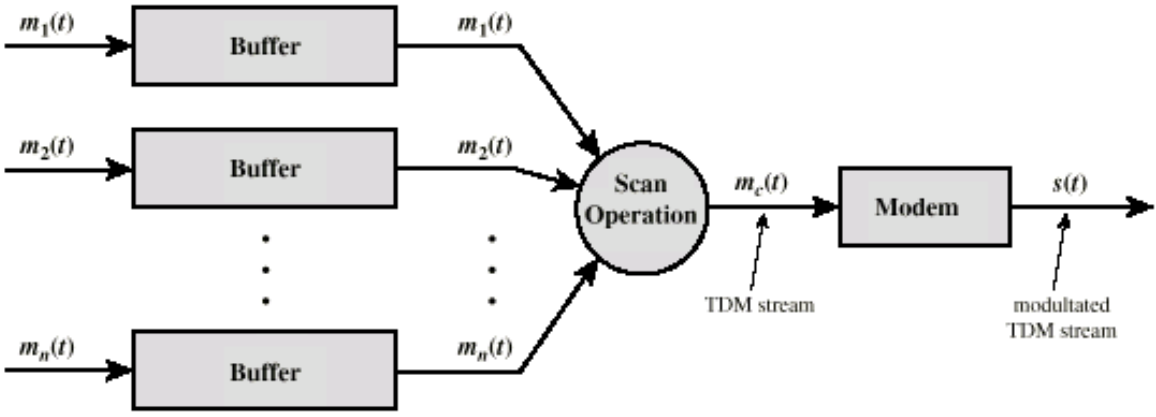
Synchronous Time Division Multiplexing

- Data rate of medium exceeds data rate of digital signal to be transmitted
- Multiple digital signals interleaved in time
- May be at bit level of blocks
- Time slots preassigned to sources and fixed
- Time slots allocated even if no data
- Time slots do not have to be evenly distributed amongst sources

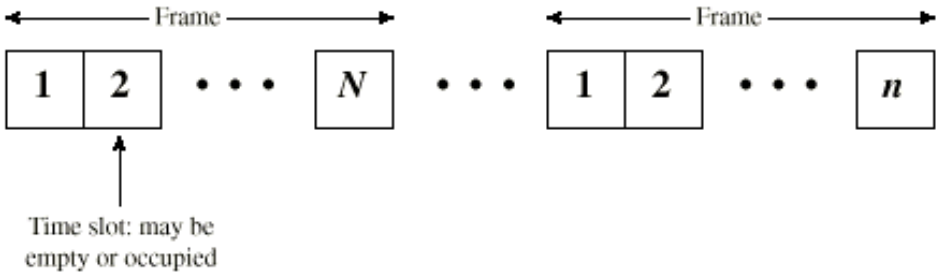
Time Division Multiplexing



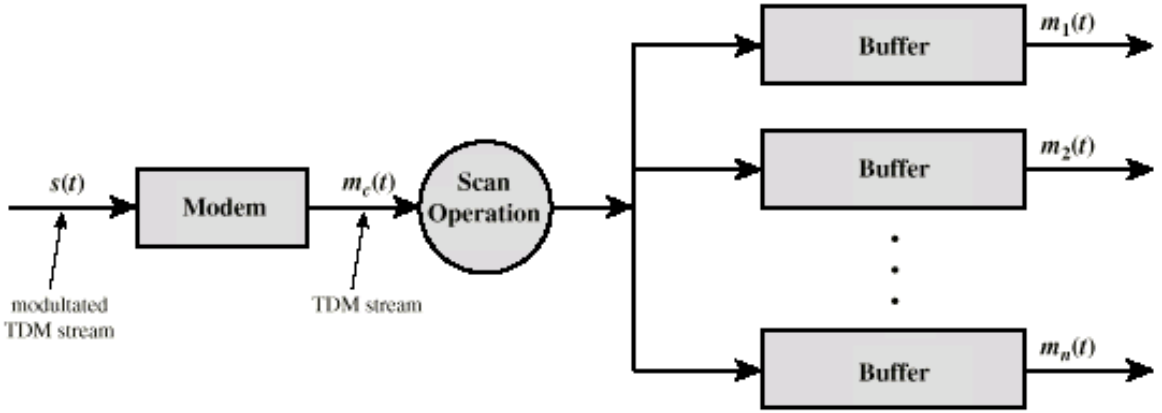
TDM System



(a) Transmitter



(b) TDM Frames

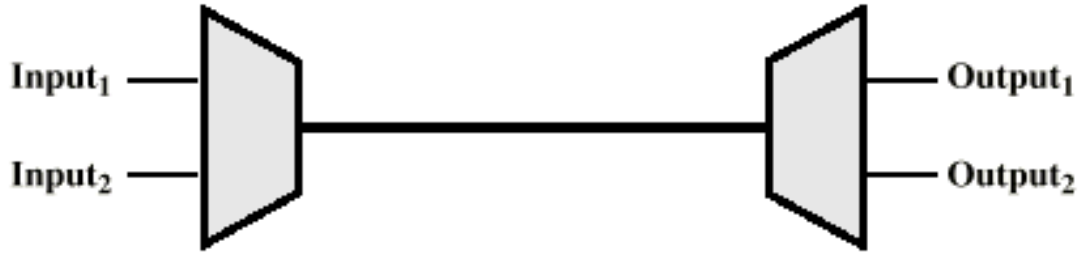


(c) Receiver

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
  - The corresponding source must be quenched
  - This leaves empty slots
- Error control
  - Errors are detected and handled by individual channel systems

Data Link Control on TDM



(a) Configuration

$Input_1$ ····· F_1 f_1 f_1 d_1 d_1 d_1 C_1 A_1 F_1 f_1 f_1 d_1 d_1 d_1 C_1 A_1 F_1

$Input_2$ ··· F_2 f_2 f_2 d_2 d_2 d_2 d_2 C_2 A_2 F_2 f_2 f_2 d_2 d_2 d_2 d_2 C_2 A_2 F_2

(b) Input data streams

··· f_2 F_1 d_2 f_1 d_2 f_1 d_2 d_1 d_2 d_1 C_2 d_1 A_2 C_1 F_2 A_1 f_2 F_1 f_2 f_1 d_2 f_1 d_2 d_1 d_2 d_1 d_2 d_1 C_2 C_1 A_2 A_1 F_2 F_1

(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

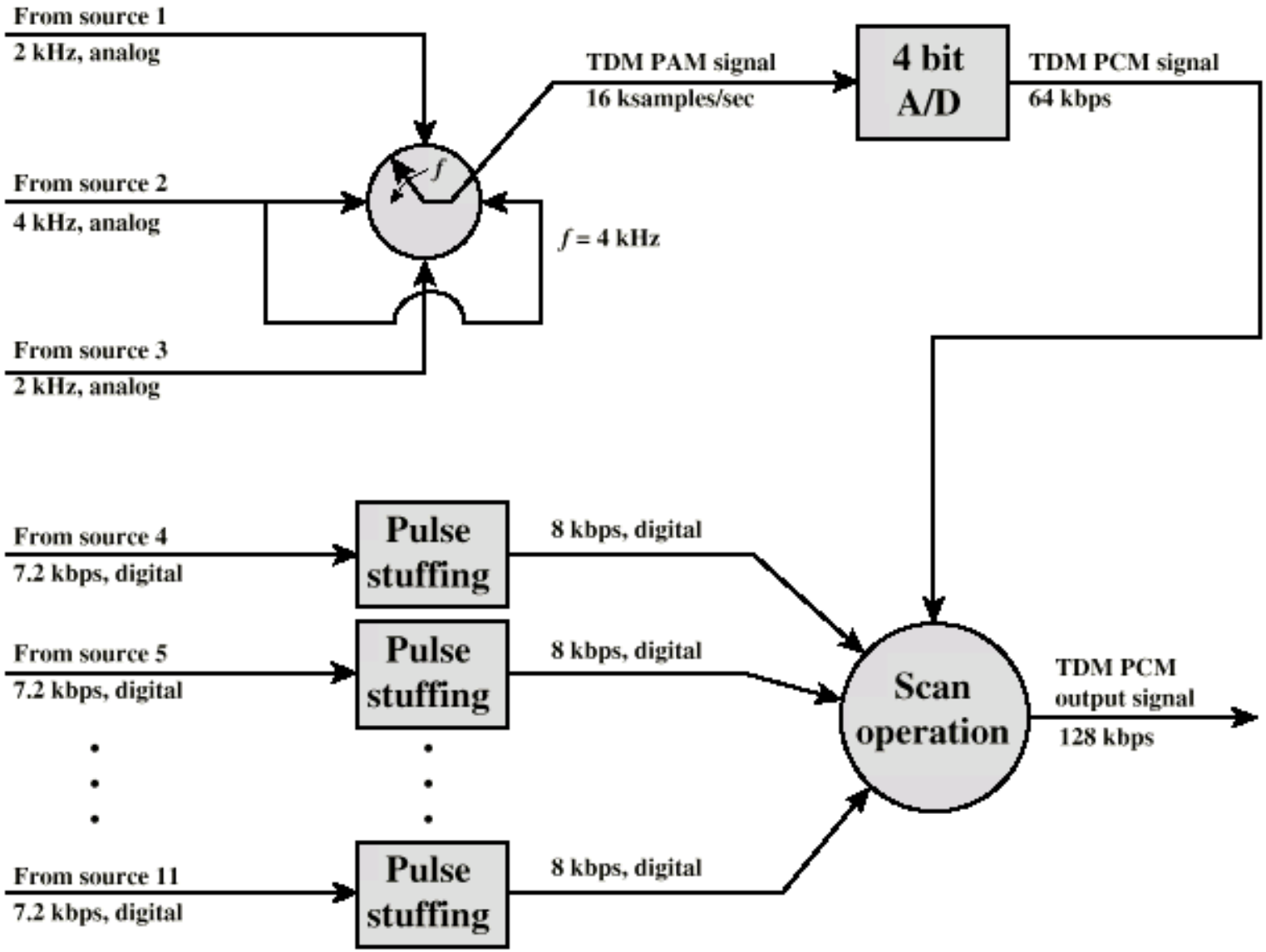
Framing

- No flag or SYNC characters bracketing TDM frames
- Must provide synchronizing mechanism
- Added digit framing
  - —One control bit added to each TDM frame
    - Looks like another channel - “control channel”
  - —Identifiable bit pattern used on control channel
  - —e.g. alternating 01010101…unlikely on a data channel
  - —Can compare incoming bit patterns on each channel with sync pattern

Pulse Stuffing

- Problem - Synchronizing data sources
- Clocks in different sources drifting
- Data rates from different sources not related by simple rational number
- Solution - Pulse Stuffing
  - —Outgoing data rate (excluding framing bits) higher than sum of incoming rates
  - —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

TDM of Analog and Digital Sources



Digital Carrier Systems

- Hierarchy of TDM
- USA/Canada/Japan use one system
- ITU-T use a similar (but different) system
- US system based on DS-1 format
- Multiplexes 24 channels
- Each frame has 8 bits per channel plus one framing bit
- 193 bits per frame

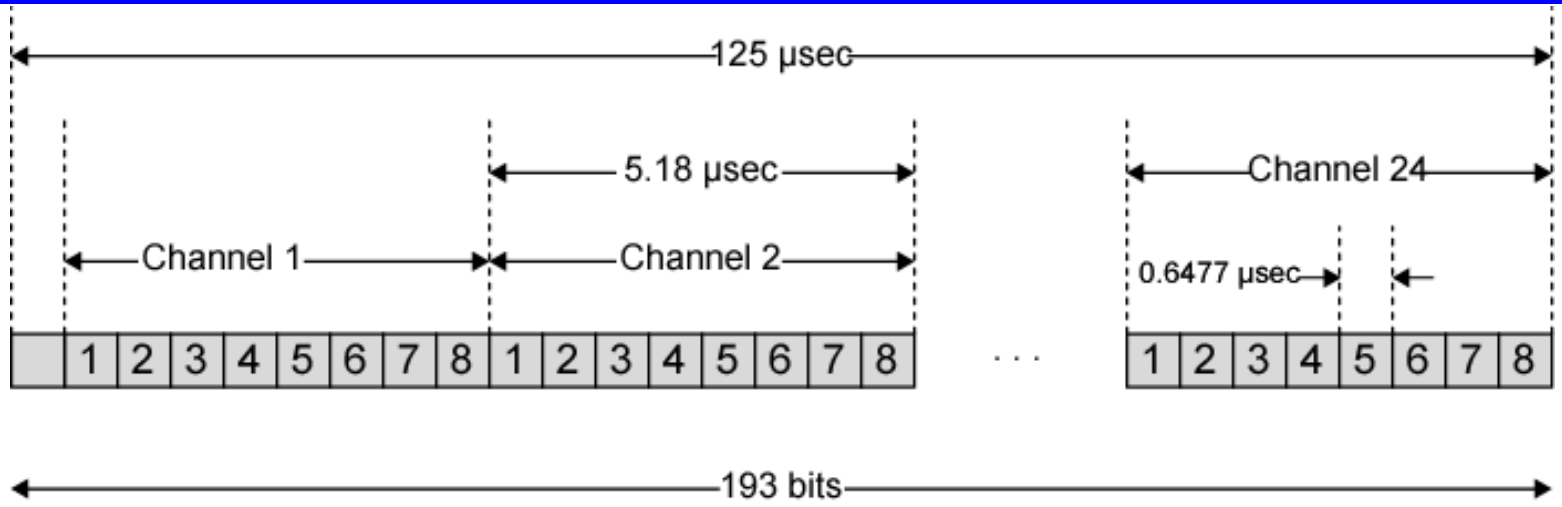
Digital Carrier Systems (2)

- For voice each channel contains one word of digitized data (PCM, 8000 samples per sec)
  - —Data rate 8000x193 = 1.544Mbps
  - —Five out of six frames have 8 bit PCM samples
  - —Sixth frame is 7 bit PCM word plus signaling bit
  - —Signaling bits form stream for each channel containing control and routing info
- Same format for digital data
  - —23 channels of data
    - 7 bits per frame plus indicator bit for data or systems control
  - —24th channel is sync

Mixed Data

- DS-1 can carry mixed voice and data signals
- 24 channels used
- No sync byte
- Can also interleave DS-1 channels
  - Ds-2 is four DS-1 giving 6.312Mbps

DS-1 Transmission Format



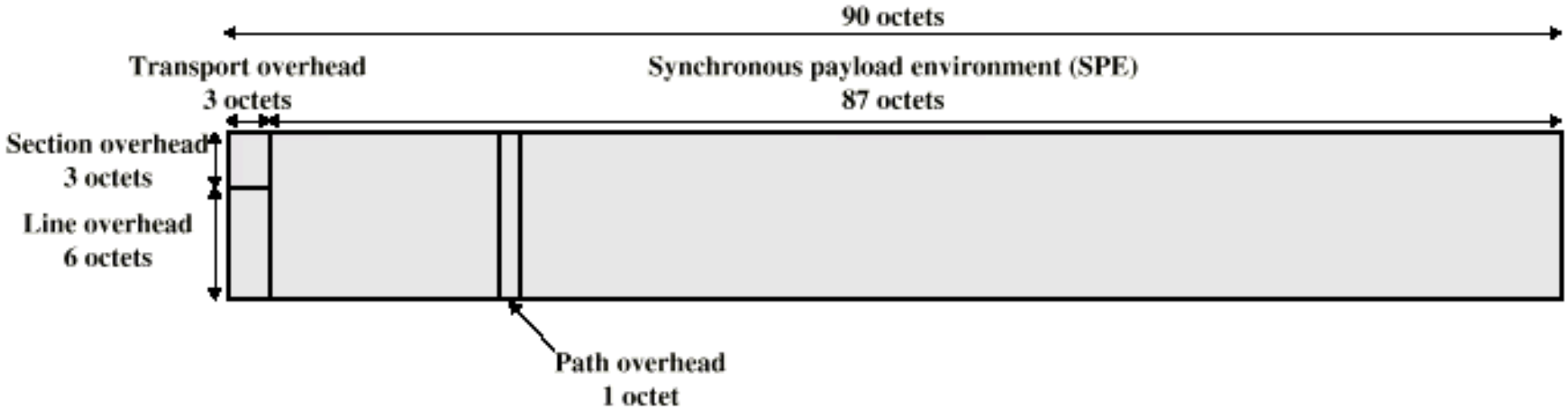
Notes:

1. The first bit is a framing bit, used for synchronization.
2. Voice channels:
   8-bit PCM used on five of six frames.
   7-bit PCM used on every sixth frame; bit 8 of each channel is a signaling bit.
3. Data channels:
   Channel 24 is used for signaling only in some schemes.
   Bits 1-7 used for 56 kbps service
   Bits 2-7 used for 9.6, 4.8, and 2.4 kbps service.

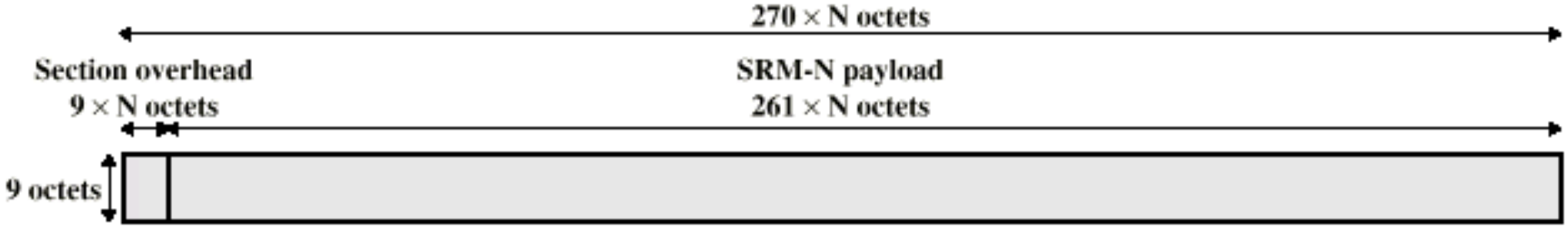
SONET/SDH

- Synchronous Optical Network (ANSI)
- Synchronous Digital Hierarchy (ITU-T)
- Compatible
- Signal Hierarchy
  - Synchronous Transport Signal level 1 (STS-1) or Optical Carrier level 1 (OC-1)
  - 51.84Mbps
  - Carry DS-3 or group of lower rate signals (DS1 DS1C DS2) plus ITU-T rates (e.g. 2.048Mbps)
  - Multiple STS-1 combined into STS-N signal
  - ITU-T lowest rate is 155.52Mbps (STM-1)

SONET Frame Format

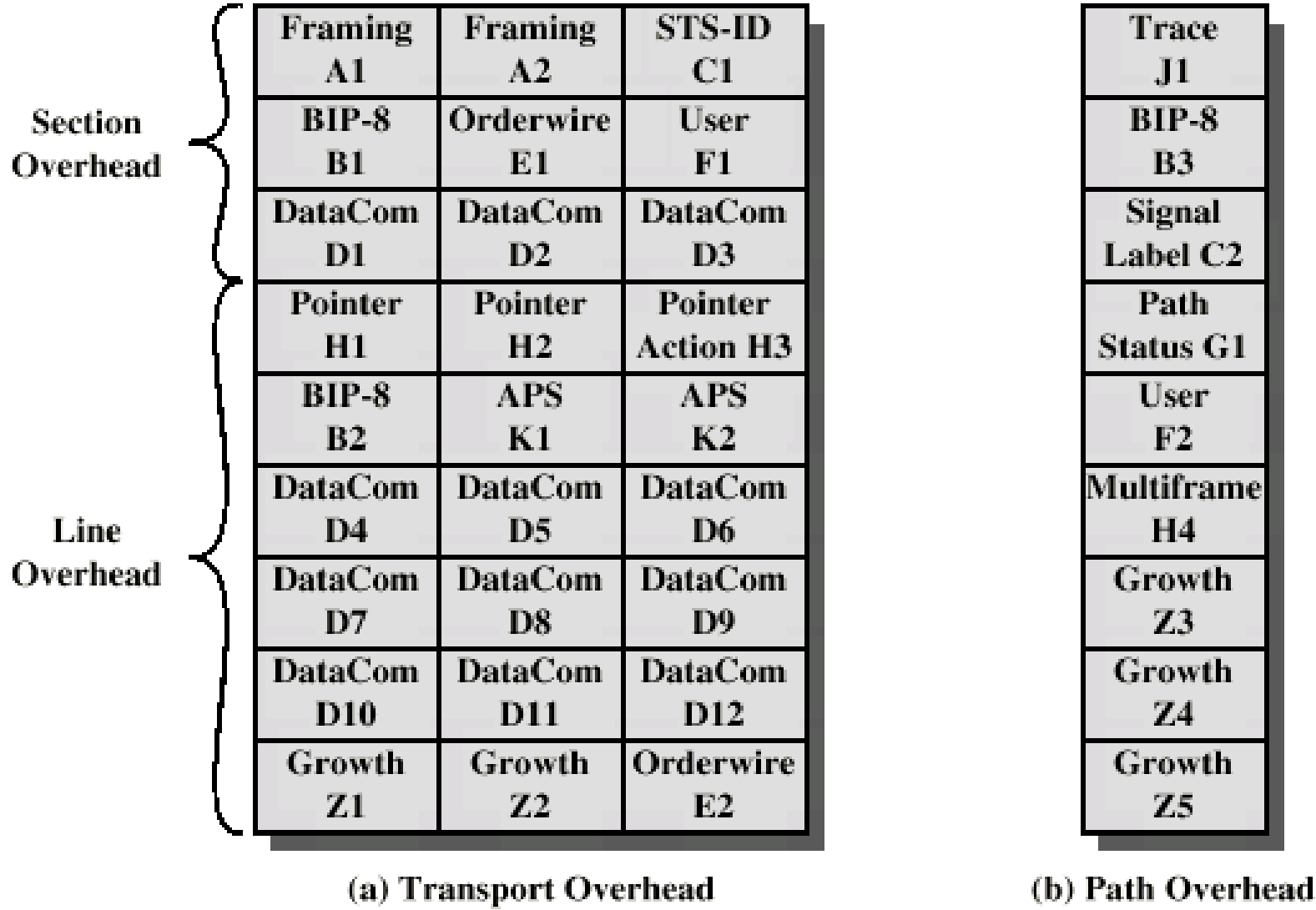


(a) STS-1 frame format



(b) STM-N frame format

SONET STS-1 Overhead Octets



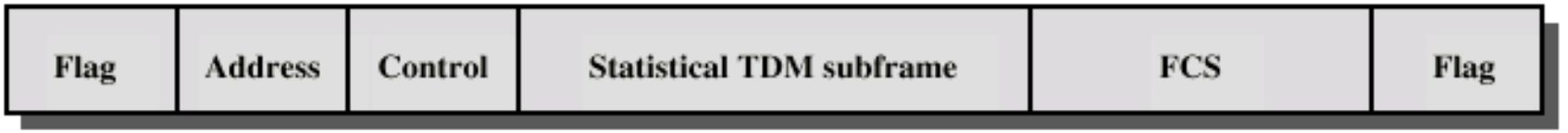
(a) Transport Overhead

(b) Path Overhead

Statistical TDM

- In Synchronous TDM many slots are wasted
- Statistical TDM allocates time slots dynamically based on demand
- Multiplexer scans input lines and collects data until frame full
- Data rate on line lower than aggregate rates of input lines

Statistical TDM Frame Formats



(a) Overall frame

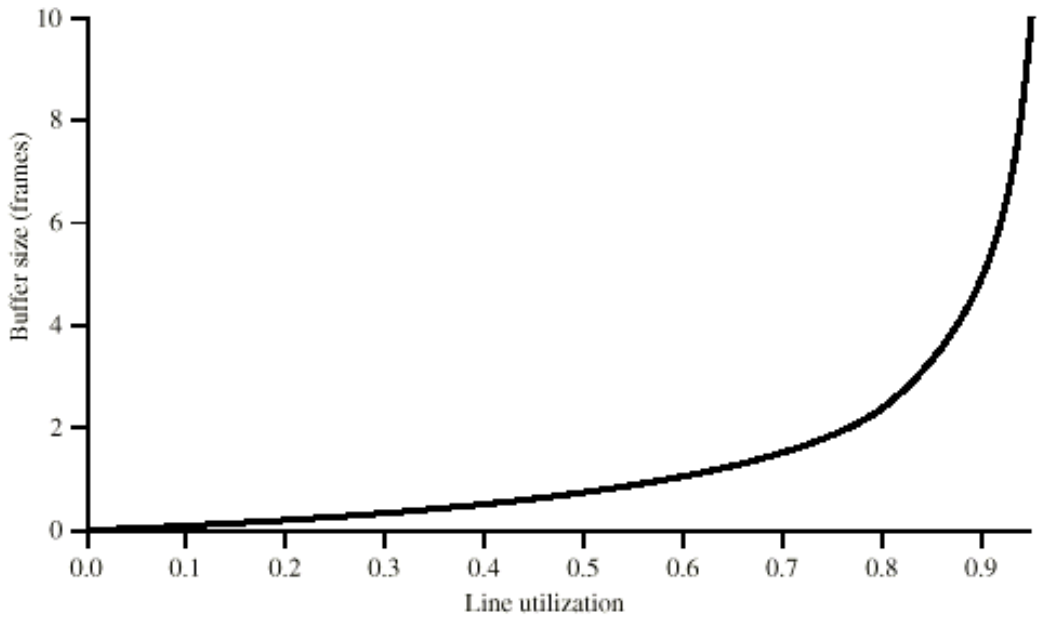
(b) Subframe with one source per frame

(c) Subframe with multiple sources per frame

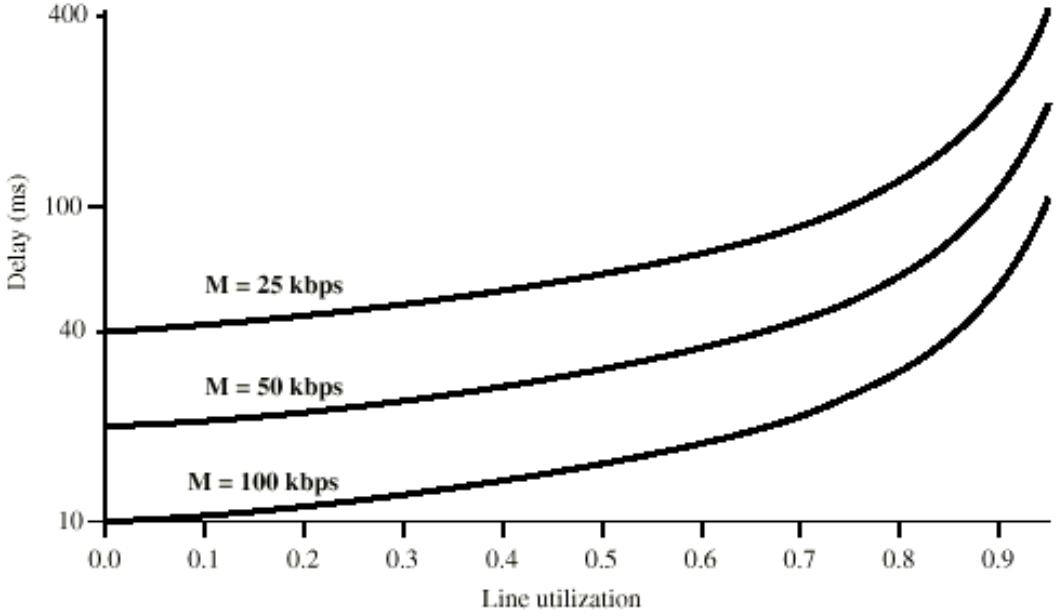
Performance

- Output data rate less than aggregate input rates
- May cause problems during peak periods
  - —Buffer inputs
  - —Keep buffer size to minimum to reduce delay

Buffer Size and Delay



(a) Mean buffer size versus utilization



(a) Mean delay versus utilization

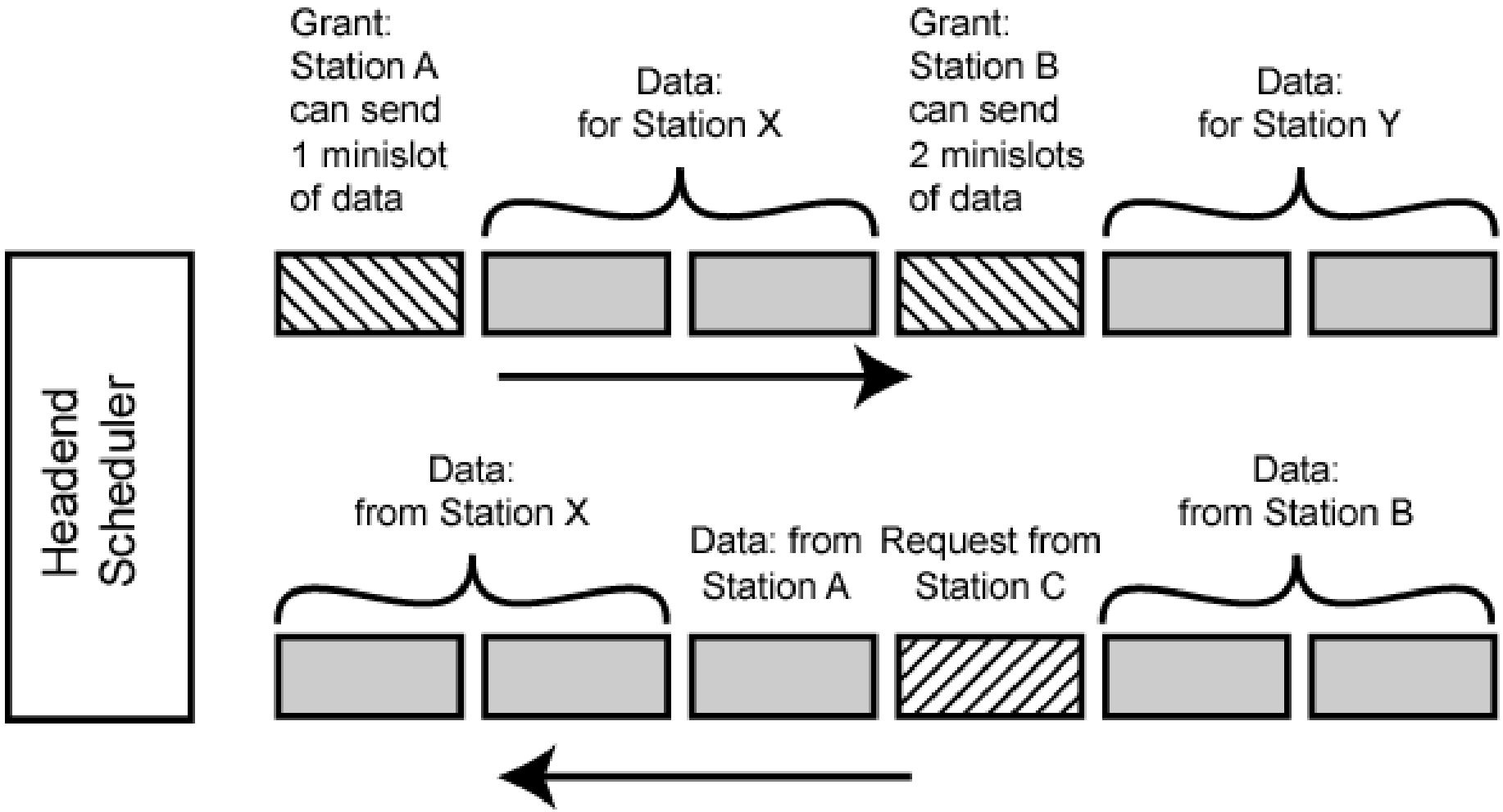
Cable Modem Outline

- Two channels from cable TV provider dedicated to data transfer
  - One in each direction
- Each channel shared by number of subscribers
  - Scheme needed to allocate capacity
  - Statistical TDM

Cable Modem Operation

- Downstream
  - Cable scheduler delivers data in small packets
  - If more than one subscriber active, each gets fraction of downstream capacity
    - May get 500kbps to 1.5Mbps
  - Also used to allocate upstream time slots to subscribers
- Upstream
  - User requests timeslots on shared upstream channel
    - Dedicated slots for this
  - Headend scheduler sends back assignment of future tme slots to subscriber

Cable Modem Scheme



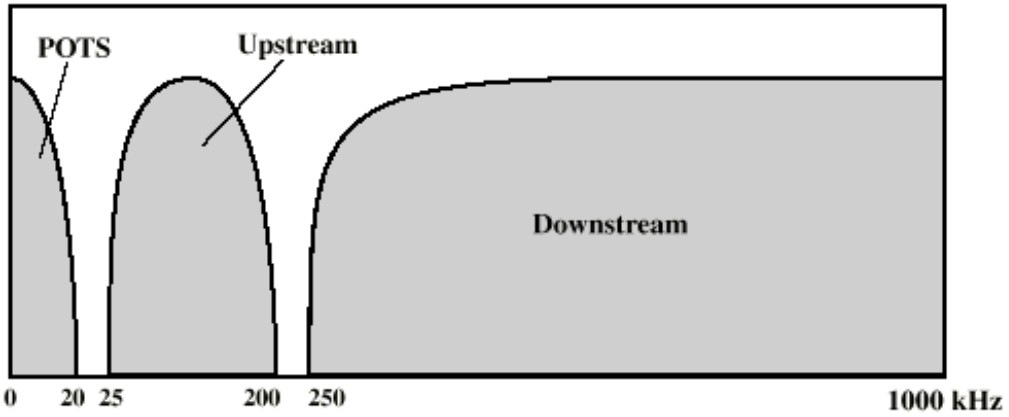
Asymmetrical Digital Subscriber Line

- ADSL
- Link between subscriber and network
  - —Local loop
- Uses currently installed twisted pair cable
  - —Can carry broader spectrum
  - —1 MHz or more

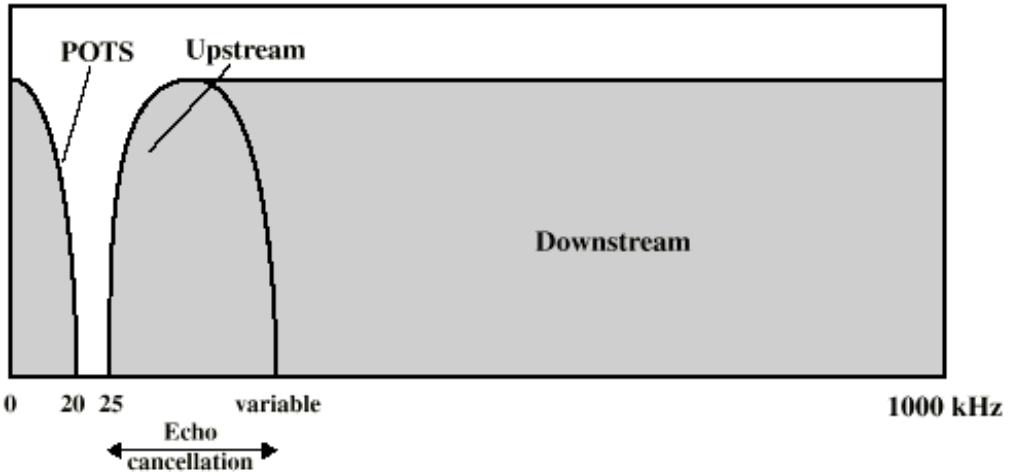
ADSL Design

- Asymmetric
  - —Greater capacity downstream than upstream
- Frequency division multiplexing
  - —Lowest 25kHz for voice
    - Plain old telephone service (POTS)
  - —Use echo cancellation or FDM to give two bands
  - —Use FDM within bands
- Range 5.5km

ADSL Channel Configuration



(a) Frequency-division multiplexing

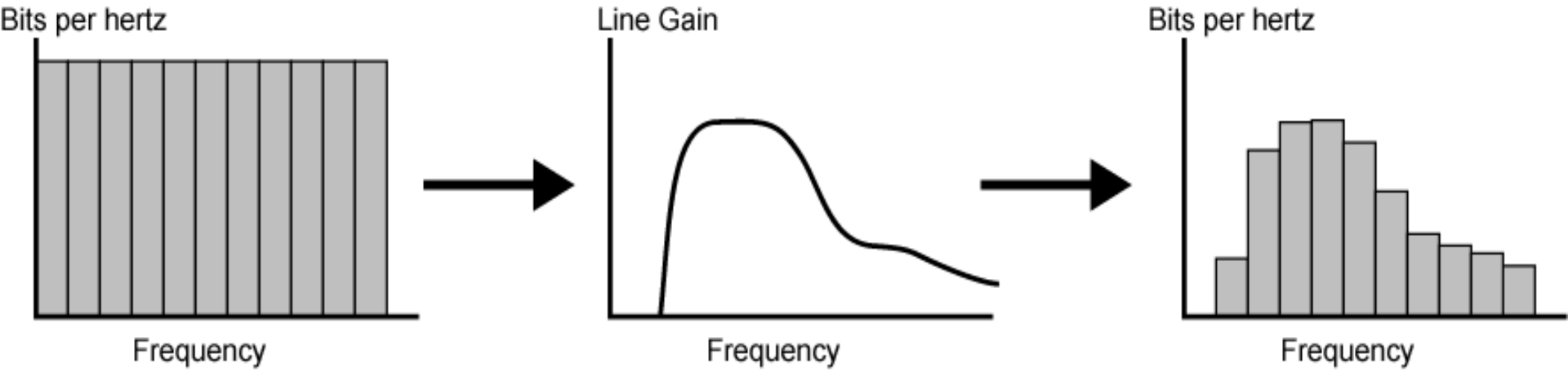


(b) Echo cancellation

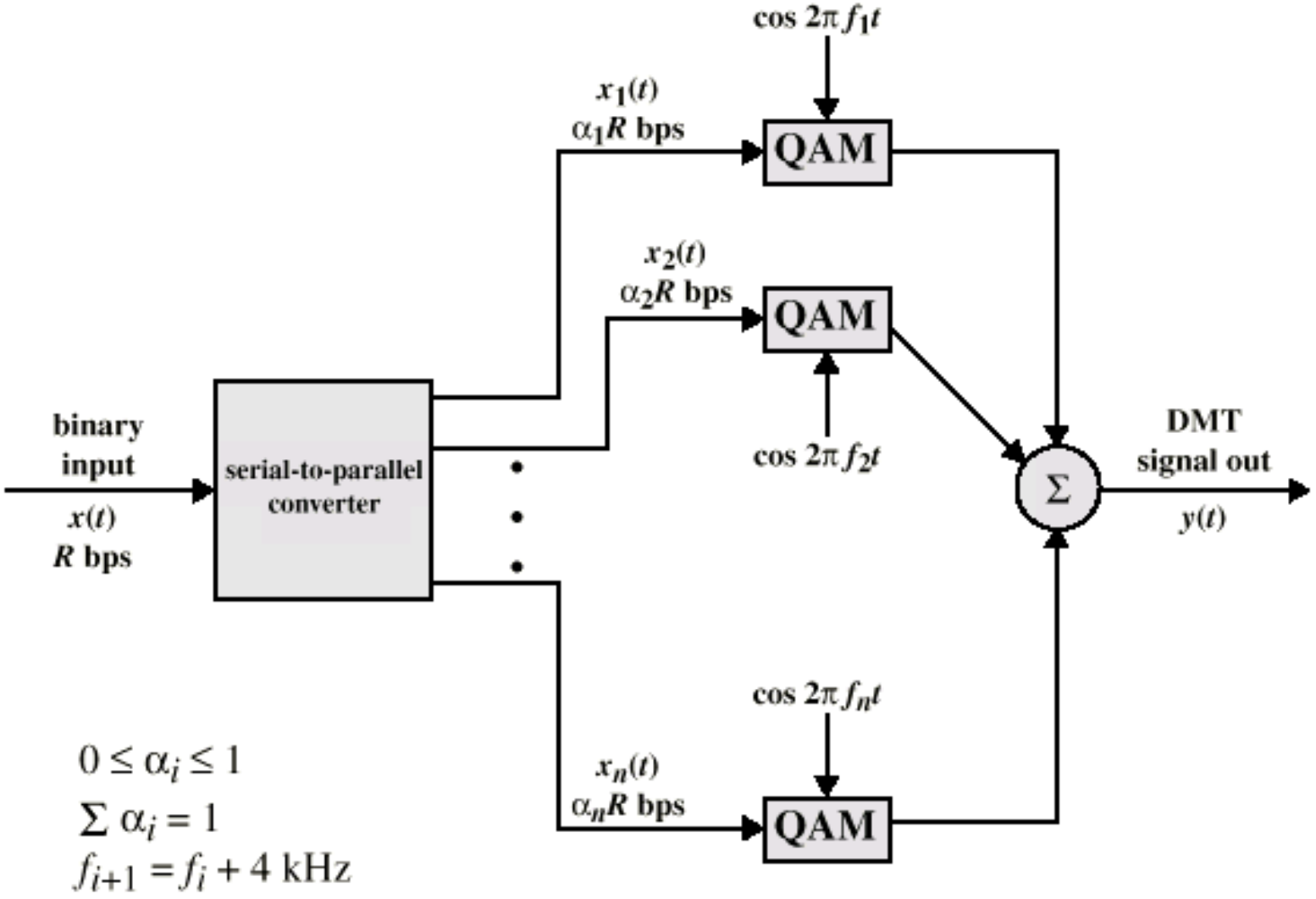
Discrete Multitone

- DMT
- Multiple carrier signals at different frequencies
- Some bits on each channel
- 4kHz subchannels
- Send test signal and use subchannels with better signal to noise ratio
- 256 downstream subchannels at 4kHz (60kbps)
  - —15.36MHz
  - —Impairments bring this down to 1.5Mbps to 9Mbps

DTM Bits Per Channel Allocation



DMT Transmitter



xDSL

- High data rate DSL
- Single line DSL
- Very high data rate DSL

Required Reading

- Stallings chapter 8
- Web sites on
  - ADSL
  - SONET