Multiplexing
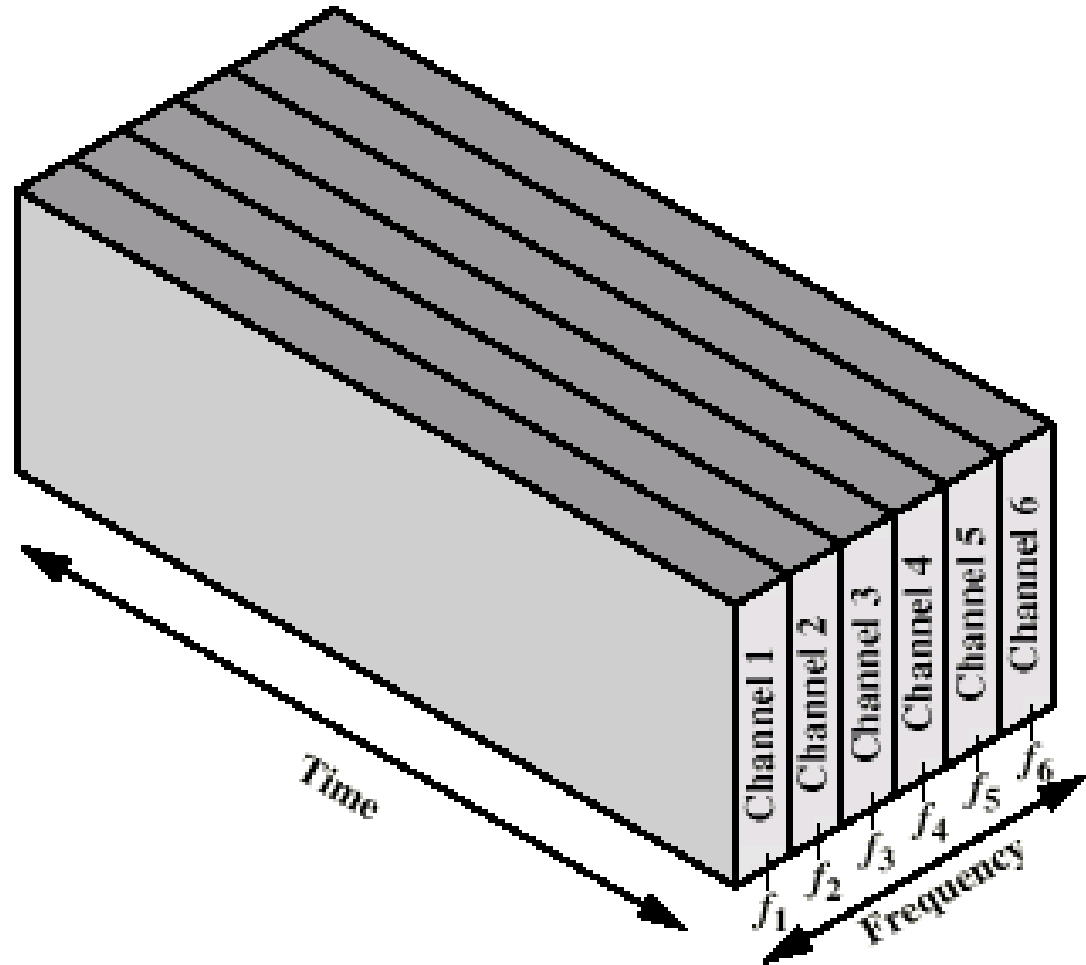

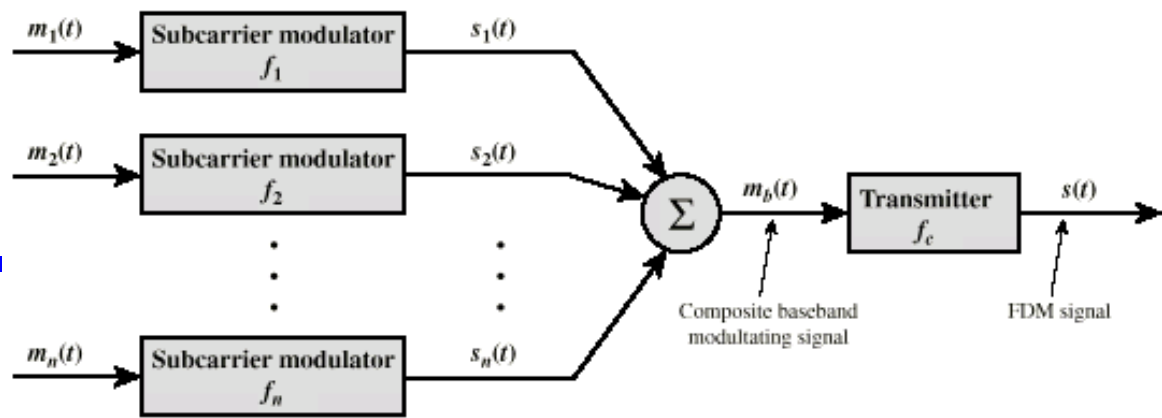*n* inputs — MUX — 1 link, *n* channels — DEMUX — *n* outputs

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)
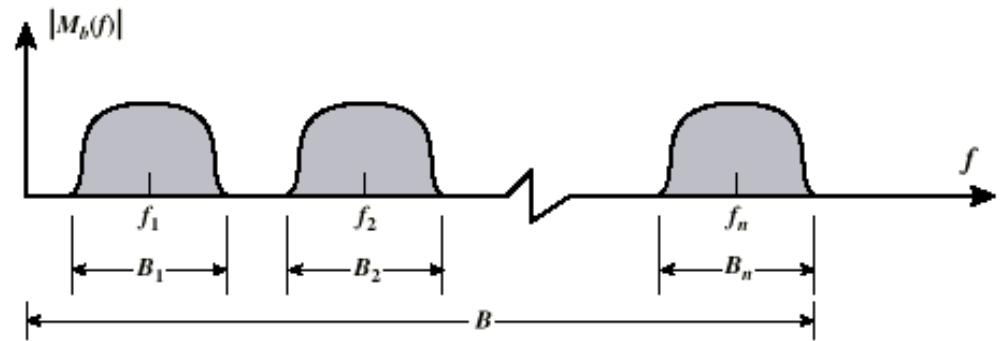- e.g. broadcast radio
- Channel allocated even if no data

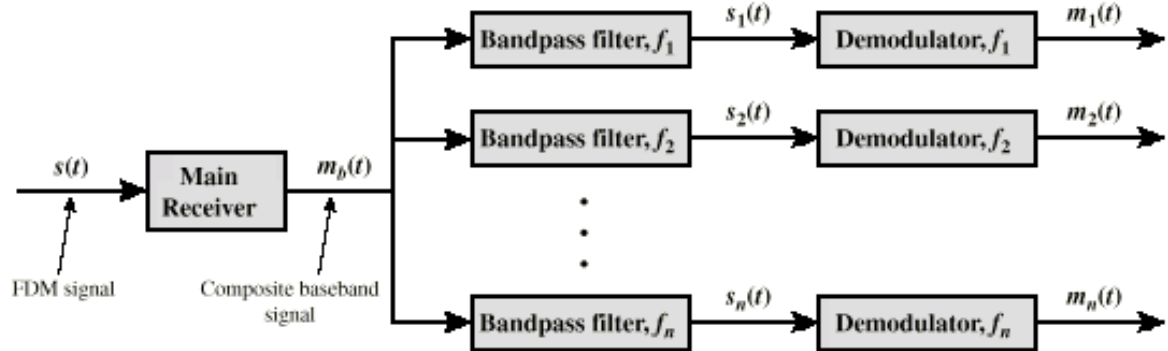# Frequency Division Multiplexing Diagram
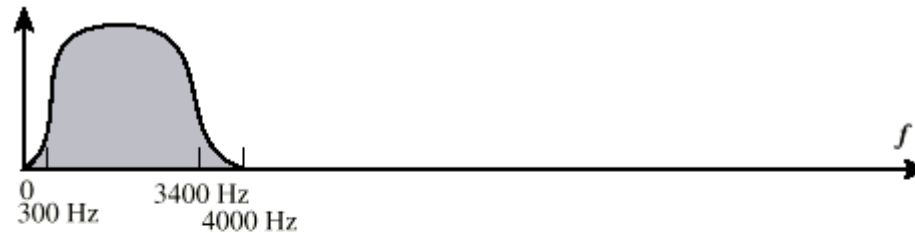
FDM System

(a) Transmitter

$m_1(t)$ → Subcarrier modulator f_1 → $s_1(t)$

$m_2(t)$ → Subcarrier modulator f_2 → $s_2(t)$

$m_n(t)$ → Subcarrier modulator f_n → $s_n(t)$

Σ → $m_b(t)$ → Transmitter f_c → $s(t)$

Composite baseband modultating signal

FDM signal

(b) Spectrum of composite baseband modulating signal

$|M_b(f)|$

f_1 f_2 f_n

B_1 B_2 B_n

B

(c) Receiver

$s(t)$ → Main Receiver → $m_b(t)$

FDM signal

Composite baseband signal

Bandpass filter, f_1 → $s_1(t)$ → Demodulator, f_1 → $m_1(t)$

Bandpass filter, f_2 → $s_2(t)$ → Demodulator, f_2 → $m_2(t)$

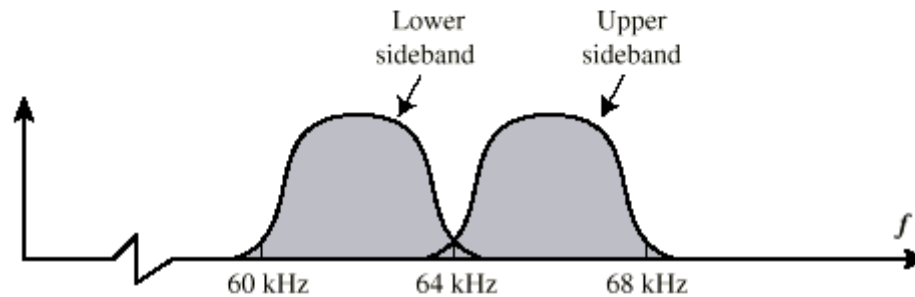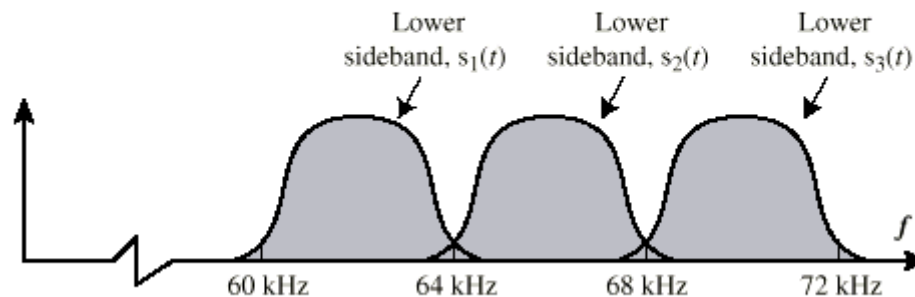Bandpass filter, f_n → $s_n(t)$ → Demodulator, f_n → $m_n(t)$

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
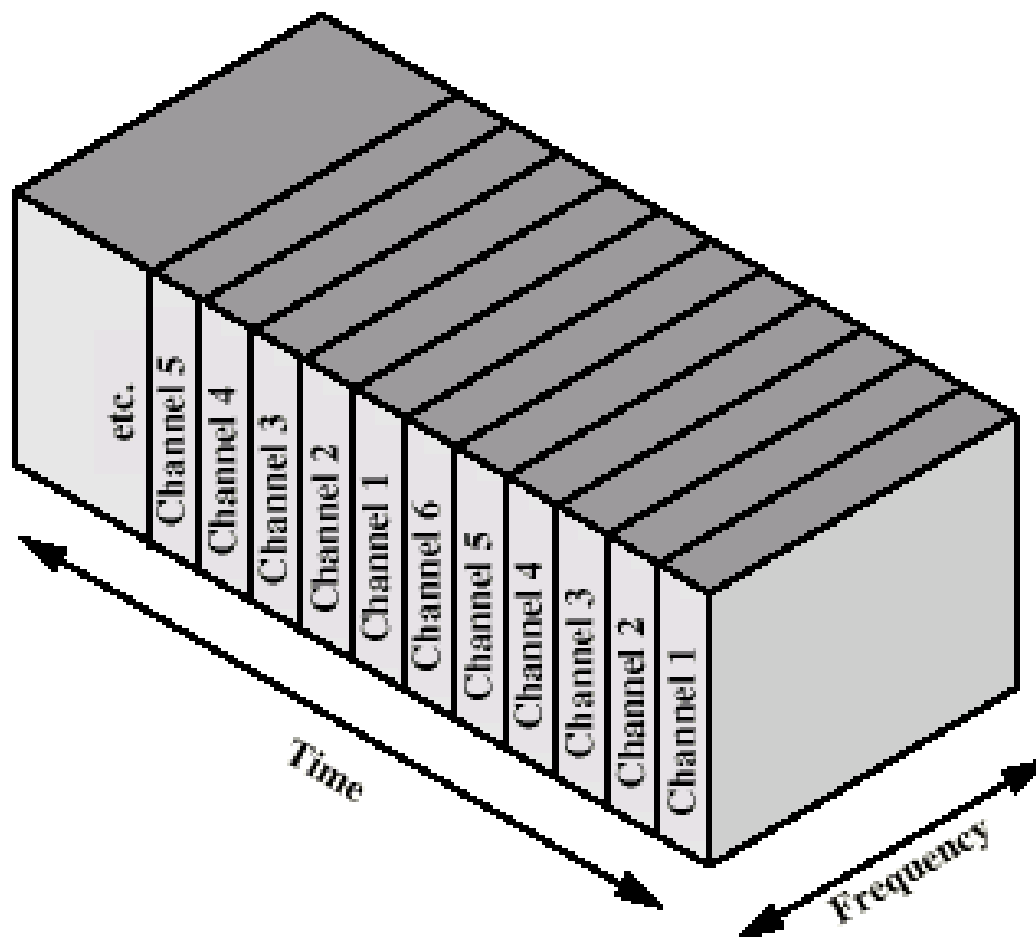- Mostly 1550nm wavelength range
- Was 200MHz per channel
- Now 50GHz

Dense Wavelength Division Multiplexing

- DWDM

- No official or standard definition

- Implies more channels more closely spaced that WDM
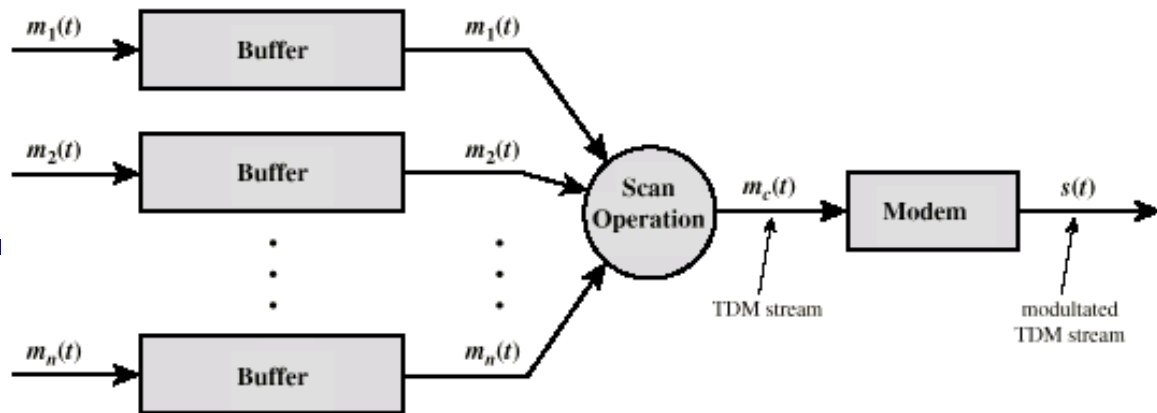
- 200GHz or less

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
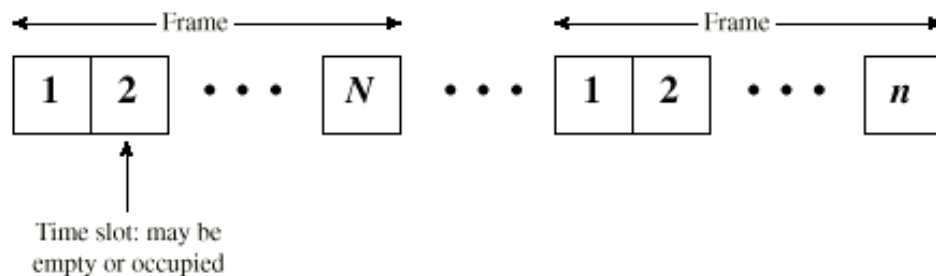- Time slots do not have to be evenly distributed amongst sources

Time Division Multiplexing

TDM System

$m_1(t)$ → Buffer → $m_1(t)$
$m_2(t)$ → Buffer → $m_2(t)$
$m_n(t)$ → Buffer → $m_n(t)$

Scan Operation → $m_c(t)$ → Modem → $s(t)$

TDM stream

modultated TDM stream

(a) Transmitter

Frame ← 1 | 2 · · · N · · · 1 | 2 · · · n → Frame

Time slot: may be empty or occupied

(b) TDM Frames

$s(t)$ → Modem → $m_c(t)$ → Scan Operation → Buffer → $m_1(t)$
Buffer → $m_2(t)$
Buffer → $m_n(t)$

modultated TDM stream
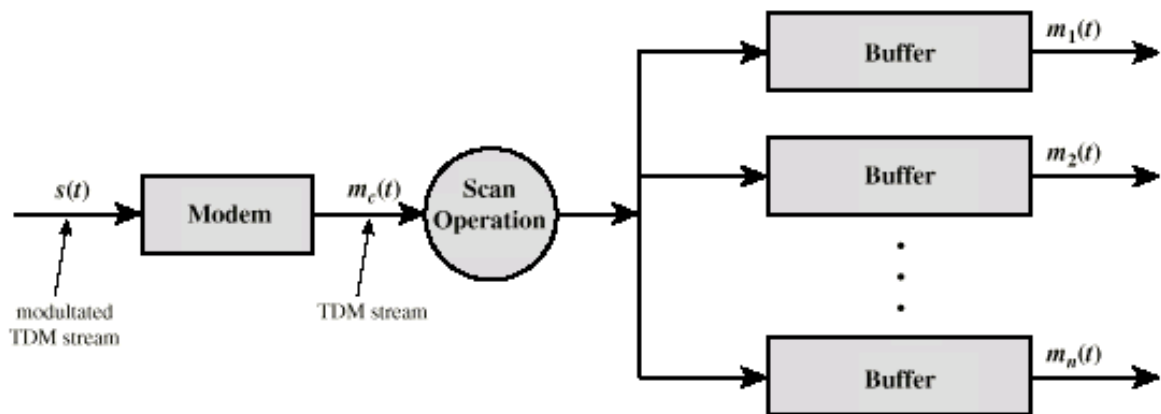
TDM stream

(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
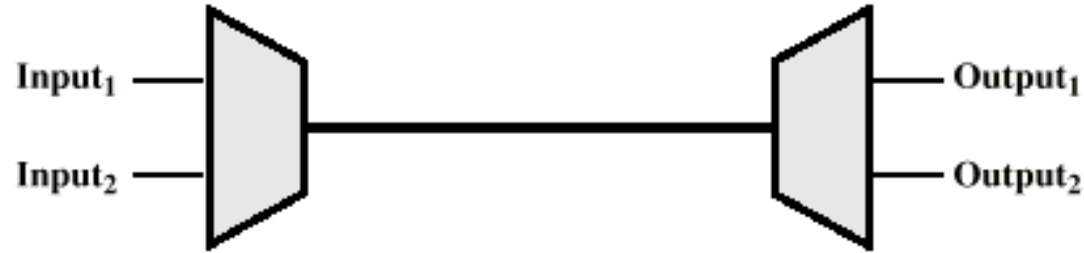
(a) Configuration

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
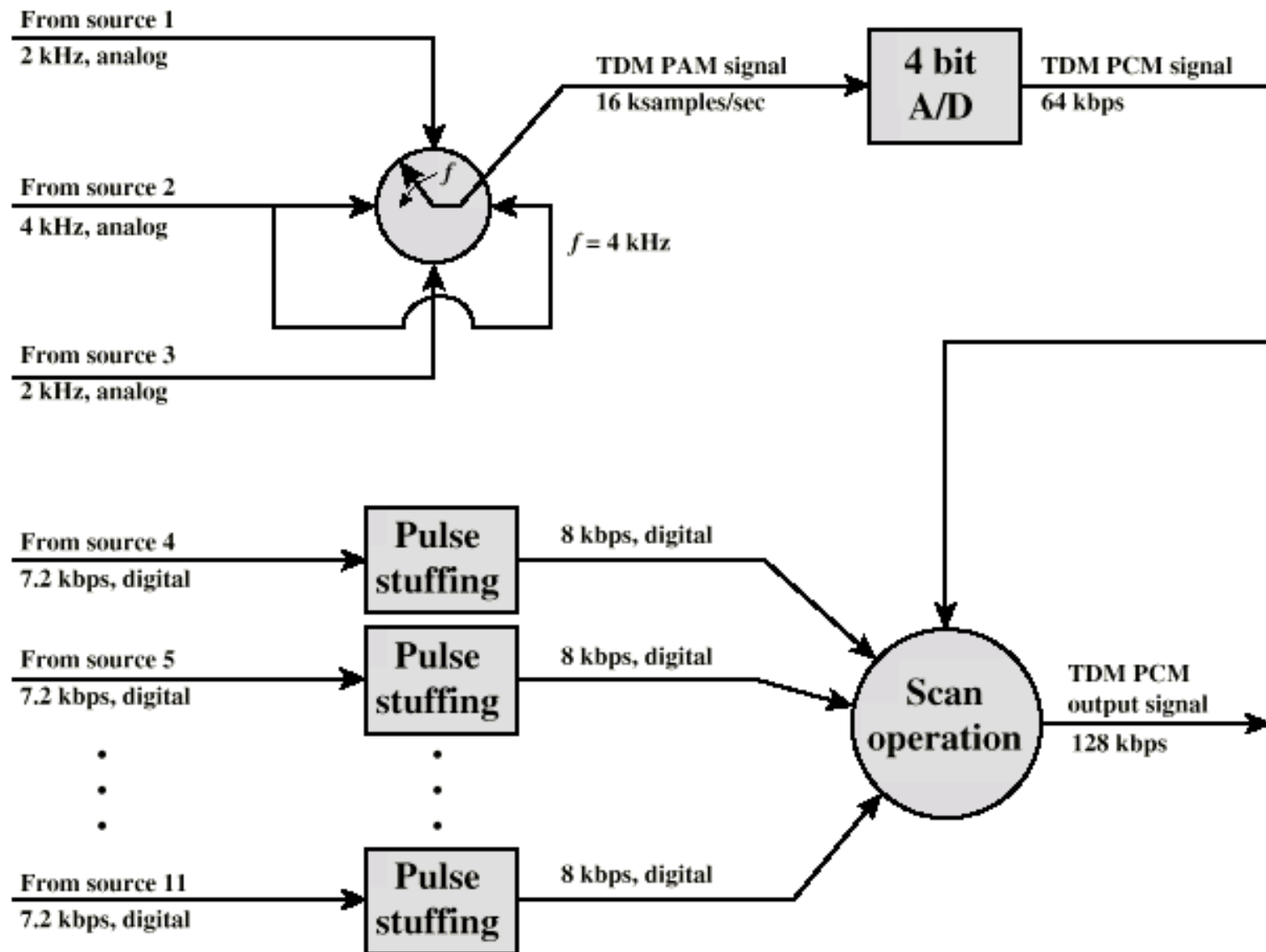
Digital Carrier Systems

- 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