# Data and Computer Communications

Tenth Edition

by William Stallings

# CHAPTER 8

## Multiplexing

*“It was impossible to get a conversation going, everybody was talking too much.”*

- Yogi Berra

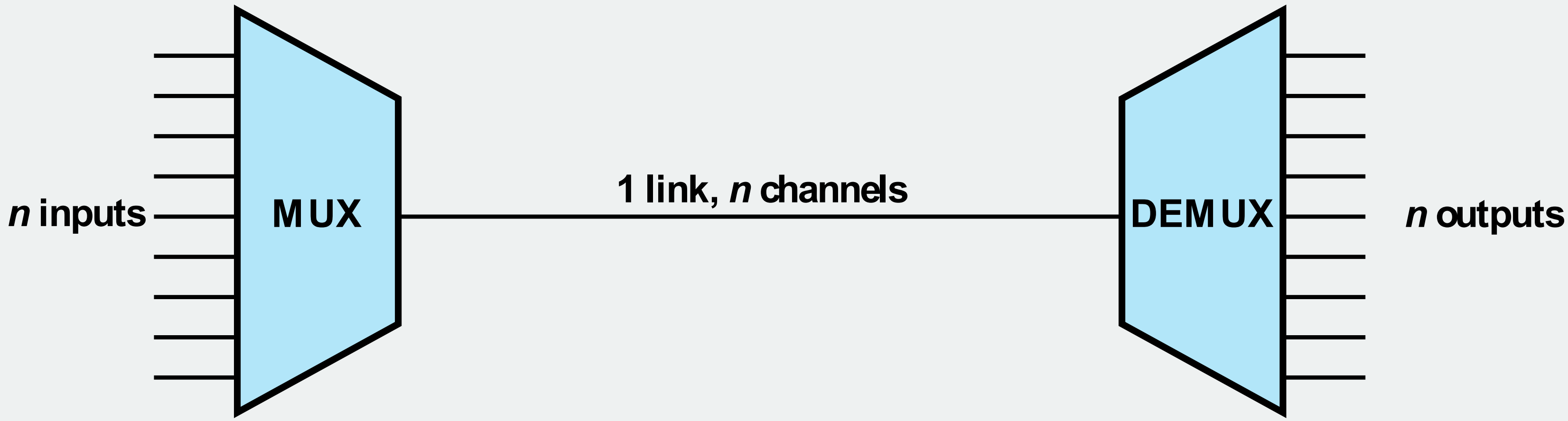
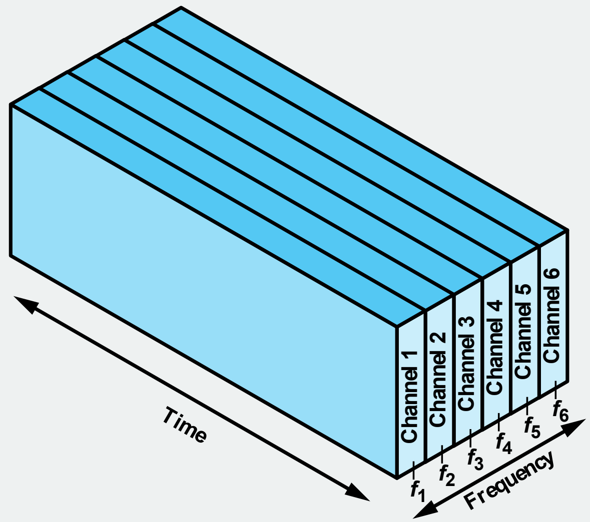
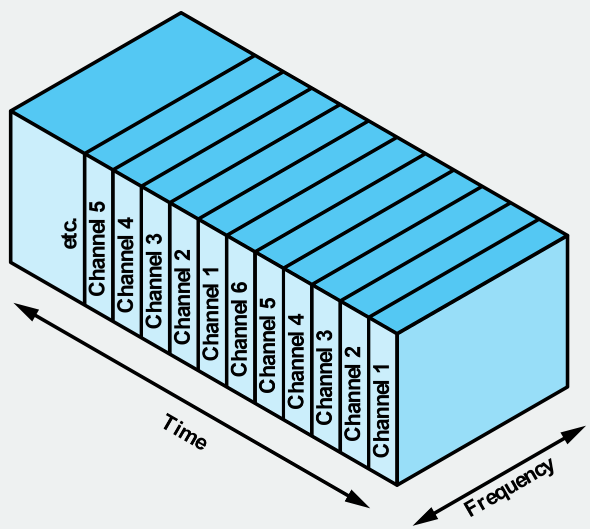



Figure 8.1 Multiplexing




(a) Frequency division multiplexing




(b) Time division multiplexing

**Figure 8.2 FDM and TDM**

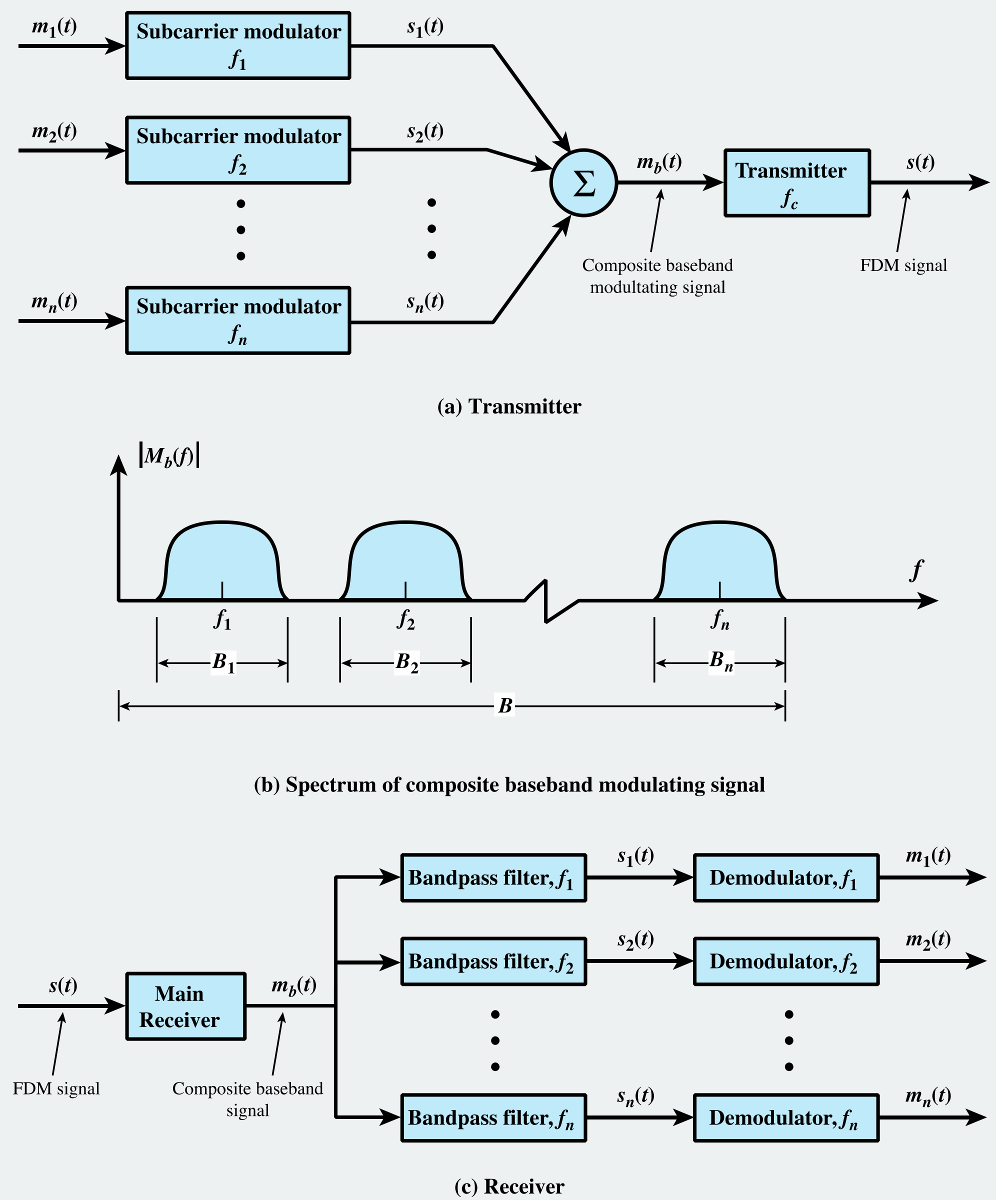



**Figure 8.3 FDM System**

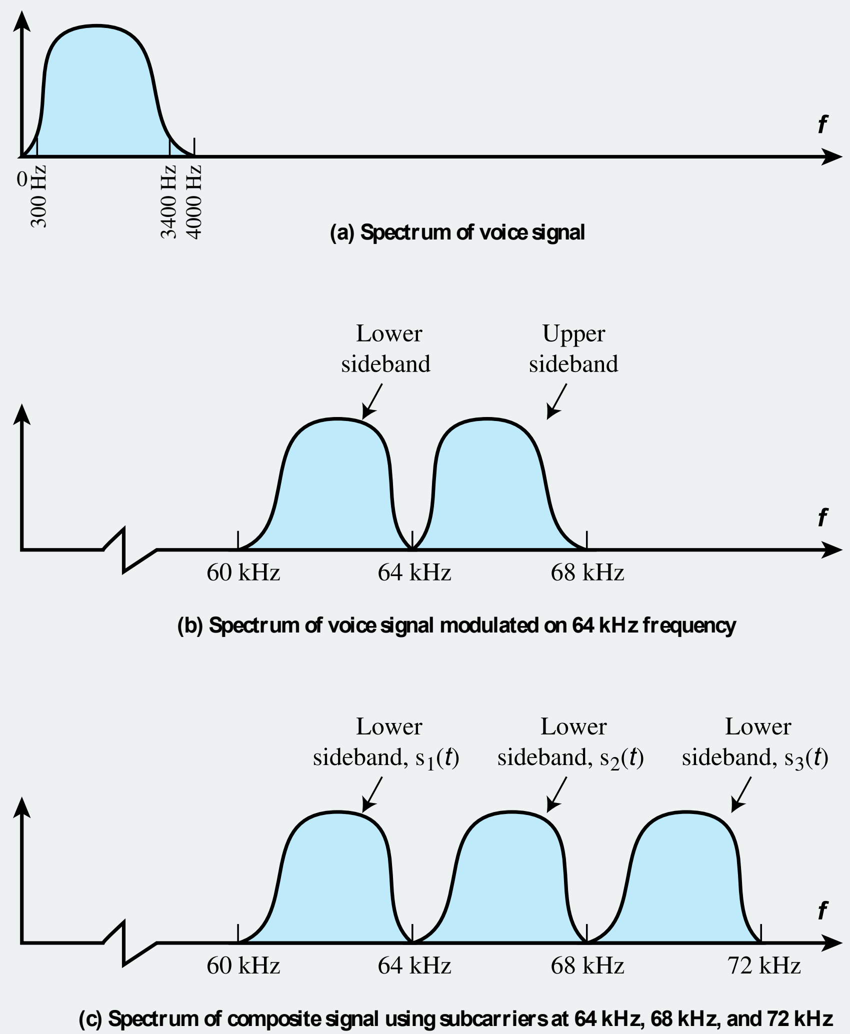



**Figure 8.4 FDM of Three Voiceband Signals**

# Analog Carrier Systems

- Long-distance links use an FDM hierarchy
- AT&T (USA) and ITU-T (International) variants

| Group | Supergroup | Mastergroup |
|---|---|---|
| • 12 voice channels (4kHz each) = 48kHz<br>• Range 60kHz to 108kHz | • FDM of 5 group signals supports 60 channels<br>• Carriers between 420kHz and 612 kHz | • FDM of 10 supergroups supports 600 channels |

- Original signal can be modulated many times

# Table 8.1
## 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* 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 | |

# Wavelength Division Multiplexing (WDM)

Multiple beams of light at different frequencies

Carried over optical fiber links

- Commercial systems with 160 channels of 10 Gbps
- Lab demo of 256 channels 39.8 Gbps

Architecture similar to other FDM systems

- Multiplexer consolidates laser sources (1550nm) for transmission over single fiber
- Optical amplifiers amplify all wavelengths
- Demultiplexer separates channels at destination

Dense Wavelength Division Multiplexing (DWDM)

- Use of more channels more closely spaced

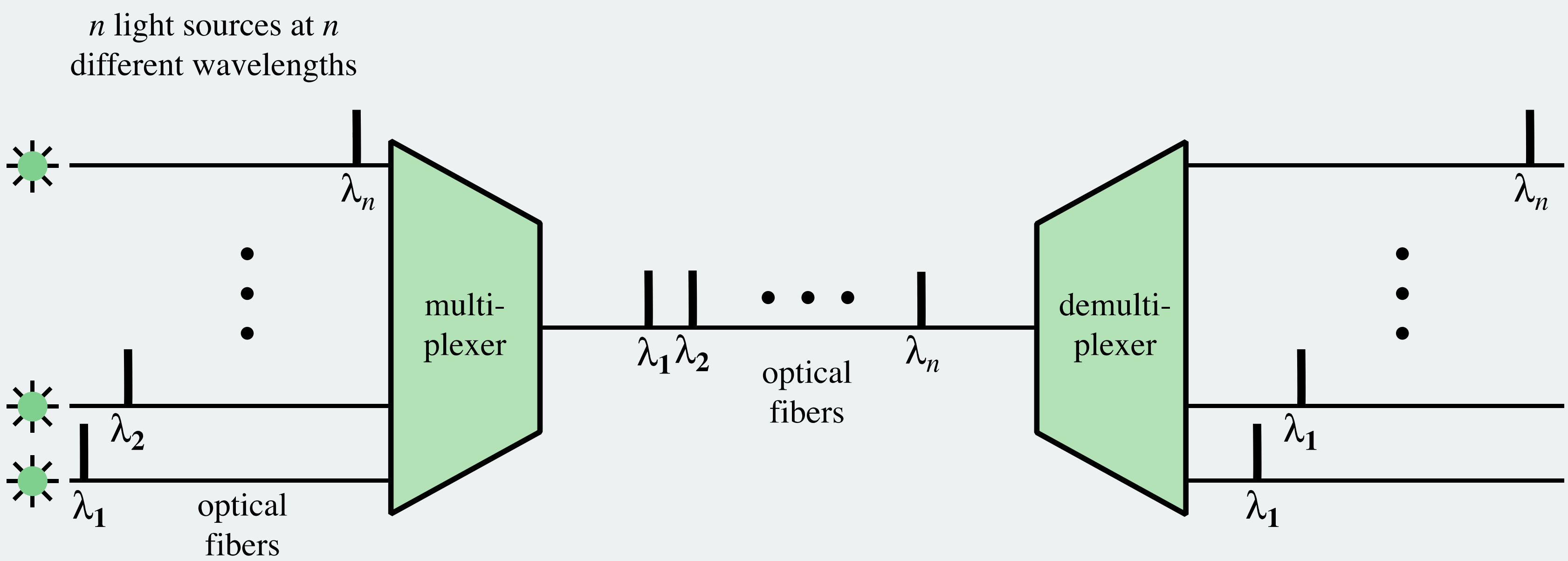



**Figure 8.5 Wavelength Division Multiplexing**

# Table 8.2
# ITU WDM Channel Spacing (G.692)

| Frequency (THz) | Wavelength in Vacuum (nm) | 50 GHz | 100 GHz | 200 GHz |
|---|---|---|---|---|
| 196.10 | 1528.77 | X | X | X |
| 196.05 | 1529.16 | X | | |
| 196.00 | 1529.55 | X | X | |
| 195.95 | 1529.94 | X | | |
| 195.90 | 1530.33 | X | X | X |
| 195.85 | 1530.72 | X | | |
| 195.80 | 1531,12 | X | X | |
| 195.75 | 1531.51 | X | | |
| 195.70 | 1531.90 | X | X | X |
| 195.65 | 1532.29 | X | | |
| 195.60 | 1532.68 | X | X | |
| … | … | | | |
| 192.10 | 1560.61 | X | X | X |

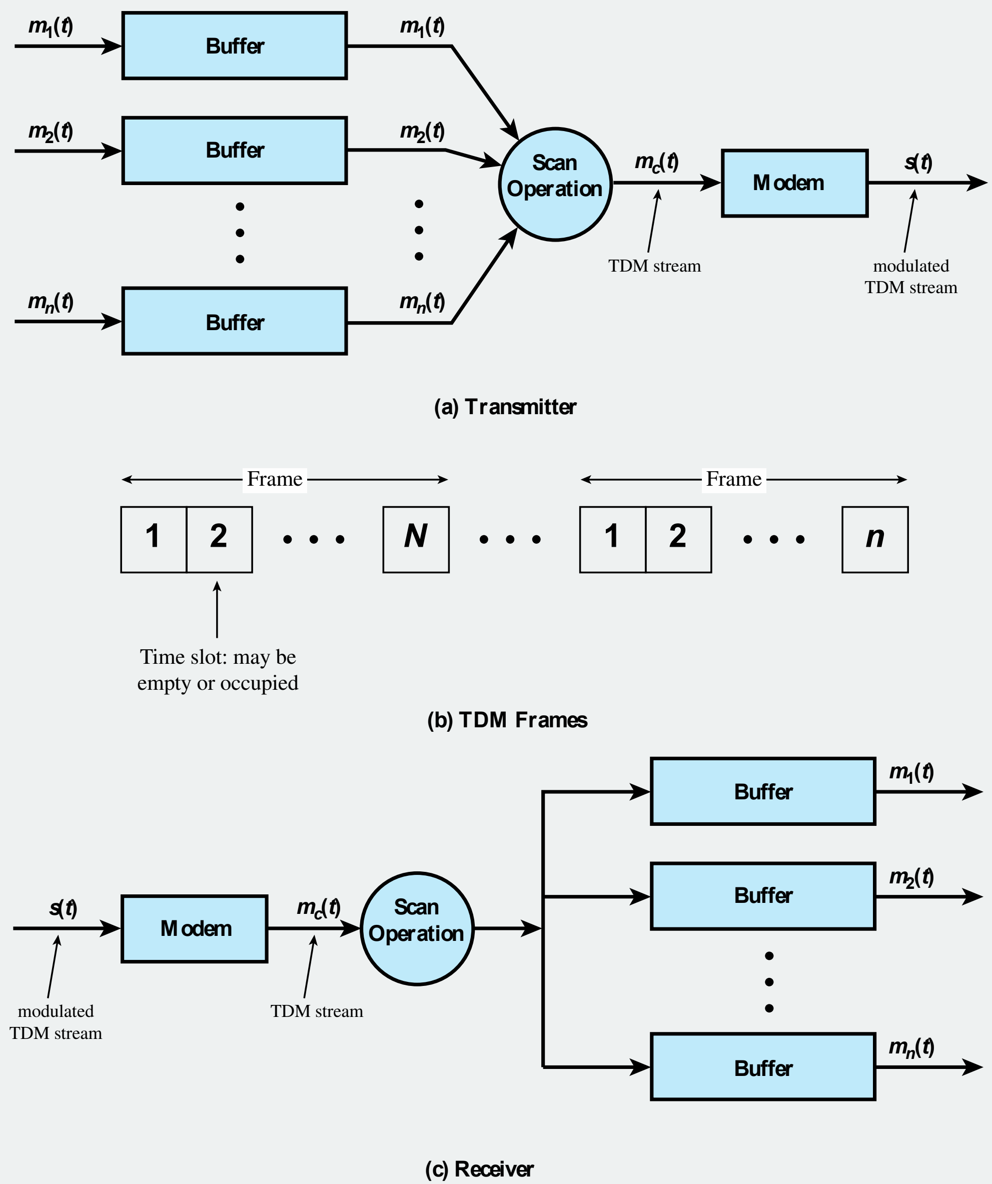



**Figure 8.6 Synchronous TDM System**

# 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
  - Leaving empty slots
- Error control
  - Errors detected and handled on individual channel


**(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**

**• • • $f_2$ $F_1$ $d_2$ $f_1$ $d_2$ $f_1$ $d_2$ $d_1$ $d_2$ $d_1$ $C_2$ $d_1$ $A_2$ $C_1$ $F_2$ $A_1$ $f_2$ $F_1$ $f_2$ $f_1$ $d_2$ $f_1$ $d_2$ $d_1$ $d_2$ $d_1$ $d_2$ $d_1$ $C_2$ $C_1$ $A_2$ $A_1$ $F_2$ $F_1$**

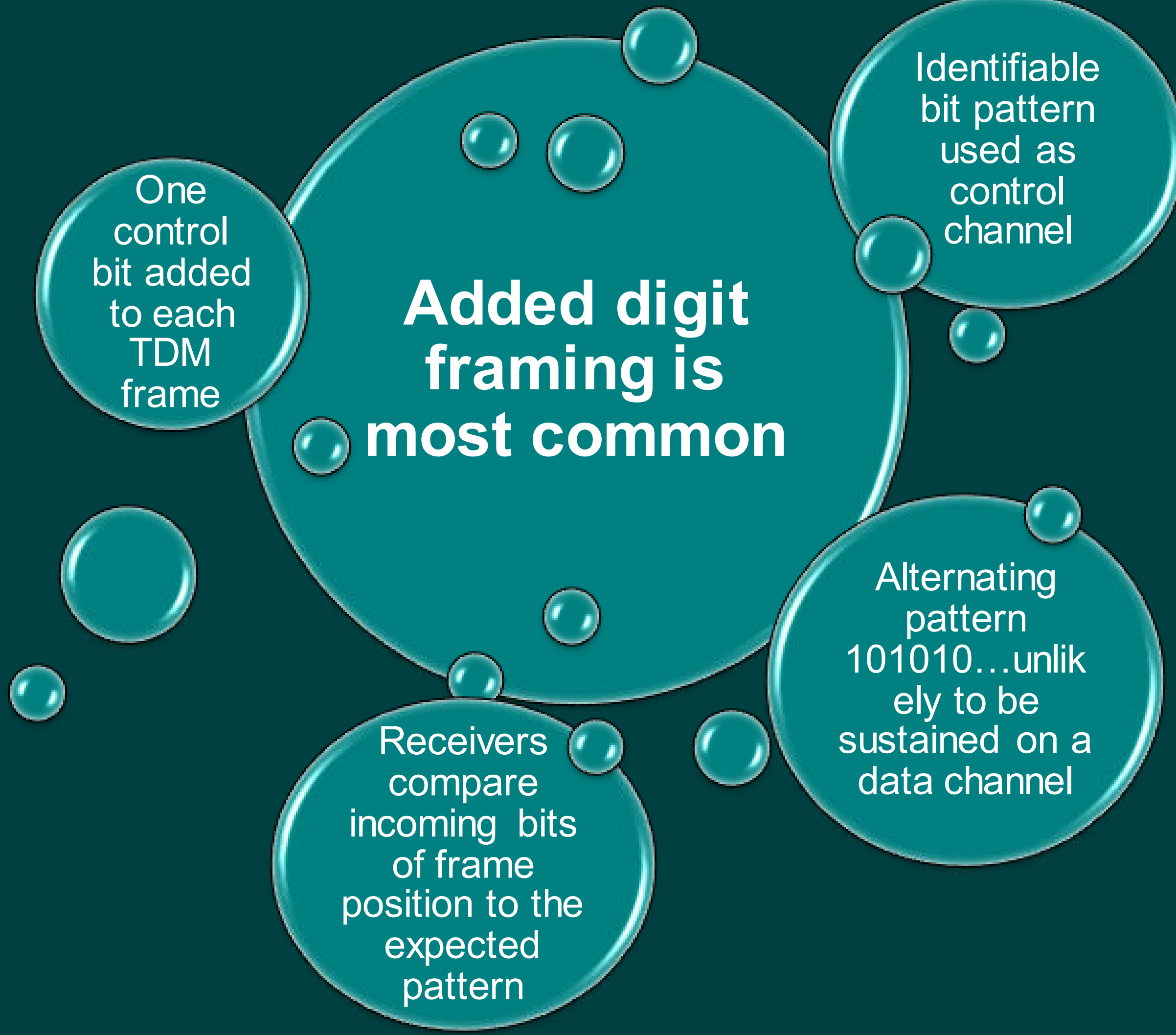
**(c) Multiplexed data stream**

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

# Figure 8.7 Use of Data Link Control on TDM Channels

# Framing

- No flag or SYNC characters bracketing TDM frames
- Must still provide synchronizing mechanism between source and destination clocks



# Pulse Stuffing is a common solution

| | | |
|---|---|---|
| Have 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 |

- Problem of synchronizing various data sources
- Variation among clocks could cause loss of synchronization
- Issue of data rates from different sources not related by a simple rational number

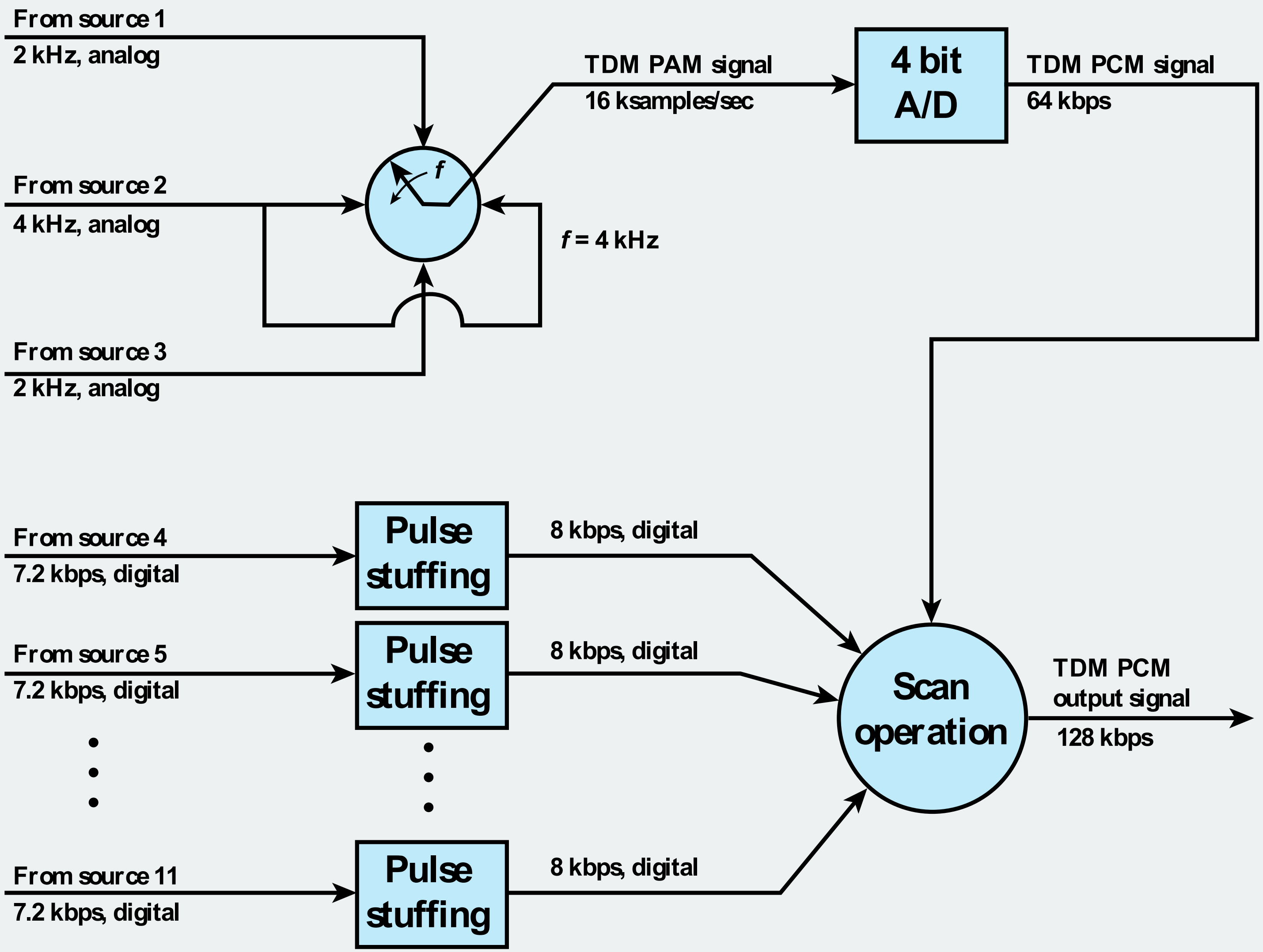
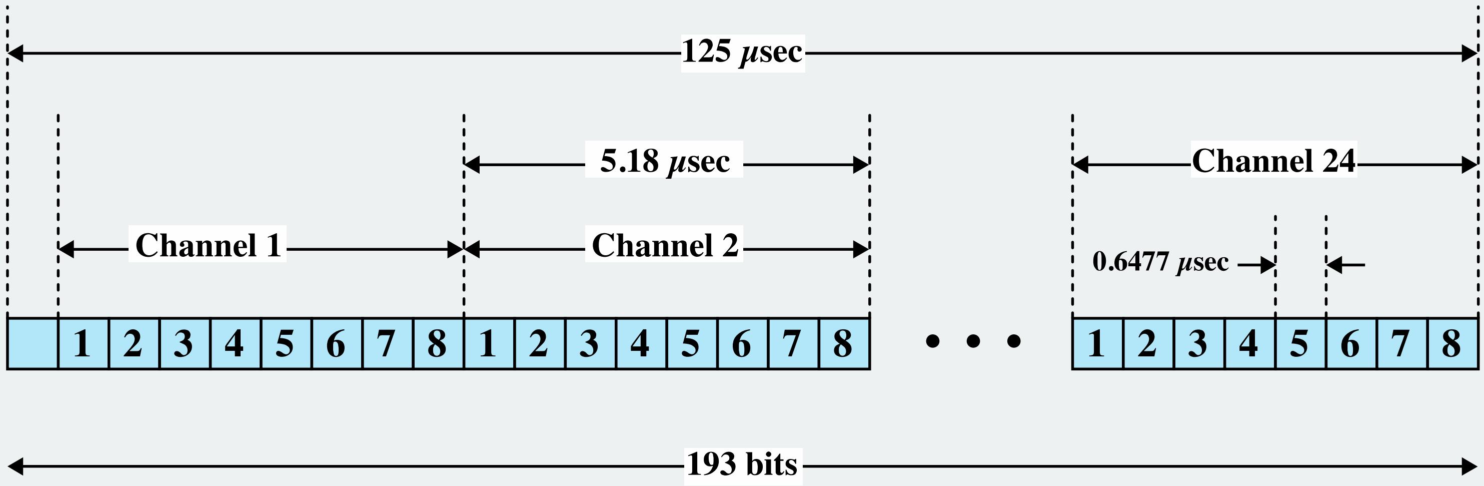



Figure 8.8 TDM of Analog and Digital Sources

# Table 8.3

## North American and International TDM Carrier Standards

| North American | | | International (ITU-T) | | |
|---|---|---|---|---|---|
| Designation | Number of Voice Channels | Data Rate (Mbps) | Level | Number of Voice Channels | Data Rate (Mbps) |
| DS-1 | 24 | 1.544 | 1 | 30 | 2.048 |
| DS-1C | 48 | 3.152 | 2 | 120 | 8.448 |
| DS-2 | 96 | 6.312 | 3 | 480 | 34.368 |
| DS-3 | 672 | 44.736 | 4 | 1920 | 139.264 |
| DS-4 | 4032 | 274.176 | 5 | 7680 | 565.148 |




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.

**Figure 8.9 DS-1 Transmission Format**

# SONET/SDH

- Synchronous Optical Network (ANSI)
- Synchronous Digital Hierarchy (ITU-T)
- High speed capability of optical fiber
- Defines 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 (e.g., 2.048Mbps)
  - Multiple STS-1 combine into STS-N signal
  - ITU-T lowest rate is 155.52Mbps (STM-1)

# Table 8.4
# SONET/SDH Signal Hierarchy

| SONET Designation | ITU-T Designation | Data Rate | Payload Rate (Mbps) |
|---|---|---|---|
| STS-1/OC-1 | | 51.84 Mbps | 50.112 Mbps |
| STS-3/OC-3 | STM-1 | 155.52 Mbps | 150.336 Mbps |
| STS-12/OC-12 | STM-4 | 622.08 Mbps | 601.344 Mbps |
| STS-48/OC-48 | STM-16 | 2.48832 Gbps | 2.405376 Gbps |
| STS-192/OC-192 | STM-64 | 9.95328 Gbps | 9.621504 Gbps |
| STS-768 | STM-256 | 39.81312 Gbps | 38.486016 Gbps |
| STS-3072 | | 159.25248 Gbps | 153.944064 Gbps |

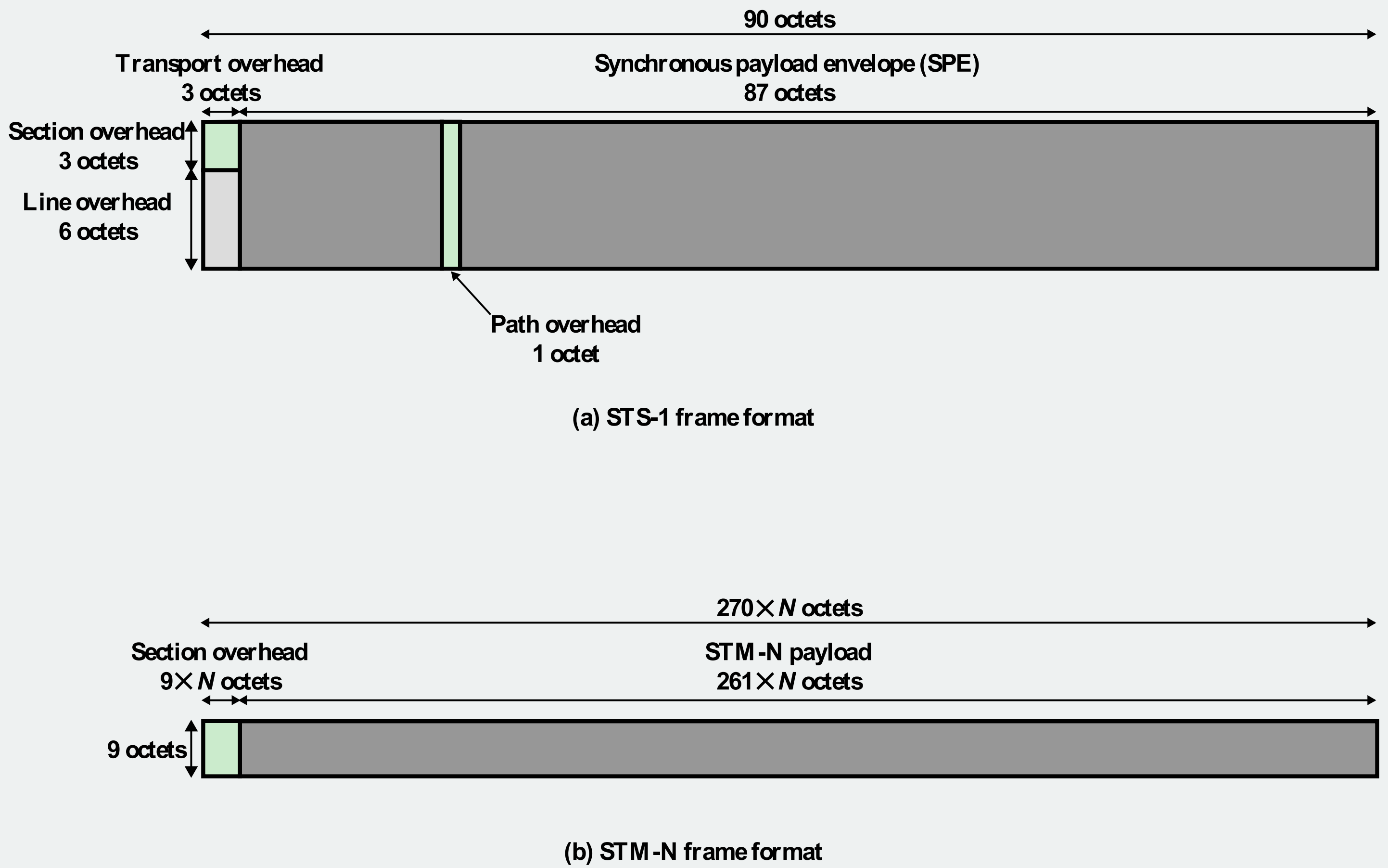



**Figure 8.10 SONET/SDH Frame Formats**

| | | | |
|---|---|---|---|
| Section Overhead | Framing A1 | Framing A2 | trc/grwth J0/Z0 |
| | BIP-8 B1 | Orderwire E1 | User F1 |
| | DataCom D1 | DataCom D2 | DataCom D3 |
| Line Overhead | Pointer H1 | Pointer H2 | Pointer Action H3 |
| | BIP-8 B2 | APS K1 | APS K2 |
| | DataCom D4 | DataCom D5 | DataCom D6 |
| | DataCom D7 | DataCom D8 | DataCom D9 |
| | DataCom D10 | DataCom D11 | DataCom D12 |
| | Status S1/Z1 | Error M0/M1 | Orderwire E2 |

(a) Transport Overhead

| |
|---|
| Trace J1 |
| BIP-8 B3 |
| Signal Label C2 |
| Path Status G1 |
| User F2 |
| Multiframe H4 |
| Growth Z3 |
| Growth Z4 |
| Growth Z5 |

(b) Path Overhead

## Figure 8.11 SONET STS-1 Overhead Octets

# Table 8.5

# STS-1 Overhead Bits

**Section Overhead**

| | |
|---|---|
| A1, A2: | Framing bytes = F6,28 hex; used to indicate the beginning of the frame. |
| J0/Z0: | Allows two connected sections to verify the connections between them by transmitting a sixteen-byte message. This message is transmitted in sixteen consecutive frames with first byte (J0) carried in first frame, second byte in second frame and so on (Z0). |
| B1: | Bit-interleaved parity byte providing even parity over previous STS-*N* frame after scrambling; the *i*th bit of this octet contains the even parity value calculated from the *i*th bit position of all octets in the previous frame. |
| E1: | Section level 64-kbps PCM orderwire; optional 64-kbps voice channel to be used between section terminating equipment, hubs, and remote terminals. |
| F1: | 64-kbps channel set aside for user purposes. |
| D1-D3: | 192-kbps data communications channel for alarms, maintenance, control, and administration between sections. |

**Line Overhead**

| | |
|---|---|
| H1-H3: | Pointer bytes used in frame alignment and frequency adjustment of payload data. |
| B2: | Bit-interleaved parity for line level error monitoring. |
| K1, K2: | Two bytes allocated for signaling between line level automatic protection switching equipment; uses a bit-oriented protocol that provides for error protection and management of the SONET optical link. |
| D4-D12: | 576-kbps data communications channel for alarms, maintenance, control, monitoring, and administration at the line level. |
| S1/Z1: | In the first STS-1 of an STS-N signal, used for transporting syncrhonization message (S1). Undefined in the second through *N*th STS-1 (Z1) |
| M0/M1: | Remote error indication in first STS-1 (M0) and third frames |
| E2: | 64-kbps PCM voice channel for line level orderwire. |

**Path Overhead**

| | |
|---|---|
| J1: | 64-kbps channel used to send repetitively a 64-octet fixed-length string so a receiving terminal can continuously verify the integrity of a path; the contents of the message are user programmable. |
| B3: | Bit-interleaved parity at the path level, calculated over all bits of the previous SPE. |
| C2: | STS path signal label to designate equipped versus unequipped STS signals. *Unequipped* means the the line connection is complete but there is no path data to send. For equipped signals, the label can indicate the specific STS payload mapping that might be needed in receiving terminals to interpret the payloads. |
| G1: | Status byte sent from path terminating equipment back to path originating equipment to convey status of terminating equipment and path error performance. |
| F2: | 64-kbps channel for path user. |
| H4: | Multiframe indicator for payloads needing frames that are longer than a single STS frame; multiframe indicators are used when packing lower rate channels (virtual tributaries) into the SPE. |
| Z3-Z5: | Reserved for future use. |

(Table can be found on page 277 in textbook)

# Cable Modems

## 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

-Dedicate two cable TV channels to data transfer
-Each channel shared by number of subscribers using statistical TDM

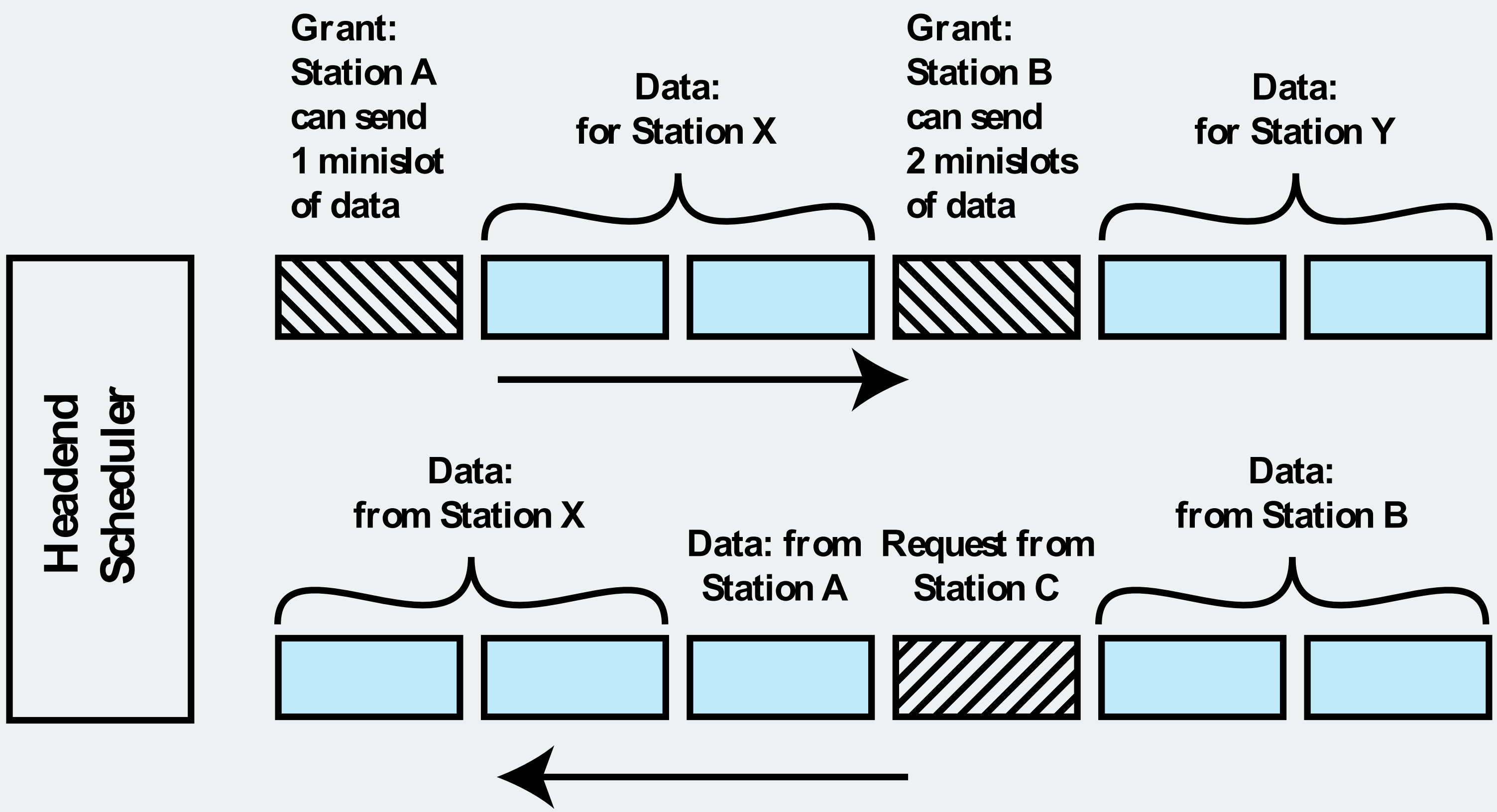



**Figure 8.12 Cable Modem Scheme**

# Cable Spectrum Division

- To support both cable television programming and data channels, the cable spectrum is divided in to three ranges:
  - User-to-network data (upstream): 5 - 40 MHz
  - Television delivery (downstream): 50 - 550 MHz
  - Network to user data (downstream): 550 - 750 MHz

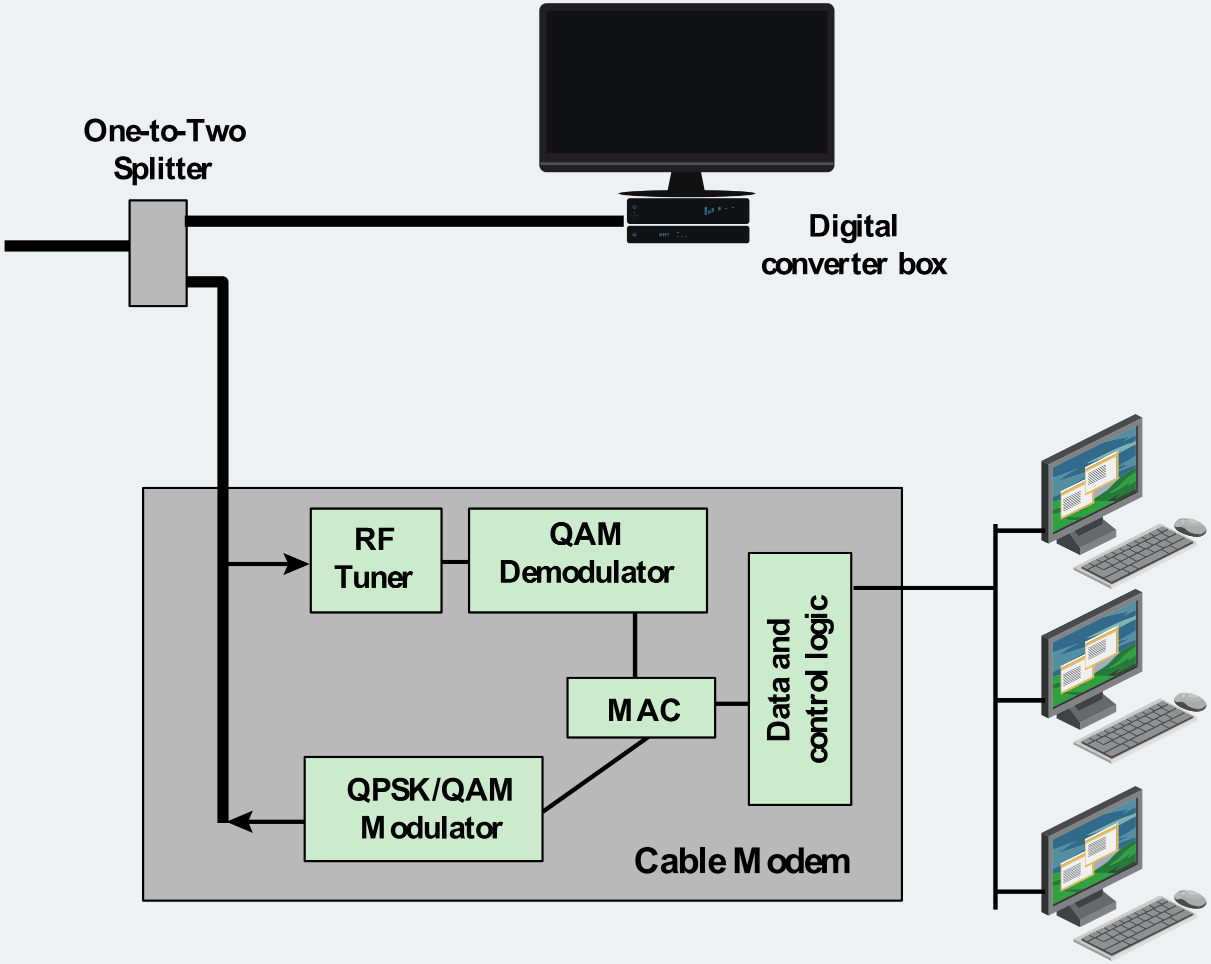
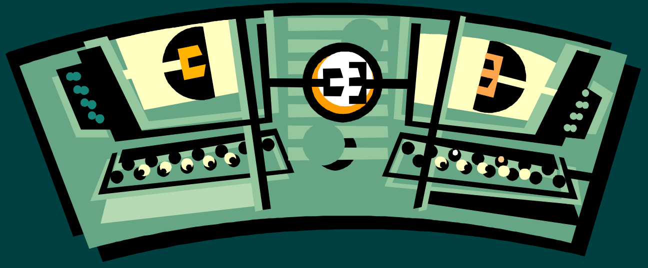



Figure 8.13 Cable Modem Configuration

# 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



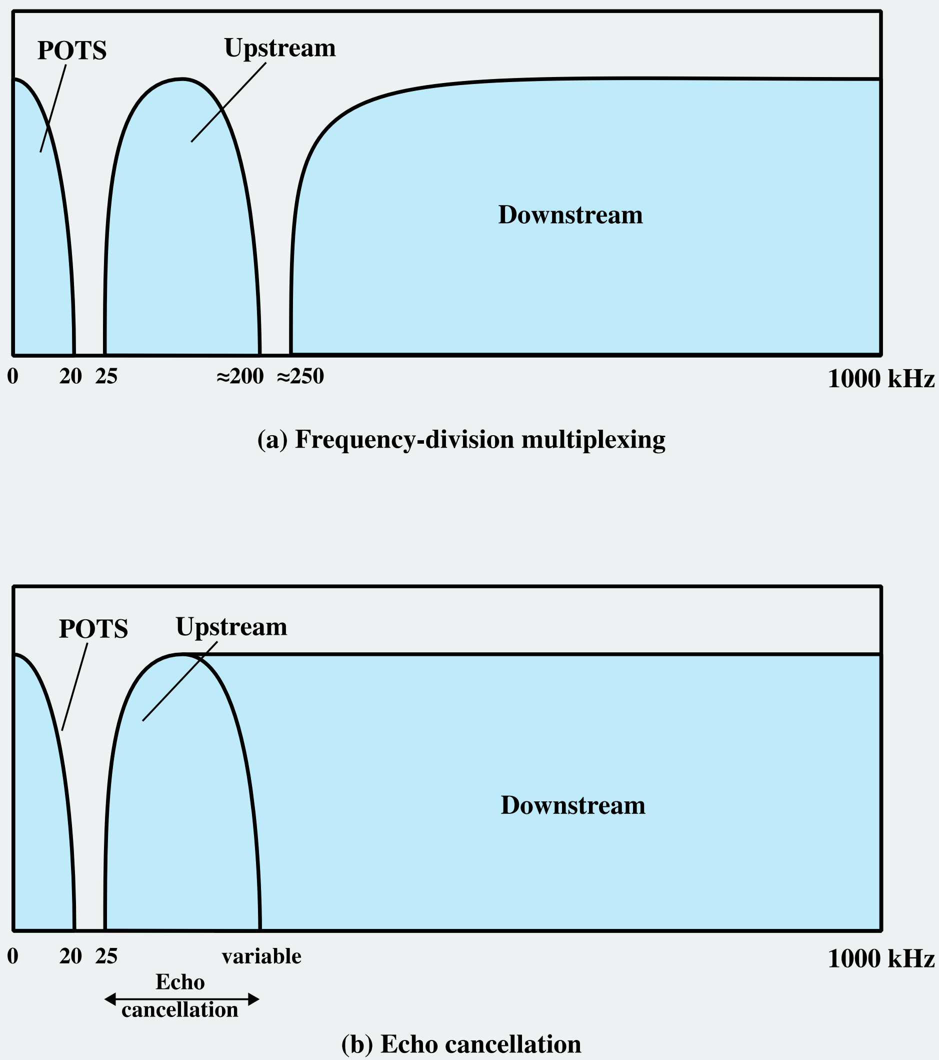



**Figure 8.14 ADSL Channel Configuration**

# Discrete Multitone (DMT)

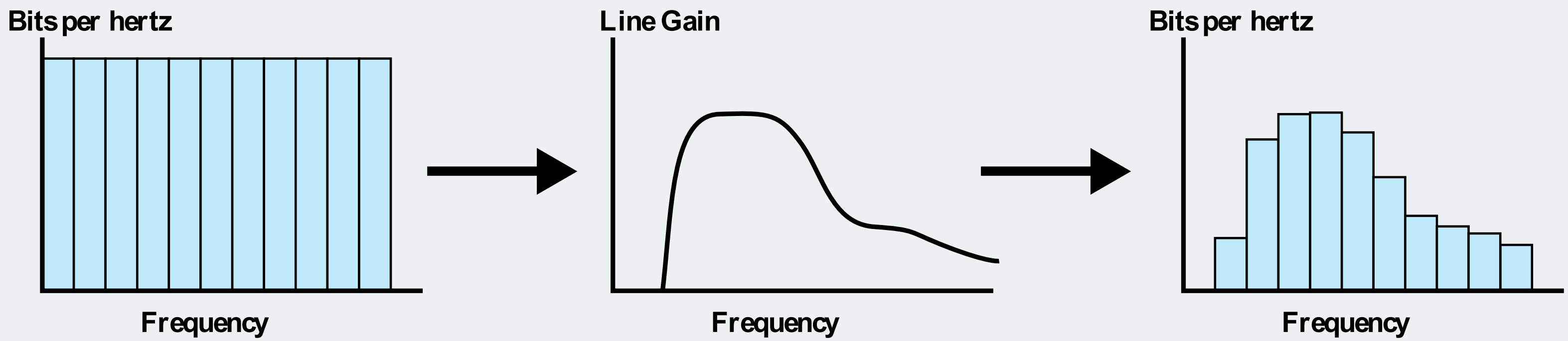



Figure 8.15 DMT Bits per Channel Allocation

- 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

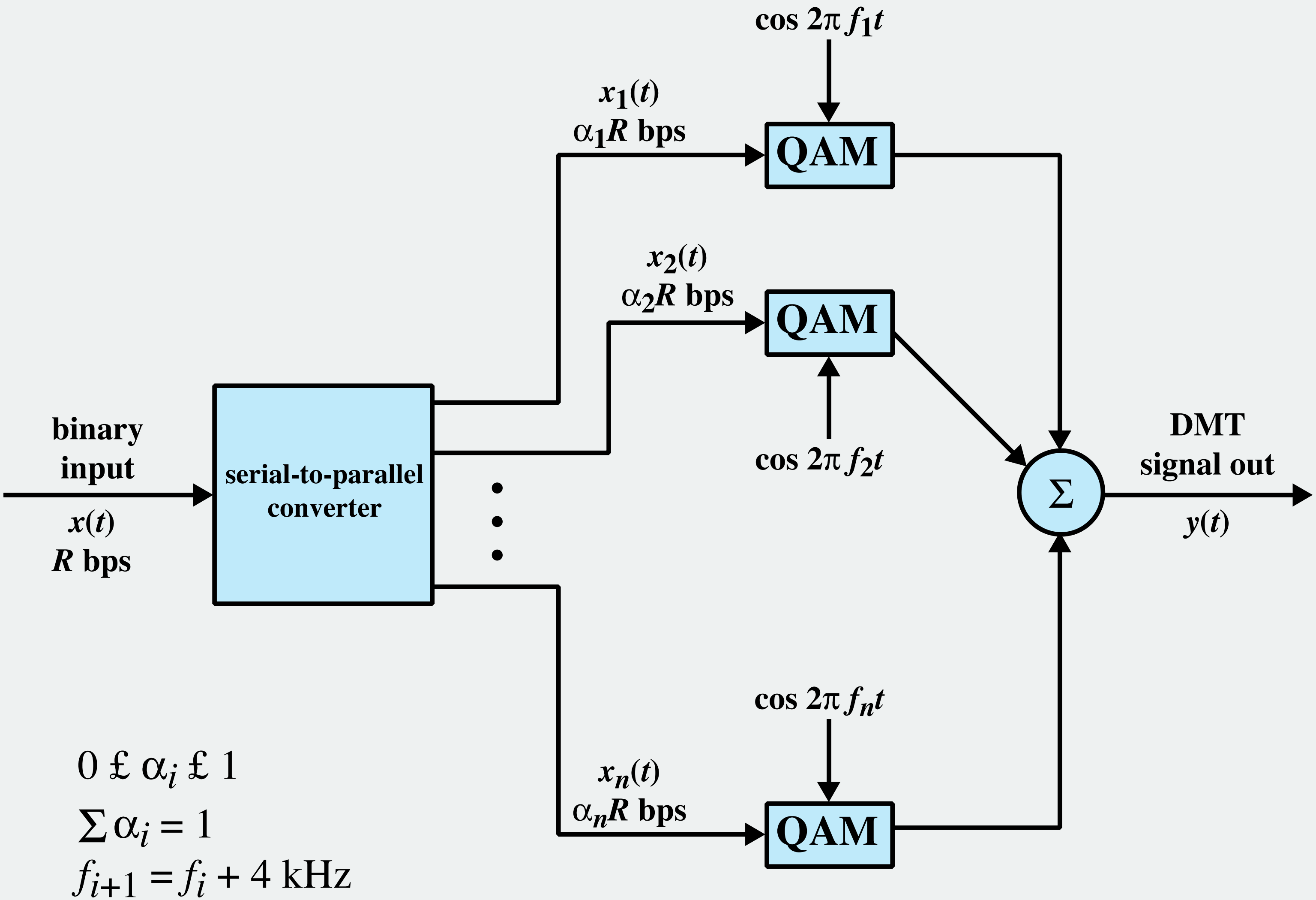
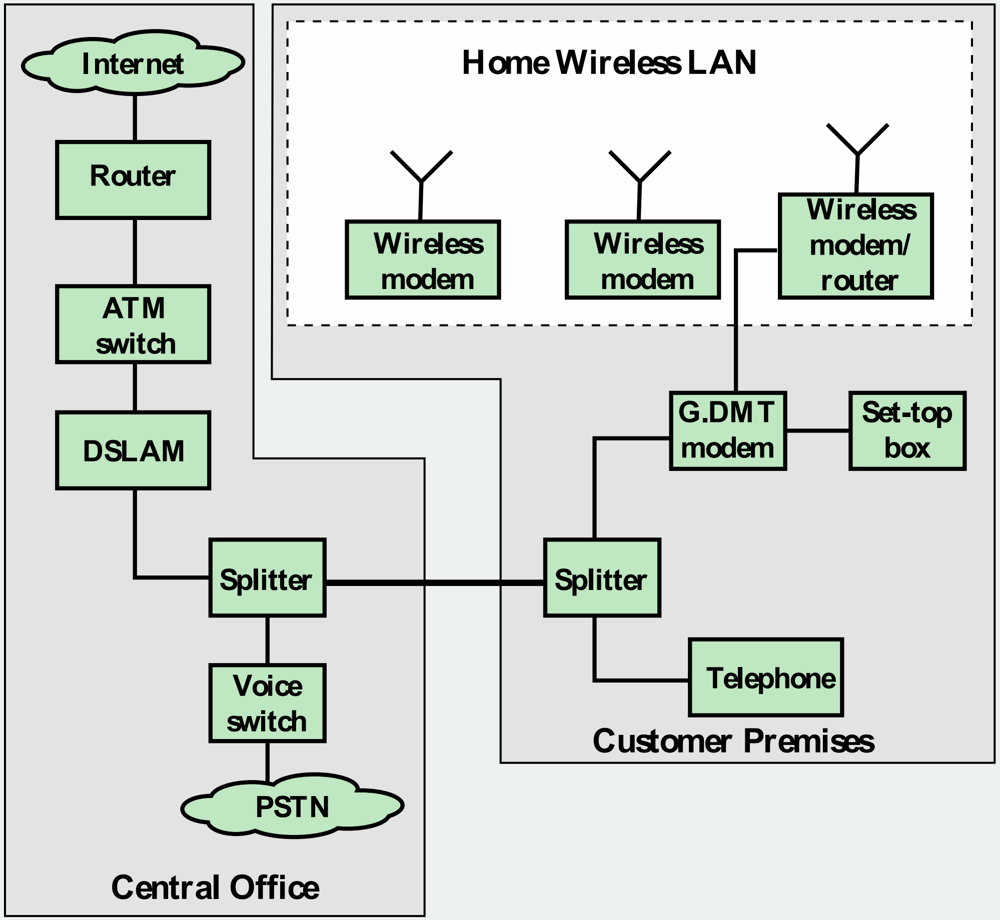



**Figure 8.16 DMT Transmitter**




ATM = Asynchronous Transfer Mode
DSLAM = Digital Subscriber Line Access Multiplexer
PSTN = Public Switched Telephone Network
G.DMT = G.992.1 Discrete Multitone

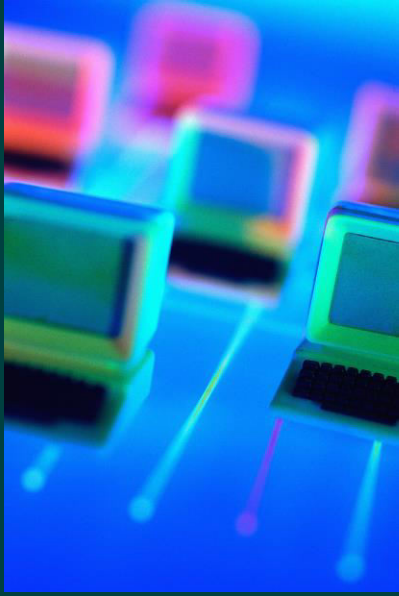
**Figure 8.17 DSL Broadband Access**

# Table 8.6
# Comparison of xDSL Alternatives

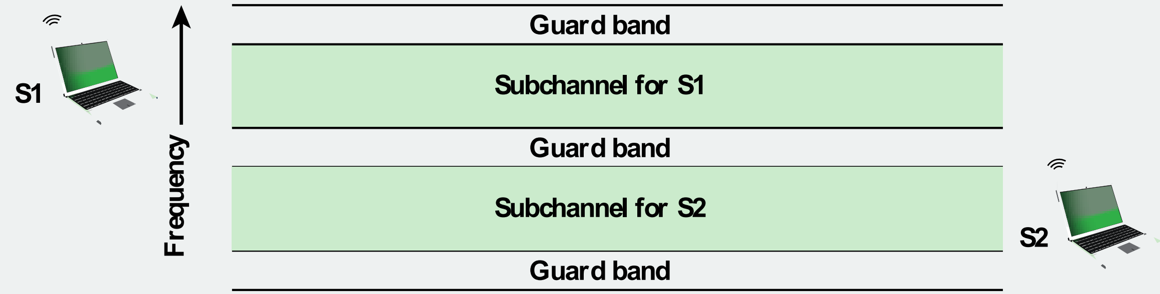
| | ADSL | HDSL | SDSL | VDSL |
|---|---|---|---|---|
| **Data rate** | 1.5 to 9 Mbps downstream<br>16 to 640 kbps upstream | 1.544 or 2.048 Mbps | 1.544 or 2.048 Mbps | 13 to 52 Mbps downstream<br>1.5 to 2.3 Mbps upstream |
| **Mode** | Asymmetric | Symmetric | Symmetric | Asymmetric |
| **Copper pairs** | 1 | 2 | 1 | 1 |
| **Range (24-gauge UTP)** | 3.7 to 5.5 km | 3.7 km | 3.0 km | 1.4 km |
| **Signaling** | Analog | Digital | Digital | Analog |
| **Line code** | CAP/DMT | 2B1Q | 2B1Q | DMT |
| **Frequency** | 1 to 5 MHz | 196 kHz | 196 kHz | $\geq$ 10 MHz |
| **Bits/cycle** | Varies | 4 | 4 | Varies |

UTP = unshielded twisted pair

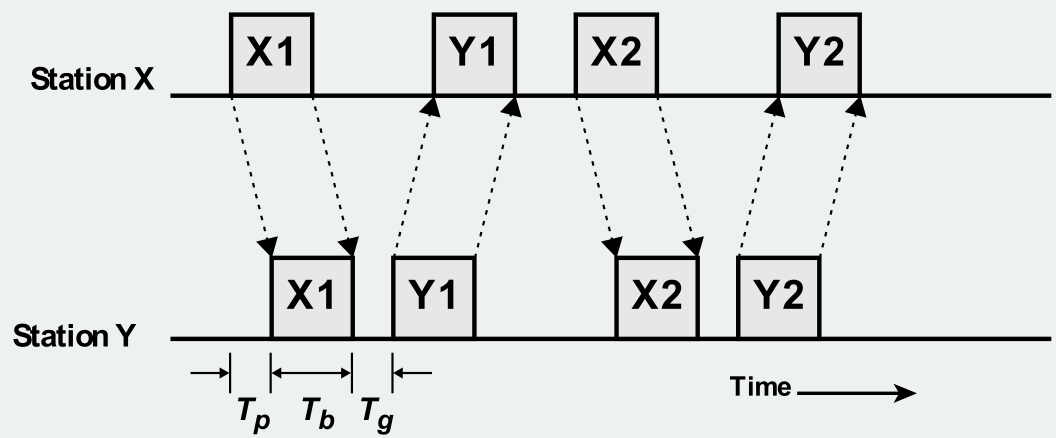
# xDSL



- High data rate DSL (HDSL)
  - 2B1Q coding on dual twisted pairs
  - Up to 2Mbps over 3.7km
- Single line DSL
  - 2B1Q coding on single twisted pair (residential) with echo cancelling
  - Up to 2Mbps over 3.7km
- Very high data rate DSL
  - DMT/QAM for very high data rates
  - Separate bands for separate services




(a) Frequency-division duplex (FDD)




$T_p$ = Propagation delay

$T_b$ = Burst transmission time

$T_g$ = Guard time

(b) Time-division duplex (TDD)

**Figure 8.18 Duplex Access Techniques**

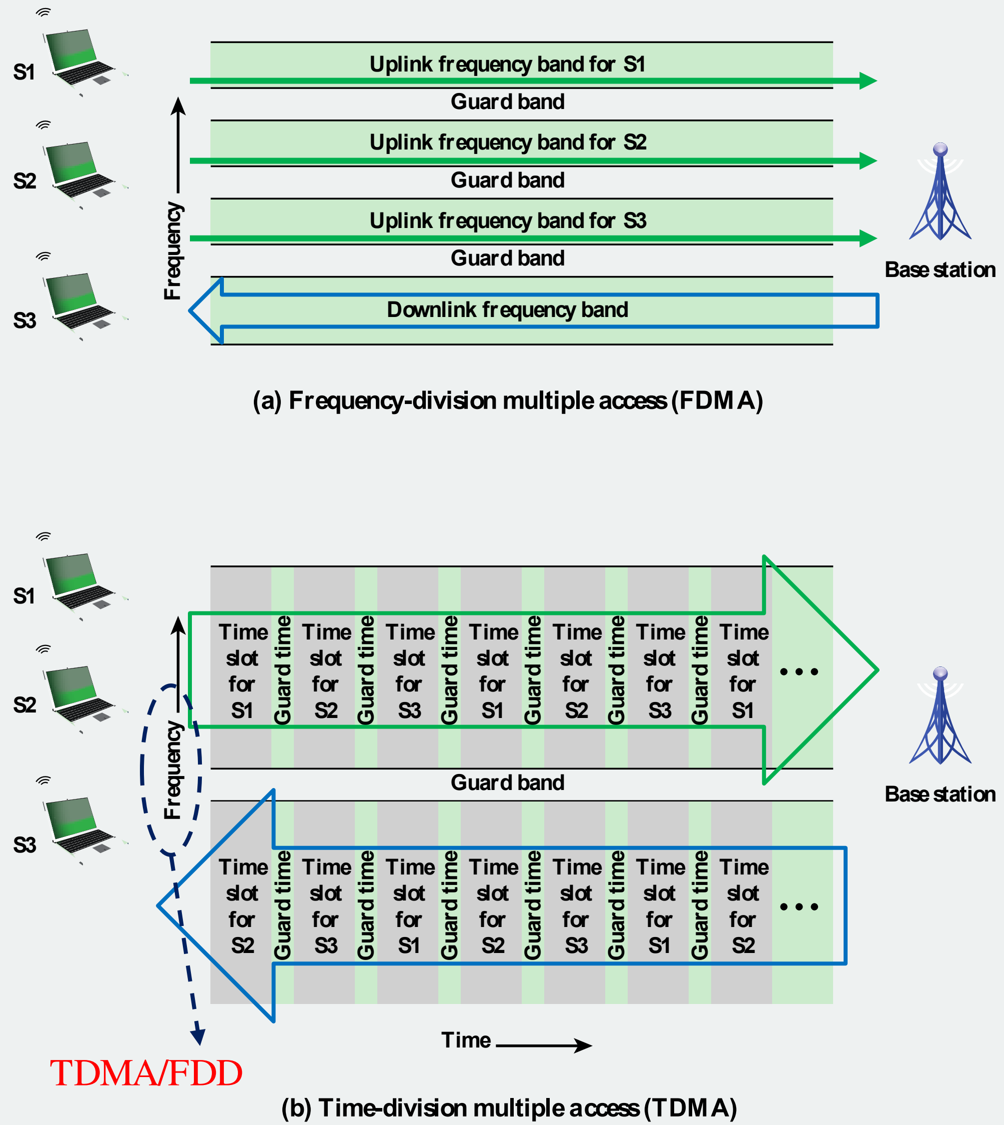



**Figure 8.19 Multiple Channel Access Techniques**

# FDMA

- Frequency-Division Multiple Access
  - Technique used to share the spectrum among multiple stations
  - Base station assigns bandwidths to stations within the overall bandwidth available
  - Key features:

Each subchannel is dedicated to a single station

If a subchannel is not in use, it is idle; the capacity is wasted

Requires fewer overhead bits because each subchannel is dedicated

Individual subchannels must be separated by guard bands to minimize interference

# TDMA

- Time-Division Multiple Access
  - There is a single, relatively large, uplink frequency band that is used to transmit a sequence of time slots
  - Repetitive time slots are assigned to an individual subscriber station to form a logical subchannel
  - Key features:

Each subchannel is dedicated to a single station

For an individual station data transmission occurs in bursts rather than continuously

Guard times are needed between time slots, to account for lack of perfect synchronization among the subscriber station

Downlink channel may be on a separate frequency band

The uplink and downlink transmission may be on the same frequency band

# Summary

- Frequency-division multiplexing
  - Characteristics
  - Analog carrier systems
  - Wavelength division multiplexing
- Synchronous time-division multiplexing
  - Characteristics
  - TDM link control
  - Digital carrier systems
  - SONET/SDH
- Cable modems
- Asymmetric digital subscriber line
  - ADSL design
  - Discrete multitone
  - Broadband access configuration
- xDSL
  - High data rate digital subscriber line
  - Single-line digital subscriber line
  - Very high data rate digital subscriber line
- Multiple channel access
  - Frequency-division duplex (FDD)
  - Time-division duplex (TDD)
  - Frequency-division multiple access (FDMA)
  - Time-division multiple access (TDMA)