Chapter 8: Multiplexing
Multiplexing

• What is multiplexing?
  — Frequency-Division Multiplexing
  — Time-Division Multiplexing (Synchronous)
  — Statistical Time-Division Multiplexing, etc.
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 Voicebands

(a) Spectrum of voice signal

(b) Spectrum of voice signal modulated on 64 kHz frequency

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

- Long-distance links use FDM hierarchy
- AT&T (USA) ITU-T (International) variants
- Group
  - 12 voice channels (4kHz each) = 48kHz
  - Range 60kHz to 108kHz
- Supergroup
  - FDM of 5 group signals on carriers between 420kHz and 612 kHz
  - Supports 60 channels (=5*12 😊)
- Mastergroup
  - 10 supergroups, which supports 600 channels

CS420/520 Axel Krings
## North American and International FDM Carrier Standards

<table>
<thead>
<tr>
<th>Number of Voice Channels</th>
<th>Bandwidth</th>
<th>Spectrum</th>
<th>AT&amp;T</th>
<th>ITU-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>48 kHz</td>
<td>60–108 kHz</td>
<td>Group</td>
<td>Group</td>
</tr>
<tr>
<td>60</td>
<td>240 kHz</td>
<td>312–552 kHz</td>
<td>Supergroup</td>
<td>Supergroup</td>
</tr>
<tr>
<td>300</td>
<td>1.232 MHz</td>
<td>812–2044 kHz</td>
<td>Mastergroup</td>
<td>Mastergroup</td>
</tr>
<tr>
<td>600</td>
<td>2.52 MHz</td>
<td>564–3084 kHz</td>
<td>Mastergroup</td>
<td>Mastergroup</td>
</tr>
<tr>
<td>900</td>
<td>3.872 MHz</td>
<td>8.516–12.388 MHz</td>
<td></td>
<td>Supermaster group</td>
</tr>
<tr>
<td>$N \times 600$</td>
<td></td>
<td></td>
<td>Mastergroup multiplex</td>
<td></td>
</tr>
<tr>
<td>3,600</td>
<td>16.984 MHz</td>
<td>0.564–17.548 MHz</td>
<td>Jumbogroup</td>
<td></td>
</tr>
<tr>
<td>10,800</td>
<td>57.442 MHz</td>
<td>3.124–60.566 MHz</td>
<td>Jumbogroup multiplex</td>
<td></td>
</tr>
</tbody>
</table>
Wavelength Division Multiplexing (WDM)

- Multiple beams of light at different frequency carried by optical fiber
  - A form of FDM
- Each colour of light (wavelength) carries separate data channel
  - most WDM use single mode fiber optical cable (9µm core)
- 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 span
## ITU WDM Channel Spacing (G.692)

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
<th>Wavelength in Vacuum (nm)</th>
<th>50 GHz</th>
<th>100 GHz</th>
<th>200 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>196.10</td>
<td>1528.77</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>196.05</td>
<td>1529.16</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>196.00</td>
<td>1529.55</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>195.95</td>
<td>1529.94</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>195.90</td>
<td>1530.33</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>195.85</td>
<td>1530.72</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>195.80</td>
<td>1531.12</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>195.75</td>
<td>1531.51</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>195.70</td>
<td>1531.90</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>195.65</td>
<td>1532.29</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>195.60</td>
<td>1532.68</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>192.10</td>
<td>1560.61</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Dense Wavelength Division Multiplexing

- DWDM
- Implies more channels more closely spaced than WDM
- 200GHz or less could be considered “dense”
- Recommendation ITU-T G.694.1
  — Check it out to see what recommendations look like
Dense Wavelength Division Multiplexing

ITU-T G.694.1

TELECOMMUNICATION STANDARIZATION SECTOR OF ITU

SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media and optical systems characteristics – Characteristics of optical systems

Spectral grids for WDM applications: DWDM frequency grid
Time Division Multiplexing
Time-Division Multiplexing TDM (synchronous)

- fixed time slots: take your turn or loose it
- each slot is of duration \( T \)
- frame is of duration \( NT \) and then repeats itself
- X sends at constant data rate and Y receives at that rate - no buffering or flow control needed - though channels may have own flow control (such as V.24 DSR/DTR and RTS/CTS)
- errors on one channel do not affect behavior of system
- character interleaving - can eliminate start/stop bits and reinsert later for asynchronous sources
- can use 1 bit/frame to indicate slot/frame alignment (101010...)
- differing data rates managed by buffers and use-based allocation
Figure 8.6 Synchronous TDM System
Multiplexing

— TDM Link Control

• multiplexer does not need link control
• data rate on the multiplexed lines is fixed
• what does one do if a channel is down?
  – Some channel might not send data
  – Answer: tough luck - the efficiency goes down - no big deal
• what does one do if the data on a channel is corrupted?
  – Need error control within the multiplexer?
  – Answer: data link control (e.g. HDLC) on a per-channel basis
Multiplexing

(a) Configuration

\[
\text{Input}_1 \rightarrow \text{Output}_1 \\
\text{Input}_2 \rightarrow \text{Output}_2
\]

(b) Input data streams

\[
\begin{align*}
\text{Input}_1 & : F_1 \ f_1 \ f_1 \ d_1 \ d_1 \ C_1 \ A_1 \ F_1 \ f_1 \ f_1 \ d_1 \ d_1 \ C_1 \ A_1 \ F_1 \\
\text{Input}_2 & : F_2 \ f_2 \ f_2 \ d_2 \ d_2 \ d_2 \ C_2 \ A_2 \ F_2 \ f_2 \ f_2 \ d_2 \ d_2 \ d_2 \ C_2 \ A_2 \ F_2
\end{align*}
\]

(c) Multiplexed data stream

\[
\cdots \ f_2 \ F_1 \ d_2 \ f_1 \ d_2 \ f_1 \ d_2 \ d_1 \ C_2 \ d_1 \ A_2 \ C_1 \ F_2 \ A_1 \ f_2 \ F_1 \ f_2 \ f_1 \ d_2 \ f_1 \ d_2 \ d_1 \ d_2 \ d_1 \ C_2 \ C_1 \ A_2 \ A_1 \ F_2 \ F_1 \cdots
\]

Legend:

- \( F \) = flag field
- \( d \) = one octet of data field
- \( A \) = address field
- \( f \) = one octet of FCS field
- \( C \) = control field
Multiplexing

Framing

- character interleaving - can eliminate start/stop bits and reinsert later for asynchronous sources
- need some synchronization
  - if no synchronization is provided to prevent input and output to get out of step
- “added-digit framing”
  - use 1 bit/frame to indicate slot/frame alignment
  - alternate this bit
    - kind of “logical channel with pattern (101010...) pattern”
    - if synchronization is lost, look at successive frames to find the pattern again.
  - This is called “framing search mode”
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
TDM of Analog and Digital Sources

From source 1
2 kHz, analog

From source 2
4 kHz, analog

From source 3
2 kHz, analog

F = 4 kHz

TDM PAM signal
16 ksamples/sec

4 bit A/D

TDM PCM signal
64 kbps

From source 4
7.2 kbps, digital

From source 5
7.2 kbps, digital

From source 11
7.2 kbps, digital

Pulse stuffing

Pulse stuffing

Pulse stuffing

TDM PCM output signal
128 kbps

Scan operation

8 kbps, digital

8 kbps, digital

8 kbps, digital
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 $8000 \times 193 = 1.544 \text{Mbps}$
  — 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

- voice digitization: 4kHz => 8000 samples/s
  - 8 bit sample every 125 microseconds
  - in US 24 voice channels grouped together (30 for ITU-I)
  - resulting aggregate bit rate is 1.544 Mbs (2.048Mbs)
  - actually (24 x 8 + 1)bits/125µs = 1.544Mbps
  - called DS1 or T1 link
  - 4 x T1 = T2
  - 7 x T2 = T3
  - 6 x T3 = T4
Multiplexing

Hal96 fig 2.26
Multiplexing

Hal96 fig 2.26
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.
Multiplexing

(b) 1 frame = 125 ms = 24 time slots + 1 framing bit = 1.544 Mbps

--- 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 ---

1 framing bit

7 coding bits (56 kbps) 1 signaling bit (bit 8)

(i) North America

Time slots 6, 12

Time slots 1–5, 7–11, 13–24

8 coding bits (64 kbps)

Hal96 fig 2.26
Multiplexing

1 frame = 125 ms = 32 time slots = 2.048 Mbps

--- 31 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 0 1 ---

Frame alignment/synchronization

Signaling channel

(ii) ITU-T

8 coding bits

Time slots 1–15, 17–31

Hal96 fig 2.26
### TDM Carrier Standards

- **North America (based on 24 channels)**

<table>
<thead>
<tr>
<th>Designation</th>
<th># voice channels</th>
<th>Data Rate (Mbps)</th>
<th>Level</th>
<th># voice channels</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>24</td>
<td>1.544</td>
<td>1</td>
<td>30</td>
<td>2.048</td>
</tr>
<tr>
<td>DS-1C</td>
<td>48</td>
<td>3.152</td>
<td>2</td>
<td>120</td>
<td>8.448</td>
</tr>
<tr>
<td>DS-2</td>
<td>96</td>
<td>6.312</td>
<td>3</td>
<td>480</td>
<td>34.368</td>
</tr>
<tr>
<td>DS-3</td>
<td>672</td>
<td>44.736</td>
<td>4</td>
<td>1920</td>
<td>139.264</td>
</tr>
<tr>
<td>DS-4</td>
<td>4032</td>
<td>274.176</td>
<td>5</td>
<td>7680</td>
<td>565.148</td>
</tr>
<tr>
<td>DS-5</td>
<td>5760</td>
<td>400.352</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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)
## Table 8.4

SONET/SDH Signal Hierarchy

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

CS420/520 Axel Krings
"Sequence 8"
SONET Frame Format

(a) STS-1 frame format

(b) STM-N frame format
Figure 8.11  SONET STS-1 Overhead Octets
Statistical TDM

- In Synchronous TDM many slots are wasted
- Statistical TDM allocates time slots dynamically based on demand
  - Make use of the fact that slots are not always active, so can support more devices on same channel
  - Requires use of extra overhead for identifying channel, and buffering
Multiplexing

- Statistical Multiplexer principle

Central computer

Port 1
Port 2
Port 3
... 
Port N

EIA-232D/V.24 asynchronous

M

EIA-530/V.35 synchronous

4-wire leased line (4.8, 9.6, 19.2 kbps)

Synchronous modems

= Personal computer

= Statistical multiplexer
### Statistical TDM Frame Formats

<table>
<thead>
<tr>
<th>Flag</th>
<th>Address</th>
<th>Control</th>
<th>Statistical TDM subframe</th>
<th>FCS</th>
<th>Flag</th>
</tr>
</thead>
</table>

(a) Overall frame

<table>
<thead>
<tr>
<th>Address</th>
<th>Data</th>
</tr>
</thead>
</table>

(b) Subframe with one source per frame

<table>
<thead>
<tr>
<th>Address</th>
<th>Length</th>
<th>Data</th>
<th>Address</th>
<th>Length</th>
<th>Data</th>
</tr>
</thead>
</table>

(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
Multiplexing

— let $m_c$ be maximum data rate of multiplexed trunk
— let $m_i$ be maximum data rate of source $i$

$m_c$ can be less than the sum of all $m_i$ iff probabilities $p_i$ are such that the sum of $p_i m_i$ is less than $m_c$: By how much? (rule of thumb is 80%)

Example: How many 9600bps terminals can be supported on a 56Kbps line using TDM if $p_i 75%$?
Buffer Size and Delay

assume data is transmitted in 1000-bit frames
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
    • e.g., may get 500kbps to 20Mbps
  — 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 time slots to subscriber
Grant: Station A can send 1 minislot of data

Data: for Station X

Grant: Station B can send 2 minislots of data

Data: for Station Y

Data: from Station A Request from Station C

Data: from Station B

Figure 8.12  Cable Modem Scheme
Cable Spectrum Division

- To support both cable television programming and data channels, the cable spectrum is divided into 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
  - 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
- 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
DMT Transmitter

\[ x_1(t) = \alpha_1 R \text{ bps} \]
\[ x_2(t) = \alpha_2 R \text{ bps} \]
\[ x_n(t) = \alpha_n R \text{ bps} \]

Binary input \( x(t) \) \( R \text{ bps} \)

Serial-to-parallel converter

\[ 0 \leq \alpha_i \leq 1 \]
\[ \sum \alpha_i = 1 \]
\[ f_{i+1} = f_i + 4 \text{ kHz} \]
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

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

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
Figure 8.18  Duplex Access Techniques

(a) Frequency-division duplex (TDD)

(b) Time-division duplex (TDD)

Station X

Station Y

$T_p$ = Propagation delay

$T_b$ = Burst transmission time

$T_g$ = Guard time

Figure 8.18  Duplex Access Techniques
Figure 8.19  Multiple Channel Access Techniques

(a) Frequency-division multiple access (FDMA)

(b) Time-division multiple access (TDMA)
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:

  1. Each subchannel is dedicated to a single station
  2. For an individual station data transmission occurs in bursts rather than continuously
  3. Guard times are needed between time slots, to account for lack of perfect synchronization among the subscriber station
  4. Downlink channel may be on a separate frequency band
  5. 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)