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

Channel 1

Channel 2

Channel 3

Channel 4

Channel 5

Channel 6

f_1
f_2
f_3
f_4
f_5
f_6

Time

Frequency
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
  - Support 60 channels (=5*12)
- Mastergroup
  - 10 supergroups, which supports 600 channels
# 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></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>
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<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 STANDARDIZATION 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
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

Input₁

Output₁

Input₂

Output₂

(b) Input data streams

Input₁: F₁ f₁ d₁ d₁ C₁ A₁ F₁ f₁ d₁ d₁ C₁ A₁ F₁

Input₂: F₂ f₂ d₂ d₂ C₂ A₂ F₂ f₂ d₂ d₂ C₂ A₂ F₂

(c) Multiplexed data stream

... f₂ F₁ d₂ f₁ d₂ f₁ d₂ d₁ C₂ d₁ A₂ C₁ F₂ A₁ f₂ F₁ f₂ f₁ d₁ d₂ d₁ d₂ d₂ d₁ C₂ C₁ A₂ A₁ F₂ F₁

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”
Multiplexing

— Pulse Stuffing

• big problem is synchronizing various data sources
  – if sources have different clocks: all clocks drift a little bit
  – data rates of input data stream might not be related by a simple rational number

• principle
  – design output data rate bigger than input data rate
  – stuff dummy bits into input data stream until its rate is raised to that of the locally generated clock signal.
  – The stuffing bits are removed by the demultiplexer
TDM of Analog and Digital Sources

From source 1
2 kHz, analog

TDM PAM signal
16 ksamples/sec

4 bit A/D

TDM PCM signal
64 kbps

From source 2
4 kHz, analog

From source 3
2 kHz, analog

f = 4 kHz

4

f

8

16

Pulse stuffing

From source 4
7.2 kbps, digital

8 kbps, digital

Pulse stuffing

From source 5
7.2 kbps, digital

Pulse stuffing

From source 11
7.2 kbps, digital

8 kbps, digital

Scan operation

TDM PCM output signal
128 kbps
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 \((24 \times 8 + 1) \text{bits/125}\mu\text{s} = 1.544\text{Mbps}\)
  - called DS1 or T1 link
  - \(4 \times \text{T1} = \text{T2}\)
  - \(7 \times \text{T2} = \text{T3}\)
  - \(6 \times \text{T3} = \text{T4}\)
Multiplexing

Hal96 fig 2.26

Coder circuits

Time-division multiplexer

Digital bit stream

Analog voice input circuits

1
2
... 
24/30
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

1 frame = 125 μs = 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
- Time slots 1–15, 17–31
- 8 coding bits

(ii) ITU-T

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>
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<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>
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<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)
SONET Frame Format

(a) STS-1 frame format

(b) STM-N frame format
## SONET STS-1 Overhead Octets

<table>
<thead>
<tr>
<th>Section Overhead</th>
<th></th>
<th>Line Overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Framing A1</td>
<td>Framing A2</td>
<td>STS-ID C1</td>
</tr>
<tr>
<td>BIP-8 B1</td>
<td>Orderwire E1</td>
<td>User F1</td>
</tr>
<tr>
<td>DataCom D1</td>
<td>DataCom D2</td>
<td>DataCom D3</td>
</tr>
<tr>
<td>Pointer H1</td>
<td>Pointer H2</td>
<td>Pointer Action H3</td>
</tr>
<tr>
<td>BIP-8 B2</td>
<td>APS K1</td>
<td>APS K2</td>
</tr>
<tr>
<td>DataCom D4</td>
<td>DataCom D5</td>
<td>DataCom D6</td>
</tr>
<tr>
<td>DataCom D7</td>
<td>DataCom D8</td>
<td>DataCom D9</td>
</tr>
<tr>
<td>DataCom D10</td>
<td>DataCom D11</td>
<td>DataCom D12</td>
</tr>
<tr>
<td>Growth Z1</td>
<td>Growth Z2</td>
<td>Orderwire E2</td>
</tr>
<tr>
<td>(a) Transport Overhead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trace J1</td>
<td>BIP-8 B3</td>
<td>Signal Label C2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path Status G1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>User F2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiframe H4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Growth Z3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Growth Z4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Growth Z5</td>
</tr>
<tr>
<td>(b) Path Overhead</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
**Statistical TDM Frame Formats**

(a) Overall frame

| Flag | Address | Control | Statistical TDM subframe | FCS | Flag |

(b) Subframe with one source per frame

| Address | Data |

(c) Subframe with multiple sources per frame

<table>
<thead>
<tr>
<th>Address</th>
<th>Length</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
Cable Modem Scheme

- **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 X

- **Data:** from Station A
- **Request from:** Station C

- **Data:** from Station B
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
DMT Bits Per Channel Allocation
DMT Transmitter

binary input

$x(t)$  
$R$ bps

$\sum x_i(t)$  
$\alpha_i R$ bps

$\sum f_i = f_i + 4$ kHz

$0 \leq \alpha_i \leq 1$  
$\sum \alpha_i = 1$
xDSL

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

<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>DM1T</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>
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</table>

UTP = unshielded twisted pair