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

FDM System

FDM of Three Voiceband Signals
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 than 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**

- 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**

- 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**

- 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
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
- 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

- 2.048Mbps
- 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/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)
  - 155.52Mbps
  - 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 STS-1 Overhead Octets**

<table>
<thead>
<tr>
<th>Section Overhead</th>
<th>Line Overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Framing A1</td>
<td>Framing A2</td>
</tr>
<tr>
<td>Bits B1</td>
<td>ODUw B1</td>
</tr>
<tr>
<td>DataCon D1</td>
<td>DataCon D2</td>
</tr>
<tr>
<td>B2</td>
<td>K1</td>
</tr>
<tr>
<td>R1</td>
<td>H2</td>
</tr>
<tr>
<td>ROP-B</td>
<td>APS-B</td>
</tr>
<tr>
<td>Buffer Z1</td>
<td>Z2</td>
</tr>
</tbody>
</table>

(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**

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

**Performance**

**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 time 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**

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

**Required Reading**
- Stallings chapter 8
- Web sites on
  - ADSL
  - SONET