Multiplexing

Multiplexing is the set of techniques that allows the simultaneous transmission of multiple signals across a single physical medium.

The following two factors in data communications lead to multiplexing:

- Multiple signals tend to be communicated between sites.
- Using the same medium, the cost on a per-bit basis is typically lower for a higher-speed communication line.
DIFFERENT WAY FOR COMMUNICATING MULTIPLE SIGNALS

The need for communicating multiple signals between sites can be met in the following three basic ways:

- Use one circuit per device. This method, however, wastes the unused bandwidth (e.g., 350 bits/second of data on a 1,200 bit/second line wastes 850 bits/second of potential data transmission bandwidth).

- Use devices that are intelligent enough to be polled by a host. (An intelligent device is addressable, has memory, and can perform computations.) This method requires intelligent devices at both ends of the circuit.

- Use devices, called multiplexers. Multiplexers allow multiple signals to be transferred across a single link, which eliminates the waste of bandwidth and the need for intelligence in the devices.
Multiplexers

Multiplexers have these three significant characteristics:

- They can combine multiple signals on a single communication link, thereby allowing multiple terminals to share a common circuit.

- They are non-intelligent (dumb) devices that do not modify or delay the multiplexed signals in any way, thereby appearing transparent to the end user.

- They are used in pairs connected by a single link. There are an identical number of inputs to and outputs from the pair. The sending multiplexer is called a mux, and the receiving multiplexer is called a demultiplexer or demux. However, the sending and receiving muxes can reverse roles.
Dividing a link into channels

In a multiplexed system, n lines share the bandwidth of one link.
Categories of multiplexing

- **FDM** - Frequency division multiplexing
- **WDM** - Wave division multiplexing
- **TDM** - Time division multiplexing
FDM - Frequency division multiplexing

Multiplexing Process
Demultiplexing Process
The Analog Hierarchy
Other Applications of FDM
Implementation
FDM is an analog multiplexing technique that combines signals.
**FDM (Frequency division multiplexing) process**
Example 1

Assume that a voice channel occupies a bandwidth of 4 KHz. We need to combine three voice channels into a link with a bandwidth of 12 KHz, from 20 to 32 KHz. Show the configuration using the frequency domain without the use of guard bands.
We want to find the minimum bandwidth for a circuit with FDM multiplexing, where:

- there are four sources, each requiring 2,000 Hz
- the guard bands are 200 Hz
- To satisfy the requirement, we calculate as follows:
  - 4 \times 2,000 \text{ Hz} for the data
  - 3 \times 200 \text{ Hz} for the guard bands
  - to get a total of 8.6 \text{ KHz}
Example

Five channels, each with a 100-KHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 KHz between the channels to prevent interference?

For five channels, we need at least four guard bands. This means that the required bandwidth is at least $5 \times 100 + 4 \times 10 = 540$ KHz,

Guard band of 10 kHz

100 kHz 100 kHz 100 kHz 100 kHz 100 kHz

540 kHz
Example

Four data channels (digital), each transmitting at 1 Mbps, use a satellite channel of 1 MHz. Design an appropriate configuration using FDM

The satellite channel is analog. We divide it into four channels, each channel having a 250-KHz bandwidth.
One solution is 16-QAM modulation.
Analog hierarchy

- 12 voice channels
  - 4 kHz
  - 4 kHz

- FDM
  - 48 kHz
  - 12 voice channels

- Group
  - 240 kHz
  - 60 voice channels

- Supergroup
  - 2.52 MHz
  - 600 voice channels

- Master group
  - 16.984 MHz
  - 3600 voice channels

- Jumbo group

- 5 groups
- 10 supergroups
- 6 master groups
The Advanced Mobile Phone System (AMPS) uses two bands.
The first band, $\textbf{824 to 849 MHz}$, is used for sending; and $\textbf{869 to 894 MHz}$ is used for receiving. Each user has a bandwidth of 30 KHz in each direction. The 3-KHz voice is modulated using FM, creating 30 KHz of modulated signal. How many people can use their cellular phones simultaneously?

\textbf{Solution}

Each band is 25 MHz. If we divide 25 MHz into 30 KHz, we get 833.33. In reality, the band is divided into 832 channels.
Wave Division Multiplexing

WDM is an analog multiplexing technique to combine optical signals.
In **fiber-optic communications**, wavelength-division multiplexing (WDM) is a technology which **multiplexes** multiple **optical carrier** signals on a single **optical fibre** by using different **wavelengths** (colors) of **laser light** to carry different signals. This allows for a multiplication in capacity, in addition to making it possible to perform **bidirectional** communications over one strand of fibre. The term **wavelength-division multiplexing** is commonly applied to an optical carrier (which is typically described by its wavelength), whereas **frequency-division multiplexing** typically applies to a radio carrier (which is more often described by frequency).
Figure 6.11  Prisms in WDM multiplexing and demultiplexing
WDM systems

- A WDM system uses a **multiplexer** at the transmitter to join the signals together, and a **demultiplexer** at the receiver to split them apart. With the right type of fiber it is possible to have a device that does both simultaneously, and can function as an optical **add-drop multiplexer**.

- Most WDM systems operate on single mode fiber optical cables, which have a core diameter of 9 µm. Certain forms of WDM can also be used in multi-mode fiber cables (also known as premises cables) which have core diameters of 50 or 62.5 µm.
WDM systems

- WDM systems are divided into two market segments, dense and coarse WDM.
- Systems with more than 8 active wavelengths per fibre are generally considered **Dense WDM (DWDM)** systems,
- Systems with fewer than eight active wavelengths are classed as **Coarse WDM (CWDM)**.
- CWDM and DWDM technology are based on the same concept of using multiple wavelengths of light on a single fiber, but the two technologies differ in the spacing of the wavelengths, number of channels, and the ability to amplify signals in the
The basic DWDM system contains several main components:

1. **A DWDM terminal multiplexer.**
   - The terminal mux actually contains one wavelength converting transponder for each wavelength signal it will carry. The wavelength converting transponders receive the input optical signal, convert that signal into the electrical domain, and retransmit the signal using a 1550-nm band laser. The terminal mux also contains an optical multiplexer, which takes the various 1550-nm band signals and places them onto a single SMF-28 fiber. The terminal mux may or may not also support a local EDFA for power amplification of the multiwavelength optical signal.

2. **An intermediate optical terminal, or Optical Add-drop multiplexer.**
   - This is a remote amplification site that amplifies the multiwavelength signal that may have traversed up to 140 km or more before reaching the remote site. Optical diagnostics and telemetry are often extracted or inserted at such a site, to allow for sectionalization of any fiber breaks or signal impairments. In more sophisticated systems (which are no longer point-to-point), several signals out of the multiwavelength signal may be removed and dropped locally.

3. **A DWDM terminal demux.**
   - The terminal demux breaks the multiwavelength signal back into individual signals and outputs them on separate fibers for client-layer systems to detect. Originally, this demultiplexing was performed entirely passively, except for some telemetry, as most SONET systems can receive 1550-nm signals. However, in order to allow for transmission to remote client-layer systems (and to allow for digital domain signal integrity determination) such demultiplexed signals are usually sent to O/E/O output transponders prior to being relayed to their client-layer systems.

4. **Optical Supervisory Channel.**
   - This is an additional wavelength usually outside the EDFA amplification band (at 1510nm, 1620nm, 1310nm or another proprietary wavelength). The OSC carries information about the multiwavelength optical signal as well as remote conditions at the optical terminal or EDFA site. It is also normally used for remote software upgrades and user (ie, network operator) Network Management information.
Curs 4
Time Slots and Frames
Interleaving
Synchronizing
Bit Padding
Digital Signal (DS) Service
T Lines
Inverse TDM
More TDM Applications
TDM is a digital multiplexing technique to combine data.

Time slots are grouped into frames, with each frame covering one complete cycle of all the inputs. Thus, in figure 2-24 above, there are two frames each covering T1, T2, T3, and T4. Each frame starts with one or more framing bits to help synchronize the mux and demux.
Calculation Involving TDM Frames

Four signal sources (A, B, C, and D) are multiplexed using TDM.

Each source produces 100 characters per second.

- If there is byte interleaving and each frame requires one bit for synchronization, then:
  - the frame rate is 100 frames per second
  - each frame has $8 \times 4 + 1 = 33$ bits
  - the data rate is $100 \times 33 = 3.3$ Kbps
- Each frame has the following composition:
  - characterD characterC characterB characterA framing bit
Data are taken from each line every 3T seconds.

Each frame is 3 time slots.
Each time slot duration is T seconds.
Example

Four 1-Kbps connections are multiplexed together. A unit is 1 bit.

Find:
(1) the duration of 1 bit before multiplexing,
(2) the transmission rate of the link,
(3) the duration of a time slot, and
(4) the duration of a frame?

Solution

We can answer the questions as follows:
1. The duration of 1 bit is $1/1$ Kbps, or 0.001 s (1 ms).
2. The rate of the link is 4 Kbps.
3. The duration of each time slot $1/4$ ms or 250 μs.
4. The duration of a frame 1 ms.
In a TDM, the data rate of the link is $n$ times faster, and the unit duration is $n$ times shorter.
Interleaving
Example

Four channels are multiplexed using TDM. If each channel sends 100 bytes/s and we multiplex 1 byte per channel, show the frame traveling on the link, the size of the frame, the duration of a frame, the frame rate, and the bit rate for the link.

Solution

Frame 4 bytes 32 bits

100 Frames/s
3200 bps
Frame duration = 1/100 s
A multiplexer combines four 100-Kbps channels using a time slot of 2 bits. Show the output with four arbitrary inputs. What is the frame rate? What is the frame duration? What is the bit rate? What is the bit duration?

**Solution**

Figure shows the output for four arbitrary inputs.

Frame duration = 1/50,000 s = 20 ms

50,000 Frames/s
400 kbps
Framing bits

Synchronization pattern

Frame 3

C3 | B3 | A3 | 1

Frame 2

B2 | A2 | 0

Frame 1

C1 | A1 | 1
We have four sources, each creating 250 characters per second. If the interleaved unit is a character and 1 synchronizing bit is added to each frame, find (1) the data rate of each source, (2) the duration of each character in each source, (3) the frame rate, (4) the duration of each frame, (5) the number of bits in each frame, and (6) the data rate of the link.

We can answer the questions as follows:
1. The data rate of each source is 2000 bps = 2 Kbps.
2. The duration of a character is 1/250 s, or 4 ms.
3. The link needs to send 250 frames per second.
4. The duration of each frame is 1/250 s, or 4 ms.
5. Each frame is 4 x 8 + 1 = 33 bits.
6. The data rate of the link is 250 x 33, or 8250 bps.
Example

Two channels, one with a bit rate of 100 Kbps and another with a bit rate of 200 Kbps, are to be multiplexed. How this can be achieved? What is the frame rate? What is the frame duration? What is the bit rate of the link?

Solution

We can allocate one slot to the first channel and two slots to the second channel. Each frame carries 3 bits. The frame rate is 100,000 frames per second because it carries 1 bit from the first channel. The frame duration is 1/100,000 s, or 10 ms. The bit rate is 100,000 frames/s x 3 bits/frame, or 300 Kbps.
Statistical Time-division Multiplexing (STDM)

- **Statistical Time-division Multiplexing (STDM)**
- **STDM** is an advanced version of TDM in which both the address of the terminal and the data itself are transmitted together for better routing. Using STDM allows bandwidth to be split over 1 line.

- Example:
  - If there is one 10MBit line coming into the building, STDM can be used to provide 178 terminals with a dedicated 56k connection (178 * 56k = 9.96Mb).

- STDM does NOT reserve a time slot for each terminal, rather assign a slot when the terminal is requiring data to be sent/received.
In the STDM transmission each piece of 8-bit character data requires a terminal address (shown as a 5-bit address).

A total of 78 bits (5 + 8 = 13 bits for each of the 6 time slots) is required to transmit 6 characters.

Even though the STDM requires more bits to transmit each character, it is more efficient because it transmits only when there are data to transmit. It is therefore able to handle more terminals than TDM because each terminal is not being utilized 100 percent of the time.

Inverse multiplexing is the opposite of multiplexing. There is one input to and one output from the mux-demux pair and multiple lines to carry the signal between the mux-demux pair. Thus, if there is a need to transmit at a rate of 512 Kbps, four 128-Kbps lines can be used.
Digital Service

- Digital service includes switched/56 service, digital data (DSS) service, and digital signal (DS) service.

- Switched/56 service is the digital equivalent of an analog switched line that allows data rates of up to 56 Kbps. Subscribers use digital service units (DSUs) instead of modems because they are transmitting digital signals instead of analog signals. The DSU also formats the data from the sender into the proper format for the switched/56 service.
Digital data

- Digital data (DSS) service is the digital line that allows data rates of 64 Kbps. Digital signal service is a hierarchy of multiplexed DSS services that go from DS-0 to DS-4.
- These lines are grouped into a digital hierarchy of multiplexed signals as indicated below:
  - DS-0, a single digital channel of 64 Kbps that carries 1 DSS channel
  - DS-1, a 1.544-Mbps service that can multiplex 24 DS-0 channels
  - DS-2, a 6.312-Mbps service that can multiplex 4 DS-1 or 96 DS-0 channels
  - DS-3, a 44.376-Mbps service that can multiplex 7 DS-2, 28 DS-1, or 672 DS-0 channels
  - DS-4, a 274.176-Mbps service that can multiplex 6 DS-3, 42 DS-2, 168 DS-1, or 4,032 DS-0 channels
- The DS-1 through DS-4 data rates include overhead. These services can also be used to carry one signal covering the full bandwidth or any other combination of channels desired.
- The DS-1 through DS-4 services are implemented with T-1 through T-4 lines.
DS hierarchy

- 64 kbps (DS-0)
- 1.544 Mbps (24 DS-0)
- 6.312 Mbps (4 DS-1 or 96 DS-0)
- 44.376 Mbps (7 DS-2 or 28 DS-1 or 672 DS-0)
- 274.176 Mbps (6 DS-3 or 42 DS-2)
### Table: DS and T lines rates

<table>
<thead>
<tr>
<th>Service</th>
<th>Line</th>
<th>Rate (Mbps)</th>
<th>Voice Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>T-1</td>
<td>1.544</td>
<td>24</td>
</tr>
<tr>
<td>DS-2</td>
<td>T-2</td>
<td>6.312</td>
<td>96</td>
</tr>
<tr>
<td>DS-3</td>
<td>T-3</td>
<td>44.736</td>
<td>672</td>
</tr>
<tr>
<td>DS-4</td>
<td>T-4</td>
<td>274.176</td>
<td>4032</td>
</tr>
</tbody>
</table>

T-1 lines were originally developed to handle 24 analog phone lines by converting the analog data into time-multiplexed digital data using the pulse code modulation techniques.
Sampling at 8000 samples/s using 8 bits per sample

T-1 line for multiplexing telephone lines

- 24 voice channels
- 4 kHz
- 64,000 bps

PCM

TDM

T-1 line 1.544 Mbps
24 x 64 kbps + 8 kbps overhead
**T-1 frame structure**

Sample $n$

1 frame = 193 bits

Frame 8000

Frame $n$

Frame 2

Frame 1

T-1: 8000 frames/s = 8000 x 193 bps = 1.544 Mbps
### Table: E line rates

<table>
<thead>
<tr>
<th>E Line</th>
<th>Rate (Mbps)</th>
<th>Voice Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-1</td>
<td>2.048</td>
<td>30</td>
</tr>
<tr>
<td>E-2</td>
<td>8.448</td>
<td>120</td>
</tr>
<tr>
<td>E-3</td>
<td>34.368</td>
<td>480</td>
</tr>
<tr>
<td>E-4</td>
<td>139.264</td>
<td>1920</td>
</tr>
</tbody>
</table>
Multiplexing and inverse multiplexing

![Diagram showing multiplexing and inverse multiplexing](image)

- One high-speed line
  - Inverse MUX
  - Four low-speed lines
  - Inverse DEMUX
- One high-speed line