Multiplexing

References

– Frequency-division multiplexing and Time-division multiplexing
  • Chapter 7, W. Stallings, *Data and Computer Communications*, Prentice Hall.
Introduction

- Generally, two communicating stations will not utilize the full capacity of a data link
  - Example: transmit a voice signal over a optical fiber
- Multiplexing allows multiple users sharing the capacity of a transmission link
Introduction

Components

– Multiplexer
  • combines data from the $n$ input lines

– Link
  • with $n$ separate channels
  • example: optical fiber or microwave link

– Demultiplexer
  • separates the data according to channel
  • delivers them to the appropriate output lines
Multiplexing Techniques

Frequency-division multiplexing (FDM)

– each channel occupies a fraction of the bandwidth of the link
– a channel is defined by its center frequency, and its bandwidth.

– Example: radio and television signal transmission
Introduction

Time-division multiplexing (TDM)

– each channel occupies the entire bandwidth of the link for a very short period of time
– a channel is made up of a sequence of time slots

– Synchronous TDM
  • time slot are assigned to each channel in a regular sequence
  • Example: multiplexing digitalized voice signals and data streams
Introduction

– Statistical
  • improve the efficiency of synchronous TDM by adding complexity to the multiplexer
  • time slots are assigned to signals as they arrive at the multiplexer

Code-division multiplexing (CDM)

– each channel occupies the entire bandwidth
– signals are differentiated by modulating them with orthogonal codes
– mainly used for mobile communications
**FDM**

- FDM is possible when the useful bandwidth of the medium excess the required bandwidth of signals to be transmission
  
  - \((BW_{\text{medium}} \gg BW_{\text{signal}})\)
  
  - Example: voice signal is transmitted via an optical fiber

- A number of signals are transmitted simultaneously if each signal is modulated onto a different carrier frequency, and the carrier frequencies are sufficiently separated that the bandwidths of the signals do not overlap
FDM

The diagram illustrates the concept of Frequency Division Multiplexing (FDM). It shows a 3D representation with axes labeled as Code, Time, and Frequency. The diagram contains multiple channels labeled as Channel 1, Channel 2, Channel 3, and Channel N, indicating how different channels can be multiplexed.
**FDM**

**Multiplexing**

– $N$ sources are fed into a multiplexer

– the multiplexer modulates each signal onto a different frequency

– each modulated signal requires a certain bandwidth centered around its carrier frequency, referred to as a channel

– The modulated signals are summed to produce a composite signal
The composite signal transmitted across the medium is analog

- The input signals may be either digital or analog
- A digital signal must be passed through a modem
FDM

– to prevent interference, the channels are separated by guard bands, which are unused portions of the spectrum
Demultiplexing

– At the receiving end, the composite signal is passed through $N$ bandpass filters, each filter centered at $f_{sci}$ and having a bandwidth $B_{sci}$

– Each component is then demodulated to recover the original signal
Example: Transmitting 3 voice signals

- the bandwidth of a voice signal is taken to be 4kHz, with an effective spectrum of 300 to 3400Hz
If this signal is used to amplitude-modulate a 64 kHz carrier, the spectrum becomes.
The modulated signal has a bandwidth of 8 kHz, extending from 60 to 68 kHz.
FDM

– To make efficient use of bandwidth, we transmit only the lower sideband.
– If three voice signals are used to modulate carriers at 64, 68, and 72 kHz, the spectrum is
FDM

Problems of FDM

– Crosstalk
  • occur if the spectra of adjacent component signals overlap

– Intermodulation noise
  • on a long link, the nonlinear effects of amplifiers on a signal in one channel could produce frequency components in other channels
Analog Carrier Systems

- designed to transmit voiceband signals over high-capacity transmission links
  
  • Example: use coaxial cable and microwave systems

- First level of the hierarchy
  
  • 12 voice channels are combined to produce a group signal with a bandwidth of $12 \times 4 \text{ kHz} = 48 \text{ kHz}$, in the range of 60 to 108 kHz.
Second level

- 60-channel supergroup
- formed by frequency-division multiplexing five-group signals.

- Each group is treated as a single signal with a 48 kHz bandwidth and is modulated by a subcarrier.

- The subcarrier have frequencies from 420 to 612 kHz in increments of 48 kHz.
- The resulting signal occupies 312 to 552 kHz.
Variation of supergroup formation

- Case I
  - Each of the five inputs to the supergroup multiplexer may be a group channel containing 12 multiplexed voice signals

- Case II
  - Any signal up to 48 kHz wide whose bandwidth is contained within 60 to 108 kHz may be used as input to the supergroup multiplexer

- Case III
  - Directly combine 60 voiceband channels into a supergroup
FDM

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– Third level
  • 60-channel supergroup
  • formed by frequency-division multiplexing five-group signals.

  • Each group is treated as a single signal with a 48 kHz bandwidth and is modulated by a subcarrier.

  • The subcarrier have frequencies from 420 to 612 kHz in increments of 48 kHz.
  • The resulting signal occupies 312 to 552 kHz.
<table>
<thead>
<tr>
<th>Group</th>
<th>No. of voice channel</th>
<th>Bandwidth</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>12</td>
<td>48 kHz</td>
<td>60-108 kHz</td>
</tr>
<tr>
<td>Supergroup</td>
<td>60</td>
<td>240 kHz</td>
<td>312-552 kHz</td>
</tr>
<tr>
<td>Mastergroup</td>
<td>300</td>
<td>2.52 MHz</td>
<td>564-3084 kHz</td>
</tr>
<tr>
<td>Jumbogroup</td>
<td>3600</td>
<td>16.984 MHz</td>
<td>0.564 - 17.584 MHz</td>
</tr>
</tbody>
</table>
FDM

- Note that the original voice or data signal may be modulated many times

  • Example
  
  - a data signal may be encoded using PSK to form an analog voice signal
  
  - The signal could then be used to modulated a 76 kHz carrier to form a component of a group signal.
  
  - This group signal could then be used to modulate a 516 kHz carrier to form a component of a supergroup signal.

- Each stage can distort the original data if the modulator/multiplexer contains nonlinearities or introduces noise
TDM

– Synchronous TDM is possible when the achievable data rate (sometimes, unfortunately, called bandwidth) of the medium exceeds the data rate of digital signals to be transmitted.

\[ r_{\text{medium}} \gg r_{\text{signal}} \]

– TDM is the time interleaving of samples from several sources so that the information from these sources can be transmitted serially over a single communication link.
Synchronous TDM

Diagram showing the concept of Synchronous TDM with channels layered over time slots, code, and frequency axes.
Synchronous TDM

Transmitter

- A number of signals are to be multiplexed onto the same transmission medium
Synchronous TDM

- The incoming data from each source are briefly buffered.
  - Each buffer is typically one bit or one character in length
  - The buffers are scanned sequentially to form a composite digital data stream
  - The scan operation is sufficiently rapid so that each buffer is emptied before more data can arrive

- The composite digital signal stream may be transmitted directly or passed through a modem so that an analog signal is transmitted
Synchronous TDM

- The data are organized into frames.
  - Each frame contains a cycle of time slots.
  - In each frame, one or more slots is dedicated to each data source.
  - The sequence of slot dedicated to one source, from frame to frame, is called a channel.
Synchronous TDM

- Length of slot
  - The slot length equals the transmitter buffer length, typically a bit or a character
  - The characteristic-interleaving technique is used with asynchronous sources.
    - Each time slot contains one character of data
    - The start and stop bits of each character are eliminated before transmission and reinserted by the receiver.
Synchronous TDM

- The bit-interleaving technique is used with synchronous sources and may also be used with asynchronous source
  - Each time slot contains just one bit
Synchronous TDM

Receiver

- The interleaved data are demultiplexed and routed to the appropriate destination buffer.
Synchronous TDM

- Synchronous TDM is called synchronous not because synchronous transmission is used but because the time slots are preassigned to sources and fixed.
- The time slots for each source are transmitted whether or not the source has data to send
  - capacity is wasted to simplify the hardware implementation

- It is possible for a synchronous TDM device to handle sources of different data rates. For example, the slowest input device could be assigned one slot per cycle, while faster devices are assigned multiple slots per cycle.
Pulse Stuffing

– The most difficult problem in the design of a synchronous TDM system is the synchronization of various data sources.

– If each source has a separate clock, any variation among clocks could cause loss of synchronization.

– Also, in some cases, the data rates of the input data streams are not related by a simple rational number
Synchronous TDM

– With pulse stuffing, the outgoing data rate of the multiplexer, excluding framing bits, is higher than the sum of the maximum instantaneous incoming rates.

  • The extra capacity is used by stuffing extra dummy bits or pulses into each incoming signal until its rate is raised to that of a locally generally clock signal.
  • The stuffed pulses (bits) are inserted at fixed locations in the multiplexer frame format so that they may be identified and removed at the demultiplexer.
Digital input signals

Channel 1

Time division multiplexer

Channel 2

Output TDM Signal

Input channel number

* = stuffed bit
Example:

Source 1
2 kHz, analog

Source 2
4 kHz, analog

Source 3
2 kHz, analog

Source 4
7.2 kbps, digital

Source 11
7.2 kbps, digital

TDM PAM signal
16 kHz

4 bit A/D

TDM PCM signal
64 kbps

16-bit buffer

Scan

TDM signal
128 kbps
Synchronous TDM

- Source 1: Analog, 2 kHz bandwidth
- Source 2: Analog, 4 kHz bandwidth
- Source 3: Analog, 2 kHz bandwidth
- Source 4-11: Digital, 7200 bps synchronous

- The analog sources are converted to digital using PCM
  - Sampling rate = 2 x bandwidth
  - The samples are quantized using a 4 bit A/D

- For the digital sources, pulse stuffing is used to raise each source to a rate of 8 kbps
Synchronous TDM

– A frame can consist of multiple cycles of 32 bits, each containing 16 PCM bits and two bits from each of the eight digital source.
Digital Carrier Systems

Plesiochronous Digital Hierarchy (PHD) or TDM Hierarchy

Multiplexing

– At each step, the multiplexer has to take into account the fact that the clocks of the inputs are all slightly different.

– Each clock is allowed a certain range of speeds. The multiplexer reads each input at the highest allowed clock speed. When there are no bits in the input buffer as the bits are arriving according to a slower clock, it adds a “stuffing” bit to “stuff” the signal up to the higher clock speed.
Demultiplexing

- It also has a mechanism to signal the demultiplexer that it has performed stuffing, and the demultiplexer must know which bit to throw it out.
<table>
<thead>
<tr>
<th>Digital Signal Number</th>
<th>Number of Voice Channels</th>
<th>Data rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>24</td>
<td>1.544</td>
</tr>
<tr>
<td>DS-1C</td>
<td>48</td>
<td>3.152</td>
</tr>
<tr>
<td>DS-2</td>
<td>96</td>
<td>6.312</td>
</tr>
<tr>
<td>DS-3</td>
<td>672</td>
<td>44.736</td>
</tr>
<tr>
<td>DS-4</td>
<td>4032</td>
<td>274.176</td>
</tr>
<tr>
<td>DS-5</td>
<td>8064</td>
<td>560.160</td>
</tr>
</tbody>
</table>

(North American hierarchy)