Digital Communications Engineering 1

(COMM2108)

Multiplexing
Multiplexing

- Multiplexing and Multiple Access refer to the sharing of a fixed communications resource (CR) between a number of signal sources.

- The overall objective is to allow the various signal sources share a common CR without creating unmanageable interference to each other in the detection process.
Multiplexing

- With *multiplexing* - the sharing of the CR is fixed and the resource allocation is assigned *a priori* (i.e. beforehand) and is usually performed locally.

- With *multiple access* - the sharing of the CR is performed remotely (usually in a distributed or decentralised manner). The signalling or control requirements of such a scheme constitute an overhead which sets an upper limit on the efficiency and utilisation of the CR.
Multiplexing

• The basic ways to distribute or share out the communications resource (CR) are:
  – Frequency Division
  – Time Division
  – Code Division
  – Space Division
  – Polarization Division

• Here we will only consider frequency division and time division in any detail.
Multiplexing

• In *Frequency Division Multiplexing (FDM)/ Frequency Division Multiple Access (FDMA)*, the bandwidth of the CR is divided up into sub-bands which are shared out amongst the various signal sources.

• In other words, each signal is allocated its own frequency channel for its transmission.

• Simple technique where no timing or synchronisation is required between the channels.

• Example: Cable TV where 10-15 TV channels share the same coaxial cable medium without interfering with each other.
Multiplexing

• In time division multiplexing (TDM)/time division multiple access (TDMA), access to the CR is shared out on a time basis using periodically recurring time slots.
• Each signal source takes it in turn to use the full bandwidth of the CR for a short time.
• The simplest TDM/TDMA scheme is the fixed assignment scheme where the \( M \) time slots that make up a frame are pre-assigned to the various signal sources.
Multiplexing

- Multiple access schemes are termed fixed assignment when a source has periodic access to the CR independent of its actual need.
- A fixed assignment TDM/TDMA is extremely efficient when the source requirements are predictable and the traffic is heavy (i.e. all the time slots are filled).
- Timing or synchronisation information needs to be included in the scheme.
Multiplexing

• Dynamic assignment (or demand assignment multiple access) schemes give the source access to the CR only when it requests access.

• Dynamic assignment schemes operate on the basis that the actual demand for access rarely equals the peak demand for access.

• When the source requirements are unpredictable there are more efficient schemes involving the dynamic assignment of time slots. Such schemes are known as packet-switched systems, statistical multiplexers or concentrators.
Multiplexing

- Code division multiplexing (CDM)/code division multiple access (CDMA) may be viewed as a hybrid of FDM and TDM techniques where both frequency and time are shared out among the signal sources.
- This technique is part of an important class of techniques known as spread-spectrum which have a number of significant advantages over conventional FDM and TDM.
- CDM/CDMA is the basis for 3G mobile phone systems.
Multiplexing

• In *space division (or multiple beam frequency reuse)* highly directional antennas are used to separate radio signals by pointing in different directions. This allows the reuse of the same frequency band.

• In *polarization division (or dual polarization frequency reuse)* orthogonal polarizations are used to separate the signals. This allows for reuse of the same frequency band.
Multiplexing

- Performance Comparison of FDMA and TDMA
- We assume that:
  - The communications resource is capable of supporting a total of \( R \) bits/sec.
  - There are \( M \) sources that generate information at an average rate of \( R/M \) bits/sec. Furthermore, the information is transmitted in groups or packets of \( b \) bits/pkt.
  - In the FDMA system, the system bandwidth \( W \) (Hz) is divided equally into \( M \) disjoint frequency sub-bands of width \( W/M \) (Hz).
  - In the TDMA system, the frame is divided into \( M \) time slots.
Multiplexing

• In the FDMA system, the $b$ bit packets are transmitted in $T$ seconds over the $M$ disjoint channels. Therefore, the total bit rate $R_{FDMA}$ required is:

$$R_{FDMA} = M \left(\frac{b}{T}\right) \text{ bits/sec}$$

• In the TDMA system, the $b$ bits packets are transmitted in $T/M$ seconds from each source. Therefore the total bit rate $R_{TDMA}$ required is:

$$R_{TDMA} = \frac{b}{(T/M)} = M \left(\frac{b}{T}\right) = R_{FDMA}$$

• Both systems have the equivalent bit rate performance.
Multiplexing

• Considering another performance metric, for example the average packet delay.
• For simplicity we assume deterministic data sources are used and that the CR is fully utilised, i.e. all the frequency sub-bands in FDMA are used and all the time slots in TDMA are used.
• Furthermore, we assume there are no overhead costs as a result of guard bands or guard times.
• The message delay $D$ can be defined as $D = w + \tau$ where $w$ is the average packet waiting time and $\tau$ is the packet transmission time.
Multiplexing

• In the case of FDMA, each packet is sent over a $T$ second interval, so the packet transmission time for FDMA is

$$\tau_{FD} = T$$

• Since the FDMA channel is continuously available and packets are sent as soon as they are generated, the waiting time

$$w_{FD} = 0$$

• The average delay time for FDMA is therefore

$$D_{FD} = T$$
Multiplexing

• In the case of TDMA, each packet is sent in slots of \( T/M \) seconds, so the packet transmission time for TDMA is

\[
\tau_{TD} = T/M = b/R
\]

• From the handout, it can be seen that each slot begins at a different point in the \( T \) second frame, i.e. each packet \( S_{mk} \) will start at \( (m-1)T/M \) seconds. Therefore, the average waiting time that a TMDA packets undergoes before transmission is

\[
W_{TD} = \frac{1}{M} \sum_{m=1}^{M} (m-1) \frac{T}{M}
\]
Multiplexing

• Substituting \( n \) for \((m-1)\) we get

\[
W_{TD} = \frac{T}{M^2} \sum_{n=0}^{M-1} n
\]

\[
= \frac{T}{M^2} \left( \frac{(M - 1)M}{2} \right)
\]

\[
= \frac{T}{2} \left( 1 - \frac{1}{M} \right)
\]
Multiplexing

• The average delay time for TDMA is

\[ D_{TD} = \frac{T}{2} \left( 1 - \frac{1}{M} \right) + \frac{T}{M} = \frac{T}{2} - \frac{T}{2M} + \frac{T}{M} \]

\[ = \frac{T}{2} + \frac{T}{2M} = T - \frac{T}{2} \left( 1 - \frac{1}{M} \right) \]

\[ = D_{FD} - \frac{T}{2} \left( 1 - \frac{1}{M} \right) \]

• This result indicates that TDMA is inherently superior from a message delay point of view.
Multiplexing

• TDM Case Study:
  – TDM is best illustrated by a study of the European standard used for multiplexing digitized voice channels in the modern digital telephone network (PSTN).
  – Known as the 30 Channel PCM/TDM System.
  – Recall that for telephony purposes, voice channels are bandlimited to 3.4 kHz and oversampled at 8 kHz. The samples are quantised using A-law companding and encoded using an 8-bit code word. This whole process yields a digitized toll-quality voice signal at 64 kbits/sec.
Multiplexing

• 30 Channel PCM/TDM System:
  – In this scheme 30 PCM encoded voice channels (including 2 additional control channels) are multiplexed together using TDM to an overall digital signal at 2.048 Mbits/sec (known as the \textit{E1 rate}).
  – In this 30+2 channel scheme there is a \textit{frame} and \textit{multiframe} structure used for synchronisation and signalling purposes.
  – It is worth noting that North America and Japan have their own telephony TDM scheme based multiplexing 24 voice channels and 1 control channels to give a 1.544 Mbits/sec digital signal (known as the \textit{T1 rate}).
Multiplexing

- 1 multiframe (2 msec) = 16 frame slots
- 1 frame slot (125 μsec) = 32 channel slots
- 1 channel slot (3.9 μsec) = 8 pulse slots
- 1 pulse slot (488 nsec) = Logic 0/1
- Bit Rate = $1/488 \times 10^{-9} = 2.048 \text{ Mbits/sec}$
  (or 2 Mbits/sec for short)
Multiplexing

• Channel slots 0 and 16 in a frame are reserved for synchronisation and signalling purposes.
• Channel slot 0 is always used for frame synchronisation.
• Channel slot 16 is used for multiframe synchronisation (in frame slot 0 only) and for signalling.
• Signalling is used to support features such as dialling tones, engaged tones, alarms etc.
Multiplexing

- Frame 0 (in a multiframe)
  - Channel slot 0  = Frame alignment word (frame synchronisation)
  - Channel slot 1  = 1\textsuperscript{st} sample from voice channel 1
  - Channel slot 2  = 1\textsuperscript{st} sample from voice channel 2
  - \ldots
  - Channel slot 15 = 1\textsuperscript{st} sample from voice channel 15
  - Channel slot 16 = Multiframe alignment word (multiframe synchronisation, frame 0 only!!)
  - Channel slot 17 = 1\textsuperscript{st} sample from voice channel 16
  - \ldots
  - Channel slot 31 = 1\textsuperscript{st} sample from voice channel 30
Multiplexing

- Frame 1 (in a multiframe)
  - Channel slot 0 = Frame alignment word (frame synchronisation)
  - Channel slot 1 = 2\textsuperscript{nd} sample from voice channel 1
  - Channel slot 2 = 2\textsuperscript{nd} sample from voice channel 2
  - Channel slot 15 = 2\textsuperscript{nd} sample from voice channel 15
  - Channel slot 16 = Bits 1-4 Signalling for voice channel 1
    Bits 5-8 Signalling for voice channel 16
  - Channel slot 17 = 2\textsuperscript{nd} sample from voice channel 16
  - Channel slot 31 = 2\textsuperscript{nd} sample from voice channel 30
Multiplexing

- Frame 2 (in a multiframe)
  - Channel slot 0 = Frame alignment word (frame synchronisation)
  - Channel slot 1 = 3rd sample from voice channel 1
  - Channel slot 2 = 3rd sample from voice channel 2
  - Channel slot 15 = 3rd sample from voice channel 15
  - Channel slot 16 = Bits 1-4 Signalling for voice channel 2
    Bits 5-8 Signalling for voice channel 17
  - Channel slot 17 = 3rd sample from voice channel 16
  - Channel slot 31 = 3rd sample from voice channel 30
Multiplexing

- Frame 15 (in a multiframe)
  - Channel slot 0 = Frame alignment word (frame synchronisation)
  - Channel slot 1 = 16\textsuperscript{th} sample from voice channel 1
  - Channel slot 2 = 16\textsuperscript{th} sample from voice channel 2
    : 
  - Channel slot 15 = 16\textsuperscript{th} sample from voice channel 15
  - Channel slot 16 = Bits 1-4 Signalling for voice channel 15
    Bits 5-8 Signalling for voice channel 30
  - Channel slot 17 = 16\textsuperscript{th} sample from voice channel 16
    : 
  - Channel slot 31 = 16\textsuperscript{th} sample from voice channel 30
Multiplexing

- The 2.048 Mbits/sec multiplex level is known as the primary multiplex level group as it represents the first level in a hierarchy of multiplexing.
- By combining 4 such 2.048 Mbits/sec signals (or tributaries) together, one gets a 8.488 Mbits/sec signal that can support 120 voice channels.
- It is possible to continue multiplexing signals together in this fashion. This leads to the development of a multiplexing hierarchy.
**Multiplexing**

<table>
<thead>
<tr>
<th>Multiplexing Order</th>
<th>Bit Rate (Mbits/sec)</th>
<th>No. of Voice Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.048</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>8.488</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>34.368</td>
<td>480</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>1,920</td>
</tr>
<tr>
<td>5</td>
<td>565</td>
<td>7,680</td>
</tr>
<tr>
<td>6</td>
<td>1.2 Gbits/s</td>
<td>30,720</td>
</tr>
<tr>
<td>7</td>
<td>2.4 Gbits/s</td>
<td>122,880</td>
</tr>
</tbody>
</table>
Multiplexing

• The digital telephone network in North America and Japan use a completely different multiplexing hierarchy.
• Based upon 24 voice channels and 1 control channel multiplexed together to give a primary multiplex rate of 1.544 Mbits/sec.
• A similar multiplexing hierarchy exists for this standard.
• Unfortunately, the two standards are incompatible which means that complex and costly interworking equipment is required.
Multiplexing

- There is a major drawback associated with this PCM/TDM multiplexing hierarchy.
- In assembling a PCM/TDM multiplexing hierarchy, the various tributaries will have been generated at different locations and in many cases using different equipment.
- As there is no master clock available for the system, there will always be slight variations in the exact bit rates of the tributaries.
- Consequently, the system must be able to accommodate slight variations in the bit rates if it is to be able to operate in the real world.
Multiplexing

- The fact that the system can tolerate variations in the tributary bit rates, means that the system is *plesiochronous* or almost synchronous.
- Hence, this multiplexing hierarchy is often referred to as the *Plesiochronous Digital Hierarchy* or *PDH* for short.
- In order to bring all the bit streams up to the same rate, extra “dummy” or *justification bits* are added to the bit streams.
Multiplexing

- Elastic stores (i.e. buffers) are used in a typical multiplexer to ensure sufficient bits are always available for transmission or reception.
- Stores are required because PDH interleaves bytes together for the primary multiplex level but interleaves bits at higher levels.
- A *frame alignment signal* is used for synchronisation and the correct mapping of tributaries to the appropriate outputs.
- The *ITU-T G.702* recommendation defines the complete PDH.
Multiplexing

- PDH was developed at a time when transmission costs were low relative to switching costs. However, this is no longer valid.
- PDH was designed for point-to-point transmission applications in which the entire multiplex is decoded at the far end. This is a complicated process requiring complete demultiplexing at each level and removal of the justification bits.
- A single 2 Mbits/sec channel cannot be added to or extracted from a higher multiplex level without multiplexing down and remultiplexing up.
- PDH does not support definite or clear identification of the channels being carried.
Multiplexing

• PDH is severely limited in its ability to meet the requirements of future networks.
• PDH does not provide a cost effective, flexible architecture for today’s networks.
• There is no extra capacity in the PDH frame structure to support network OAMP&P (Operations, Administration, Maintenance, and Provisioning).
• Finally, PDH is not a global standard, i.e. the standard for North America and Japan is based upon a primary multiplex level of 1.544 Mbits/sec.
Multiplexing

- The SONET (Synchronous Optical Network) concept was introduced in the USA in 1986 to establish wideband transmission standards so that international operators could interface using standard frame formats and signalling protocols.

- SONET also included network flexibility and intelligence, and additional channels to carry control and performance information between network elements and control centres.

- In 1988, adopted by the ITU-T (and ETSI) and renamed SDH (Synchronous Digital Hierarchy), establishing a world wide standard.
Multiplexing

• Advantages of SONET/SDH:
  – Easier to add and drop signals
  – More bandwidth available for network management.
  – Easier to introduce new services.
  – World wide standard.

• Some ITU-T Recommendations for SDH are:
  – G.707 at 155 Mbits/sec
  – G.708 at 622 Mbits/sec
  – G.709 at 2.5 Gbits/sec
1 multiframe (2 msec) = 16 frames

1 frame (125 µsec) = 32 channel slots

Frame 0 only

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Frame alignment word

Multiframe alignment word

All other frames

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Frame alignment word

Bits 0-3: Signalling for channels 1-15

Bits 4-8: Signalling for channels 16-30

1 channel slot (3.9 µsec) = 8 pulse slots

PCM code word

0 1 2 3 4 5 6 7