7 - Multiplexing

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Note: These slides contain figures from Stallings, Halsall and Forouzan, and are based on a set developed by Dr. A Pullin.

1. Introduction and Revision.
2. Data Transmission.
3. Transmission Media.
4. Data Encoding.
5. Data Communications Interface.
6. Data Link Control.
7. Multiplexing.
8. LAN Technology.
9. LAN Systems.
10. Asynchronous Transfer Mode (ATM).
11. Subject revision.

- Make efficient use of high-speed telecommunications using multiplexing.
  - Frequency Division (FDM) - multiple analog signals carried simultaneously.
  - Time Division (TDM) - analog or digital data assigned to time slots.
  - Statistical TDM - more efficient implementation of TDM.
- ADSL uses FDM to achieve adaptive rates.

Multiplexing

- **Multiplexing**: Combining multiple data (voice) channels for transmission on a common medium. Multiple devices sharing one physical link.
- **Demultiplexing**: Recovering the original separate channels from a multiplexed signal.
- Multiplexing and demultiplexing are performed by a multiplexor.
- The two common forms of multiplexing are frequency-division multiplexing (FDM) and time-division multiplexing (TDM).

**Frequency-Division Multiplexing (FDM)**

- Useful bandwidth of the medium exceeds the required bandwidth of the channel.
- Each signal is modulated to a different carrier frequency.
- Carrier frequencies are separated so signals do not overlap (guard bands).
- E.g. broadcast radio, television, cable television, etc.
- Channel allocated even if there is no data to be sent.

![Multiplexing Diagram]

![Frequency-Division Multiplexing (FDM) Diagram]
Frequency-Division Multiplexing (FDM)

Transmitter:
- Analog or digital inputs: $m_i(t), i = 1, n$.
- Each is modulated onto a subcarrier: $f_i$.
- Signals summed to produce a composite baseband: $m_b(t), \text{where } B > \sum_{i=1}^{n} B_i$.
- $f_i$ chosen such that there is no overlap.

Receiver:
- $m_b(t)$ is passed through $n$ bandpass filters with response centred on $f_i$.
- Each $s_i(t)$ component is demodulated.

FDM of Three Voiceband Signals

- Effective spectrum of voice: 300-3400Hz.
- AM a 64-kHz carrier: produces an 8 kHz bandwidth (60-68kHz).
- For efficiency, only transmit lower sideband.
- Three carriers at 64, 68 and 72 kHz.
- Must guard against crosstalk (overlap) and intermodulation noise.
- Nonlinear effects of amplifiers in one channel can produce frequency components in other channels.

Analog Carrier Systems

- Long distance voiceband signals over high-capacity links (coaxial cable, microwave).
- AT&T (USA) designated a hierarchy of FDM schemes.
  - Group:
    - 12 voice channels (4kHz each) = 48kHz.
    - Range from 60kHz to 108kHz.
    - Lower sideband and carrier suppressed for each signal.
  - Supergroup:
    - 60 channels.
    - FDM of 5 group signals on carriers between 420 kHz and 612 kHz.
    - Each group is treated as a separate signal with 48 kHz bandwidth.
  - Mastergroup:
    - 10 supergroups.
    - 600 voice channels with a bandwidth of 2.52 MHz.
### Multplexing

**Analog Hierarchy**
- 48 KHz: 12 voice channels
- 240 KHz: 60 voice channels
- 2.52 MHz: 600 voice channels

**Synchronous Time-Division Multiplexing**
- Data rate of the medium exceeds the data rate of the digital signal to be transmitted.
- Multiple digital signals interleaved in time: May be at the bit level or blocks of bytes.
- Time slots preassigned to the data sources and fixed.
- Time slots allocated even if no data is sent (like FDM).
- Time slots do not have to be evenly distributed amongst sources.

### Synchronous TDM System
- **Transmitter**:
  - Digital inputs, $m_i(i), i = 1, n$, are briefly buffered.
  - Buffers are scanned sequentially to form a composite signal: $m_i(t)$.
  - Scanning is rapid enough so buffers are emptied before data arrives.
  - Data organised into frames of one cycle.
- **Receiver**:
  - Interleaved data is demultiplexed and routed to destination buffers.

**TDM System Diagram**

- **Interleaving**:
  - Can be compared to a very fast rotating switch which selects each device at a constant rate and a fixed order.
  - Each device sends a fixed number of bits in its timeslot.
- **Weakness of Synchronous TDM**: fixed time slot allocations can lead to empty slots when a device has nothing to send.
**TDM Link Control**

- No headers and trailers usually associated with synchronous transmission.
- Reason: Data link control protocols are not needed.
- Flow control:
  - Data rate of the multiplexed line is fixed.
  - If one channel receiver cannot receive data, the others must carry on.
  - The corresponding source must cease transmission.
  - This leaves empty slots for the corresponding channel.
- Error control:
  - Should not retransmit an entire TDM frame.
  - Errors are detected and handled by individual channel systems.

**Framing Bits**

- There is no flag or SYNC characters bracketing TDM frames.
- Must provide a synchronising mechanism.
- Most common mechanism: Added digit framing.
  - One control bit added to each TDM frame:
    - Looks like another channel - “control channel”
  - Identifiable bit pattern used on the control channel.
  - E.g. alternating 01010101 which is unlikely to be sustained on a data channel.
  - Can compare incoming bit patterns on each channel with the sync pattern.
  - Once synchronised, the receiver monitors the control channel.

**Synchronous TDM System Example**

- Each device sends 250 characters/second = 250 x 8 = 2000 bps.
- Transmission is character interleaved, and each frame has one framing bit.
- Therefore, the devices create 2000 x 4 = 8000 bits of data per second, and the multiplexer adds 250 bits of overhead per second.
**Pulse/Bit Stuffing**

- It is possible to connect devices of different rates using different time slot allocations.
- Since a fixed number of bits are transmitted in each time slot, each device must have a data rate which is an integer multiple of the channel rates.
- For example: a bit-interleaved multiplexer has a device which is three times faster than the other devices. This device will use three time slots.
- Problem - What do we do for a device 3.75 times faster.
- Solution - Pulse/Bit Stuffing:
  - The multiplexer adds extra dummy bits or pulses into the devices data stream to force the integer speed relationship.
  - Therefore the 3.75 times faster device will be raised to 4 times faster.
  - Stuffed bits are inserted at fixed locations in the frame and removed at the demultiplexer.

**Example TDM of Analog and Digital Sources**

- TDM PCM signal 64 kbps
- TDM PAM signal 16 ksamples/sec
- TDM PCM output signal 128 kbps

**Digital Carrier Systems**

- Hierarchy of TDM.
- USA/Canada/Japan use one system and ITU-T use a similar (but different) system.
- Digital Signal (DS) Service DS-1 format: Multiplexes 24 channels.
- Each frame has 8 bits per channel plus one framing bit: $8 \times 24 + 1 = 193$ bits per frame.
- The DS service is implemented using T lines.

**Digital Carrier Systems Format**

- For voice each channel contains one word of digitised data (PCM, 8000 samples per sec):
  - Frames are transmitted at 8000 per second: Data rate = $8000 \times 193 = 1.544$ Mbps.
  - Five out of the six frames have 8 bit PCM samples.
  - Sixth frame is 7 bit PCM word plus a signalling bit.
  - Signalling bits form a stream for each channel containing control and routing info.
- Same format for digital data (uniformity):
  - 23 channels of data:
    - 7 bits per frame plus indicator bit for data or systems control ($7 \times 8000 = 56$ kbps).
    - 24th channel is a special sync byte (faster reframing).
- DS-1 can carry mixed voice and data signals:
  - 24 channels used with no sync byte.
### Digital Carrier Systems Format

- **Sampling at 8000 samples/second using 8 bits per sample**
- **4 KHz**
- **64,000 bps**
- **24 voice channels**
- **24 x 64 Kbps + 8 Kbps overhead**
- **T−1 line 1.544 Mbps**
- **1 second**
- **1 frame = 193 bits**

\[
\text{Frame 1} \quad \text{Frame 2} \quad \ldots \quad \text{Frame n} \\
\text{1 second} \\
\text{1 frame = 193 bits} \\
\text{T−1: 8000 frames/s x 193 bit/frame = 1.544 Mbps}
\]

### Digital Carrier Systems Hierarchy

- **These DS specifications are implemented on T lines (T-1, T-2, T-3 and T-4).**

### ISDN User Network Interface

- ISDN allows multiplexing of user devices over a single ISDN line.
- Two interfaces:
  - **Basic ISDN Interface**
  - **Primary ISDN Interface.**

### Basic ISDN Interface

- Digital data exchanged between subscriber and NTE in full duplex.
- Separate physical line for each direction.
- Pseudoternary coding scheme at a data rate of 192 kbps:
  - \(1 = \text{no voltage}, \ 0 = \text{positive or negative pulse of 750 mV +/-10\%}.\)
- Basic access is two 64 kbps B channels and one 16 kbps D channel.
- This gives 144 kbps multiplexed over 192 kbps.
- Remaining capacity is used for framing and sync.
- B channel is the basic user channel: Data, PCM voice.
- Separate logical 64 kbps connections to different destinations.
- D channel is used for control or data using LAPD frames.
- Each frame is 48 bits long: One frame every 250\(\mu\)s.
Frame Structure for ISDN Basic Rate

- D-channel echoing used for collision detection on a multipoint line.

**Frame Structure**

- **F** = Framing bit
- **L** = DC balancing bit
- **E** = D-echo channel bit
- **A** = Activation bit
- **N** = Set to opposite of FA
- **M** = Multiframing bit

**Primary ISDN**

- Only a point-to-point connection allowed.
- Typically supporting a digital PBX (private branch exchange).
- Rate at 1.544 Mbps:
  - Based on the US DS-1 and used on T1 services.
  - 193-bit frames with 24 8-bit time slots at 8000 frames per second.
  - 23 B channels plus one D channel, each at 64 kbps.
  - Line coded using AMI (alternate mark inversion) and B8ZS.
- Rate at 2.048 Mbps:
  - Based on European standards for the same data rate.
  - 256-bit frames with 32 8-bit time slots at 8000 frames per second.
  - 30 B channels plus one D channel, each at 64 kbps.
  - Line coding is AMI and HDB3.

**Primary ISDN Frame Formats**

(a) Interface at 1.544 Mbps

1 frame = 193 bits; 125 \( \mu \)sec

(b) Interface at 2.048 Mbps

1 frame = 256 bits; 125 \( \mu \)sec

**SONET/SDH**

- Synchronous Optical Network (BellCore and ANSI).
- Synchronous Digital Hierarchy (ITU-T).
- Both standards are compatible and designed for the speed and capacity of fibre.
- Signal Hierarchy:
  - Synchronous Transport Signal level 1 (STS-1) or Optical Carrier level 1 (OC-1).
  - 51.84 Mbps.
  - Carry a single DS-3 or a group of lower rate signals (DS1, DS1C, DS2) plus ITU-T rates (e.g. 2.048Mbps).
  - Multiple STS-1 signals combined into an STS-N signal.
  - ITU-T SDH lowest rate is 155.52Mbps (STM-1) and corresponds to STS-3.
- Frame Format:
  - STS-1 frame contains 9 rows of 90 octets = 810 octets every 125\( \mu \)s \( \rightarrow \) 51.84 Mbps.
SONET Frame Format

(a) STS−1 frame format

- Transport overhead
  - A2 (3 octets)
- Synchronous payload environment (SPE)
  - 87 octets
- Section overhead
  - 3 octets
- Line overhead
  - 6 octets
- Path overhead
  - 1 octet

(b) STM−N frame format

- Section overhead
  - $9 \times N$ octets
- SRM−N payload
  - $261 \times N$ octets
- Line overhead
  - 6 octets
- Path overhead
  - 1 octet

Statistical TDM

- In synchronous TDM many slots are wasted (empty slots).
- Statistical or Asynchronous TDM allocates time slots dynamically based on demand.
- The multiplexer scans the input lines and collects data until the frame is full.
- The data rate on the line is lower than the aggregate rates of the input lines.

Statistical TDM Examples

- Case 1: Only three lines sending data
- Case 2: Only four lines sending data.
- Case 3: All five lines sending data.
Statistical TDM Frame Formats

- Need destination address information for the data in the frames: greater overhead.
- Generally use a synchronous protocol such as HDLC.
- Include one (b) or more (c) sources of data in each HDLC frame (a).

<table>
<thead>
<tr>
<th>Flag</th>
<th>Address</th>
<th>Control</th>
<th>Statistical TDM subframe</th>
<th>FCS</th>
<th>Flag</th>
</tr>
</thead>
</table>

(a) Overall frame

<table>
<thead>
<tr>
<th>Address</th>
<th>Data</th>
</tr>
</thead>
</table>

(b) Subframe with one source per frame

<table>
<thead>
<tr>
<th>Address</th>
<th>Length</th>
<th>Data</th>
</tr>
</thead>
</table>

(c) Subframes with multiple sources per frame

Performance

- Output data rate is less than the aggregate input rates.
- Anticipate the average rate is less than the multiplexed capacity.
- May cause problems during peak periods:
  - Buffer inputs.
  - Keep buffer size to minimum to reduce delay.
- \( M \) = effective capacity of multiplexed line (after accounting for overhead).
- As utilisation rises, so do the buffer requirements and delay.

Asymmetrical Digital Subscriber Line (ADSL)

- Link between the subscriber and the network: Local loop.
- Uses currently existing twisted pair cables:
  - Can carry broader spectrum than just voice bandwidth (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 for downstream and upstream.
    - Use FDM within bands each band.
  - Range 5.5 km.
- xDSL: High data rate DSL (HDSL), Single line DSL (SDSL) and Very high data rate DSL (VDSL).

ADSL Channel Configuration

(a) Frequency-division multiplexing

(b) Echo cancellation
Discrete Multitone (DMT)

- Multiple carrier signals at different frequencies.
- Send some bits on each channel.
- Available bandwidth divided into 4kHz subchannels.
- Send a test signal and assign more bits to subchannels with better signal-to-noise ratio.
- Use quadrature amplitude modulation (QAM): easy to assign variable number of bits.
- Presently 256 downstream subchannels at 4kHz (60kbps):
  - 15.36 Mbps possible, impairments bring this down to 1.5 Mbps to 9Mbps.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Bits per hertz</th>
<th>Frequency</th>
<th>Bits per hertz</th>
<th>Frequency</th>
</tr>
</thead>
</table>

DMT Transmitter

\[
0 \leq \alpha_i \leq 1 \quad \sum_{i=1}^{n} \alpha_i = 1
\]

\[f_{i+1} = f_i + 4 \text{ kHz}\]

QPSK and QAM Revisited...

Further Reading