Comm 502: Communication Theory

Lecture 4

Line Coding – M-ary PCM-Delta Modulation
PCM Decoder
PCM Waveform Types (Line Coding)

- Representation of binary sequence into the electrical signals that enter the channel
  - Ex. “1” maps to +A square pulse; “0” to –A square pulse

- **Line Coding:**
  - Unipolar - Manchester
  - Polar - Differential
  - Bipolar
Choice of Suitable Line Coding

• The Choice of suitable Line Coding is generally made according one or more of the following considerations:

  ■ **Self Synchronization**: There should be sufficient information in the transitions and zero-crossings to permit symbol timing clock regeneration.

  ■ **Spectrum suited to the channel**: The PSD of the transmitted signal should be compatible with the channel frequency response $H_c(w)$, eg:

    ■ Many channels cannot pass dc level (zero frequency) owing to ac coupling.

  ■ **Bandwidth**.

  ■ the property that any arbitrary symbol, or bit, pattern can be transmitted and received.
Lack of Synchronization

- To correctly interpret the signals received from the sender, the receiver’s bit intervals must correspond exactly to the sender’s bit intervals.
- If the receiver clock is faster or slower, the bit intervals are not matched and the receiver might interpret the signals differently than the sender intended.
DC Component

- Having zero-frequency has two undesirable cases
  - If a signal is to pass through a system that does not allow the passage of a dc component, the signal is distorted and may create errors in the output.
  - This component is extra energy residing on the line and is useless.

![Graphs showing a signal with and without dc component](image)
Line Coding

Return to Zero (RZ)

The waveform returns to a zero level for a portion of the bit interval.

Non-return to Zero (NRZ)

The waveform does not return to a zero level for a portion of the bit interval.
### Unipolar NRZ
- “1” is represented by a +A pulse of length T sec.
- “0” is represented by a silent interval of length T sec.
- The waveform has a nonzero DC value.
- Can use circuits that require only one power supply (+5 V for TTL circuits).
- Long string of 0s causes receiver to lose synch.

### Polar NRZ
- “1” is represented by a +A/2 pulse of length T sec.
- “0” is represented by a -A/2 pulse of length T sec.
- The waveform has zero DC level because (for long sequences, the number of ones approaches the number of zeros).
- The circuits that produce it require a negative voltage power supply as well as a positive voltage power supply.
Unipolar NRZ

Advantages:
- Simplicity in implementation.
  - Doesn’t require a lot of bandwidth for transmission.

Disadvantages:
- Presence of DC level (indicated by spectral line at 0 Hz).
- Contains low frequency components. Causes “Signal Droop”
- Does not posses any clocking component for ease of synchronisation.
- Long string of zeros causes loss of synchronisation.
Unipolar NRZ

Power Spectral Density of Unipolar NRZ

Figure. PSD of Unipolar NRZ
Unipolar NRZ

- When Unipolar NRZ signals are transmitted over links with capacitor coupled (AC) repeaters, the DC level is removed converting them into a polar format.

- The continuous part of the PSD is also non-zero at 0 Hz (i.e. contains low frequency components). This means that AC coupling will result in distortion of the transmitted pulse shapes. AC coupled transmission lines typically behave like high-pass RC filters and the distortion takes the form of an exponential decay of the signal amplitude after each transition. This effect is referred to as “Signal Droop” and is illustrated in figure below.
Unipolar NRZ

Figure Distortion (Signal Droop) due to AC coupling of unipolar NRZ signal
Polar NRZ

Advantages:
- Simplicity in implementation.
- No DC component.

Disadvantages:
- Continuous part is non-zero at 0 Hz. Causes “Signal Droop”.
- Does not posses any clocking component for ease of synchronisation.
Polar NRZ

Power Spectral Density of Polar NRZ

Polar NRZ almost has identical spectra to unipolar NRZ. However, due to the opposite polarity of the 1 and 0 symbols, it does not have any spectral lines.

Figure. PSD of Polar NRZ
Bipolar RZ Line Code

- Three signal levels: \{-A, 0, +A\}
- “1” is represented by +A or –A in alternation of length \( T/2 \) sec.
- “0” is represented by a silent interval of length \( T \) sec.
- +ve and –ve pulses alternate. No DC component (for long sequences).
- Long string of 0s causes receiver to lose synch.
Bipolar RZ Line Code

Power Spectral Density of BiPolar RZ

Figure. PSD of BiPolar RZ
Bipolar RZ Line Code

- Alternating the mark level voltage ensures that the bipolar spectrum has a null at DC and that signal droop on AC coupled lines is avoided.

**Advantages:**
- No DC component.
- Does not suffer from signal droop (suitable for transmission over AC coupled lines).

**Disadvantages:**
- Does not possess any clocking component for ease of synchronisation.
Manchester Line Code

• “1” is represented by \( A/2 \) first \( T/2 \) sec, and \(-A/2\) last \( T/2 \) sec.
• “0” is represented by \(-A/2\) first \( T/2 \) sec, and \(+A/2\) last \( T/2 \) sec.
• No dc component regardless of the data sequence.

**Note:** There is always a transition at the centre of bit duration.
Manchester Line Code

- In Manchester encoding, the transition at the middle of the bit is used for synchronization.

Power Spectral Density of Manchester Line Code:
Manchester Line Code

- Manchester encoding is called self-synchronizing. Synchronization at the receiving end can be achieved by locking on to the transitions, which indicate the middle of the bits.

Advantages:
- No DC component.
- Does not suffer from signal droop (suitable for transmission over AC coupled lines).
- Easy to synchronise with.

Disadvantages:
- Because of the greater number of transitions it occupies a significantly large bandwidth.
$e_n = d_n \oplus e_{n-1}$
Differential Coding (cont.)

\[ e_n = d_n \oplus e_{n-1} \quad \text{For encoding} \]
\[ \tilde{d}_n = \tilde{e}_n \oplus \tilde{e}_{n-1} \quad \text{For decoding} \]

<table>
<thead>
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<th>Encoding</th>
<th></th>
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<td>Input sequence</td>
<td>( d_n )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Encoded sequence</td>
<td>( e_n )</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reference digit</td>
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</tbody>
</table>

| Decoding (with correct channel polarity) | | | | | | | | |
| Received sequence | \( \tilde{e}_n \) | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| (correct polarity) | | | | | | | | |
| Decoded sequence | \( \tilde{d}_n \) | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |

| Decoding (with inverted channel polarity) | | | | | | | | |
| Received sequence | \( \tilde{e}_n \) | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 |
| (inverted polarity) | | | | | | | | |
| Decoded sequence | \( \tilde{d}_n \) | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
M-Ary Coding (Signaling)

• In binary coding:
  – Data bit ‘1’ has waveform 1
  – Data bit ‘0’ has waveform 2
  – Data rate = bit rate = symbol rate

• In M-ary coding, take $M$ bits at a time ($M = 2^k$) and create a waveform (or symbol). For example:
  – ‘00’ $\rightarrow$ waveform (symbol) 1
  – ‘01’ $\rightarrow$ waveform (symbol) 2
  – ‘10’ $\rightarrow$ waveform (symbol) 3
  – ‘11’ $\rightarrow$ waveform (symbol) 2
  – Symbol rate = bit rate/k
M-Ary Coding

• **Advantages:**
  – Low bandwidth

• **Disadvantages:**
  – Probability of Error is higher than the Binary transmission.
M-ary Signaling

8-level signaling

8-ary PCM

2-level signaling
M-ary (Multilevel) Signaling

- M-ary signals reduce required bandwidth
- Instead of transmitting one pulse for each bit (binary PCM), we transmit one multilevel pulse a group of $k$-bits ($M=2^k$)
- Bit rate = $R_b$ bits/s $\rightarrow$ BW = $R$
- Symbol rate = $R_b/k$ sym/s $\rightarrow$ BW = $R_b/k$
- Needed bandwidth goes down by $k$
- Trade-off is relatively high bit error rate (BER)
Advantages & Disadvantages of PCM

Advantages of PCM:
(1) Immune against channel interference and noise.
(2) Efficient regeneration of the coded signal.
(3) Secure communication through the use of encryption.
(4) Uniform format of different types of baseband signals

Disadvantages of PCM:
(1) Increased channel Bandwidth.
(2) Increased system complexity.
Delta Modulation

• The advantages of the PCM are attained at the cost of increased system complexity and increased bandwidth.

• If the simplicity of implementation is a necessary requirements, we can use delta modulation as an alternative to PCM.

• In delta modulation, the analog signal is oversampled to increase the correlation between adjacent samples of the signal. This is done to permit the use of a simple quantizing strategy for constructing the encoded signal.
In its basic form, delta modulation provides a staircase approximation to the oversampled version of the message signal as shown in the following figure.

The difference between the input and the approximation is quantized into only two levels, namely, $+\Delta$ and $-\Delta$ corresponding to positive and negative differences respectively.
• Thus if the approximation falls below the signal at any sampling period, it is increased by $\Delta$. If the approximation lies above the signal, it is reduced by $\Delta$.

• Provided that the signal does not change too rapidly from sample to sample, we find that the staircase approximation remains within $\pm \Delta$ of the input signal.
DM Transmitter block Diagram

\[ m[n] = m(nT_s), \quad n = 0, \pm 1, \pm 2, \ldots \]

where \( T_s \) is the sampling period

\[ e[n] = m[n] - m_q[n - 1] \]

\[ e_q = \Delta \text{sgn}(e[n]) \]

\[ m_q[n] = m_q[n - 1] + e_q[n] \]
The signal $mq(t)$ is reconstructed by passing the sequence of positive and negative pulses produced at the decoder output through an accumulator in a manner similar to that used in the transmitter. Finally, the quantization noise in the high frequency staircase waveform $mq(t)$ is rejected by the LPF with bandwidth $B$. 

Bandwidth: $B$
Delta Modulation - Advantages

• Simple Encoding and decoding.
• Inexpensive
• Does not require word synchronization.
• Smaller Bandwidth than PCM (B.W=Fs in DM)
Slope Overload noise

Occurs when the step size $\Delta$ is too small and cannot follow fast changes in the input signal.

Granular Noise

- Occurs when the signal is nearly constant.
- Will occur for all sizes of $\Delta$ but it is smaller when $\Delta$ is small.
Delta Modulation - Problems
Due to the fixed step size, the staircase approximation of the signal may not be able to follow the original signal when the rate of change is very high (slope overload) or when the signal is constant (granular noise or hunting).
Slope Overload

• When the analog waveform is changing very rapidly than the staircase can follow
• System can’t keep up with rapid changes in voltage

Slope Overload

Noise

increases

as

Step size decrease
Slope Overload (Cont.)

• To avoid slope overload problem, the sequence of the samples $m_q[n]$ must increases as fast as the input sequence $m[n]$ in the region of maximum slope of $m(t)$. This is satisfied by:

$$\Delta \geq \max \left| \frac{dm(t)}{dt} \right|$$
Example:
A linear delta modulator is designed to operate on speech signals limited to 3.4 kHz. The specifications of the modulator are as follows:

- Sampling rate $= 10f_{\text{Nyquist}}$, where $f_{\text{Nyquist}}$ is the Nyquist rate of the speech signal.
- Step size $\Delta = 100 \text{ mV}$.

The modulator is tested with a 1-kHz sinusoidal signal. Determine the maximum amplitude of this test signal required to avoid slope overload.

Solution

$$f_s = 10f_{\text{Nyquist}} \quad f_{\text{Nyquist}} = 6.8 \text{ kHz} \quad f_s = 10 \times 6.8 \times 10^3 = 6.8 \times 10^4 \text{ Hz}$$

$$\frac{\Delta}{T_s} \geq \max \left| \frac{dm(t)}{dt} \right| \quad \text{For the sinusoidal signal } m(t) = A_m \sin(2\pi f_m t), \text{ we have}$$

$$\frac{dm(t)}{dt} = 2\pi f_m A_m \cos(2\pi f_m t) \quad \text{Hence,} \quad \left| \frac{dm(t)}{dt} \right|_{\text{max}} = \left| 2\pi f_m A_m \right|_{\text{max}}$$

or, equivalently,

$$\frac{\Delta}{T_s} \geq \left| 2\pi f_m A_m \right|_{\text{max}} \quad \Rightarrow \quad |A_m|_{\text{max}} = \frac{\Delta}{T_s \times 2\pi \times f_m} = \frac{\Delta f_s}{2\pi f_m}$$

$$= 1.08 \text{ V}$$
Granular noise

• When the analog waveform is changing very slowly

Granular noise increases as Step size increase
Delta Modulation – SQNR calculations

Power Spectral density (PSD) for Quantizing noise is:

\[ S_N(f) = \frac{\Delta^2}{6f_s} \Rightarrow \text{See Page 244 “Communication Systems” Book for proof} \]

Total noise in band \( N = \int_{-B}^{B} S_N(f) \, df = \frac{\Delta^2 B}{3f_s} \)

where \( B \) is the reconstruction filter at the demodulator

For a sine wave with frequency \( f_m \): \( A = \frac{\Delta f_s}{2\pi f_m} \) and Signal power: \( S = \frac{A^2}{2} \) (1)

Then \( \Delta = \frac{2\pi f_m A}{f_s} \Rightarrow N = \frac{4\pi^2 A^2 f_m^2 B}{3f_s^3} \) (2)

From (1) and (2); the SQNR of Delta Modulation is given by:

\[
\left( \frac{S}{N} \right)_{out} = \frac{3}{8\pi^2} \frac{f_s^3}{f_m^2 B}
\]
One of the solution of these problems is to use Adaptive Delta Modulation. The step size is not kept fixed.

Adaptive delta modulation:

- Increase $\Delta$ for the fast change of the input signal and decrease $\Delta$ when the signal is nearly constant.

It reduces effect of slope overload and granular noises.
Adaptive Delta Modulation

Linear Delta Modulation

Adaptive Delta Modulation

Linear Delta Modulation