CHAPTER-4
Line Codes

In base band transmission best way is to map digits or symbols into pulse waveform. This waveform is generally termed as Line codes.

**RZ:** Return to Zero [pulse for half the duration of \( T_b \)]

**NRZ** Return to Zero [pulse for full duration of \( T_b \)]
“1” maps to +A pulse “0” maps to no pulse

- Poor timing
- Low-frequency content
- Simple
- Long strings of 1s and 0s, synchronization problem

**Polar - (NRZ)**

```
+A
0
-A
```

**Polar NRZ**

“1” maps to +A pulse “0” to –A pulse

- Better Average Power
- Simple to implement
- Long strings of 1s and 0s, synchronization problem
- Poor timing

**Bipolar Code**

```
V
0 1 0 1 0 0 1 1 0 1
```

- Three signal levels: {-A, 0, +A}
- “1” maps to +A or –A in alternation
- “0” maps to no pulse
- Long string of 0’s causes receiver to loose synchronization
- Suitable for telephone systems.

**Manchester code**
1. “1” maps into A/2 first for Tb/2, and -A/2 for next Tb/2
2. “0” maps into -A/2 first for Tb/2, and A/2 for Tb/2
3. Every interval has transition in middle
   - Timing recovery easy
4. Simple to implement
5. Suitable for satellite telemetry and optical communications

**Differential encoding**
- It starts with one initial bit. Assume 0 or 1.
- Signal transitions are used for encoding.

**Example NRZ - S and NRZ – M**
- NRZ –S: symbol 1 by no transition, Symbol 0 by transition.
- NRZ-M: symbol 0 by no transition, Symbol 1 by transition
- Suitable for Magnetic recording systems.

**M-ary formats**
Bandwidth can be properly utilized by employing M-ary formats. Here grouping of bits is done to form symbols and each symbol is assigned some level.

**Example**
Polar quaternary format employs four distinct symbols formed by dibits.
Gray and natural codes are employed

**Parameters in choosing formats**
1. Ruggedness
2. DC Component
3. Self Synchronization.
4. Error detection
5. Bandwidth utilization
6. Matched Power Spectrum

**Power Spectra of Discrete PAM Signals:**
The discrete PAM signals can be represented by random process
\[ X(t) = \sum_{k=-\infty}^{\infty} A_k V(t - KT) \]

Where \( A_k \) is discrete random variable, \( V(t) \) is basic pulse, \( T \) is symbol duration. \( V(t) \) normalized so that \( V(0) = 1 \).

Coefficient \( A_k \) represents amplitude value and takes values for different line codes as:

**Unipolar**
\[ A_k = \begin{cases} 1 & \text{Symbol 1=}1 \\ 0 & \text{Symbol 0=}0 \end{cases} \]

**Polar**
\[ A_k = \begin{cases} +1 & \text{Symbol 1=}+1 \\ -1 & \text{Symbol 0}=-1 \end{cases} \]

**Bipolar**
\[ A_k = \begin{cases} +1 & \text{AlternateSymbol 1 takes} =+1,-1 \\ 0 & \text{Symbol 0=}0 \end{cases} \]

**Manchester**
\[ A_k = \begin{cases} +1 & \text{Symbol 1=}1 \\ -1 & \text{Symbol 0}=-1 \end{cases} \]

As \( A_k \) is discrete random variable, generated by random process \( X(t) \), we can characterize random variable by its ensemble averaged auto correlation function given by

\[ R_A(n) = E[A_k A_{k-n}^*], \]

\( A_k, A_{k-n} \) = amplitudes of \( k^{th} \) and \((k-n)^{th}\) symbol position

**PSD & auto correlation function** form **Fourier Transform pair** & hence auto correlation function tells us something about bandwidth requirement in frequency domain.

Hence PSD \( S_X(f) \) of discrete PAM signal \( X(t) \) is given by

\[ S_X(f) = \frac{1}{T} |V(f)|^2 \sum_{n=-\infty}^{\infty} R_A(n)e^{-j2\pi f n T} \]

Where \( V(f) \) is Fourier Transform of basic pulse \( V(t) \). \( V(f) \) & \( R_A(n) \) depends on different line codes.
Power Spectra of NRZ Unipolar Format

Consider unipolar form with symbol 1’s and 0’s with equal probability i.e.
\[ P(A_k=0) = \frac{1}{2} \quad \text{and} \quad P(A_k=1) = \frac{1}{2} \]

For \( n=0 \);

Probable values of \( A_k.A_k = 0 \times 0 \) & \( a \times a \)

\[ = E[A_k.A_{k-0}] = E[A_k^2] = 0^2 \times P[A_k=0] + a^2 \times P[A_k=1] \]
\[ R_A(0) = \frac{a^2}{2} \]

If \( n \neq 0 \)

\( A_k.A_{k-n} \) will have four possibilities (adjacent bits)
\( 0 \times 0, 0 \times a, a \times 0, a \times a \) with probabilities \( \frac{1}{4} \) each.

\[ E[A_k.A_{k-n}] = 0 \times \frac{1}{4} + 0 \times \frac{1}{4} + 0 \times \frac{1}{4} + a^2 / 4 \]
\[ = \frac{a^2}{4} \]

\( V(t) \) is rectangular pulse of unit amplitude, its Fourier Transform will be sinc function.

\[ V(f) = \mathcal{F}[V(t)] = T_b \text{Sinc} (fT_b) \quad \text{PSD is given by} \]
\[ S_X(f) = \frac{1}{T} |V(f)|^2 \sum_{n=-\infty}^{\infty} R_A(n) e^{-j2\pi fnT} \]

Substituting the values of \( V(f) \) and \( R_A(n) \)

\[ S_X(f) = \frac{1}{T_b} \left[ T_b 2 \text{Sinc}^2(fT_b) \sum_{n=-\infty}^{\infty} R_A(n) e^{-j2\pi fnT_b} \right] \]
\[ = \left[ T_b \text{Sinc}^2(fT_b) \right] R_A(0) + \sum_{n=-\infty}^{\infty} R_A(n) e^{-j2\pi fnT_b} \]
\[ = \left[ T_b \text{Sinc}^2(fT_b) \right] \frac{a^2}{2} + \frac{a^2}{4} \sum_{n=-\infty}^{\infty} e^{-j2\pi fnT_b} \]
\[
\sum_{n=-\infty}^{\infty} e^{-j2\pi fnT_b} = \frac{1}{T_b} \sum_{n=-\infty}^{\infty} \delta(f - \frac{n}{T_b})
\]

Using Poisson's formula

\[
S_X(f) = \frac{a^2}{4} T_b \text{Sinc}^2(fT_b) + \frac{a^2}{4} T_b \text{Sinc}^2(fT_b) \frac{1}{T_b} \sum_{n=-\infty}^{\infty} \delta(f - \frac{n}{T_b})
\]

\[
\sum_{n=-\infty}^{\infty} \delta(f - \frac{n}{T_b}) \quad \text{is Dirac delta train which multiplies Sinc function which has nulls at } \pm \frac{1}{T_b}, \pm \frac{2}{T_b}, \ldots \ldots
\]

As a result,

\[
\sin^2(fT_b) \sum_{n=-\infty}^{\infty} \delta(f - \frac{n}{T_b}) = \delta(f)
\]

Where \( \delta(f) \) is delta function at \( f = 0 \),

Therefore

\[
S_X(f) = \frac{a^2 T_b}{4} \sin^2(fT_b) + \frac{a^2}{4} \delta(f)
\]

**Power Spectra of Bipolar Format**

Here **symbol 1** has levels \( \pm a \), and **symbol 0** as 0. Totally three levels.

Let 1’s and 0’s occur with equal probability then

\[
P(A_k = a) = 1/4 \quad \text{For Symbol 1}
\]

\[
P(A_k = -a) = 1/4
\]

\[
P(A_k = 0) = 1/2 \quad \text{For Symbol 0}
\]

For \( n = 0 \)

\[
E[A_k^2] = a \times a P(A_k = a) + (0 \times 0) P[A_k = 0] +
\]

\[
(-a \times -a) P(A_k = -a)
\]

\[
= \frac{a^2}{4} + 0 + \frac{a^2}{4} = \frac{a^2}{2}
\]
For $n \neq 0$, i.e. say $n = 1$;

Four possible forms of $A_k A_{k-1}$
00, 01, 10, 11 i.e. dibits are
0 $\times$ 0, 0 $\times$ $\pm a$, $\pm a \times$ 0,  $\pm a \times$ $\pm a$
with equal probabilities $\frac{1}{4}$.

$E[A_k A_{k-1}] = 0 \times \frac{1}{4} + 0 \times \frac{1}{4} + 0 \times \frac{1}{4} - a^2 \times \frac{1}{4}$
$= -\frac{a^2}{4}$

For $n > 1$, 3 bits representation 000, 001, 010 . . . . . . 111. i.e. with each probability of $\frac{1}{8}$
which results in

$E[A_k A_{k-n}] = 0$

Therefore $R_A(n) = \begin{cases} 
  \frac{a^2}{2} & n = 0 \\
  -\frac{a^2}{4} & n = \pm 1 \\
  0 & n > 1 
\end{cases}$

$S_X(f) = \frac{1}{T} \left| V(f) \right|^2 \sum_{n=-\infty}^{\infty} R_A(n) e^{-j2\pi fnT}$

PSD is given by

$S_X(f) = \frac{1}{T_b} \left[ T_b^2 \text{SinC}^2(fT_b) \right] \sum_{n=-\infty}^{\infty} R_A(n) e^{-j2\pi fnT}$

$S_X(f) = T_b \text{SinC}^2(fT_b) \left[ \frac{a^2}{2} - \frac{a^2}{4} (e^{j2\pi fnT} + e^{-j2\pi fnT}) \right]$

$S_X(f) = \left[ \frac{a^2 T_b}{2} \text{SinC}^2(fT_b) \right] \left[ 1 - \text{Cos}(2\pi fT_b) \right]$

$S_X(f) = \left[ \frac{a^2 T_b}{2} \text{SinC}^2(fT_b) \right] \left[ 2 \text{Sin}^2(fT_b) \right]$

$S_X(f) = \left[ \frac{a^2 T_b}{2} \text{SinC}^2(fT_b) \right] \text{Sin}^2(fT_b)$
Spectrum of Line codes

- Unipolar: most of signal power is centered around origin and there is waste of power due to DC component that is present.
- Polar format: most of signal power is centered around origin and they are simple to implement.
- Bipolar format: does not have DC component and does not demand more bandwidth, but power requirement is double than other formats.
- Manchester format: does not have DC component but provides proper clocking.

Spectrum suited to the channel.
- The PSD of the transmitted signal should be compatible with the channel frequency response
- Many channels cannot pass dc (zero frequency) owing to ac coupling
- Low pass response limits the ability to carry high frequencies

Inter symbol Interference

Generally, digital data is represented by electrical pulse, communication channel is always band limited. Such a channel disperses or spreads a pulse carrying digitized samples passing through it. When the channel bandwidth is greater than bandwidth of pulse, spreading of pulse is very less. But when channel bandwidth is close to signal bandwidth, i.e. if we transmit digital data which demands more bandwidth which exceeds channel bandwidth, spreading will occur and cause signal pulses to overlap. This overlapping is called Inter Symbol Interference. In short it is called ISI. Similar to interference caused by other sources, ISI causes degradations of signal if left
uncontrolled. This problem of ISI exists strongly in Telephone channels like coaxial cables and optical fibers.

In this chapter main objective is to study the effect of ISI, when digital data is transmitted through band limited channel and solution to overcome the degradation of waveform by properly shaping pulse.

\[
\begin{array}{c}
1 \\
0 \\
1 \\
1 \\
\end{array}
\quad \quad \quad
\text{T}_b
\]

Transmitted Waveform \quad \text{Pulse Dispersion}

The effect of sequence of pulses transmitted through channel is shown in fig. The spreading of pulse is greater than symbol duration, as a result adjacent pulses interfere. i.e. pulses get completely smeared, tail of smeared pulse enter into adjacent symbol intervals making it difficult to decide actual transmitted pulse.

First let us have look at different formats of transmitting digital data. In base band transmission best way is to map digits or symbols into pulse waveform. This waveform is generally termed as Line codes.

**BASEBAND TRANSMISSION:**

\[
\{b_k\} \xrightarrow{\text{Pulse Amp Genr}} \text{Transmitter Filter} \quad x(t) \xrightarrow{\text{AWAN}} r(t) \quad \text{Receiver Filter} \quad y(t) \xrightarrow{\text{Decision Device}} t = iT_b
\]

PAM signal transmitted is given by
\[ x(t) = \sum_{K=-\infty}^{\infty} a_K V(t - KT_b) \] \hspace{1cm} \text{(1)}

\( V(t) \) is basic pulse, normalized so that \( V(0) = 1 \),
\( x(t) \) represents realization of random process \( X(t) \) and \( a_k \) is sample value of random variable \( a_k \) which depends on type of line codes.

The receiving filter output
\[ y(t) = \mu \sum_{K=-\infty}^{\infty} a_k P(t - KT_b) \] \hspace{1cm} \text{(2)}

The output pulse \( \mu P(t) \) is obtained because input signal \( a_k \cdot V(t) \) is passed through series of systems with transfer functions \( H_T(f), H_C(f), H_R(f) \)

Therefore
\[ \mu P(f) = V(f) \cdot H_T(f) \cdot H_C(f) \cdot H_R(f) \] \hspace{1cm} \text{(3)}

\[ P(f) \longleftrightarrow p(t) \text{ and } V(f) \longleftrightarrow v(t) \]

The receiving filter output \( y(t) \) is sampled at \( t_i = iT_b \). where \( 'i' \) takes intervals
\( i = \pm 1, \pm 2 \ldots \)

\[ y(iT_b) = \mu \sum_{K=-\infty}^{\infty} a_k P(iT_b - KT_b) \]

\[ y(iT_b) = \mu a_i P(0) + \mu \sum_{K=-\infty}^{\infty} a_k P(iT_b - KT_b) \] \hspace{1cm} \text{(4)}

\( K = i \quad K \neq i \)

In equation (4) first term \( \mu a_i \) represents the output due to \( i^{th} \) transmitted bit. Second term represents residual effect of all other transmitted bits that are obtained while decoding \( i^{th} \) bit. This unwanted residual effect indicates ISI. This is due to the fact that when pulse of short duration \( T_b \) is transmitted on band limited channel, frequency components of the pulse are differentially attenuated due to frequency response of channel causing dispersion of pulse over the interval greater than \( T_b \).

In absence of ISI desired output would have \( y(t_i) = \mu a_i \)

**Nyquist Pulse Shaping Criterion**
In detection process received pulse stream is detected by sampling at intervals ±KT\textsubscript{b}, then in detection process we will get desired output. This demands sample of \textsuperscript{i}\textsuperscript{th} transmitted pulse in pulse stream at K\textsuperscript{th} sampling interval should be

\[
P(iT_b - KT_b) = \begin{cases} 
1 & K=i \\
0 & K \neq i
\end{cases} \quad (5)
\]

If received pulse \( P(t) \) satisfy this condition in time domain, then

\[y(t_i) = \mu a_i\]

Let us look at this condition by transform eqn(5) into frequency domain.

Consider sequence of samples \{P(nT_b)\} where \( n=0, \pm 1, \ldots \). by sampling in time domain, we write in frequency domain

\[p_\delta(f) = \frac{1}{T_b} \sum_{n=-\infty}^{\infty} p(f-n/T_b) \quad (6)\]

Where \( p_\delta(f) \) is Fourier transform of an infinite period sequence of delta functions of period \( T_b \) but \( p_\delta(f) \) can be obtained from its weighted sampled \( P(nT_b) \) in time domain

\[p_\delta(f) = \int \sum_{m=-\infty}^{\infty} p(mT_b) \delta(t-mT_b) e^{-j2\pi ft} dt = p(t)\delta(t)\]

Where \( m = i-k, \) then \( i=k, m=0; \) so

\[p_\delta(f) = \int p(0) \delta(t) e^{-j2\pi ft} dt\]

Using property of delta function

\[\text{i.e. } \int \delta(t) dt = 1\]

Therefore \( p_\delta(f) = p(0) = 1\)

\[P_\delta(f) = 1 \quad (7)\]

\( p(0) = 1, \text{i.e pulse is normalized (total area in frequency domain is unity) }\)

Comparing (7) and (6)

\[\frac{1}{T_b} \sum_{n=-\infty}^{\infty} p(f-n/T_b) = 1\]
Or
\[
\sum_{n=-\infty}^{\infty} p(f - n/T_b) = T_b = \frac{1}{R_b}
\]

Where \( R_b \) = Bit Rate
Is desired condition for zero ISI and it is termed Nyquist’s first criterion for distortion less base band transmission. It suggests the method for constructing band limited function to overcome effect of ISI.

**Ideal Solution**

Ideal Nyquist filter that achieves best spectral efficiency and avoids ISI is designed to have bandwidth as suggested

\[ B_0 = \frac{1}{2T_b} \quad \text{(Nyquist bandwidth) = } R_b / 2 \]

ISI is minimized by controlling \( P(t) \) in time domain or \( P(f) \) to be rectangular function in frequency domain.

\[
P(f) = \frac{1}{2B_0} \text{ rect} \left( \frac{f}{2B_0} \right)
\]

Impulse response in time domain is given by

\[
P(t) = \frac{\sin(2\pi B_0 t)}{2\pi B_0 t}
\]
Disadvantage of Ideal solution
- P(f) to be flat from \(-B_o\) to \(+B_o\) and zero elsewhere, abrupt transition is physically not realizable.
- For large values of 't', function P(t) decreases as resulting in slower decay of sinc function due to discontinuity of P(f).
  This causes timing error which results in ISI.

Practical solution
Raised Cosine Spectrum
- To design raised cosine filter which has transfer function consists of a flat portion and a roll off portion which is of sinusoidal form.
- Bandwidth \(B_o = \frac{1}{2T_b}\) is an adjustable value between \(B_o\) and \(2B_o\).

\[
P(f) = \begin{cases} 
\frac{1}{2B_o} & |f| < f_i \\
\frac{1}{4B_o} \left[\frac{1}{1 + \cos \left(\frac{\pi f_i - f}{2B_o f_i}\right)}\right] & f_i \leq |f| < 2B_o - f_i \\
0 & |f| \geq 2B_o - f_i 
\end{cases}
\]

The frequency \(f_i\) and bandwidth \(B_o\) are related by
\[
\alpha = 1 - \frac{f_i}{B_o}, \quad \alpha \text{ is called the roll off factor}
\]
for $\alpha = 0$, $f_1 = B_0$ and $B_W = B_0$ is the minimum Nyquist bandwidth for the rectangular spectrum.

- For given $B_0$, roll off factor $\alpha$ specifies the required excess bandwidth
- $\alpha = 1$, indicates required excess bandwidth is 100% as roll off characteristics of $P(f)$ cuts off gradually as compared with ideal low pass filters. This function is practically realizable.

Impulse response $P(t)$ is given by

$$P(t) = \text{sinc}(2B_0 t) \frac{\cos(2\pi \alpha B_0 t)}{1 - 16\alpha B_0^2 t^2}$$

$P(t)$ has two factors

- $\text{sinc}(2B_0 t)$ which represents ideal filter - ensures zero crossings
- second factor that decreases as fast decay - helps in reducing tail of sinc pulse i.e.

$$P(t) = \text{sinc}(4B_0 t)$$

- For $\alpha = 1$,

$$t = \frac{T_b}{2} \quad P(t) = 0.5$$
Pulse width measured exactly equal to bit duration $T_b$. Zero crossings occur at $t = \pm 3T_b, \pm 5T_b...$ In addition to usual crossings at $t = \pm T_b, \pm 2T_b...$ Which helps in time synchronization at receiver at the expense of double the transmission bandwidth.

Transmission bandwidth required can be obtained from the relation

$$B = 2B_0 - f_1$$

Where $B =$ Transmission bandwidth

$$B_0 = \frac{1}{2T_b} \text{ Nyquist bandwidth}$$

But

$$\alpha = 1 - \frac{f_1}{B_0}$$

using

$$f_1 = B_0 (1 - \alpha)$$

$$B = 2B_0 - B_0(1 - \alpha)$$

therefore

$$B = B_0(1 + \alpha)$$

$\alpha = 0; B = B_0, \text{minimum bandwidth}$

$\alpha = 1; B = 2B_0, \text{sufficient bandwidth}$

Roll-off factor

Smaller roll-off factor:

• Less bandwidth, but
• Larger tails are more sensitive to timing errors

Larger roll-off factor:

• Small tails are less sensitive to timing errors, but
• Larger bandwidth

Example 1

A certain telephone line bandwidth is 3.5Khz. calculate data rate in bps that can be transmitted if binary signaling with raised cosine pulses and roll off factor $\alpha = 0.25$ is employed.
Solution:
\[ \alpha = 0.25 \quad ---- \text{roll off} \]
\[ B = 3.5\text{Khz} \quad ----\text{transmission bandwidth} \]

\[ B = B_0(1+ \alpha) \]
\[ B_0 = \frac{1}{2T_b} = \frac{R_b}{2} \quad \text{Ans: } R_b= 5600\text{bps} \]

Example 2

A source outputs data at the rate of 50,000 bits/sec. The transmitter uses binary PAM with raised cosine pulse in shaping of optimum pulse width. Determine the bandwidth of the transmitted waveform. Given

a. \( \alpha = 0 \)

b. \( \alpha = 0.25 \)

c. \( \alpha = 0.5 \)

d. \( \alpha = 0.75 \)

e. \( \alpha = 1 \)

Solution
\[ B = B_0(1+ \alpha) \quad \text{B}_0=\frac{R_b}{2} \]

a. Bandwidth = 25,000(1 + 0) = 25 kHz

b. Bandwidth = 25,000(1 + 0.25) = 31.25 kHz

c. Bandwidth = 25,000(1 + 0.5) = 37.5 kHz

d. Bandwidth = 25,000(1 + 0.75) = 43.75 kHz

e. Bandwidth = 25,000(1 + 1) = 50 kHz

Example 3

A communication channel of bandwidth 75 KHz is required to transmit binary data at a rate of 0.1Mb/s using raised cosine pulses. Determine the roll off factor \( \alpha \).

\[ R_b = 0.1\text{Mbps} \]
\[ B = 75\text{KHz} \]
\[ \alpha = ? \]

\[ B = B_0(1+ \alpha) \]
\[ B_0 = \frac{R_b}{2} \quad \text{Ans : } \alpha =0.5 \]
So far we treated ISI as an undesirable phenomenon that produces a degradation in system performance, but by adding ISI to the transmitted signal in a controlled manner, it is possible to achieve a bit rate of $2B_0$ bits per second in a channel of bandwidth $B_0$ Hz. Such a scheme is **correlative coding** or **partial-response signaling** scheme. One such example is **Duo binary signaling**.

Duo means transmission capacity of system is doubled.

**Duo binary coding**

Consider binary sequence $\{b_k\}$ with uncorrelated samples transmitted at the rate of $R_b$ bps. Polar format with bit duration $T_b$ sec is applied to duo binary conversion filter. when this sequence is applied to a duobinary encoder, it is converted into three level output, namely -2, 0 and +2. To produce this transformation we use the scheme as shown in fig. The binary sequence $\{b_k\}$ is first passed through a simple filter involving a single delay elements. For every unit impulse applied to the input of this filter, we get two unit impulses spaced $T_b$ seconds apart at the filter output. Digit $C_k$ at the output of the duobinary encoder is the sum of the present binary digit $b_k$ and its previous value $b_{k-1}$

$$C_k = b_k + b_{k-1}$$
The correlation between the pulse amplitude $C_k$ comes from $b_k$ and previous $b_{k-1}$ digit, can be thought of as introducing ISI in controlled manner, i.e., the interference in determining $\{b_k\}$ comes only from the preceding symbol $\{b_{k-1}\}$ The symbol $\{b_k\}$ takes $\pm 1$ level thus $C_k$ takes one of three possible values -2,0,+2. The duo binary code results in a three level output. In general, for M-ary transmission, we get $2M-1$ levels

**Transfer function of Duo-binary Filter**

The ideal delay element used produce delay of $T_b$ seconds for impulse will have transfer function $e^{-j 2\pi f T_b}$.

Overall transfer function of the filter $H(f)$

$$H(f) = H_c(f) + H_c(f) e^{-j 2\pi f T_b}$$

$$= 2H_c(f) \left[ e^{j \frac{\pi f T_b}{2}} + e^{-j \frac{\pi f T_b}{2}} \right] e^{-j \pi f T_b}$$

$$= 2H_c(f) \cos(\pi f T_b) e^{-j \pi f T_b}$$

As ideal channel transfer function

$$H_c(f) = \begin{cases} 1 & |f| \leq \frac{1}{2T_b} \\ 0 & \text{otherwise} \end{cases}$$

Thus overall transfer function

$$H(f) = \begin{cases} 2 \cos(\pi f T_b) e^{-j \pi f T_b} & |f| \leq \frac{1}{2T_b} \\ 0 & \text{otherwise} \end{cases}$$
H(f) which has a gradual roll off to the band edge, can also be implemented by practical and realizable analog filtering. Fig. shows Magnitude and phase plot of Transfer function.

![Magnitude and phase plot of Transfer function](image)

Advantage of obtaining this transfer function H(f) is that practical implementation is easy.

**Impulse response**

Impulse response h(t) is obtained by taking inverse Fourier transformation of H(f)

\[
h(t) = \int_{-\infty}^{\infty} H(f)e^{j2\pi ft} df
\]

\[
= \frac{1}{2T_B} \int_{-\frac{1}{2T_B}}^{\frac{1}{2T_B}} 2\cos(\pi f T_B) e^{-j\pi f T_B} \left[ e^{j2\pi f t} \right] df
\]

\[
= \sin\left(\frac{\pi t}{T_B}\right) + \sin\left[\frac{\pi(t-T_B)}{T_B}\right]
\]

\[
= \sin\left(\frac{\pi t}{T_B}\right) - \sin\left[\frac{\pi(t-T_B)}{T_B}\right]
\]
Impulse response has two sinc pulses displaced by $T_b$ sec. Hence overall impulse response has two distinguishable values at sampling instants $t = 0$ and $t = T_b$. 

$$h(t) = \frac{T_b 2 \sin \left[ \frac{\pi t}{T_b} \right]}{\pi (T_b - 1)}$$

**Overall Impulse response**
Duo binary decoding

**Encoding**: During encoding the encoded bits are given by

\[ C_k = b_k + b_{k-1} \]

**Decoding**: At the receiver original sequence \( \{b_k\} \) may be detected by subtracting the previous decoded binary digit from the presently received digit \( C_k \). This demodulation technique (known as nonlinear decision feedback equalization) is essentially an inverse of the operation of the digital filter at the transmitter.

If \( \hat{b}_k \) is estimate of original sequence \( b_k \) then

\[ \hat{b}_k = C_k - \hat{b}_{k-1} \]

**Disadvantage**

\[ \hat{b}_{k-1} \]
If $C_k$ and previous estimate is received properly without error then we get correct decision and current estimate. Otherwise once error made it tends to propagate because of decision feedback. Current $\{b_k\}$ depends on previous $b_{k-1}$.

Example

Consider sequence 0010110

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Received Sequence ${c_k}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary Sequence ${b_k}$</td>
<td>0 0 1 0 1 1 0</td>
</tr>
<tr>
<td>Polar Amplitudes</td>
<td>-1 -1 1 -1 1 1 -1</td>
</tr>
<tr>
<td>Coding Rule $c_k = b_k + b_{k-1}$ (transmitted signal)</td>
<td>-2 0 0 0 2 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decoding Decision Rule</td>
</tr>
<tr>
<td>If $c_k = 2$, decide that $b_k = 1$ (symbol 1)</td>
</tr>
<tr>
<td>If $c_k = -2$, decide that $b_k = -1$ (symbol 0)</td>
</tr>
<tr>
<td>If $c_k = 0$, decide opposite of the previous decision</td>
</tr>
<tr>
<td>Received Sequence ${c_k}$</td>
</tr>
<tr>
<td>Decoded sequence in bipolar form</td>
</tr>
<tr>
<td>Decoded sequence $b_k$</td>
</tr>
</tbody>
</table>

Precoding
In case of duo binary coding if error occurs in a single bit it reflects as multiple errors because the present decision depends on previous decision also. To make each decision independent we use a precoder at the receiver before performing duo binary operation.

The precoding operation performed on the input binary sequence $\{b_k\}$ converts it into another binary sequence $\{a_k\}$ given by

$$a_k = b_k \oplus a_{k-1}$$

a modulo 2 logical addition

Unlike the linear operation of duo binary operation, the precoding is a non-linear operation.
Fig. A precoded duo binary scheme.

\( \{a_k\} \) is then applied to duobinary coder, which produce sequence \( \{C_k\} \)

\[
C_k = a_k + a_{k-1}
\]

If that symbol at precoder is in polar format \( C_k \) takes three levels,

\[
C_k = \begin{cases} 
\pm 2v & \text{if } b_k = \text{symbol 0} \\
0v & \text{if } b_k = \text{symbol 1}
\end{cases}
\]

The decision rule for detecting the original input binary sequence \( \{b_k\} \) from \( \{c_k\} \) is

\[
b_k^\wedge = \begin{cases} 
symbol 0 & \text{if } |C_k| > 1v \\
symbol 1 & \text{if } |C_k| \leq 1v
\end{cases}
\]
Example: with start bit as 0, reference bit 1

<table>
<thead>
<tr>
<th><strong>Transmitter</strong></th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Binary Sequence</strong> ( {b_k} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Precoded Sequence</strong> ( a_k = b_k - a_{k-1} ) &lt;br&gt; (assume start bit as 1 or 0)</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>polar Representation of</strong>&lt;br&gt;<strong>Precoded Sequence</strong> ( a_k )</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td><strong>Duo binary coder output</strong>&lt;br&gt;( C_k = a_k + a_{k-1} )</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td><strong>Decoding decision Rule</strong></td>
<td>If ( c_k = \pm 2 ) decide ( b_k = \text{Symbol 0} ) &lt;br&gt; If ( c_k = 0 ) decide ( b_k = \text{Symbol 1} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Receiver</strong></th>
<th>2</th>
<th>2</th>
<th>0</th>
<th>-2</th>
<th>0</th>
<th>0</th>
<th>-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Received sequence</strong> ( c_k )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Decoded binary sequence</strong> ( b_k )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Example: with start bit as 0, reference bit 0

<table>
<thead>
<tr>
<th><strong>Transmitter</strong></th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Binary Sequence</strong> ( {b_k} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Precoded Sequence</strong> ( a_k = b_k - a_{k-1} ) &lt;br&gt; (assume start bit as 1 or 0)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>polar Representation of</strong>&lt;br&gt;<strong>Precoded Sequence</strong> ( a_k )</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td><strong>Duo binary coder output</strong>&lt;br&gt;( C_k = a_k + a_{k-1} )</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>+2</td>
<td>0</td>
<td>0</td>
<td>+2</td>
</tr>
<tr>
<td><strong>Decoding decision Rule</strong></td>
<td>If ( c_k = \pm 2 ) decide ( b_k = \text{Symbol 0} ) &lt;br&gt; If ( c_k = 0 ) decide ( b_k = \text{Symbol 1} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Receiver</strong></th>
<th>-2</th>
<th>-2</th>
<th>0</th>
<th>+2</th>
<th>0</th>
<th>0</th>
<th>+2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Received sequence</strong> ( c_k )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Decoded binary sequence</strong> ( b_k )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Example: with start bit as 1, reference bit 1

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary Sequence {b_k}</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>Precoded Sequence ak (a_k = b_k + a_{k-1})</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(assume start bit as 1 or 0)</td>
<td>(a_{k-1})</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>polar Representation of Precoded Sequence (a_k)</td>
<td>0</td>
<td>0</td>
<td>+2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>Duo binary coder output (C_k = a_k + a_{k-1})</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
| Decoding decision Rule | \(c_k = \pm 2\) decide \(b_k = \) Symbol 0 
\(c_k = 0\) decide \(b_k = \) Symbol 1 |

Example: with start bit as 1, reference bit 0

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary Sequence {b_k}</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>Precoded Sequence ak (a_k = b_k + a_{k-1})</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(assume start bit as 1 or 0)</td>
<td>(a_{k-1})</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>polar Representation of Precoded Sequence (a_k)</td>
<td>0</td>
<td>0</td>
<td>-2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Duo binary coder output (C_k = a_k + a_{k-1})</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
| Decoding decision Rule | \(c_k = \pm 2\) decide \(b_k = \) Symbol 0 
\(c_k = 0\) decide \(b_k = \) Symbol 1 |

Receiver

| Received sequence \(c_k\) | 0 | 0 | +2 | 0 | -2 | -2 | 0 |
| Decoded binary sequence \(b_k\) | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
Today the duo-binary techniques are widely applied throughout the world. While all current applications in digital communications such as data transmission, digital radio, and PCM cable transmission, and other new possibilities are being explored. This technique has been applied to fiber optics and to high density disk recording which have given excellent results.

Example

The binary data 001101001 are applied to the input of a duo binary system.

a) Construct the duo binary coder output and corresponding receiver output, without a precoder.

b) Suppose that due to error during transmission, the level at the receiver input produced by the second digit is reduced to zero. Construct the new receiver output.

c) Repeat above two cases with use of precoder without a precoder

<table>
<thead>
<tr>
<th>Input Sequence ( {b_k} )</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Voltage Representation</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>( c_k = b_k + b_{k-1} )</td>
<td></td>
<td></td>
<td>-2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td>( b_k^\wedge = c_k - b_{k-1}^\wedge )</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>Decoded ( b_k^\wedge )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

If error occurs in second position, \( c_k \) received is 0 instead of -2V

<table>
<thead>
<tr>
<th>Received ( c_k )</th>
<th>0</th>
<th>0</th>
<th>2</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>-2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>polar form ( b_k^\wedge = c_k - b_{k-1}^\wedge )</td>
<td>-1</td>
<td>-1</td>
<td>3</td>
<td>-3</td>
<td>+3</td>
<td>+3</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>Decoded ( b_k^\wedge )</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
With a precoder (start bit 1)

<table>
<thead>
<tr>
<th>Input Sequence ( {b_k} )</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoded sequence ( {a_k} = b_k \oplus a_{k-1} )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Polar Representation</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>Duobinary coded sequence</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>Decision ( b_k )</td>
<td>0</td>
<td>0</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>( c_k = 1 ) symbol 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( c_k = 1 ) symbol 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If error occurs in 2\textsuperscript{nd} position then voltage level of \( c_k = 0 \), then

<table>
<thead>
<tr>
<th>Received ( c_k )</th>
<th>2</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>2</th>
<th>0</th>
<th>-2</th>
<th>-2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision for ( b_k )</td>
<td>0</td>
<td>1</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>( c_k = 1 ) symbol 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( c_k = 1 ) symbol 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With a precoder (start bit 0)
The Transfer function $H(f)$ of Duo binary signalling has non zero spectral value at origin, hence not suitable for channel with Poor DC response. This drawback is corrected by Modified Duobinary scheme.

**Modified Duobinary scheme.**

It is an extension of the duo-binary signaling. The modified duo binary technique involves a correlation span of two binary digits. Two-bit delay causes the ISI to spread over two symbols. This is achieved by subtracting input binary digits spaced $2T_b$ secs apart.

**Modified Duobinary scheme.**

<table>
<thead>
<tr>
<th>Input Sequence ${b_k}$</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoded sequence ${a_k}$ = $b_k + a_{k-1}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Polar Representation</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Duobinary coded sequence</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>-2</td>
<td>0</td>
<td>+2</td>
<td>+2</td>
<td>0</td>
</tr>
<tr>
<td>Decision $b_k$</td>
<td>0</td>
<td>0</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>$c_k &gt; 1$ symbol 0</td>
<td>0</td>
<td>0</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>$c_k &lt; 1$ symbol 1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

If error occurs in 2nd position then voltage level of $c_k = 0$, then

<table>
<thead>
<tr>
<th>Received $c_k$</th>
<th>-2</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>-2</th>
<th>0</th>
<th>+2</th>
<th>+2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision for $b_k$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

![Graph of Transfer Function H(f)](image)

The Transfer function $H(f)$ of Duo binary signalling has non zero spectral value at origin, hence not suitable for channel with Poor DC response. This drawback is corrected by Modified Duobinary scheme.
**Transmitter**

The precoded output sequence is given by a modulo 2 logical addition

\[ a_k = b_k \oplus a_{k-2} \]

If \( a_k = \pm 1V \), \( C_k \) takes one of three values 2,0,-2.

Output sequence of modified duo binary filter is given by \( C_k \)

\[ C_k = a_k - a_{k-2} \]

\( C_k \) takes one of three values 2,0,-2

\( C_k = 0V, \) if \( b_k \) is represented by symbol 0

\( C_k = \pm 2V, \) if \( b_k \) is represented by symbol 1

**Receiver**

At the receiver we may extract the original sequence \( \{b_k\} \) using the decision rule

\[ b_k = \begin{cases} 
\text{symbol 0 if } |C_k| > 1V \\
\text{symbol 1 if } |C_k| \leq 1V 
\end{cases} \]

The Transfer function of the filter is given by
The Transfer function has zero value at origin, hence suitable for poor dc channels.

Impulse response

Impulse response \( h(t) \) is obtained by taking Inverse Fourier transformation of \( H(f) \)

\[
h(t) = \int_{-\infty}^{\infty} H(f) e^{j2\pi ft} df
\]
Impulse response has three distinguishable levels at the sampling instants.

\[
\begin{align*}
\frac{1}{2T_b} & \int_{-\frac{1}{2T_b}}^{\frac{1}{2T_b}} 2 j \sin(2\pi f T_b) e^{-j2\pi f T_b} e^{j2\pi f t} df \\
& = \frac{1}{2T_b} \sin\left(\frac{\pi t}{T_b}\right) \sin\left(\frac{\pi (t-2T_b)}{T_b}\right) \\
& = \frac{1}{2T_b} \sin\left(\frac{\pi t}{T_b}\right) \sin\left(\frac{\pi (t-2T_b)}{T_b}\right) \\
& = 2T_b^2 \sin\left(\frac{\pi t}{T_b}\right) \\
& = 2T_b^2 \sin\left(\frac{\pi t}{T_b}\right)
\end{align*}
\]

Impulse response has three distinguishable levels at the sampling instants.
To eliminate error propagation modified duo binary employs Precoding option same as previous case.

Prior to duo binary encoder precoding is done using modulo-2 adder on signals spaced $2T_b$ apart

$$a_k = b_k \oplus a_{k-2}$$

Example: Consider binary sequence \(\{b_k\} = \{01101101\}\) applied to input of a precoded modified duobinary filter. Determine receiver output and compare with original \(\{b_k\}\).

<table>
<thead>
<tr>
<th>Binary sequence ({b_k})</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoded sequence (a_k = b_k \oplus a_{k-2})</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Polar Representation</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Transmitted output (c_k = a_k - a_{k-2})</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>+2</td>
<td>+2</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td>Received Sequence decision (</td>
<td>c_k</td>
<td>&lt; 1V \rightarrow 0) (</td>
<td>c_k</td>
<td>&gt; 1V \rightarrow 1)</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>Decoded (\hat{b}_k)</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Consider binary sequence \( \{b_k\} = \{01101101\} \)

<table>
<thead>
<tr>
<th>Binary sequence ( {b_k} )</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoded sequence ( a_k = b_k \oplus a_{k-2} )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Polar Representation</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Transmitted output ( c_k = a_{k} - a_{k-2} )</td>
<td>0</td>
<td>+2</td>
<td>2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Received Sequence decision(</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( c_k )</td>
<td>0</td>
<td>+2</td>
<td>2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Decoded ( \hat{b}_k )</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**Example**

The binary data 01100101 are applied to the input of a modified duo binary system.

a) Construct the modified duobinary coder output and corresponding receiver output, without a precoder.

b) Suppose that due to error during transmission, the level at the receiver input produced by the third digit is reduced to zero. Construct the new receiver output.

c) Repeat above two cases with use of precoder
### Modified duo binary coder output and corresponding receiver output, with a precoder

<table>
<thead>
<tr>
<th>Binary sequence ( {b_k} )</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Representation</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Transmitted output</td>
<td>-2</td>
<td>0</td>
<td>+2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( c_k = b_k - b_{k-2} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Received Sequence</td>
<td>-2</td>
<td>0</td>
<td>+2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Decision ( b_k = c_k + b_{k-2} )</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Decoded ( b_k^* )</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

If error occurs in 3rd position then voltage level of \( c_k = 0 \), then

| Received \( c_k \)             | -2| 0 | 0 | 0 | -2| -2| 2 | 0 | 0 |
| Decision for \( b_k \)         | +1| +1| -1| +1| +1| -1| -1| +1| -1| -1|
| \( b_k = c_k + b_{k-2} \)      |   |   |   |   |   |   |   |   |   |
| Decoded                        | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |

<table>
<thead>
<tr>
<th>Binary sequence ( {b_k} )</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoded sequence</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( a_k = b_k \oplus a_{k-2} )</td>
<td>(a_{k-2})</td>
<td>(a_{k-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polar Representation</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Transmitted output</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( c_k = a_k - a_{k-2} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Received Sequence decision</td>
<td>(</td>
<td>C_k</td>
<td>&lt; 1 V \rightarrow 0)</td>
<td>(</td>
<td>C_k</td>
<td>&gt; 1 V \rightarrow 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decoded</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| Decoded                         | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
If error occurs in 3rd position then voltage level of $c_k = 0$, then

<table>
<thead>
<tr>
<th>Received $c_k$</th>
<th>0</th>
<th>-2</th>
<th>0</th>
<th>2</th>
<th>0</th>
<th>0</th>
<th>2</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision for $b_k$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_k &gt; 1$ symbol 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_k &lt; 1$ symbol 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{N-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|   | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |

Generalized form of correlative coding scheme

Fig. Generalized Correlative Coding
The Duo binary and modified Duo binary scheme have correlation spans of one binary digit and two binary digits respectively. This generalisation scheme involves the use of a tapped delay line filter with tap weights $f_0, f_1, f_2, \ldots f_{n-1}$. A correlative samples $C_k$ is obtained from a superposition of 'N' successive input sample values $b_k$

$$C_k = \sum_{n=0}^{N-1} f_n b_{k-n}$$

By choosing various combination values for $f_n$, different correlative coding schemes can be obtained from simple duo binary.

**Base band Transmission of M-ary data**

In base band M-ary PAM, output of the pulse generator may take on any one of the $M$ possible amplitude levels with $M>2$ for each symbol. The blocks of $n$-message bits are represented by $M$-level waveforms with $M=2^n$.

Ex: $M=4$ has 4 levels. possible combination are 00, 10, 11, 01

$T=2T_b$ is termed **symbol duration**.

In general symbol duration $T = T_b \log_2 M$.

M-ary PAM system is able to transmit information at a rate of $\log_2 M$ faster than binary PAM for given channel bandwidth.

$$R = \frac{R_b}{\log_2 M}$$

$R_b = \text{bit rate for binary system}$

$R = \text{symbol rate for binary system}$

M-ary PAM system requires more power which is increased by factor equal to $M^2/\log_2 M$ for same average probability of symbol error.

M-ary Modulation is well suited for the transmission of digital data over channels that offer a **limited bandwidth and high SNR**

**Example**

An analog signal is sampled, quantised and encoded into a binary PCM wave. The number of representation levels used is 128. A synchronizing pulse is added at
the end of each code word representing a sample of the analog signal. The resulting PCM wave is transmitted over a channel of bandwidth 12kHz using binary PAM system with a raised cosine spectrum. The roll off factor is unity.

a) Find the rate (in BPS) at which information is transmitted through the channel.
b) Find the rate at which the analog signal is sampled. What is the maximum possible value for the highest frequency component of the analog signal.

Solution
Given Channel with transmission BW $B=12kHz$.
Number of representation levels $L = 128$
Roll off $\alpha = 1$

a) $B = B_0(1+\alpha)$.
Hence $B_0 = 6kHz$.
$B_0 = \frac{R_b}{2}$ therefore $R_b = 12kbps$.

b) For $L=128$, $L = 2^n$, $n = 7$
symbol duration $T = T_b \log_2 M = nT_b$
sampling rate $f_s = \frac{R_b}{n} = 12/7 = 1.714kHz$.
And maximum frequency component of analog signal is
From LP sampling theorem $w = \frac{f_s}{2} = 857Hz$.

Eye pattern
The quality of digital transmission systems are evaluated using the bit error rate. Degradation of quality occurs in each process modulation, transmission, and detection. The eye pattern is experimental method that contains all the information concerning the degradation of quality. Therefore, careful analysis of the eye pattern is important in analyzing the degradation mechanism.

- Eye patterns can be observed using an oscilloscope. The received wave is applied to the vertical deflection plates of an oscilloscope and the sawtooth wave at a rate equal to transmitted symbol rate is applied to the horizontal deflection plates, resulting display is eye pattern as it resembles human eye.
- The interior region of eye pattern is called eye opening
We get superposition of successive symbol intervals to produce eye pattern as shown below.

- The width of the eye opening defines the time interval over which the received wave can be sampled without error from ISI.
- The optimum sampling time corresponds to the maximum eye opening.
- The height of the eye opening at a specified sampling time is a measure of the margin over channel noise.

The sensitivity of the system to timing error is determined by the rate of closure of the eye as the sampling time is varied.

Any non-linear transmission distortion would reveal itself in an asymmetric or squinted eye. When the extent of ISI is excessive, traces from the upper portion of the eye pattern cross traces from lower portion with the result that the eye is completely closed.

**Example of eye pattern:**

Binary-PAM  Perfect channel (no noise and no ISI)
Example of eye pattern: Binary-PAM with noise no ISI

**Example 1**

A binary wave using polar signaling is generated by representing symbol 1 by a pulse of amplitude -1v; in both cases the pulse duration equals the bit duration. The signal is applied to a low pass RC filter with transfer function

\[ H(f) = \frac{1}{1 + \frac{f}{f_0}} \]

Construct eye pattern for the filter for
1. Alternating 1s and 0s
2. A long sequence of 1s followed by long sequence of zeros.
Example 2

The binary sequence 011010 is transmitted through channel having a raised cosine characteristics with roll off factor unity. Assume the use of polar signaling, format. construct the Eye pattern

Adaptive equalization for data transmission

This technique is another approach to minimize signal distortion in the base band data transmission. This is Nyquist third method for controlling ISI.
Equalization is essential for high speed data transmission over voice grade telephone channel which is essentially linear and band limited. High speed data transmission involves two basic operations:

i) **Discrete pulse amplitude modulation:**
   
   The amplitudes of successive pulses in a periodic pulse train are varied in a discrete fashion in accordance with incoming data stream.

ii) **Linear modulation:**
   
   Which offers band width conservation to transmit the encoded pulse train over telephone channel.

   At the receiving end of the systems, the received waves is demodulated and then synchronously sampled and quantized. As a result of dispersion of the pulse shape by the channel the number of detectable amplitude levels is limited by ISI rather than by additive noise. If the channel is known, then it is possible to make ISI arbitrarily small by designing suitable pair of transmitting and receiving filters for pulse shaping.

   In switched telephone networks we find that two factors contribute to pulse distortion.

   1. Differences in the transmission characteristics of individual links that may be switched together.

   2. Differences in number of links in a connection

   Because of these two characteristics, telephone channel is random in nature. To realize the full transmission capability of a telephone channel we need adaptive equalization.

**Adaptive equalization**

- An equalizer is a filter that compensates for the dispersion effects of a channel. Adaptive equalizer can adjust its coefficients continuously during the transmission of data.

**Pre channel equalization**

- requires feed back channel
- causes burden on transmission.
**Post channel equalization**
Achieved prior to data transmission by training the filter with the guidance of a training sequence transmitted through the channel so as to adjust the filter parameters to optimum values.

**Adaptive equalization** – It consists of tapped delay line filter with set of delay elements, set of adjustable multipliers connected to the delay line taps and a summer for adding multiplier outputs.

The output of the Adaptive equalizer is given by

\[ y(nt) = \sum_{i=0}^{M-1} c_i x(nT - iT) \]

\( c_i \) is weight of the \( i^{th} \) tap  
Total number of taps are \( M \).
Tap spacing is equal to symbol duration \( T \) of transmitted signal.
In a conventional FIR filter the tap weights are constant and particular designed response is obtained. In the adaptive equaliser the \( C_i \)'s are variable and are adjusted by an algorithm.

**Two modes of operation**

1. Training mode  
2. Decision directed mode
Mechanism of adaptation

Training mode

A known sequence \(d(nT)\) is transmitted and synchronized version of it is generated in the receiver applied to adaptive equalizer.

This training sequence has maximal length PN Sequence, because it has large average power and large SNR, resulting response sequence (Impulse) is observed by measuring the filter outputs at the sampling instants.

The difference between resulting response \(y(nT)\) and desired response \(d(nT)\) is error signal which is used to estimate the direction in which the coefficients of filter are to be optimized using algorithms.

Methods of implementing adaptive equalizer

i) Analog
   ii) Hard wired digital
   iii) Programmable digital

Analog method

- **Charge coupled devices** [CCD’s] are used.
- CCD- FET’s are connected in series with drains capacitively coupled to gates.
- The set of adjustable tap widths are stored in digital memory locations, and the multiplications of the analog sample values by the digitized tap weights done in analog manner.
- Suitable where symbol rate is too high for digital implementation.
**Hard wired digital technique**

- Equalizer input is first sampled and then quantized in to form that is suitable for storage in shift registers.

- Set of adjustable lap weights are also stored in shift registers. Logic circuits are used for required digital arithmetic operations.

- widely used technique of equalization

**Programmable method**

- Digital processor is used which provide more flexibility in adaptation by programming.

  Advantage of this technique is same hardware may be timeshared to perform a multiplicity of signal processing functions such as filtering, modulation and demodulation in modem.