The use of an appropriate waveform for baseband representation of digital data is basic to its transmission from a source to a destination. This means that digital pulse modulation can be used for transmitting the output of a digital source.

We know that the signal symbols can amplitude modulate some carrier to generate amplitude modulated pulse train. Therefore, such signal may be represented as,

$$x(t) = \sum_{k=-\infty}^{\infty} a_k \, p(t-kT) \quad ...(12.1)$$

Here, a_k is the amplitude of k^{th} symbol in the message sequence.

$p(t)$ is the pulsed carrier signal, *i.e.* is a basic pulse shape. It's pulses are modulated by a_k.

T is the maximum duration (*i.e.*, time period) allowed for the carrier pulse. The unmodulated carrier pulse $p(t)$ is the rectangular pulse and it can take variable duty cycle. It can be represented as,

$$p(t) = \begin{cases} 1 & \text{for} \quad t = 0 \\ 0 & \text{for} \quad t = \pm T, \pm 2T, ... \end{cases} \quad ...(12.2)$$

$x(t)$ is the pulse waveform. To recover the original digital signal from $x(t)$ we have to sample $x(t)$ at some fixed intervals and check the signal in these intervals. This checking is the detection of the transmitted symbols. From equation (12.1), we observe that if $p(t)$ is zero, then $x(t)$ is also zero. Therefore, it is preferable to sample $x(t)$ when $p(t)$ is zero. This means that at this time $[p(t) = 0]$ no digital information is present/transmitted in the pulse waveform. Therefore, $x(t)$ can be sampled periodically at $t = kT$ where $k = 0, \pm 1, \pm 2$, ...etc.

Also, $p(t)$ is the rectangular pulse and may be written as,

$$p(t) = rect\left(\frac{t}{\tau}\right) \quad ...(12.3)$$

Because, the pulse to pulse interval is 'T', therefore the width of the pulse τ should be less than or equal to T.

i.e., $\tau \leq T$

The signalling rate is given as,

$$r = \frac{1}{T} \quad ...(12.4)$$

If 'T' represents the duration of one bit, then $T = T_b$ and signalling rate will be,

$$r = \frac{1}{T_b} \quad ...(12.5)$$

12.4. Line Coding and its Properties

The digital data can be transmitted by various transmission or line codes such as on-off, polar, bipolar and so on. This is called **line-coding**. Each type of line-code has its advantages and disadvantages.

Thus, among other desirable properties, a line code must have the following properties:

1. Transmission bandwidth

For a line-code, the transmission bandwidth must be as small as possible.

2. Power efficiency

For a given bandwidth and a specified detection error probability, the transmitted power for a line code should be as small as possible.

3. **Error detection and correction capability**

It must be possible to detect and preferably correct detection errors. For example, in a bipolar case, a signal error will cause bipolar violation and thus can easily be detected.

4. **Favourable power spectral density**

It is desirable to have zero power spectral density (PSD) at $w = 0$ (*i.e.*, dc) since ac coupling and transformers are used at the repeaters. Significant power in low-frequency components causes dc wander in the pulse stream when ac coupling is used. The a.c. coupling is required since the dc paths provided by the cable pairs between the repeater sites are used to transmit the power required to operate the repeaters.

5. **Adequate timing content**

It must be possible to extract timing or clock information from the signal.

6. **Transparency**

It must be possible to transmit a digital signal correctly regardles of the pattern of 1's and 0's.

12.5. Various PAM Formats or Line Codes

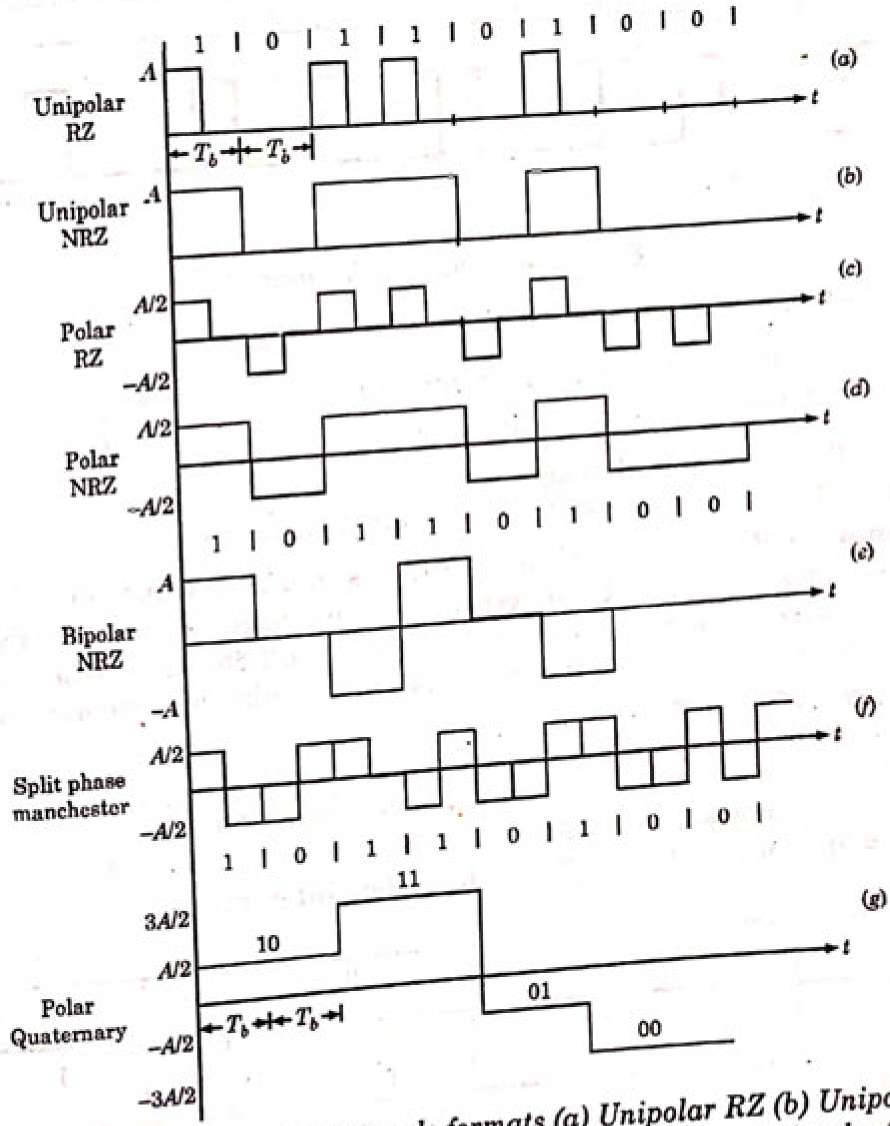

Fig. 12.3. *Various digital PAM signals formats (a) Unipolar RZ (b) Unipolar NRZ (c) Polar RZ (d) Polar NRZ (e) Bipolar NRZ (f) Split phase Manchester (g) Polar quaternary NRZ.*

Some of the important PAM formats are as under:

(i) Non-return to zero (NRZ) and return to zero (RZ) unipolar format.

(ii) NRZ and RZ polar format.

(iii) Non-return to zero bipolar format.

(iv) Manchester format.

(v) Polar quaternary NRZ format.

All the formats have been shown for a binary message 10110100. Figure 12.3 shows various PAM formats or line codes.

12.6. Unipolar RZ and NRZ

In unipolar format, the waveform has a single polarity. The waveform can have +5 or +12 volts when high. The waveform is simple on-off. In the unipolar RZ form, the waveform has zero value when symbol '0' is transmitted and waveform has 'A' volts when '1' is transmitted. In RZ form, the 'A' volts is present for $T_b/2$ period if symbol '1' is transmitted and for remaining $T_b/2$, waveform returns to zero value, *i.e.*, for unipolar RZ form, we have

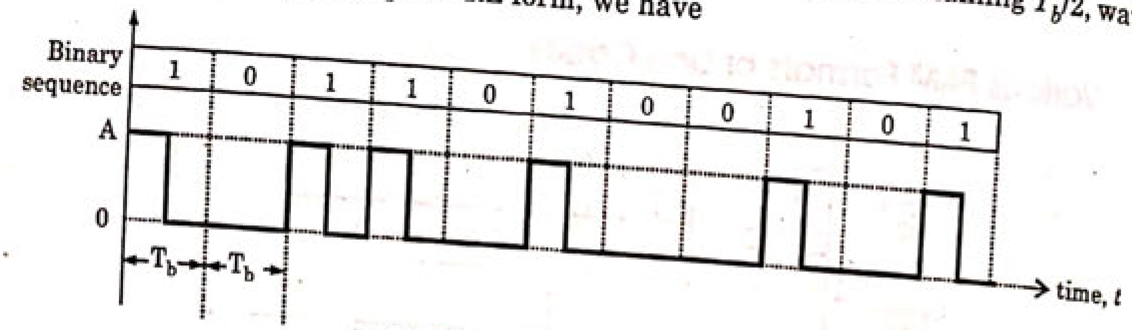

Fig. 12.4. *Unipolar RZ format.*

If symbol '1' is transmitted, then we have

$$x(t) = \begin{cases} A \text{ for } 0 \le t < T_b/2 & \text{(Half interval)} \\ 0 \text{ for } T_b/2 \le t < T_b & \text{(Half interval)} \end{cases} \quad \text{....(12.6)}$$

and if symbol '0' is transmitted, then

$$x(t) = 0 \quad \text{for} \quad 0 \le t < T_b \quad \text{(complete interval)} \quad \text{...(12.7)}$$

Hence, in unipolar RZ format, each pulse returns to a zero value. Figure 12.4 shows this signal format. A unipolar NRZ (*i.e.*, not return to zero) format is shown in figure 12.5. When symbol '1' is to be transmitted, the signal has 'A' volts for full duration. When symbol '0' is to be transmitted, the signal has zero volts (*i.e.* no signal) for complete symbol duration.

Thus, for unipolar NRZ format,

If symbol '1' is transmitted, we have

$$x(t) = A \quad \text{for} \quad 0 \le t < T_b \quad \text{(complete interval)} \quad \text{...(12.8)}$$

If symbol '0' is transmitted, we have

$$x(t) = 0 \quad \text{for} \quad 0 \le t < T_b \quad \text{(complete interval)} \quad \text{...(12.9)}$$

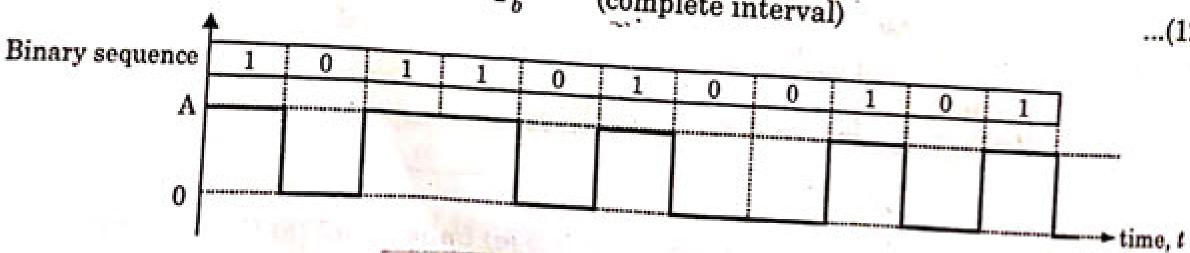

Fig. 12.5. *Unipolar NRZ format.*

For NRZ format, it may be observed that the pulse does not return to zero on its own. If symbol '0' is to be transmitted, then pulse becomes zero. *Internal computer waveforms are usually of unipolar NRZ type.*

Because, there is no separation between the pulses, therefore, the receiver needs synchronization to detect unipolar NRZ pulse. As compared to RZ format, NRZ pulse width (pulse to pulse interval is same) is more. Thus, energy of the pulse is more. However, unipolar format has some average DC value. This DC value does not carry any information.

12.7. Polar RZ and NRZ

In the polar RZ format, symbol '1' is represented by positive voltage polarity whereas symbol '0' is represented by negative voltage polarity. Because this is RZ format, the pulse is transmitted only for half duration. Thus, for polar RZ, if symbol '1' is transmitted, then

$$x(t) = \begin{cases} +\frac{A}{2} & \text{for } 0 \le t < T_b/2 \\ 0 & \text{for } T_b/2 \le t < T_b \end{cases} \quad ...(12.10)$$

and if symbol '0' is transmitted, then

$$x(t) = \begin{cases} -\frac{A}{2} & \text{for } 0 \le t < T_b/2 \\ 0 & \text{for } T_b/2 \le t < T_b \end{cases} \quad ...(12.11)$$

Polar RZ waveform has been shown in figure 12.6. The polar NRZ is shown in figure 12.7. In polar NRZ format, symbol '1' is represented by positive polarity whereas symbol '0' is represented by negative polarity. These polarities are maintained over the complete pulse duration *i.e.*, for polar NRZ, we have

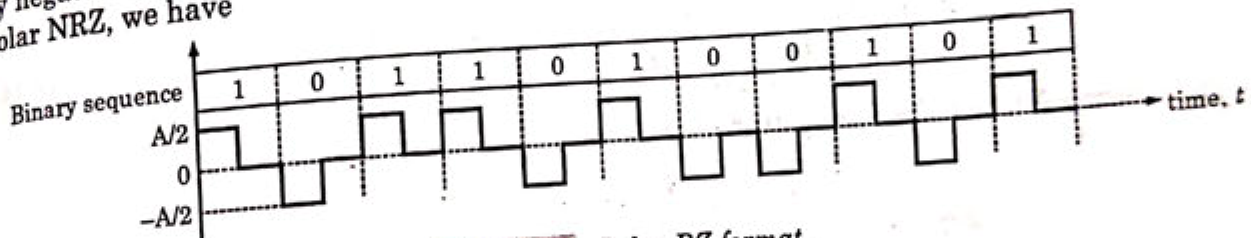

Fig. 12.6. *Polar RZ format.*

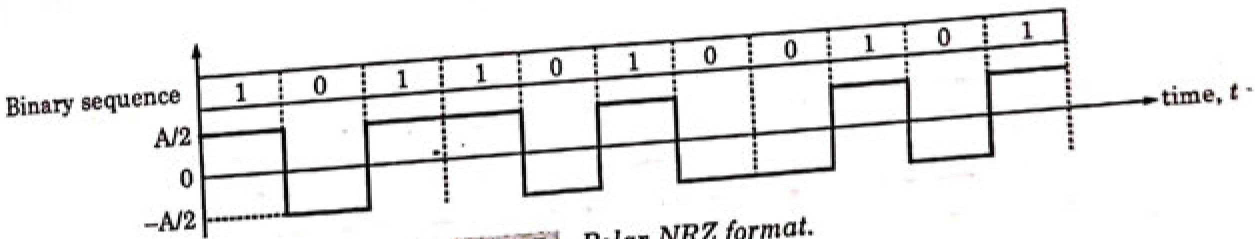

Fig. 12.7. *Polar NRZ format.*

If symbol '1' is transmitted, then

$$x(t) = +\frac{A}{2} \qquad \text{for} \qquad 0 \le t < T_b \quad ...(12.12)$$

and if symbol '0' is transmitted, then

$$x(t) = -\frac{A}{2} \qquad \text{for} \qquad 0 \le t < T_b \quad ...(12.13)$$

Since polar RZ and NRZ formats are bipolar, therefore, the average DC value is minimum in these waveforms. If probabilities of occurrence of symbols '1' and '0' are same, then average DC components of the waveform would be zero.

12.8. Bipolar NRZ [Alternate Mark Inversion (AMI)]

In this format, the successive '1's are represented by pulses with altenate polarity and '0's are represented by no pulses. Figure 12.8 illustrates the Bipolar NRZ or AMI waveform. If there are even number of 1's, the DC component of the waveform would be zero. The advantage of this format is that the ambiguities due to transmission sign inversion are eliminated.

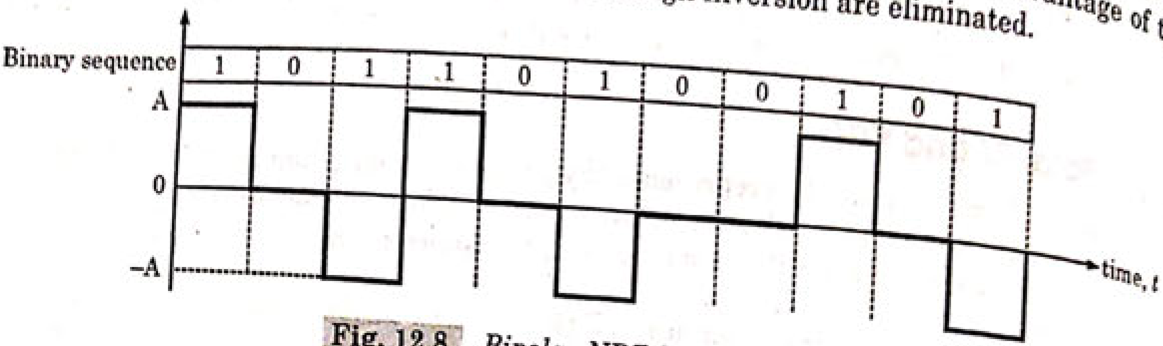

Fig. 12.8. *Bipolar NRZ format (AMI).*

12.9. Split Phase Manchester Format

This type of waveform is shown in figure 12.9. In this case, if symbol '1' is to be transmitted, then a positive half interval pulse is followed by a negative half interval pulse. If symbol '0' is to be transmitted, then a negative half interval pulse is followed by a positive half interval pulse. Hence, for any symbol the pulse takes positive as well as negative value *i.e.*,

If symbol '1' is to be transmitted, then

$$x(t) = \begin{cases} \dfrac{A}{2} & \text{for } 0 \le t < \dfrac{T_b}{2} \\ -\dfrac{A}{2} & \text{for } \dfrac{T_b}{2} \le t < T_b \end{cases} \quad ...(12.14)$$

and if symbol '0' is to be transmitted, then

$$x(t) = \begin{cases} -\dfrac{A}{2} & \text{for } 0 \le t < \dfrac{T_b}{2} \\ \dfrac{A}{2} & \text{for } \dfrac{T_b}{2} \le t < T_b \end{cases} \quad ...(12.15)$$

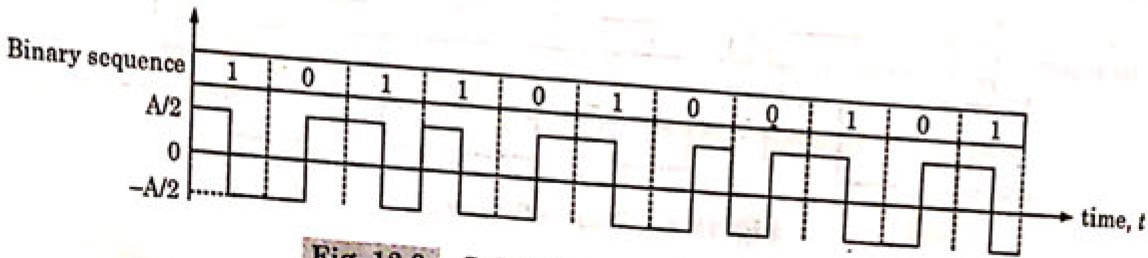

Fig. 12.9. *Split phase manchester format.*

The primary advantage of this format is that irrespective of the probability of occurrence of symbol '1' and '0' the waveform has zero average value. Therefore by this mode, the power saving is quite more.

However, the drawback of this format is that it requires absolute sense of polarity at the receiver end.

12.10. Polar Quaternary NRZ Format

Figure 12.10 shows the waveform of this format. This format is derived to reduce the signalling rate '*r*'. The message bits are grouped in the blocks of two. Therefore there are four possible combinations 00, 01, 10 and 11. To these four combinations, four amplitude levels are assigned. The Table 12.1 shows how this can be achieved

Table 12.1. **Polar quaternary NRZ Format: Combinations of bits**

Message combination	$x(t) = a_n$
00	$-\frac{3A}{2}$
01	$-\frac{A}{2}$
10	$\frac{A}{2}$
11	$\frac{3A}{2}$

In the waveform of figure 12.10, the first combination of two bits is 10. Thus, from Table 12.1, we may observe that the level should be $\frac{A}{2}$. The second combination in figure 12.10 is 11, hence from Table 12.1, the level taken is $\frac{3A}{2}$. Similarly other levels are selected. Hence, for two message bits only one pulse is transmitted with duration $2T_b$, *i.e.*,

$$T_s = 2T_b$$

and signalling rate is given as,

$$r = \frac{r_b}{2} = \frac{1}{2T_b} \quad \text{...(12.16)}$$

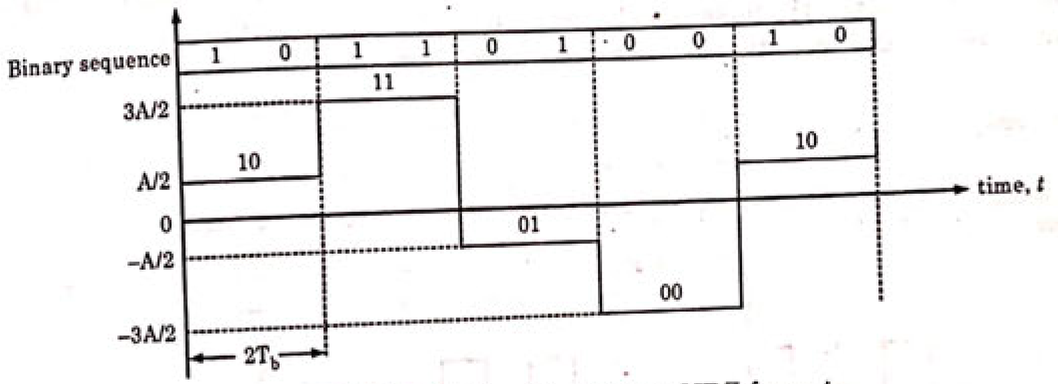

Fig. 12.10. *Polar Quaternary NRZ format.*

12.11. High Density Bipolar (HDB) Signalling

In case of bipolar NRZ or AMI signal, the transmitted signal is equal to zero when a binary "0" is to be transmitted. This is true even for the unipolar RZ and unipolar NRZ signals. The absence of transmitted signal can cause problems in synchronization at the receiver, if long sequence of binary "0"s are being transmitted. This problem can be solved by adding (transmitting) pulses when long strings of 0's exceeding a number n are being transmitted. This type of coding is called as **High Density Bipolar coding**. It is denoted by **HDBN**. Here, $N = 1, 2, 3, ...$ The most widely used HDB format is with $N = 3$ *i.e.*, HDB3.

In the string of message bits, when $(N + 1)$ or mm number of zeros occur, they are replaced by special binary sequences of $(N + 1)$ length. As shown in figure 12.11, these sequences contain some binary 1's which are necessary for synchronization at the receiver end. The $(N + 1)$ long special sequences for the HDB3 coding are 000V and B00V where B and V both are considered to be binary 1's. When the number of consecutive zeros exceed $(N + 1)$ *i.e.*, 4 in case of HDB3, the abovementioned special sequences are inserted as shown in figure 12.11.

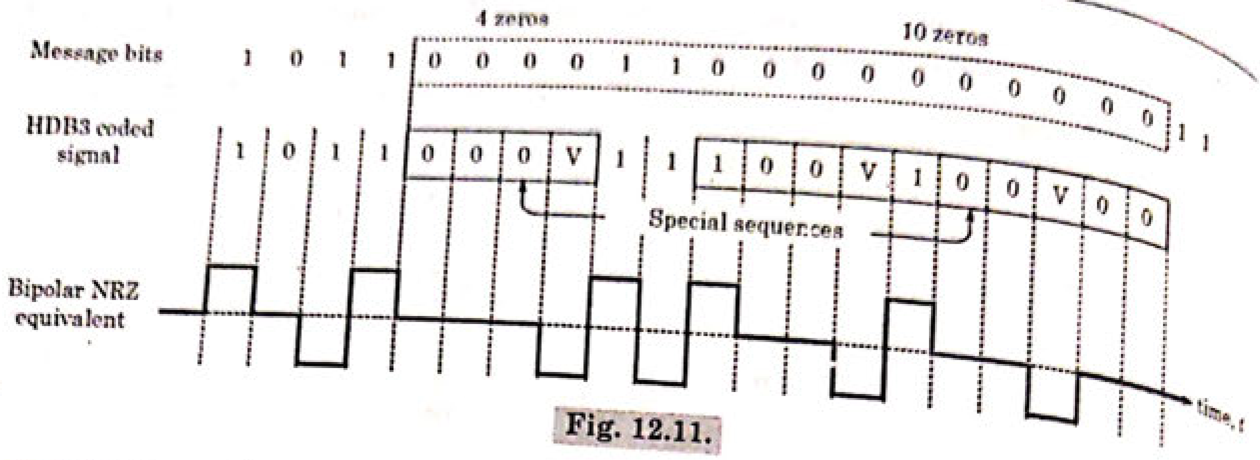

Fig. 12.11.

12.12. B8ZS Line Code

We have discussed about the codes in this chapter. We know that in order to have synchronization between the transmitter and receiver, the line code needs to cross the zero line frequently. As per U.S. T_1 standard, not more than 15 0's can be sent in succession to ensure proper synchronization. In order to solve the problems related to synchronization a new line code called B8Zs (Binary 8-zeros suppression) was developed. Whenever eight successive 0's are detected, the implementation of this line code will automatically insert a special 8 bit sequence containing a bipolar violation. This can bed easily detected and corrected by the CSU/DSU (channel service unit/digital service unit). Figure 12.12 gives a clear idea about the B8ZS line code. The violations (BPV in figure 12.12), will distinguish a byte substituted for all 0's from a normal byte which contains 1's. The B8ZS does not allow more than 8, consecutive 0's and the bipolar violation pattern uniquely identifies the eight 0's. It may that the voltage levels in the "violating byte", has a zero average (dc) value.

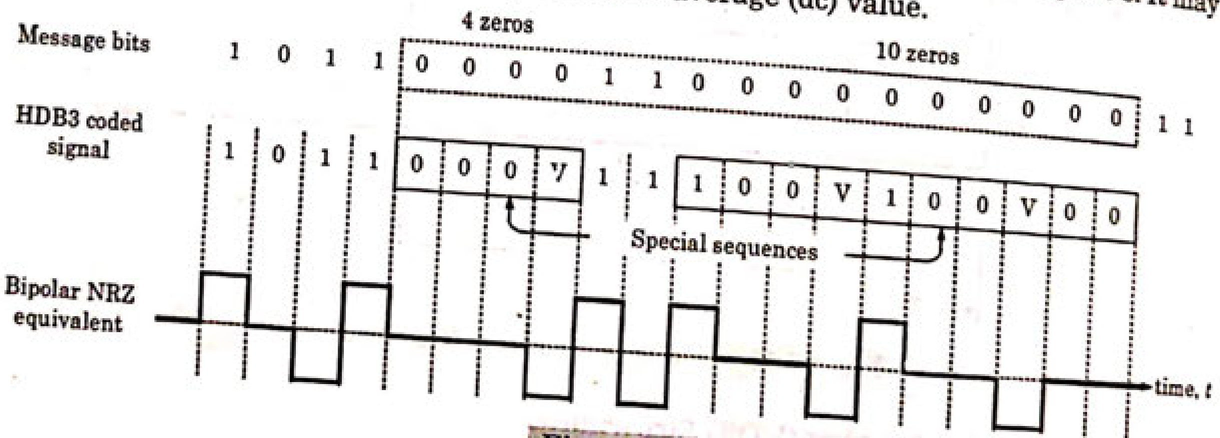

Fig. 12.12.

12.13. Power Spectra of Discrete PAM Signals (Various Line Codes)

As discussed earlier, we can represent all the discrete PAM signals with the help of a single expression as under:

$$x(t) = \sum_{k=-\infty}^{\infty} a_k p(t-kT) \quad ...(12.17)$$

where a_k = coefficient

$p(t)$ = the basic pulse shape

T = symbol duration

Now, let us assume that the basic pulse $p(t)$ is centered at the origin ($t = 0$) and normalized such that $p(0) = 1$.

Table 12.2 lists the value of coefficients a_k for different PAM formats.

Table 12.2. Values of a_k for various data formats.

S. No.	NRZ formats	Coefficient a_k		Basic pulse $p(t)$
		for symbol 0	for symbol 1	
1.	Unipolar NRZ	$a_k = 0$	$ak = A$	Basic pulse $p(t)$ is a rectangular
2.	Polar NRZ	$a_k = -A$	$a_k = A$	pulse of unit amplitude and
3.	Bipolar NRZ	$a_k = 0$	$a_k = A$ or $-A$ alternately for 1s.	duration T_b.
4.	Manchester	$a_k = -A$	$a_k = +A$	$p(t)$ consists of double pulses of amplitude ± 1 and duration T_b.
5.	Polar Quaternary	$a_k = -3A/2$ for 00	$-A/2$ for 01 and	$p(t)$ is a rectangular pulse of unit amplitude and duration $2T_b$.

Now, let us discuss few important terms as under:

(i) Data Signalling Rate

It is defined as the number of bits of data transmitted per second. It is measured in bits/second.

The data signalling rate is also called as data rate and it is defined as follows:

$$R_b = 1/T_b \quad \text{...(12.18)}$$

where T_b represents the bit duration.

(ii) Modulation Rate

It is defined as the rate at which the signal level is changed. The modulation rate is measured in bauds or symbols per second.

(iii) Power Spectra

We can represent any PAM format as follows:

$$x(t) = \sum_{k=-\infty}^{\infty} a_k p(t-kT)$$

Each format $x(t)$ may be considered as a random process and each coefficient a_k as a random variable. Let these coefficients be generated by a discrete stationary random source which is characterized by the following relation between autocorrelation and ensemble average *i.e.*,

$$R_\tau(n) = E[a_k\, a_{k-n}] \quad \text{...(12.19)}$$

where $R_\tau(n)$ = Autocorrelation function

and E = Expectation operator

Also, power spectral density (psd) of PAM signal $x(t)$ is given by

$$S(f) = \frac{1}{T}|P(f)|^2 \sum_{n=-\infty}^{\infty} R_\tau(n)\, e^{-j2\pi nfT} \quad \text{...(12.20)}$$

where $P(f)$ = Fourier transform of the basic pulse $p(t)$.

It may be noted that the values of $P(f)$ and $R_\tau(n)$ depends upon the type of PAM format.

12.14. Power Spectral Density (psd) of NRZ Unipolar Format

For simplicity, let us assume that the 0s and 1s are equally likely to happen or have equal probability.

$$P(a_k = 0) = P(a_k = A) = 1/2$$

(*iv*) Manchester Format

Curve *d* in figure 12.15 shows the normalized power spectra of Manchester format. Here most of power lies inside the bandwidth equal to $2/T_b$ which is twice the bandwidth of unipolar, polar and bipolar NRZ formats.

Table 12.3. Comparison of Various Line Codes

S. No.	*Parameter of Comparison*	*Polar RZ*	*Polar NRZ*	*AMI*	*Manchester*	Polar Quaternary NRZ
1.	Transmission of DC component	Yes	Yes	No	No	Possible
2.	Signalling rate	$1/T_b$	$1/T_b$	$1/T_b$	$1/T_b$	$1/2\ T_b$
3.	Noise immunity	Low	Low	High	High	High
4.	Synchronizing capability	Poor	Poor	Very good	Very good	Poor
5.	Bandwidth requirement	$1/T_b$	$1/2\ T_b$	$1/2\ T_b$	$1/T_b$	$1/2T_b$
6.	Crosstalk	High	High	Low	Low	Low

Example 12.1. Encode the following binary data stream into return to zero (RZ), Non-return