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CRITERIA FOR CHOOSING LINE CODES IN DATA COMMUNICATION

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ABSTRACT

In this paper, line codes used in data communication are investigated. The need for the line codes is emphasized, classification of line codes is presented, coding techniques of widely used line codes are explained with their advantages and disadvantages and criteria for chosing a line code are given.

Keywords: Line codes, correlative coding, criteria for chosing line codes..

1. INTRODUCTION

High-voltage-high-power pulse current The purpose of applying line coding to digital signals before transmission is to reduce the undesirable effects of transmission medium such as noise, attenuation, distortion and interference and to ensure reliable transmission by putting the signal into a form that is suitable for the properties of the transmission medium. For example, a sampled and quantized signal is not in a suitable form for transmission. Such a signal can be put into a more suitable form by coding the quantized samples.

Line coding must be applied by considering the properties of the transmission channel to be used. For example, metallic cables show low-pass frequency characterstics. For applications using this kind of medium, line coding is generally the last coding function before transmission. For band-pass channels, such as optical fiber, radio systems and analog telephone networks, line coding is either performed just before the modulation or it is combined with the modulation process. The place of line coding in transmission systems is shown in Figure 1.

The line coder at the transmitter and the corresponding decoder at the receiver must operate at the transmitted symbol rate. For this reason, epecially for high-speed systems, a reasonably simple design is usually essential.

2. ISSUES TO BE CONSIDERED IN LINE CODING

Required Transmission Bandwidth: In applications where the transmission bandwith is the limiting factor, a multilevel line code is used to reduce the symbol transmission rate. Here, each transmitted signal represents more than one bit of information. A multilevel line code will require a better SNR (Signal-to-Noise Ratio) than a corresponding binary code.

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Spectrum at Low Frequency: Low frequency components (especially the D.C. component) of the line code is to be kept at zero or near zero level. Because, the coupling circuit components such as capacitors and transformers introduce low-frecuency spectral cut-off and do not permit the low-frequency components to pass. Hence, long-term intersymbol interference is avoided.

Timing Content: Timing information must be reliable extracted from the transmitted symbol sequence at the receiver and at the intermediate repeaters (if used) in order to time their decision-making circuits. This process is generally called clock extraction. To enable clock extraction at the receiver (or at the repeater), the line code should provide an adequate density of transitions in the transmitted sequence. For example, in a binary signal, transition means changing of the symbol level from 0 bit to 1 bit or vice versa.

Error Monitoring: A line code can provide a means of monitoring the error rate of its transmission link by adding redundancy into the information stream. For example, if the line code is constraint so that it never produces certain symbol sequences, the occurrence of these illegal sequences will provide a means of detecting transmission errors and hence estimating the error performance of the link.

Efficiency: In order to provide the above features it is usually necessary to add extra information (redundancy) into the transmitted digital signal. This redundancy decreases the efficiency of the line code defined by Eq.1.

$$E = \% \, (H / H_{max}) \text{ x } 100 \qquad (1)$$

Here,

E : Efficiency of the line code,
H : Avarage information content per transmitted symbol.
H_{max} : Maximum possible information content per symbol (with no redundancy added).

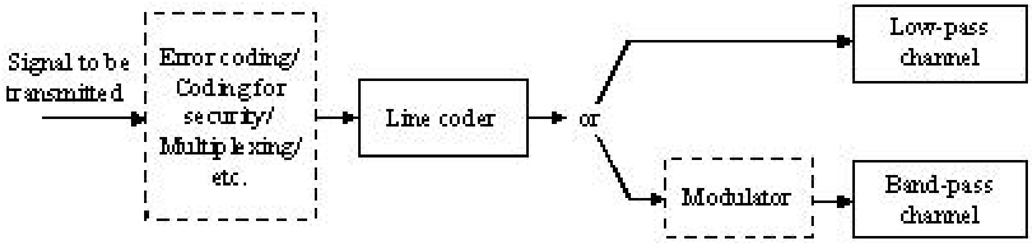

Figure 1. Place of line coding in

3. CLASSIFICATION OF LINE CODES

Line codes can be classified as follows [1]:

(1) Bit-by-bit codes,
(2) Block codes:
  - Bit insertion,
  - Block insertion,
(3) Correlative coding (or partial response codes)

Some codes belong to more than one of these classes.

4. BIT-BY-BIT CODES

Widely used bit-by-bit codes are illustrated in the following paragraphs.

4.1 Unipolar NRZ Code

NRZ (Non Return to Zero) means that the voltage level of the coded signal does not change and it does not return to zero level in a T second bit interval. An example of unipolar NRZ code and the T second bit interval is shown in Figure 2 (1). The coding of 0 bits and 1 bits in a unipolar NRZ code is as follows:

0 bit : Coded as zero volt level for the T second bit interval.
1 bit : Coded as +V volt level for the T second bit interval.

This coding method has two disadvantages: The spectrum of the coded signal contains D.C.

component and clock extraction at the receiver is impossible.

4.2 Polar NRZ Code

The coding of 0 bits and 1 bits in a polar NRZ code is as follows:

0 bit : Coded as -V volt level for the T second bit interval.
1 bit : Coded as +V volt level for the T second bit interval.

An example of polar NRZ code and the T second bit interval is shown in Figure 2 (2). The advantage of this coding method is that the frequency spectrum of the coded signal does not contain D.C. component. Disadvantage of this code is that clock extraction at the receiver is impossible.

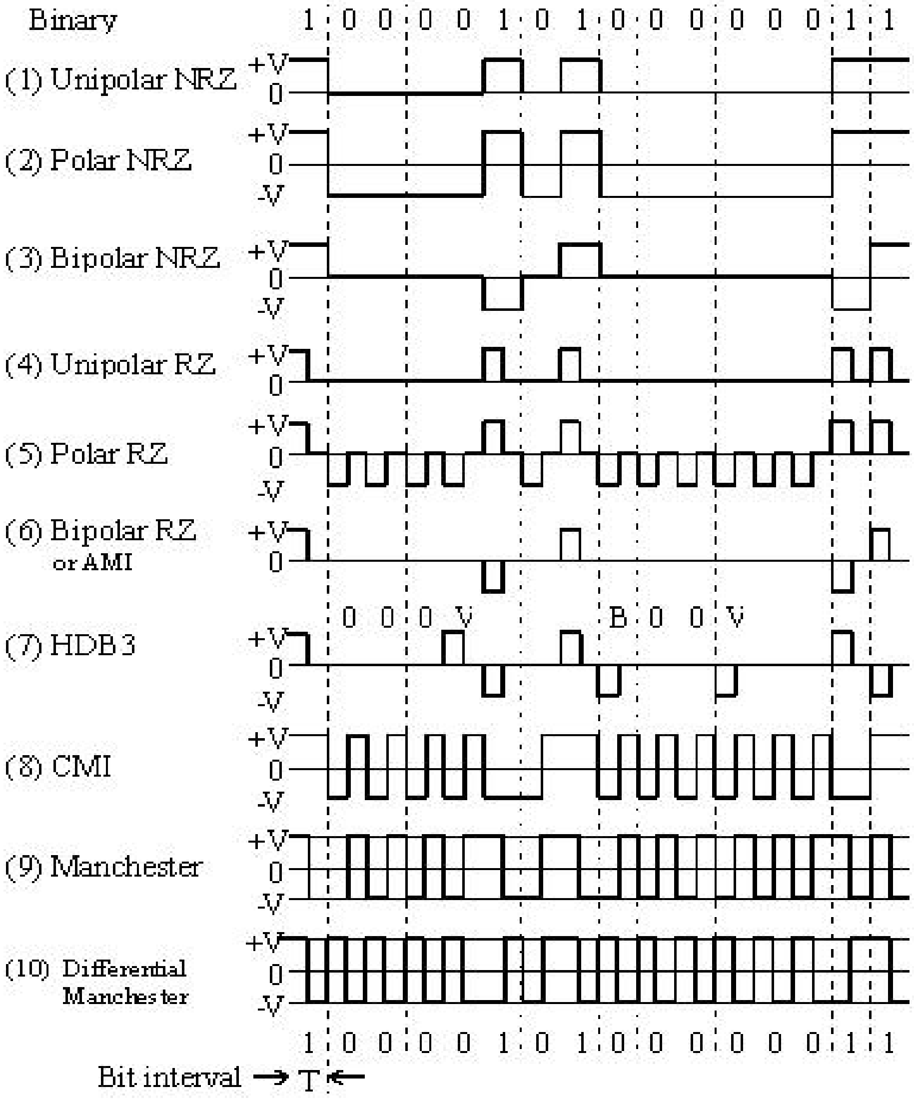

Figure 2. Examples of some line codes.

4.3 Bipolar NRZ Code

The coding of 0 bits and 1 bits in a bipolar NRZ code is as follows:

0 bit : Coded as 0 volt level for the T second bit interval.
1 bit : Coded as alternating +V and –V volt levels for the T second bit interval.

An example of bipolar NRZ code and the T second bit interval is shown in Figure 2 (3). The advantage of this coding method is that the frequency spectrum of the coded signal does not contain D.C. component. Disadvantage of this code is that clock extraction at the receiver is impossible.

4.4 Unipolar RZ Code

RZ (Return to Zero) means that for 1 bit the voltage level of the coded signal returns to zero volt level (changes the voltage level from +V or – V to zero) at the middle of the T second bit interval. The coding of Unipolar RZ code is as follows:

0 bit : Coded as 0 volt level for the T second bit interval.
1 bit : Coded as +V or –V volt level for the first T/2 part of the bit interval, and as zero level for the second T/2 part of the bit interval T.

An example of unipolar RZ code and the T second bit interval is shown in Figure 2 (4). The advantage of this coding method is that transmission of successively sent 1 bits enables clock extraction at the receiver. There are two disadvantages: Successive 0 bits in transmission makes clock extraction impossible. RZ type coding requires twice the bandwidth required by NRZ type coding.

4.5 Polar RZ Code

Coding of polar RZ code is as follows:

0 bit : Coded as –V volt levels for the first T/2 part of the bit interval T, and as zero level for the second T/2 part of the bit interval T.
1 bit : Coded as +V volt levels for the first T/2 part of the bit interval, and as zero level for the second T/2 part of the bit interval T.

An example of polar RZ code and the T second bit interval is shown in Figure 2 (5). The advantage of this coding method is that it enables clock extraction at the receiver. The disadvantage is that RZ type coding requires twice the bandwidth required by NRZ type coding.

4.6 Bipolar RZ (or AMI) Code

Bipolar RZ code is also called AMI code (Alternate Mark Inversion Code) or pseudoternary code. The coding of bipolar RZ is as follows:

0 bit : Coded as 0 volt level for the T second bit interval.
1 bit : Coded alternately as +V and –V volt levels for the first T/2 part of the bit interval T, and as zero level for the succeeding T/2 part of the bit interval T.

An example of bipolar RZ code and the T second bit interval is shown in Figure 2 (6). The advantage of this coding method is that the coded signal does not contain D.C. component. There are two disadvantages: Successive 0 bit transmission makes clock extraction impossible, and RZ type coding requires twice the bandwidth required by NRZ type coding.

4.7 HDB3 Code

HDB3 (High Density Bipolarity with a maximum of 3 zeros) code does not permit the transmission of more than 3 zero bits in succession. In HDB3 code, 1 bits and up to 3 successive 0 bits are coded as described for the AMI code. A substitution code (0001 or 1001) is transmitted instead of 4 successive 0 bits. In order to enable the receiver to distinguish between 1 bits that belong to data and 1 bits used in the substitution code, the substitution code has a code violation. Here, The code violation means not to obey the rule of sending 1 bits in alternate polarities as +V and –V volgage levels. The receiver repleces 4 successive 0 bits (0000), whenever it detects a substitution code. Table 1 shows the substitution rule used in HDB3 code. Figure 2

(7) and Figure 3 show examples of HDB3 code. The substitution rule used in this code can also be explained as follows:

(1) If the polarities of the last transmitted 1 bit of the data and the last bit of the last transmitted substitution code are the same, then B00V is chosen as the substitution code to be sent. Here, B represents the bipolar 1 bit, and V represents the violating 1 bit.

(2) If the polarities of the last transmitted 1 bit of the data and the last bit of the last transmitted substitution code are different, then 000V is chosen as the substitution code to be sent.

HDB3 code is used in 30 channel PCM (Pulse Code Modulation) telephone systems. There are two advantages of this coding method: The coded signal does not contain D.C. component and clock extraction at the receiver is possible. Disadvantage of this code is that it requires twice the bandwidth bandwidth by NRZ type coding.

Table 1. Substitution rule for HDB3 code.

Polarity of the last	Number of Bipolar Pulses (1 bits) since last Substitution	
Transmitted 1 bit	Odd	Even
–	0 0 0 –	+ 0 0 +
+	0 0 0 +	– 0 0 –

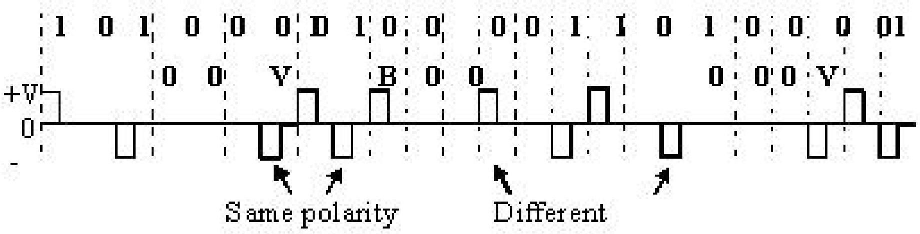

Figure 3. An example of HDB3

4.8 CMI Code

CMI (Coded Mark Inversion) code is a bipolar type code. Coding of 0 bits and 1 bits are as follows:

0 bit : Coded as –V volt levels for the first half of the bit interval T and as +V volt level for the second half of the bit interval T. In other words, 0 bit is coded as 01. Hence, there is always a positive transition (from negative level to positive level) at the mid point of the bit interval T.

1 bit: Coded alternately as +V and –V volt levels for the whole bit interval T.

An example of CMI code is shown in Figure 2 (8). There are two advantages of this coding method: The coded signal does not contain D.C. component and clock extraction at the receiver is possible. Disadvantage of this code is that it requires twice the bandwidth of NRZ type coding.

4.9 Manchester Code

Manchester coding is a bipolar NRZ type code, and the coding rule is as follows [2], [3], [4]:

0 bit : Coded as bipolar 01. In other words, 0 bit is coded by –V volt level in the first half of the bit interval T and by +V volt level in the second half of the bit interval T. Hence, 0 bit always includes a positive transition (transition from negative level to positive level at the middle of the bit duration T.

1 bit : Coded as bipolar 10. In other words, 0 bit is coded by +V volt level in the first half of the bit interval T and by –V volt level in the second half of the bit interval T. Hence, 0 bit always includes a negative transition (transition from positive level to negative level at the middle of the bit interval T.

An example of Manchester coding is shown in Figure 2 (9). Manchester code is used in storing digital signal on a magnetic storage medium and in IEEE 802.3 Ethernet LANs. There are two advantages of this coding method: The coded signal does not contain D.C. component and clock extraction at the receiver is possible. Disadvantage of this code is that it requires twice the bandwidth required by NRZ type coding.

4.10 Differential Manchester Code

Differential Manchester coding is a bipolar NRZ type code, and the coding rule is as follows [2], [3], [4]:

0 bit : Coded by making a transition both at the start and at the mid point of the bit interval.

1 bit : Coded by making a transition only at the mid point of the bit interval. There is no transition at the start of the bit interval.

An example of differential Manchester coding is shown in Figure 2 (9) and Figure 4. This coding is used in IEEE 802.5 token ring type LANs. The advantages of this coding method: The coded signal does not contain D.C. component, clock extraction at the receiver is possible and its noise immunity is better than that of Manchester code. Differential Manchester encoder requires more complex equipment and twice the bandwith required by NRZ code.

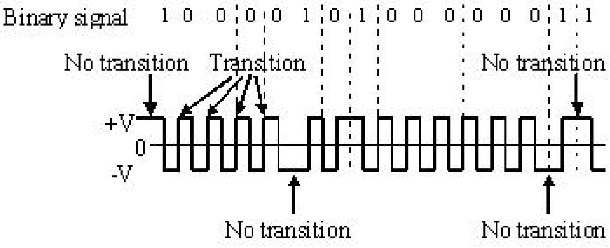

Figure 4. An example of differential Manchester coding.

4.11 B8ZS Code

B8ZS code does not permit transmitting 8 successive zeros (00000000). A substitution code is sent instead of 8 successive zeros. As shown in Figure 5, in B8ZS code, 1 bits and maximum 7 successive 0 bits are coded as they are in AMI code. In order to enable the receiver to distinguish between the 1 bits that belong to data and the 1 bits used in the substitution code, the substitution code has a code violation. The substitution rule used in this code can also be explained as follows:

(1) If the 1 bit preceeding the substitution code has positive polarity, the substitution code is chosen as (0 0 0 + — 0 — +).

(2) If the 1 bit preceeding the substitution code has negative polarity, the substitution code is chosen as (0 0 0 — + 0 + —).

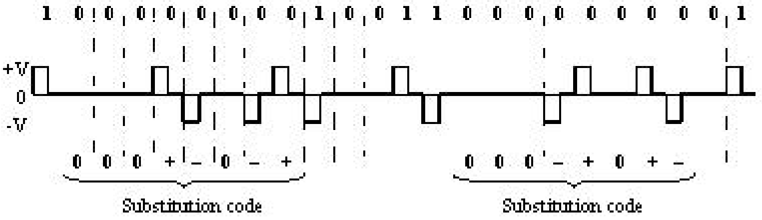

Figure 5. An example of B8ZS code.

B8ZS kode is used in 24 channel PCM telephone systems (T1 line). There are two advantages of this coding method: The coded signal does not contain D.C. component and clock extraction at the receiver is possible. Disadvantage of this code is that it requires twice the bandwidth required by NRZ type coding.

5. BLOCK CODES

Coding a group of bits as a block is called block coding. Some examples of block coding are given below.

5.1 mB1C Code

This code is a bit insertion type block code. In mB1C code, a D.C balancing bit is added for a block of m information bits to provide long-term polarity balance. Hence, long-term D.C. component of the coded signal will be zero. For a reliable application, it may be necessary to scramble the source data before coding to ensure that it is adequately randomized. The added bit also ensures a minimum clock content and some redundancy to enable transmission error monitoring. In practice, m is chosen between 7 and 23 bits [1].

The advantages of this code can be stated as follows: The coded signal has no D.C. component, clock extraction is possible at the receiver, the added C bit helps the receiver to make clock extraction and to detect transmission errors. Its coding efficiency is high and it has simple hardware. For this reason, this coding method is preferred in high-speed applications like fiber optic communication systems. There is no remarkable disadvantage of this coding method.

5.2 mBnB Code

This code is also a substitution type of block code. In mBnB code, binary coded m information bits are mapped into n binary bits for transmission. Redundancy is added into the code to provide the desired transmission features by making n > m, in general n = m + 1 is applied.

In Table 2, code conversion table of 7B8B (7 Binary 8 Binary) code is given as an example of mBnB code [1]. The 7B8B code coverts binary coded 7 information bits into 8 bits according to Table 2. The signal at the output of the 7B8B encoder is a ternary signal having +V, 0, and –V levels. For this coding method, the encoder has a disparity control counter to have long-term D.C. balancing. This counter shows the number of +V and –V levels at the encoder output. The encoder selects the conversion code with positive, negative or zero mean for transmission according to the counter value.

Table 2. 7B8B code conversion table.

Encoder Input (7 bit)	Encoder Output (8 bit)			Disparity Counter
	Negative Disparity	Zero Disparity	Positive Disparity	
1 1 1 1 1 1 1		+ – + – + – + –		0
⋮				
1 0 1 0 0 0 1	+ – – – + – – +	or	– + + + – + + –	± 2
⋮				
0 1 0 1 0 0 1	– + – – – + – –	or	+ – + + + – + +	± 4
⋮				
0 0 0 0 0 0 0		+ + + – + – – –		0

In the 7B8B code, some of the combinations of the 8-bit output code words may not be used. Unused code words bring design flexibility. The following features should be ensured in selecting the code words that will be used in coding:

(1) Good timing information,

(2) Error monitoring,

(3) Word alignment,

(4) Minimum error propagation in decoding.

A computer search may be used to optimize the code conversion table (mapping).

The advantages of this code can be stated as follows: Coded signal does not contain D.C. component, clock extraction at the receiver is possible, and it has error-monitoring feature. There is no remarkable disadvantage of this coding method.

5.3 4B3T Code

4B3T code converts four binary input bits into three ternary output symbols according to the translation rule given in Table 3. The ternary output symbols take the values of +V, 0 and –V. In 4B3T coding, the encoder has a disparity control counter to have long-term D.C. balancing. This counter shows the number of +V and –V levels at the encoder output. The encoder selects the conversion code with positive, negative or zero mean for transmission according to the counter value. An example of 4B3T code is shown in Figure 6. This code was used in Basic Access ISDN subscriber line in the early applications, later it left its place to 2B1Q code.

It is advantageous that in 4B3T code, the coded signal has no D.C. component and clock extraction is possible at the receiver. The disadvantage of 4B3T code is that it requires more transmission bandwidth compared to 2B1Q code.

Table 3. 4B3T code conversion table.

Encoder Input (four bits)	Encoder Output (3 ternary symbols) Negative Mean	Zero Mean	Positive Mean	Disparity Counter
1111		– 0 +		0
1110		0 + –		0
1101	0 0 –		0 0 +	± 1
1100	0 – 0		0 + 0	± 1
1011	– 0 0		+ 0 0	± 1
1010	– + –		+ – +	± 1
1001	+ – –		– + +	± 1
1000	– – +		+ + –	± 1
0111	– – –		+ + +	± 3
0110	– 0 –		+ 0 +	± 2
0101	0 – –		0 + +	± 2
0100	– – 0		+ + 0	± 2
0011		+ – 0		0
0010		0 – +		0
0001		– + 0		0
0000		+ 0 –		0

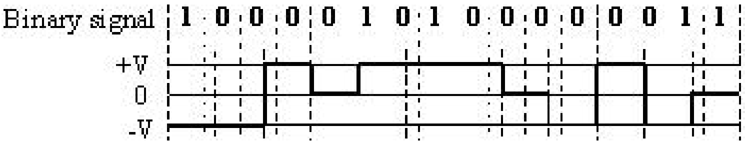

Figure 6. An example of 4B3T

5.4 2B1Q Code

This is a block code that coverts two binary input bits into a single four-level (quaternary symbol) according to the conversion rule given in Table 4. Scrambling is applied to the binary signal to ensure that the input data is unlikely to have long sequence of similar transmitted symbols. Hence, a loss of D.C. balancing and timing problems are eliminated. An example of 2B1Q code is shown in Figure 7. This coding method is used in Basic Access ISDN subscriber lines.

The advantages of 2B1Q code can be stated as follows: The coded signal has no D.C. component, clock extraction at the receiver is possible, coding efficient is % 100, encoder and decoder circuits are simple, there is no need for synchronization word, bandwith requirement is half of the bandwith required by the binary coded signal. The disadvantage of this code is that it does not permit link error monitoring since it does not have any redundancy [3].

Table 4. 2B1Q code conversion table.

Encoder Input (two bits)	Encoder Output (one quaternary symbol)
10	+3
11	+1
01	–1
00	–3

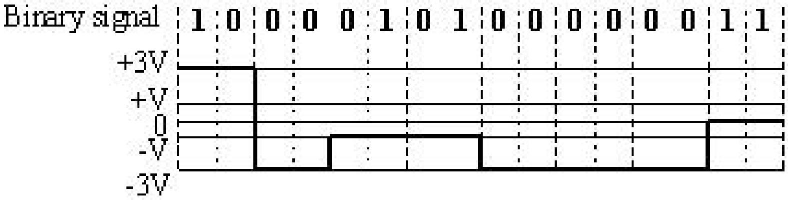

Figure 7. An example of 2B1Q

6. CORRELATIVE CODING

Correlative codes (or partial respons codes) deliberately introduce a controlled amount of intesymbol interference (ISI) into the transmitted signal by combining the bits of binary signal according to a certain rule. The coded signal has correlation in time and after passing through a bandlimited channel it can be obtained in its original form. Deliberatly generated ISI at the transmitter is eliminated at the receiver. Hence, it becomes possible to achieve the maximum transmission rate of R=2B bps through a transmission channel of bandwith B Hz. This type of coding also provides spectrum shaping for the signal to make its spectrum suitable for the limitations of the transmission medium.

Duobinary coding (or duobinary signaling) and modified duobinary coding (or modified duobinary signaling) can be shown as the examples of correlation coding [2], [3], [4]. The word "duo", which has the meaning of two, indicates here that the transmission capacity is doubled for binary coded signals. In correlative coding, it does not make any difference whether or not the adjacent bits of the binary signal at the input of the encoder belong to the same signal. That is, correlative coding can be applied to multiplexed signals. In inorder to make pulse shaping in binary communication, the binary signal can be passed through a sinusoidal roll-off filter to obtain sinx/x shaped pulses at the output.

If correlative coding will be used in a binary communication system where multiplexing, pulse shaping and modulation methods are used, the order of applying these processes are as follows: (1) Obtaining the binary coded signal, (2) Time Division Multiplexing, (3) Correlative coding, (4) Pulse shaping and (5) Modulation.

6.1 Duobinary Coding

Duobinary coding is a line coding method that is used in transmission over band-limited channels in telephone networks or computer networks to double the transmission speed. The Duobinary encoder, which is also called duobinary filter, consists of a simple filter involving a single delay element and a summer, and an ideal low pass filter modeling the band-limited transmission medium.

Consider a binary sequence $\{b_k\}$ consisting of uncorrelated binary symbols 1 (represented by +1 volt) and 0 (represented by –1 volt), each having a duration T. Let's apply this sequence to the input of a duobinary encoder and define the output sequence of symbols by $\{c_k\}$. As shown in Eq. (2), each c_k symbol of the output sequence will be equal to the sum of the present input pulse b_k and the previous input pulse b_{k-1}.

$$c_k = b_k + b_{k-1} \qquad (2)$$

Hence, a three-level output signal (+2, 0, -2 volt) is obtained at the output of the duobinary encoder. One of the effects of the transformation described in Eq. (2) is to change the input sequence $\{a_k\}$ of uncorrelated two-level input pulses into a sequence of $\{c_k\}$ of correlated three-level pulses. This correlation between the adjacent pulses may be viewed as introducing ISI into the transmitted signal in an artificial maner. This deliberately introduced ISI forms the bases of the correlative coding.

In order to obtain the estimate of the original bit sequence at the decoder output, the reverse operation is performed at the receiver. This operation is shown in Eq. (3). Here, b'_k and b'_{k-1} are the estimates of b_k and b_{k-1} respectively.

$$b'_k = c_k - b'_{k-1} \qquad (3)$$

The technique of using a stored estimate of the previous symbol is called decision feedback. As it can be seen from Eq. (3), if b_{k-1} bit is estimated incorrectly, b'_k will also be incorrect. This phenomenon is called error propagation.

A practical means of avoiding the error propagation phenomenon is to use precoding. The precoding operation performed on the binary data sequence $\{b_k\}$ and coverts it into another binary sequence as defined by Eq. (4).

$$a_k = b_k \oplus a_{k-1} \text{ modulo } 2 \qquad (4)$$

Here, the symbol $\oplus$ denotes modulo-two addition and it is equivalent to a two-input EXCLUSIVE OR operation (the output is 0 if the inputs are the same, the output is 1 if the inputs are different). As shown in Figure 8, the output of the precoder is applied to the input of the doubinary filter. The symbol sequence $\{c_k\}$ is obtained at the output of the duobinary filter as defined by Eqs. (5) and (6).

$$c_k = a_k + a_{k-1} \qquad (5)$$

$$c_k = (b_k \oplus a_{k-1}) + a_{k-1} \qquad (6)$$

The operation performed in the precoding is not linear as it is in duobinary coding.

The frequency perponse of the duobinary encoder is shown in Figure 9. Since its amplitude response is in the form of a half wave cosine function it can easily be realized in practice. Assuming +1 volt for logical 1 and –1 volt for logical zero, the truth table for Eq. (6) can be obtained as given in Table 5.

Table 5. Truth table for Eq. (6)

b_k	a_{k-1}	$a_k = b_k \oplus a_{k-1}$	$c_k = a_k + a_{k-1}$
+1	+1	Logical 0: –1	0
+1	–1	Logical 1: +1	0
–1	+1	Logical 1: +1	+2
–1	–1	Logical 0: –1	–2

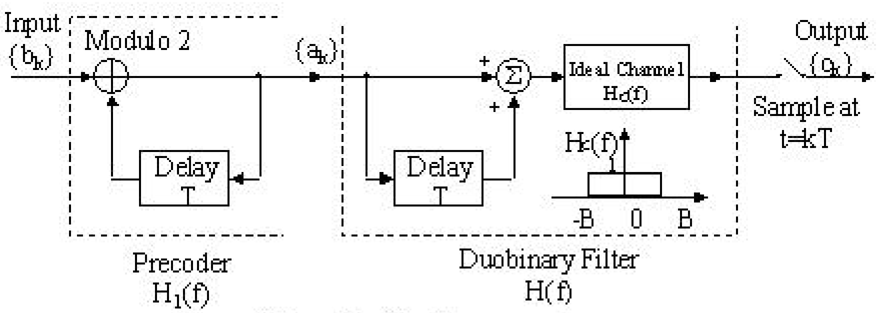

Figure 8. Duobinary encoder.

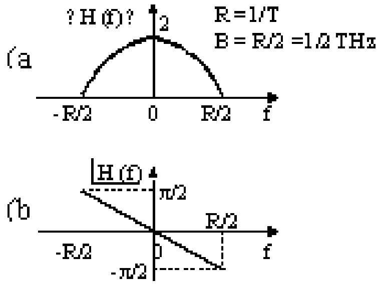

Figure 9. Frequency response of the duobinary encoder. (a) Amplitude response, (b) Phase response.

As it can be seen from the truth table, the output symbol sequence $\{c_k\}$ takes the values of ± 2 volt and 0 volt.

$c_k = \pm 2$ volt, for $b_k = -1$ volt (logical 0)
$c_k = 0$ volt, for $b_k = +1$ volt (logical 1) (7)

Based on this coding rule, the estimated bit sequence $\{b_k'\}$ at the decoder output can be obtained according to Eq. (8). If there is no transmission error, then the estimated bit sequence $\{b_k'\}$ and the original bit sequence $\{b_k\}$ will be the same.

$b'_k = -1$ volt (logical 0), if $|c_k| > 1$ volt
$b'_k = +1$ volt (logical 1), if $|c_k| < 1$ volt (8)

According to this decision rule, the detector consists of a rectifier the output of which is compared by a decision device to a threshold level of 1 volt. The block diagram of the decoder is shown in Figure 10. A useful feature of this detector is that only the present sample is used for decision. Hence, error propagation cannot occur in the detector.

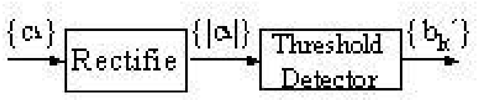

Figure 10. Detector for recovering original binary sequence from the precoded duobinary coded signal.

Example: Consider that the bit sequence $\{b_k\}$ = 0 0 1 0 1 1 0 is applied to precoded duobinary encoder. In order to start the coding operation a_{k-1} bit is assumed at random. Suppose that it is chosen as logical 1. Choosing a_{k-1} bit as logical 0 also gives the same result. Table 6 shows the operations of obtaining the precoded sequence $\{a_k\}$ according to Eq. (4), duobinary output sequence $\{c_k\}$ according to Eq. (6), and the decoder output $\{b_k'\}$ according to Eq. (8).

Table 6: Input and output sequences of the precocer, duobinary encoder and decoder for the given example.

	Randomly chosen (a_{k-1}) bit							
Binary sequence $\{b_k\}$, logical :		**0**	**0**	**1**	**0**	**1**	**1**	**0**
Binary sequence $\{a_k\}$, logical :	**1**	**1**	**1**	**0**	**0**	**1**	**0**	**0**
Binary sequence $\{a_k\}$, polar :	**+1**	**+1**	**+1**	**–1**	**–1**	**+1**	**–1**	**–1**
Duobinary encoder output $\{c_k\}$, polar :		**+2**	**+2**	**0**	**–2**	**0**	**0**	**–2**
Decoder output at the receiver $\{b'_k\}$, logical :		**0**	**0**	**1**	**0**	**1**	**1**	**0**

6.2 Modified Duobinary Coding

The block diagram of the modified duobinary encoder is shown in Figure 11. This coding method has two differences in comparison to duobinary coding. The first one is that 2T second delay elements are used in both the precoder and the modified duobinary coder instead of T second delay elements. Hence, the present pulse and the pulse two interval behind the present pulse are related. As the second difference, subtraction is used at the output of the precoder instead of addition.

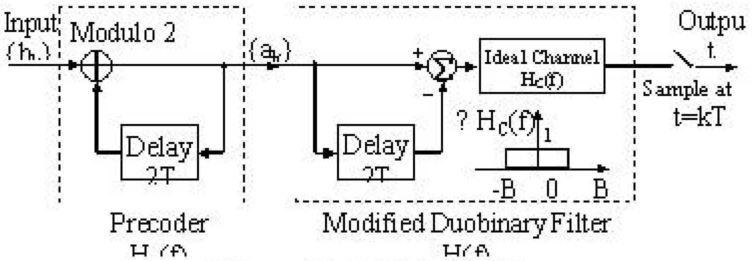

Figure 11. Modified duobinary

The precoding rule is given in Eq. (9), and coding rule is given in Eq. (10) and (11).

$$a_k = b_k \oplus a_{k-2} \quad \text{modulo 2} \tag{9}$$
$$c_k = a_k - a_{k-2} \tag{10}$$
$$c_k = (b_k \oplus a_{k-2}) - a_{k-2} \tag{11}$$

Assuming that the sequence $\{a_k\}$ is a polar signal, we can take $a_k = \pm 1$ volt. In this case, the output sequence is $c_k = \pm 2$ volts or 0 volt. The truth table for Eq. (11) is given in Table 7.

Table 7. Truth table for Eq. (11).

b_k	a_{k-2}	$a_k = b_k \oplus a_{k-2}$	$c_k = a_k - a_{k-2}$
+1	+1	Logical 0: –1	–2
+1	–1	Logical 1: +1	+2
–1	+1	Logical 1: +1	0
–1	–1	Logical 0: –1	0

The symbol sequence $\{c_k\}$ at the output of the encoder takes the following values.

$$c_k = \pm 2 \text{ volt, for } b_k = +1 \text{ volt (logical 1)}$$
$$c_k = 0 \text{ volt, for } b_k = -1 \text{ volt (logical 0)} \tag{12}$$

Based on Eq. (12), similar to the duobinary decoder, we can use a rectifier preceding a threshold detector to realize a modified duobinary decoder. If we assume that there is no transmission error, then the estimated bit sequence $\{b_k'\}$ at the output of the modified duobinary decoder is obtained as follows:

$b'_k = -1$ volt (logical 0), for $|c_k| < 1$ volt
$b'_k = +1$ volt (logical 1), for $|c_k| > 0$ volt (13)

An advantage of this detector is that since only the present sample is used for decision, error propagation cannot occur in the detector. The frequency response of the modified duobinary encoder is shown in Figure 12. Since its amplitude response is in the form of a half wave sine function the coded signal does not contain D.C. component.

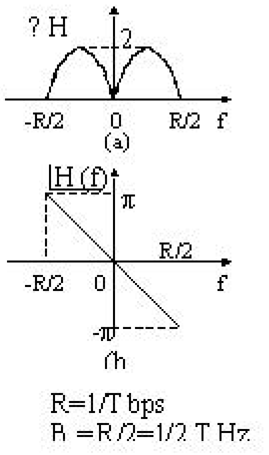

Figure 12. Frequency response of the modified duobinary encoder. (a) Amplitude response, (b) Phase response.

7. GENERALIZED FORM OF CORRELATIVE CODING

The generalized form of correlative coding (partial response signaling), the block diagram of which is shown in Figure 13, involves the use of a tapped-delay-line filter with tap weights w_n. The relation between the symbols c_k at the output of the encoder and the input bits b_k is given by Eq. (14).

$$c_k = \sum_{n=0}^{N-1} w_n b_{k-n} \qquad (14)$$

Different correlative encoders can be obtained by changing the tap weights. For example, for $w_o = +1$, $w_1 = +1$ and $w_n = 0$ for $n \geq 2$ duobinary encoder is obtained; for $w_o = +1$, $w_1 = 0$, $w_2 = -1$ and $w_n = 0$ for $n \geq 3$ modified duobinary encoder is obtained.

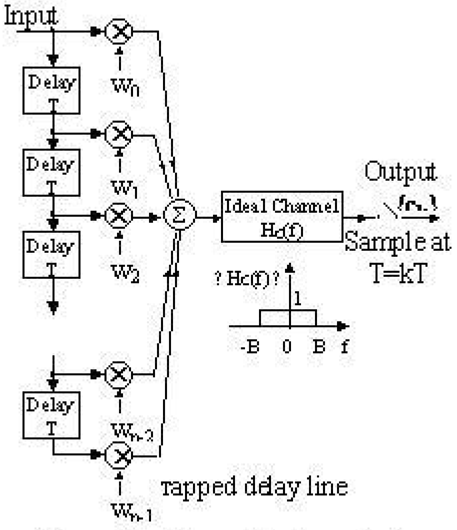

Figure 13. Generalized correlative

8. CRITERIA FOR CHOOSING LINE CODES

The fundamentals factors to be considered when choosing a line code for a particular application were stated in section 2 as follows:

(1) Bandwith requirement,
(2) Spectrum at low frequency,
(3) Timing content,
(4) Error monitoring,
(5) Coding efficiency.

The most important of these factors is the opportunity to trade transmission bandwith against the number of amplitude levels in the transmitted symbol. By using a multilevel code we can increase the information carried per symbol and so reduce the transmitted symbol rate and hence reduce the required transmission bandwidth. A bound is derived on this trade-off by considering that M-level symbol can carry a maximum of $\log_2 M$ bits of information per symbol [1]. Since an M-level symbol enables bandwith reduction proportional to $\log_2 M$ bits/symbol and so a similar reduction in channel noise entering the receiver, information content of a symbol ($\log_2 M$ bits/symbol) is defined as "Noise Bandwidth Reduction Factor". On the other hand, an M-level received signal needs an $(M^2-1)/3$ improvement in signal-to-noise ratio (SNR) relative to binary communication for the same error probability [1]. This factor is called "SNR improvement factor" to be provided by the receiver. Hence, the bound for M-level transmission can be defined as the SNR penalty to be paid relative to binary communication and it is given by Eq. (15).

$$\text{SNR penalty (relative to binary)} = \frac{\text{SNR improvment factor required at the receiver}}{\text{Noise bandwidth reduction factor}} = \frac{M^2-1}{3\log_2 M} \qquad (15)$$

Figure 14 shows the plot of SNR penalty (relative to binary) versus number of levels (M). This bound is based on the receiver noise bandwidth assumption but there are also other factors. For example, in applications where the channel bandwith is not insufficient, cross talk may occur on multipair metallic cables. In such cases multilevel coding must be used to reduce the transmission rate. The 2B1Q code can be given as an example for such applications.

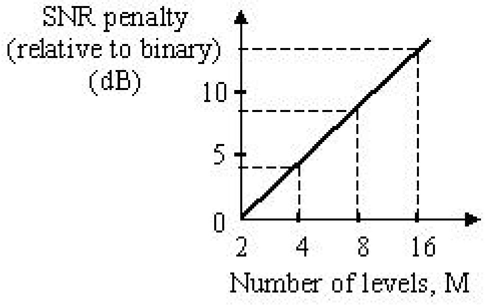

Figure 14. SNR bound for M-level transmission.

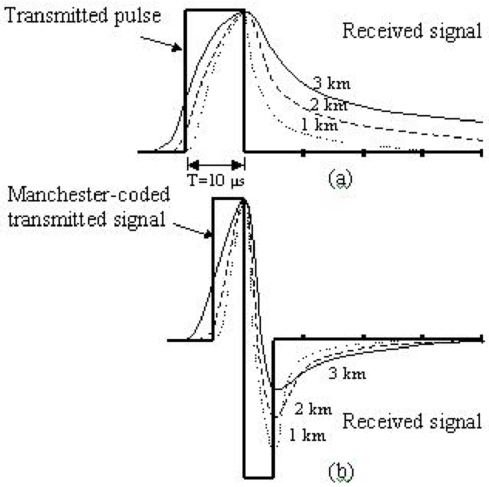

Figure 15. Pulse response of a twin line metallic cable (0.4mm copper): (a) Received waveforms for a single transmitted pulse. (b) Self equalizing properties of the Manchester code.

Another important factor to be considered in choosing a line code is equilazation. The degree of precision when equalizing for channel distortion may also have to be considered, bearing in mind any self-equalizing properties and the fact that multilevel codes require more precise equalization than binary. Some line codes, for example, the Manchester code has self-equalizing property. As shown in Figure

15, due to this property of Manchester coding a considerable amount of tail cancellation occurs which causes reduction in undesired ISI. The line codes having self-equalizating property may not need an extra equalization process. In Figure 15, it can be easily seen that a considerable amount of ISI occurs if the 10 µs spaced pulses are transmitted without equalization [1].

9. CONCLUSION

Choosing a proper line code for a particular application needs to consider many interrelated factors. These factors can be summarized as: Bandwith requirement, spectrum at low frequency, timing content, error monitoring, and coding efficiency. Therefore, line coding must be applied according to the properties of the transmission channel that will be used.

Transmission mediums using metal cables show low-pass frequency characteristics. In such applications, line coding is the last process before transmission. Fiber optic transmission systems and radio systems are bandpass systems in which line coding is performed before the modulation or in combination with modulation. Encoder at the transmitter and decoder at the receiver must operate at the symbol transmission speed. Therefore, especially at high-speed encoder and decoder designs should be as simple as possible.

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