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A SURVEY OF DIGITAL BASEBAND SIGNALING TECHNIQUES

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16. ABSTRACT

A brief tutorial survey of 25 basic baseband signaling techniques was made to choose the most applicable signaling technique for a space shuttle data bus. The following baseband signaling techniques were considered: unipolar non-return-to-zero level (NRZ-L), polar NRZ-L, NRZ-mark, NRZ-space, unipolar return-to-zero (RZ), polar RZ, bipolar RZ, bipolar NRZ, delay modulation (Miller code or DM), dicode RZ, dicode NRZ, pair selected ternary (PST), time polarity control (TPC), return-to-bias (RB), biphase level (split phase or Manchester), biphase mark, biphase space, multilevel signaling, biternary, duobinary, the general polybinary scheme, pulse duration modulation (PDM), pulse position modulation (PPM), spatial multiplexing, and sequency multiplexing.

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A SURVEY OF DIGITAL BASEBAND SIGNALING TECHNIQUES

INTRODUCTION

Signaling techniques can be classified, in general, as carrier or as noncarrier (baseband) types. Twenty-five of the latter methods, in which the digital data are transmitted directly or with some shaping but does not involve modulation of a sinusoidal carrier signal, are considered here. Each of the signals is described and signaling technique parameters that affect a group of selection criteria are specified for each so that comparisons of the signals can be made and a particular signal subsequently might be selected for use in a specific electronic system.

A number of criteria exist and must be considered when attempting to select a particular baseband signaling scheme for an electronic system. The following five, however, are used most often to compare various methods:

1. Signal spectral characteristics

2. Signal bit-synchronization capabilities

3. Signal error-detecting capabilities

4. Signal interference and noise immunity

5. Cost and complexity of circuit implementation

The individual importance of these criteria and that of one signal's advantage over another when these are used for comparison naturally depends upon the application.

Considering each of these criteria in order, the signal's spectral characteristics dictate both the required transmission bandwidth for the signal and the bandwidth efficiency; two factors which are most important in evaluating any communication system. Another important signal characteristic that can be obtained from spectral information is whether a signal has zero frequency or very low frequency information. This is important because frequently these baseband signals are transmitted through ac-coupled networks and the zero and low frequency information is lost. Signals with dc energy must have this lost average-value information restored before detection.

Bit synchronization must be provided for any system and three methods by which this can be accomplished are: (1) to provide a separate sync-pulse or clock line, (2) to reconstruct the clock from the data signal, and (3) to frequency-division multiplex the clock with the data. The choice of a particular method depends on whether the clock information can be easily derived from the signaling data, which naturally depends on the format of the signal. For example, clocking information is much easier (circuit implementation is less complicated and also less expensive) to obtain from signals with transitions every bit period than from a signal with randomly occurring transitions.

Many signaling schemes have an inherent error detecting quality. Since error detection and subsequent correction are usually requirements, additional error detecting bits are often not required for these signaling techniques, a quality that certainly must be appraised when comparing signaling schemes.

A prime consideration in any design is the signal's immunity to interference, whether it be caused by the presence of noise or, just as important in baseband data transmission, intersymbol interference. The former is the inevitable contaminate always present in electrical systems. The effects of this type of interference can usually be reduced by increasing the signal power and thereby decreasing the error probability. Intersymbol interference is caused by the nonlinearities in the amplitude and phase characteristics of the transmission media. These nonlinearities cause the transmitted pulses to be distorted and have positive and negative overshoots. Eventually, overlapping of overshoots of past pulses into the bit-period interval of the currently transmitted pulse occurs. This problem cannot be totally negated by increasing the signal power. The simplest means of improving this situation is to compensate, using the adjustable parameters of the transmitting and receiving filters, for the effects of the transmission media.

The final criteria, cost and complexity, depend directly on the preceding four, upon the state-of-the-art circuit development which usually changes from month to month, and upon the particular application. Obviously, these factors vary and are difficult to specify. Consequently, very little further consideration will be given to these items in this report.

The 25 baseband signals are described in the following sections. In addition, many of the signaling parameters that affect the selection of a particular signal are outlined (more details for each can be obtained from the list of references).

UNIPOLAR NON-RETURN-TO-ZERO LEVEL (NRZ-LEVEL)

By far the simplest baseband signaling format is to represent each piece of data by either one binary (on-off) pulse or a group of binary pulses. With added complexity, baseband messages can also be transmitted by allowing the phase, width, or amplitude of the binary pulse, or a transition in the signal level, to represent the information. The baseband signaling scheme whereby a binary "one" is represented by one signal level and the "zero" by a second level is the basic non-return-to-zero (NRZ) [1] scheme which has been given the designation NRZ-level (NRZ-L) in the IRIG Telemetry Standards Document [2]. When the symbol "one" is represented by a signal level and "zero" by a zero level signal, the wave is denoted as unipolar NRZ-L or simply NRZ-L to distinguish it from the polar NRZ-L signal in which equal positive and negative signal amplitudes correspond to the two binary symbols. A typical unipolar NRZ-L wave is shown in Figure 1.

The frequency spectrum for the unipolar NRZ-L wave is described by [3]

$$S(f) = \frac{|N(f)|^2 P(1-P)}{T} + \frac{|N(f)|^2 P^2}{T^2} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{T}\right) \quad . \qquad (1)$$

In equation (1), P and (1 - P) are the probability of a "one" and "zero," respectively, and N(f) is the Fourier transform of a single pulse of width T. As shown in the spectrum envelope (Fig. 2) for this function, the NRZ signal has a definite zero frequency component which requires that the transmission system have dc response or a dc restoration circuit.

Practical schemes exist for obtaining bit synchronization from the NRZ-L signal but implementation is complex. Finally, the unipolar NRZ-L has an immunity to Gaussian noise that is inferior by a factor of 3dB to that of polar NRZ-L which has the best noise immunity of any of the signals.

POLAR NRZ-L

As shown in Figure 1, the only difference between unipolar NRZ-L and polar NRZ-L is that opposite polarity signal levels represent the corresponding binary digits in polar NRZ-L, and a signal and the absence of a signal designate the binary digits in unipolar NRZ-L. The basic characteristics of this signal, except for immunity to noise, are the same as those discussed for unipolar NRZ-L. The polar NRZ-L signal yields the smallest probability of error, for a given energy per bit, of any of the schemes.

NRZ-MARK

In both NRZ-mark (NRZ-M) and NRZ-space (NRZ-S) the information is encoded in terms of the signal transitions. This signaling format is often referred to as differential

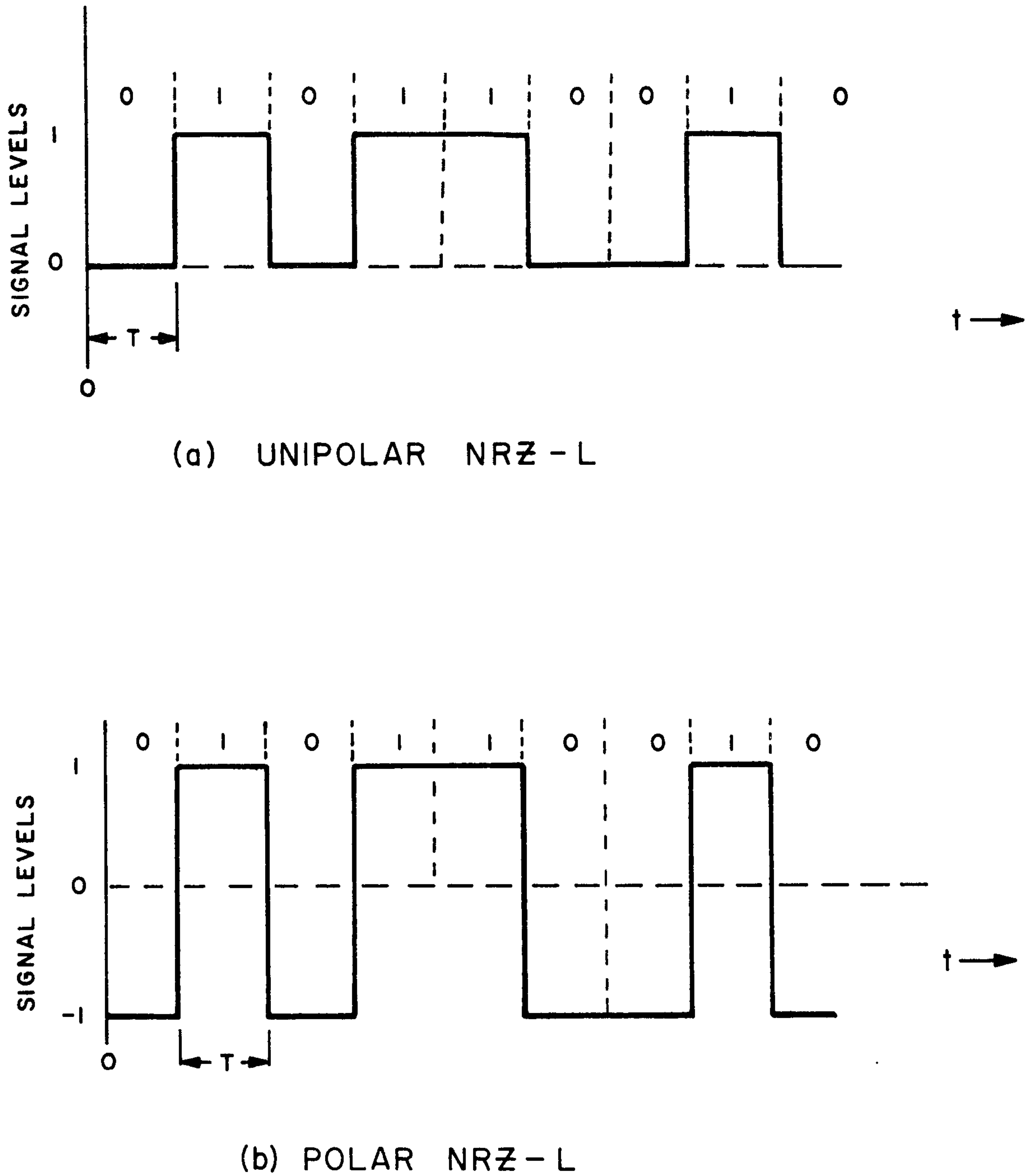


Figure 1. Waveform representation of a typical unipolar NRZ-L signal and a typical polar NRZ-L signal.

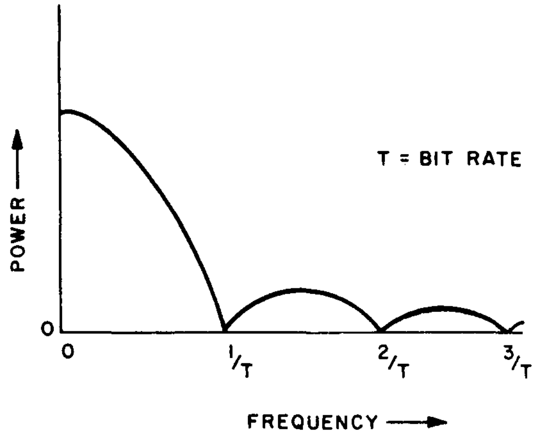


Figure 2. Envelope of the power spectrum for NRZ signals.

encoding [1] of the binary information. In NRZ-M a "one" is represented by a change in amplitude and a "zero" by no change in amplitude. Here no distinction is made between unipolar and polar signals because the information is not in the level of the pulses but rather in whether a transition was made. A typical NRZ-M wave is depicted in Figure 3.

Since the NRZ-M wave is basically the same two-valued signal as the unipolar NRZ-L, its frequency spectrum is described by equation (1) and bit synchronization is obtained as it is for NRZ-L [4].

NRZ-SPACE

The NRZ-space (NRZ-S) signal (Fig. 3) differs from the NRZ-M signal in that in the former a "zero" or space is denoted by a signal transition and a "one" by no signal change; whereas in the latter a "one" or mark is represented by the transition. For comparison, both signals are shown in Figure 3. The properties of the NRZ-S signal are naturally the same as those for NRZ-M which were previously discussed.

UNIPOLAR RETURN TO ZERO (UNIPOLAR RZ)

The basic form of the return-to-zero signal as described by the IRIG document [2] is that a "one" is represented by a pulse one-half a bit period wide and a "zero" by absence of a signal. To distinguish this signal from the signal that represents the binary information with equal and opposite one-half bit period pulses (polar RZ), it is denoted here as unipolar RZ. (Often, the term unipolar is omitted in the literature.) For comparison, both signals are shown in Figure 4, and the polar RZ signal is discussed in the next section.

The spectrum of the unipolar RZ can be described by equation (1). It must, however, be remembered that in this case the term N(f) describes the Fourier transform of a pulse with width T/2; whereas in the preceding cases for the NRZ signals, the pulse widths were T which is the bit period. The envelope of the resulting spectrum is shown in Figure 5. Comparing this spectrum and that shown in Figure 2, the resulting spectral difference between NRZ and RZ is apparent.

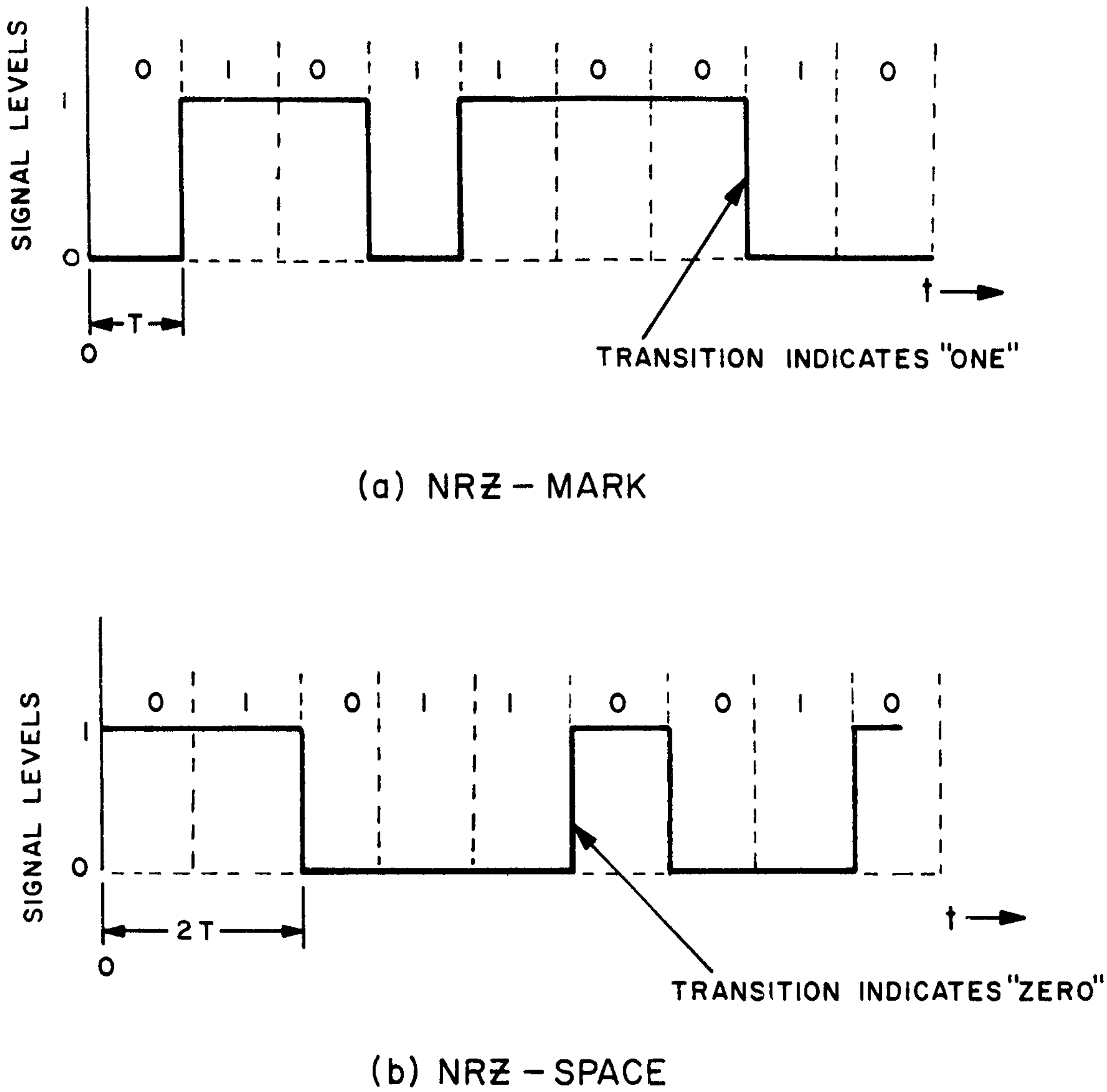
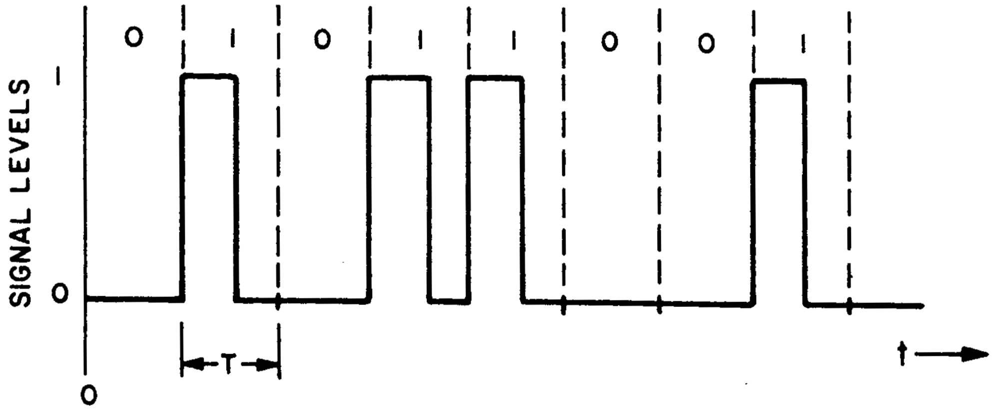


Figure 3. A typical NRZ-M waveform and an NRZ-S waveform.

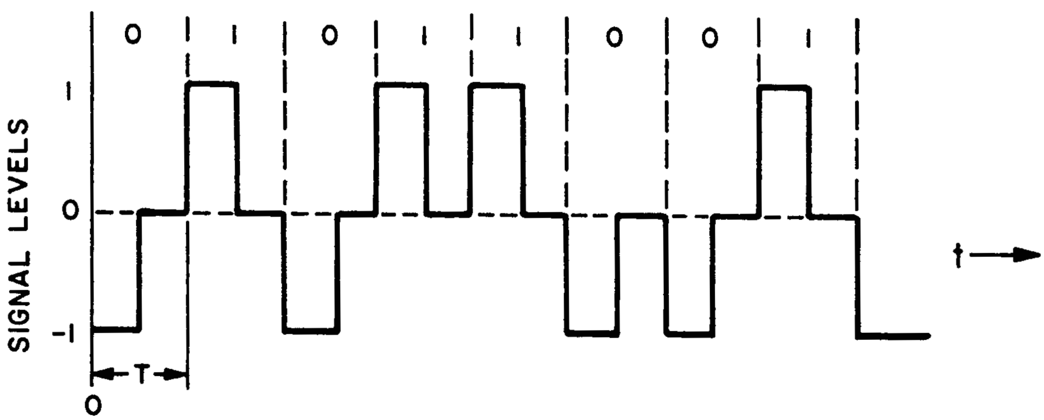
The bit synchronization schemes used for NRZ-L [4] can be used for the unipolar RZ. It was concluded that this scheme has no advantages over the NRZ-L schemes.

POLAR RZ

The structure of polar RZ is shown in Figure 4; binary "ones" and "zeros" are represented by opposite-level-polar pulses that are one-half a bit period wide.



(a) UNIPOLAR RZ



(b) POLAR RZ

Figure 4. Waveform representations of typical unipolar RZ and polar RZ waveforms.

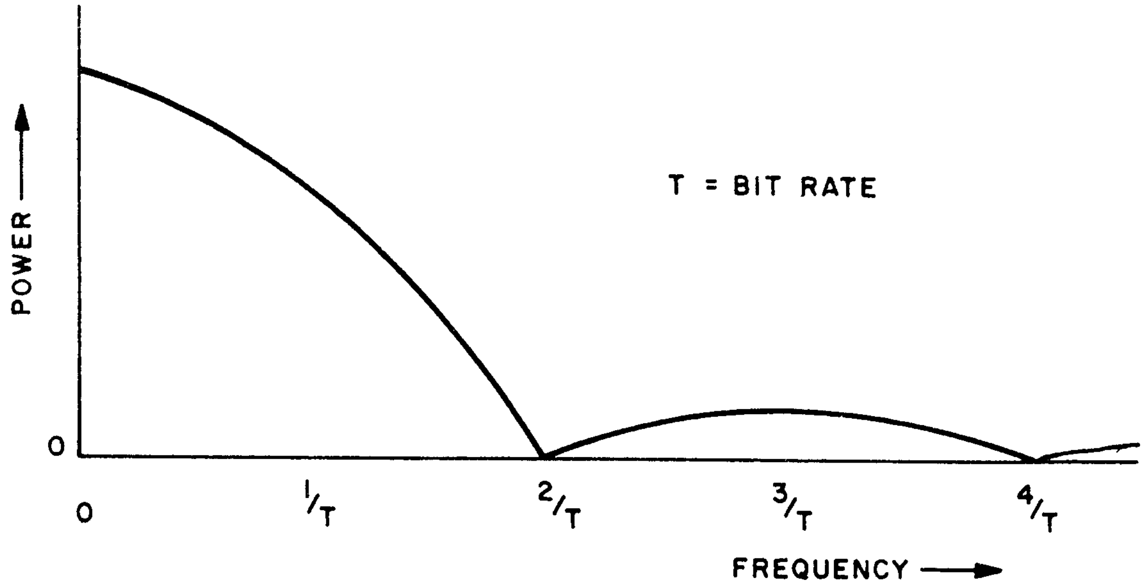


Figure 5. Envelope of the power spectrum of an RZ pulse train.

Again, the spectrum is given by equation (1) with N(f) describing the Fourier transform of a pulse with width T/2. The spectral nulls are located at integer multiples of 2/T and there is a dc component.

Obtaining bit synchronization is much easier for this signal than for any of the signals considered thus far. In fact, clocking information can be obtained directly from a full wave rectified version of the signal. The performance in Gaussian noise is the same as that of unipolar RZ previously discussed.

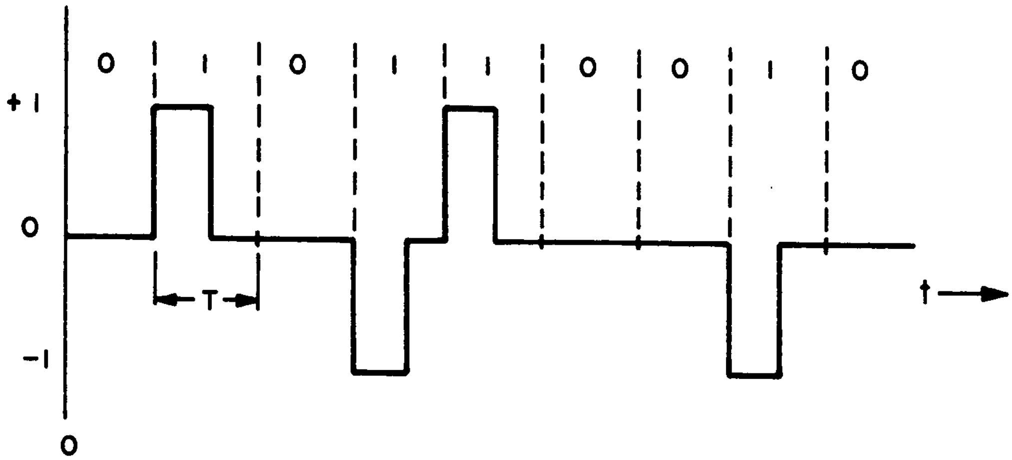
BIPOLAR RZ

The bipolar RZ scheme is a three level signaling method whereby a "zero" is represented by a zero signal level and successive "ones" are represented by equal-magnitude opposite-polarity pulses that are one-half a bit period wide. A typical bipolar RZ wave is shown in Figure 6.

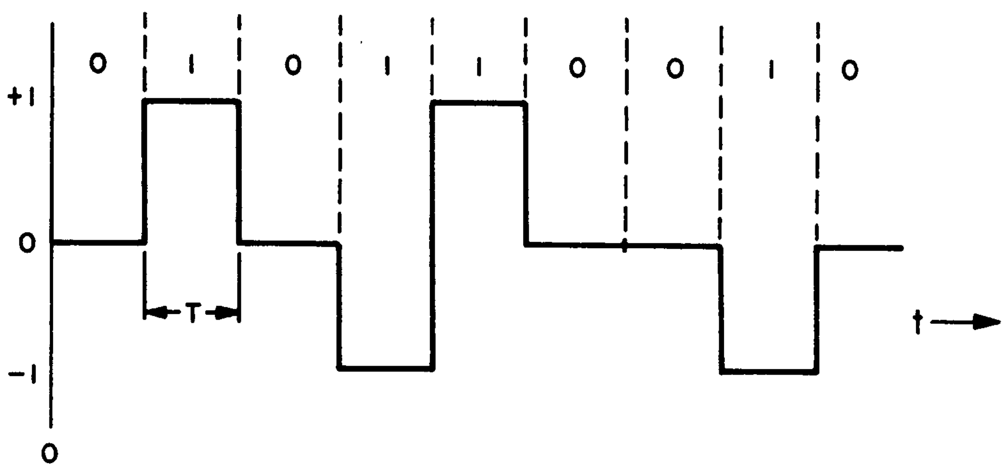
The expression for the spectral density of the bipolar RZ wave is [4]

$$\left[\frac{2\,P(1-P)}{T}\right]\left[1-\cos\frac{(\omega T)}{2}\right]\quad |N(f)|^2 \qquad (2)$$

where again, as in equation (1), P and (1 - P) are the probability of a "one" and "zero," respectively, and N(f) is the Fourier transform of a single pulse of width T/2. The



(a) BIPOLAR RZ



(b) BIPOLAR NRZ

Figure 6. Waveforms representing a typical bipolar RZ signal and a typical bipolar NRZ signal.

spectrum of this bipolar RZ pulse train is shown in Figure 7. The two dominant features that should be noticed are that the wave has no dc component and the spectrum nulls at frequencies that are integer multiples of twice the bit rate frequency, 2/T.

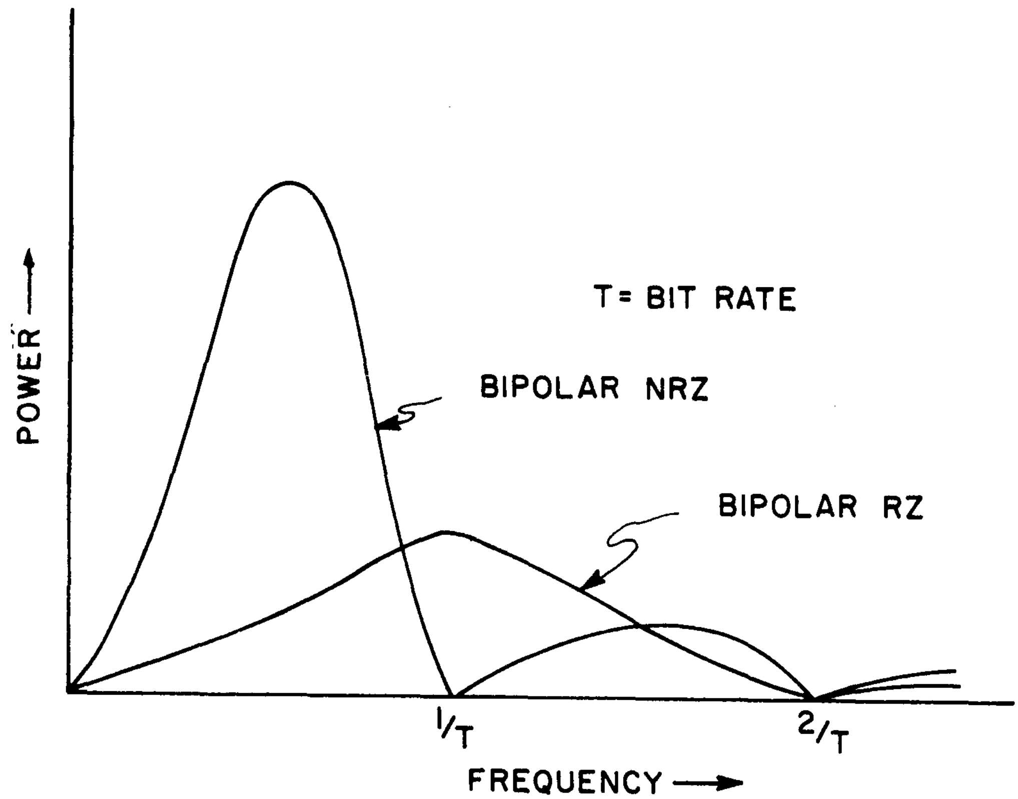


Figure 7. Power spectrum of bipolar signals.

The bipolar RZ signal is used by the Bell System in the T1 Carrier System. Implementation and bit synchronization techniques and signal characteristics are therefore available [3-9]. One of the most important characteristics of this method is that it has a built-in error detecting capability [9], which allows single bit errors to be detected when the alternating property of the pulses in the scheme is violated.

BIPOLAR NRZ

The bipolar NRZ signal (Fig. 6) is a three-level scheme whereby a "zero" is represented by a zero-level signal and successive "ones" are represented by equal-magnitude-opposite-polarity pulses that are one bit period wide.

From the spectrum shown in Figure 7, this wave has no dc component and the spectrum has nulls at M/T, where M = 0, 1, 2, ...

The other characteristics are essentially the same for this signal as for the bipolar RZ signal which was previously discussed.

DELAY MODULATION (MILLER CODE)

The delay modulation (DM) [10, 11] or Miller code [12] encoding procedure is a scheme which has advantages in some applications. The format of this code is shown in Figure 8; a binary "one" is represented by a signal transition at the midpoint of the bit interval. No transition represents a "zero" unless it is followed by another zero. In this latter instance, a transition is placed at the end of the bit period of the first zero.

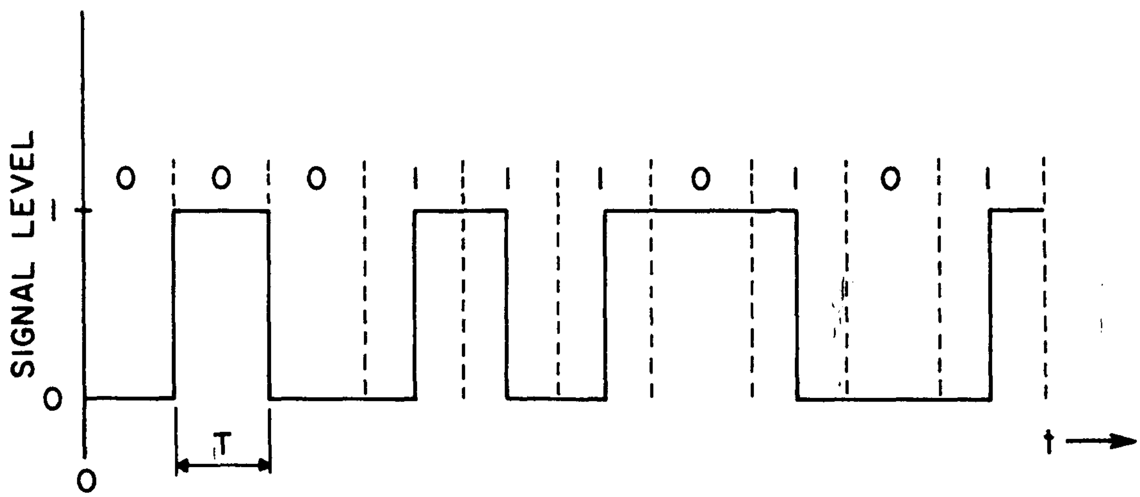


Figure 8. Representation of a DM waveform.

The spectral density, described mathematically by Hecht and Guida [10] as

$$\left\{\frac{2}{\omega^2 T\,[17 + 8\cos(\omega T/2)]}\right\} \Big[23 - 2\cos(\omega T/2) - 22\cos(\omega T)$$

$$- 12\cos\left(\frac{3}{2}\,\omega T\right) + 5\cos(2\omega T) + 12\cos\left(\frac{5}{2}\,\omega T\right)$$

$$+ 2\cos(3\omega T) - 8\cos\left(\frac{7}{2}\,\omega T\right) + 2\cos(4\omega T)\Big] \quad , \qquad (3)$$

is given in Figure 9. The signal has a small dc component and the spectrum nulls at frequencies M/T, M = 1, 2, 3, ...

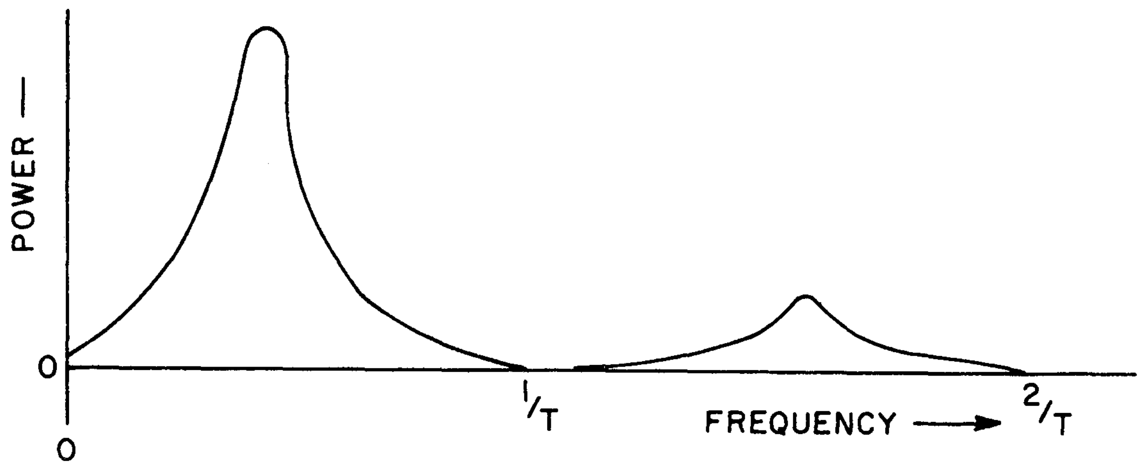


Figure 9. Spectral density of a DM signal.

Bit synchronization can be easily obtained from the signal since a transition occurs at least every other bit interval. To obtain the proper phasing of the clock, however, it is necessary to send a "one"-"zero"-"one" sequence.

DICODE RZ (MEACHAM'S TWINNED BINARY)

In both the dicode RZ and dicode NRZ, polar pulses indicate transitions in the digital information [1, 13]. As shown in Figure 10, the pulses alternate in polarity for successive transitions.

This signal has the same basic spectral expression as for the bipolar RZ signal, which is described mathematically in equation (2) and shown in Figure 7. The signal has no dc component and has the interesting property that the average power of the signal varies proportionally with the density of the transitions of information [1].

Bit synchronization can be derived from the dicode signal using techniques used on the bipolar signals.

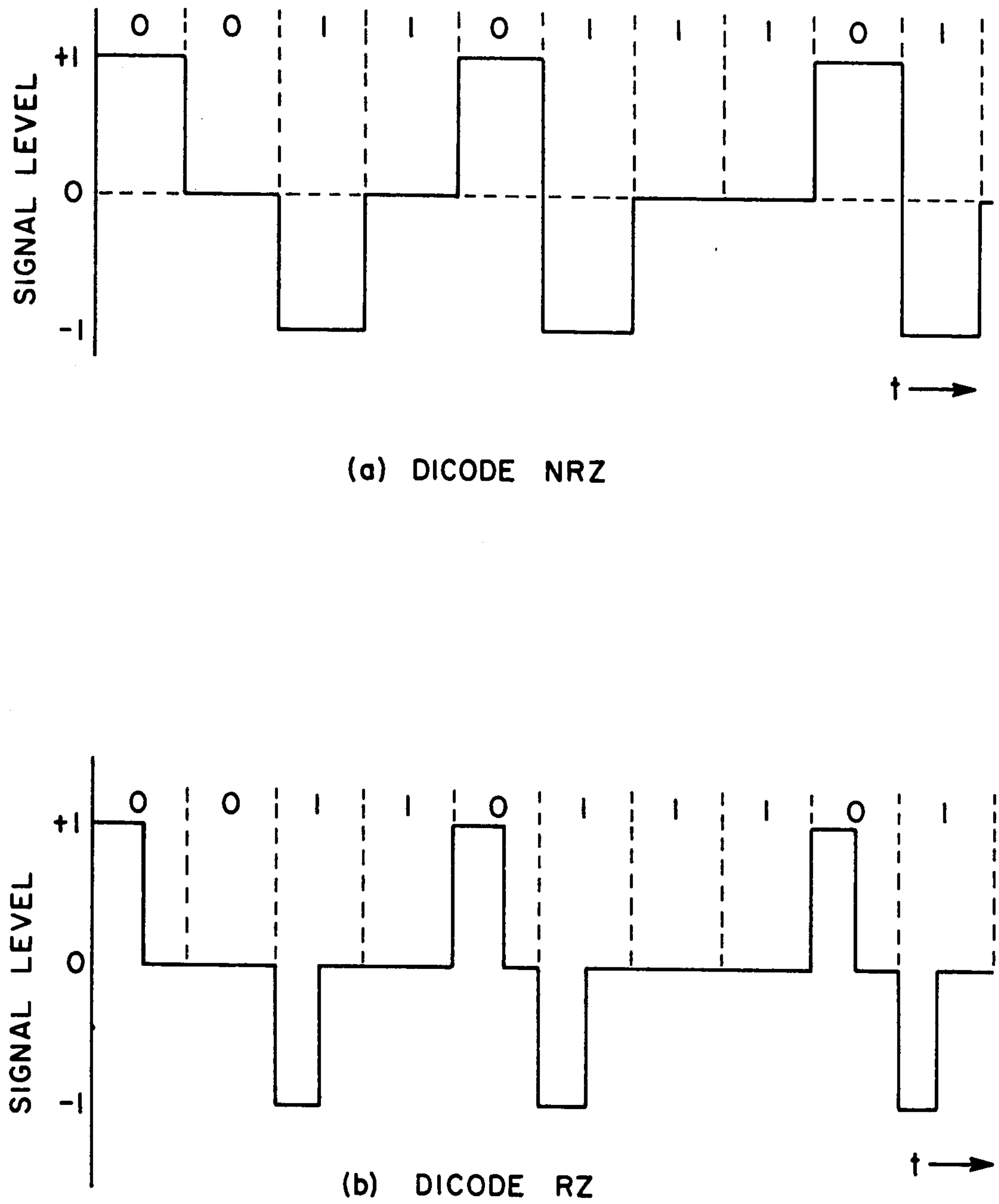


Figure 10. Waveforms illustrating the format of a typical dicode NRZ signal and a dicode RZ signal.

DICODE NRZ

The dicode NRZ wave is identical to the dicode RZ wave previously discussed except for the width of the pulses which represent the data transitions: the pulse width is T in dicode NRZ and T/2 for dicode RZ (Fig. 10).

The spectrum for dicode NRZ is identical to the spectrum of the bipolar NRZ described by equation (2) and shown in Figure 7.

PAIR SELECTED TERNARY (PST)

In the PST [14] scheme, bits of the binary sequence are coded by pairs into a three-level signal according to the following table:

Possible Bit Pairs	Signal Levels, Mode 1	Signal Levels, Mode 2
11	+-	+-
10	+0	-0
01	0+	0-
00	-+	-+
Change Mode After Each 01 or 10		

A signal incorporating these properties is shown in Figure 11.

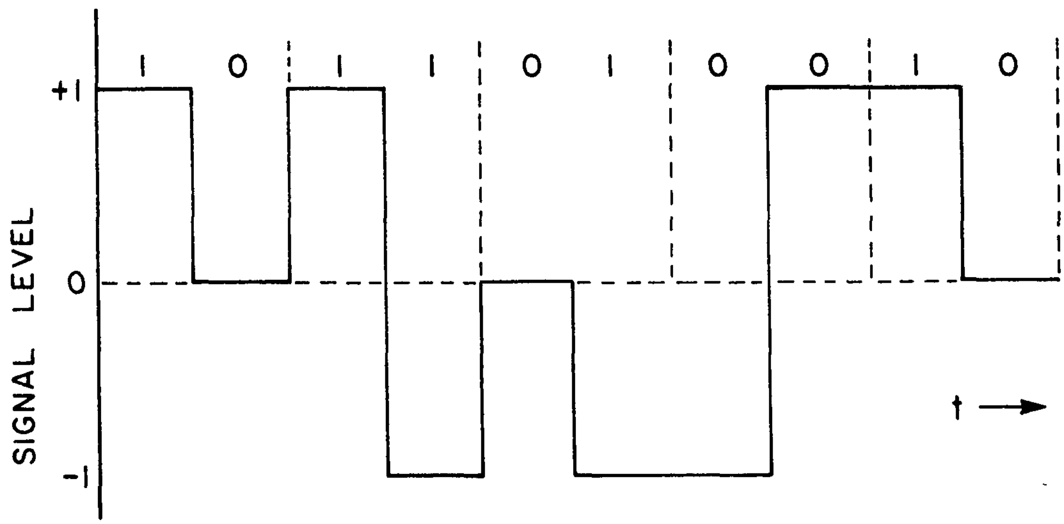


Figure 11. Waveform representation of a typical PST signal.

The resulting spectrum of this wave is similar to that for the bipolar NRZ signal. Consequently, this signal has no zero frequency energy.

The signal has built-in error detecting properties, which result when violation of certain of the PST signal's properties occur, and a framing property [8]. Clock information can be extracted by the same technique that is used with a bipolar pulse train.

TIME POLARITY CONTROL (TPC)

The TPC transmission scheme was suggested by L. C. Thomas [15]. In this method, the bit-period time slots are labeled with alternate positive and negative signs. The unipolar pulse train is converted into a TPC train in the following manner: if a "one" occurs in a negatively marked time interval, it is transmitted as a negative pulse; whereas if a "one" occurs in a positive time slot, it is transmitted as a positive pulse (Fig. 12). "Zeros" are unaltered and consequently transmitted as zero level signals.

The spectrum for this signal is represented mathematically [15] as

$$\frac{P(1-P)}{T} |N(f)|^2 + \frac{P^2}{T^2} |N(f)|^2 \sum_{n=-\infty}^{\infty} \delta \left[f - \frac{(2n-1)}{2T} \right] \quad . \tag{4}$$

The terms of this expression are defined as they were in equations (1) and (2). Furthermore, the continuous part (or first term) of equation (4) is identical to the first term of equation (1) which is the expression for the unipolar NRZ signal. Detection of this signal, after rectification, is the same as for the unipolar NRZ wave.

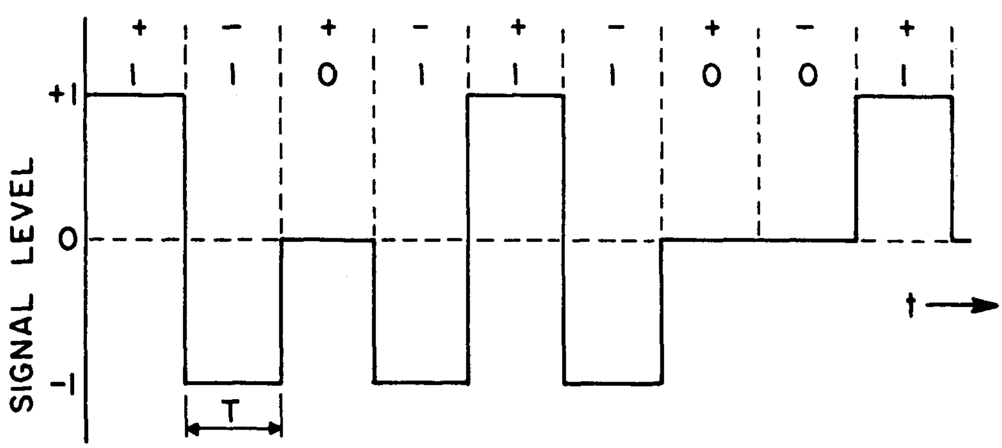


Figure 12. Representation of a typical TPC signal.

RETURN-TO-BIAS (RB)

The return-to-bias [16] transmission scheme uses three signal levels (Fig. 13) in the following manner: "ones" are represented by one-half bit-period pulses that extend from the lowest or bias level to the highest level and "zeros" are represented by one-half bit-period pulses that extend from the bias level to the intermediate level. The signal is always at the lowest level during the latter half of each bit period.

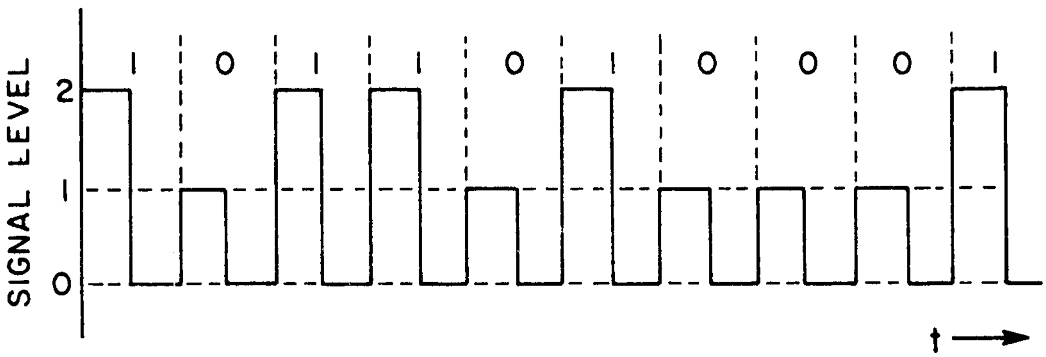


Figure 13. Representation of a typical RB signal.

This signal contains two transitions per bit period which makes the task of extracting clock information a very simple one.

The spectrum for the RB signal is described mathematically as [1]

$$\frac{2P(1-P)}{T} |N_0(f) - N_1(f)|^2 + \left(\frac{1}{T}\right)^2 + \left[P\,N_0(0) + (1-P)\,N_1(0)\right]^2 \delta(f)$$

$$+ \frac{2}{T^2} \sum_{m=1}^{\infty} |P\,N_0(m/T) + (1-P)\,N_1(m/T)|^2 \,\delta(f - m/T) \quad , \qquad (5)$$

where P, 1 - P, and T are defined as they were in equation (1). The expressions $N_0(f)$ and $N_1(f)$ represent the spectral density of the pulses which depict a binary one and binary zero, respectively.

BIPHASE LEVEL (SPLIT PHASE OR MANCHESTER)

In the biphase-level (Bi-ϕ-L) signaling arrangement, both "ones" and "zeros" are represented by a bilevel signal; the "ones" by a signal that has the highest of the two possible signal levels during the first half of a bit period and the lowest level during the last half of the bit period, and the "zeros" by a signal that is the inverse of the signal representing the "ones." A representation of a typical signal is given in Figure 14.

An expression describing the spectral envelope of the biphase signal is [17]

$$\frac{T}{2\pi}\left[\frac{\sin^4\left(\frac{\omega T}{4}\right)}{(\omega T/4)^2}\right] \tag{6}$$

where T is the bit period and ω is the angular frequency. This spectrum is shown in Figure 15. There is no zero frequency information and the spectrum nulls at frequencies that are integer multiples of 2/T and at 0; i.e.,

$$2n/T \quad \text{where} \quad n = 0, 1, 2, 3, \ldots. \tag{7}$$

Clock information is readily available from the signal because there is an amplitude change at least every bit period. Also, the immunity to noise of this signal is comparable to that of the polar NRZ-L signal which is the best.

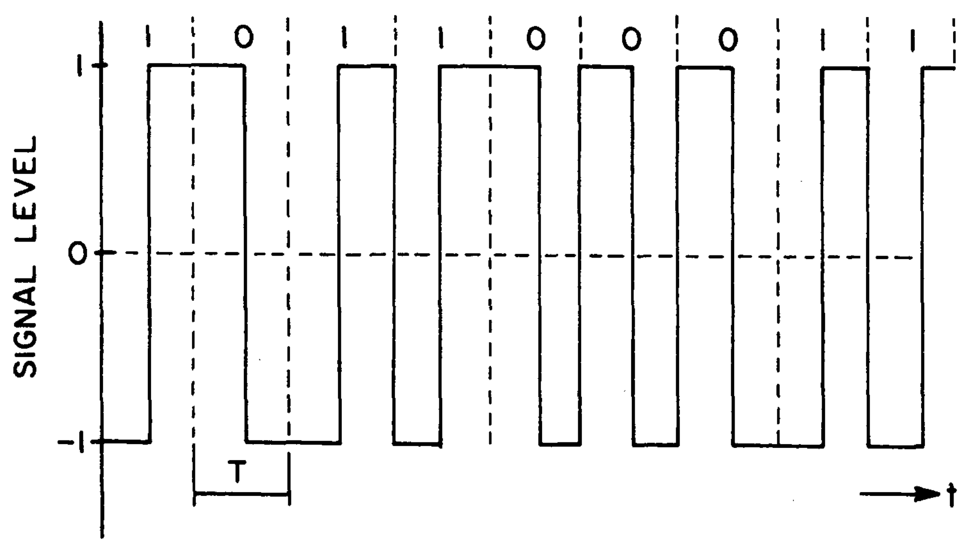


Figure 14. Typical biphase-level waveform.

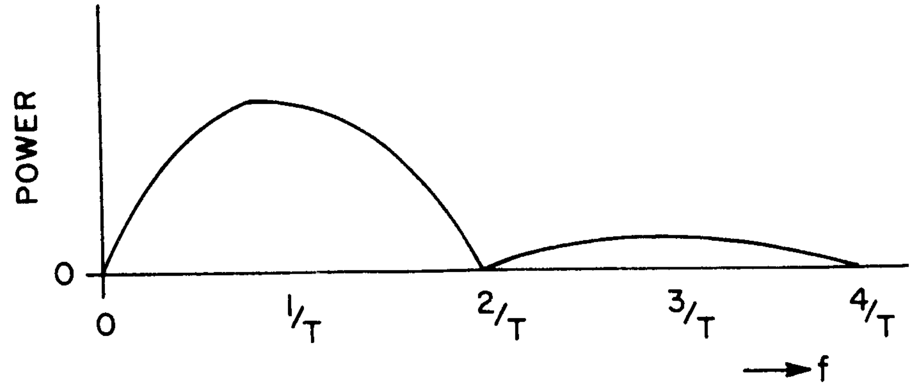


Figure 15. Spectral density of biphase-level signal.

BIPHASE MARK

In the biphase mark (Bi-ϕ-M) signal a transition occurs at the beginning of every bit period. A "one" is represented by a second transition one-half a bit period later and a "zero" is represented by no second transition [2]. A typical Bi-ϕ-M waveform is shown in Figure 16. The spectral characteristics of this signal are the same as those for Bi-ϕ-L; as in Bi-ϕ-L, clock information is easily obtained from the signal.

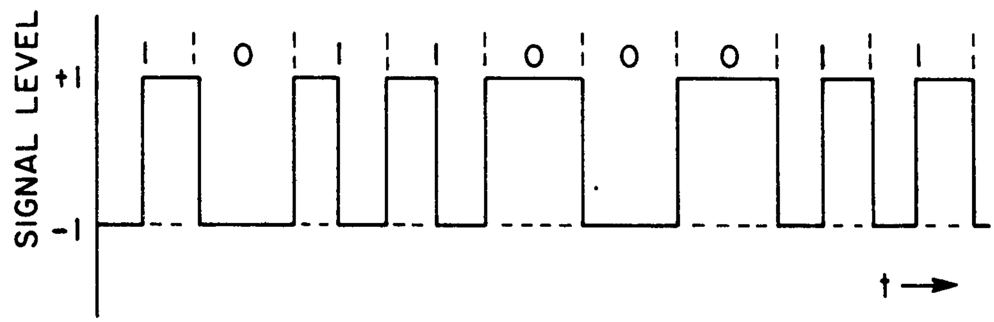


Figure 16. Typical Bi-ϕ-M waveform.

BIPHASE SPACE

The biphase space (Bi-ϕ-S) signal contains a transition at the beginning of every bit period. A "zero" is represented by a second transition one-half a bit period later and a "one" by no second transition (Fig. 17). The other characteristics are again the same as those given for Bi-ϕ-L.

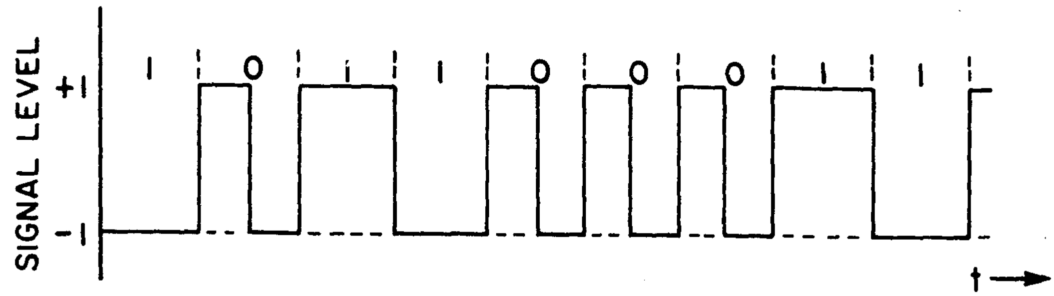


Figure 17. Typical Bi-ϕ-S waveform.

MULTILEVEL SIGNALING

The multilevel signal uses more than two signal levels to represent a group of binary digits. More specifically, each signal level of a group of 2^n transmits n binary digits of information. A typical quadlevel waveform is depicted in Figure 18.

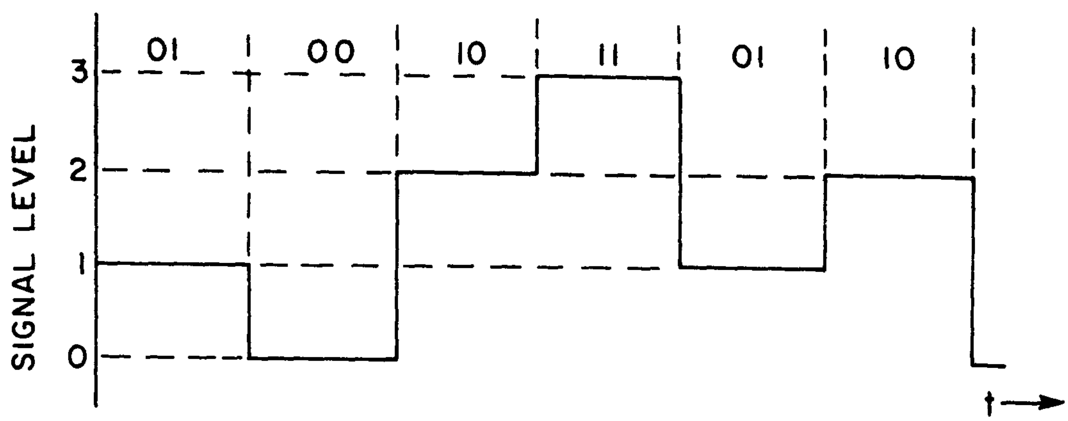


Figure 18. Typical quaternary waveform.

The spectrum for the multilevel signal is essentially the same as that for the NRZ signal. This indicates that the bit packing capability (or bit rate/bandwidth) is higher for the multilevel signals than for the NRZ signal. Of course, there are definite "costs" for this improvement; namely, an approximate noise penalty of 20 log $_{10}$ $(2^n - 1)$ relative to

NRZ signals results from the greater number of signal levels [1] and the system implementation of multilevel signals is more complex.

BITERNARY

The biternary transmission technique [18, 19] is a method whereby two separate NRZ pulse trains, one of which is delayed by one-half a bit period, are added to form the biternary signal; the results being a doubling of the bit rate with an increase in the required transmission bandwidth. Two typical NRZ waves and the biternary signal resulting from their sum are depicted in Figure 19; as shown, the resulting wave is a trilevel signal.

Detection entails sampling the biternary signal at half the bit-period intervals (every T/2 seconds). Individual samples of the biternary signal related to the two original signals, $F_1(t)$ and $F_2(t)$, follow:

F_1	F_t	F_2
0	-1	0
0	0	1
1	0	0
1	+1	1

The obvious ambiguity resulting from detection of a zero in the biternary signal can be resolved by using the information that is available from a previous sample [19].

Biternary signals have inherent properties which reveal the presence of an error when signal levels occur that are impossible when correct data are being transmitted.

Signals of this form have been given the general designation of correlative level codes [14]. The name biternary comes from the combination of part of the word binary and the word ternary since two binary signals are summed to form a ternary signal. Such signals are said to have noise penalties approximated by the equation given for multilevel signaling; namely, $20 \log_{10} (m-1)$ where m is the number of levels and is three in this case.

DUOBINARY

The duobinary coding scheme [14, 20] is another correlative-level-coding method in which the binary data are transformed into a three-level signal. In duobinary, each of

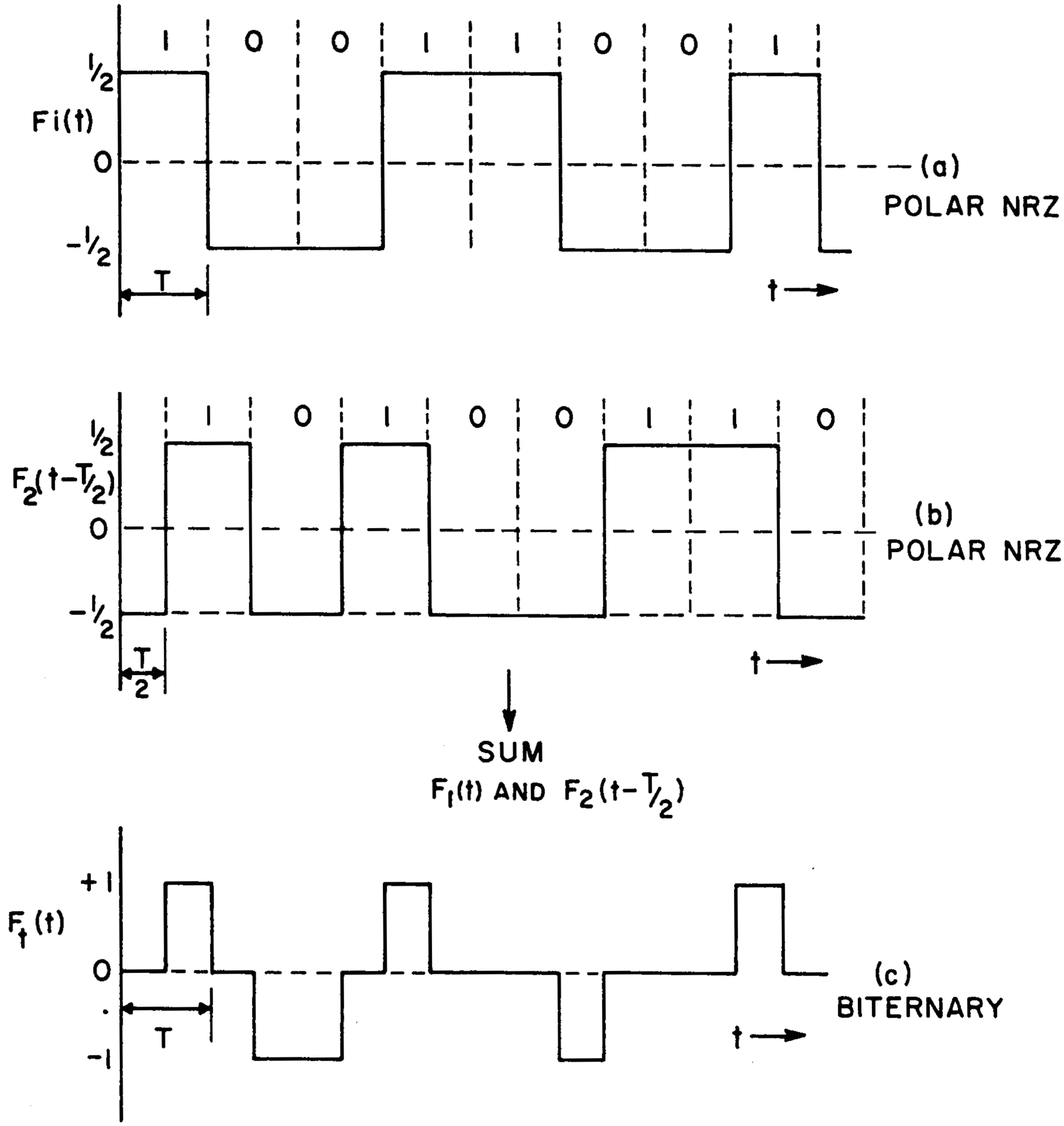


Figure 19. Waveform representations of two NRZ signals (a and b) and the biternary signal (c) formed from their sum.

the three resulting levels is associated with the existing binary digit and preceding bits; thus the term correlative level is used.

The three signaling levels of the duobinary signal are numbered consecutively as zero, one, and two. The signal is coded such that if either of the two even numbered levels results, a binary zero is being transmitted; conversely, if the signal is at the odd (one) level, a binary one is being transmitted. A zero that follows an even number of consecutive ones is assigned the same level as the last zero; a zero that follows an odd number of consecutive ones is assigned the alternate level. Such a wave can be obtained digitally using the circuitry of Figure 20. The waves that occur at individual locations on the block diagram are also represented in this figure.

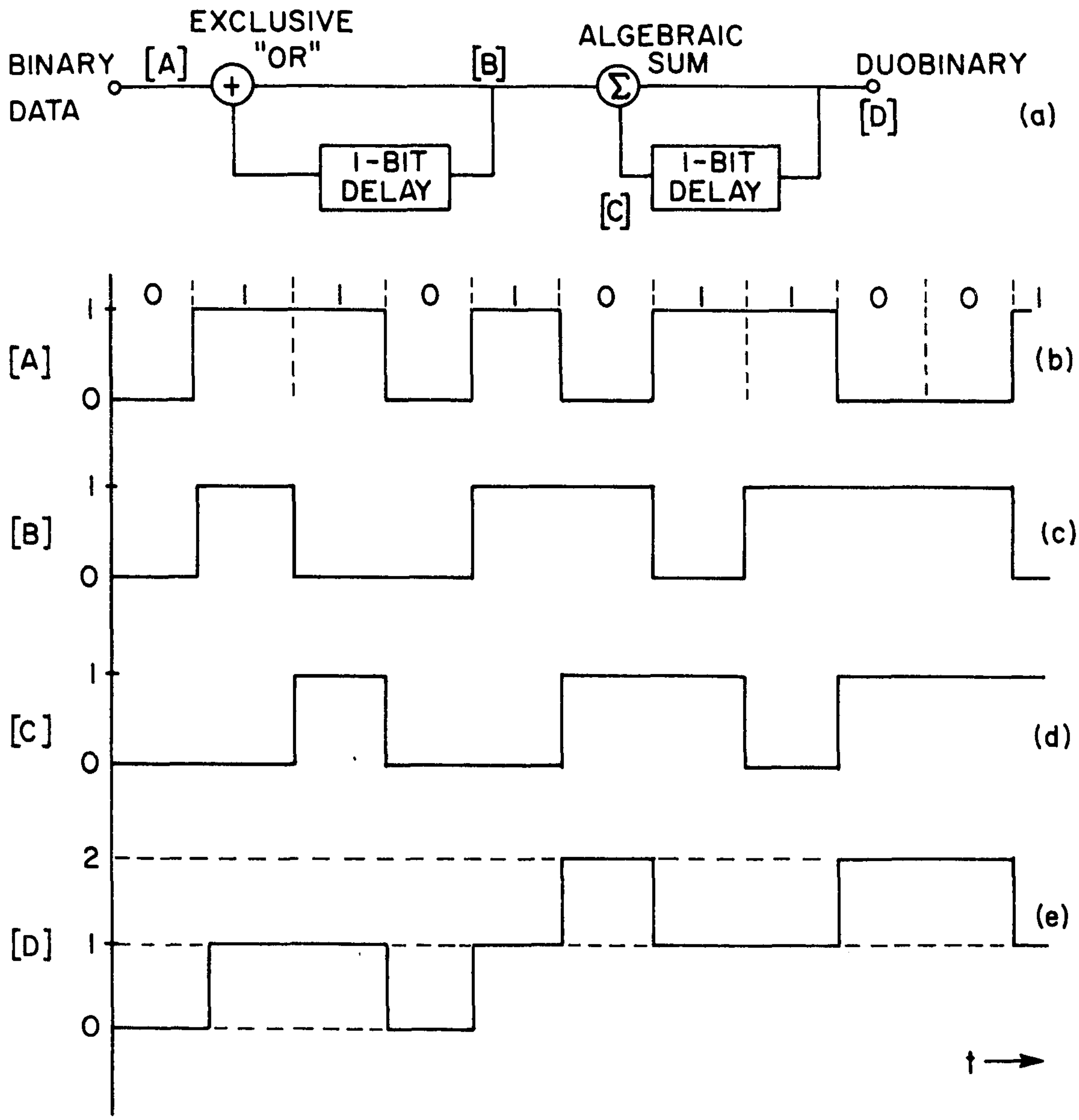


Figure 20. Representation of (a) the circuitry used to form the duobinary signal, (b) the original binary data, (c) the signal at [B], (d) the signal at [C], and (e) the signal at [D].

According to Lender [20], the equation for the spectrum of the duobinary signal is

$$\frac{1}{8T} |N(f)|^2 \left[1 + \cos(\omega T)\right] . \qquad (8)$$

Again, N(f) is the Fourier transform of a pulse of width T, where T is the bit period. Equation (7) implies that the spectrum for the duobinary wave has nulls (Fig. 21) at $\frac{n}{2T}$, n = 1, 2, 3 - - - . Comparing this spectrum with the spectrum of the NRZ wave (Fig. 2) that has the same bit rate T, the improvement in data transmission speed (bit packing) is obvious. Further bandwidth compression, according to Lender, is possible if the transmitted pulses are shaped properly by a filter.

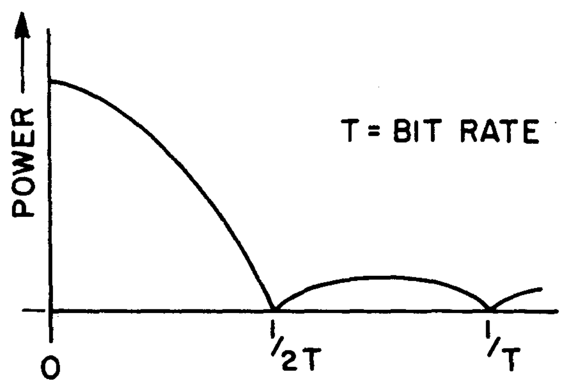


Figure 21. Spectral density of a duobinary signal.

Because the duobinary scheme is a three-level signaling method, there is a definite noise penalty, again given by $20 \log_{10} (n - 1)$, relative to the NRZ signals. The penalty, however, is not as great as that for the four-level signaling scheme; a scheme which has the same transmission speed as that of duobinary, namely, twice that of the NRZ signal.

A unique characteristic of the duobinary signal is that for any two consecutive bit periods, the signal can differ in value by only one level. Consequently, the code possesses an inherent ability to detect errors.

THE GENERAL POLYBINARY SCHEME

A generalization of the biternary and duobinary techniques considered in the preceding two sections was suggested by Lender [14] and studied further by Howson [21]. The general polybinary technique consists of transforming the binary data into an M-level polybinary signal. This is accomplished in two steps and is actually a generalization of the method used to form the duobinary signal.

First, the binary data, which consist of a binary sequence $\{a_n\}$, are encoded into a second binary sequence $\{b_n\}$ by using M + 2 exclusive-or logic operations to form the i^{th} member of the sequence as follows:

$$b_i = a_i \oplus b_{i-1} \oplus b_{i-2} \cdots b_{i-m+2} \tag{9}$$

Next, the M-level polybinary sequence $\{C_m\}$ is formed in such a way that the i^{th} element of the sequence is proportional to the algebraic sum of the M-1 successive digits of $\{b_n\}$.

The specific case of a three-level polybinary signal was previously considered. Notice, for this case, that equation (9) reduces to $b_i = a_i \oplus b_{i-1}$ and the three levels are formed by summing b_i and b_{i-1} operations which are represented in Figure 20.

The M-levels of the polybinary signal are consecutively numbered zero through M-1 and all even numbered levels are interpreted as binary zeros and odd levels as binary ones.

The signal possesses an inherent capability to detect single bit errors since the signal value during any bit period can differ by only one level from the value during the two adjacent bit periods.

PULSE DURATION MODULATION (PDM)

In this method, the binary data are caused to modulate the width of a pulse signal. A typically modulated signal is shown in Figure 22. The format for this signal is that binary "ones" are represented by pulses that have a width of 3T/4; whereas binary "zeros" are represented by T/4-wide pulses.

The signal's spectrum is described by equation (5) with $N_0(f)$ and $N_1(f)$ representing spectra of pulses with widths T/4 and 3T/4, respectively. Clock information is readily available from the signal because there is a definite transition every bit period.

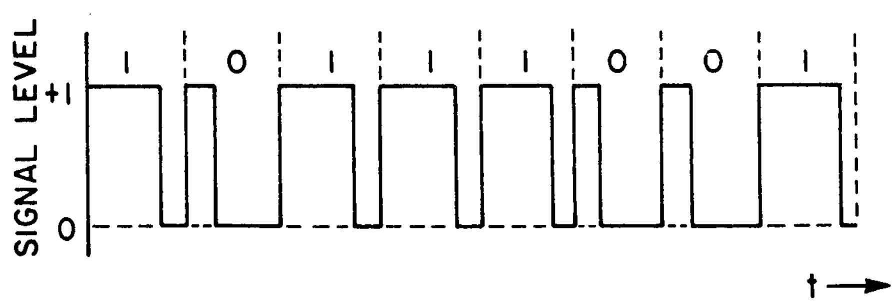


Figure 22. A pulse duration modulated wave.

PULSE POSITION MODULATION (PPM)

In a pulse position modulated signal, pulse signals of a fixed width are position-modulated by the binary data. Such a signal is shown in Figure 23. The pulses of this signal are T/4 wide and their positions depend on the binary data as follows: if the datum is a "zero," the leading edge of the pulse occurs at the beginning of the bit interval; if it is a "one," the pulse begins in the center of the bit period.

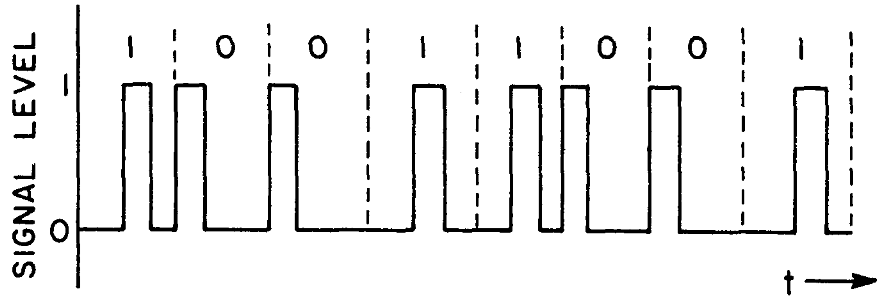


Figure 23. A pulse position modulated wave.

The equation for the spectrum of this signal is equation (5) with $N_0(f)$ and $N_1(f)$ representing the spectrum of the two pulses.

SPATIAL MULTIPLEXING

The spatial multiplexing scheme is depicted in Figure 24. As indicated, if a binary one occurs in the data, the signal on line one is a pulse of width T and there is no signal on line two. Conversely, if the binary datum is a zero, a pulse of width T is sent on line two and no signal is sent on line one. The original NRZ signal is therefore transmitted on line one and the inverse of this signal is transmitted on line two. The characteristics of the signals on each line are therefore identical to those of the NRZ signal previously discussed.

SEQUENCY MULTIPLEXING

In this scheme, each of n digital or analog messages is multiplied by one of a group of n orthogonal Walsh functions and then summed to form a sequency multiplexed signal [22]. Depicted in Figure 25 are four such orthogonal Walsh functions and the Hadamard matrix [23] from which they were formed.

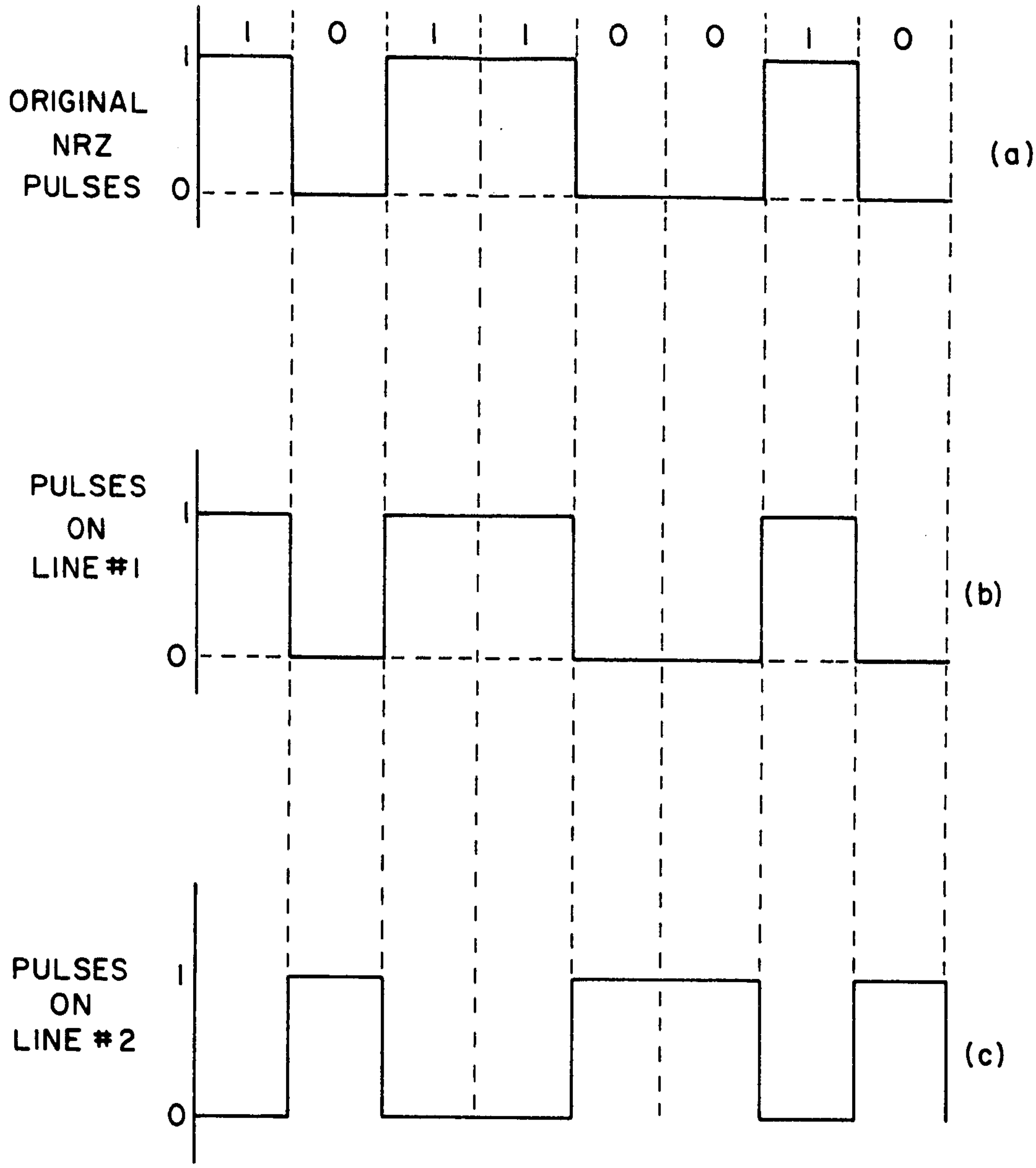


Figure 24. Representation of (a) NRZ data and the signals on (b) transmission line one and on (c) transmission line two.

For the interested reader, many aspects about Walsh functions and their use in communications are given by H. F. Harmuth [22].

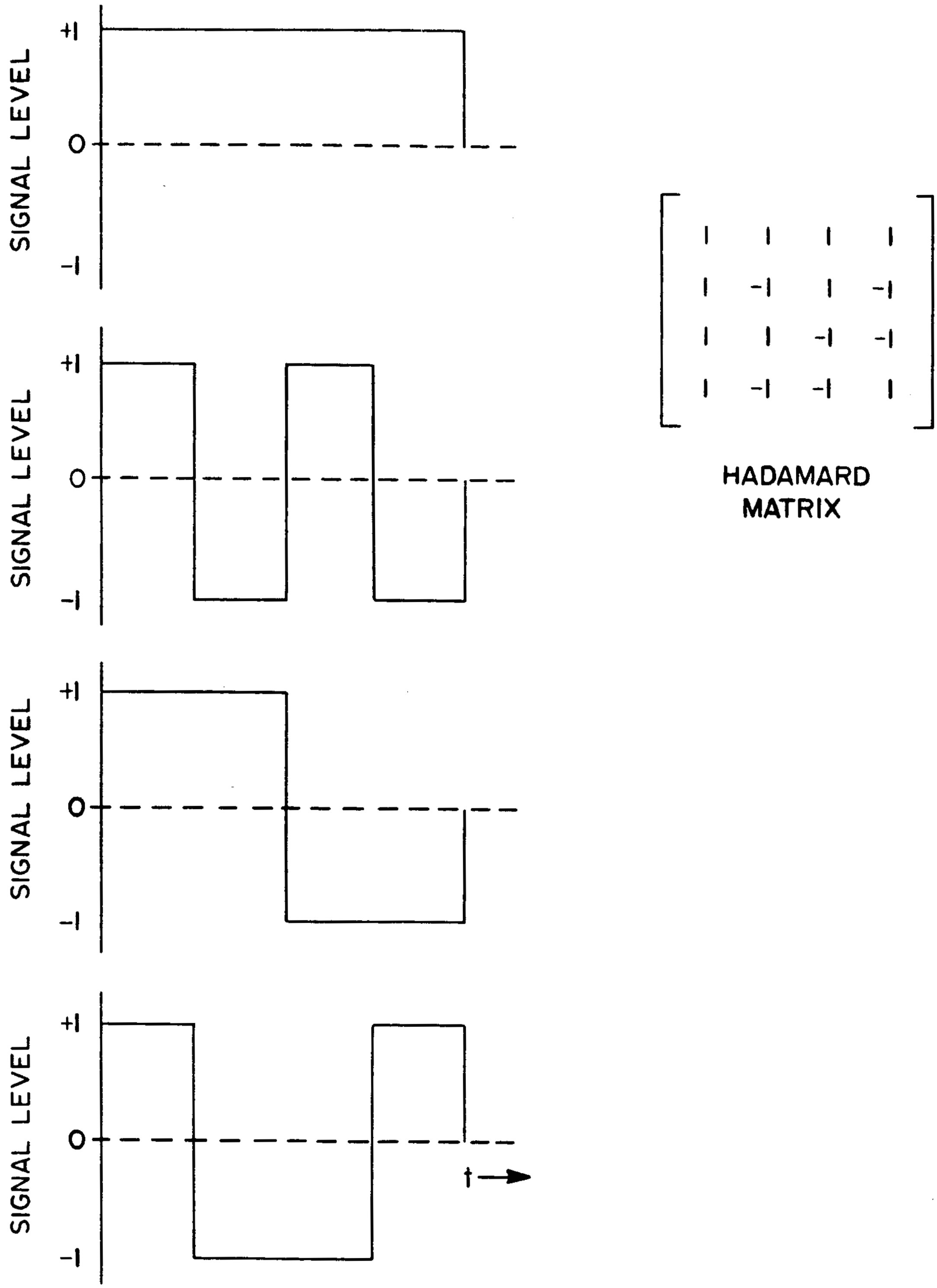


Figure 25. Four Walsh functions and the Hadamard matrix from which they were obtained.

CONCLUSIONS

Since the various signals and the signal characteristics which affect selection criteria are known, the choice of a given scheme might proceed with the first step being to study the characteristics of the engineering system in which the signal is to be used; i.e., determine such items as the system's transmission bandwidth and whether bit synchronization must be obtained from the data signal. With this knowledge of the particular system's characteristics, the five criteria can be "weighted" and then listed in order of importance. The signaling parameters of the various schemes (given in more detail in the articles listed in the references) can then be compared using the rearranged criteria and the most applicable scheme can be selected.

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