COMPARING BANDWIDTH REQUIREMENTS FOR DIGITAL BASEBAND SIGNALS

R. C. HOUTS and T. A. GREEN
Department of Electrical Engineering
University of Alabama at Tuscaloosa

Summary This paper describes the relative, bandwidth requirements of the common digital baseband signaling techniques used for data transmission. Bandwidth considerations include the percentage of total power in a properly encoded PN sequence passed at bandwidths of 0.5, 1, 2 and 3 times the reciprocal of the bit interval, T_b. The signals considered in this study are limited to the binary class, i.e., each decision at the receiver yields one bit of information, in contrast to signaling schemes which encode groups of bits into a given signal amplitude, phase shift, etc. The study compares such signaling techniques as delay modulation (DM), bipolar (BP), biternary (BT), duobinary (DB), pair selected ternary (PST), and time polarity control (TPC) in addition to the conventional NRZ, RZ and BIϕ schemes. It is shown that several of the signals can be transmitted over channels which block frequencies below 10% of the bit rate and still lose less than 5% of the total signal power. Based upon the dual consideration of a large number of regularily-spaced level transitions to assure synchronization plus a minimum of bandwidth and no dc response, it is concluded that DM and PST are the best choices.

Introduction There are several properties which can be considered when comparing the relative merits of digital baseband signaling schemes. Such properties include bandwidth requirements, ease of recording on magnetic tape, synchronization features, implementation complexity, noise margin and error detection features. This paper is primarily concerned with bandwidth considerations to include the bandwidth required to pass 5% of the total power, and the percent power found in a bandwidth equal to various multiples of the bit rate, $1/T_b$. With this information, one can evaluate the tape recording feature. Synchronization information is included in terms of the relative percentage of bit intervals which have level transitions. The other features are discussed in a technical report [1].

Baseband Signals Baseband signals are defined as those which have a large percentage of their power near dc, as opposed to carrier signals which have spectra centered about some carrier frequency and typically require at least twice the bandwidth of a baseband signal transmitting digital data at the same rate. The IRIG standard [2] defines three basic classes of digital signals, namely NRZ, RZ and BIϕ. The bandwidth requirements of these three classes are well known and a comparative analysis has been documented [3]. However, other types of baseband signals have been used [4] and hold considerable promise with regard to bandwidth utilization. Six of the signals studied are classified as multi-level binary (MLB) because they use more than one voltage level to indicate a binary Zero and/or One. Encoded versions of a 7-bit PN sequence are shown in Fig. 1 for each of these. Four other binary signaling schemes studied are shown in Fig. 2. More detail regarding each technique can be found in the literature [5-10]. A comparison of the amplitude spectra for the four basic classes of signals is shown in Fig. 3. It is evident that the BIϕ signals do not require dc response, while the MLB signals require less bandwidth to pass a given percentage of total power. All signal spectra are based upon a 1 volt peak-to-peak signal.

Bandwidth Algorithm The power in a truly random digital signal can be obtained by integrating the power-density spectrum from dc to any desired bandwidth B Hz, Unfortunately, it is not always a simple matter to obtain the power-density expression. Moreover, the desire to compare several signaling techniques dictates a different approach. The encoded signals are compared by using each technique to encode a 127-bit PN sequence [11]. Such a sequence contains 64 Ones and 63 Zeros so arranged as to obey the rules of random variable theory, even though the sequence is generated in a deterministic fashion. Consequently, the sequence is often referred to as a pseudo-noise (PN) sequence. The sequence generator repeats the original sequence after L bits, where L is the sequence length. The resulting waveforms after encoding either are still periodic or can be made periodic by adding one additional Zero to the PN sequence. As can be seen from inspection of Fig. 1, it is necessary to add the additional bit to data encoded by the PST and TPC schemes; likewise, for DM in Fig. 2. Consequently, the resulting signal power Ps can be obtained by applying Parseval's theorem.

$$P_s = |G(0)|^2 + 2 \sum_{n=1}^{\infty} |G(n/T_o)|^2 \quad . \tag{1}$$

$G(n/T_o)$ is the Fourier coefficient of the periodic signal at the n^{th} harmonic of the fundamental frequency $1/T_o$) where T_o is the period of the encoded PN sequence, i.e., LT_b. The power spectrum for an NRZ encoded 15-bit PN sequence is shown in Fig. 4. The number of spectral lines between dc and the first null, $1/T_b$, is equal to the sequence length. Although the power at a given frequency decreases with L, the basic shape of the spectrum is unaltered. Consequently, the relative amount of power contained in a bandwidth B should be equivalent to that contained in a truly random data signal. It was found that L = 127 gave an adequate approximation. The bandwidth algorithm consists of three segments; namely, a signal generator program written in Fortran IV which generates and then encodes the 127-bit sequence, an exponential Fourier series (EFS) program written in the user-oriented language SAP [12] which calculates the Fourier coefficients, and a power computation program written in Fortran IV which essentially performs the power computation given by Eqn. 1. One modification was performed to eliminate the dc bias which would otherwise distort the bandwidth considerations, assuming that the channel does not possess dc response. It was replaced in each spectrum by $|G(1/T_o)|$ and the total power was similarly altered. Consequently, the resultant power calculation resembles an elementary numerical approximation to the integral of a continuous function. The results were checked by an alternative algorithm which first calculated the periodic autocorrelation function of the encoded signal, after which the corresponding power spectrum $S(n/T_o)$ was obtained by an EFS operation. The power was then obtained by summing $S(n/T_o)$. Results were essentially equivalent; however, the first technique was used since it involved less computer time.

Bandwidth Results The percentage of total power passed by ideal lowpass channels with bandwidths of 0.5, 1, 2 and 3 times the bit rate are found in Table I. The NRZ class is limited to the polar signal, since other NRZ signals, i.e., unipolar, Mark, and Space, all possess the same spectrum. Four signals in the RZ class are considered, namely Polar, Pulse Duration Modulation (PDM), Pulse Position Modulation (PPM) and return-to-bias (RB). Since the latter three contain discrete components at one or more of the bandwidths considered, both percentages are listed. All RZ signals require roughly twice the bandwidth of NRZ signals. Delay modulation (DM) has a voltage transition in the middle of a One which makes it similar in appearance to BIϕ; consequently, both are classified as split-phase (SPϕ) signals. However, it is evident that DM requires considerably less bandwidth than BIϕ. The MLB class contains several interesting signals. As is well known [8], the duobinary (DB) scheme requires essentially half the bandwidth of NRZ to pass 90% of the total power. However, biternary (BT) also effectively doubles the data rate for a given bit time through a process of adding two phase shifted polar NRZ signals. The DM, BP/NRZ and PST schemes also achieve a doubling of NRZ bit rate, provided the percent power passed is lowered to -65-70%. The MLB class contains several signals which do not require near-dc response. This feature is studied by comparing the bandwidth required, in terms of a percent of the bit rate, to pass 5% of the total power. However, it is evident that the SPϕ class exhibits the best performance.

Recording on magnetic tape dictates a combination of large 5% bandwidth and low total bandwidth. Consequently, DM which is also known as Miller code, appears to possess the best combination of these two features.

Synchronization Synchronizing a digital signal at the receiver usually requires a phase-locked loop (PU). Consequently, it is desirable that the signal possesses transitions regularly spaced at the bit interval. Furthermore, the signal should not go too long without transitions or the PLL will lose lock. The RZ class is designed to guarantee a

TABLE I

COMPARISON OF BANDWIDTH REQUIREMENTS

CLASS	NAME	BANDWIDTH UTILIZATION (% P_t)				BANDWIDTH FOR 5% P_t (% $1/T_b$)	% LEVEL CHANGES
		$1/2T_b$	$1/T_b$	$2/T_b$	$3/T_b$		
NRZ	Polar	77.3	90.2	95.0	>96.5	2.5	50
RZ	Polar	46.9	77.5	90.3	93.1	5.0	100
	PDM	24.5	40.4/61.5	68.2/89.2	90.6/93.0	9.6	100
	PPM	6.1	31.1	55.8/83.1	88.1	46.4	100
	RB	8.5	14.1/80.4	82.7	83.2/90.6	28.0	100
SPϕ	BIϕ	16.2	64.6	85.6	89.6	32.3	100
	DM	74.0	85.2	92.5	94.9	21.2	>50
MLB	BP/NRZ	64.4	85.5	92.5	94.9	16.1	50
	BP/RZ	44.8	77.6	90.1	93.2	20.4	50
	BT	69.4	89.8	95.0	>96.5	15.1	>50
	DB	90.2	94.9	>96.5	>96.5	13.6	50
	DI/NRZ	64.4	85.5	92.5	94.9	16.1	50
	PST	68.3	86.9	93.2	95.4	11.4	>50
	TPC	39.0/79.1	85.4	92.4	94.8	7.9	>50

transition in each bit interval; however, as noted previously, this characteristic is obtained at the expense of bandwidth. This transition-bandwidth tradeoff is also a shortcoming of the BIϕ signal. Delay modulation and several of the MLB techniques guarantee a level transition in at least 50% of the bit intervals. However, the only two which guarantee that no more than one bit interval passes without a level transition are delay modulation and pair-selected ternary. Consequently, it appears that for a given data rate they represent the best binary signaling techniques from the viewpoint of good synchronization with a minimum of bandwidth.

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This work was supported by the National Aeronautics and Space Administration under Contract No. NAS8-20172.

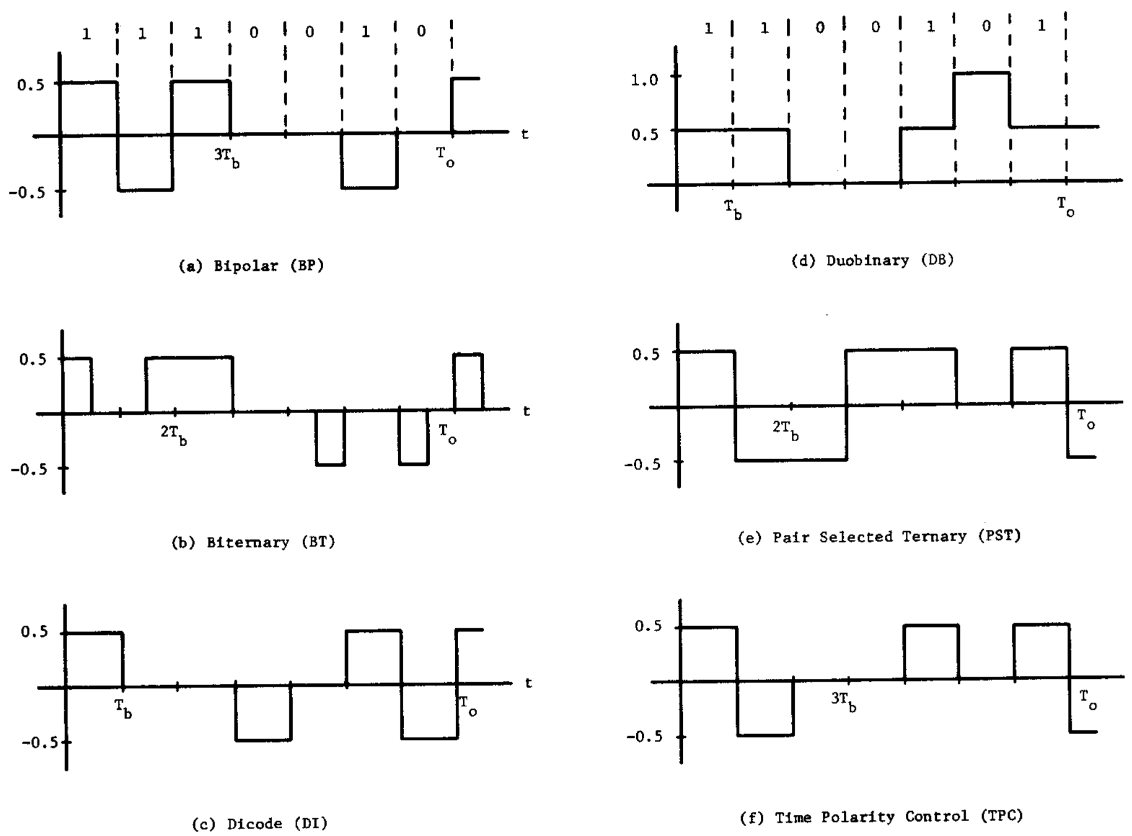
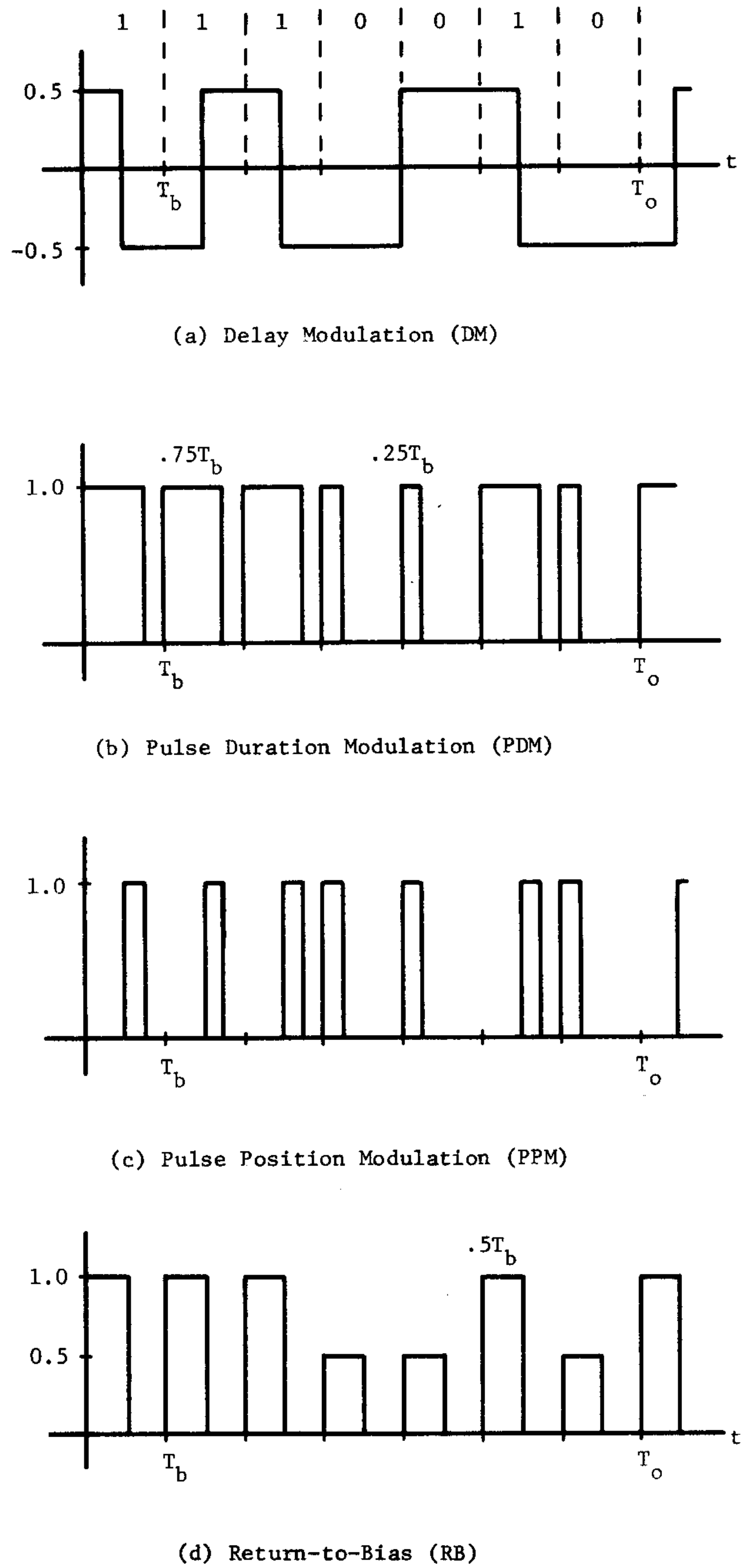


Fig. 1 - Multilevel Binary Schemes.



(a) Delay Modulation (DM)

(b) Pulse Duration Modulation (PDM)

(c) Pulse Position Modulation (PPM)

(d) Return-to-Bias (RB)

Fig. 2 - Two-Level Binary Schemes.

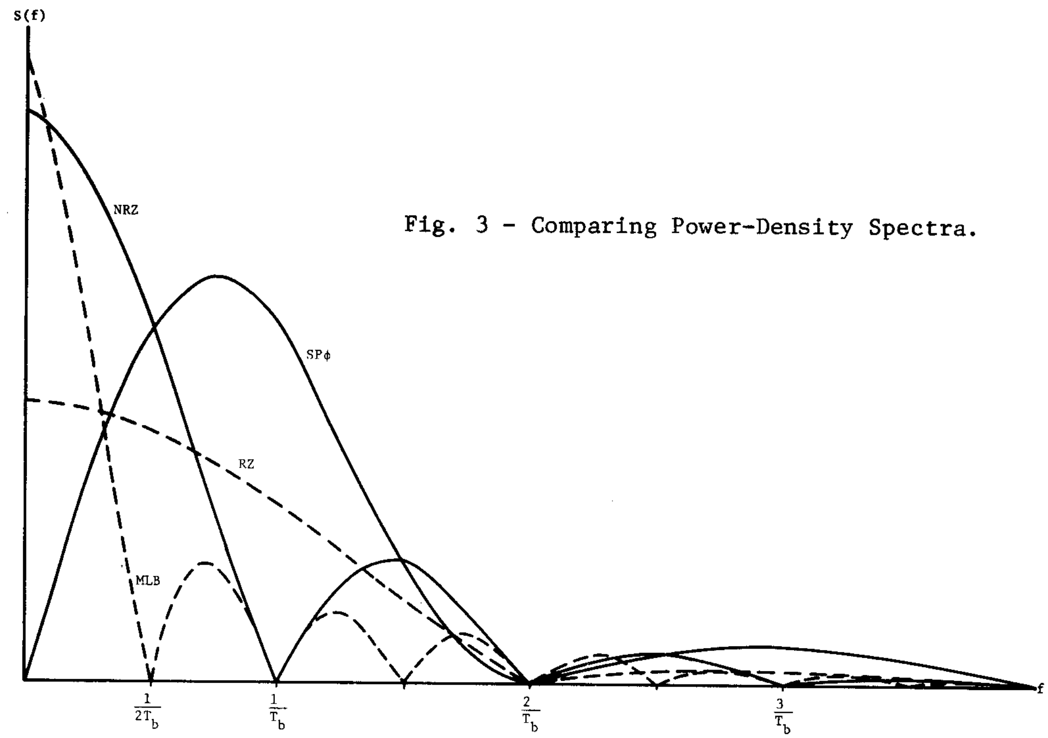


Fig. 3 - Comparing Power-Density Spectra.

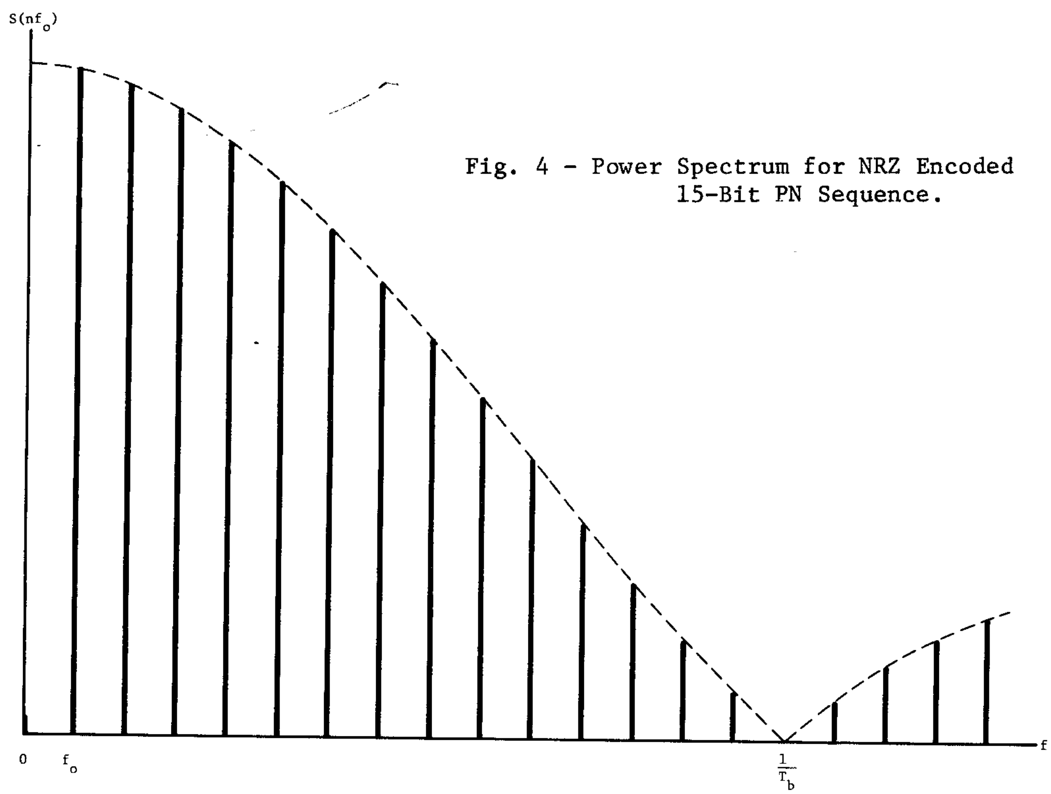


Fig. 4 - Power Spectrum for NRZ Encoded 15-Bit PN Sequence.