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Some Studies on Minimization of Intersymbol Interference By Coding Techniques

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Codes of different lengths and their effect on interference of a base-band PAM system, particularly intersymbol interferences, are considered. Results of simulation study of several coding schemes such as, level coded correlative technique, frequency concept codes, and time domain codes used for minimizing intersymbol interference are presented briefly. The objective of the simulation study is to develop a new code of length 5 for English alphabets which might provide very insignificant inter code word interference and will provide greater transmission rate to band-width ratio. Numerical simulation results showing the performance of various coding techniques for quantitative comparison and curve of the vertical eye-openings versus data transmission rate are also presented.

1. Introduction

The present paper is a part of the investigation being carried out by the authors on minimization of intersymbol interference effects in information transmission, processing, and storage systems.[1,2]

In high speed data transmission applications, such as for space communication systems,[3,4] linear modulated techniques are more efficient because of their optimum use of available band-width and power, although for proper utilization of such band-width, the system becomes complex as coherent detection of carrier and phase is essential.

Since a base-hand signal spectrum has a gradual roll-off beyond the Nyquist minimum, during translation of such a base-band spectrum to bandpass channel, the system generates additional side frequencies which are needed for recovery of the signal. So the recent data communicating systems generally require more band-width than ½ per symbol.

Various authors have tried to minimize the signal distortion. Schreiner *et al.*[5] introduced a scheme for compensating distortion in pulse transmission by pre-distorting the input waveform in such a way that the main peak becomes the midpoint of the output pulse and all other peaks are reduced to zero. Becker *et al.*[6] devised a new method in which the need for excess bandwidth was avoided during base-band shaping such that the received signal spectrum is a half-period sinusoid. It permits intersymbol interference strictly in prescribed amounts. Such symbol response as in Fig. 1 extending over several symbol intervals requires compensating decoding at the receiver. Lender[7] introduced a scheme for compensating error by pre-coding the signal at the transmitter using the rule,

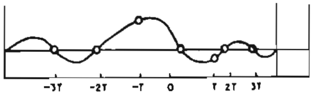

Fig. 1—Partial pulse response

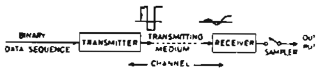

Fig. 2—Communication system model

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

where $\{b_k\}$ is the binary data sequence after pre-coding before transmission and $\{a_k\}$ is the input sequence.

In this paper we have investigated quantitatively the relation between the channel imperfections[8-9] and intersymbol interference and also the effect of different coding techniques on minimization of intersymbol interference.

Digital alphabets of different lengths have been considered which are inherently modulating and have the error correcting properties.[10] Signal energies of such families of alphabets are concentrated into a pre-determined frequency spectrum envelop and can be chosen to match specific requirements in the design of transmission, multiplexing or storage systems.

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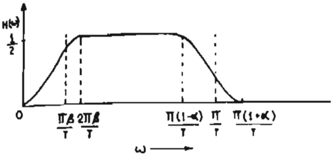

Fig. 3—Channel response characteristic

2. Intersymbol Interference in a Base-band Channel

We consider a communication model for our investigation as in Fig. 2 and a channel having transmission characteristic shown in Fig. 3 to investigate the relation between channel imperfections and intersymbol interference. Analysis is restricted to a particular class of channel which is assumed to be band-limited with sinusoidal roll-off.

If $H(f)$ be the overall frequency characteristic of the transmitter, base-band channel and receiver including equalizer, the discrete impulse response function at the sampler output is

$$h^*(t) = \sum_{l=-\infty}^{l=+\infty} h(lT)\,\delta(t - lT) \qquad \ldots(1)$$

The Fourier transform

$$H^*(f) = \frac{l}{T}\sum_{m=-\infty}^{m=+\infty} H\left(f - \frac{m}{T}\right) \qquad \ldots(2)$$

where an asterisk denotes a sampled function and T is the time interval in sec between the successive symbols. The frequency spectrum $H(\omega, \alpha, \beta)$ of such a channel consists of a flat portion of amplitude with sinusoidal roll-off and is given by,

$$H(\omega, \alpha, \beta) = \begin{cases} \frac{T}{2}\left\{1 - \sin\left[\frac{T}{2\beta}\left(\omega - \frac{\pi\beta}{T}\right)\right]\right\} & 0 < |\omega| < \frac{2\pi\beta}{T} \\ \frac{T}{2} & \frac{2\pi\beta}{T} \leqslant |\omega| < (1-\alpha)\frac{\pi}{T} \\ \frac{T}{2}\left\{1 - \sin\left[\frac{T}{2\alpha}\left(\omega - \frac{\pi}{T}\right)\right]\right\} & \frac{\pi}{T}(1-\alpha) \leqslant |\omega| < \frac{\pi}{T}(1+\alpha) \\ 0 & \frac{\pi}{T}(1+\alpha) < |\omega| \end{cases} \qquad \ldots(3)$$

where α and β (shown in Fig. 3) correspond to the amount of band-width used in excess of the minimum Nyquist band-width at the upper and lower frequency ends of the channel characteristic. The impulse response of such a channel which corresponds to the above characteristic is,

$$h(t, \alpha, \beta) \quad \frac{\sin 2\pi t/T}{2\pi t/T} \cdot \frac{\cos 2\pi\alpha t/T}{1 - (4\alpha t/T)^2} - \frac{\sin 2\pi\beta t/T}{2\pi t/T} \cdot \frac{\cos 2\pi\beta t/T}{1 \quad (4\beta t/T)^2} \qquad \ldots(4)$$

Efficient utilization of a band-width is possible for a given rate of transmission using smaller roll-off, although channel equalization and synchronization becomes difficult.

For lowpass channel, $\beta = 0$, the transfer function becomes $H(f, \alpha, 0)$ and impulse response function $h(l/2, \alpha, 0) = \delta_{l0}$ where $l = 0, \pm 1 \cdots$ and $0 < \alpha \leqslant 1$. Thus a sequence can be sent with no intersymbol interference at the rate of 2 bits/sec through a channel having transfer function $H(f, \alpha, 0)$, but intersymbol interference predominates when the transmission rate deviates by 2 bits/sec.

If the channel shape parameter $\beta \neq 0$, intersymbol interference of a different type[11] occurs. Performance of a data transmission system and a quantitative measurement of a intersymbol interference can be judged from the measurements of eye openings by computing usual eye pattern of a given model (Fig. 2) and the system degradation can be measured from the widest vertical openings at its best sampling time.

We consider a finite length of a sequence a_{-L}, $a_{-L+1} \cdots a_0 \quad a_{-L-1}, a_{-L}$ at the input where L is the integer such that $T_{max}\ R \leqslant L < T_{max}\ (R + 1)$ and R is the digit rate of the sequence. The input signal to the channel (Fig. 2) is given by

$$x(t) = \sum_{l=-L}^{l=+L} a_l g(t - lT) = \sum_{-L}^{+L} a_l g\left(t - \frac{T}{R}\right) \qquad \ldots(5)$$

where $g(t)$ is the transmitted pulse shape. The received signal output at the sampler without noise is given by

$$y(t) = \sum_{-L}^{+L} a_l h(t - lT, \alpha, \beta) = \sum_{-L}^{+L} a_l h\left(t - \frac{l}{R}, \alpha, \beta\right) \qquad \ldots(6)$$

where $h(t, \alpha, \beta)$ is the output pulse shape. The vertical eye openings (ϵ) at any instant $t=0$ and $a_l = \pm 1$, can be obtained from the following quantities,

$$\epsilon_1 = \min_{(a_l), a_0 = 1} y(0) = h(0, \alpha, \beta) \sum_{-L}^{+L'} \left| h\left(-\frac{l}{R}, \alpha, \beta\right)\right|$$

and

$$\left.\epsilon_2 = \max_{(a_l), a_0 = -1} y(0) = -\epsilon_1 \right\} \qquad \ldots(7)$$

where the prime $\sum'$ indicates deletion of the term for $l = 0$.

3. Coding Techniques for Minimization of Intersymbol Interference

In the previous section, an attempt was made to establish relationships between channel imperfections and the channel response functions while in this section an evaluation of the effects of various coding schemes in reducing intersymbol interference is made. The coding schemes we study include the correlative level coding,[12-14] Gorog's frequency concept codes, and Kobayashi's time-domain designed alphabets along with the modification by the present authors.

3.1 Correlative Level Coding

For high speed data requirements, the speed capabilities of a binary transmission system is limited and hence multilevel systems are used. For correlative level coding or digital modulation among these discrete levels, the energy is redistributed in such a manner that it is concentrated at low frequencies and only transitions between adjacent levels are permitted such that intersymbol interference is smaller than in multilevel systems.

If $\{a_l\}$ be the input binary sequence to a correlative level coding system, the corresponding output will be $\{b_l\}$, then the input-output relation will be

$$b_l = \tfrac{1}{2}(a_l + a_{l-1}) \qquad \ldots (8)$$

Thus

$$\left.\begin{aligned} b_l &= +1 \text{ when } a_l = a_{l-1} = 1 \\ b_l &= 0 \text{ when } a_l = -a_{l-1} \\ b_l &= -1 \text{ when } a_l = a_{l-1} = -1 \end{aligned}\right\} \qquad \ldots (9)$$

This shows that direct transition between 1 (top) and − 1 (bottom) levels never occur, thus intersymbol interference can be made smaller with this correlative level coding techniques.

Vertical eye opening (ϵ) versus transmission rate (R) for a code word length $L = 4$ is shown in Fig. 4. Due to three level signals there are two vertical eye openings, the upper eye denoted by the quantities ϵ_3 and ϵ_4 and the lower eye denoted by ϵ_5 and ϵ_6. There are two different correlative level coding systems. The impulse response function corresponding to the first type of coding is,

$$g(t) = \tfrac{1}{2}\left\{h(t) + h\left(t - \frac{1}{R}\right)\right\} \qquad \ldots (10)$$

Now,

$$\epsilon_3 = h(0, \alpha, \beta) + h\left(\frac{1}{R}, \alpha, \beta\right) - \sum_{\substack{l=-\infty \\ (l\neq 0, l\neq -1)}}^{+\infty}{}' \left| h\left(\frac{l}{R}, \alpha, \beta\right) + h\left\{\frac{(l+1)}{R}, \alpha, \beta\right\}\right|$$

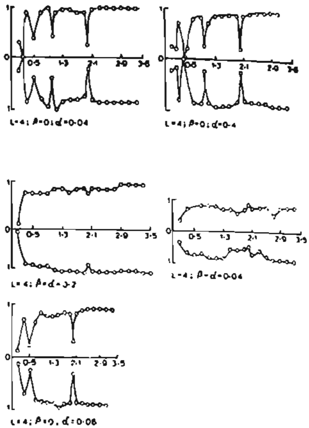

Fig. 4 — Vertical eye opening (ϵ) versus transmission rate (R) for a code word length $L = 4$

$$\epsilon_4 = \left| h(0, \alpha, \beta) \quad h\left(\frac{1}{R}, \alpha, \beta\right)\right| + \sum_{\substack{l=-\infty \\ (l\neq 0, l\neq -1)}}^{+\infty}{}' \left| h\left(\frac{l}{R}, \alpha, \beta\right) + h\left\{\frac{(l+1)}{R}, \alpha, \beta\right\}\right|$$

$$\epsilon_5 = -\epsilon_4$$

$$\epsilon_6 = -\epsilon_3 \qquad \ldots (11)$$

while the impulse response function for the second type of coding is given by

$$g(t) = \tfrac{1}{2}\left\{h(t) - h\left(t - \frac{2}{R}\right)\right\} \qquad \ldots (12)$$

The corresponding upper eye will be ϵ_7 and ϵ_8 and the lower eye ϵ_9 and ϵ_{10}.

$$\epsilon_7 = h(0, \alpha, \beta) - h\left(\frac{2}{R}, \alpha, \beta\right) - \sum_{\substack{l=-\infty \\ (l\neq 0, l\neq -2)}}^{+\infty}{}' \left| h\left(\frac{l}{R}, \alpha, \beta\right) - h\left\{\frac{(l+2)}{R}, \alpha, \beta\right\}\right|$$

$$\epsilon_8 = \left| h(0, \alpha, \beta) + h\left(\frac{2}{R}, \alpha, \beta\right)\right| + \sum_{\substack{l=-\infty \\ (l\neq 0, l\neq -2)}}^{+\infty}{}' \left| h\left(\frac{l}{R}, \alpha, \beta\right) - h\left\{\frac{(l+2)}{R}, \alpha, \beta\right\}\right|$$

$$\epsilon_9 = -\epsilon_8$$

$$\epsilon_{10} = -\epsilon_7 \qquad \ldots (13)$$

where Σ^* indicates deletion of two terms for different values of l,

3.2 Frequency Concept Codes

The digital alphabets of various lengths are generally redundant and at the same time modulating. The entire signal energy is concentrated into a predetermined range of the frequency spectrum. The frequency spectrum of discrete valued signals having sequence $a_1, a_2, \ldots a_L$ is given by,

$$S(f) = \sum_{K=1}^{L} a_k \exp(-j2\pi) fT(K-1) \qquad \ldots(14)$$

Code words can be constructed from the frequency spectrum envelop λ [Eq. (14)] so that $S(f)$ have zero values at $f = 1/KT$ where K is an integer, and since $S(f)$ is a continuous periodic function of frequency f and period $1/T$, a sequence can be obtained satisfying the following conditions :

$$S(f) = 0 \text{ at } f = 0, \sum_{K=1}^{L} a_k = 0 \qquad \ldots(15a)$$

$$S(f) = 0 \text{ at } f = \frac{1}{2T}, \sum_{k=1}^{L} a_k(-1)^{k-1} = 0 \qquad \ldots(15b)$$

If the channel has imperfections in the high frequency region, the input sequence should satisfy the second condition of Eq. (15b) only. But if the channel characteristic has imperfections at both the lower and upper frequency regions, the sequence of the new class of binary alphabets having frequency spectrum at both $f = 0$ and $f = 1/2T$ will satisfy both the conditions [Eqs. (15a) and (15b)] or equivalently,

$$\sum_{K=1}^{L/2} a_{2K-1} = 0 \qquad \ldots(16a)$$

and

$$\sum_{K=1}^{L/2} a_{2K} = 0 \qquad \ldots(16b)$$

such a new sequence is suitable for data transmission as transmission at the rate of $1/lT$ words per sec is possible through a non-ideal filter of band width having frequency $1/2T$ and satisfies the condition of transmission of binary data without intersymbol interference.

If the channel characteristic contains imperfections at both the upper and lower frequency ends of the spectrum, intersymbol interference will be very much reduced for those sequences satisfying the above conditions. Gorog designed a simple transmission of English alphanumeric code (STEAN) which contains 36 binary codewords corresponding to 26 letters and 10 numbers (Table 1) of codelength $L = 8$.

Table 1 — Gorog's STEAN Code of Length 8

0	1	1	0	0	1	1	0	0	I	1	1	0	0	0	1	1	0
1	0	1	1	0	0	1	1	0	J	0	1	0	1	1	0	1	0
2	0	0	1	1	0	0	1	1	K	0	0	1	0	1	1	0	1
3	1	0	0	1	1	0	0	1	L	1	0	0	1	0	1	1	0
4	1	1	1	0	0	1	0	0	M	0	1	0	0	1	0	1	1
5	0	1	1	1	0	0	1	0	N	0	1	1	0	0	0	1	1
6	0	0	1	1	1	0	0	1	O	1	0	1	1	0	0	0	1
7	1	0	0	1	1	1	0	0	P	1	1	1	0	0	0	0	1
8	0	1	0	0	1	1	1	0	Q	1	1	0	0	0	0	1	1
9	0	0	1	0	0	1	1	1	R	1	1	0	1	1	0	0	0
A	1	0	0	1	0	0	1	1	S	0	1	1	0	1	1	0	0
B	1	0	1	0	0	1	0	1	T	0	0	1	1	0	1	1	0
C	1	1	0	1	0	0	1	0	U	1	0	0	0	0	1	1	1
D	1	1	0	0	1	0	0	1	V	0	0	0	0	1	1	1	1
E	0	0	0	1	1	0	1	1	W	0	0	0	1	1	1	1	0
F	0	1	1	0	1	0	0	1	X	0	0	1	1	1	1	0	0
G	1	0	1	1	0	1	0	0	Y	0	1	1	1	1	0	0	0
H	1	0	0	0	1	1	0	1	Z	1	1	1	1	0	0	0	0

The 1's and 0's correspond to the +1's and −1's

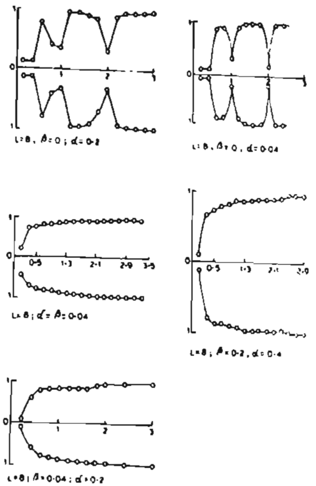

Fig. 5 — Vertical eye opening (ϵ) versus transmission rate (R) for a code word length $L = 8$

Vertical eye opening (ϵ) versus transmission rate (R) for a code word of length $L = 8$ is shown in Fig. 5. The basic theory also holds for non-binary digital signals and is also applicable for m-level alphabet. But the disadvantage encountered in such class of codes is regarding the reduction of intersymbol interference among the neighbouring digits computed to the remote ones, when the transfer characteristics corresponding to lower and upper frequency portions of the channel are not narrow compared with $1/LT$.

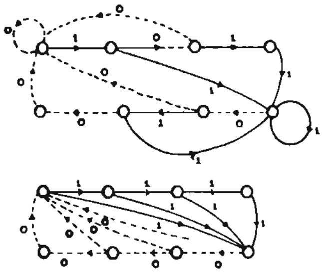

Fig. 6 — Graphic representation of constraints in time domain on binary sequences

Table 2 — The 5, 2, 1, 1 Decimal Code of Length 4

Decimal Numerial	Binary Code			
0	0	0	0	0
1	0	0	0	1
2	0	0	1	1
3	0	1	1	0
4	0	1	1	1
5	1	0	0	0
6	1	0	0	1
7	1	1	0	0
8	1	1	1	0
9	1	1	1	1

3.3 Time Domain Codes

Sequences of binary symbols allowed for data transmission depending upon a number of possible states in the time domain was designed by Kobayashi. When either 0 or 1 has been generated, the state changes to a new state which depends upon the symbol (0 or 1) generated and also upon the original state. Such a system can be graphically shown as in Fig. 6. A natural binary decimal code having weights 5,2, 1, 1 from left for a set of 10 codewords satisfying Fig. 6 is given in Table 2.

If the channel transfer characteristics has imperfection in upper and lower frequency ends of the spectrum, a sequence containing longer word length suffers more intersymbol interference and such sequence containing large runs of 1 or 0, occurring at every second digit is undesirable. Kobayashi tried to avoid such difficulties by dividing such sequences into two sub-sequences, (i) odd numbered digits, and (ii) even numbered digits, these sequences should satisfy the constraint shown in Fig. 6.

For block codes of length 6 given in Table 3 and Fig. 7, are 64 possible code words. If we eliminate such code words in which 1 and 0 occur alternately, then there remain exactly 36 code words. These code words possess the following properties. (1) the run lengths of 1's and 0's in any sequence of code words are less than 8, (2) the alternating sequence of 1's and 0's in any sequence of code words are of length less than 8, (3) the new 5-bit codes corresponding to English alphabets are designed in the time domain. There are 32 code words of 5 bits

Table 3 — A Selected Alphanumeric Code* of Length 6

0	0	0	0	1	1	0	1	0	0	1	0	1	0	0	0	0	1	1	1	0	0	0	0
0	0	0	1	1	0	0	1	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	1
0	0	0	1	1	1	0	1	0	1	1	0	1	0	0	1	0	0	1	1	0	0	1	0
0	0	1	0	0	1	0	1	1	0	0	0	1	0	0	1	0	1	1	1	0	0	1	1
0	0	1	0	1	1	0	1	1	0	0	1	1	0	0	1	1	0	1	1	0	1	0	0
0	0	1	1	0	0	0	1	1	0	1	0	1	0	0	1	1	1	1	1	0	1	1	0
0	0	1	1	0	1	0	1	1	0	1	1	1	0	1	0	0	1	1	1	1	0	0	0
0	0	1	1	1	0	0	1	1	1	0	0	1	0	1	1	0	0	1	1	1	0	0	1
0	0	1	1	1	1	0	1	1	1	1	0	1	0	1	1	0	1	1	1	1	1	0	0

* 1's and 0's correspond to the +1's and −1's

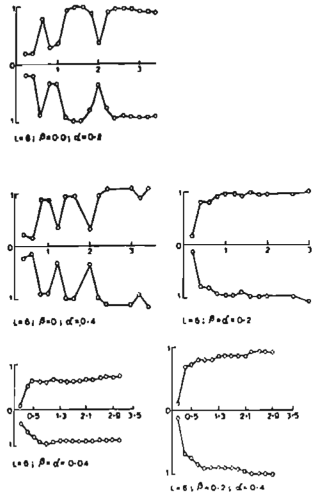

Fig. 7 — Vertical eye openings (ϵ) versus transmission rate (R) for a code word length $L = 6$

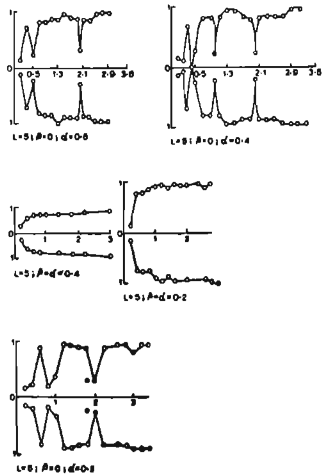

Fig. 8 — Vertical eye openings (ϵ) versus transmission rate (R) for a code word length $L = 5$

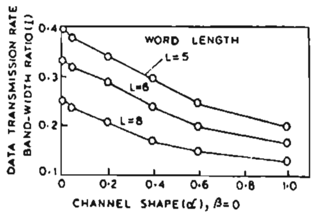

Fig. 9 — Relative figure of merits (I) versus channel shape parameter (α), $\beta = 0$ corresponding to different code word lengths (L)

Table 4 — A New Selected Code* of English Alphabets of length 5

A	0	0	0	0	1	N	0	1	1	1	1
B	0	0	0	1	0	O	1	0	0	0	0
C	0	0	0	1	1	P	1	0	0	0	1
D	0	0	1	0	0	Q	1	0	0	1	0
E	0	0	1	0	1	R	1	0	0	1	1
F	0	0	1	1	0	S	1	0	1	0	0
G	0	0	1	1	1	T	1	0	1	1	0
H	0	1	0	0	0	U	1	0	1	1	1
I	0	1	0	0	1	V	1	1	0	0	0
J	0	1	0	1	1	W	1	1	0	0	1
K	0	1	1	0	0	X	1	1	0	1	0
L	0	1	1	0	1	Y	1	1	0	1	1
M	0	1	1	1	0	Z	1	1	1	0	0

*The 1's and 0's correspond to + 1's and − 1's

if all possible combinations of 0 and 1 are allowed. If we denote a code word $[a_1, a_2, a_3, a_4, a_5]$ in which $a_1 = a_2 = a_3$ or $a_3 = a_4$, there are exactly 26 code words. Such a code is presented in Table 4. If we denote $[a_k]$, an infinite binary sequence consisting of 5-bits code words in that class, the run length of 1 (or 0) should not continue over more than 5 bits in the sequence $[a_k]$ and $[a_k^{-(1)^k}]$. The vertical eye openings versus data transmission rate is illustrated in Fig. 8. It is obvious from Fig. 8 that an appropriate selection of code words can reduce intersymbol interference significantly. If we denote a code word of length 6 by $a_1, a_2, a_3, a_4, a_5, a_6$ where $a_k = \pm 1$ in which + 1 or − 1 corresponds to 1 or 0 in Table 3 the Eqs. (15a) and (15b) for frequency domain codes becomes,

$$\sum_{k=1}^{6} a_k = -2, 0 \text{ or } +2 \qquad \ldots(17a)$$

$$\sum_{k=1}^{5} a_k (-1)^k = -2, 0 \text{ or } +2 \qquad \ldots(17b)$$

4. Comparison of Figure of Merits

The figure of merit (I) of a code word of length L may be regarded as the ratio of digital data transmission rate to the corresponding band width, $I = R/\{L(1+\alpha)\}$, where R denotes the maximum bit rate with which a binary code can be transmitted maintaining all L eye openings larger than a given amount.

We have compared the respective figure of merits corresponding to different word lengths ($L = 5, 6$ and 8). Fig. 9 shows the relation between the respective figure of merit (I) and the channel shape parameter α with β being kept at zero.

Comparison of these curves shows that selection of an appropriate code can reduce intersymbol interference effectively. The selected new alphabetic code of length 5 compared with other curves at the same symbol rate R is found to be superior when the roll-off parameter α is small.

5. Discussion

In this paper, we have investigated the performance of different coding schemes and have made a quantitative comparison of these schemes with simulated results from the view point of minimizing intersymbol interference. We have considered two classes of band limited channel, (i) high frequency with sinusoidal roll-off ($\beta = 0$), (ii) channels having sinusoidal roll-off at both high and low frequency ends.

Performance of different coding schemes have been studied with the help of vertical eye openings (ϵ) versus transmission rate (R). Figs. 4, 7, 5, 8 illustrate the corresponding curves for binary 4 bits decimal (5, 2, 1, 1) code, the alphanumeric 36 code words of 6 bits, Gorog's code of 8 bits and the new 5 bits code for English alphabets. These curves are useful in the design of a data transmission system and provides theoretical limit for various channel shapes. Comparison of these curves shows clearly that selection of an appropriate code can minimize intersymbol interference.

Code words transmission rate to band-width ratio $[I = R/L(1+\alpha)]$ versus channel shape parameter α for different lengths is given in Fig. 9. The curve corresponding to 5 bits English alphabets achieves better performance than any other code and have the additional property that intercode word interference is made zero. The corresponding values of I for length 5, 6 and 8 are 0·4, 0·33 and 0·25 respectively

Regarding the properties of different coding techniques, correlative level coding has a better performance than frequency concept codes or time domain codes with fewer digits but 8-bits STEAN code proposed by Gorog possesses the property that Hamming distance is two.

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