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An Efficient Error Control Line Code with Improved Code Rate Based on the (8,4) Extended Hamming Code

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부호율이 개선된 (8,4) 확대 Hamming 부호를 이용한 효율적인 오류제어선로부호

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ABSTRACT

An efficient error control line code with a special property of zero codeword disparity is proposed and its performance is analyzed in this paper. The proposed error control line code is based on the (8,4) extended Hamming code which is capable of single error correction and double error detection, and to increase its code rate, two blocks of error control codes are used as a line code with simple pre-coding. Thus, the proposed code can be well suited for high speed communication links, where DC-free pulse format, channel error control, and low-complexity encoder-decoder implementations are required. As results of the performance analysis and comparison, the proposed code shows better spectral characteristics in low frequency region and lower residual bit error rate than the error correcting line code using the (7,4) Hamming code, and higher code rate than the conventional error control line code using the (8,4) extended Hamming code. In addition, the proposed code can be implemented with far less complexity.

要 約

본 논문에서는 부호어의 디스패러티가 모두 영인 효율적인 오류제어선로부호를 제안하고 그 성능을 분석한다. 제안된 부호는 한 개의 오류를 정정할 수 있고 두 개의 오류를 검출할 수 있는 (8,4) 확대 Hamming 부호를 사용하고, 부호율을 증가시키기 위해서 간단한 선부호화를 행한 후 오류제어부호 두 블럭을 하나의 선로부호로 사용한다. 그러므로, 제안된 부호는 무직류 펄스 형태, 채널오류제어, 간단한 형태의 부-복호화기가 요구되어지는 고속 통신선로에 적합하다. 성능분석 및 비교의 결과, 제안된 부호는 (7,4) Hamming 부호를 이용한 기존의 오류정정선로부호에 비해 우수한 저주파대역의 스펙트럼특성 및 더 적은 복호비트오율의 성능을 보이며, (8,4) 확대 Hamming 부호를 이용한 기존의 부호에 비해서는 더 높은 부호율을 보인다. 또한 제안된 부호는 훨씬 간단한 형태로 구현될 수 있다.

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I. Introduction

Recently, transmission media such as magnetic or optical recording devices and fiber optic links which respectively make possible storage of bulk data and high speed communication have been developed. To make the coded sequence suitable for transmission through these media, binary line coding techniques are required. In general, the purpose of a line code is to suppress DC and low frequency component and to facilitate synchronization[1-5]. Thus, line codes have little or no error control capability.

Linear block error control codes can be designed to have powerful error correcting and error detecting capabilities and can be encoded and decoded efficiently due to their elegant algebraic structures[6-10]. However, they do not usually possess a desirable line coding feature.

Traditionally, the cascaded scheme of error control coding and line coding techniques has been used such that transmitted code sequences simultaneously have both features. This cascaded scheme has two main drawbacks, the decrease of overall code rate and the reduction of error control capability[11]. To solve these problems, combined error control line codes (ECLCs) have been introduced by Herro and Deng[12], and developed by O'Reilly and Popplewell[13-17]. In particular, O'Reilly and Popplewell[13] considered groups of error control words as the available line codewords instead of considering the individual error control words as line codewords, in order to improve coding efficiency. The number of error control codewords grouped per a line codeword is called the block number. However, to maximize error correcting capability in most ECLCs, they use a linear block error correcting codes whose code length is odd. In this case, codeword disparity defined as the difference between the number of ones and zeros in a codeword can not be zero. Thus, these ECLCs may be somewhat insufficient to suppress low frequency component. To increase the suppression capability of low frequency component, obviously it is desirable that the disparity of codewords should be zero, which means even codeword length.

In this paper, an efficient ECLC with a special property of zero codeword disparity is proposed and its performance is analyzed. The proposed code is based on the (8,4) extended Hamming code with simple pre-coding and is capable of single error correction and double error detection. Since the encoding and decoding algorithm of the proposed code is very simple and efficient, it can be well suited for high speed communication links.

Parameters of line coding are introduced briefly in section II, then the encoding and decoding procedures of the proposed code are discribed in section III. In section IV, the performance of the proposed code is analyzed and compared with that of the conventional ECLCs.

II. Parameters of line coding

There are some basic theorems that define the capability of a line code in terms of disparity, running disparity and runlength. If we substitute the physical symbol set {-1, 1} of a codeword for the logical symbol set {0, 1}, the disparity or digital sum of a k-digit codeword is

$$d = \sum_{i=1}^{k} a_i, \quad a_i = 1 \ or \ -1, \tag{1}$$

where a_i is the ith digit of the codeword. And the running disparity or running digital sum which is defined as sum of disparity up to the nth codeword is

$$D_n = \sum_{i=1}^{n} d_i , \qquad (2)$$

where d_i is the disparity of the ith codeword.

In transmission links such as a fiber optic link, it is desirable that a transmitted sequence has the characteristics of elimination of DC and suppression of low frequency component. For DC-free property, the running disparity of (2) must be bounded[5]. That is, the maximum running disparity[12] should satisfy

$$D_{MAX} = \underset{m}{MAX} \left| \sum_{i=1}^{m} b_i \right| < \infty, \quad b_i = -1 \ or \ 1, \qquad (3)$$

where b_i is the ith bit in the transmitted sequence.

The runlength defined as the number of consecutive ones or zeros in a transmitted sequence is also an important parameter of a line code. Limiting the runlength facilitates suppression of low frequency component as well as synchronization. Let us suppose that a set of codewords is transparent and does not contain the all one or all zero words, then the maximum runlength[17] as a measure of runlength limitation is defined as

$$R_{MAX} = MAX\{R_{MID}, R_{START} + R_{END}\} \qquad (4)$$

where R_{MID} is the maximum number of consecutive ones or zeros in any codeword, R_{START} and R_{END} is the maximum number of consecutive ones or zeros at the start and end of any codeword, respectively.

Ⅲ. The proposed code

The binary Hamming codes are an important family of single error correcting codes and they are easy to encode and decode[10]. In general, the (7,4) Hamming code whose codeword length is 7 and message length is 4 is widely used and is conveniently defined by specifying its parity check matrix or generator matrix. An example of generator matrix for the (7,4) Hamming code is

$$G = \begin{bmatrix} 1&0&0&0&1&1&1 \\ 0&1&0&0&1&0&1 \\ 0&0&1&0&1&1&0 \\ 0&0&0&1&0&1&1 \end{bmatrix} . \qquad (5)$$

The (8,4) extended Hamming code is the code obtained from (7,4) Hamming code by adding an parity check bit (hence, its codeword length is 8). Table 1 shows the full 16 codewords and disparity for the (8,4) extended Hamming code generated from the above matrix. The last bit of codewords is an even parity check bit.

Table 1. Codewords and disparity for the (8,4) extended Hamming code.

Message	Codeword	Disparity
0 0 0 0	0 0 0 0 0 0 0 0	- 8
0 0 0 1	0 0 0 1 0 1 1 1	0
0 0 1 0	0 0 1 0 1 1 0 1	0
0 0 1 1	0 0 1 1 1 0 1 0	0
0 1 0 1	0 1 0 1 1 1 0 0	0
0 1 1 0	0 1 1 0 0 1 1 0	0
0 1 1 1	0 1 1 1 0 0 0 1	0
1 0 0 0	1 0 0 0 1 1 1 0	0
1 0 1 0	1 0 1 0 0 0 1 1	0
1 0 1 1	1 0 1 1 0 1 0 0	0
1 1 0 0	1 1 0 0 0 1 0 1	0
1 1 0 1	1 1 0 1 0 0 1 0	0
1 1 1 0	1 1 1 0 1 0 0 0	0
1 1 1 1	1 1 1 1 1 1 1 1	8

In Table 1, the disparity of 14 out of 16 codewords is zero. If we use these zero-disparity codewords only, we can construct an ECLC which is DC-free and has a good property of suppression of low frequency component.

Recently, the ECLC based on the (8,4) extended Hamming code with block number 1[18] is introduced and has better spectral characteristics and error performance than the ECLCs based on the (7,4) Hamming code[13]. But, its code rate is rather low, since it uses only 8 codewords among 14 zero-disparity codewords of the (8,4) extended Hamming code.

Thus, if more than 8 zero-disparity codewords are used, the code rate of the ECLC can be increased. To encode 7-bit messages, 128(=27) codewords are required. From Table 1, if two zero-disparity codewords are connected, 196(=14 14) zero-disparity codewords can be made and among them 128 codewords can be chosen for an zero-disparity ECLC whose message length is 7. Therefore, a zero-disparity ECLC for 7-bit messages can be made by mapping 7-bit messages into 8-bit words which do not have 0000 or 1111 at the first or last 4-bit and then applying the (8,4) extended Hamming coding technique to each 4-bit word.

1. Encoding

Pre-coding procedure which converts 7-bit message U to 8-bit word V is required before applying the (8,4) extended Hamming encoder. The following step shows the procedure. At first, an 8-bit word $\dot{U}$ can be formed from a 7-bit message U by adding 0, where U and $\dot{U}$ can be expressed as follows

$$U = u_1\ u_2\ u_3\ u_4\ u_5\ u_6\ u_7, \tag{6}$$

and

$$\dot{U} = \dot{u}_1\, \dot{u}_2\, \dot{u}_3\, \dot{u}_4\, \dot{u}_5\, \dot{u}_6\, \dot{u}_7\, \dot{u}_8 = \underbrace{0\ u_1 u_2 u_3}_{\dot{U}_1}\ \underbrace{u_4 u_5 u_6 u_7}_{\dot{U}_2}. \tag{7}$$

Here $\dot{U}_1$ or $\dot{U}_2$ of a word $\dot{U}$ may be 0001 or 1110. According to (4) and Table 1, codewords for these messages enlarge the maximum runlength of a transmitted codeword sequence, since their R_{START} and R_{END} are 3. Thus we form a new 8-bit word V which does not contain 0001 and 1110 as well as 0000 and 1111 in the first and the last 4 bits.

Algorithm for getting a word V from $\dot{U}$ is as follows. If A of (8) is equal to 1, a word $\ddot{U}$ is obtained by inverting $\dot{u}_1$, $\dot{u}_3$, $\dot{u}_5$, and $\dot{u}_7$.

$$\overline{\dot{u}}_2\, \overline{\dot{u}}_3 + \overline{\dot{u}}_5\, \overline{\dot{u}}_6\, \overline{\dot{u}}_7 + \dot{u}_5\, \dot{u}_6\, \dot{u}_7 = A. \tag{8}$$

Even by this peration $\ddot{U}_1$ and $\ddot{U}_2$ of word $\ddot{U}$ can be 0000, 0001, 1110 or 1111 again. Thus, if B of (9) is equal to 1, a word V is obtained by inverting $\ddot{u}_2$, $\ddot{u}_3$, $\ddot{u}_6$, and $\ddot{u}_7$.

$$\ddot{u}_1\, \ddot{u}_2\, \ddot{u}_3 + \overline{\ddot{u}}_5\, \overline{\ddot{u}}_6\, \overline{\ddot{u}}_7 + \ddot{u}_5\, \ddot{u}_6\, \ddot{u}_7 = B. \tag{9}$$

Consequently, when both A of (8) and B of (9) are equal to 1, $\dot{u}_1$, $\dot{u}_2$, $\dot{u}_5$, and $\dot{u}_6$ of word $\dot{U}$ is inverted. For convenience of implementation, (9) can be written as

$$A(\overline{\dot{u}}_2 \dot{u}_3 + \overline{\dot{u}}_5 \dot{u}_6 \overline{\dot{u}}_7 + \dot{u}_5\, \overline{\dot{u}}_6\, \dot{u}_7) = B. \tag{10}$$

Pre-encoding procedure is simply implemented as shown in Fig. 1. And the mapping table of this procedure is shown in Table 2, where 7-bit messages are represented as hexadecimal notation. Blanks in Table 2 are unused words.

Finally, using the two 4-bit words V_1, V_2 which are the first and second half of the 8-bit word V, and the (8,4) extended Hamming code generator, the 16-bit codeword W can be

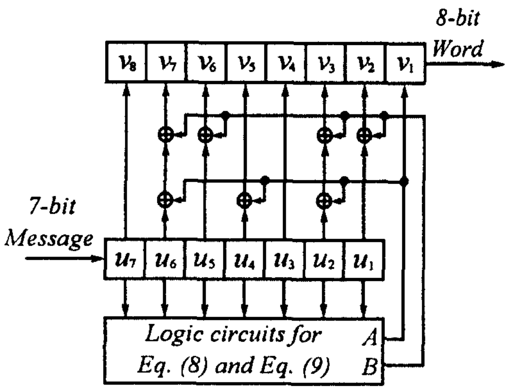

Fig. 1. Logic diagram of 7-bit message to 8-bit word encoder.

Table 2. Mapping table of 7-bit message U to 8-bit word V.

v_5	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
v_6	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
v_7	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
v_8 / $v_1v_2v_3v_4$	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
0 0 0 0																
0 0 0 1																
0 0 1 0			22	23	24	25	26	27	28	29	2A	2B	2C	2D		
0 0 1 1			32	33	34	35	36	37	38	39	3A	3B	3C	3D		
0 1 0 0			42	43	44	45	46	47	48	49	4A	4B	4C	4D		
0 1 0 1			52	53	54	55	56	57	58	59	5A	5B	5C	5D		
0 1 1 0			62	63	64	65	66	67	68	69	6A	6B	6C	6D		
0 1 1 1			72	73	74	75	76	77	78	79	7A	7B	7C	7D		
1 0 0 0			**4E**	**4F**	2E	2F					20	21	**40**	**41**		
1 0 0 1			**5E**	**5F**	3E	3F					30	31	**50**	**51**		
1 0 1 0			08	09	0E	0F	0C	0D	02	03	00	01	06	07		
1 0 1 1			18	19	1E	1F	1C	1D	12	13	10	11	16	17		
1 1 0 0					6E	6F	**0A**	**0B**	**04**	**05**	60	61				
1 1 0 1					7E	7F	**1A**	**1B**	**14**	**15**	70	71				
1 1 1 0																
1 1 1 1																

obtained. A simple example of encoding procedure is presented as follows.

Example 1 : Let an information message U=0011010, and the (7,4) Hamming code be generated by the generator matrix shown in (5).

(i) add zero to U as the first bit. Then, $\dot{U}$ =00011010, and $\dot{U}_1$ =0001, $\dot{U}_2$ =1010.

(ii) invert $\dot{u}_1$, $\dot{u}_3$, $\dot{u}_5$, and $\dot{u}_7$, since $\dot{U}_1$ =0001. Then, $\ddot{U}$=10110000, and $\ddot{U}_1$ =1011, $\ddot{U}_2$=0000

(iii) invert $\ddot{u}_2$, $\ddot{u}_3$, $\ddot{u}_6$, and $\ddot{u}_7$, since $\ddot{U}_2$=0000. Then, V =11010110, and V_1 =1101, V_2 =0110.

(iv) apply the (8,4) extended Hamming encoding rule to both V_1 and V_2. Then, W_1 =11010010, W_2 =01100110

(v) transmit $W = W_1 W_2$ =1101001001100110

2. Decoding

Since the proposed code uses two blocks of the (8,4) extended Hamming code, we divide the received vector $\hat{W}$ into the first 8-bit vector $\hat{W}_1$ and the last 8-bit vector $\hat{W}_2$. And by using the (8,4) extended Hamming decoders for $\hat{W}_1$ and $\hat{W}_2$ respectively, we form a pair of 4-bit word $\hat{V}_1$, $\hat{V}_2$. Here, if the word $\hat{V}$ which is series combination of $\hat{V}_1$ and $\hat{V}_2$ is an unused word, it is detected as an error sequence and retransmission may be requested. Otherwise, we get the message $\hat{U}$ from $\hat{V}$, which is the reverse procedure of pre-encoding V from U. In the pre-encoding procedure, some of the bits in a codeword inverted in 2 steps by (8) and (9). Therefore in decoding, the corresponding bits should be re-inverted. First, those inverted by (9) are checked by (11), that is, if C of (11) is equal to 1, a word $\hat{\hat{U}}$ is obtained by inverting $\hat{v}_2$, $\hat{v}_3$, $\hat{v}_6$ and $\hat{v}_7$

$$\hat{v}_1 \overline{\hat{v}_3} \cdot (\hat{v}_5 \oplus \hat{v}_7) = C. \quad (11)$$

The words corresponding to C=1 are marked in bold-lined boxes in Table 2. Then those by (8) i.e., $\hat{\hat{u}}_1$, $\hat{\hat{u}}_3$, $\hat{\hat{u}}_5$ and $\hat{\hat{u}}_7$ are re-inverted if $\hat{\hat{u}}_1$

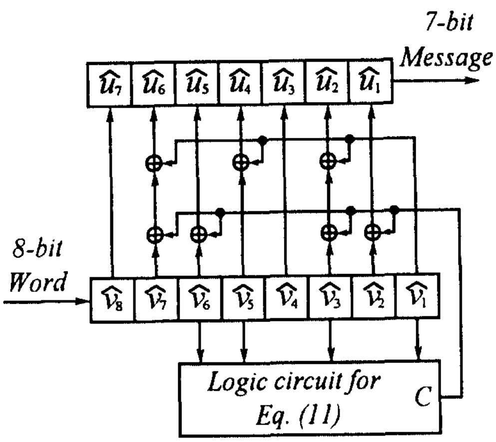

Fig. 2. Logic diagram of 8-bit word to 7-bit message decoder.

is 1. Finally, we remove $\hat{u}_1$ and get a 7-bit message $\hat{U}$. Fig. 2 shows the logic diagram to find the message $\hat{U}$ from $\hat{V}$, and an example of the decoding procedure is followed.

Example 2 : Suppose that the encoded codeword W of Example 1 is received at the decoder, with two errors in the first bit and the 13th bit. i.e. $\hat{W}$ = 0101001001101110,

$\hat{W}_1$ = 0 1010010, and $\hat{W}_2$ = 01101110.

(i) apply the (8,4) extended Hamming decoding rule to both $\hat{W}_1$ and $\hat{W}_2$. Thus $\hat{V}_1$ = 11 01, $\hat{V}_2$ = 0110, and $\hat{V}$ = 11010110 are obtained. Here, errors are corrected, since the (8,4) extended Hamming code has single error correcting capability.

(ii) invert $\hat{v}_2$, $\hat{v}_3$, $\hat{v}_6$, and $\hat{v}_7$, since C = 1. Then, U = 10110000.

(iii) invert $\hat{u}_1$, $\hat{u}_3$, $\hat{u}_5$, and $\hat{u}_7$, since u_1=1. Then, $\hat{U}$ = 00011010.

(iv) remove $\hat{u}_1$, and finally get the 7-bit message $\hat{U}$ = 0011010.

Ⅳ. Performance Analysis and Discussion.

With respect to the characteristics of line coding, error control performance and complexity, we compare the proposed code with the conventional error control line codes.

1. Characteristics of line coding.

Since the proposed code is constructed by zero-disparity codewords, both the disparity and the running disparity are zero. And the maximum running disparity and the maximum runlength is 2 and 4, respectively, since R_{START} and R_{END} of the codewords is 2. The code rate of the proposed code is 0.4375 because its codeword and message length is 16 and 7, respectively.

In Table 3, the parameters of the proposed code and the conventional ECLCs are summarized, and line coding properties of proposed code are shown to be superior to those of the conventional codes. Here, code A is the ECLC based on the (8,4) extended Hamming code with block number 1[18]. Similarly code B and C are the ECLCs based on the (7,4) Hamming code with block number 1 and 2, respectively[13].

The power spectral density for line code with bounded disparity may be determined by the algorithm of Cariolaro and Tronca[19]. The same procedure can be used to determine the power spectrum of the proposed code. The power spectral density of the proposed code and the conventional codes is shown in Fig. 3. Obviously, the proposed code has better spectral characteristics at DC and low frequency region than code B and C. And almost identical spectrum is obtained for the proposed code and code A since both of them are based on the same error control code and

Table 3. Comparison of the line coding parameters.

	proposed code	code A	code B	code C
d	0	0	-7~7	-2~2
D	0	0	-7~6	-5~0
D_{MAX}	2	2	-9	-5
R_{MAX}	4	4	12	6
code rate	0.4375	0.375	0.429	0.5

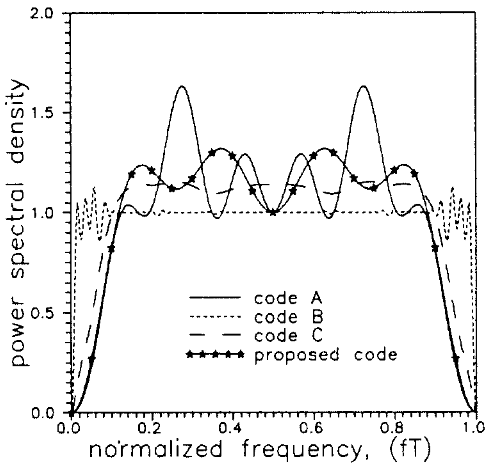

Fig. 3. Power spectral density.

show the same line coding parameter.

2. Error control performance

In order to calculate error performance of the ECLC, the following conditions are assumed[11]: 1) All bit errors in the channel are statistically independent, and occur with probability P_{ce}. 2) If a codeword is decoded incorrectly, half of the information bits are in error. In general, the above proportion is dependent on the error control code used in a ECLC as well as the form of the decoder.

By the assumptions, channel errors are binomially distributed and the probability that j errors will occur in a n-bit codeword is

$$P(e=j) = \binom{n}{j}(1-P_{ce})^{n-j}P_{ce}^{j}, \quad j=0,1,\cdots,n. \tag{12}$$

The number of errors occured in a 16-bit codeword is between 0 and 16. If the number of errors is 0 or 1, the received vector can be decoded correctly. Although the number of errors is more than 1, these errors can be corrected or detected in accordance with the position of errors occured in the first and second block. And, if the decoded word $\hat{V}$ is an unused word, additional errors can be detected, which can not be detected by the decoding rule of the extended Hamming code.

The received vector which has single error per block can be decoded correctly. When double errors are occured, the probability that single error is occurred in each block is 8/15, since the number of occurrences of double errors in any 16 bit position is $120(={}_{16}C_2)$ and that of single error in each block among them is $64(={}_8C_1\times{}_8C_1)$. Thus, the probability that a codeword is decoded correctly is

$$P_{cor} = P(e=0) + P(e=1) + \frac{8}{15}P(e=2). \tag{13}$$

And the probability that errors are detected[20,21] except the cases of correcting errors is

$$P_{det} = \sum_{j=1}^{16}\frac{Det_j}{N_j}P(e=j), \quad N_j = \binom{16}{j}. \tag{14}$$

Here, when j errors are occurred, N_j is the number of error patterns that can be occurred and Det_j is the number of error patterns that can be detected except the case of correcting errors and also the case of decoding incorrectly. Note that when errors are occurred, some of them can not be detected and decoded incorrectly. And some of the detected errors can be corrected.

At this point, using Table 2, we can find Det_j according to the number of errors. In (12), the case which the number of errors is more than 6 hardly affects the probability. Thus, we can approximate (14) as follows

$$P_{det} \cong 0.467P(e=2)+0.872P(e=3)+0.676P(e=4) +0.951P(e=5)+0.751P(e=6). \quad (15)$$

here the coefficient of each term is the result of exhaustive searching according to codewords and error patterns.

When retransmission is considered, the probability of a codeword error is given by

$$P_{cwe}=1-(P_{cor}+P_{det}P_{cor}+P^2_{det}P_{cor}+P^3_{det}P_{cor}+\cdots) = 1-\frac{P_{cor}}{1-P_{det}}. \quad (16)$$

Hence, by the assumption, the residual bit error rate of the proposed code is

$$P_{re}=\frac{1}{2}\cdot P_{cwe}. \quad (17)$$

Fig 4. shows the residual bit error rate of the proposed code and the conventional codes. And it shows that the error control capability of the proposed code is similar to that of the code A because both of them are based on the (8,4) extended Hamming code. A litter bit higher residual bit error rate for the proposed code is result from reduction in the number of unused codewords. Compared with code B and C, however, the residual bit error rate for a channel error rate 10^{-2} and 10^{-5} is reduced by approximately 1/100 and 1/100,000, respectively.

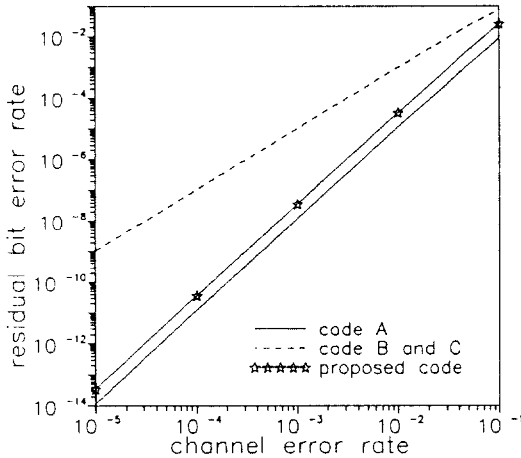

Fig. 4. Residual bit error rate.

3. Complexity

For the conventional ECLCs based on the (7,4) Hamming code[13], computation of codeword disparity and running disparity is required for encoding and decoding. Furthermore, if block number is more than 1, additional look up table may be required.

On the other hand, only simple pre-encoding and decoding circuits shown in Fig. 1 and Fig. 2 are required for the proposed code. We do not have to worry about the disparities since all the codeword dispairty should be zero. And no look up table is required. Therefore, it is clear that the proposed code has far less circuitry and complexity than the conventional codes based on the (7,4) Hamming code.

V. Conclusions

In this paper, we proposed an efficient ECLC which is based on the (8,4) extended Hamming code in order to improve the spectral characteristics at DC and low frequency region and the code rate. Since the line coding parameters of disparity, running disparity, maximum running disparity and maximum runlength of the proposed code are better than those ECLCs based on the (7,4) Hamming code, the proposed code has shown elimination of DC and better suppression of low frequency components.

The proposed code has the additional capability of error detection by the unused codewords besides the intrinsic error control capability of the (8,4) extended Hamming code. Hence, the residual bit error rate of the proposed code was much lower than that of ECLCs based on the (7,4) Hamming code, but similar to the ECLC based on the (8,4) extended Hamming code because both of them are based on the same code. Due to reduction in the number of unused codewords, the code rate of the proposed code was shown to be higher than that of ECLC based on the (8,4) extended Hamming code as well as ECLC based on the (7,4) Hamming code with block number 1.

In addition, implementation of the proposed code can be accomplished by simple pre-encoding and decoding circuits with the (8,4) extended Hamming coder and decoder. Therefore, it has been shown that the complexity of the proposed code is much less than that of the conventional codes based on the (7,4) Hamming code.

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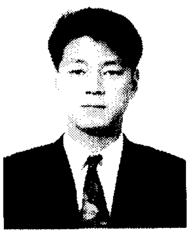

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