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A Binary Error Control Line Code with the Property of Minimum Bandwidth

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최소대역폭 특성을 갖는 이진 오류제어선로부호

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ABSTRACT

A new class of minimum-bandwidth binary error control line codes(MB-ECLCs) based on the (8,4) extended Hamming code is proposed and its performance is analyzed in this paper. First, an MB-ECLC with simple codeword format is introduced. To increase its code rate, two blocks of error control codes are used as a line code with simple pre-coding. As results of performance analysis, the proposed codes are shown to have null points at DC and Nyquist frequency and low levels of complexity. In addition, the proposed codes have wider eyewidth due to its minimum-bandwidth property. Therefore the proposed codes can be well suited for high speed communication links and/or bulk storage systems, where DC-free property, minimum-bandwidth pulse format, channel error control, and low-complexity encoder-decoder implementations are required.

要 約

본 논문에서는 (8,4) 확대 Hamming 부호를 사용한 새로운 형태의 최소대역폭 이진 오류제어선로부호를 제안하고 그 성능을 분석한다. 먼저, 간단한 부호어 형태를 갖는 최소대역폭 이진 오류제어선로부호를 소개한다. 그리고 부호율을 증가시키기 위해서 간단한 선부호화를 행한 후 오류제어부호 두 블록을 하나의 선로부호로 사용한다. 성능 분석의 결과, 제안된 부호는 DC와 Nyquist 주파수에서 전력 영점을 가지고, 간단한 형태로 구현될 수 있음을 보인다. 또한 제안된 부호는 최소대역폭 특성 때문에 보다 넓은 눈 폭을 가진다. 그러므로 제안된 부호는 무직류와 최소대역폭 펄스 형태, 채널오류제어, 간단한 형태의 부-복호화기가 요구되는 고속 통신선로 또는 대량 기억장치에 적합하다.

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Ⅰ. Introduction

Owing to recent advances in transmission media such as magnetic or optical recording devices and optic fiber links, an interest in channel coding is emerged again. Channel codes can be divided into two classes : error control codes[1-5] and line codes[6-8]. Binary linear block error control codes can be designed to have powerful error correcting and detecting capabilities and can be encoded and decoded efficiently due to their elegant algebraic structures. And line codes can be designed to provide following capabilities: i) runlength limitation to facilitate synchronization, ii) elimination of DC and suppression of low frequency components to match source data with characteristics of transmission media, iii) elimination of Nyquist frequency for stable minimum bandwidth condition.

In general, transmission channels require all the above mentioned error control and line coding characteristics simultaneously. Traditionally, to satisfy these requirements, the cascaded scheme of error control coding and line coding techniques has been used[9]. However this cascaded scheme has two main drawbacks, the decrease of overall code rate and the reduction of error control capability. To solve these problems, combined error control line codes such as runlength limited error control codes (RLLECCs)[10], error control line codes (ECLCs)[11-14] and minimum-bandwidth binary(MB) line codes[15-18] are introduced. But, these codes do not have all the required characteristics simultaneously.

In this paper, a new class of ECLCs without DC and Nyquist frequency is proposed and its performance is analyzed. The proposed codes are based on the (8,4) extended Hamming code with simple pre-coding and are capable of single error correction and double error detection. Since the encoding and decoding algorithm of the proposed codes are very simple and efficient, it can be well suited for high speed communication links. In addition, due to the minimum-bandwidth property, the proposed codes have wider eyewidth.

Ⅱ. Parameters and properties of the MB line code

To make the coded sequence suitable for transmission through communication channels, MB line codes have some principal properties such as limited runlength, elimination of DC and Nyquist frequencies.

The runlength is defined as the number of consecutive ones or zeros in a transmitted bit sequence. To limit 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 as a measure of runlength limitation is defined as[10]

$$R_{MAX} = MAX\{R_{MID},\ R_{START}+R_{END}\}\ , \tag{1}$$

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

Parameters to describe DC-free property of a binary line code are digital sum, running digital sum and maximum running digital sum. Let the k-bit codeword would be represented by the vector C. And if we substitute the physical symbol set {-1, 1} of a codeword for the logical symbol set {0, 1}, the digital sum of vector C is defined as

$$d = \sum_{i=1}^{k} c_i, \quad c_i = 1 \text{ or } -1, \tag{2}$$

where c_i is the ith digit of the codeword.

The running digital sum to the nth codeword in a transmitted codeword sequence is accumulation of digital sum and is defined as follows:

$$D_n = \sum_{i=1}^{n} d_i, \tag{3}$$

where d_i is the digital sum of the ith codeword.

A necessary and sufficient condition for a spectral null at DC is that the running digital sum, D_n, is uniformly bounded for all n. That is, the maximum running digital sum should satisfy[15]

$$D_{MAX} = \underset{n}{MAX} \left| \sum_{i=1}^{n} b_i \right| < \infty, \; b_i = -1 \text{ or } 1, \tag{4}$$

where b_i is the ith bit in the transmitted bit sequence. In addition, if maximum running digital sum of a binary line code is bounded, its runlength is also limited.

Similarly, parameters to describe Nyquist-free property of a binary line code are alternating digital sum, running alternating digital sum and maximum running alternating digital sum. The alternating digital sum of vector C is defined as

$$a = \sum_{i=1}^{k} (-1)^k c_i, \; c_i = 1 \text{ or } -1, \tag{5}$$

And the running alternating digital sum to the nth codeword is defined as follows:

$$A_n = \begin{cases} \sum_{i=1}^{n} a_i, & \text{if codeword length=even,} \\ \sum_{i=1}^{n} (-1)^{i-1} a_i, & \text{if codeword length=odd,} \end{cases} \tag{6}$$

where a_i is the alternating digital sum of the ith codeword.

A necessary and sufficient condition for a spectral null at Nyquist frequency is that the running digital sum, A_n, is uniformly bounded for all n. That is, the maximum running alternating digital sum should satisfy[15]

$$A_{MAX} = \underset{n}{MAX} \left| \sum_{i=1}^{n} (-1)^i b_i \right| < \infty, \tag{7}$$
$$b_i = -1 \text{ or } 1.$$

Therefore, in order to have both DC-free and minimum-bandwidth properties, the maximum running digital sum and maximum running alternating digital sum of a code should be bounded simultaneously.

Ⅲ. Proposed code

Hamming codes are the first class of linear codes devised for error correction[19]. These codes and their variations have been widely used for error control in digital communication and data storage systems. Among them, the (7,4) Hamming code whose code length is 7 and message length is 4 is the most well known code. As its variation, an (8,4) extended Hamming code is obtained by adding a parity check bit to a (7,4) Hamming code (hence, its code length is 8). Table 1 shows the all 16 codewords, digital sum and alternating digital sum for the (8,4) extended Hamming code generated from the matrix of (8).

$$G = \begin{bmatrix} 10000111 \\ 01001011 \\ 00101101 \\ 00011110 \end{bmatrix}. \tag{8}$$

If both the digital sum and alternating digital sum of all codewords of a code are zero, it is obvious that the code has DC-free and minimum-bandwidth properties. In Table 1, the digital sum and alternating digital sum of 12 out of 16 codewords are zero. If we use these codewords only, we can construct an

ECLC which has DC-free and minimum-bandwidth properties. 4 codewords which should be excluded are denoted by ＊.

Here, let the number of error control codewords grouped per a line codeword be the block number N[11]. In this section, first we propose an MB-ECLC(N=1) whose block number is 1, and then we propose an MB-ECLC(N=2) whose block number is 2 and show that it has higher code rate than MB-ECLC(N=1).

1. MB-ECLC(N=1)

12 codewords are sufficient for 3-bit message. Thus to construct a code for 3-bit message, we can select only 8 codewords among 12 codewords. In table 1, 4 codewords denoted by ＊＊, among 12 candidate codewords, can increase maximum runlength of the coded sequence because their R_{START} or R_{END} is 3. Therefore, in order to reduce the maximum runlength, these 4 codewords are also excluded.

Table 1. Codewords, digital sum and alternating digital sum for an (8,4) extended Hamming code.

Message	Codeword	Digital sum	Alternating digital sum
0000*	00000000	-8	0
0001**	00011110	0	0
0010	00101101	0	0
0011	00110011	0	0
0100	01001011	0	0
0101*	01010101	0	8
0110	01100110	0	0
0111**	01111000	0	0
1000**	10000111	0	0
1001	10011001	0	0
1010*	10101010	0	-8
1011	10110100	0	0
1100	11001100	0	0
1101	11010010	0	0
1110**	11100001	0	0
1111*	11111111	8	0

(1) Encoding

Let the 3-bit message U be represented as follows:

$$U = u_1 u_2 u_3. \qquad (9)$$

To construct 8-bit codewords of MB-ECLC(N=1), precoding procedure which converts 3-bit message U to 4-bit word V is required before applying the (8,4) extended Hamming encoder. The following step shows the procedure.

i) Add u_3 to U as the first bit of $\dot{U}$. Then $\dot{U} = u_3 u_1 u_2 u_3$.

ii) If $\dot{U}$ is 0000 or 1111, that is, A of (10) is equal to 1, then $V = \dot{u}_1 \dot{u}_2 \overline{\dot{u}_3} \overline{\dot{u}_4}$. Else $V = \dot{U}$.

$$A = \overline{u_1}\,\overline{u_2}\,\overline{u_3} + u_1 u_2 u_3 \qquad (10)$$

iii) Finally, using 4-bit word V and the (8,4) extended Hamming encoder, the 8-bit codeword $W(=V \cdot G)$ can be obtained.

Fig. 1 is the logic diagram of 3-bit message U to 4-bit word V encoder and shows that pre-encoding procedure can be simply implemented.

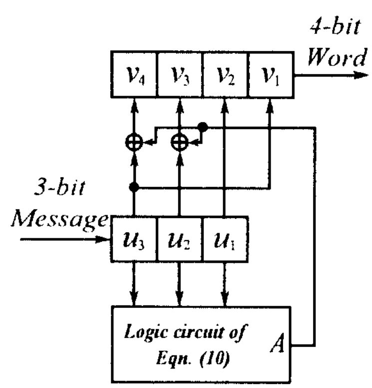


Fig. 1. Logic diagram of 3-bit message to 4-bit word encoder.

mented.

Table 2 shows the coding procedure of 3-bit message U to 8-bit codeword W of MB-ECLC(N=1). In this table, the proposed code is shown to be transparent.

Table 2. Coding procedure of MB-ECLC(N=1).

U	V	W
000	0011	001100110
001	1001	10011100
010	0010	00101101
011	1011	10110001
100	0100	01001110
101	1101	11010010
110	0110	01100011
111	1100	11001001

(2) Decoding

Basically decoding procedure of MB-ECLC(N=1) is identical to the reverse procedure of encoding W from U.

i) Apply the (8,4) extended Hamming decoding rule to the received vector $\hat{W}$. Here, if the decoded word $\hat{V}$ is an unused word, it is detected as an error sequence and retransmission may be requested.

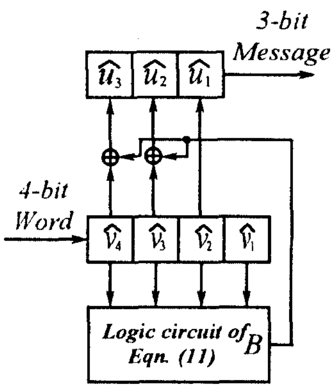


Fig. 2. Logic diagram of 4-bit word to 3-bit message decoder.

ii) If the word $\hat{V}$ is 0011 or 1100, that is, B of (11) is equal to 1, then $\hat{U} = \hat{v}_1 \hat{v}_2 \overline{\hat{v}_3}\, \overline{\hat{v}_4}$. Else $\hat{U} = \hat{V}$.

$$B = \overline{\hat{v}_1}\, \overline{\hat{v}_2}\, \hat{v}_3 \hat{v}_4 + \hat{v}_1 \hat{v}_2 \overline{\hat{v}_3}\, \overline{\hat{v}_4} \qquad (11)$$

iii) Remove $\hat{u}_1$, and get a 3-bit message $\hat{U}$.

Fig. 2 shows the logic diagram to find the message $\hat{U}$ from $\hat{V}$.

2. MB-ECLC(N=2)

The code rate of MB-ECLC(N=1) is rather low, since it uses only 8 codewords out of 12 possible candidate codewords. Thus, if all 12 codewords are used, the code rate of the ECLC can be increased. To encode 7-bit message, 128(=2^7) codewords are required. From Table 1, if two 12 candidate codewords are connected, 144(=12×12) codewords can be made and among them 128 codewords can be chosen for a new ECLC whose message length is 7. Therefore, an MB-ECLC for 7-bit message can be obtained by mapping 7-bit message into 8-bit codewords without 4 codewords denoted by * at the first and last 4 bits and then applying the (8,4) extended Hamming coding technique to each 4-bit codeword.

(1) Encoding

Similar to MB-ECLC(N=1), 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.

i) Add 0 to U as the first bit of $\dot{U}$. Where U and $\dot{U}$ can be expressed as follows:

$$U = u_1 u_2 u_3 u_4 u_5 u_6 u_7, \qquad (12)$$

and

$$\dot{U} = \dot{u}_1 \dot{u}_2 \dot{u}_3 \dot{u}_4 \dot{u}_5 \dot{u}_6 \dot{u}_7 \dot{u}_8$$

$$= \underbrace{0\ u_1 u_2 u_3}_{\dot{U}_1}\ \underbrace{u_4 u_5 u_6 u_7}_{\dot{U}_2} \tag{13}$$

ii) If $\dot{U}_1$ or $\dot{U}_2$ is 0000, 0101, 1010 or 1111, that is C of (14) equal to 1, invert $\dot{u}_1$ and $\dot{u}_5$ to give a word $\ddot{U}$. Else $\ddot{U} = \dot{U}$.

$$C = \overline{\dot{u}_3}(\dot{u}_2 \odot \dot{u}_4) + (\dot{u}_5 \odot \dot{u}_7)(\dot{u}_6 \odot \dot{u}_8) \tag{14}$$

iii) Even by this operation, $\ddot{U}_1$ and $\ddot{U}_2$ of word $\ddot{U}$ can be 0000, 0101, 1010 or 1111 again. Thus, if D of (15) is equal to 1, then a word V is obtained by inverting $\ddot{u}_2$ and $\ddot{u}_6$. Else $V = \ddot{U}$.

$$D = \ddot{u}_1 \ddot{u}_3(\ddot{u}_2 \odot \ddot{u}_4) + (\ddot{u}_5 \odot \ddot{u}_7)(\ddot{u}_6 \odot \ddot{u}_8)$$
$$= C\{\dot{u}_3(\dot{u}_2 \odot \dot{u}_4) + (\dot{u}_5 \oplus \dot{u}_7)(\dot{u}_6 \odot \dot{u}_8)\}. \tag{15}$$

iv) Apply the (8,4) extended Hamming encoding rule to 4-bit words V_1 and V_2, respectively. Finally a 16-bit codeword $W(=W_1\ W_2 = V_1 \cdot G\ \ V_2 \cdot G)$ for MB-ECLC(N=2) can be obtained.

Pre-encoding procedure of MB-ECLC(N=2) is also simply implemented as shown in Fig. 3. And the mapping table of this procedure is shown in Table 3, where 7-bit messages are represented as hexa-decimal notation. Blanks in Table 3 are unused words.

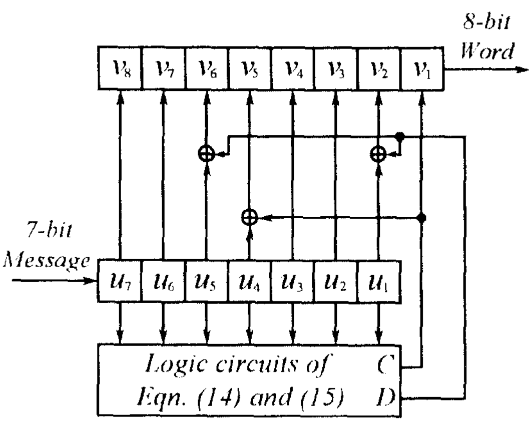


Fig. 3. Logic diagram of 7-bit message to 8-bit word encoder.

Table 3. Mapping table of 7-bit message U to 8-bit word V.

$v_5v_6v_7v_8$ / $v_1v_2v_3v_4$	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0000																
0001		11	12	13	14		16	17	18	19		1B	1C	1D	1E	
0010		21	22	23	24		26	27	28	29		2B	2C	2D	2E	
0011		31	32	33	34		36	37	38	39		3B	3C	3D	3E	
0100		41	42	43	44		46	47	48	49		4B	4C	4D	4E	
0101																
0110		61	62	63	64		66	67	68	69		6B	6C	6D	6E	
0111		71	72	73	74		76	77	78	79		7B	7C	7D	7E	
1000		09	0A	0B	0C		0E	0F	00	01		03	04	05	06	
1001		5D	1A		58			1F	10			57		15	52	
1010																
1011			3A	7F			7A	3F	30	75			70	35		
1100		0D	4A		08			4F	40			07		45	02	
1101		59	5A	5B	5C		5E	5F	50	51		53	54	55	56	
1110			6A	2F			2A	6F	60	25			20	66		
1111																

(2) Decoding

i) Apply the (8,4) extended Hamming decoding rule to the first and last 8-bit vector $\hat{W}_1$ and $\hat{W}_2$ of the received vector $\hat{W}$. Then an 8-bit word $\hat{V}\ (=\hat{V}_1\ \hat{V}_2)$ can be obtained. Here, if the word $\hat{V}$ is an unused word, it is detected as an error sequence and retransmission may be requested.

ii) If E of (16) is equal to 1, invert $\hat{v}_2$ and $\hat{v}_6$ to give a word $\hat{\ddot{U}}$. Else $\hat{\ddot{U}} = \hat{V}$.

$$E = \hat{v}_1(\hat{v}_2 \oplus \hat{v}_4)(\hat{v}_6 \oplus \hat{v}_8) \tag{16}$$

iii) If $\ddot{u}_1$ is equal to 1, invert $\hat{\ddot{u}}_1$ and $\hat{\ddot{u}}_5$ to give a word $\hat{\dot{U}}$. Else $\hat{\dot{U}} = \hat{\ddot{U}}$.

iv) Finally, remove $\dot{u}_1$ and get a 7-bit message $\hat{U}$.

Fig. 4 shows the logic diagram to find the 7-bit message $\hat{U}$ from 8-bit word $\hat{V}$.

Note that the above mentioned code can not be obtained from any (8,4) extended Hamming codes. The number of generator matrices of systematic (8,4) Hamming codes is 24. Among them, only 4 generator matrices can be used to construct the proposed code. The codes obtained from the remaining matri

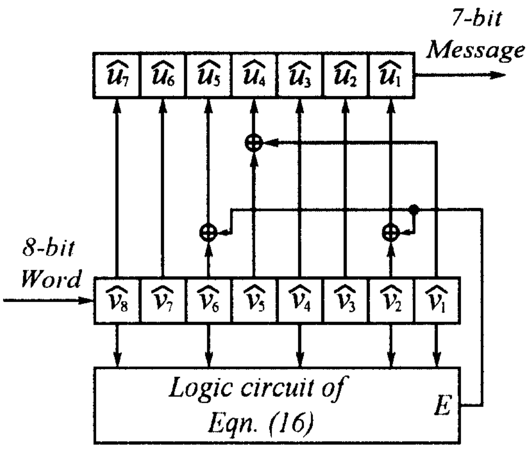


Fig. 4. Logic diagram of 8-bit word to 7-bit message decoder.

ces do not have enough codewords which satisfy the property of zero alternating digital sum. This can be proved by exhaustive searching. And, in the case of N=1, slight modification in pre-encoding and post-decoding procedure may be required according to the candidate generator matrices.

Ⅳ. Performance analysis and discussion

1. Characteristics of line coding.

Since the proposed codes are constructed by using zero digital sum and zero alternating digital sum codewords, both the running digital sum and running alternating digital sum are also zero. The maximum running digital sum, maximum running alternating digital sum and maximum runlength of MB-ECLC(N=1) are 2, 2 and 4, respectively. And those of MB-ECLC(N=2) are 3, 3 and 6, respectively. Because maximum R_{START} and maximum R_{END} of MB-ECLC(N=1) are 2, and those of MB-ECLC(N=2) are 3.

The code rate of the MB-ECLC(N=1) and MB-ECLC(N=2) are 0.375 and 0.4375, respectively.

In Table 4, line coding parameters and code rate of the proposed codes are summarized. Table 4 shows that the parameters of MB-ECLC(N=1) are better than or as good as those of MB-ECLC(N=2) and the code rate of MB-ECLC(N=2) is higher than that of MB-ECLC(N=1).

Table 4. Line coding parameters and code rate of the proposed codes.

	MB-ECLC(N=1)	MB-ECLC(N=2)
d	0	0
D_n	0	0
D_{MAX}	2	3
a	0	0
A_n	0	0
A_{MAX}	2	3
R_{MAX}	4	6
code rate	0.375	0.4375

2. Spectral characteristics

The power spectral density for line codes with bounded digital sum may be determined by the algorithm of Cariolaro and Tronca[20]. The same procedure can be used to determine the power spectral density of the proposed codes. Fig. 5 shows the power spectral density of the proposed codes. It shows that the proposed codes have good spectral characteristics at low frequency region and has null points at DC and Nyquist frequency and MB-ECLC(N=1) has rather better spectral characteristics than MB-ECLC(N=2).

3. Eye diagram

In a system which uses the raised cosine filter of roll-off factor α=0, eye diagrams of

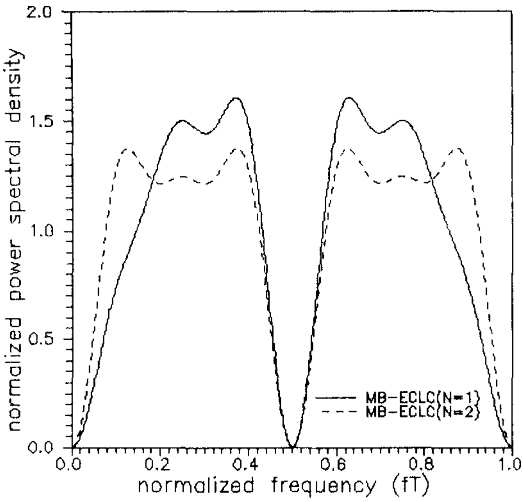
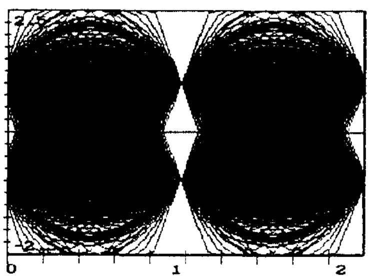
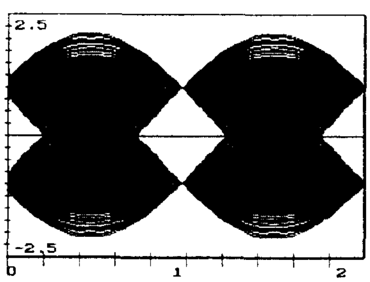


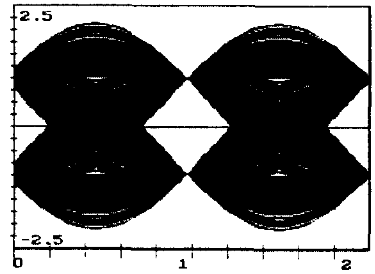
Fig. 5. Power spectral density of the proposed codes.



(a) PRBS.



(b) MB-ECLC(N=1).



(C) MB-ECLC(N=2).

Fig. 6. Eye diagrams.

a pseudo random binary sequence(PRBS) and a sequence of the proposed codes are illustrated in Fig. 6. The eyewidth of the proposed codes are clearly shown to be wider than that of a PRBS.

Ⅴ. Conclusions

In this paper, we proposed the minimum-bandwidth binary ECLCs. The proposed codes have the additional capability of error detection by the unused codewords besides the intrinsic error control capability of the (8,4) extended Hamming code. And they have good line coding properties since their running digital sum and running alternating digital sum are zero. Through the power spectral density of the proposed codes, we verified that they have null points at DC and Nyquist frequency. Wider eyewidth of the proposed codes are shown by comparing the eye diagrams. In addition, implementation of the proposed code can be accomplished by simple pre-coding and post-decoding circuits with the (8,4) extended Hamming coder and decoder. Therefore the proposed codes can be well suited for high speed communication links and/or bulk storage systems.

Reference

1. S. Lin and D. J. Costello, Jr., *Error Control Coding : Fundamentals and Applications*, Prentice-Hall, Englewood Cliffs, New Jersey, 1983.
2. R. E. Blahut, *Theory and Practice of Error Control Codes*, Addison-Wesley, Reading, Mass., 1983.
3. E. R. Berlekamp, *Algebraic Coding Theory*, McGraw-Hill, New York, 1968.
4. R. G. Gallager, *Information Theory and Reliable Communication*, John Wiley and Sons, New York, 1968.
5. R. Hill, *A First Course in Coding Theory*, Oxford, New York, 1986.
6. H. Kobayashi, "A survey of coding schemes for transmission or recording of digital data," *IEEE Trans. Commun. Technol.*, vol. COM-19, no. 6, pp.1087-1100, Dec. 1971.
7. K. A. Schouhamer Immink, *Coding Techniques for Digital Recorders*, Prentice Hall, New York, 1991.
8. D. J. Morris, *Pulse Code Formats for Fiber Optical Data Communication : Basic Principles and Applications*, Marcel Dekker, Inc., New York, 1983.
9. P. H. Siegel and J. K. Wolf, "Modulation and coding for information storage," *IEEE Commun. Mag.*, vol. 29, no. 12, pp.68-86, Dec. 1991.
10. A. Popplewell and J. J. O'Reilly, "Runlength limited binary error control codes," *IEE Proceedings-I*, vol. 139, no. 3, pp.349-355, Jun. 1992.
11. A. Popplewell and J. J. O'Reilly, "Class of disparity reducing transmission codes with embedded error protection," *IEE Proceedings-I*, vol. 137, no. 2, pp.73-77, Apr. 1990.
12. J. G. Kim, C. K. Jeong, S. I. Lee, and E. K. Joo, "An error control line code based on extended Hamming code," *J. KICS*, vol. 19, no. 5, pp.912-918, May 1994.
13. J. G. Kim, C. K. Jeong, and E. K. Joo, "An efficient error control line code with improved code rate based on the (8,4) extended Hamming code," *J. KICS*, vol. 20, no. 5, pp.1213-1223, May 1995.
14. S. I. Lee, J. G. Kim, and E. K. Joo, "Class of DC-free error correcting codes based on convolutional codes," *Electron. Lett.*, vol. 30, no. 19, pp.1588-1590, Sep. 1994.
15. L. J. Fredrickson, "On the Shannon capacity of DC- and Nyquist-free codes," *IEEE Trans. Inform. Theory*, vol. IT-37, no., 3, pp.918-923, May 1991.
16. J. H. Kim and D. Y. Kim, "Design and analysis of a minimum bandwidth binary line code MB34," *J. KITE*, vol. 29-A, no. 8, pp.621-628, Aug. 1992.
17. J. H. Kim and D. Y. Kim, "Design and analysis of binary line code MB46," *J. KICS*, vol. 17, no. 9, pp.963-970, Sep. 1992.
18. J. H. Kim and D. Y. Kim, "Design and analysis of a memoryless minimum bandwidth binary line code MB58," *J. KICS*, vol. 17, no. 10, pp.918-923, May 1991.
19. R. W. Hamming, "Error detecting and error correcting codes," *Bell Syst. Tech. J.*, vol. 29, pp.147-160, Apr. 1950.
20. G. L. Cariolaro and G. P. Tronca, "Spectra of block coded digital signals," *IEEE Trans. Commun.*, vol. COM-22, no. 10, pp. 1555-1564, Oct. 1974.

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