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On A Class of Error Correcting Binary Group Codes*

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A general method of constructing error correcting binary group codes is obtained. A binary group code with n places, k of which are information places is called an (n,k) code. An explicit method of constructing t-error correcting (n,k) codes is given for $n = 2^m-1$ and $k = 2^m-1-\mathrm{R}(m,t) \geqq 2^m-1-mt$ where $R(m,t)$ is a function of m and t which cannot exceed mt. An example is worked out to illustrate the method of construction.

SECTION 1

Consider a binary channel which can transmit either of two symbols 0 or 1. However, due to the presence of "noise" a transmitted zero may sometimes be received as 1, and a transmitted 1 may sometimes be received as 0. When this happens we say that there is an error in transmitting the symbol. The symbols successively presented to the channel for transmission constitute the "input" and the symbols received constitute the "output."

A v-letter n-place binary signalling alphabet A_n may be defined as a set of v distinct sequences α_0, α_1, $\cdots$, α_{v-1} of n binary digits. The individual sequences may be called the letters of the alphabet. Given a set of v distinct messages, we get an encoder $E_{n,v}$ by setting up a $(1,1)$ correspondence between the messages and the letters of the alphabet. To transmit a message over the channel the n individual symbols of the corresponding letter of the alphabet are presented to the channel in succession. The output is then an n-place binary sequence belonging to the set B_n of all possible binary sequences. A decoder $D_{n,v}$ is obtained by partitioning B_n into v disjoint sets S_1, S_2, $\cdots$, S_v and setting up a

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correspondence between these subsets and the letters of the alphabet so that if a sequence belonging to S_i is received as an output, it is read as the letter α_i and interpreted as the corresponding message. The encoder $E_{n,v}$ together with the decoder $D_{n,v}$ constitute a binary n-place code.

Each sequence of B_n can be regarded as an n-vector with elements from the Galois field $GF(2)$. The addition of these vectors may then be defined in the usual manner, the sum of two vectors being obtained by adding the corresponding elements (mod 2). For example, if $n = 6$ and $\gamma_1 = (110011)$ and $\gamma_2 = (101001)$ then $\gamma_1 + \gamma_2 = (011010)$. Clearly the set B_n of all binary n-place sequences forms a group under vector addition. The weight $w(\gamma)$ of any sequence is defined as the number of unities in the sequence. Thus in the example considered $w(\gamma_1) = 4$, $w(\gamma_2) = 3$. The Hamming distance $d(\gamma_1, \gamma_2)$ between two sequences γ_1 and γ_2 is defined as the number of places in which γ_1 and γ_2 do not match (Hamming, 1950). Clearly $d(\gamma_1, \gamma_2) = w(\gamma_1 + \gamma_2)$. In the example $d(\gamma_1, \gamma_2) = 3 = w(\gamma_1 + \gamma_2)$. The Hamming distance satisfies the three conditions for a metric, namely

$$(a)\ d(\gamma_1, \gamma_2) = 0 \text{ if and only if } \gamma_1 = \gamma_2 .$$

$$(b)\ d(\gamma_1, \gamma_2) = d(\gamma_2, \gamma_1),$$

$$(c)\ d(\gamma_1, \gamma_2) + d(\gamma_2, \gamma_3) \geqq d(\gamma_1, \gamma_3).$$

Let the letter α_i of the alphabet A_n be transmitted over the channel. Let ϵ_i be the vector which has unities in those places, where an error occurs in transmitting a symbol of α_i. Then ϵ_i is the noise vector. The output received is the sequence $\alpha_i + \epsilon_i$, and the number of errors is $w(\epsilon_i)$. The code is said to be t-error correcting if $\alpha_i + \epsilon_i$ belongs to S_i whenever $w(\epsilon_i) \leqq t (i = 0,1 \cdots, v - 1)$. It is clear that under these circumstances if there are t or a lesser number of errors in transmitting a letter α_i, the received message will be correctly interpreted.

A particularly important class of codes has been studied by Slepian (1956). For this class $v = 2^k$ and the letters of the alphabet A_n form a subgroup of B_n. The null sequence is the unit element of B_n, and must also belong to A_n. We shall suppose without loss of generality that $\alpha_0 = (0,0, \cdots, 0)$. Slepian's decoder may be described as follows: If $r = n - k$, then the group B_n can be partitioned into 2^r cosets with respect to the subgroup A_n. The coset containing a particular sequence β consists of the sequences

$$\alpha_0 + \beta, \alpha_1 + \beta, \cdots, \alpha_{v-1} + \beta.$$

In the jth coset we can choose a sequence β_j whose weight does not exceed the weight of any other sequence in the coset, and call it the coset leader. Let $\beta_0, \beta_1, \cdots, \beta_{u-1}$, $(u = 2^r)$ be the coset leaders, where $\beta_0 = \alpha_0$ is the null sequence and leader of the 0th coset A_n. Let S_j be the set of sequences

$$\alpha_j + \beta_0, \alpha_j + \beta_1, \cdots, \alpha_j + \beta_{u-1} \qquad j = 0,1, \cdots, v - 1.$$

Then the decoder is obtained by partitioning B_n into $S_0, S_1, \cdots, S_{v-1}$ and setting up the rule that if the sequence received as an output belongs to S_j, it is read as the letter α_j. The code thus obtained may be called an (n,k) binary group code. It is clear that a transmitted message will be correctly interpreted if and only if the error vector happens to be a coset leader. Hence a necessary and sufficient condition for the code to be t-error correcting is that if β is any n-place binary sequence for which $w(\beta) \leq t$, then β is a coset leader. The following lemma, due to Hamming (1950), is then easy to deduce.

LEMMA 1. The necessary and sufficient condition for an (n,k) binary group code to be t-error correcting is that each letter of the alphabet except the null letter has weight $2t + 1$ or more.

Since the $v = 2^k$ messages can be transmitted by a k-place binary code if there is no possibility of error, the number $r = n - k$ is called the redundancy for an (n,k) binary group code. In constructing a t-error correcting (n,k) binary group code for given n and t one would like to maximize k (that is, maximize the number of different messages that it is possible to transmit). Varšamov (1957) has shown that if k satisfies the inequality

$$S_r^{2t-1} + \binom{k-1}{1} S_r^{2t-2} + \cdots + \binom{k-1}{2t-2} S_r^{1} + \binom{k-1}{2t-1} < 2^r \quad (1)$$

where

$$S_r^{q} = 1 + \binom{r}{1} + \binom{r}{2} + \cdots + \binom{r}{q} \quad (2)$$

then a t-error correcting (n,k) group code exists.

The main result of the present paper is the following: If $n = 2^m - 1$, then there exists a t-error correcting (n,k) binary group code with $k \geqq 2^m - 1 - mt$.

The method of proof is constructive and is illustrated by considering the case $n = 15$, $t = 3$, for which a 3-error correcting (15,5) binary group code is explicitly obtained.

As an example of comparison between Varšamov's result and our theorem consider the case $n = 31$. Varšamov's result then shows that a 2-error correcting binary group code can be obtained with $k = 18$, and a 3-error correcting binary group code can be obtained with $k = 13$ but is inconclusive for larger values of k. Our method, however, gives an explicit construction for a 2-error correcting binary group code with $k = 21$, and a 3-error correcting binary group code with $k = 16$.

The following table gives some of the values of n, k and t for which a t-error correcting (n,k) binary group code can be constructed by our method. The transmission rate $R = k/n$ is also given.

TABLE I

t	n	k	R
1	15	11	0.73
2	15	7	0.47
2	31	21	0.68
2	63	51	0.81
2	127	113	0.89
3	15	5	0.33
3	31	16	0.52
3	63	45	0.71
3	127	106	0.83
4	63	39	0.64
4	127	99	0.78
5	127	92	0.72

SECTION 2

We shall now prove a theorem which gives a necessary and sufficient condition for the existence of a t-error correcting (n,k) group code. This theorem appears in a different form in an earlier paper by Bose (1947) but is given here for the sake of completeness.

THEOREM 1. The necessary and sufficient condition for the existence of a t-error correcting (n,k) binary group code is the existence of a matrix A of order $n \times r$ and rank $r = n - k$ with elements from $GF(2)$, such that any set of $2t$ row vectors from A are independent.

PROOF OF SUFFICIENCY. The matrix A has the property (P_{2t}) that any

$2t$ row vectors of A are independent. Clearly $r \geqq 2t$. The property (P_{2t}) is invariant under the following operations: (1) interchange of two rows or columns and (2) replacement of the ith column by the sum of ith and jth column, $i \neq j$. By these operations A can be transformed to the matrix.

$$A^* = \left\| \begin{matrix} I_r \\ C \end{matrix} \right\| \tag{3}$$

where A^* has the property (P_{2t}), I_r is the unit matrix of order r, and C is a matrix of order $k \times r$. Consider the matrix

$$C^* = \|C, I_k\| . \tag{4}$$

Then C^* is of order $k \times n$. We shall show that the k rows of C^* (under vector addition (mod 2)) are generators of a group G of order 2^k such that if α is any arbitrary (nonnull) element of G, then $w(\alpha) \geqq 2t + 1$. Let α be the sum of any d row vectors of C^*, $d \leqq k$. We can write $\alpha = (\gamma, \epsilon)$, where γ is the part coming from C and ϵ the part coming from I_k. Now

$$w(\alpha) = w(\gamma) + w(\epsilon) = w(\gamma) + d.$$

Hence

$$w(\alpha) \geqq 2t + 1 \text{ if } d > 2t.$$

Suppose $d \leqq 2t$. If $w(\alpha) < 2t + 1$, then $w(\gamma) \leq 2t - d$. Let $w(\gamma) = c$. There are exactly c positions in γ which are occupied by unity. Corresponding to each such position we can find a row vector of I_r which has unity in this position (and zero in all other positions). Then these c vectors of I_r together with the d row vectors of C whose sum is γ, constitute a set of $c + d$ vectors which are dependent. Since $c + d \leqq 2t$, this contradicts the fact that A^* has the property (P_{2t}). Thus the weight of any nonnull element of G is greater than or equal to $2t + 1$. It follows from Lemma 1 that the sequences of the subgroup generated by the k rows of C^* form the alphabet of a t-error correcting (n,k) group code.

Proof of Necessity. Suppose there exists a t-error correcting (n,k) binary group code. We can then find a set of k n-place binary sequences, or n-vectors with elements from $GF(2)$, which under addition generate the group of sequences which constitute the letters of the alphabet. By Lemma 1 if α is a sequence of this group $w(\alpha) \geq 2t + 1$. Consider the $k \times n$ matrix C^* whose row vectors are given by these sequences. If we

interchange any two rows or columns of C^*, or replace the ith row of C^* by the sum of the ith and the jth row ($i \neq j$), the transformed matrix still retains the property that its rows generate under addition a group, each sequence of which has weight $2t + 1$ or more. Hence we can without loss of generality take C^* in the canonical form (4) where C is of order $r \times k$ and I_k is the unit matrix of order k. By retracing the arguments used in proving the first part of the theorem, we see that the matrix A^* of order $n \times r$, given by (3), has the property that any two $2t$ row vectors are independent. This proves that the condition of the theorem is necessary.

COROLLARY 1. The existence of a t-error correcting (n,k) binary group code implies the existence of a t-error correcting $(n - c, k - c)$ binary group code, $0 < c < k$.

If in the matrix C^* given by (4) we delete the last c rows and the last c columns, we get a matrix

$$C_1^* = \|C_1, I_{k-c}\|$$

of order $(k - c) \times (n - c)$, the rows of which generate a group for which each nonnull element is of weight $2t + 1$ or more. The rows of C_1^* generate the alphabet of the required code.

Let V_r denote the vector space of all r-vectors whose elements belong to GF(2). One may then ask the following question. What is the maximum number of vectors in a set Σ chosen from V_r, such that any $2t$ distinct vectors from Σ are independent. This number may be denoted $n_{2t}(r)$, and the problem of finding the set Σ may be called the packing problem (of order $2t$) for V_r. For a given t, $n_{2t}(r)$ is a monotonically increasing function of r.

Let $k = k_t(n)$ denote the maximum value of k such that a t-error correcting (n,k) binary group code for given t and n exists. We can then state the following.

THEOREM 2. If $n_{2t}(r) \geq n > n_{2t}(r - 1)$, then $k_t(n) = n - r$.

From Theorem 1 there exists a t-error correcting $[n_{2t}(r), n_{2t}(r) - r]$ binary group code. Taking $c = n_{2t}(r) - n$ in Corollary 1, there exists a t-error correcting $(n, n - r)$ group code. But a t-error correcting $(n, n - r + 1)$ binary group code cannot exist, since from Theorem 1 its existence would imply that $n_{2t}(r - 1) \geq n$. Hence $k_t(n) = n - r$ is the maximum value of k for which a t-error correcting (n,k) binary group code exists.

Thus the problem of finding a t-error correcting n-place binary group code, with the maximum transmission rate k/n, is equivalent to determining the smallest r for which there exists a set of n or more distinct vectors of V_r, such that any $2t$ distinct vectors from the set are independent.

SECTION 3

The theorem to be proved in the next section depends upon the following lemma.

LEMMA 2. If $x_1, x_2, \cdots, x_l$ are different nonzero elements of the Galois field $GF(2^m)$, then the equations

$$x_1^{2i-1} + x_2^{2i-1} + \cdots + x_l^{2i-1} = 0, i = 1,2, \cdots, t \tag{5}$$

cannot simultaneously hold if $l \leqq 2t$.

Suppose, if possible, the Eqs. (5) hold simultaneously. Let

$$x^l + p_1 x^{l-1} + p_2 x^{l-2} + \cdots + p_l = 0 \tag{6}$$

be the algebraic equation whose roots are $x_1, x_2, \cdots, x_l$. Then p_j belongs to $GF(2^m)$ and is the sum of the products of the roots taken j at a time ($j = 1,2, \cdots, l$). We define s_j as the sum of the jth powers of the roots. For a field of characteristic 2 the well-known relations between the symmetric functions s_j and p_j become (Levi, 1942),

$$\begin{aligned} &s_1 + \delta_1 p_1 = 0 \\ &s_2 + p_1 s_1 + \delta_2 p_2 = 0 \\ &s_3 + p_1 s_2 + p_2 s_1 + \delta_3 p_3 = 0 \\ &\vdots \\ &s_l + p_1 s_{l-1} + p_2 s_{l-2} + \cdots + \delta_l p_l = 0 \end{aligned} \tag{7}$$

where $\delta_i = 0$ or 1 according as i is even or odd. From Eqs. (5) $s_j = 0$ when j is odd ($j < 2t$). It then follows from (7) that $s_j = 0$ if j is even ($j \leqq l$) and $p_j = 0$ if j is odd ($j \leqq l$).

CASE I. If l is odd then $p_l = x_1 x_2 \cdots x_l \neq 0$, since $x_1, x_2, \cdots, x_l$ are nonzero. This is a contradiction.

CASE II. If l is even, say $l = 2c$, the Eq. (6) becomes

$$x^{2c} + p_2 x^{2c-2} + \cdots + p_{2c} = 0 \tag{8}$$

therefore

$$(x^c + q_1 x^{c-1} + \cdots + q_c)^2 = 0 \tag{9}$$

where q_j is the unique square root of p_{2j} in $GF(2^m)$. Hence (6) cannot have more than c distinct roots, which again is a contradiction, since $x_1, x_2, \cdots, x_l$ are distinct by hypothesis.

Hence the lemma is true whether l is odd or even.

SECTION 4

Let V_m be the vector space of m-vectors with elements from $GF(2)$. We can institute a correspondence between the vector $\alpha = (a_0, a_1, \cdots, a_{m-1})$ of $\mathbf{V}_m$ and the element $a_0 + a_1 x + \cdots + a_{m-1} x^{m-1}$ of $GF(2^m)$, where x is a given primitive element of the field. This is a $(1,1)$ correspondence in which the null vector α_0 of V_m corresponds to the null element of $GF(2^m)$, and the sum of any two vectors of V_m corresponds to the sum of the corresponding elements of $GF(2^m)$. We can therefore identify the vector α of V_m and the corresponding element of $GF(2^m)$. This in effect defines a multiplication of the vectors of V_m and converts it into a field. In particular we can speak of powers of any vector.

Let V_{mt} be the vector space of all mt-vectors with elements from $GF(2)$. To any vector α_i of V_m there corresponds a unique vector α_i^* of V_{mt} defined by

$$\alpha_i^* = (\alpha_i, \alpha_i^3, \cdots, \alpha_i^{2t-1}) \tag{10}$$

though the converse is not true.

There are $n = 2^m - 1$ distinct nonnull vectors in V_m. Let

$$M^* = \begin{Vmatrix} \alpha_1, \alpha_1^3, \cdots, \alpha_1^{2t-1} \\ \alpha_2, \alpha_2^3, \cdots, \alpha_2^{2t-1} \\ \vdots \\ \alpha_n, \alpha_n^3, \cdots, \alpha_n^{2t-1} \end{Vmatrix} \tag{11}$$

be the $n \times mt$ matrix, which has for row vectors the corresponding vectors $\alpha_1^*, \alpha_2^*, \cdots, \alpha_n^*$. We shall show that M^* has the property

(P_{2t}) that any of $2t$ distinct row vectors belonging to M^* are independent. For this it is sufficient that the sum of any l row vectors of M^*, $l \leqq 2t$, is nonnull. This is ensured by Lemma 2, since α_i can also be regarded as elements of $GF(2^m)$.

Now rank $(M^*) \leqq mt$. Since there is essentially only one Galois field $GF(2^m)$, this rank is a definite function of m and t and will be denoted by $R(m,t)$. When $R(m,t) < mt$, we can choose $R(m,t)$ independent columns of M^*, and delete the other columns dependent on them. The matrix A so obtained has still the property (P_{2t}). Using Theorem 1 we have

THEOREM 3. If $n = 2^m - 1$, we can obtain a t-error correcting (n,k) binary group code where

$$k = 2^m - 1 - R(m,t) \geq 2^m - 1 - mt.$$

When n is not of the form $2^m - 1$ t-error correcting (n,k) binary group codes can be deduced from those obtainable from Theorem 3, by using Corollary 1 of Theorem 1. Stronger results than those which can be obtained in this way will be given in a subsequent communication.

SECTION 5

The proofs of the theorems in Sections 2 and 4 are constructive in the sense that they give an actual procedure for obtaining the required codes. We shall illustrate the procedure to be followed by taking the case $m = 4$, $t = 3$. Then $n = 15$ and the rank $R(m,t)$ turns out to be 10. We thus obtain a 3-error correcting (15,5) group code. The roots of the equation

$$x^4 = x + 1 \tag{12}$$

are primitive elements of $GF(2^4)$, that is all the nonzero elements of the field can be expressed as the powers of a root x (Carmichael, 1937, p. 262). Using (12) the powers of x can be expressed alternatively as polynomials in x of degree 3 or less.The 15 nonzero elements or vectors are listed in the following table in two equivalent forms, (1) as powers of the primitive element, and (2) as polynomials of degree 3 or less in the primitive element. We thus have the following table of the 15 nonzero elements or vectors.

$$
\begin{aligned}
x^0 &= 1 && = (1,0,0,0) = \alpha_1\\
x &= x && = (0,1,0,0) = \alpha_2\\
x^2 &= x^2 && = (0,0,1,0) = \alpha_3\\
x^3 &= x^3 && = (0,0,0,1) = \alpha_4\\
x^4 &= 1 + x && = (1,1,0,0) = \alpha_5\\
x^5 &= x + x^2 && = (0,1,1,0) = \alpha_6\\
x^6 &= x^2 + x^3 && = (0,0,1,1) = \alpha_7\\
x^7 &= 1 + x + x^3 && = (1,1,0,1) = \alpha_8\\
x^8 &= 1 + x^2 && = (1,0,1,0) = \alpha_9\\
x^9 &= x + x^3 && = (0,1,0,1) = \alpha_{10}\\
x^{10} &= 1 + x + x^2 && = (1,1,1,0) = \alpha_{11}\\
x^{11} &= x + x^2 + x^3 && = (0,1,1,1) = \alpha_{12}\\
x^{12} &= 1 + x + x^2 + x^3 && = (1,1,1,1) = \alpha_{13}\\
x^{13} &= 1 + x^2 + x^3 && = (1,0,1,1) = \alpha_{14}\\
x^{14} &= 1 + x^3 && = (1,0,0,1) = \alpha_{15}
\end{aligned}
$$

In obtaining the powers of the elements it should be remembered that each nonzero element of $GF(2^m)$ satisfies $x^{2^m-1} = 1$. Since $m = 4$ we have

$$x^{15} = 1.$$

Thus for example

$$\alpha_7^3 = (x^6)^3 = x^{18} = x^3 = (0,0,0,1) = \alpha_4$$
$$\alpha_7^5 = (x^6)^5 = x^{30} = x^0 = (1,0,0,0) = \alpha_1 .$$

It is now easy to calculate the matrix M^* given by (11). For example, the seventh row is $(\alpha_7, \alpha_7^3, \alpha_7^5)$ or (0 0 1 1, 0 0 0 1, 1 0 0 0). Thus

$$M^* = \left\|\begin{array}{cccccccccccc}
1&0&0&0&1&0&0&0&1&0&0&0\\
0&1&0&0&0&0&0&1&0&1&1&0\\
0&0&1&0&0&0&1&1&1&1&1&0\\
0&0&0&1&0&1&0&1&1&0&0&0\\
1&1&0&0&1&1&1&1&0&1&1&0\\
0&1&1&0&1&0&0&0&1&1&1&0\\
0&0&1&1&0&0&0&1&1&0&0&0\\
1&1&0&1&0&0&1&1&0&1&1&0\\
1&0&1&0&0&1&0&1&1&1&1&0\\
0&1&0&1&1&1&1&1&1&0&0&0\\
1&1&1&0&1&0&0&0&0&1&1&0\\
0&1&1&1&0&0&0&1&1&1&1&0\\
1&1&1&1&0&0&1&1&1&0&0&0\\
1&0&1&1&0&1&0&1&0&1&1&0\\
1&0&0&1&1&1&1&1&1&1&1&0
\end{array}\right\|$$

where the vertical divisions separate the parts coming from α, α^3 and α^5. From M^* we can drop the last null column and the 11th column which is identical with the 10th. The 10×15 matrix of rank 10 so obtained we can take as the matrix A of Theorem 1. From what has been shown in Section 4, this matrix has the property $P(6)$ that any 6 row vectors are independent. Using operations (1) and (2) of Section 2, we can then transform A to A^* where

$$A^* = \left\| \begin{matrix} I_{10} \\ C \end{matrix} \right\|$$

and I_{10} is the unit matrix of order 10, and C is the 5×10 matrix given by

$$C = \left\| \begin{matrix} 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \end{matrix} \right\|$$

Taking

$$C^* = \|C, I_5\|$$

we have a matrix of order 5×15 whose rows generate under vector addition (mod 2), the group of 32 sequences which constitute the letters of the alphabet of the required 3-error correcting (15,5) binary group alphabet. It is easy to verify that of the 31 nonnull sequences 15 have weight 7, 15 have weight 8 and one has weight 15, which checks with Lemma 1.

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