INFORMATION AND CONTROL **53**, 74–80 (1982)

An Exponential Number of Generalized Kerdock Codes

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If $n-1$ is an odd composite integer then there are at least $2^{(1/2)\sqrt{n}}$ pairwise inequivalent binary error-correcting codes of length 2^n, size 2^{2n}, and minimum distance $2^{n-1}-2^{(1/2)n-1}$.

1. INTRODUCTION

If a subcode of the second order Reed–Muller code of length 2^n has minimum distance $2^{n-1}-2^{(1/2)n-1}$ then it has at most 2^{2n} words. A *generalized Kerdock code* is defined to be such a subcode in which this maximum is attained. Such codes were first constructed by Kerdock [7]. His codes are extended cyclic codes, in the sense that there is an automorphism of order 2^n-1 fixing one coordinate and cyclically permuting the remaining ones. In this note we will construct a large number of cyclic generalized Kerdock codes:

THEOREM 1. *If $n-1$ is odd and composite, then there are more than $2^{(1/2)\sqrt{n}}$ pairwise inequivalent extended cyclic generalized Kerdock codes of length 2^n.*

For the same values of n, we will also construct more than $2^{(1/2)\sqrt{n}}$ pairwise inequivalent generalized Kerdock codes of length 2^n which are not extended cyclic.

There is a well-known formal duality between Kerdock codes and Preparata codes: their weight-enumerators are related in the same manner as are those of a linear code and its dual [5; 8, p. 468]. However, the weight enumerators of all generalized Kerdock codes of length 2^n coincide [8, p. 668], which suggests that the aforementioned apparent relationship is merely a coincidence. It should be noted that fewer than n "generalized Preparata codes" of length 2^n are presently known [1, 6].

* This research was supported in part by NSF Grant MCS 79-03130.

0019-9958/82 $2.00

All generalized Kerdock codes also have design-theoretic properties in common. The codewords of each weight in such a code form a 3-design [8, pp. 162, 461].

This article can be regarded as a continuation of [4, 5]: several results found near the beginning of those articles will be used. However, in order to prove Theorem 1 only rough estimates will be required, instead of the precise discussions of equivalence found in those articles.

2. Kerdock Sets

A binary *Kerdock set* $\mathscr{K}$ is a set of 2^{n-1} binary skew symmetric $n \times n$ matrices, each having zero diagonal, such that the sum of any two is nonsingular. Clearly, n must be even. We will always assume that $0 \in \mathscr{K}$.

Corresponding to each Kerdock set $\mathscr{K}$ is a generalized Kerdock code $C(\mathscr{K})$, defined as follows. Each $M = (\mu_{ij}) \in \mathscr{K}$ determines a quadratic form $Q_M((x_i)) = \sum_{i<j} \mu_{ij} x_i x_j$, where $(x_i) \in \mathbb{Z}_2^n$. Let L denote a linear functional on $\mathbb{Z}_2^n$. Then $C(\mathscr{K})$ consists of all subsets of $\mathbb{Z}_2^n$ which are the zero sets of functions of the form $Q_M(v) + L(v) + c$, where M ranges through $\mathscr{K}$, L is an arbitrary linear functional, and c is constant (so $c = 0$ or 1). A proof that this defines a generalized Kerdock code can be found in [2]. Letting $M = 0$, we see that $C(\mathscr{K})$ contains the first order Reed–Muller code C_0.

Lemma 1. (i) *Aut* $C(\mathscr{K})$ *is contained in the group of all affine transformations of* $\mathbb{Z}_2^n$.

(ii) Aut $C(\mathscr{K})$ *contains all translations* $v \to v + b$ *of* $\mathbb{Z}_2^n$.

(iii) Aut $C(\mathscr{K})$ *is transitive on coordinates.*

Proof. (i) Since C_0 consists of all words in $C(\mathscr{K})$ of weight 0, 2^n or 2^{n-1}, Aut $C(\mathscr{K}) \leqslant$ Aut C_0.

(ii) Let $v = (x_i)$ and $M = (\mu_{ij}) \in \mathscr{K}$ with $Q_M(v) = 0$. Set $b = (b_i)$ and $(y_i) = v + b$. Then

$$0 = \sum_{i<j} \mu_{ij} x_i x_j = \sum_{i<j} \mu_{ij}(y_i + b_i)(y_j + b_j)$$

$$= \sum_{i<j} \mu_{ij} y_i y_j + \sum_{i<j} \mu_{ij} b_i y_j + \sum_{i<j} \mu_{ij} b_j y_i + \sum_{i<j} \mu_{ij} b_i b_j,$$

so that $(y_i) - C(\mathscr{K})$.

(iii) This is immediate in view of (ii).

Lemma 2. *Let* $\mathscr{K}$ *and* $\mathscr{K}'$ *be Kerdock sets of* $n \times n$ *matrices. Then*

$C(\mathscr{K})$ and $C(\mathscr{K}')$ are equivalent if and only if there is a nonsingular $n \times n$ matrix A such that the transformation $M \to AMA^t$ sends $\mathscr{K}$ to $\mathscr{K}'$.

Proof. Let g: $C(\mathscr{K}) \to C(\mathscr{K}')$ be an equivalence. Since g sends C_0 to itself, g is induced by an affine transformation of $\mathbb{Z}_2^n$. By Lemma 1(ii), we may assume that g has the form $v \to vA^{-1}$ for some nonsingular matrix A^{-1}.

Let $M = (\mu_{ij}) \in \mathscr{K}$, and write $A = (a_{ij})$. If $(x_i) \in C(\mathscr{K})$ and $Q_M((x_i)) = 0$, set $(y_i) = (x_i)A^{-1}$ and compute as follows.

$$0 = \sum_{i<j} \mu_{ij} x_i x_j = \sum_{i<j} \mu_{ij} \left(\sum_k y_k a_{ki}\right)\left(\sum_l y_l a_{lj}\right)$$

$$= \sum_{k,l} \left(\sum_{i<j} a_{ki} \mu_{ij} a_{lj}\right) y_k y_l.$$

Let $v_{kl} = \sum_{i,j} a_{ki} \mu_{ij} a_{lj}$ and $c_k = \sum_{i<j} a_{ki} \mu_{ij} a_{kj}$. Then

$$0 = \sum_{k<l} v_{kl} y_k y_l + \sum_k c_k y_k.$$

It follows that $(v_{kl}) = AMA^t \in \mathscr{K}'$, as required. The converse is obtained by reversing this argument.

Lemma 2 reduces the proof of Theorem 1 to the construction of sufficiently many Kerdock sets. The next reduction involves orthogonal geometry.

Define the quadratic form Q on $\mathbb{Z}_2^{2n}$ by $Q((x_i)) = \sum_{i=1}^n x_i x_{i+n}$. A vector (x_i) is *singular* if $Q((x_i)) = 0$. Let E be the n-space in $\mathbb{Z}_2^{2n}$ defined by $x_i = 0$ for $i > n$; similarly, let F be defined by $x_i = 0$ for $i \leqslant n$. Then $Q(E) = Q(F) = 0$: these are *totally singular* (*t.s.*) n-spaces.

Let $\mathscr{K}$ be any Kerdock set of $n \times n$ matrices, and define $\mathscr{S}(\mathscr{K})$ as follows:

$$\mathscr{S}(\mathscr{K}) = \{E\} \cup \left\{ F \begin{pmatrix} I & 0 \\ M & I \end{pmatrix} \,\middle|\, M \in \mathscr{K} \right\}.$$

Then $\mathscr{S}(\mathscr{K})$ is an *orthogonal spread*: a family of $2^{n-1} + 1$ t.s. n-spaces such that every nonzero singular vector is in exactly one of them [4, Sect. 5]. Conversely, each orthogonal spread containing E and F produces a Kerdock set: just reverse this construction. Moreover, if $\mathscr{S}(\mathscr{K})$ and $\mathscr{S}(\mathscr{K}')$ are two orthogonal spreads which are inequivalent under the orthogonal group $O^+(2n, 2)$, then Lemma 2 and [4, (5.4)] imply that $C(\mathscr{K})$ and $C(\mathscr{K}')$ are inequivalent codes.

LEMMA 3. *Let $\mathscr{S}(\mathscr{K})$ be as above, and assume that there is an orthogonal transformation of order $2^{n-1} - 1$ fixing E and F and cyclically* *permuting the remaining members of* $\mathscr{S}(\mathscr{K})$. *Then* $C(\mathscr{K})$ *is an extended cyclic code.*

Proof. The given transformation can be viewed as a matrix $\left(\begin{smallmatrix} A & 0 \\ 0 & B \end{smallmatrix}\right)$, where A, B and 0 are $n \times n$ matrices. Since Q is preserved, $B = (A^{-1})^t$. The calculation used in Lemma 2 shows that the linear transformation $M \to AMA^t$ acts on $C(\mathscr{K})$ as desired (compare [4, (5.4)]).

In order to prove Theorem 1, we can now ignore codes and focus on spreads. Thus, Theorem 1 is an immediate consequence of the next result (for $q = 2$).

THEOREM 2. *If* q *is even and* $n - 1$ *is odd and composite, then an* $\Omega^+(2n, q)$ *space has more than* $q^{(1/2)\sqrt{n}}$ *pairwise inequivalent spreads each of which admits an orthogonal automorphism fixing two members and cyclically permuting the remaining ones.*

Here, an $\Omega^+(2n, q)$ space is (up to a change of coordinates) the vector space $GF(q)^{2n}$ equipped with the quadratic form $Q((x_i)) = \sum_{i=1}^n x_i x_{n+i}$. A vector (x_i) or 1-space $\langle (x_i) \rangle$ is called *singular* if $Q((x_i)) = 0$ and *nonsingular otherwise*; and a subspace E is again called *t.s.* if $Q(E) = 0$. A spread of such a space is a family of $q^{n-1} + 1$ t.s. n-spaces partitioning the nonzero singular vectors. Equivalence is defined in terms of the group $\Gamma O^+(2n, q)$ of semilinear transformations preserving Q projectively (cf. [4, Sect. 2]); when $q = 2$ this is just the orthogonal group determined by Q.

There is also a bilinear form $(u, v) = Q(u + v) + Q(u) + Q(v)$ on $GF(q)^{2n}$, and hence a notion of perpendicularity. If S is any subset of $GF(q)^{2n}$ then $S^\perp = \{v \in V \mid (v, S) = 0\}$. If y is any 1-space then $y \subset y^\perp$ (since $(v, v) = 0$ for any vector v), and we can form the quotient space $y^\perp/y$. This inherits the form (u, v) via $(u + y, v + y) = (u, v)$, but it does not inherit Q if y is nonsingular. A subspace X of $y^\perp/y$ is called *totally isotropic* if $(X, X) = 0$.

For further background, see [4, 5].

3. PROOF OF THEOREM 2

Set $n - 1 = me$, where $e \geqslant m > 1$.

In [3; 4, Sect. 3], a spread Σ of an $\Omega^+(2m + 2, q^e)$ space was constructed (called a desarguesian orthogonal spread). Here, Σ admits an orthogonal automorphism g of order $(q^e)^m - 1$ fixing two members of Σ and cyclically permuting the others. The proof of Theorem 2 will consist of suitably modifying Σ as described in [5, Sect. 2].

The transformation g fixes $q^e - 1$ nonsingular 1-spaces y of the underlying vector space. The $2m$-dimensional space $y^\perp/y$ inherits a symplectic structure. The family

$$\Sigma(y) = \{\langle y, y^\perp \cap X\rangle/y \mid x \in \Sigma\}$$

consists of $(q^e)^m + 1$ totally isotropic $m-1$-spaces which partition the set of all nonzero vectors in $y^\perp/y$. Turn $y^\perp/y$ into a $2me$-dimensional symplectic space over $GF(q)$ (by following the bilinear form on $y^\perp/y$ with the trace map $GF(q^e) \to GF(q)$). Then $\Sigma(y)$ becomes a family $\Sigma(y)^e$ of $q^{me}+1$ totally isotropic me-spaces which still partitions the nonzero vectors in $y^\perp/y$. Note that g induces a symplectic transformation of $y^\perp/y$ preserving both $\Sigma(y)$ and $\Sigma(y)^e$, and permuting their members exactly as it permutes those of Σ.

Let V be an $\Omega^+(2me+2, q)$ space. Fix a nonsingular 1-space z of V, and identify $z^\perp/z$ with $y^\perp/y$. Then the family $\Sigma(y)^e$ determines an essentially unique orthogonal spread Σ^y (called $\mathbf{S}(\Sigma(y)^e)$ in [5, Sect. 2]) such that $\Sigma^y(z) = \Sigma(y)^e$. Moreover, g extends to an orthogonal transformation g^* of V fixing z, preserving Σ^y and permuting Σ^y as required in Theorem 2.

We will show that, as y ranges over the original set of q^e-1 nonsingular 1-spaces in the $\Omega^+(2m+2, q^e)$ space we started with, Σ^y ranges over sufficiently many pairwise inequivalent $\Omega^+(2me+2, q)$ spreads.

Consider the symplectic spreads $\Sigma(y)^e$. If N is the number of pairwise inequivalent symplectic spreads of this sort, then $N \geqslant (q^e-2)/(2\log_2 q^e)$ (by [4, (4.2) or (3.5)]). These produce N orthogonal spreads Σ^y. Since $N/(q+1) > q^{(1/2)\sqrt{n}}$, Theorem 2 is a consequence of the following lemma.

LEMMA 4. *There do not exist $q+2$ choices $y(1),\ldots, y(q+2)$ for y such that the symplectic spreads $\Sigma(y(i))$ are pairwise inequivalent while the orthogonal spreads $\Sigma^{y(i)}$ are pairwise equivalent.*

Proof. Fix y, and let V, z and g^* be as above. There is a prime $r \mid q^{me}-1$ such that $r \nmid 2^i - 1$ whenever $1 < 2^i < q^{em}$ [9]. Let $\langle h\rangle$ be a Sylow r-subgroup of $\langle g^*\rangle$. Then $\langle h\rangle$ is also a Sylow r-subgroup of $\Gamma O^+(2me+2, q)$. Since h induces the identity on both z and $V/z^\perp$, there is a 2-space Z in V on which h induces the identity. Then h acts on $Z^\perp/(Z \cap Z^\perp)$; using the order of h, we find that $Z \cap Z^\perp = 0$ and Z consists of all vectors fixed by h. Let G consist of all elements of $\Gamma O^+(2me+2, q)$ preserving Σ^y.

Now consider two further choices y' and y'' such that $\Sigma(y)^e$, $\Sigma(y')^e$ and $\Sigma(y'')^e$ are pairwise inequivalent but such that Σ^y is equivalent to both $\Sigma^{y'}$ and $\Sigma^{y''}$. Define V', z', h', Z', G' and V'', z'', Z'' in the obvious manner. We may assume that $V = V' = V''$.

Let $\varphi, \psi \in \Gamma O^+(2me+2, q)$, where $(\Sigma^{y'})^\varphi = \Sigma^y$ and $(\Sigma^{y''})^\psi = \Sigma^y$.

Clearly, $G'^\varphi = G$ and $\langle h'\rangle$ is a Sylow r-subgroup of G. Thus, we may assume that $h'^{\varphi} = h$. Then $Z'^{\varphi} = Z$. Similarly, we may assume that $Z''^{\psi} = Z$.

The points z, z'^{φ} and z'^{ψ} are all different. For example, if $z'^{\varphi} = z''^{\psi}$ then $\varphi\psi^{-1}$ sends $\Sigma^{y'}(z')$ to $\Sigma^{y''}(z'')$, whereas $\Sigma(y')^e$ and $\Sigma(y'')^e$ are inequivalent.

Thus, if we leave y fixed and vary y', there are at most q possibilities for z'^{φ}. This proves the lemma, and completes the proof of Theorems 1 and 2.

4. Concluding Remarks

1. Replacing $(q^e)^m - 1$ by $(q^e)^m + 1$ throughout Section 3, we obtain the following result.

THEOREM 3. *If q is even and $n-1$ is odd and composite, then an $\Omega^+(2n, q)$ space has more than $q^{(1/2)\sqrt{n}}$ pairwise inequivalent spreads, each of which admits an orthogonal automorphism cyclically permuting its $q^{n-1}+1$ members.*

Moreover, no orthogonal spread arising in Theorem 3 can be equivalent to any appearing in Theorem 2 (by [5, (3.3)]). Similarly, no generalized Kerdock code arising from Theorem 3 (with $q = 2$) can be extended cyclic.

2. In Section 3, Z has only $q-1$ nonsingular 1-spaces. The estimates leading to $q^{(1/2)\sqrt{n}}$ are very crude.

3. The Kerdock sets implicitly constructed in Section 3 are given explicitly in [5, (9.2)]. However, it is not clear how to choose more than $2^{(1/2)\sqrt{n}}$ of them which produce pairwise inequivalent codes.

It seems likely that Σ^y and $\Sigma^{y'}$ are inequivalent whenever $\Sigma(y)$ and $\Sigma(y')$ are.

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