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Codes over an infinite family of algebras

Research Article

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Abstract: In this paper, we will show some properties of codes over the ring $B_k = \mathbb{F}_p[v_1, \ldots, v_k]/(v_i^2 = v_i, \forall i = 1, \ldots, k)$. These rings, form a family of commutative algebras over finite field $\mathbb{F}_p$. We first discuss about the form of maximal ideals and characterization of automorphisms for the ring B_k. Then, we define certain Gray map which can be used to give a connection between codes over B_k and codes over $\mathbb{F}_p$. Using the previous connection, we give a characterization for equivalence of codes over B_k and Euclidean self-dual codes. Furthermore, we give generators for invariant ring of Euclidean self-dual codes over B_k through MacWilliams relation of Hamming weight enumerator for such codes.

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1. Introduction

Codes over finite rings has been an interesting topic in algebraic coding theory since the discovery of codes over $\mathbb{Z}_4$, see [4]. An example of finite rings which has interesting properties is the ring $A_k = \mathbb{F}_2[v_1, \ldots, v_k]$, where $v_i^2 = v_i$, for $1 \leq i \leq k$, because it has two Gray maps which relate codes over such ring and binary codes, see [2]. This ring also has non-trivial automorphisms which can be used to define skew-cyclic codes, for example in [1], skew-cyclic codes over the ring $A_1 = \mathbb{F}_2 + v\mathbb{F}_2$, where $v^2 = v$, which give some optimal Euclidean and Hermitian self-dual codes. Furthermore, Abualrub *et al.* show that skew-cyclic codes over A_1 have a connection to left submodules over a skew-polynomial ring and

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give skew-polynomial generators for these codes. In [6], skew-cyclic codes over the ring A_1 have been characterized using a Gray map. This characterization gives a way to construct skew-cyclic codes over the ring A_1 from binary cyclic or quasi-cyclic codes, and also gives decoding algorithm for some codes over such ring. Meanwhile, Gao [3] consider skew-cyclic codes over the ring $B_1 = \mathbb{F}_p + v\mathbb{F}_p$, where $v^2 = v$, and found that these codes are equivalent to either cyclic codes or quasi-cyclic codes. Using this connection, Gao is able to give an enumeration for skew-cyclic codes which are constructed using an automorphism with order relatively prime to the length of the codes.

In this paper, we consider codes over the ring $B_k = \mathbb{F}_p[v_1, \ldots, v_k]$, where $v_i^2 = v_i$ for $1 \le i \le k$, which is a generalization of the ring A_k in [2] and B_1 in [3]. We study its maximal ideals, automorphisms, equivalence codes, and Euclidean self-dual codes over these rings, including the generators for its invariant ring. This paper is organized as follows: Section 2 describes some properties of the ring B_k such as maximal ideals and automorphisms. Meanwhile, in Section 3, we describe a Gray map for the ring B_k, and we characterize linear codes and equivalent codes over the ring B_k. Finally, in Section 4, we characterize Euclidean self-dual codes, give the shape of MacWilliams relation and generators of invariant rings for Euclidean self-dual codes.

2. The ring B_k

As we readily see, the ring B_k forms a commutative algebra over prime field $\mathbb{F}_p$. Let $\Omega = \{1, 2, \ldots, k\}$ and 2^Ω is the collection of all subsets of Ω. Also, let w_i be an element in the set $\{v_i, 1 - v_i\}$, for $1 \le i \le k$. Then, we will prove the following observation.

Lemma 2.1. *$\omega \in B_k$ is a zero divisor if and only if $\omega \in \langle w_1, w_2, \ldots, w_k\rangle$.*

Proof. ($\Longleftarrow$) It is clear that, $v_i(1 - v_i) = 0$, for all $i = 1, \ldots, k$. Therefore, if $\omega \in \langle w_1, w_2, \ldots, w_k\rangle$, then it is a zero divisor in B_k.

($\Longrightarrow$) Consider the equation,

$$(\alpha + \beta v_k)(\gamma + \epsilon v_k) = a + bv_k$$

given $\alpha + \beta v_k, a + bv_k \in B_k$, for some $\alpha, \beta, a, b \in B_{k-1}$. We have $\gamma = a\alpha^{-1}$ and $\epsilon = (b - \beta a)(\alpha(\beta + \alpha))^{-1}$. Therefore, if $a + bv_k = 1$, then $\gamma = 1$ and $\epsilon = -\beta(\alpha(\beta + \alpha))^{-1}$. Which implies, $\alpha + \beta v_k$ is a unit if and only if α and $\alpha + \beta$ are also units. Considering this observation for elements in $B_{k-1}, B_{k-2}, \ldots, B_1$, we have $\alpha + \beta v \in B_1$ is a unit if and only if $\alpha, \alpha + \beta \in \mathbb{F}_p$ are non zero elements. Since, every element in finite commutative ring is either a unit or a zero divisor, we can see that the only zero divisors in B_1 are the elements in the ideals generated by βv or $\alpha(1 - v)$. By generalizing this result recursively, we have the intended conclusion. □

Also, we can easily show that $I = \langle w_1, w_2, \ldots, w_k\rangle$ is a maximal ideal in B_k.

Lemma 2.2. *Let $I = \langle w_1, w_2, \ldots, w_k\rangle$. Then I is a maximal ideal in B_k.*

Proof. Consider quotient ring B_k/I. If $v_i \in I$, then $1 - v_i \equiv 1 \mod I$, and if $1 - v_i \in I$, then $v_i = 1 - (1 - v_i) \equiv 1 \mod I$. Consequently, B_k/I is a field. So, I is a maximal ideal. Moreover, $B_k/I \cong \mathbb{F}_p$. □

The following lemma is needed to prove Proposition 2.4.

Lemma 2.3. *$\alpha^p = \alpha$, for all $\alpha \in B_k$.*

Proof. Let $\alpha = \sum_{A\subseteq\{1,\ldots,k\}} \alpha_A v_A$, for some $\alpha_A \in \mathbb{F}_p$, where $v_A = \prod_{j\in A} v_j$. Then, consider

$$\alpha^p = \sum_{i=0}^{p} \binom{p}{i} \alpha_{A_1}^i v_{A_1} \left(\sum_{A\neq A_1} \alpha_A v_A \right)^{p-i} = \alpha_{A_1} v_{A_1} + \left(\sum_{A\neq A_1} \alpha_A v_A \right)^{p}$$

since $\mathbb{F}_p$ has characteristic p and $\beta^{p-1} = 1$ for all $\beta \in \mathbb{F}_p$. If we continue this procedure, then we have $\alpha^p = \alpha$. $\square$

The following result shows that the ring B_k is a principal ideal ring.

Proposition 2.4. *Let $I = \langle \alpha_1, \ldots, \alpha_m\rangle$ be an ideal in B_k, for some $\alpha_1, \ldots, \alpha_m \in B_k$. Then,*

$$I = \langle \sum_{A\subseteq\{1,\ldots,m\}, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} \rangle.$$

Proof. Consider $\alpha_i \sum_{A\subseteq\{1,\ldots,m\},A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1}$. For any $A \subseteq \{1, \ldots, m\}$, if $i \in A$, then

$$\alpha_i (-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} = (-1)^{|A|+1} \alpha_i (\prod_{j\in A-\{i\}} \alpha_j)^{p-1}$$

since $\alpha_i^p = \alpha_i$ by Lemma 2.3. Consequently, there is a unique $A' = A - \{i\} \subseteq \{1, \ldots, m\}$, such that

$$\alpha_i \left((-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} + (-1)^{|A'|+1} (\prod_{j\in A} \alpha_j)^{p-1} \right) = 0.$$

Otherwise, if $i \notin A$, then there is a unique $A'' = A \cup \{i\} \subseteq \{1, \ldots, m\}$ such that

$$\alpha_i \left((-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} + (-1)^{|A''|+1} (\prod_{j\in A} \alpha_j)^{p-1} \right) = 0.$$

So, every term will be vanish except $\alpha_i \alpha_i^{p-1} = \alpha_i$. Therefore,

$$I \subseteq \langle \sum_{A\subseteq\{1,\ldots,m\}, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} \rangle.$$

It is clear that

$$\langle \sum_{A\subseteq\{1,\ldots,m\}, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} \rangle \subseteq I.$$

Thus, $I = \langle \sum_{A\subseteq\{1,\ldots,m\},A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \alpha_j)^{p-1} \rangle$. $\square$

The following proposition shows that the ideal in Lemma 2.2 is the only maximal ideal in B_k.

Proposition 2.5. *An ideal I in B_k is maximal if and only if $I = \langle w_1, w_2, \ldots, w_k\rangle$.*

Proof. ($\Longleftarrow$) It is clear by Lemma 2.2.

($\Longrightarrow$) Let J be a maximal ideal in B_k. By Proposition 2.4, B_k is a principal ideal ring. Then, let $J = \langle \omega \rangle$, for some $\omega \in B_k$. Note that, ω is not a unit in B_k, so it is a zero divisor. By Lemma 2.1, ω is an element of some $m_i = \langle w_1, w_2, \ldots, w_k\rangle$, which means $J \subseteq m_i$. Consequently, $J = m_i$, because J is a maximal ideal. $\square$

Using the above result, we have the following lemmas.

Lemma 2.6. *The ring B_k can be viewed as an $\mathbb{F}_p$-vector space with dimension 2^k whose basis consists of elements of the form $w_S = \prod_{i\in S} w_i$, where $S \in 2^\Omega$.*

Proof. As we can see, every element $a \in B_k$ can be written as $a = \sum_{S\in 2^\Omega} \alpha_S v_S$, for some $\alpha_S \in \mathbb{F}_p$, where $v_S = \prod_{i\in S} v_i$ and $v_\emptyset = 1$. So, B_k is a vector space over $\mathbb{F}_p$ whose basis consists of elements of the form $v_S = \prod_{i\in S} v_i$, where $v_\emptyset = 1$ and there are $\sum_{j=0}^{k} \binom{k}{j} = 2^k$ elements of basis. Now, we will show that the set $\{1, w_{S_2}, \dots, w_{S_{2^k}}\}$ is also a basis. Consider,

$$\alpha_1 + \alpha_2 w_{S_2} + \cdots + \alpha_{2^k} w_{S_{2^k}} = 0$$

for some $\alpha_i \in \mathbb{F}_p$, for all $i = 1, \dots, 2^k$, which gives,

$$-\alpha_1 = \alpha_2 w_{S_2} + \cdots + \alpha_{2^k} w_{S_{2^k}}.$$

If $\alpha_1 \neq 0$, then $\xi_1 = \left(\alpha_2 w_{S_2} + \cdots + \alpha_{2^k} w_{S_{2^k}}\right)$ is a unit, a contradiction to the fact that $\xi_1 \in \langle w_1, \dots, w_k\rangle$. So, $\alpha_1 = 0$, which means,

$$-\left(\alpha_2 w_{S_2} + \cdots + \alpha_{k+1} w_{S_{k+1}}\right) = \alpha_{k+2} w_{S_{k+2}} + \cdots + \alpha_{2^k} w_{S_{2^k}}.$$

If $\left(\alpha_2 w_{S_2} + \cdots + \alpha_{k+1} w_{S_{k+1}}\right) \neq 0$, then it is a contradiction to the fact that $|S_j| \geq 2$, for all $j = k+2, \dots, 2^k$. Consequently, $\left(\alpha_2 w_{S_2} + \cdots + \alpha_{k+1} w_{S_{k+1}}\right) = 0$. We have to note that, the set with elements of the w_S, where $S \in 2^\Omega$, is also linearly independent over $\mathbb{F}_p$, because S_k is a vector space over $\mathbb{F}_p$ with element of basis are of the form v_S, where $S \subseteq \Omega$. Therefore, $\left(\alpha_2 w_{S_2} + \cdots + \alpha_{k+1} w_{S_{k+1}}\right) = 0$ gives $\alpha_2 = \cdots = \alpha_{k+1} = 0$. By continuing this process, we have $\alpha_1 = \cdots = \alpha_{2^k} = 0$, which means they are linearly independent over $\mathbb{F}_p$. □

Lemma 2.7. *The ring B_k has characteristic p and cardinality p^{2^k}.*

Proof. It is immediate since characteristic of $\mathbb{F}_p$ is p, and B_k can be viewed as a $\mathbb{F}_p$-vector space with dimension $\sum_{i=0}^{k} \binom{k}{i} = 2^k$. So, $|B_k| = p^{2^k}$. □

The following theorem characterizes the shape of automorphisms in the ring B_k.

Theorem 2.8. *Let θ be an endomorphism in B_k. Then, θ is an automorphism if and only if $\theta(v_i) = w_j$, for every $i \in \Omega$, and θ, when restricted to $\mathbb{F}_p$, is an identity map.*

Proof. ($\Longrightarrow$) Let $J = \langle v_1, \dots, v_k\rangle$ and $J_\theta = \langle \theta(v_1), \dots, \theta(v_k)\rangle$. Consider the map

$$\begin{array}{rccc} \lambda : & \dfrac{B_k}{J} & \to & \dfrac{B_k}{J_\theta} \\ & a + J & \mapsto & \theta(a) + J_\theta \end{array}$$

We can see that the map λ is a ring homomorphism. For any $a, b \in B_k/J$ where $\lambda(a) = \lambda(b)$, let $a = a_1 + J$ and $b = b_1 + J$ for some $a_1, b_1 \in B_k$. As we can see, $\theta(a_1 - b_1) \in J_\theta$, so $a_1 - b_1 \in J$. Consequently, $a - b = 0 + J$, which means $a = b$, in other words, λ is a monomorphism. Moreover, for any $a' \in B_k/J_\theta$, let $a' = a_2 + J_\theta$ for some $a_2 \in B_k$, then there exists $a = \theta^{-1}(a_2) + J$ such that $\lambda(a) = a'$. Therefore, $\mathbb{F}_p \simeq B_k/J \simeq B_k/J_\theta$, which implies J_θ is also a maximal ideal. By Proposition 2.5, $J_\theta = \langle w_1, \dots, w_k\rangle$, where $w_i \in \{v_i, 1 - v_i\}$ for $1 \leq i \leq k$. By Proposition 2.4,

$$J_\theta = \langle \sum_{A\subseteq\Omega, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} w_j)^{p-1}\rangle = \langle \sum_{A\subseteq\Omega, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \theta(v_j))^{p-1}\rangle$$

which means, $\sum_{A\subseteq\Omega, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} w_j)^{p-1}$ and $\sum_{A\subseteq\Omega, A\neq\emptyset} (-1)^{|A|+1} (\prod_{j\in A} \theta(v_j))^{p-1}$ are associate. Therefore, $\theta(v_i) = \beta w_j$ for some unit β which satisfies $\left(\beta^{|A|}\right)^{p-1} = \beta$, for all $A \neq \emptyset$. Consequently, we have $\beta^{p-1} = \beta$, but by Lemma 2.3, $\beta^p = \beta$. Since β is a unit, we have that $\beta^{p-1} = 1$. Therefore, β must be equal to 1. Moreover, since θ is an automorphism, $\theta(v_i) \neq \theta(v_j)$ whenever $i \neq j$. Also, since the only automorphism in $\mathbb{F}_p$ is identity map, we have the conclusion.

($\Longleftarrow$) Suppose that $\theta(v_i) = w_j$, and $\theta(v_i) \neq \theta(v_j)$ whenever $i \neq j$. By Lemma 2.6, we can see that θ is also an automorphism. $\square$

Now, we have to note that every element a in B_k can be written as

$$a = \sum_{S \in 2^\Omega} \alpha_S w_S$$

for some $\alpha_S \in \mathbb{F}_p$, where $w_S = \prod_{i \in S} w_i$. Define a map φ as follows.

$$\begin{array}{rcl} \varphi \ : \ B_k & \to & \mathbb{F}_p^{2^k} \\ a = \sum_{i=1}^{2^k} \alpha_{S_i} w_{S_i} & \mapsto & \left(\sum_{S \subseteq S_1} \alpha_S, \sum_{S \subseteq S_2} \alpha_S, \ldots, \sum_{S \subseteq S_{2^k}} \alpha_S\right) \end{array}$$

We can show that this map φ is a bijection map. Furthermore, this map can be extended n tuples of B_k as follows.

$$\begin{array}{rcl} \overline{\varphi} \ : \ B_k^n & \to & \mathbb{F}_p^{n2^k} \\ (a_1, \ldots, a_n) & \mapsto & (\varphi(a_1), \ldots, \varphi(a_n)). \end{array}$$

Since φ is a bijection map, we also have $\overline{\varphi}$ is a bijection map. We have to note that, the map φ is a permutation, based on the choice of subsets $S_i \in 2^\Omega$, of Gray maps in [2].

3. Codes over the ring B_k

A subset $C \subseteq B_k^n$ is called *code* over B_k of length n. If C is a B_k-submodule of B_k^n, then C called *linear code*. The following proposition gives a characterization of B_k-linear codes using the map $\overline{\varphi}$.

Proposition 3.1. *C is a linear code over B_k if and only if there exist linear codes $C_1, \ldots, C_{2^k}$ over $\mathbb{F}_p$ such that $C = \overline{\varphi}^{-1}(C_1, \ldots, C_{2^k})$.*

Proof. ($\Longrightarrow$) Since $\overline{\varphi}$ is a bijection, there exist $C_1, \ldots, C_{2^k}$ such that $C = \overline{\varphi}^{-1}(C_1, \ldots, C_{2^k})$. Now, we only need to show that C_i is a linear code over $\mathbb{F}_p$ for all $i = 1, \ldots, 2^k$. For any C_i, let c_1 and c_2 be two codewords in C_i. For $l = 1, 2$, let $c_l = (\alpha_1^{(l)}, \ldots, \alpha_n^{(l)})$, for some $\alpha_j^{(l)}$ in $\mathbb{F}_p$. Consider

$$\begin{array}{rcl} c'_l & = & \overline{\varphi}^{-1}(\mathbf{0}, \ldots, \mathbf{0}, \lambda_l c_l, \mathbf{0}, \mathbf{0}) \\ & = & \left(\varphi^{-1}(0, \ldots, 0, \lambda_l \alpha_1^{(l)}, 0, \ldots, 0), \ldots, \varphi^{-1}(0, \ldots, 0, \lambda_l \alpha_n^{(l)}, 0, \ldots, 0)\right) \\ & = & \left(\lambda_l \alpha_1^{(l)} \left(w_{S_l} - \sum_{j \in \{1,\ldots,k\} - S_l} w_{S_l \cup \{j\}}\right), \ldots, \lambda_l \alpha_n^{(l)} \left(w_{S_l} - \sum_{j \in \{1,\ldots,k\} - S_l} w_{S_l \cup \{j\}}\right)\right), \end{array}$$

for any λ_l in $\mathbb{F}_p^\times$ for all $l = 1, 2$. The last equality holds since

$$\varphi\left(\alpha_t^{(l)} \left(w_{S_l} - \sum_{j \in \{1,\ldots,k\} - S_l} w_{S_l \cup \{j\}}\right)\right) = (0, \ldots, 0, \alpha_t^{(l)}, 0, \ldots, 0)$$

for all $1 \leq t \leq n$. Since $C = \overline{\varphi}^{-1}(C_1, \ldots, C_{2^k})$, we have c'_l is in C for all $l = 1, 2$, and $c'_1 + c'_2$ is also in C. Then, consider

$$\overline{\varphi}(c_1'+c_2') = \begin{pmatrix} 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \\ \lambda_1\alpha_1^{(1)}+\lambda_2\alpha_1^{(2)} & \cdots & \lambda_1\alpha_l^{(1)}+\lambda_2\alpha_l^{(2)} & \cdots & \lambda_1\alpha_n^{(1)}+\lambda_2\alpha_n^{(2)} \\ 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \end{pmatrix}.$$

Hence, $\lambda_1 c_1 + \lambda_2 c_2$ is also in C_i.

($\Longleftarrow$) Take any two codewords c_3 and c_4 in C. Let

$$c_3 = \left(\sum_{S\in 2^\Omega} \alpha_S^{(1)} w_S, \ldots, \sum_{S\in 2^\Omega} \alpha_S^{(n)} w_S\right)$$

and

$$c_4 = \left(\sum_{S\in 2^\Omega} \beta_S^{(1)} w_S, \ldots, \sum_{S\in 2^\Omega} \beta_S^{(n)} w_S\right),$$

for some α_i, β_i in $\mathbb{F}_p$, where $i = 1, \ldots, 2^k$. For any λ_3 and λ_4 in $\mathbb{F}_p^\times$ we have

$$\overline{\varphi}(\lambda_3 c_3 + \lambda_4 c_4) = \begin{pmatrix} \lambda_3\alpha_{S_1}^{(1)} + \lambda_4\beta_{S_1}^{(1)} & \cdots & \lambda_3\alpha_{S_1}^{(n)} + \lambda_4\beta_{S_1}^{(n)} \\ \lambda_3 \sum_{S\subseteq S_2} \alpha_S^{(1)} + \lambda_4 \sum_{S\subseteq S_2} \beta_S^{(1)} & \cdots & \lambda_3 \sum_{S\subseteq S_2} \alpha_S^{(n)} + \lambda_4 \sum_{S\subseteq S_2} \beta_S^{(n)} \\ \vdots & \vdots & \vdots \\ \lambda_3 \sum_{S\subseteq S_{2^k}} \alpha_S^{(1)} + \lambda_4 \sum_{S\subseteq S_{2^k}} \beta_S^{(1)} & \cdots & \lambda_3 \sum_{S\subseteq S_{2^k}} \alpha_S^{(n)} + \lambda_4 \sum_{S\subseteq S_{2^k}} \beta_S^{(n)} \end{pmatrix}$$

is also in $(C_1, \ldots, C_{2^k})$, since C_i is a linear code for every $i = 1, \ldots, 2^k$. Therefore, $\lambda_3 c_3 + \lambda_4 c_4$ is also in C. $\square$

Now, following [5], we define permutation equivalence of codes as follows.

Definition 3.2. *Two codes are permutation equivalent if one can be obtained from the other by permuting the coordinates.*

Using Definition 3.2, we can define the following notion of equivalence between two codes.

Definition 3.3. *Two codes C and C' over B_k are equivalent if either they are permutation-equivalent or C is permutation equivalent to the code $\theta(C')$ for some automorphism θ in B_k, i.e. the code $\theta(C')$ obtained from C' by changing α with $\theta(\alpha)$ in all coordinates.*

Note that, the above definition is similar to the one in [5]. Now, let Π_θ be a permutation on 2^k tuples of $\mathbb{F}_p$ induced by automorphism θ. Then we have

$$(\Pi_\theta \circ \overline{\varphi})(c) = \overline{\varphi}(\theta(c)) \tag{1}$$

for any $c \in B_k^n$. Then, we have the following characterization.

Theorem 3.4. *Let C and C' be two codes over B_k. Then, C and C' are equivalent if and only if there exists a permutation which sends $(C_1, \ldots, C_{2^k})$ to $(C_1', \ldots, C_{2^k}')$ or to $(\Pi_\theta(C_1'), \ldots, \Pi_\theta(C_{2^k}'))$.*

Proof. ($\Longrightarrow$) Let $C = \overline{\varphi}^{-1}(C_1, \ldots, C_{2^k})$ and $C' = \overline{\varphi}^{-1}(C'_1, \ldots, C'_{2^k})$, where C_i and C'_i are codes over $\mathbb{F}_p$, for all $1 \leq i \leq 2^k$. If there exists an automorphism θ such that C is permutation equivalent to $\theta(C')$, then by equation 1, we have $C = \overline{\varphi}^{-1}(C_1, \ldots, C_{2^k})$ is permutation equivalent to $\left(\Pi_\theta(C'_1), \ldots, \Pi_\theta(C'_{2^k})\right)$.

($\Longleftarrow$) If there exists a permutation which sends $(C_1, \ldots, C_{2^k})$ to

$$(\Pi_\theta(C'_1), \ldots, \Pi_\theta(C'_{2^k})),$$

for some bijective map Π_θ, then we can have the automorphism θ using the equation 1. $\square$

4. Invariant ring

In this section, we describe some aspect of Euclidean self-dual codes as well as MacWiliams identity and invariant ring.

Related to Euclidean self-dual codes over the ring B_k, we have the following result.

Proposition 4.1. *Let $C = \overline{\varphi}^{-1}(C_1, C_2, \ldots, C_{2^k})$, for some p-ary codes $C_1, \ldots, C_{2^k}$. Then, C is Eulidean self-dual codes over B_k if and only if C_i is also Euclidean self-dual codes, for $1 \leq i \leq 2^k$.*

Proof. ($\Longrightarrow$) For any $c_i \in C_i$, let $c_i = (\alpha_{S_i}^{(0)}, \ldots, \alpha_{S_i}^{(n-1)})$, for some $\alpha_{S_i}^{(j)} \in \mathbb{F}_p$, where $0 \leq j \leq n-1$. Let $c = \overline{\varphi}^{-1}(0, \ldots, 0, c_i, 0, \ldots, 0) \in C$, then we have $\langle c, c' \rangle = 0$ for every $c' \in C$. To make the representation for any element in the ring B_k easier, we will use the basis whose elements are of the form v_S, for all $S \subseteq \{1, 2, \ldots, k\}$. Now, let

$$c' = \left(\beta_{S_i}^{(0)} v_{S_i} + \sum_{S \in 2^\Omega, S \neq S_i} \beta_S^{(0)} v_S, \ldots, \beta_{S_i}^{(n-1)} v_{S_i} + \sum_{S \in 2^\Omega, S \neq S_i} \beta_S^{(n-1)} v_S\right).$$

Consider,

$$\begin{aligned} c &= \overline{\varphi}^{-1}(0, \ldots, 0, c_i, 0, \ldots, 0) \\ &= \left(\alpha_{S_i}^{(0)}(v_{S_i} - \textstyle\sum_{j \in \{1,\ldots,k\}-S_i} v_{S_i \cup \{j\}}), \ldots, \alpha_{S_i}^{(n-1)}(v_{S_i} - \textstyle\sum_{j \in \{1,\ldots,k\}-S_i} v_{S_i \cup \{j\}})\right). \end{aligned}$$

Since $\langle c, c' \rangle = 0$ for every $c' \in C$ and $v_S^2 = v_S$ for every $S \in 2^\Omega$, we have

$$\sum_{j=0}^{n-1} \left(\alpha_{S_i}^{(j)} \beta_{S_i}^{(j)} v_{S_i} - \sum_{j \in \{1,\ldots,k\}-S_i} \alpha_{S_i}^{(j)} \beta_{S_i \cup \{j\}}^{(j)} v_{S_i \cup \{j\}} = 0\right).$$

Consequently, $\sum_{j=0}^{n-1} \alpha_{S_i}^{(j)} \beta_{S_i}^{(j)} = 0$.

Take any $c'_i \in C_i$. Let $c'_i = (\gamma_{S_i}^{(0)}, \ldots, \gamma_{S_i}^{(n-1)})$, for some $\gamma_{S_i}^{(j)} \in \mathbb{F}_p$, where $0 \leq j \leq n-1$. Since $c' = \overline{\varphi}^{-1}(0, \ldots, 0, c_i, 0, \ldots, 0) \in C$, we have $\langle c, c' \rangle = 0$. So

$$\langle c_i, c'_i \rangle = \sum_{j=0}^{n-1} \alpha_{S_i}^{(j)} \gamma_{S_i}^{(j)} = 0.$$

Therefore $C_i \subseteq C_i^\perp$.

For any $c_1 \in C_i^\perp$, let $c_1 = (\zeta_0, \ldots, \zeta_{n-1})$ for some $\zeta_j \in \mathbb{F}_p$, where $0 \leq j \leq n-1$. Since $\langle c_1, c_i \rangle = 0$, we have $\sum_{j=0}^{n-1} \zeta_j \alpha_{S_i}^{(j)} = 0$. We can see that

$$\begin{aligned} c'_1 &= \overline{\varphi}^{-1}(0, \ldots, 0, c_1, 0, \ldots, 0) \\ &= \left(\zeta_0(v_{S_i} - \textstyle\sum_{j \in \{1,\ldots,k\}-S_i} v_{S_i \cup \{j\}}), \ldots, \zeta_{n-1}(v_{S_i} - \textstyle\sum_{j \in \{1,\ldots,k\}-S_i} v_{S_i \cup \{j\}})\right). \end{aligned}$$

Now, since $\sum_{j=0}^{n-1} \zeta_j \alpha_{S_i}^{(j)} = 0$, we also have $\langle c_1', c_2 \rangle = 0$ for every $c_2 \in C$. Remember that $C = C^{\perp}$, which gives $c_1' \in C$. So, $c_1 \in C_i$, or in other words $C_i^{\perp} \subseteq C_i$. Thus, C_i is a Euclidean self-dual code, for all $i = 1, \ldots, 2^k$.

($\Longleftarrow$) Take any $c_1, c_2 \in C$. For every $i = 1, 2$, let

$$c_i = \left(\sum_{S \subseteq \{1,\ldots,k\}} c_S^{(i,0)}, \ldots, \sum_{S \subseteq \{1,\ldots,k\}} c_S^{(i,n-1)} \right),$$

for some $c_S^{(i,j)} \in \mathbb{F}_p$, where $i = 1, 2$, and $j = 0, \ldots, n-1$. Consider,

$$\begin{aligned} \overline{\varphi}(c_i) \;=\; & \Big(\textstyle\sum_{S \subseteq S_1} c_S^{(i,0)}, \ldots, \sum_{S \subseteq S_1} c_S^{(i,n-1)}, \ldots \\ & \ldots, \textstyle\sum_{S \subseteq S_l} c_S^{(i,0)}, \ldots, \sum_{S \subseteq S_l} c_S^{(i,n-1)}, \ldots \\ & \ldots, \textstyle\sum_{S \subseteq S_{2^k}} c_S^{(i,0)}, \ldots, \sum_{S \subseteq S_{2^k}} c_S^{(i,n-1)} \Big), \end{aligned}$$

where $i = 1, 2$. Since C_l is a Euclidean self-dual code, for all $l = 1, \ldots, 2^k$, we have

$$\begin{aligned} \langle c_1, c_2 \rangle &= \textstyle\sum_{j=0}^{n-1} \sum_{S_l \in 2^{\Omega}} \sum_{S \subseteq S_l} c_S^{(1,j)} c_S^{(2,j)} v_S \\ &= 0. \end{aligned}$$

So, $C \subseteq C^{\perp}$.

Now, take any $c_3 \in C^{\perp}$. Since $\langle c_3, c \rangle = 0$ for all $c \in C$, we have

$$\sum_{j=0}^{n-1} \sum_{S \subseteq S_l} c_S^{(1,j)} c_S^{(2,j)} v_S = 0,$$

for all $S \in 2^{\Omega}$. Remember that C_l is a Euclidean self-dual code, for all $l = 1, 2, \ldots, 2^k$, which give

$$\sum_{j=0}^{n-1} \sum_{S \subseteq S_l} c_S^{(1,j)} c_S^{(2,j)} v_S = 0,$$

for all $S \in 2^{\Omega}$, and moreover $c_3 \in C$. So, $C^{\perp} \subseteq C$. Therefore, C is a Euclidean self-dual code. □

The following lemma gives MacWilliams identity for codes over the ring B_k.

Lemma 4.2. *The MacWilliams identity for Hamming weight enumerators for codes over B_k is :*

$$W_{C^{\perp}}(X, Y) = \frac{1}{|C|} W_C(X + (p^{2^k} - 1)Y, X - Y) \tag{2}$$

Proof. The identity follows from [7, Theorem 8.3] and Proposition 4.1. □

As we can see from Lemma 4.2, MacWilliams identity gives a transformation between polynomial representing a code and polynomial representing its corresponding dual code. We have to note that if C is an Euclidean self-dual code, then the weight enumerator of C is invariant under this transformation. The above transformation can be formulated as an action '$\circ$' by a matrix group G generated by matrices $T = \begin{pmatrix} \frac{1}{p^{2^{k-1}}} & \frac{p^{2^k}-1}{p^{2^{k-1}}} \\ \frac{1}{p^{2^{k-1}}} & \frac{-1}{p^{2^{k-1}}} \end{pmatrix}$ and $D = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$. The action of any $g = \begin{pmatrix} a_1 & a_2 \\ a_3 & a_4 \end{pmatrix} \in G$ to a polynomial $f(X, Y)$ is written as

$$g \circ f(X, Y) = f(a_1 X + a_2 Y, a_3 X + a_4 Y).$$

Note that the matrix T is derived from the identity in Lemma 4.2 and the matrix D is derived from the condition that n is always even. Also, it is easy to see that $G = \{I, D, T, -T\}$. Formally, we have the following result.

Lemma 4.3. *If $W_C(X,Y)$ is a Hamming weight enumerator for an Euclidean self-dual code C over B_k, then $W_C(X,Y)$ is invariant under the action of G.*

Let R_G be a set of all polynomials in two variables which are invariant under the action $\circ$ of G. We can easily prove that R_G is a ring, and by the above Lemma we can see that every Hamming weight enumerator of Euclidean self-dual codes must be inside R_G. This ring R_G called *invariant ring* for Euclidean self-dual codes over B_k. The following theorem gives generators for R_G.

Theorem 4.4. *Invariant ring of G is generated by*

$$W_{C_0}(x,y) = x^2 + (p^{2^k} - 1)y^2$$

and

$$\tilde{f}(x,y) = \frac{1}{4}\left(\frac{2p^{2^{k-1}} + 2}{p^{2^k}}x^2 + \frac{4\left(p^{2^k} - 1\right)}{p^{2^{k-1}}}xy + \frac{2(p^{2^k} - 1)^2}{p^{2^{k-1}}}y^2\right).$$

Proof. Consider the Molien series,

$$\begin{aligned} \Phi(\lambda) &= \tfrac{1}{|G|}\textstyle\sum_{A\in G} \tfrac{1}{\det(I-\lambda A)} \\ &= \tfrac{1}{4}\left(\tfrac{1}{(1+\lambda)^2} + \tfrac{1}{(1-\lambda)^2} + \tfrac{2}{(1-\lambda^2)}\right) \\ &= \tfrac{1}{(1-\lambda^2)^2} \\ &= 1 + 2\lambda^2 + 3\lambda^4 + 4\lambda^6 + 5\lambda^8 + \cdots + n\lambda^{2(n-1)} + \ldots \end{aligned}$$

we can see that, the invariant ring generated by two invariants of degree 2. Consider the weight enumerator for self-dual code

$$C_0 = \{cc | \forall c \in A_k\}$$

i.e. $W_{C_0}(x,y) = x^2 + (p^{2^k} - 1)y^2$. This weight enumerator is of degree 2 and invariant under the action of G. So, this weight enumerator is one of the generator. We use averaging method to find the other one. Let $f(x) = x^2$, then by averaging method, we have

$$\tilde{f}(x,y) = \frac{1}{4}\left(\frac{2p^{2^{k-1}} + 2}{p^{2^k}}x^2 + \frac{4\left(p^{2^k} - 1\right)}{p^{2^{k-1}}}xy + \frac{2(p^{2^k} - 1)^2}{p^{2^{k-1}}}y^2\right)$$

$\tilde{f}(x,y)$ are algebraically independent. □

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