

The Generalized Reed-Muller codes in a modular group algebra

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Article**

Abstract

We study some properties of the modular group algebra of the additive group of a Galois ring over a finite field. A description of the Generalized Reed-Muller codes in this group algebra is presented.

Keywords: Generalized Reed-Muller codes; group algebra; Galois ring; Jennings basis

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1 Introduction

It is well known that the Reed-Muller codes of length p^m over the prime field $\mathbb{F}_p$ are the radical powers of the modular group algebra $\mathbb{F}_p[\mathbb{F}_{p^m}]$ ([3],[4]).

In general, this property is no longer true for the Generalized Reed-Muller (GRM) codes over a non prime field $\mathbb{F}_{p^r}$ ($r > 1$). Let M be the radical of the modular group algebra $\mathbb{F}_{p^r}[G]$ where G is the additive group of the Galois ring $GR(p^r, m)$ of characteristic p^r and of rank m . Since $\mathbb{F}_{p^r}[G]$ is isomorphic to $\mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}]/(X_0^{p^r} - 1, \dots, X_{m-1}^{p^r} - 1)$ (see Proposition 3.7), then as shown in [1], except for M^0 , M and $M^{m(p^r-1)}$, none of the radical powers of $\mathbb{F}_{p^r}[G]$ is a GRM code over the non prime field $\mathbb{F}_{p^r}$.

Many authors have described the GRM codes in group algebras, especially in the group algebra $\mathbb{F}_{p^r}[H]$ where H is an elementary abelian p -group or H is the additive group of an extension field of $\mathbb{F}_{p^r}$ ([4],[5],[9]).

We give a description of the GRM codes over an arbitrary finite field $\mathbb{F}_{p^r}$ in the group algebra $\mathbb{F}_{p^r}[G]$ where G is the additive group of the Galois ring $GR(p^r, m)$. The main theorem is Theorem 3.4.

2 Preliminaries

2.1 Galois ring

Let us start with some basic properties of Galois rings (see [10]).

Set $\mathbb{Z}_{p^r} := \mathbb{Z}/p^r\mathbb{Z}$ and let $h(X) \in \mathbb{Z}_{p^r}[X]$ be a monic basic irreducible polynomial of degree m . Such a polynomial always exists by Hensel's Lemma. The Galois ring of characteristic p^r and of rank m , denoted by $GR(p^r, m)$, is defined as the quotient ring

$$\mathbb{Z}_{p^r}[X]/(h(X)). \quad (2.1)$$

In particular, $GR(p^r, 1) = \mathbb{Z}_{p^r}$ and $GR(p^1, m) = \mathbb{F}_{p^m}$.

$GR(p^r, m)$ is a local ring with maximal ideal $pGR(p^r, m)$ and residue field

$$GR(p^r, m)/pGR(p^r, m) \cong \mathbb{F}_{p^m}.$$

The Galois ring $GR(p^r, m)$ is a finite chain ring; all the ideals of $GR(p^r, m)$ are ordered as follows:

$$\{0\} = p^r GR(p^r, m) \subset p^{r-1} GR(p^r, m) \subset \dots \subset p GR(p^r, m) \subset GR(p^r, m).$$

Each element $v \in GR(p^r, m)$ can be expressed as $v = p^t u$ where u is an invertible element in $GR(p^r, m)$ and in this expression t is unique up to modulo p^{r-t} .

Finally, we recall that if m_1 is a positive integer such that $m_1 \mid m$, then $GR(p^r, m_1)$ is a subring of $GR(p^r, m)$. Conversely, any subring of $GR(p^r, m)$ is of the form $GR(p^r, m_1)$ for some $m_1 \mid m$.

2.2 Group algebra of an elementary abelian p-group

We recall in this subsection some properties of the group algebra $\mathbb{F}_{p^r}[\mathbb{F}_{p^m}]$ treated in [2]. Let $F := \mathbb{F}_{p^r}$ be any subfield of $\mathbb{F}_{p^m}$. Set G equal to the additive group of the finite field $\mathbb{F}_{p^m}$. Thus G can be viewed as an elementary abelian p -group of order p^m . Set

$$R = F[G]$$

the group algebra of G over the field F . Using polynomial notation, an element of R , which is a function from G to F , is a formal sum $\sum_{g \in G} a_g X^g$ where the coefficient a_g is simply the value of the function at the group element g .

The operations in the group algebra R are defined as follows:

$$\begin{aligned} \sum_{g \in G} a_g X^g + \sum_{g \in G} b_g X^g &= \sum_{g \in G} (a_g + b_g) X^g; \\ \left(\sum_{g \in G} a_g X^g \right) \left(\sum_{g \in G} b_g X^g \right) &= \sum_{g, h \in G} a_g b_h X^{g+h} = \sum_{k \in G} \left(\sum_{h \in G} a_{k-h} b_h \right) X^k; \end{aligned}$$

and, for $c \in F$,

$$c \left(\sum_{g \in G} a_g X^g \right) = \sum_{g \in G} (c a_g) X^g.$$

X^0 is the multiplicative identity of the group algebra R ; i.e. $X^0 a = a$ for every $a \in R$. We will simply denote it by 1.

The augmentation map

$$\begin{aligned} \phi: R &\longrightarrow F \\ \sum_{g \in G} a_g X^g &\longmapsto \sum_{g \in G} a_g \end{aligned} \quad (2.2)$$

is an algebra homomorphism.
The kernel of ϕ is denoted by

$$M = \left\{ \sum_{g \in G} a_g X^g \in R \mid \sum_{g \in G} a_g = 0 \right\}. \quad (2.3)$$

Thus, M is an ideal of R .

Since G is an elementary abelian p -group and the coefficients are in a field of characteristic p , then we have

$$\left(\sum_{g \in G} a_g X^g \right)^p = \sum_{g \in G} (a_g)^p X^{pg} = \sum_{g \in G} (a_g)^p X^0 = \left(\sum_{g \in G} a_g \right)^p X^0. \quad (2.4)$$

Proposition 2.1. *R is a local group algebra with unique maximal ideal $M = \text{Rad}(R) = \{a \in R \mid a^p = 0\}$.*

Remark 2.1. Let p be a prime number. Then

1. $(-1)^{p-1} = 1 \pmod{p}$.
2. $\binom{p-1}{i} = (-1)^i \pmod{p}$ for all $i = 0, 1, \dots, p-1$.

Proposition 2.2. *Provided $g \neq 0$, we have*

$$(X^g - 1)^{p-1} = \sum_{i=0}^{p-1} X^{ig}$$

Remark 2.2. Let U be a non-empty subset of G . Then

$$\prod_{g \in U} (X^g - 1)^{p-1} = \begin{cases} \sum_{g \in \langle U \rangle} X^g & \text{if } U \text{ is a linearly independent set} \\ 0 & \text{otherwise} \end{cases}$$

where $\langle U \rangle$ is the subspace spanned by U .

Let S be a subset of $R = F[G]$. The annihilator of S is defined by

$$\text{Ann}(S) := \{a \in R \mid as = 0 \text{ for all } s \in S\}.$$

Theorem 2.1. *Let G be an elementary abelian p -group of order p^m , F a field of characteristic p and $R = F[G]$.*

1. *For any basis $\{g_0, \dots, g_{m-1}\}$ of G , the p^m elements $\prod_{\nu=0}^{m-1} (X^{g_\nu} - 1)^{e_\nu}$ where $0 \leq e_\nu < p$ form a linear basis for R .*
2. *Moreover, $\{\prod_{\nu=0}^{m-1} (X^{g_\nu} - 1)^{e_\nu} \mid \sum_{\nu=0}^{m-1} e_\nu \geq t, 0 \leq e_\nu < p\}$ form a linear basis of M^t , where M is the radical of R .*
3. $\text{Ann}(M^t) = m^{m(p-1)+1-t}$.

Definition 2.1. The basis for $F[G]$ given in theorem 2.1. is called a Jennings basis of the group algebra.

3 Main Results

3.1 Group algebra of the additive group of a Galois ring

In this subsection, we give some natural generalizations of the properties of the group algebra $\mathbb{F}_{p^r}[\mathbb{F}_{p^m}]$ formulated in subsection 2.2.

Let F be the field $\mathbb{F}_{p^r}$ of p^r elements where p is a prime number and $r \geq 1$ is an integer. Set G equal to the additive group of the Galois ring $GR(p^r, m)$. Set

$$R = F[G] = \left\{ \sum_{g \in G} a_g X^g \mid a_g \in F \right\} \quad (3.1)$$

the group algebra of G over the field F . The operations in R are defined as in subsection 2.2.

We consider the ideal $M := \left\{ \sum_{g \in G} a_g X^g \in R \mid \sum_{g \in G} a_g = 0 \right\}$ of R .

Since G is of characteristic p^r and the coefficients are in the field of p^r elements, we have by the Freshmen identity

$$\left(\sum_{g \in G} a_g X^g \right)^{p^r} = \sum_{g \in G} (a_g)^{p^r} X^{p^r g} = \sum_{g \in G} a_g X^0 = \left(\sum_{g \in G} a_g \right) X^0. \quad (3.2)$$

Proposition 3.1. *R is a local group algebra with unique maximal ideal*

$$M = \text{Rad}(R) = \left\{ a \in R \mid a^{p^r} = 0 \right\}.$$

Proof. The relation (3.2) shows that $\left(\sum_{g \in G} a_g X^g \right)^{p^r}$ is zero if and only if $\sum_{g \in G} a_g = 0$. Thus, M is the radical of R .

Moreover, it shows also that every element of R that is not in M is a unit of R and it follows that M is the unique maximal ideal of R . $\square$

Remark 3.1. The set $\{X^g \mid g \in G\}$ is a linear basis of R considered as a vector space over F .

Proposition 3.2. *The ideal M is generated linearly over the field F by the elements $X^g - 1$ where $g \in G - \{0\}$.*

Proof. Each element $X^g - 1$ is in M . Conversely, let $\sum_{g \in G} a_g X^g \in M$, i.e. $\sum_{g \in G} a_g = 0$. We have

$$\begin{aligned} \sum_{g \in G} a_g X^g &= \sum_{g \in G} a_g [(X^g - 1) + 1] \\ &= \sum_{g \in G} [a_g (X^g - 1) + a_g 1] = \sum_{g \in G} a_g (X^g - 1) + \sum_{g \in G} a_g 1 \\ &= \sum_{g \in G} a_g (X^g - 1) + \left(\sum_{g \in G} a_g \right) 1 = \sum_{g \in G} a_g (X^g - 1) \\ &= \sum_{g \in G - \{0\}} a_g (X^g - 1). \end{aligned}$$

$\square$

Lemma 3.1. *Let p be a prime number and $r \geq 1$ an integer. Then*

1. $(-1)^{p^r-1} = 1 \pmod{p}$.
2. $\binom{p^r-1}{i} = (-1)^i \pmod{p}$ for all $i = 0, 1, \dots, p^r - 1$.

Proof. The first assertion is trivial. The second can be proved by induction on i . □

Proposition 3.3. *Provided $g \neq 0$, we have*

$$(X^g - 1)^{p^r-1} = \sum_{i=0}^{p^r-1} X^{ig}$$

Proof.

$$\begin{aligned} (X^g - 1)^{p^r-1} &= \sum_{i=0}^{p^r-1} \binom{p^r-1}{i} (-1)^{p^r-1-i} X^{ig} \\ &= \sum_{i=0}^{p^r-1} \binom{p^r-1}{i} (-1)^{p^r-1} (-1)^{-i} X^{ig} = \sum_{i=0}^{p^r-1} X^{ig} \end{aligned}$$

by Lemma 3.1. □

From (2.1), notice that

$$\begin{aligned} GR(p^r, m) &= \mathbb{Z}_{p^r}[X]/(h(X)) \\ &= \{i_0 + i_1\alpha + \dots + i_{m-1}\alpha^{m-1} \mid i_l \in \mathbb{Z}_{p^r}, 0 \leq l \leq m-1\} \end{aligned} \quad (3.3)$$

where $\alpha := X + (h(X))$.

Proposition 3.4. *We have*

$$(X^1 - 1)^{p^r-1} (X^\alpha - 1)^{p^r-1} \dots (X^{\alpha^{m-1}} - 1)^{p^r-1} = \sum_{g \in G} X^g$$

Proof. By Proposition 3.3, we have

$$\begin{aligned} &(X^1 - 1)^{p^r-1} (X^\alpha - 1)^{p^r-1} \dots (X^{\alpha^{m-1}} - 1)^{p^r-1} \\ &= \left(\sum_{i_0=0}^{p^r-1} X^{i_0 1} \right) \left(\sum_{i_1=0}^{p^r-1} X^{i_1 \alpha} \right) \dots \left(\sum_{i_{m-1}=0}^{p^r-1} X^{i_{m-1} \alpha^{m-1}} \right) \\ &= \sum_{0 \leq i_l \leq p^r-1, 0 \leq l \leq m-1} X^{i_0 1} X^{i_1 \alpha} \dots X^{i_{m-1} \alpha^{m-1}} \\ &= \sum_{0 \leq i_l \leq p^r-1, 0 \leq l \leq m-1} X^{i_0 1 + i_1 \alpha + \dots + i_{m-1} \alpha^{m-1}} = \sum_{g \in G} X^g \end{aligned}$$

□

Set

$$E := \{0, 1, \dots, p^{mr} - 1\}$$

the set of integers between 0 and $p^{mr} - 1$. Let i be an element of E and

$$i = i_0 + i_1 p^r + i_2 p^{2r} + \dots + i_{m-1} p^{(m-1)r}$$

where $0 \leq i_l \leq p^r - 1$ for all $l = 0, 1, \dots, m-1$ its p^r -adic expansion.

The p^r -weight of i is defined by

$$\omega_{p^r}(i) := \sum_{l=0}^{m-1} i_l. \quad (3.4)$$

Then, set

$$V_i := (X^1 - 1)^{i_0} (X^\alpha - 1)^{i_1} \dots (X^{\alpha^{m-1}} - 1)^{i_{m-1}} \quad (3.5)$$

and

$$B_t := \{V_i \mid i \in E, \omega_{p^r}(i) \geq t\} \quad (3.6)$$

for all t such that $0 \leq t \leq m(p^r - 1)$.

Proposition 3.5. B_0 is a linear basis of R over F .

Proof. We have $\text{card}(B_0) = p^{rm} = \dim_F(R)$.

Let us prove that B_0 is a linearly independant set over F . Consider the linear combination

$\sum_{\omega_{p^r}(i) \geq 0} \lambda_i V_i = 0$, where $\lambda_i \in F$ for all i . We have $\lambda_0 V_0 + \sum_{\omega_{p^r}(i) \geq 1} \lambda_i V_i = 0$ where $V_0 = 1$ is the identity element of R . Multiplying by $V_{p^{rm}-1}$, we get $\lambda_0 V_{p^{rm}-1} + \sum_{\omega_{p^r}(i) \geq 1} \lambda_i V_i V_{p^{rm}-1} = 0$.

Let $i = \sum_{l=0}^{m-1} i_l p^{lr}$ such that $\omega_{p^r}(i) \geq 1$. Then, there is an integer l ($0 \leq l \leq m-1$) such that $i_l \geq 1$. thus, $i_l + p^r - 1 \geq p^r$. Since $(X^g - 1)^{p^r} = 0$ for any g , we have $V_i V_{p^{rm}-1} = (X^1 - 1)^{i_0 + p^r - 1} \dots (X^{\alpha^l} - 1)^{i_l + p^r - 1} \dots (X^{\alpha^{m-1}} - 1)^{i_{m-1} + p^r - 1} = 0$. Then, $0 = \lambda_0 V_{p^{rm}-1} = \lambda_0 \sum_{g \in G} X^g$ by Proposition 3.4. Hence, $\lambda_0 = 0$.

Thus, we have $\sum_{\omega_{p^r}(i) \geq 1} \lambda_i V_i = 0$.

Let $i = \sum_{l=0}^{m-1} i_l p^{lr}$ such that $\omega_{p^r}(i) = 1$.

We have $\lambda_i V_i + \sum_{\omega_{p^r}(j) \geq 1, j \neq i} \lambda_j V_j = 0$. Multiplying by $V_{p^{rm}-1-i}$, we have

$$\lambda_i V_i V_{p^{rm}-1-i} + \sum_{\omega_{p^r}(j) \geq 1, j \neq i} \lambda_j V_j V_{p^{rm}-1-i} = 0.$$

Let $j = \sum_{l=0}^{m-1} j_l p^{lr} \neq i$ such that $\omega_{p^r}(j) \geq 1 = \omega_{p^r}(i)$. Then, there is an integer l ($0 \leq l \leq m-1$) such that $j_l > i_l$, and hence $j_l \geq i_l + 1$ and $j_l + p^r - 1 - i_l \geq (i_l + 1) + p^r - 1 - i_l = p^r$. Since $(X^g - 1)^{p^r} = 0$ for any g , we have $V_j V_{p^{rm}-1-i} = (X^1 - 1)^{j_0 + p^r - 1 - i_0} \dots (X^{\alpha^l} - 1)^{j_l + p^r - 1 - i_l} \dots (X^{\alpha^{m-1}} - 1)^{j_{m-1} + p^r - 1 - i_{m-1}} = 0$.

Consequently, $0 = \lambda_i V_i V_{p^{rm}-1-i} = \lambda_i \sum_{g \in G} X^g$.

Hence $\lambda_i = 0$.

Continuing in this way, we have

$\lambda_i = 0$ for all i such that $\omega_{p^r}(i) = 1$, and

$\lambda_i = 0$ for all i such that $\omega_{p^r}(i) = 2, 3, \dots, m(p^r - 1)$. □

Corollary 3.2. B_1 is a linear basis of M over F .

Proof. Since $B_1 \subset B_0$, then B_1 is a linearly independant set of R over F . And since $V_i \in M$ for all i such that $\omega_{p^r}(i) \geq 1$, $B_1 \subseteq M$. Moreover, we have $\dim_F(M) = p^{rm} - 1 = \text{card}(B_1)$. □

Corollary 3.3. B_t is a linear basis of M^t over F where $1 \leq t \leq m(p^r - 1)$.

Proof. Since $B_t \subset B_0$, B_t is a linearly independant set of R over F . M^t is generated as ideal by the set $\{a_1 a_2 \dots a_t \mid a_i \in M, 1 \leq i \leq t\}$. Consider a product $a_1 a_2 \dots a_t$ where $a_i \in M$ for all i ($1 \leq i \leq t$). Since M is linearly generated by B_1 over F , then we have $a_i = \sum_{j=1}^{p^{rm}-1} \lambda_{i,j} V_j$, where $\lambda_{i,j} \in F$ for all i and j . Therefore, $a_1 a_2 \dots a_t = \prod_{i=1}^t (\sum_{j=1}^{p^{rm}-1} \lambda_{i,j} V_j) = \sum_{\omega_{p^r}(j) \geq t} \beta_j V_j \in B_t$ where $\beta_j \in F$. And it is clear that a finite sum of such products is a linear combination of the elements of B_t with coefficients in F . Thus, M^t is generated by B_t over F . □

Remark 3.2. The index of nilpotency of the radical M is $1 + m(p^r - 1)$. And we have the following sequence of ideals:

$$\{0\} = M^{1+m(p^r-1)} \subset M^{m(p^r-1)} \subset \dots \subset M^2 \subset M \subset R.$$

Proposition 3.6. $\text{Ann}(M^t) = M^{1+m(p^r-1)-t}$ where $1 \leq t \leq m(p^r - 1)$.

Proof. Let t be an integer such that $1 \leq t \leq m(p^r - 1)$. By Corollary 3.3, (3.6), (3.5) and (3.3), $B_t := \{V_i \mid i \in E, \omega_{p^r}(i) \geq t\}$ is a linear basis of M^t over F where $V_i := (X^1 - 1)^{i_0} (X^\alpha - 1)^{i_1} \dots (X^{\alpha^{m-1}} - 1)^{i_{m-1}}$ and $i = i_0 + i_1 p^r + \dots + i_{m-1} p^{(m-1)r}$ ($0 \leq i_l \leq p^r - 1, \forall l$).
 By definition, $\text{Ann}(M^t) := \{a \in R \mid as = 0 \text{ for all } s \in M^t\}$.
 Since the index of nilpotency of M is $1 + m(p^r - 1)$, then we have $\text{Ann}(M^t) \supseteq M^{1+m(p^r-1)-t}$.
 Let $a \in \text{Ann}(M^t)$. Since $a \in R$, we have $a = \sum_{\omega_{p^r}(i) \geq 0} \lambda_i V_i$ where $\lambda_i \in F$ for all i .
 Let i such that $\omega_{p^r}(i) = m(p^r - 1)$. Thus, $i = p^{rm} - 1$.
 Since $V_{p^{rm}-1} \in M^{m(p^r-1)} \subseteq M^t$, then $aV_{p^{rm}-1} = \lambda_0 V_{p^{rm}-1} = \lambda_0 \sum_{g \in G} X^g = 0$. Hence, $\lambda_0 = 0$.
 Let $i \in E$ such that $\omega_{p^r}(i) = m(p^r - 1) - 1$.
 Since $V_i \in M^{m(p^r-1)-1} \subseteq M^t$, then $aV_i = \lambda_{\bar{i}} \sum_{g \in G} X^g = 0$ where $\bar{i} = (p^r - 1 - i_0) + (p^r - 1 - i_1)p^r + \dots + (p^r - 1 - i_{m-1})p^{(m-1)r}$. Hence $\lambda_{\bar{i}} = 0$. We have $\omega_{p^r}(\bar{i}) = m(p^r - 1) - \omega_{p^r}(i) = 1$.
 Therefore, $\lambda_{\bar{i}} = 0$ for all i such that $\omega_{p^r}(i) = m(p^r - 1) - 1$.
 Let i such that $\omega_{p^r}(i) = m(p^r - 1) - 2$.
 Since $V_i \in M^{m(p^r-1)-2} \subseteq M^t$, then $aV_i = \lambda_{\bar{i}} \sum_{g \in G} X^g = 0$. Hence $\lambda_{\bar{i}} = 0$. It follows that $\lambda_{\bar{i}} = 0$ for all i such that $\omega_{p^r}(i) = m(p^r - 1) - 2$, i.e $\omega_{p^r}(\bar{i}) = 2$. Continuing in this way, finally let i such that $\omega_{p^r}(i) = t$.
 Since $V_i \in M^t$, then $aV_i = \lambda_{\bar{i}} \sum_{g \in G} X^g = 0$. Hence $\lambda_{\bar{i}} = 0$ with $\omega_{p^r}(\bar{i}) = m(p^r - 1) - t$.
 It follows that $\lambda_{\bar{i}} = 0$ for all i such that $\omega_{p^r}(i) = t$, i.e $\omega_{p^r}(\bar{i}) = m(p^r - 1) - t$.
 Then $a \in M^{m(p^r-1)-t+1}$. □

3.2 Isomorphism

We give here an isomorphism between $\mathbb{F}_{p^r}[G]$ and $\mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}]/(X_0^{p^r} - 1, \dots, X_{m-1}^{p^r} - 1)$ where G is the additive group of the Galois ring $GR(p^r, m)$.

Recall that $\mathbb{F}_{p^r}[G] = \left\{ \sum_{g \in G} a_g X^g \mid a_g \in \mathbb{F}_{p^r} \right\}$.

Proposition 3.7. *The group algebra $\mathbb{F}_{p^r}[G]$ is isomorphic to the quotient ring*

$\mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}]/(X_0^{p^r} - 1, \dots, X_{m-1}^{p^r} - 1)$.

Proof. Consider the mapping

$$\begin{aligned} \psi : \quad \mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}] &\longrightarrow \mathbb{F}_{p^r}[G] \\ X_i &\longmapsto X^{\alpha^i} \end{aligned} \tag{3.7}$$

where α is defined in (3.3).

It is clear that the ideal $\langle X_i^{p^r} - 1 \mid 0 \leq i \leq m-1 \rangle \subseteq \ker \psi$.

Conversely, let $a(X_0, \dots, X_{m-1}) \in \ker \psi$. By using the division algorithm in $\mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}]$ (see [6]) with the lexicographic order such that $X_0 > X_1 > \dots > X_{m-1}$, let us divide $a(X_0, \dots, X_{m-1})$ by $\{X_0^{p^r} - 1, \dots, X_{m-1}^{p^r} - 1\}$. We have

$$a(X_0, \dots, X_{m-1}) = b_0(X_0^{p^r} - 1) + \dots + b_{m-1}(X_{m-1}^{p^r} - 1) + g(X_0, \dots, X_{m-1})$$

where $b_i \in \mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}]$ for all i and

$$g(X_0, \dots, X_{m-1}) = \sum_{0 \leq i_k \leq p^r-1} g_{i_0, \dots, i_{m-1}} X_0^{i_0} \dots X_{m-1}^{i_{m-1}}$$

with $g_{i_0, \dots, i_{m-1}} \in \mathbb{F}_{p^r}$.

Then

$$\begin{aligned} \psi(a(X_0, \dots, X_{m-1})) &= \psi(g(X_0, \dots, X_{m-1})) \\ &= \sum_{0 \leq i_k \leq p^r-1} g_{i_0, \dots, i_{m-1}} X^{i_0 \alpha + i_1 \alpha^2 + \dots + i_{m-1} \alpha^{m-1}} = 0. \end{aligned}$$

By Remark 3.1, $g_{i_0, \dots, i_{m-1}} = 0$ for all i_k such that $0 \leq i_k \leq p^r - 1$ ($0 \leq k \leq m-1$). This implies that $g(X_0, \dots, X_{m-1}) = 0$ and thus $a(X_0, \dots, X_{m-1}) \in \langle X_i^{p^r} - 1 \mid 0 \leq i \leq m-1 \rangle$. □

3.3 Description of the GRM codes

We describe the GRM codes in $\mathbb{F}_{p^r}[GR(p^r, m)]$.

Set $n := q^m - 1$ where $q = p^r$, p is a prime number and r, m are integers ≥ 1 . Let $A = \mathbb{F}_q[Z]/(Z^n - 1)$. We have

$A = \{a_0 + a_1z + \dots + a_{n-1}z^{n-1} \mid a_i \in \mathbb{F}_q\}$ where $z = Z + (Z^n - 1)$.

The shortened Generalized Reed-Muller code of length n and of order ν ($0 \leq \nu < m(q-1)$) over $\mathbb{F}_q$ denoted by $HC_\nu(m, q)$ is the ideal of A generated by

$$f_\nu(z) = \prod_{0 < \omega_q(i) \leq m(q-1) - \nu - 1} (z - \gamma^i) \quad (3.8)$$

where γ is a primitive element of the finite field $\mathbb{F}_{q^m}$ ([8],[11]), and $\omega_q(i)$ is defined in (3.4).

Recall that G is the additive group of the Galois ring $GR(p^r, m)$.

Let us order the elements of $G = \{0, g_0, g_1, \dots, g_{q^m-2}\}$ as follows:

$$0 < g_0 < g_1 < \dots < g_{q^m-2}.$$

Thus, we have the following identification:

$$\sum_{g \in G} a_g X^g \in \mathbb{F}_q[G] \longleftrightarrow (a_g)_{g \in G} \in (\mathbb{F}_q)^{q^m}.$$

Let us order the monomials $\{X^g \mid g \in G\}$ such that

$$X^{g_i} < X^{g_j} \text{ if and only if } g_i < g_j.$$

For $a = \sum_{g \in G} a_g X^g \in \mathbb{F}_q[G]$, set $\text{md}(a) := \max \{g \in G \mid a_g \neq 0\}$.

We define the leading term of a by $\text{LT}(a) := a_{\text{md}(a)} X^{\text{md}(a)}$.

Consider the linear transformation

$$\begin{aligned} \varphi : A &\longrightarrow \mathbb{F}_q[G] \\ a_0 + a_1z + \dots + a_{n-1}z^{n-1} &\longmapsto \left(-\sum_{i=0}^{n-1} a_i\right)X^0 + \sum_{i=0}^{n-1} a_i X^{g_i} \end{aligned} \quad (3.9)$$

The Generalized Reed-Muller codes of length q^m and of order ν ($0 \leq \nu < m(q-1)$) over $\mathbb{F}_q$ is defined by

$$C_\nu(m, q) = \varphi(HC_\nu(m, q)).$$

We have the following sequence:

$$\{0\} \subset C_0(m, q) \subset C_1(m, q) \subset \dots \subset C_{m(q-1)-1}(m, q) \subset \mathbb{F}_q[G] \quad (3.10)$$

The morphism φ sets up a one to one correspondance between $HC_\nu(m, q)$ and $C_\nu(m, q)$, thus

$$\dim_{\mathbb{F}_q}(C_\nu(m, q)) = \dim_{\mathbb{F}_q}(HC_\nu(m, q)). \quad (3.11)$$

Since $HC_\nu(m, q)$ is the cyclic code of length $q^m - 1$ over $\mathbb{F}_q$ generated by $f_\nu(z)$, then

$$\dim_{\mathbb{F}_q}(HC_\nu(m, q)) = q^m - 1 - \deg(f_\nu(z)). \quad (3.12)$$

Set

$$\theta_\nu^j = \varphi(z^j f_\nu(z)) \quad (3.13)$$

where $0 \leq \nu \leq m(q-1) - 1$.

By (3.9), we have

$$\text{LT}(\theta_\nu^j) = X^{g_{\deg(z^j f_\nu(z))}}. \quad (3.14)$$

Set

$$N(t) := \text{card}(\{k \in [0, q^m - 1] \mid \omega_q(k) = t\})$$

where $[0, q^m - 1]$ is the set of integers between 0 and $q^m - 1$.

Theorem 3.4. *We have*

1. $\{\theta_0^0\}$ is a linear basis of $C_0(m, q)$.
2. The set $K_\nu := \{\theta_0^0\} \cup \{\theta_i^j \mid 1 \leq i \leq \nu, 0 \leq j \leq N(m(q-1)-i)-1\}$ forms a linear basis for $C_\nu(m, q)$ where $1 \leq \nu \leq m(q-1)-1$.

Proof. Let ν be an integer such that $0 \leq \nu \leq m(q-1)-1$.

We have $\theta_0^0 = \varphi(f_0(z)) = \varphi(\prod_{i=1}^{q^m-2} (z - \gamma^i)) = \varphi(1 + z + z^2 + \dots + z^{q^m-2}) = \sum_{g \in G} X^g$.

Since $\dim_{\mathbb{F}_q}(C_0(m, q)) = \dim_{\mathbb{F}_q}(HC_0(m, q)) = q^m - 1 - (q^m - 2) = 1$, then the first assertion is proved.

For the integer ν such that $1 \leq \nu \leq m(q-1)-1$, $f_\nu(z)$ is a monic polynomial and by (3.8), $\deg(f_\nu(z)) = \sum_{i=1}^{m(q-1)-\nu-1} N(t)$.

Thus, $\deg(z^j f_\nu(z)) = j + \sum_{i=1}^{m(q-1)-\nu-1} N(t)$ for $1 \leq j \leq N(m(q-1)-\nu)-1$.

By (3.14), for the elements θ_i^j in K_ν , we have

$$\text{LT}(\theta_\lambda^j) < \text{LT}(\theta_\mu^k) \text{ if } \lambda > \mu, \text{ and } \text{LT}(\theta_\mu^j) < \text{LT}(\theta_\mu^k) \text{ if } j < k.$$

This implies that the elements of K_ν are linearly independant. And by (3.10), they are elements of $C_\nu(m, q)$.

It is clear that $\text{card}(K_\nu) = 1 + \sum_{i=1}^\nu N(m(q-1)-i)$.

And since

$$\begin{aligned} N(m(q-1)-i) &= \deg(f_{i-1}(z)) - \deg(f_i(z)) \\ &= (q^m - 1 - \deg(f_i(z))) - (q^m - 1 - \deg(f_{i-1}(z))) \\ &= \dim_{\mathbb{F}_q}(HC_i(m, q)) - \dim_{\mathbb{F}_q}(HC_{i-1}(m, q)) \\ &= \dim_{\mathbb{F}_q}(C_i(m, q)) - \dim_{\mathbb{F}_q}(C_{i-1}(m, q)), \end{aligned}$$

then $\text{card}(K_\nu) = \dim_{\mathbb{F}_q}(C_\nu(m, q))$. □

For $m = 1$, we consider the case of the Reed-Solomon codes $C_\nu(1, q)$ of length q and of order ν over $\mathbb{F}_q$.

Corollary 3.5. $C_\nu(1, q)$ is linearly generated over $\mathbb{F}_q$ by the set $\{\theta_i^0 \mid 0 \leq i \leq \nu\}$ where $0 \leq \nu \leq q-2$.

3.4 Example

We consider the GRM codes of length 16 over $\mathbb{F}_4$ in $\mathbb{F}_4[GR(2^2, 2)]$. Let $G = \{0, g_0, g_1, \dots, g_{14}\}$ be the additive group of the Galois ring $GR(2^2, 2)$ with $0 < g_0 < g_1 < \dots < g_{14}$.

$C_0(2, 4)$:

We have $C_0(2, 4) = \varphi(HC_0(2, 4))$ with $HC_0(2, 4) = (f_0(z))$ and

$$f_0(z) = \prod_{0 < \omega_4(i) \leq 5} (z - \gamma^i) = \prod_{i=1}^{14} (z - \gamma^i) = 1 + z + z^2 + \dots + z^{14}$$

where γ is a primitive element of $\mathbb{F}_{16}$. We have $\theta_0^0 = \varphi(f_0(z)) = X^0 + X^{g_0} + X^{g_1} + \dots + X^{g_{14}}$. Thus, $\text{LT}(\theta_0^0) = X^{g_{14}}$.

And by (3.11) and (3.12), we have

$$\dim_{\mathbb{F}_4}(C_0(2, 4)) = \dim_{\mathbb{F}_4}(HC_0(2, 4)) = 15 - \deg(f_0(z)) = 15 - 14 = 1.$$

Thus, $C_0(2, 4)$ is linearly generated over $\mathbb{F}_4$ by θ_0^0 .

$C_1(2, 4)$:

We have $C_1(2, 4) = \varphi(HC_1(2, 4))$ with $HC_1(2, 4) = (f_1(z))$ and

$$f_1(z) = \prod_{0 < \omega_4(i) \leq 4} (z - \gamma^i).$$

Consider $N(5) := \text{card}(\{k \in [0, 15] \mid \omega_4(k) = 5\}) = \text{card}(\{11, 14\}) = 2$.

We have $\deg(f_1(z)) = \deg(f_0(z)) - N(5) = 14 - 2 = 12$.

And by (3.11) and (3.12),

$$\dim_{\mathbb{F}_4}(C_1(2, 4)) = \dim_{\mathbb{F}_4}(HC_1(2, 4)) = 15 - \deg(f_1(z)) = 15 - 12 = 3.$$

On the other hand, by (3.14), we have $\text{LT}(\theta_1^0) = X^{g_{12}}$, $\text{LT}(\theta_1^1) = X^{g_{13}}$.

From (3.10), we have $C_0(2, 4) \subset C_1(2, 4)$. Thus, $\{\theta_0^0, \theta_1^0, \theta_1^1\} = K_1$ is a linearly independent set in $C_1(2, 4)$. Then it is a linear basis of $C_1(2, 4)$.

$C_2(2, 4)$:

We have $C_2(2, 4) = \varphi(HC_2(2, 4))$ with $HC_2(2, 4) = (f_2(z))$ and

$$f_2(z) = \prod_{0 < \omega_4(i) \leq 3} (z - \gamma^i).$$

Consider $N(4) := \text{card}(\{k \in [0, 15] \mid \omega_4(k) = 4\}) = \text{card}(\{7, 10, 13\}) = 3$.

We have $\deg(f_2(z)) = \deg(f_1(z)) - N(4) = 12 - 3 = 9$.

And by (3.11) and (3.12),

$$\dim_{\mathbb{F}_4}(C_2(2, 4)) = \dim_{\mathbb{F}_4}(HC_2(2, 4)) = 15 - \deg(f_2(z)) = 15 - 9 = 6.$$

On the other hand, by (3.14), we have $\text{LT}(\theta_2^0) = X^{g_9}$, $\text{LT}(\theta_2^1) = X^{g_{10}}$, $\text{LT}(\theta_2^2) = X^{g_{11}}$.

From (3.10), we have $C_0(2, 4) \subset C_1(2, 4) \subset C_2(2, 4)$. Thus, $\{\theta_0^0, \theta_1^0, \theta_1^1, \theta_2^0, \theta_2^1, \theta_2^2\} = K_2$ is a linearly independent set in $C_2(2, 4)$. Then it is a linear basis of $C_2(2, 4)$.

$C_3(2, 4)$:

We have $C_3(2, 4) = \varphi(HC_3(2, 4))$ with $HC_3(2, 4) = (f_3(z))$ and

$$f_3(z) = \prod_{0 < \omega_4(i) \leq 2} (z - \gamma^i).$$

Consider $N(3) := \text{card}(\{k \in [0, 15] \mid \omega_4(k) = 3\}) = \text{card}(\{3, 6, 9, 12\}) = 4$.

We have $\deg(f_3(z)) = \deg(f_2(z)) - N(3) = 9 - 4 = 5$.

And by (3.11) and (3.12),

$$\dim_{\mathbb{F}_4}(C_3(2, 4)) = \dim_{\mathbb{F}_4}(HC_3(2, 4)) = 15 - \deg(f_3(z)) = 15 - 5 = 10.$$

On the other hand, by (3.14), we have $\text{LT}(\theta_3^0) = X^{g_5}$, $\text{LT}(\theta_3^1) = X^{g_6}$, $\text{LT}(\theta_3^2) = X^{g_7}$, $\text{LT}(\theta_3^3) = X^{g_8}$.

From (3.10), we have $C_0(2, 4) \subset C_1(2, 4) \subset C_2(2, 4) \subset C_3(2, 4)$. Thus, $\{\theta_0^0, \theta_1^0, \theta_1^1, \theta_2^0, \theta_2^1, \theta_2^2, \theta_3^0, \theta_3^1, \theta_3^2, \theta_3^3\} = K_3$ is a linearly independent set in $C_3(2, 4)$. Then it is a linear basis of $C_3(2, 4)$.

$C_4(2, 4)$:

We have $C_4(2, 4) = \varphi(HC_4(2, 4))$ with $HC_4(2, 4) = (f_4(z))$ and

$$f_4(z) = \prod_{0 < \omega_4(i) \leq 1} (z - \gamma^i).$$

Consider $N(2) := \text{card}(\{k \in [0, 15] \mid \omega_4(k) = 2\}) = \text{card}(\{2, 5, 8\}) = 3$.

We have $\deg(f_4(z)) = \deg(f_3(z)) - N(2) = 5 - 3 = 2$.

And by (3.11) and (3.12),

$$\dim_{\mathbb{F}_4}(C_4(2, 4)) = \dim_{\mathbb{F}_4}(HC_4(2, 4)) = 15 - \deg(f_4(z)) = 15 - 2 = 13.$$

On the other hand, by (3.14), we have $\text{LT}(\theta_4^0) = X^{g_2}$, $\text{LT}(\theta_4^1) = X^{g_3}$, $\text{LT}(\theta_4^2) = X^{g_4}$.

From (3.10), we have $C_0(2, 4) \subset C_1(2, 4) \subset C_2(2, 4) \subset C_3(2, 4) \subset C_4(2, 4)$. Thus, $\{\theta_0^0, \theta_1^0, \theta_1^1, \theta_2^0, \theta_2^1, \theta_2^2, \theta_3^0, \theta_3^1, \theta_3^2, \theta_3^3, \theta_4^0, \theta_4^1, \theta_4^2\} = K_4$ is a linearly independent set in $C_4(2, 4)$. Then it is

a linear basis of $C_4(2, 4)$.

$C_5(2, 4)$:

We have $C_5(2, 4) = \varphi(HC_5(2, 4))$ with $HC_5(2, 4) = (f_5(z))$ and

$$f_5(z) = \prod_{0 < \omega_4(i) \leq 0} (z - \gamma^i) = 1.$$

Then $\deg(f_5(z)) = 0$.

And by (3.11) and (3.12),

$$\dim_{\mathbb{F}_4}(C_5(2, 4)) = \dim_{\mathbb{F}_4}(HC_5(2, 4)) = 15 - \deg(f_5(z)) = 15.$$

On the other hand, by (3.14), $LT(\theta_5^0) = X^{g_0}$, $LT(\theta_5^1) = X^{g_1}$.

From (3.10), we have $C_0(2, 4) \subset C_1(2, 4) \subset C_2(2, 4) \subset C_3(2, 4) \subset C_4(2, 4) \subset C_5(2, 4)$. Thus, $\{\theta_0^0, \theta_1^0, \theta_1^1, \theta_2^0, \theta_2^1, \theta_2^2, \theta_3^0, \theta_3^1, \theta_3^2, \theta_3^3, \theta_4^0, \theta_4^1, \theta_4^2, \theta_5^0, \theta_5^1\} = K_5$ is a linearly independent set in $C_5(2, 4)$. Then it is a linear basis of $C_5(2, 4)$.

4 CONCLUSIONS

- a In the subsection (2.1), we recall the definition and some properties of the Galois ring $GR(p^r, m)$.
- b In the subsection (2.2), we summarize some results on the group algebra $\mathbb{F}_{p^r}[\mathbb{F}_{p^m}]$ developed by Assmus and Key in [2]. In particular, some facts about a linear basis of the group algebra $\mathbb{F}_{p^r}[\mathbb{F}_{p^m}]$ called Jennings basis ([7]) are pointed out.
- c In the subsection (3.1), We give some generalizations of the properties of $\mathbb{F}_{p^r}[\mathbb{F}_{p^m}]$ presented in subsection (2.2) by considering the group algebra $\mathbb{F}_{p^r}[G]$ where G is the additive group of the Galois ring $GR(p^r, m)$.
- d In the subsection (3.2), we establish a natural isomorphism between $\mathbb{F}_{p^r}[G]$ and $\mathbb{F}_{p^r}[X_0, X_1, \dots, X_{m-1}]/(X_0^{p^r} - 1, \dots, X_{m-1}^{p^r} - 1)$.
- e In the subsection (3.3), we describe the GRM codes over a finite field $\mathbb{F}_{p^r}$ in $\mathbb{F}_{p^r}[G]$ by using the fact that GRM codes are extended cyclic codes.
- f In the subsection (3.4), an example is given.

A possible future work is to determine a new decoding algorithm according to this description of the GRM codes.

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