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Singleton Bounds for Codes over Finite Rings*

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Abstract. We introduce the Singleton bounds for codes over a finite commutative quasi-Frobenius ring.

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1. Introduction

Let R be a finite commutative quasi-Frobenius (QF) ring (see [1]), and let $V := R^n$ be the free module of rank n consisting of all n-tuples of elements of R. A *code* C of length n over R is an R-submodule of V. An element of C is called a *codeword* of C.

In this paper, we will use a general notion of weight, abstracted from the Hamming, the Lee and the Euclidean weights. For every $x = (x_1, \ldots, x_n) \in V$ and $r \in R$, the *complete weight* of x is defined by

$$n_r(x) := |\{i \mid x_i = r\}|.$$

To define a *general weight function* $w(x)$, let a_r, $(0 \neq) r \in R$, be positive real numbers, and set $a_0 = 0$. Set

$$w(x) := \sum_{r \in R} a_r n_r(x). \tag{1}$$

If we set $a_r = 1$, $(0 \neq)\forall r \in R$, then $w(x)$ is just the Hamming weight of x. For later use, we denote

$$A := \max\{a_r \mid r \in R\}. \tag{2}$$

For example, if $R = \mathbb{Z}_4 = \{0, 1, 2, 3\}$, then setting $a_1 = a_3 = 1$ and $a_2 = 2$ yields the Lee weight, while setting $a_1 = a_3 = 1$ and $a_2 = 4$ yields the Euclidean weight.

Put $N := \{1, 2, \ldots, n\}$. Define the *support* $\mathrm{supp}(x)$ of a vector $x = (x_1, \ldots, x_n) \in V$ by

$$\mathrm{supp}(x) := \{i \in N \mid x_i \neq 0\}.$$

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The *minimum weight* of a code C, denoted by d, is

$$d := \min\{w(x) \mid (0 \neq)x \in C\}.$$

We make the important (and elementary) observation that

$$w(x) \leq A|\text{supp}(x)|. \tag{3}$$

The *inner product* of vectors $x = (x_1, \ldots, x_n)$, $y = (y_1, \ldots, y_n) \in V$ is defined by

$$\langle x, y\rangle = x_1 y_1 + \cdots + x_n y_n.$$

The *dual code* of C is defined by

$$C^{\perp} := \{y \in V \mid \langle x, y\rangle = 0 \quad (\forall x \in C)\}.$$

The following proposition is well-known as the Singleton bound (see [4]).

Proposition 1 *Let C be a linear $[n, k, d]$-code over $GF(q)$, where d is the minimum Hamming weight of C. Then*,

$$d \leq n - k + 1.$$

The main purpose of this paper is to find a similar bound for the minimum weight of a general weight function $w(x)$ over R.

2. Singleton bound

For a submodule D of V and a subset $M \subseteq N = \{1, 2, \ldots, n\}$, let

$$D(M) := \{x \in D \mid \text{supp}(x) \subseteq M\},$$
$$D^* := \text{Hom}_R(D, R).$$

Clearly $D(M) = D \cap V(M)$ is a submodule of V, and $|V(M)| = |R|^{|M|}$. It is also the case that $|D| = |D^*|$ for any submodule of V. The following lemma is essential. (There is a similar result over $GF(q)$ in [6]).

Lemma 1 *Let C be a code of length n over R and $M \subseteq N$. Then there is an exact sequence of R-modules*:

$$0 \to C^{\perp}(M) \xrightarrow{\text{inc}} V(M) \xrightarrow{f} C^* \xrightarrow{\text{res}} C(N - M)^* \to 0,$$

where the maps inc, res *denote the inclusion map*, *restriction map*, *respectively*, *and the map f is defined by*

$$f : y \mapsto (\hat{y} : x \mapsto \langle x, y\rangle).$$

Proof: The exactness of the sequence at $C^{\perp}(M)$ and at $V(M)$ is clear. That the map res is surjective follows from R being an injective module over itself (the meaning of R being QF).

Clearly we note that $\mathrm{Im}\, f \subseteq \ker(\mathrm{res})$. Conversely, if we take any $\lambda \in \ker(\mathrm{res})$, then

$$\lambda(x) = 0 \quad (\forall x \in C(N - M)).$$

Note that $V \to C^*; v \mapsto \hat{v}$ is surjective, so there exists $y \in V$ with $\lambda = \hat{y}$. For any $x \in C(N - M)$, $\langle x, y\rangle = 0$, so that,

$$\begin{aligned} y &\in (C(N - M))^{\perp} = (C \cap V(N - M))^{\perp} \\ &= C^{\perp} + V(N - M)^{\perp} = C^{\perp} + V(M). \end{aligned}$$

Since $\hat{z} = 0$ for any $z \in C^{\perp}$, we have

$$\ker(\mathrm{res}) \subseteq \mathrm{Im}\, f.$$

Thus the sequence is also exact at C^*, and the lemma follows. □

We remark that we can prove the MacWilliams identity for codes over $\mathbb{Z}_4$ ([3]) by using Lemma 1 (there are similar results over $GF(q)$ in [5] and [6]).

Using the above lemma, we establish the Singleton bound for a general weight function over R.

Theorem 1 *Let C be a code of length n over a finite commutative QF ring R. Let $w(x)$ be a general weight function on C, as in* (1), *and with maximum a_r-value A, as in* (2). *Suppose the minimum weight of $w(x)$ on C is d. Then*

$$\left[\frac{d-1}{A}\right] \leq n - \log_{|R|} |C|,$$

where $[b]$ is the integer part of b.

Proof: By Lemma 1, we have

$$|C| \cdot |C^{\perp}(N - \tilde{M})| = |V(N - \tilde{M})| \cdot |C(\tilde{M})|,$$

where $\tilde{M} = N - M$. If we take a subset M of N with $|\tilde{M}| = [\frac{d-1}{A}]$, then $|C(\tilde{M})| = 1$ by (3). Since we always have $|C^{\perp}(N - \tilde{M})| \geq 1$, we see that

$$|C| \leq |V(N - \tilde{M})| = |R|^{|N - \tilde{M}|}.$$

Hence the theorem follows. □

3. An application to codes over $\mathbb{Z}_l$

The ring $R = \mathbb{Z}_l$ is a good example of a finite commutative QF ring. Let $k := [l/2]$, and regard $\mathbb{Z}_l$ as the set $\{0, \pm 1, \ldots, \pm k\}$ (with $k = -k$, when $l = 2k$ is even). On codes over $\mathbb{Z}_l$, there are three special weight functions:

1. the *Hamming weight*, where each $a_i = 1$, $i \neq 0$,
2. the *Lee weight*, where $a_i = |i|$, and
3. the *Euclidean weight*, where $a_i = |i|^2$.

Denote the minimum weight of a code C with respect to these three weights by d_H, d_L and d_E, respectively. It is clear that the maximum a_r-value A is 1, k and k^2, respectively. The next result follows immediately from Theorem 1.

Theorem 2 *Using the above notation for a code C of length n over $\mathbb{Z}_l$, there are the following bounds on minimum weights*:

$$d_H \le n - \log_l |C| + 1,$$
$$\left\lceil \frac{d_L - 1}{k} \right\rceil \le n - \log_l |C|,$$
$$\left\lceil \frac{d_E - 1}{k^2} \right\rceil \le n - \log_l |C|.$$

The Gray map $\phi : \mathbb{Z}_4 \to \mathbb{Z}_2^2$ is defined by $\phi(0) = 00$, $\phi(1) = 01$, $\phi(2) = 11$, and $\phi(3) = 10$. It is well-known that ϕ is a weight-preserving map from ($\mathbb{Z}_4^n$, Lee weight) to ($\mathbb{Z}_2^{2n}$, Hamming weight) (see [2]). Using the above theorem, we have the Singleton bound for certain binary nonlinear codes.

Corollary 1 *If a binary nonlinear $(2n, M, d)$-code B, where $M := |B|$ and d is the minimum Hamming weight of B, is the Gray map image of a code C of length n over $\mathbb{Z}_4$, then*

$$\left\lceil \frac{d - 1}{2} \right\rceil \le n - \log_4 M.$$

Proof: Since $M = |C|$ and d is also the minimum Lee weight of C, the corollary follows from Theorem 2. □

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