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Betti Numbers and Generalized Hamming Weights

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We can associate to each linear code \mathcal{C} defined over a finite field the matroid $M[H]$ of its parity check matrix H . For any matroid M one can define its generalized Hamming weights which are the same as those of the code \mathcal{C} . In [2] the authors show that the generalized Hamming weights of a matroid are determined by the \mathbb{N} -graded Betti numbers of the Stanley-Reisner ring of the simplicial complex whose faces are the independent set of M . In this talk we go a step further. Our practical results indicate that the generalized Hamming weights of a linear code \mathcal{C} can be obtained from the monomial ideal associated with a test-set for \mathcal{C} . Moreover, recall that in [3] we use the Gröbner representation of a linear code \mathcal{C} to provide a test-set for \mathcal{C} .

Our results are still a work in progress, but its applications to Coding Theory and Cryptography are of great value.

1 Notation and Prerequisites

We begin with an introduction of basic definitions and some known results. By \mathbb{N} , \mathbb{Z} , \mathbb{F}_q (where q is a primer power) we denote the set of positive integers, the set of integers and the finite field with q elements, respectively.

Definition 1 *A matroid M is a pair (E, I) consisting of a finite set E called ground set and a collection I of subsets of E called independent sets, satisfying the following conditions:*

1. *The empty set is independent, i.e. $\emptyset \in I$*
2. *If $A \in I$ and $B \subset A$, then $B \in I$*
3. *If $A, B \in I$ and $|A| < |B|$, then there exists $e \in B \setminus A$ such that $A \cup \{e\} \in I$*

Let $M = (E, I)$ be a matroid. A maximal independent subset of E is called a *basis* of M . A direct consequence of the previous definition is that all bases of M have the same cardinality. Thus, we define the *rank* of the matroid M as the cardinality of any basis of M , denoted by $\text{rank}(M)$. A subset E that does not belong

to I is called *dependent set*. Minimal dependent subsets of E are known as *circuits* of M . A set is said to be a *cycle* if it is a disjoint union of circuits. The collection of cycles of M is denoted by $\mathcal{C}(M)$. For all $\sigma \in E$, the *nullity function* of σ is given by $n(\sigma) := |\sigma| - \text{rank}(M_\sigma)$ with $\text{rank}(M_\sigma) = \max\{|A| \mid A \in I \text{ and } A \subset \sigma\}$, i.e. the restriction of $\text{rank}(M)$ to the subsets of σ .

Let us consider an $m \times n$ matrix A in \mathbb{F}_q whose columns are indexed by $E = \{1, \dots, n\}$ and take I to be the collection of subsets J of E for which the column vectors $\{A_j \mid j \in J\}$ are linearly independent over \mathbb{F}_q . Then (E, I) defines a matroid denoted by $M[A]$. A matroid $M = (E, I)$ is \mathbb{F}_q -representable if it is isomorphic to $M[A]$ for some $A \in \mathbb{F}_q^{m \times n}$. Then the matrix A is called the representation matrix of M . The following well known results describes the relation between the collection of all cycles of a matroid M and its representation matrix.

Proposition 1 *Let $M = (E, I)$ be a \mathbb{F}_q -representable matroid. Then $\mathcal{C}(M)$ is the null space of a representation matrix of M . Furthermore, the dimension of $\mathcal{C}(M)$ is $|E| - \text{rank}(M)$.*

Let Δ be a simplicial complex on the finite ground set E . Let \mathbb{K} be a field and let \mathbf{x} be the indeterminates $\mathbf{x} = \{x_e \mid e \in E\}$. The *Stanley-Reisner ideal* of Δ is, by definition,

$$I_\Delta = \langle \mathbf{x}^\sigma \mid \sigma \notin \Delta \rangle$$

The *Stanley-Reisner ring* of I_Δ , denoted by R_Δ , is defined to be the quotient ring $R_\Delta = \frac{\mathbb{K}[\mathbf{x}]}{I_\Delta}$. This ring has a minimal free resolution as \mathbb{N}^E -graded module:

$$0 \longleftarrow R_\Delta \longleftarrow P_0 \longleftarrow P_1 \longleftarrow \dots \longleftarrow P_l \longleftarrow 0$$

where each P_i is given by $P_i = \bigoplus_{\alpha \in \mathbb{N}^E} \mathbb{K}[\mathbf{x}](-\alpha)^{\beta_{i,\alpha}}$. We write $\beta_{i,\alpha}$ for the \mathbb{N}^E -graded Betti Numbers of Δ .

1.1 Matroids and Simplicial complex

A matroid $M = (E, I)$ is a simplicial complex whose faces are the independent sets. Thus, $I_M := \langle \mathbf{x}^\sigma \mid \sigma \in \mathcal{C} \rangle$ where \mathcal{C} is the set of all circuits of M . Define $N_i = \{\sigma \in N \mid n(\sigma) = d\}$.

Theorem 1 ([2]Theorem 1) *Let M be a matroid on the ground set E . Let $\sigma \subset E$. Then, $\beta_{i,\sigma} \neq 0$ if and only if σ is minimal in N_i .*

Definition 2 *Let $M = (E, I)$ be a matroid, we define the generalized Hamming weights of M to be $d_i = \min\{|\sigma| \mid n(\sigma) = i\}$.*

Corollary 1 *Let M be a matroid on the ground set E . Then,*

$$d_i = \min\{d \mid \beta_{i,d} \neq 0 \text{ for all } 1 \leq i \leq |E| - \text{rank}(M)\}.$$

1.2 Matroids and linear codes

An $[n, k]_q$ linear code \mathcal{C} is a k -dimensional subspace of \mathbb{F}_q^n . We define a *generator matrix* of \mathcal{C} to be a $k \times n$ matrix G whose row vectors span \mathcal{C} , while a *parity check matrix* of \mathcal{C} is an $(n - k) \times n$ matrix H whose null space is \mathcal{C} .

Let us denote by $d_H(\cdot, \cdot)$ and $w_H(\cdot)$ the *Hamming distance* and the *Hamming weight* on \mathbb{F}_q^n , respectively. We write d for the *minimum Hamming distance* of the code \mathcal{C} , which is equal to its minimum weight. Thus, the error correcting capability of \mathcal{C} is $t = \lfloor \frac{d-1}{2} \rfloor$ where $\lfloor \cdot \rfloor$ is the greatest integer function. For every codeword $\mathbf{c} \in \mathcal{C}$ its *support*, $\text{supp}(\mathbf{c})$, is defined as its support as a vector in \mathbb{F}_q^n , i.e. $\text{supp}(\mathbf{c}) = \{i \mid c_i \neq 0\}$. We will denote by $\mathcal{M}_{\mathcal{C}}$ the set of codewords of minimal support of \mathcal{C} .

A *test-set* $\mathcal{T}_{\mathcal{C}}$ for \mathcal{C} is a set of codewords such that for every word $\mathbf{y} \in \mathbb{F}_q^n$, either \mathbf{y} belongs to the set of coset leaders, or there exists an element $\mathbf{t} \in \mathcal{T}_{\mathcal{C}}$ such that $w_H(\mathbf{y} - \mathbf{t}) < w_H(\mathbf{y})$.

Definition 3 The r^{th} *generalized Hamming weight* of \mathcal{C} denoted by $d_r(\mathcal{C})$ is the *smallest support of an r -dimensional subcode of \mathcal{C}* . That is,

$$d_r(\mathcal{C}) = \min \{ \text{supp}(D) \mid D \subseteq \mathcal{C} \text{ and } \text{rank}(D) = r \}$$

In [3] the authors associate a binomial ideal to an arbitrary linear code provided by the rows of a generator matrix and the relations given by the additive table of the defining field.

Let \mathbf{X} denote n vector variables X_1, \dots, X_n such that each variable X_i can be decomposed into $q - 1$ components $x_{i,1}, \dots, x_{i,q-1}$ with $i = 1, \dots, n$. A monomial in \mathbf{X} is a product of the form:

$$\mathbf{X}^{\mathbf{u}} = X_1^{\mathbf{u}_1} \dots X_n^{\mathbf{u}_n} = \left(x_{1,1}^{u_{1,1}} \dots x_{1,q-1}^{u_{1,q-1}} \right) \dots \left(x_{n,1}^{u_{n,1}} \dots x_{n,q-1}^{u_{n,q-1}} \right)$$

where $\mathbf{u} \in \mathbb{Z}_{\geq 0}^{n(q-1)}$. The total degree of $\mathbf{X}^{\mathbf{u}}$ is the sum $\text{deg}(\mathbf{X}^{\mathbf{u}}) = \sum_{i=1}^n \sum_{j=1}^{q-1} u_{i,j}$. When $\mathbf{u} = (0, \dots, 0)$, note that $\mathbf{X}^{\mathbf{u}} = 1$. Then, the polynomial ring $\mathbb{K}[\mathbf{X}]$ is the set of all polynomials in \mathbf{X} with coefficients in \mathbb{K} .

Recall that the multiplicative group \mathbb{F}_q^* of nonzero elements of \mathbb{F}_q is cyclic. A generator of the cyclic group \mathbb{F}_q^* is called a primitive element of \mathbb{F}_q , i.e. \mathbb{F}_q consist of 0 and all powers from 1 to $q - 1$ of that primitive element. Let α be a primitive element of \mathbb{F}_q . We define by \mathcal{R}_{X_i} , the set of all the binomials on the variables X_i associated to the relations given by the additive table of the field $\mathbb{F}_q = \langle \alpha^j \mid j = 1, \dots, q - 1 \rangle \cup \{0\}$, i.e.

$$\mathcal{R}_{X_i} = \left\{ \{x_{i,u}x_{i,v} - x_{i,w} \mid \alpha^u + \alpha^v = \alpha^w\} \cup \{x_{i,u}x_{i,v} - 1 \mid \alpha^u + \alpha^v = 0\} \right\}$$

with $i = 1, \dots, n$. Note that there are $\binom{q}{2}$ different binomials in \mathcal{R}_{X_i} . We define $\mathcal{R}_{\mathbf{X}}$ as the ideal generated by the union of all binomial ideals \mathcal{R}_{X_i} , i.e. $\mathcal{R}_{\mathbf{X}} = \langle \cup_{i=1}^n \mathcal{R}_{X_i} \rangle$

We will use the following characteristic crossing functions. These applications aim at describing a one-to-one correspondence between the finite field \mathbb{F}_q with q elements and the standard basis of \mathbb{Z}^{q-1} , denoted as $E_q = \{\mathbf{e}_1, \dots, \mathbf{e}_{q-z}\}$ where \mathbf{e}_i is the unit vector with a 1 in the i -th coordinate and 0's elsewhere.

$$\Delta: \mathbb{F}_q \longrightarrow E_q \cup \{\mathbf{0}\} \subseteq \mathbb{Z}^{q-1} \quad \text{and} \quad \nabla: E_q \cup \{\mathbf{0}\} \longrightarrow \mathbb{F}_q$$

1. The map Δ replaces the element $\mathbf{a} = \alpha^i \in \mathbb{F}_q$ by the vector \mathbf{e}_i and $0 \in \mathbb{F}_q$ by the zero vector $\mathbf{0} \in \mathbb{Z}^{q-1}$.
2. The map ∇ recovers the element $\alpha^j \in \mathbb{F}_q$ from the unit vector \mathbf{e}_j and the zero element $0 \in \mathbb{F}_q$ from the zero vector $\mathbf{0} \in \mathbb{Z}^{q-1}$.

These maps will be used with matrices and vectors acting coordinate-wise. Although Δ is not a linear function. Note that we have:

$$\mathbf{X}^{\Delta \mathbf{a}} \cdot \mathbf{X}^{\Delta \mathbf{b}} = \mathbf{X}^{\Delta \mathbf{a} + \Delta \mathbf{b}} = \mathbf{X}^{\Delta(\mathbf{a} + \mathbf{b})} \quad \text{mod } \mathcal{R}_{\mathbf{X}} \text{ for all } \mathbf{a}, \mathbf{b} \in \mathbb{F}_q^n.$$

Let \mathcal{C} be an $[n, k]_q$ linear code. We define the *ideal associated* to \mathcal{C} as the binomial ideal:

$$I(\mathcal{C}) = \langle \{\mathbf{X}^{\Delta \mathbf{a}} - \mathbf{X}^{\Delta \mathbf{b}} \mid \mathbf{a} - \mathbf{b} \in \mathcal{C}\} \rangle \subseteq \mathbb{K}[\mathbf{X}]$$

Given the rows of a generator matrix \mathcal{C} , labelled by $\{\mathbf{w}_1, \dots, \mathbf{w}_k\} \subseteq \mathbb{F}_q^n$, we define the following ideal:

$$I_+(\mathcal{C}) = \left\langle \left\{ \mathbf{X}^{\Delta(\alpha^j \mathbf{w}_i)} - 1 \right\}_{\substack{i=1, \dots, n \\ j=1, \dots, q-1}} \cup \{\mathcal{R}_{X_i}\}_{i=1, \dots, n} \right\rangle \subseteq \mathbb{K}[\mathbf{X}]$$

Theorem 2 [3][Theorem 2.3] $I(\mathcal{C}) = I_+(\mathcal{C})$

Remark 1 In the binary case, given a generator matrix $G \in \mathbb{F}_2^{k \times n}$ of an $[n, k]_2$ -code \mathcal{C} and let label its rows by $\{\mathbf{w}_1, \dots, \mathbf{w}_k\} \subseteq \mathbb{F}_2^n$. We define the ideal associated to \mathcal{C} as the binomial ideal:

$$I_+(\mathcal{C}) = \left\langle \left\{ \mathbf{X}^{\mathbf{w}_i} - 1 \right\}_{i=1, \dots, k} \cup \{x_i^2 - 1\}_{i=1, \dots, n} \right\rangle \subseteq \mathbb{K}[\mathbf{X}]$$

Now, let $\mathcal{G} = \{g_1, \dots, g_s\}$ be the reduced Gröbner basis of the ideal $I_+(\mathcal{C})$ with respect to \succ , where we take \succ to be any degree compatible ordering on $\mathbb{K}[\mathbf{X}]$ with

$X_1 \prec \dots \prec X_n$. By Lemma [3][Lemma 3.3] we know that all elements of $\mathcal{G} \setminus \mathcal{R}_X$ are in standard form, so for $g_i \in \mathcal{G} \setminus \mathcal{R}_X$ with $i = 1, \dots, s$, we define

$$g_i = \mathbf{X}^{\Delta \mathbf{g}_i^+} - \mathbf{X}^{\Delta \mathbf{g}_i^-} \quad \text{with} \quad \mathbf{X}^{\Delta \mathbf{g}_i^+} \succ \mathbf{X}^{\Delta \mathbf{g}_i^-} \quad \text{and} \quad \mathbf{g}_i^+ - \mathbf{g}_i^- \in \mathcal{C}.$$

Using [3][Proposition 4], we know that the set $\mathcal{T} = \{\mathbf{g}_i^+ - \mathbf{g}_i^- \mid i = 1, \dots, s\}$ is a test-set for \mathcal{C} .

Example 1 Consider the $[6, 3, 2]_2$ binary code \mathcal{C} defined by the following generator matrix:

$$G = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{pmatrix} \in \mathbb{F}_2^{3 \times 6}$$

Let us label the rows of G by \mathbf{w}_1 and \mathbf{w}_2 . By the previous theorem, the ideal associated to the linear code \mathcal{C} may be defined as the following ideal:

$$\begin{aligned} I_+(\mathcal{C}) &= \left\langle \{\mathbf{X}^{\mathbf{w}_i} - 1\}_{i=1,2} \cup \{\mathcal{R}_{X_i}\}_{i=1,\dots,6} \right\rangle \\ &= \left\langle \left\{ \begin{array}{l} x_1 x_6 - 1 \\ x_2 x_3 x_5 - 1 \\ x_4 x_5 x_6 - 1 \end{array} \right\} \cup \{x_i^2 - 1\}_{i=1,\dots,6} \right\rangle \end{aligned}$$

If we compute a reduced Gröbner basis \mathcal{G} of $I_+(\mathcal{C})$ we obtained a test-set consisting of 4 codewords:

$$\mathcal{T}_{\mathcal{C}} = \{(1, 0, 0, 0, 0, 1), (0, 1, 1, 0, 1, 0), (0, 1, 1, 1, 1, 0, 1), (0, 0, 0, 1, 1, 1)\}$$

For fuller discussion of this algebraic structure see [4, 1] and the references therein.

The connection between linear codes and matroids will turn out to be fundamental for the development of the subsequent results. Thus, a brief review will be provided here.

Given an $m \times n$ matrix H in \mathbb{F}_q , then H can be seen not only as the representation matrix of the \mathbb{F}_q -representable matroid $M[H]$ but also as a parity check matrix of an $[n, k]$ -code \mathcal{C} . Furthermore, there exists a one to one correspondence between \mathbb{F}_q -representable matroids and linear codes, since for any $H, H' \in \mathbb{F}_q^{m \times n}$, $M[H] = M[H']$ if and only if H and H' are parity check matrices of the same code \mathcal{C} . This association enables us to work with \mathbb{F}_q -representable matroids and linear codes as if they were the same object and thus we can conclude some properties of linear codes using tools from matroid theory and vice-versa.

2 Our Conjecture

Let $M = (E, I)$ be a matroid and \mathcal{C} be the set of all circuits of M . Consider \mathcal{T} a collection of cycles of M with the following property: $\bigcup_{\tau \in \mathcal{C}} \tau = \bigcup_{\tau \in \mathcal{T}} \tau$. We define the ideal $I_{\mathcal{T}} = \langle \mathbf{x}^\sigma \mid \sigma \in \mathcal{T} \rangle$.

Conjecture 1 *Let $\beta'_{i,\alpha}$ the \mathbb{N}^E -graded betti number of $I_{\mathcal{T}}$, related with the minimal free resolution of $R = \frac{\mathbb{K}[X]}{I_{\mathcal{T}}}$ as \mathbb{N}^E -graded module. Then, we have a similar result as Theorem 1 and Corollary 1.*

If we talk about linear codes, the conjecture allows us to compute the set of generalized Hamming weight of a linear code \mathcal{C} using a Test-set for \mathcal{C} , in other words, by computing a Grobner basis of the ideal associated to \mathcal{C} .

Corollary 2 *Let $\mathcal{T}_{\mathcal{C}}$ be a test-set for the linear code \mathcal{C} . Consider the monomial ideal: $I_{\mathcal{T}_{\mathcal{C}}} = \langle \mathbf{x}^\sigma \mid \sigma \in \mathcal{T}_{\mathcal{C}} \rangle$. Let $\beta'_{i,\alpha}$ the \mathbb{N}^E -graded betti numbers of $I_{\mathcal{T}_{\mathcal{C}}}$. Then,*

$$d_i(\mathcal{C}) = \min \{d \mid \beta'_{i,d} \neq 0\} \text{ for } 1 \leq i \leq n - k$$

Example 2 *Now we use the same code of Example 1. In this case the support of a test-set $T_{\mathcal{C}}$ is given by: $\mathcal{T} = \{\{2, 3, 5\}, \{2, 3, 4, 6\}, \{4, 5, 6\}, \{1, 6\}\}$ i.e. we consider the ideal: $I_{\mathcal{T}} = \langle x_2x_3x_5, x_2x_3x_4x_6, x_4x_5x_6, x_1x_6 \rangle \subseteq \mathbb{K}[x_1, \dots, x_6]$. We get the Betti diagram*

	1	2	3
1	1		
2	2	1	
3	1	4	2

Thus $\beta'_{1,2}$, $\beta'_{2,4}$ and $\beta'_{3,6}$ are the minimal $\beta'_{i,d} \neq 0$ with $i = 1, 2, 3$. Or equivalently, $d_1 = 2$, $d_2 = 4$ and $d_3 = 6$.

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