

NEW QUANTUM CODES FROM EVALUATION AND MATRIX-PRODUCT CODES

CARLOS GALINDO, FERNANDO HERNANDO

INSTITUTO UNIVERSITARIO DE MATEMÁTICAS Y APLICACIONES DE CASTELLÓN
AND DEPARTAMENTO DE MATEMÁTICAS

UNIVERSITAT JAUME I, CAMPUS DE RIU SEC. 12071 CASTELLÓ (SPAIN)

AND DIEGO RUANO

DEPARTMENT OF MATHEMATICAL SCIENCES, AALBORG UNIVERSITY
FREDRIK BAJERS VEJ 7G, 9220 AALBORG EAST (DENMARK)

ABSTRACT. Stabilizer codes obtained via the CSS code construction and the Steane's enlargement of subfield-subcodes and matrix-product codes coming from generalized Reed-Muller, hyperbolic and affine variety codes are studied. Stabilizer codes with good quantum parameters are supplied, in particular, some binary codes of lengths 127 and 128 improve the parameters of the codes in <http://www.codetables.de>. Moreover, non-binary codes are presented either with parameters better than or equal to the quantum codes obtained from BCH codes by La Guardia or with lengths that cannot be reached by them.

1. INTRODUCTION

Quantum computers are based on the principles of quantum mechanics and use subatomic particles (qubits) to hold memory. The construction of efficient devices of this type would have important consequences as the breaking of some well-known cryptographical schemes [42]. Information on a recent attempt to built a quantum computer can be found in [2, 44].

Despite quantum mechanical systems are very sensitive to disturbances and arbitrary quantum states cannot be replicated, error correction is possible [43]. In this paper we are concerned with stabilizer codes which are a class of quantum error-correcting codes. Parameters of our codes will be expressed as $[[n, k, d]]_q$, where q is a power p^r of a prime number p and r a positive integer. They mean that our codes are q^k -dimensional linear subspaces of \mathbb{C}^{q^n} , \mathbb{C} being the complex field, and d its minimum distance, which determines detection and correction of errors. An stabilizer code is called to be pure to a positive integer t whenever its stabilizer group does not contain non-scalar matrices with weight less than t (see, for instance, [30, 29] for details).

Stabilizer codes can be derived from classical ones with respect to Symplectic or Hermitian inner product [7, 3, 1, 29], although this can also be done with respect to Euclidean inner product by using the so-called CSS code construction [8, 45]. The following results [29, Lemma 20 and Corollary 21] show the parameters of the stabilizer codes that one gets by using the above mentioned code construction. The reader can consult [29, Theorem 13] to see how stabilizer codes are obtained from classical ones.

Key words and phrases. Quantum codes; Steane's enlargement; Affine variety codes; Subfield-subcodes; Matrix-product codes.

Supported by the Spanish Ministry of Economy: grant MTM2012-36917-C03-03, the University Jaume I: grant PB1-1B2012-04 and the Danish Council for Independent Research, grant DFF-4002-00367.

Theorem 1. *Let C_1 and C_2 two linear error-correcting block codes with parameters $[n, k_1, d_1]$ and $[n, k_2, d_2]$ over the field \mathbb{F}_q and such that $C_2^\perp \subset C_1$, where C_2^\perp stands for the dual code of C_2 . Then, there exists an $[[n, k_1 + k_2 - n, d]]_q$ stabilizer code with minimum distance*

$$d = \min \left\{ w(c) \mid c \in (C_1 \setminus C_2^\perp) \cup (C_2 \setminus C_1^\perp) \right\},$$

which is pure to $\min\{d_1, d_2\}$, where $w(c)$ denotes the weight of a word c .

Corollary 1. *Let C be a linear $[n, k, d]$ error-correcting block code over \mathbb{F}_q such that $C^\perp \subset C$. Then, there exists an $[[n, 2k - n, \geq d]]_q$ stabilizer code which is pure to d .*

Note that we use the symbol \subset to indicate subset, in particular $C \subset C'$ holds. Next, we state the Hamada's generalization of the Steane's enlargement procedure [47] because it will be used in the paper. Given two suitable codes C and C' , the code obtained by applying this procedure will be called their Steane's enlargement and denoted by $\text{SE}(C, C')$.

Corollary 2. [20] *Let C be an $[n, k]$ linear code over the field \mathbb{F}_q such that $C^\perp \subset C$. Assume that C can be enlarged to an $[n, k']$ linear code C' , where $k' \geq k + 2$. Then, there exists a stabilizer code with parameters $[[n, k + k' - n, d \geq \min\{d', \lceil \frac{q+1}{q} d'' \rceil\}]]_q$, where $d' = w(C \setminus C'^\perp)$, $d'' = w(C' \setminus C'^\perp)$ and w denotes the minimum weight of the words of a set.*

In this paper, we provide new families of algebraically generated stabilizer codes derived essentially from the Euclidean inner product and containing a number of codes with good parameters. In fact we are able to improve some of the binary quantum codes given in [19]. Moreover we supply stabilizer codes with parameters better than or equal to those given in [31, Table III] and [33], together with others whose lengths cannot be reached in [31, 33] but exceed the Gilbert-Varshamov bounds [11, 36, 13], [29, Lemma 31], or improve those in [12] or satisfy both conditions.

Our stabilizer codes are supported in three families of linear codes: the so-called (generalized) Reed-Muller codes [28, 10], hyperbolic (or hyperbolic cascaded Reed-Solomon) codes [14, 27, 35, 40], and affine variety codes [15, 17]. Stabilizer codes obtained with Reed-Muller codes have been studied in [46] and [41]. These families allow us to get nested sequences of codes that contain their dual ones and determine stabilizer codes by applying the CSS code construction. We enlarge this set of stabilizer codes by considering suitable matrix-product codes, which were introduced in [4] (see also [37, 22]). Together with this construction, we also consider subfield-subcodes of our codes, which allows us to get codes over small fields from codes defined over larger ones, always within the same characteristic. We complement the mentioned techniques with the Steane's enlargement (Corollary 2).

Tables with parameters of our codes are distributed along the paper and testify their goodness. As mentioned, several of them improve the parameters available in the literature. These tables are presented as a complement of the different procedures described for obtaining our families of stabilizer codes. Reed-Muller and hyperbolic codes have the advantage that all their parameters are known and, as a consequence, we are able to obtain, with a simple calculation, parameters for the corresponding stabilizer codes. Affine variety codes give a broader spectrum of codes and their dimensions and lengths can be computed. Unfortunately, there is no known general formula for their distances and it seems a very difficult problem to obtain it. In this paper, we have computed them by using the computational algebra system Magma [5].

We finish this introduction with a description of each section in the paper. Section 2 reviews the concept of matrix-product code and recalls two useful results, Theorem 2 and Corollary 3. It is worthwhile to mention that using non-singular by columns matrices is a key point for obtaining matrix-product codes with good parameters that provide stabilizer codes by Corollary 1. Our supporting families of codes are introduced in Section 3. Parameters for them and conditions for self-orthogonality are the main facts we state there. In particular, Theorem 6 has interest in classical coding theory as well, since it characterizes self-orthogonal hyperbolic codes. Subfield-subcodes of the mentioned families are also an important tool for constructing our stabilizer codes and we devote Section 4 to give our main results in this line. The main theoretical results in this paper can be found in Section 5. Indeed, Theorems 10 and 11 together with Remark 2 give parameters for the stabilizer codes obtained from the previous constructions. The remaining sections of the paper show tables with quantum parameters of codes obtained as we have described. For certain small sizes, there are no non-singular by columns orthogonal matrices over the fields \mathbb{F}_2 and \mathbb{F}_3 . To avoid this difficulty, Theorems 13 and 14 in Sections 6 and 7 look for clever matrices that allow us to get self-orthogonal matrix-product codes. Codes over \mathbb{F}_3 , improving some ones in [33], are treated in Section 7 while Section 6 is devoted to binary ones, where, together with codes derived from Theorem 13, in Table 2 we show stabilizer codes of lengths 127 and 128 improving [19]. The last section in the paper, Section 8, contains a number of stabilizer codes over the fields \mathbb{F}_4 , \mathbb{F}_5 and \mathbb{F}_7 . In Table 16 and comparing with [31, Table III], the reader will find a code improving that table, another one with a new distance and some more with the same parameters; in fact our codes can reproduce most parameters in the mentioned Table III. In addition Table 16 shows stabilizer codes either improving [12] or exceeding the Gilbert-Varshamov bounds and with lengths that cannot be reached in [31, 33].

2. MATRIX-PRODUCT CODES

Along this paper, p is a prime number, $q = p^r$ a positive integer power of p and \mathbb{F}_q the finite field with q elements. Let C_1, C_2, \dots, C_s be a family of s codes of length m over \mathbb{F}_q and $A = (a_{ij})$ an $s \times l$ matrix with entries in \mathbb{F}_q . Then, the *matrix-product code* [4], given by the above data and denoted $[C_1, C_2, \dots, C_s] \cdot A$, is defined as the code over \mathbb{F}_q of length ml whose generator matrix is

$$(1) \quad \begin{pmatrix} a_{11}G_1 & a_{12}G_1 & \cdots & a_{1l}G_1 \\ a_{21}G_2 & a_{22}G_2 & \cdots & a_{2l}G_2 \\ \vdots & \vdots & \cdots & \vdots \\ a_{s1}G_s & a_{s2}G_s & \cdots & a_{sl}G_s \end{pmatrix},$$

where G_i , $1 \leq i \leq s$, is a generator matrix for the code C_i .

Given a matrix A as above, let A_t be the matrix consisting of the first t rows of A . For $1 \leq j_1 < j_2 < \dots < j_t \leq l$, we denote by $A(j_1, j_2, \dots, j_t)$ the $t \times t$ matrix consisting of the columns j_1, j_2, \dots, j_t of A_t . A *non-singular by columns matrix* over \mathbb{F}_q is a matrix A satisfying that every sub-matrix $A(j_1, j_2, \dots, j_t)$ of A , $1 \leq t \leq s$, is non-singular [4]. Some of the codes in this paper are based on matrix-product codes, whose parameters are described in the following result.

Theorem 2. [22, 37] *The matrix-product code $[C_1, C_2, \dots, C_s] \cdot A$ given by a sequence of $[m, k_i, d_i]$ -linear codes C_i over \mathbb{F}_q and a full-rank matrix A is a linear code whose length is*

ml , it has dimension $\sum_{i=1}^s k_i$ and minimum distance larger than or equal to

$$\delta = \min_{1 \leq i \leq s} \{d_i \delta_i\},$$

where δ_i is the minimum distance of the code on \mathbb{F}_q^l generated by the first i rows of the matrix A . Moreover, when the matrix A is non-singular by columns, it holds that $\delta_i = l + 1 - i$. Furthermore, if we assume that the codes C_i form a nested sequence $C_1 \supset C_2 \supset \dots \supset C_s$, then the minimum distance of the code $[C_1, C_2, \dots, C_s] \cdot A$ is exactly δ .

More information about this construction can be found in [22, 23, 21, 24]. Since we are interested in stabilizer codes obtained by applying the CSS code construction, the following results concerning duality will be of interest.

Theorem 3. [4] Assume that $\{C_1, C_2, \dots, C_s\}$ is a family of linear codes of length m and A a non-singular $s \times s$ matrix, then the following equality of codes happens

$$([C_1, C_2, \dots, C_s] \cdot A)^\perp = [C_1^\perp, C_2^\perp, \dots, C_s^\perp] \cdot (A^{-1})^t,$$

where, as usual, B^t denotes the transpose of the matrix B .

Corollary 3. Let A be an orthogonal $s \times s$ matrix (i.e., a matrix such that $(A^{-1})^t = A$) and assume that for $i = 1, 2, \dots, s$, it holds that $C_i^\perp \subset C_i$ then

$$([C_1, C_2, \dots, C_s] \cdot A)^\perp \subset [C_1, C_2, \dots, C_s] \cdot A.$$

3. SOME FAMILIES OF CODES AND THEIR DUAL ONES

Next, we introduce some known families of codes which we will use for our purposes.

3.1. Reed-Muller codes. Consider the ring of polynomials $\mathbb{F}_q[X_1, X_2, \dots, X_m]$ in m variables over the field \mathbb{F}_q and its ideal $I = \langle X_1^q - X_1, X_2^q - X_2, \dots, X_m^q - X_m \rangle$. Set $R = \mathbb{F}_q[X_1, X_2, \dots, X_m]/I$ the corresponding \mathbb{F}_q -algebra and write $Z(I) = \mathbb{F}_q^m = \{P_1, \dots, P_n\}$, the set of zeroes in \mathbb{F}_q of the ideal I . We will use the evaluation map $\text{ev} : R \rightarrow \mathbb{F}_q^n$ defined by $\text{ev}(f) = (f(P_1), \dots, f(P_n))$ for classes of polynomials $f \in R$. It is well-known that ev is, in this case, an isomorphism of \mathbb{F}_q -vector spaces. For a positive integer r , the (generalized) *Reed-Muller code* of order r on $\mathbb{F}_q[X_1, X_2, \dots, X_m]$ (or the (r, m) Reed-Muller code) is defined as $RM(r, m) = \{\text{ev}(f) \mid f \in R, \deg(f) \leq r\}$, where \deg means total degree. Notice that we always choose a canonical representative of f without powers X_i^j , $j \geq q$ and the length of the codes is $n = q^m$. The following result summarizes known results for Reed-Muller codes (see [25, 41], for instance).

Theorem 4. With the above notations, assume $0 \leq r < (q - 1)m$ and by Euclidean division, set $(q - 1)m - r = a(q - 1) + b$, $a, b \geq 0$ and $b < q - 1$. Then

- (1) The dimension of the code $RM(r, m)$ is

$$\sum_{j=0}^m (-1)^j \binom{m}{j} \binom{m+r-jq}{r-jq}.$$

- (2) The minimum distance of the code $RM(r, m)$ is $(b + 1)q^a$.
(3) The dual $RM(r, m)^\perp$ of the code $RM(r, m)$ is the Reed-Muller code $RM(m(q - 1) - (r + 1), m)$.

In order to consider matrix-product codes with Reed-Muller ones, suitable for the CSS code construction, we will consider a positive integer r such that $2r + 1 \leq m(q - 1)$. Now, writing $E = RM(r, m)$ and $C = RM(m(q - 1) - (r + 1), m)$, the equality $E = C^\perp$ happens. From the above equality, the code inclusion $C^\perp \subset C$ holds and setting $r + 1 = c(q - 1) + e$ by Euclidean division, one gets that the minimum distance of the code C is $d = (e + 1)q^c$ and its dimension is

$$(2) \quad k = \sum_{j=0}^m (-1)^j \binom{m}{j} \binom{(m-j)q - (r+1)}{m(q-j-1) - (r+1)}.$$

3.2. Hyperbolic codes. The first part of this section is based on [18]. Consider the same \mathbb{F}_q -algebra R defined in the previous subsection and fix a positive integer t , $0 \leq t \leq q^m$. Define the linear code, $\Xi(t, m)$, on \mathbb{F}_q^n generated by the vectors obtained by applying the map ev to the set of monomials:

$$(3) \quad \mathfrak{M} := \left\{ X_1^{\alpha_1} X_2^{\alpha_2} \cdots X_m^{\alpha_m} \mid 0 \leq \alpha_i < q, 1 \leq i \leq m \text{ and } \prod_{i=1}^m (\alpha_i + 1) < q^m - t \right\}.$$

The t -th hyperbolic code (on $\mathbb{F}_q[X_1, X_2, \dots, X_m]$), $\text{Hyp}(t, m)$ is, by definition, the dual code of the code $\Xi(t, m)$ above given. Therefore, the length of the codes is again $n = q^m$. For simplicity's sake, we set X^α instead of $X_1^{\alpha_1} X_2^{\alpha_2} \cdots X_m^{\alpha_m}$ for an element $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_m)$ in \mathbb{Z}^m , $\alpha_i \geq 0$. For each element α of this type, we define

$$D_\alpha = \left\{ X^\beta \mid 0 \leq \beta_i < q, 1 \leq i \leq m \text{ and } X^\beta \text{ is not divisible by } X^\alpha \right\}$$

and $n_\alpha = \text{card} D_\alpha$. Without loss of generality, we can assume that the values t used in the definition of hyperbolic codes are of the form n_α for some α such that $0 \leq \alpha_i < q$ for all i . This is assumed in the rest of the paper. To make clear the previous assumption, note that if one picks any positive integer $0 \leq s \leq q^m$, then there exists a positive integer $t \geq s$ of the form $t = n_\alpha$, for some α as above, such that $\text{Hyp}(s, m) = \text{Hyp}(t, m)$.

Theorem 5. [18] *Consider the hyperbolic code $\text{Hyp}(t, m)$ above defined, with $t = n_\alpha$, for some α . Then,*

- (1) $\text{Hyp}(t, m)$ is generated by the set of vectors in \mathbb{F}_q^n obtained by applying ev to the set of monomials X^α such that n_α is less than or equal to t .
- (2) The minimum distance of $\text{Hyp}(t, m)$ is $q^m - t$.
- (3) The dimension of $\text{Hyp}(t, m)$ is $q^m - \text{card } \mathfrak{M}$.

Bearing Theorem 5, it is not difficult to deduce that the code $\text{Hyp}(t, m)$ is generated by those vectors obtained after applying ev to the set of monomials X^α , where α runs over the set

$$(4) \quad \left\{ \alpha = (\alpha_1, \alpha_2, \dots, \alpha_m) \in \mathbb{Z}^m \mid 0 \leq \alpha_i \leq q - 1, 1 \leq i \leq m, \prod_{i=1}^m (q - \alpha_i) \geq q^m - t \right\}.$$

One may consider that, given a designed minimum distance $q^m - t$, hyperbolic codes are defined by set (3) for maximizing its dimension. It is worth to mention that the dual of a hyperbolic code is not a hyperbolic code. We desire to know for which values t the inclusion $(\text{Hyp}(t, m))^\perp \subset \text{Hyp}(t, m)$ holds. To decide it, we need the following lemma.

Lemma 1. *With the above notation, assume that $t_1 \leq t_2$ then $\text{Hyp}(t_1, m) \subset \text{Hyp}(t_2, m)$. Moreover if $t_1 < t_2$, it holds the following equality of minimum weights:*

$$w(\text{Hyp}(t_2, m) \setminus \text{Hyp}(t_1, m)) = w(\text{Hyp}(t_2, m)).$$

Proof. The first assertion follows simply by taking into account the sets of monomials determined by the tuples in (4) and involved in the construction of both codes. For the second one, $w(\text{Hyp}(t_2, m)) = q^m - t_2 < q^m - t_1 = w(\text{Hyp}(t_1, m))$, what concludes the proof. \square

The following result shows when $C^\perp \subset C$ for a hyperbolic code C .

Theorem 6. *Consider the hyperbolic code $\text{Hyp}(t, m)$ above defined, with $t = n_\alpha$, for some α . Then, the codes' inclusion $(\text{Hyp}(t, m))^\perp \subset \text{Hyp}(t, m)$ happens if, and only if, one of the following conditions hold.*

- (1) *The integer m is even and $t \geq q^m - q^{\frac{m}{2}}$.*
- (2) *Both, the integer m and the cardinality of the base field q , are odd and t satisfies $t \geq q^m - q^{\frac{m-1}{2}} \frac{q+1}{2}$.*
- (3) *The integer m is odd, the cardinality of the base field q is even and t satisfies $t \geq q^m - q^{\frac{m-1}{2}} (\frac{q}{2} + 1)$.*

Proof. Firstly we are going to prove that, in each one of the three cases in the statement, the codes' inclusion $(\text{Hyp}(t, m))^\perp \subset \text{Hyp}(t, m)$ does not hold when the corresponding inequality does not happen. To do it, we will provide a m -tuple $\mathbf{a} = (a_1, a_2, \dots, a_m)$ attached to a monomial in the set (3) which is not in the set (4).

With respect to the first case, assume that m is even and $t < q^m - q^{\frac{m}{2}}$. Set $a_i = q - 1$ for $i = 1, 2, \dots, m/2$ and $a_i = 0$ otherwise. Is clear that $\prod_{i=1}^m (a_i + 1) = q^{m/2} < q^m - t$ so $X^{\mathbf{a}}$ is in the set (3). However $\prod_{i=1}^m (q - a_i) = q^{m/2} < q^m - t$. Therefore \mathbf{a} is not in the set (4). Now, consider the second case and suppose that m and q are odd and $t < q^m - q^{\frac{m-1}{2}} \frac{q+1}{2}$. Then, the m -tuple \mathbf{a} defined as $a_i = q - 1$ for $i = 1, 2, \dots, (m-1)/2$, $a_m = (q-1)/2$ and $a_i = 0$ otherwise satisfies the requirements. Finally, in our third case, the facts m odd and q even show that if $t < q^m - q^{\frac{m-1}{2}} (\frac{q}{2} + 1)$, an m -tuple \mathbf{a} satisfying the desired condition is defined by $a_i = q - 1$ for $1 \leq i \leq (m-1)/2$, $a_m = q/2$ and $a_i = 0$ otherwise, which concludes this part of the proof.

It remains to prove that, in each one of the previous cases, when t is larger than or equal to the bounds above indicated, the inclusion $(\text{Hyp}(t, m))^\perp \subset \text{Hyp}(t, m)$ holds. Before carrying on with the technical details, we notice that Lemma 1 proves that if $t_1 \leq t_2$, then $\text{Hyp}(t_1, m) \subset \text{Hyp}(t_2, m)$ and, moreover, $(\text{Hyp}(t_1, m))^\perp \supset (\text{Hyp}(t_2, m))^\perp$. Therefore it is enough to prove the remaining part of our theorem in the mentioned cases and when t coincides with our bounds.

Consider the hypercube \mathfrak{H} of rational points (x_1, x_2, \dots, x_m) in \mathbb{Z}^m such that $0 \leq x_i \leq q - 1$ for $1 \leq i \leq m$, i.e., $\mathfrak{H} = (\{0, 1, \dots, q-1\})^m$, and the varieties on \mathbb{R}^m , H_1 and H_2 , defined, respectively, by the equations $(X_1 + 1)(X_2 + 1) \cdots (X_m + 1) = q^m - t$ and $(q - X_1)(q - X_2) \cdots (q - X_m) = q^m - t$. From the above considerations, it is clear that to prove our result, we must check the following condition that we denote by (*): All rational point in \mathfrak{H} under the variety H_1 must be under or on the variety H_2 . Notice that the expression under (respectively, under or on) H means rational points in the space bounded by the hyperplanes $X_i = 0$ and H and containing the zero vector, which also can belong to the hyperplanes but not to (respectively, and) the variety H .

The conjugation map is defined on the closure $\overline{\mathfrak{H}}$ of \mathfrak{H} as $\varphi : \overline{\mathfrak{H}} \rightarrow \overline{\mathfrak{H}}$, $\varphi(x_1, x_2, \dots, x_m) = (q - 1 - x_1, q - 1 - x_2, \dots, q - 1 - x_m)$ and will help us in our reasoning. For a start, it is straightforward to check that $\varphi(H_1) = H_2$. Now, as we announced, we are going to prove Condition (*) for each case.

In case (1), it happens that on $\overline{\mathfrak{H}}$, the hyperplane π with equation $X_1 + X_2 + \cdots + X_m = \frac{m}{2}(q-1)$ is invariant under conjugation and both varieties H_1 and H_2 intersect π at the same set S of points. S is the set of points in \mathbb{Z}^m where $m/2$ coordinates are equal to zero and the remaining ones equal $q-1$. The facts that the points in S belong to the facets of \mathfrak{H} , H_1 is convex and H_2 concave on \mathfrak{H} determine a geometric configuration that proves the result. Case (2) can be proved in a similar way although in this case H_1 and H_2 meet π at the set of points where $(m-1)/2$ coordinates equal zero, $(m-1)/2$ coordinates equal $q-1$ and the remaining one is equal to $(q-1)/2$.

To finish the proof, assume we are in case (3) and consider the hyperplanes $\pi_1 : X_1 + X_2 + \cdots + X_m = \frac{m-1}{2}(q-1) + \frac{q}{2}$ and $\pi_2 : X_1 + X_2 + \cdots + X_m = \frac{m-1}{2}(q-1) + \frac{q}{2} - 1$. Both hyperplanes are conjugated one of each other and the same happens with the varieties H_i . In addition, within $\overline{\mathfrak{H}}$, H_1 meets π_1 at the set of points satisfying that $(m-1)/2$ coordinates are equal to zero, $(m-1)/2$ coordinates equal $q-1$ and the remaining one is $q/2$. With respect to H_2 and π_2 , a similar situation happens but the remaining coordinate must be $(q/2) - 1$. This fact shows that although one can find nonrational points of $\overline{\mathfrak{H}}$ under H_1 which are not under H_2 , this fact cannot happen with rational points because the terms of the right hand of the equations for π_1 and π_2 differ in one unit. As a consequence, Condition (*) holds and the result is proved. \square

3.3. Affine variety codes. Consider again the ring of polynomials $\mathbb{F}_q[X_1, X_2, \dots, X_m]$ and, in this case, choose m positive integers N_i , $1 \leq i \leq m$, satisfying that N_i divides $q-1$. Now the ideal I defining $R = \mathbb{F}_q[X_1, X_2, \dots, X_m]/I$ will be that spanned by the set of polynomials $\{X_1^{N_1} - 1, X_2^{N_2} - 1, \dots, X_m^{N_m} - 1\}$ and the set of evaluating points $Z(I) = \{P_j\}_{j=1}^n$. As above, we will use the morphism of vector spaces $\text{ev} : R \rightarrow \mathbb{F}_q^n$. Consider the cartesian product

$$(5) \quad \mathfrak{H} = \{0, 1, \dots, N_1 - 1\} \times \{0, 1, \dots, N_2 - 1\} \times \cdots \times \{0, 1, \dots, N_m - 1\}$$

and for any nonempty subset $\Delta \subset \mathfrak{H}$, we define the *affine variety code* given by Δ , E_Δ , as the vector subspace over \mathbb{F}_q of \mathbb{F}_q^n spanned by the evaluation by ev of the classes in R of the set corresponding to monomials $X^\alpha = X_1^{\alpha_1} X_2^{\alpha_2} \cdots X_m^{\alpha_m}$ such that $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_m) \in \Delta$. Note that the length of these codes is $n = N_1 N_2 \cdots N_m$.

For a set Δ as above, we define the subset of \mathfrak{H} , $\Delta^\perp = \mathfrak{H} \setminus \{\hat{\alpha} | \alpha \in \Delta\}$, where $\hat{\alpha}$ denotes the element $\hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2, \dots, \hat{\alpha}_m)$ where, for $1 \leq i \leq m$, $\hat{\alpha}_i$ is 0 whenever $\alpha_i = 0$ and $\hat{\alpha}_i = N_i - \alpha_i$ otherwise. One can also define $\hat{\alpha}$ as $-\alpha$ in $\mathbb{Z}_{N_1} \times \cdots \times \mathbb{Z}_{N_m}$. Concerning duality, the main result is the following one that is an extension of one in [6, 39].

Proposition 1. *The dimension of an affine variety code E_Δ , defined by a set Δ as above, is the cardinality of the set Δ . Moreover, the dual code E_Δ^\perp of E_Δ is the affine variety code E_{Δ^\perp} .*

Proof. Let $\xi_i \in \mathbb{F}_q$ with order N_i , for $i = 1, 2, \dots, m$, whose existence is guaranteed by the fact that $N_i | q-1$. So, $\langle \xi_i \rangle = \{\xi_i^0, \xi_i^1, \dots, \xi_i^{N_i-1}\} = Z(X_i^{N_i} - 1)$.

Let $\mathbf{a}, \mathbf{b} \in \mathfrak{H}$, by the distributive property, $\text{ev}(X^{\mathbf{a}}) \cdot \text{ev}(X^{\mathbf{b}})$ is equal to

$$\left(\sum_{\gamma_1 \in \langle \xi_1 \rangle} \gamma_1^{a_1+b_1} \right) \left(\sum_{\gamma_2 \in \langle \xi_2 \rangle} \gamma_2^{a_2+b_2} \right) \cdots \left(\sum_{\gamma_m \in \langle \xi_m \rangle} \gamma_m^{a_m+b_m} \right).$$

If $a_i + b_i = 0$ in \mathbb{Z}_{N_i} for every $i \in \{1, 2, \dots, m\}$, then $\text{ev}(X^{\mathbf{a}}) \cdot \text{ev}(X^{\mathbf{b}}) \neq 0$ because

$$\sum_{\gamma_i \in \langle \xi_i \rangle} \gamma_i^{a_i+b_i} = \sum_{\gamma_i \in \langle \xi_i \rangle} \gamma_i^0 = N_i \neq 0 \text{ (in } \mathbb{F}_q \text{)}.$$

However, if $a_i + b_i = c \neq 0$ in \mathbb{Z}_{N_i} for some i , then $\text{ev}(X^{\mathbf{a}}) \cdot \text{ev}(X^{\mathbf{b}}) = 0$ because

$$\sum_{\gamma_i \in \langle \xi_i \rangle} \gamma_i^{a_i + b_i} = \sum_{j=0}^{N_i-1} (\xi_i^j)^c = \sum_{j=0}^{N_i-1} (\xi_i^c)^j = \frac{1 - (\xi_i^c)^{N_i}}{1 - \xi_i^c} = 0;$$

note that $\xi_i^c \neq 1$ since $c \neq 0 \in \mathbb{Z}_{N_i}$.

Then $\text{ev}(X^{\mathbf{a}}) \cdot \text{ev}(X^{\mathbf{b}}) = 0$ for $\mathbf{a} \in \Delta$, $\mathbf{b} \in \Delta^\perp$ since $\mathbf{a} + \mathbf{b} \neq \mathbf{0}$ in $\mathbb{Z}_{N_1} \times \mathbb{Z}_{N_2} \times \cdots \times \mathbb{Z}_{N_m}$. On account of the dimension of E_Δ and E_{Δ^\perp} and the linearity of the codes the result holds. \square

4. SUBFIELD-SUBCODES

Section 3 provides codes, including their derived matrix-product ones, suitable to get stabilizer codes via the CSS code construction and the Steane's enlargement procedure. However, stabilizer codes with better parameters can be obtained by considering subfield-subcodes. Next, we are going to give some details with respect to their dimensions.

Recall that $q = p^r$, assume $r > 2$ and pick a positive integer $s < r$ such that s divides r . Consider the trace type maps: $\text{tr}_r^s : \mathbb{F}_{p^r} \rightarrow \mathbb{F}_{p^s}$ defined as $\text{tr}_r^s(x) = x + x^{p^s} + \cdots + x^{p^{s(\frac{r}{s}-1)}}$; $\text{tr} : \mathbb{F}_{p^r}^n \rightarrow \mathbb{F}_{p^s}^n$, which works by applying tr_r^s componentwise and, for the different rings R defined in Section 3, $\mathcal{T} : R \rightarrow R$, $\mathcal{T}(f) = f + f^{p^s} + \cdots + f^{p^{s(\frac{r}{s}-1)}}$. We must add that we consider $f \in R$ given by a linear combination of monomials with exponents in \mathfrak{H} , \mathfrak{H} being the hypercube $(\{0, 1, \dots, q-1\})^m$ in Subsections 3.1 and 3.2, and \mathfrak{H} as defined in (5), in Subsection 3.3. In the rest of this section, we will set $N_i = q$, $1 \leq i \leq m$, when we are working with either Reed-Muller or hyperbolic codes. Otherwise, N_i will be the corresponding values for affine variety codes.

Remark 1. To define the codes in the previous section, we have considered the algebra $R = \mathbb{F}_q[X_1, \dots, X_m]/I$, where I is spanned by the set of polynomials $\{X_1^{N_1} - X_1, \dots, X_m^{N_m} - X_m\}$ for Reed-Muller and hyperbolic codes, and by the set $\{X_1^{N_1} - 1, \dots, X_m^{N_m} - 1\}$ for affine variety codes. Therefore, the algebra R is slightly different for affine variety codes in this work, the only difference residing in the fact that we are only evaluating at points with nonzero coordinates. Although the literature usually considers affine variety codes using the first ideal, we have decided to consider the second ideal in order to compare some of our codes with the ones in [31, 33], whose length is a power of q minus one.

For each index i as above, set \mathbb{Z}_{N_i} the quotient ring $\mathbb{Z}/N_i\mathbb{Z}$. A subset \mathcal{J} of the cartesian product $\mathbb{Z}_{N_1} \times \mathbb{Z}_{N_2} \times \cdots \times \mathbb{Z}_{N_m}$ is a *cyclotomic set* if it satisfies $\mathcal{J} = \{p \cdot \boldsymbol{\alpha} \mid \boldsymbol{\alpha} \in \mathcal{J}\}$, where $p \cdot \boldsymbol{\alpha} = (p\alpha_1, p\alpha_2, \dots, p\alpha_m)$. Moreover, a cyclotomic set \mathcal{J} is called *minimal* (for the exponent s above introduced) whenever every element in \mathcal{J} can be expressed as $p^{sj} \cdot \boldsymbol{\alpha}$ for some fixed $\boldsymbol{\alpha} \in \mathcal{J}$ and some nonnegative integer j . Fixing a representant $\mathbf{a} \in \mathcal{J}$ for each minimal cyclotomic set, one gets a set of representatives \mathcal{A} . Then, $\mathcal{J} = \mathcal{J}_{\mathbf{a}}$ for some $\mathbf{a} \in \mathcal{A}$. The family of minimal cyclotomic sets, with respect to s , will be $\{\mathcal{J}_{\mathbf{a}}\}_{\mathbf{a} \in \mathcal{A}}$ and we will denote $i_{\mathbf{a}} := \text{card}(\mathcal{J}_{\mathbf{a}})$. In addition, r is a multiple of $i_{\mathbf{a}}$ and, setting $\mathbf{a} = (a_1, a_2, \dots, a_m)$, the congruence $a_i \cdot p^{si_{\mathbf{a}}} \equiv a_i \pmod{N_i}$ holds.

The main advantage of considering cyclotomic sets is that any element $f \in R$ can be uniquely decomposed in the form $f = \sum_{\mathbf{a} \in \mathcal{A}} f_{\mathbf{a}}$, where $f_{\mathbf{a}}$ are classes of polynomials in R whose support (that of its canonical representative), $\text{supp}(f_{\mathbf{a}})$, is included in $\mathcal{J}_{\mathbf{a}}$.

Furthermore, it holds

$$\text{supp}(\mathcal{T}(f_{\mathbf{a}})) \subset \mathcal{J}_{\mathbf{a}}.$$

Our aim in this section consists of describing subfield-subcodes of the families of codes introduced in Section 3. We will need the concept of *element* $f \in R$ *evaluating to* \mathbb{F}_{p^s} . This means that $f(\boldsymbol{\alpha}) \in \mathbb{F}_{p^s}$ for all $\boldsymbol{\alpha} \in Z(I)$. This happens if and only if $f = \mathcal{T}(g)$ for some $g \in R$. Then, we can state the following result [16].

Theorem 7. *Let $\beta_{\mathbf{a}}$ be a primitive element of the finite field $\mathbb{F}_{p^{s i_{\mathbf{a}}}}$ and set $\mathcal{T}_{\mathbf{a}} : R \rightarrow R$ the mapping defined as $\mathcal{T}_{\mathbf{a}}(f) = f + f^{p^s} + \dots + f^{p^{s(i_{\mathbf{a}}-1)}}$. Then, a basis of the vector space of elements in R evaluating to \mathbb{F}_{p^s} is*

$$\bigcup_{\mathbf{a} \in \mathcal{A}} \left\{ \mathcal{T}_{\mathbf{a}}(\beta_{\mathbf{a}}^l X^{\mathbf{a}}) \mid 0 \leq l \leq i_{\mathbf{a}} - 1 \right\}.$$

Denote by Δ any of the sets generating (by applying ev to the monomials that represent) any of the codes described in Section 3, which we set E_{Δ} . Δ is a subset of the hypercube \mathfrak{H} for affine variety codes. For Reed-Muller codes, Δ will be the exponents set of the monomials in R of total degree less than or equal to certain positive integer r . Finally, when we consider a hyperbolic code, Δ will be the set of exponents appearing in the monomials in (3) for some value t as above mentioned. Consider the set $E_{\Delta}^{\sigma} = E_{\Delta} \cap \mathbb{F}_{p^s}^n$. E_{Δ}^{σ} is defined by the traces $\mathcal{T}(g)$ of elements $g \in R$ such that $\mathcal{T}(g)$ is in the vector space generated by monomials with exponents in Δ . As a consequence, one gets

Theorem 8. *The vector space E_{Δ}^{σ} is generated by the images under the evaluation map ev of the elements in R*

$$\bigcup_{\mathbf{a} \in \mathcal{A} \mid \mathcal{J}_{\mathbf{a}} \subset \Delta} \left\{ \mathcal{T}_{\mathbf{a}}(\beta_{\mathbf{a}}^l X^{\mathbf{a}}) \mid 0 \leq l \leq i_{\mathbf{a}} - 1 \right\}.$$

With respect to the dual code of E_{Δ}^{σ} , one can consider the following diagram:

$$\begin{array}{ccc} E_{\Delta} & \xrightarrow{\text{duality}} & E_{\Delta}^{\perp} \\ \downarrow & & \text{tr} \downarrow \\ E_{\Delta}^{\sigma} = E_{\Delta} \cap \mathbb{F}_{p^s}^n & \xrightarrow{\text{duality}} & (E_{\Delta}^{\sigma})^{\perp} = (E_{\Delta}^{\perp})^{\sigma} \end{array}$$

where we notice that the equality at the bottom right holds by Delsarte Theorem [9].

When we are dealing with affine variety codes E_{Δ} , we have defined in Subsection 3.3 the set Δ^{\perp} attached with Δ and defined the corresponding dual code. Analogously, for Reed-Muller codes, defined by the set Δ , corresponding to monomials in R of degree less than or equal to r , we can define Δ^{\perp} as the set of exponents of monomials in R of degree less than or equal to $m(q+1) - (r+1)$. Finally, for the case of hyperbolic codes $\text{Hyp}(t, m)$, the set Δ^{\perp} is showed in (4). Setting $C_{\Delta} = E_{\Delta}^{\perp}$ and $C_{\Delta}^{\sigma} = C_{\Delta} \cap \mathbb{F}_{p^s}^n$, the above diagram proves that $C_{\Delta}^{\sigma} = (E_{\Delta}^{\sigma})^{\perp}$ and thus C_{Δ}^{σ} is the vector space generated by $\text{tr}(\text{ev}(\Delta^{\perp}))$, that is the vector space generated by $\text{ev}(\mathcal{T}(\Delta^{\perp}))$, where Δ^{\perp} is defined as above. As a consequence, one gets the following result:

Theorem 9. *Let Δ be the defining set of a code as above. Consider its corresponding set Δ^{\perp} . With the above notations, the dual code C_{Δ}^{σ} of the code E_{Δ}^{σ} is generated by those vectors in $\mathbb{F}_{p^s}^n$ obtained by applying the map ev to the following set of elements in R*

$$\bigcup_{\mathbf{a} \in \mathcal{A} \mid \mathcal{J}_{\mathbf{a}} \cap \Delta^{\perp} \neq \emptyset} \left\{ \mathcal{T}_{\mathbf{a}}(\beta_{\mathbf{a}}^l X^{\mathbf{a}}) \mid 0 \leq l \leq i_{\mathbf{a}} - 1 \right\}.$$

Finally we state the next result which extends to Reed-Muller and hyperbolic codes Theorems 5 and 6 in [16].

Theorem 10. *Let Δ be an evaluating set as in Theorem 9 providing a Reed-Muller, a hyperbolic or an affine variety code. Consider the subfield-subcode E_Δ^σ and its dual one C_Δ^σ . Then*

- (1) *The dimension of the code C_Δ^σ can be computed as*

$$\dim(C_\Delta^\sigma) = \sum_{\mathbf{a} \in \mathcal{A} | \mathfrak{I}_\mathbf{a} \cap \Delta^\perp \neq \emptyset} i_\mathbf{a}.$$

- (2) *The inclusion $E_\Delta^\sigma \subset C_\Delta^\sigma$ holds if, and only if, $\mathfrak{I}_\mathbf{a} \cap \Delta^\perp \neq \emptyset$ whenever $\mathfrak{I}_\mathbf{a} \subset \Delta$, which in case of affine variety codes can be expressed as $\{\hat{\alpha} \mid \alpha \in \mathfrak{I}_\mathbf{a}\} \not\subset \Delta$ whenever $\mathfrak{I}_\mathbf{a} \subset \Delta$.*

5. QUANTUM STABILIZER CODES

This section is devoted to state results concerning quantum stabilizer codes by using results in previous sections. In this paper, using only Euclidean inner product, we will get good stabilizer codes from the above studied codes and their matrix-product codes. A nice way to do it employs orthogonal matrices over finite fields. By using a computer, it is not difficult to obtain such matrices for fields of small cardinality. We are especially interested in this situation because, in most cases, we will use subfield-subcodes. For larger fields, one can use orthogonal circulant matrices because, according to [26] (see also [34]), one may check whether the matrix is orthogonal by a condition on the polynomials determined by the first row and column of the matrix.

Now we are ready to state our main results. A_q will be an orthogonal $s \times s$ matrix over a finite field \mathbb{F}_q with attached code distances $\{\delta_i\}_{1 \leq i \leq s}$ as defined in Section 2.

Theorem 11. *Let $\{E_i\}_{i=1}^s$ (respectively, $E_1 \subset E_2 \subset \dots \subset E_s$) be a sequence (respectively, a nested sequence) of codes over a finite field \mathbb{F}_q of one of the following types:*

a) *The codes $E_i = RM(r_i, m)$, $m > 0$, $1 \leq i \leq s$, are Reed-Muller codes attached with a sequence of positive integers $\{r_i\}_{i=1}^s$ (respectively, $r_1 < r_2 < \dots < r_s$) satisfying $2r_i + 1 < m(q - 1)$ for all i (respectively, $2r_s + 1 < m(q - 1)$).*

b) *Each code E_i , $1 \leq i \leq s$, is spanned by the vectors of \mathbb{F}_q^n obtained applying ev to the set of monomials $\{X^\alpha \mid 0 \leq \alpha_j < q, 1 \leq j \leq m, \prod_{j=1}^m (\alpha_j + 1) < q^m - t_i\}$ such that, for all i , t_i is a positive integer as in Subsection 3.2 and satisfies Theorem 6 (respectively, t_i is a sequence of positive integer as in Subsection 3.2 such that $q^m > t_1 > t_2 > \dots > t_s$ and t_s satisfies Theorem 6).*

c) *$E_i = E_{\Delta_i}$ are affine variety codes such that for all i $\hat{\alpha} \notin \Delta_i$ (respectively, $\hat{\alpha} \notin \Delta_s$ and $\Delta_j \subset \Delta_{j+1}$, $1 \leq j \leq s - 1$) whenever $\alpha \in \Delta_i$ (respectively, $\alpha \in \Delta_s$).*

Consider the sequence of dual codes $\{C_i\}_{i=1}^s$ (respectively, $C_1 \supset C_2 \supset \dots \supset C_s$), where $C_i = E_i^\perp$. Then,

(1) *The matrix-product code $\mathfrak{C} = [C_1, C_2, \dots, C_s] \cdot A_q$ is an $[\mathbf{n}, \mathfrak{k}, \mathfrak{d}]$ -code over \mathbb{F}_q where $\mathbf{n} = ns$, $\mathfrak{k} = \sum_{i=1}^s k_i$ and $\mathfrak{d} \geq \min_{1 \leq i \leq s} \{\delta_i d_i\}$ (respectively $\mathfrak{d} = \min_{1 \leq i \leq s} \{\delta_i d_i\}$). Moreover according the above cases, the following statements hold.*

In case a), the dimensions k_i satisfy the equality (2) with r_i instead of r and, for all i , $d_i = (b_i + 1)q^{a_i}$, where $r_i + 1 = a_i(q - 1) + b_i$ obtained by Euclidean division.

In case b), the dimensions k_i satisfy the equality in (3) of Theorem 5 with t_i instead of t

and, for all i , $d_i = q^m - t_i$.

In case c), it happens $k_i = \text{card}(\Delta_i)$ and $d_i = \dim C_i$.

(2) \mathfrak{C} provides a stabilizer code with parameters $[[\mathbf{n}, \mathfrak{K}, \geq \mathfrak{d}]]_q$, where $\mathfrak{K} = 2\mathfrak{k} - \mathbf{n}$.

Proof. Theorem 2 together with results in Subsection 3.1 prove Statement (1) a). The same happens with Statement (1) b) and (1) c) if one uses Subsections 3.2 and 3.3, respectively. Corollaries 3 and 1 prove our Statement (2). \square

For subfield-subcodes, we get

Theorem 12. Let $\{E_i\}_{i=1}^s$ (respectively, $E_1 \subset E_2 \subset \dots \subset E_s$) be a family of codes (respectively, a nested sequence of codes) over a finite field \mathbb{F}_q defined as in Theorem 11, $q = p^r$ and consider the finite field \mathbb{F}_{p^s} , where s divides r . Set Δ_i , $1 \leq i \leq s$, the subsets of the ring R whose evaluation provides E_i and assume the following property: $\mathfrak{J}_{\mathbf{a}} \cap \Delta^\perp \neq \emptyset$ whenever $\mathfrak{J}_{\mathbf{a}} \subset \Delta$, where Δ and the minimal cyclotomic subsets $\mathfrak{J}_{\mathbf{a}}$ are as described in Section 4. Then, the matrix-product code $\mathfrak{C}^\sigma = [C_1^\sigma, C_2^\sigma, \dots, C_s^\sigma]_{A_{p^s}}$ is an $[[\mathbf{n}, \mathfrak{k}, \mathfrak{d}]]$ -code over \mathbb{F}_{p^s} , where $\mathbf{n} = ns$, $\mathfrak{k} = \sum_{i=1}^s k_i$, where $k_i = \sum_{\mathbf{a} \in \mathcal{A} | \mathfrak{J}_{\mathbf{a}} \cap \Delta^\perp \neq \emptyset} i_{\mathbf{a}}$ and $\mathfrak{d} \geq$ (respectively, $=$) $\min_{1 \leq i \leq s} \{\delta_i d_i\}$, the distances d_i being as in Theorem 11.

Finally, \mathfrak{C}^σ provides a stabilizer code with parameters $[[\mathbf{n}, \mathfrak{K}, \geq \mathfrak{d}]]_{p^s}$, where $\mathfrak{K} = 2\mathfrak{k} - \mathbf{n}$.

Proof. It follows from Theorems 10 and 11 and Corollaries 3 and 1. \square

Remark 2. The families of codes considered in this paper allow us to construct sequences of nested codes $C_1^\perp \subset \dots \subset C_s^\perp \subset C_s \subset \dots \subset C_1$. These sequences contain either codes as in Section 3 or subfield-subcodes or even matrix-product codes coming from the previous mentioned codes. Results in Section 3 and Theorems 11 and 12 give parameters $[[n, k_i, d_i]]$ for the above codes and one can get stabilizer codes by using Corollary 2. Indeed, consider two suitable subindices $1 \leq i < j \leq s$, then $C_j^\perp \subset C_j \subset C_i$ and, therefore, there exists an $[[n, k_i + k_j - n, \geq \min\{d_j, \lceil \frac{q+1}{q} \rceil d_i\}]]_q$ stabilizer code.

We devote the rest of the paper to provide new stabilizer codes over different base fields by using the results above stated.

6. QUANTUM STABILIZER CODES OVER \mathbb{F}_2

Along this section we will assume that our field is \mathbb{F}_2 . Firstly, we are going to show several quantum binary codes that improve the best known parameters given in [19]. Afterwards we will show some good stabilizer obtained with matrix-product codes coming from three constituent codes.

6.1. We get codes improving [19] by applying Corollary 2 to suitable subfield-subcodes of certain affine variety codes and also from some subcodes and extended codes of them. Indeed, with ideas and notations as in Section 4, set $p = 2, r = 7, s = 1$ and $N_1 = 127$. The following table shows parameters and defining sets Δ of stabilizer codes obtained with the CSS code construction of subfield-subcodes of the mentioned affine variety codes. Notice that, from Corollary 1, it is straightforward to get the parameters of the originally used linear codes.

Code	n	k	$d \geq$	Defining set Δ
C_1	127	85	7	{46, 92, 57, 114, 101, 75, 23, 110, 93, 59, 118, 109, 91, 55, 38, 76, 25, 50, 100, 73, 19}
C_2	127	57	11	{46, 92, 57, 114, 101, 75, 23, 110, 93, 59, 118, 109, 91, 55, 38, 76, 25, 50, 100, 73, 19, 42, 84, 41, 82, 37, 74, 21, 58, 116, 105, 83, 39, 78, 29}
C_3	127	71	9	{42, 84, 41, 82, 37, 74, 21, 6, 12, 24, 48, 96, 65, 3, 18, 36, 72, 17, 34, 68, 9, 30, 60, 120, 113, 99, 71, 15}
C_4	127	43	13	{42, 84, 41, 82, 37, 74, 21, 54, 108, 89, 51, 102, 77, 27, 6, 12, 24, 48, 96, 65, 3, 58, 116, 105, 83, 39, 78, 29, 18, 36, 72, 17, 34, 68, 9, 30, 60, 120, 113, 99, 71, 15}

TABLE 1. Stabilizer affine variety codes over \mathbb{F}_2

Steane's enlargement (in short, SE), Corollary 2, applied to the codes C_2 and C_1 (respectively, C_4 and C_3) provides stabilizer codes C_5 and C_6 . Next table shows parameters of these codes and some of their modifications. All these codes improve the best known records, which can be seen in [19] and have the same values n and k but distance one unit less.

Code	n	k	$d \geq$
$C_5 = \text{SE}(C_2, C_1)$	127	71	11
Extended code (C_5)	128	71	11
Subcode ($C_5, 70$)	127	70	11
Subcode ($C_5, 69$)	127	69	11
$C_6 = \text{SE}(C_4, C_3)$	127	57	13
Extended code (C_6)	128	57	13
Subcode ($C_6, 56$)	127	56	13

TABLE 2. Best known stabilizer codes over \mathbb{F}_2

6.2. There is no non-singular by columns orthogonal matrix of size 3×3 over \mathbb{F}_2 , however matrix-product codes suitable by providing quantum codes with $s = 3$ can be obtained by using the following matrix over \mathbb{F}_2 , whose transpose inverse is also displayed.

$$(6) \quad A = \begin{pmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}, \quad (A^{-1})^t = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix}.$$

Theorem 13. *Let C_1 and C_2 be linear codes over \mathbb{F}_2 with parameters $[n, k_1, d_1]$ and $[n, k_2, d_2]$ respectively, and such that $C_1 \supset C_1^\perp$ and $C_2 \supset C_2^\perp$. If A is the matrix showed in (6), then the following inclusion involving matrix-product codes holds:*

$$[C_1, C_1, C_2] \cdot A \supset ([C_1, C_1, C_2] \cdot A)^\perp.$$

Moreover, the previous constructed code yields a stabilizer code with parameters

$$[[3n, 2(2k_1 + k_2) - 3n, \geq \min\{2d_1, d_2\}]]_2.$$

Proof. The definition of matrix-product code and Theorem 3 show that a generic codeword of $([C_1, C_1, C_2] \cdot A)^\perp$ is of the form $(\mathbf{c}_1 + \mathbf{c}'_1 + \mathbf{c}_2, \mathbf{c}_1 + \mathbf{c}_2, \mathbf{c}'_1 + \mathbf{c}_2)$, where $\mathbf{c}_1, \mathbf{c}'_1$ are generic elements in the code C_1^\perp and \mathbf{c}_2 in C_2^\perp . Since $C_1 \supset C_1^\perp$ and $C_2 \supset C_2^\perp$, we have that $\mathbf{c}_1 \in C_1$

and $\mathbf{c}_2 \in C_2$. Switching the roles of \mathbf{c}_1 and \mathbf{c}'_1 , we conclude that $(\mathbf{c}_1 + \mathbf{c}'_1 + \mathbf{c}_2, \mathbf{c}_1 + \mathbf{c}_2, \mathbf{c}'_1 + \mathbf{c}_2)$ is also in $[C_1, C_1, C_2] \cdot A$, which proves our first statement.

By Theorem 2, the parameters of the matrix-product code $[C_1, C_1, C_2] \cdot A$ are $[3n, 2k_1 + k_2, \geq \min\{2d_1, d_2\}]$. Hence applying Corollary 1, it is obtained a stabilizer code with parameters $[[3n, 2(2k_1 + k_2) - 3n, \geq \min\{2d_1, d_2\}]_2$. \square

To finish this section, we are going to give some examples of stabilizer codes given by matrix-product codes as showed in Theorem 13. We use the same notation as in Subsections 3.1 and 3.2 and consider two cases: $m = 4$ and $m = 6$. In each case, we show a table containing parameters of stabilizer codes obtained from Reed-Muller or hyperbolic codes by using Corollary 1. Later, we present a second table of codes which are obtained with the matrix A in (6) and following Theorem 13; in the case denoted by $\text{SE}(D_3, D_1)$, we use the Steane's enlargement procedure of the codes D_3 and D_1 . With respect to the case $m = 4$, we set:

Code	n	k	$d \geq$
C_1	16	16	1
C_2	16	14	2
C_3	16	6	4

TABLE 3. Stabilizer codes over \mathbb{F}_2 by using Corollary 1, $m = 4$

As mentioned, it is not difficult to get the parameters of the original codes; for instance the stabilizer code $[[16, 14, 2]]_2$ comes from a (Reed-Muller) code C_1 over \mathbb{F}_2 with parameters $[16, 15, 2]$. Applying Theorem 13, we get stabilizer codes over \mathbb{F}_2 from matrix-product codes obtained with the previous codes C_i . Their parameters are:

Matrix-Product Code	Quantum Parameters
$D_1 := [C_1, C_1, C_2] \cdot A$	$[[48, 46, \geq 2]]_2$
$D_2 := [C_2, C_2, C_2] \cdot A$	$[[48, 42, \geq 2]]_2$
$D_3 := [C_2, C_2, C_3] \cdot A$	$[[48, 34, \geq 4]]_2$
$\text{SE}(D_3, D_1)$	$[[48, 40, \geq 3]]_2$

TABLE 4. Stabilizer codes of length 48 over \mathbb{F}_2 by using Theorem 13

Codes with these parameters are known, however this is a sample that good codes can be obtained with our techniques because our quantum code $[[48, 34, 4]]_2$ is as good as the best known quantum code with that length and dimension [19]. In addition, the parameters of the remaining codes in Table 4 cannot be improved.

Finally, with respect to $m = 6$, we give the following two tables:

Code	n	k	$d \geq$
C_4	64	64	1
C_5	64	62	2
C_6	64	50	4
C_7	64	20	8

TABLE 5. Stabilizer codes over \mathbb{F}_2 by using Corollary 1, $m = 6$

Matrix-Product Code	Quantum Parameters
$[C_4, C_4, C_5] \cdot A$	$[[192, 190, \geq 2]]_2$
$[C_5, C_5, C_6] \cdot A$	$[[192, 174, \geq 4]]_2$
$[C_6, C_6, C_7] \cdot A$	$[[192, 120, \geq 8]]_2$

TABLE 6. Stabilizer codes over \mathbb{F}_2 by using Theorem 13

Note that the first two codes in Table 6 exceed the Gilbert-Varshamov bounds [11, 36, 13], [29, Lemma 31].

7. QUANTUM STABILIZER CODES OVER \mathbb{F}_3

As in the previous section, we desire to give parameters for some stabilizer codes over the field \mathbb{F}_3 . We would also like use matrix-product codes, however, again in this case, there is no nonsingular by columns orthogonal matrix over \mathbb{F}_3 of size either 2×2 or 3×3 . A way to avoid this problem consists of using matrix-product codes with only two constituent codes. To do it, we consider the following matrix and its transpose inverse.

$$(7) \quad A = \begin{pmatrix} 1 & 1 \\ 2 & 1 \end{pmatrix}, \quad (A^{-1})^t = \begin{pmatrix} 2 & 2 \\ 1 & 2 \end{pmatrix}.$$

Theorem 14. *Let C_1, C_2 be two linear codes over \mathbb{F}_3 with parameters $[n, k_1, d_1]$ and $[n, k_2, d_2]$ respectively, and such that $C_1 \supset C_1^\perp$ and $C_2 \supset C_2^\perp$. If A is the matrix given in (7), then the following codes inclusion happens*

$$[C_1, C_2] \cdot A \supset ([C_1, C_2] \cdot A)^\perp.$$

Moreover, the above given matrix-product code yields a stabilizer quantum code with parameters

$$[[2n, 2(k_1 + k_2 - n), \geq \min\{2d_1, d_2\}]]_3.$$

Proof. A generic codeword of $([C_1, C_2] \cdot A)^\perp$ is of the form $(2\mathbf{c}_1 + \mathbf{c}_2, 2\mathbf{c}_1 + 2\mathbf{c}_2)$, where $\mathbf{c}_1 \in C_1^\perp$ and $\mathbf{c}_2 \in C_2^\perp$. Taking into account that multiplication by 2 gives an isomorphism of the field \mathbb{F}_3 and $C_1 \supset C_1^\perp$ and $C_2 \supset C_2^\perp$, we have that $(2\mathbf{c}_1 + \mathbf{c}_2, 2\mathbf{c}_1 + 2\mathbf{c}_2) \in [C_1, C_2] \cdot A$ because it corresponds to the words in $[C_1, C_2] \cdot A$ given, generically, by the elements $2\mathbf{c}_1 \in C_1$ and $2\mathbf{c}_2 \in C_2$.

The same reasoning as in Theorem 13 proves that $[C_1, C_2] \cdot A$ is a $[2n, k_1 + k_2, \geq \min\{2d_1, d_2\}]$ -code over \mathbb{F}_3 and yields a stabilizer code with parameters $[[2n, 2(k_1 + k_2 - n), \geq \min\{2d_1, d_2\}]]_3$. \square

As an example, if one considers suitable Reed-Muller codes of length 9 (respectively, hyperbolic codes of length 27) and applies Theorem 14 and Corollary 2, an $[[18, 13, 3]]_3$ (respectively, $[[54, 48, 3]]_3$) stabilizer code is obtained. Both of them exceed the Gilbert-Varshamov bounds [11, 36, 13], [29, Lemma 31], where we consider the natural extension to $q \neq 2$ of the bounds in [11, 36]. Note that the Gilbert-Varshamov bounds in [13], [29, Lemma 31] assume that $n \equiv k \pmod{2}$. In this paper, we say that an $[[n, k, d]]$ stabilizer code, $d \geq 2$, such that $n \not\equiv k \pmod{2}$ exceeds these Gilbert-Varshamov bounds when the parameters $[[n, k - 1, d]]$ do that. Next, we provide parameters of stabilizer codes, C_1 and C_2 , coming from subfield-subcodes of Reed-Muller or hyperbolic codes over \mathbb{F}_3 . With notations as in Sections 3 and 4, $p = 3, r = 2, s = 1$ and $m = 2$. Larger codes can be found with Theorem 14 as can be seen in Table 8. Note that the forthcoming code D can be

obtained with Steane's enlargement of certain matrix-product code of Reed-Muller codes.

Code	n	k	$d \geq$	Defining set Δ
C_1	81	79	2	$\{(0, 0)\}$
C_2	81	67	4	$\{(0, 0), (0, 7), (0, 5), (3, 0), (9, 0), (4, 0), (0, 4)\}$

TABLE 7. Stabilizer subfield-subcodes of Reed-Muller or hyperbolic codes over \mathbb{F}_3

Matrix-Product Code	Quantum Parameters
$[C_1, C_1] \cdot A$	$[[162, 158, \geq 2]]_3$
$[C_1, C_2] \cdot A$	$[[162, 146, \geq 4]]_3$
D	$[[162, 155, \geq 3]]_3$

TABLE 8. Stabilizer codes over \mathbb{F}_3 by using Theorem 14

We conclude this section giving parameters of several stabilizer codes over \mathbb{F}_3 obtained from subfield-subcodes of affine variety codes. As we have mentioned, we essentially consider Euclidean inner product and our parameters improve some of those given in [33], where the same inner product is used. With notations as in Section 4, setting $p = 3, r = 4, s = 1$ and $N_1 = 80$ and using suitable sets Δ and Corollary 2, we get stabilizer codes with parameters $[[80, 72, \geq 3]]_3$, $[[80, 64, \geq 4]]_3$, $[[80, 56, \geq 6]]_3$ and $[[80, 48, \geq 7]]_3$. In similar way, with $p = 3, r = 6, s = 1$ and $N_1 = 728$, we get a $[[728, 718, \geq 3]]_3$ stabilizer code. Considering Hermitian inner product, the parameters of the codes with length 80 can be improved [31, Table I]. M. Grassl communicated the authors the existence of a code with parameters $[[728, 720, \geq 3]]_3$ derived from a Hamming code over \mathbb{F}_9 .

To finish, we show quantum parameters and defining sets of a couple of codes over \mathbb{F}_3 of length 242, improving [33], for which we do not know stabilizer codes better than them. Consider $p = 3, r = 5, s = 1$ and $N_1 = 242$ and the corresponding tables for the supporting affine variety stabilizer codes and the codes improving [33] are the following:

Code	n	k	$d \geq$	Defining set Δ
C_1	242	222	4	$\{120, 118, 112, 94, 40, 75, 225, 191, 89, 25\}$
C_2	242	212	5	$\{120, 118, 112, 94, 40, 75, 225, 191, 89, 25, 21, 63, 189, 83, 7\}$
C_3	242	202	6	$\{120, 118, 112, 94, 40, 75, 225, 191, 89, 25, 21, 63, 189, 83, 7, 150, 208, 140, 178, 50\}$

TABLE 9. Stabilizer affine variety codes over \mathbb{F}_3

Code	n	k	$d \geq$
$\text{SE}(C_2, C_1)$	242	217	5
$\text{SE}(C_3, C_1)$	242	212	6

TABLE 10. Stabilizer codes over \mathbb{F}_3 improving [33]

8. QUANTUM STABILIZER CODES OVER \mathbb{F}_q : $q \neq 2, 3$

In this section, we are going to show parameters for some new and good stabilizer codes over certain finite fields \mathbb{F}_q , with $q \neq 2, 3$. To get orthogonal non-singular by columns matrices of small size, we have developed a MAGMA function to look for matrix-product

codes that produce good stabilizer codes. For a start we are going to consider matrices of size 3×3 over the fields \mathbb{F}_4 , \mathbb{F}_5 and \mathbb{F}_7 .

Set $q = 4$, there are 52 orthogonal 3×3 matrices over \mathbb{F}_4 , but only four of them are non-singular by columns. They are

$$\begin{pmatrix} 1 & a^2 & a^2 \\ a & 0 & a^2 \\ a & a & 1 \end{pmatrix}, \begin{pmatrix} 1 & a & a \\ a^2 & 0 & a \\ a^2 & a^2 & 1 \end{pmatrix}, \begin{pmatrix} a & a & 1 \\ a & 0 & a^2 \\ 1 & a^2 & a^2 \end{pmatrix}, \begin{pmatrix} a^2 & a^2 & 1 \\ a^2 & 0 & a \\ 1 & a & a \end{pmatrix},$$

a being a primitive element of the field \mathbb{F}_4 . For $q = 5$ (respectively, $q = 7$), we can say that one can find 104 (respectively, 304) orthogonal matrices over \mathbb{F}_5 (respectively, \mathbb{F}_7), 64 (respectively, 96) of them are non-singular by columns. As an example of a matrix over \mathbb{F}_5 (respectively, \mathbb{F}_7) of the last type, we have

$$\begin{pmatrix} 1 & 1 & 2 \\ 2 & 1 & 1 \\ 1 & 2 & 1 \end{pmatrix}, \left(\text{respectively, } \begin{pmatrix} 2 & 3 & 3 \\ 1 & 3 & 1 \\ 3 & 3 & 2 \end{pmatrix} \right).$$

In addition, it is not difficult to check that the only non-singular by columns orthogonal matrices of size 2×2 over \mathbb{F}_4 are:

$$\begin{pmatrix} a^2 & a \\ a & a^2 \end{pmatrix}, \begin{pmatrix} a & a^2 \\ a^2 & a \end{pmatrix}.$$

The following table contains parameters of stabilizer codes obtained with matrix-product codes of Reed-Muller or hyperbolic ones with $m = 2$. These codes are over the fields \mathbb{F}_4 , \mathbb{F}_5 or \mathbb{F}_7 , and we have used non-singular by columns matrices, as above given, and Theorem 11 and Corollary 2.

n	k	$d \geq$	Field	n	k	$d \geq$	Field
48	46	2	\mathbb{F}_4	48	42	3	\mathbb{F}_4
75	73	2	\mathbb{F}_5	75	70	3	\mathbb{F}_5
75	64	4	\mathbb{F}_5	147	145	2	\mathbb{F}_7
147	142	3	\mathbb{F}_7	147	136	4	\mathbb{F}_7

TABLE 11. Quantum codes derived from matrix-product codes

Every code in Table 11 marked with distance larger than or equal to 2 or 3 exceeds the Gilbert-Varshamov bounds [11, 36, 13], [29, Lemma 31] in the sense above explained. Our codes $[[75, 70, \geq 3]]_5$ and $[[75, 64, \geq 4]]_5$ have better relative parameters than some showed in [32] whose parameters are $[[71, 61, \geq 3]]_5$ and $[[71, 51, \geq 4]]_5$.

We look for good new stabilizer codes over the mentioned fields obtained from self-orthogonal subfield-subcodes of affine variety codes. Table 12 shows quantum parameters we have obtained from certain affine variety codes C_i . The defining subsets Δ_i are showed in Tables 13 and 14. Table 15 contains parameters obtained as described in Theorem 11 of stabilizer codes defined by using matrix-product codes with the self-orthogonal constituent codes in Table 12 and matrices as in the beginning of this section.

Code / Subset	n	k	$d \geq$	Field	Code / Subset	n	k	$d \geq$	Field
C_1 / Δ_1	63	49	4	\mathbb{F}_4	C_2 / Δ_2	63	43	6	\mathbb{F}_4
C_3 / Δ_3	63	37	7	\mathbb{F}_4	C_4 / Δ_4	63	31	8	\mathbb{F}_4
C_5 / Δ_5	63	25	9	\mathbb{F}_4	C_6 / Δ_6	496	496	1	\mathbb{F}_5
C_7 / Δ_7	496	494	2	\mathbb{F}_5	C_8 / Δ_8	496	486	3	\mathbb{F}_5
C_9 / Δ_9	496	480	4	\mathbb{F}_5	C_{10} / Δ_{10}	96	96	1	\mathbb{F}_5
C_{11} / Δ_{11}	96	94	2	\mathbb{F}_5	C_{12} / Δ_{12}	96	88	3	\mathbb{F}_5
C_{13} / Δ_{13}	96	84	4	\mathbb{F}_5	C_{14} / Δ_{14}	124	116	3	\mathbb{F}_5
C_{15} / Δ_{15}	124	110	4	\mathbb{F}_5	C_{16} / Δ_{16}	124	104	5	\mathbb{F}_5
C_{17} / Δ_{17}	624	614	3	\mathbb{F}_5	C_{18} / Δ_{18}	624	610	4	\mathbb{F}_5
C_{19} / Δ_{19}	342	328	4	\mathbb{F}_7	C_{20} / Δ_{20}	342	322	5	\mathbb{F}_7
C_{21} / Δ_{21}	144	144	1	\mathbb{F}_7	C_{22} / Δ_{18}	144	142	2	\mathbb{F}_7
C_{23} / Δ_{23}	144	136	3	\mathbb{F}_7	C_{24} / Δ_{24}	144	132	4	\mathbb{F}_7

TABLE 12. Quantum codes using affine variety codes

Finally, we use Corollary 2 for getting better stabilizer codes. The reader can find their parameters in Table 16. Comparing with [31, Table III], we obtain a new code $[[63, 31, \geq 9]]_4$ and the parameters of our remaining codes of length 63 coincide with those in [31, Table III]. Parameters of our codes on \mathbb{F}_5 of length 124 also coincide with [31] but our code $[[624, 612, 4]]_5$ is better than $[[624, 610, 4]]_5$ in [31]. Generally speaking we get the same parameters as in [31, Table III] and, occasionally, improve them. Furthermore, we also show good codes with lengths that cannot be reached in [31] and they either exceed the Gilbert-Varshamov bounds or improve [12] or satisfy both conditions.

Subset	p	r	s	N_1	N_2	N_3
$\Delta_1 = \{42, 44, 50, 11, 46, 58, 43\}$	2	6	2	63	-	-
$\Delta_2 = \{42, 44, 50, 11, 46, 58, 43, 41, 38, 26\}$	2	6	2	63	-	-
$\Delta_3 = \{42, 44, 50, 11, 46, 58, 43, 41, 38, 26, 57, 39, 30\}$	2	6	2	63	-	-
$\Delta_4 = \{42, 44, 50, 11, 46, 58, 43, 41, 38, 26, 57, 39, 30, 60, 51, 15\}$	2	6	2	63	-	-
$\Delta_5 = \{42, 44, 50, 11, 46, 58, 43, 41, 38, 26, 57, 39, 30, 60, 51, 15, 45, 54, 27\}$	2	6	2	63	-	-

TABLE 13. Defining sets of affine variety codes

Subset	p	r	s	N_1	N_2	N_3
$\Delta_6 = \emptyset$	5	3	1	31	4	4
$\Delta_7 = \{(0, 1, 3)\}$	5	3	1	31	4	4
$\Delta_8 = \{(0, 1, 3), (0, 3, 2), (9, 2, 3), (14, 2, 3), (8, 2, 3)\}$	5	3	1	31	4	4
$\Delta_9 = \{(0, 1, 3), (0, 3, 2), (9, 2, 3), (14, 2, 3), (8, 2, 3), (23, 2, 0), (22, 2, 0), (17, 2, 0)\}$	5	3	1	31	4	4
$\Delta_{10} = \emptyset$	5	6	1	24	4	-
$\Delta_{11} = \{(6, 2)\}$	5	6	1	24	4	-
$\Delta_{12} = \{(6, 2), (12, 1), (5, 2), (1, 2)\}$	5	6	1	24	4	-
$\Delta_{13} = \{(6, 2), (12, 1), (5, 2), (1, 2), (17, 3), (13, 3)\}$	5	6	1	24	4	-
$\Delta_{14} = \{(29, 0), (21, 0), (12, 0), (0, 3)\}$	5	3	1	31	4	-
$\Delta_{15} = \{(24, 0), (27, 0), (11, 0), (29, 0), (21, 0), (12, 0), (0, 3)\}$	5	3	1	31	4	-
$\Delta_{16} = \{(10, 1), (19, 1), (2, 1), (24, 0), (27, 0), (11, 0), (29, 0), (21, 0), (12, 0), (0, 3)\}$	5	4	1	624	-	-
$\Delta_{17} = \{156, 295, 227, 511, 59\}$	5	4	1	624	-	-
$\Delta_{18} = \{156, 295, 227, 511, 59, 130, 26\}$	5	4	1	624	-	-
$\Delta_{19} = \{57, 176, 206, 74, 331, 265, 145\}$	7	3	1	342	-	-
$\Delta_{20} = \{57, 176, 206, 74, 331, 265, 145, 252, 54, 36\}$	7	3	1	342	-	-
$\Delta_{21} = \emptyset$	7	2	1	48	3	-
$\Delta_{22} = \{(40, 0)\}$	7	2	1	48	3	-
$\Delta_{23} = \{(40, 0), (35, 0), (5, 0), (16, 2)\}$	7	2	1	48	3	-
$\Delta_{24} = \{(40, 0), (35, 0), (5, 0), (16, 2), (24, 1), (32, 2)\}$	7	2	1	48	3	-

TABLE 14. Defining sets of affine variety codes, continued

MP Code	Parameters	MP Code	Parameters
$D_1 := [C_6, C_7] \cdot A$	$[[992, 990, \geq 2]]_5$	$D_2 := [C_7, C_8] \cdot A$	$[[992, 980, \geq 3]]_5$
$D_3 := [C_7, C_9] \cdot A$	$[[992, 974, \geq 4]]_5$	$D_4 := [C_{10}, C_{10}, C_{10}] \cdot A$	$[[288, 286, \geq 2]]_5$
$D_5 := [C_{10}, C_{11}, C_{12}] \cdot A$	$[[288, 278, \geq 3]]_5$	$D_6 := [C_{11}, C_{11}, C_{13}] \cdot A$	$[[288, 272, \geq 4]]_5$
$D_7 := [C_{21}, C_{22}] \cdot A$	$[[288, 286, \geq 2]]_7$	$D_8 := [C_{22}, C_{23}] \cdot A$	$[[288, 278, \geq 3]]_7$
$D_9 := [C_{21}, C_{21}, C_{22}] \cdot A$	$[[432, 430, \geq 2]]_7$	$D_{10} := [C_{21}, C_{22}, C_{23}] \cdot A$	$[[432, 422, \geq 3]]_7$
$D_{11} := [C_{22}, C_{22}, C_{23}] \cdot A$	$[[432, 416, \geq 4]]_7$		

TABLE 15. Stabilizer codes coming from matrix-product codes

Corollary 2	Paramameters	Corollary 2	Paramameters
$SE(C_2, C_1)$	$[[63, 46, \geq 5]]_4$	$SE(C_4, C_2)$	$[[63, 37, \geq 8]]_4$
$SE(C_5, C_3)$	$[[63, 31, \geq 9]]_4$	$SE(C_8, C_7)$	$[[496, 490, \geq 3]]_5$
$SE(C_9, C_8)$	$[[496, 483, \geq 4]]_5$	$SE(D_2, D_1)$	$[[992, 985, \geq 3]]_5$
$SE(D_3, D_2)$	$[[992, 977, \geq 4]]_5$	$SE(C_{12}, C_{11})$	$[[96, 86, \geq 4]]_5$
$SE(D_5, D_4)$	$[[288, 283, \geq 3]]_5$	$SE(D_6, D_5)$	$[[288, 275, \geq 4]]_5$
$SE(C_{15}, C_{14})$	$[[124, 113, \geq 4]]_5$	$SE(C_{16}, C_{15})$	$[[124, 107, \geq 5]]_5$
$SE(C_{18}, C_{17})$	$[[624, 612, \geq 4]]_5$	$SE(C_{20}, C_{19})$	$[[342, 325, \geq 5]]_7$
$SE(C_{22}, C_{23})$	$[[144, 139, \geq 3]]_7$	$SE(C_{23}, C_{24})$	$[[144, 134, \geq 4]]_7$
$SE(D_8, D_7)$	$[[288, 282, \geq 3]]_7$	$SE(D_{10}, D_9)$	$[[432, 426, \geq 3]]_7$
$SE(D_{11}, D_{10})$	$[[432, 419, \geq 4]]_7$		

TABLE 16. Stabilizer codes coming from matrix-product codes and Corollary 2

9. CONCLUSION

We present new quantum stabilizer codes, our codes are obtained from algebraic linear codes using the CSS code construction and Steane's enlargement. We improve some binary codes of lengths 127 and 128 given in [19] and provide non-binary codes with parameters better than or equal to those in [31, Table III] and others whose lengths cannot be attained with the procedures in [31, 33]. In a future paper, we expect to obtain good codes using the same construction with respect to the Hermitian inner product.

ACKNOWLEDGEMENTS

The authors thank Olav Geil and Markus Grassl for helpful comments.

REFERENCES

- [1] Ashikhmin, A., Knill, E. Non-binary quantum stabilizer codes, *IEEE Trans. Inf. Theory* **47** (2001) 3065-3072.
- [2] Bian, Z. et al. Experimental determination of Ramsey numbers, *Phys. Rev. Lett.* **111** 130505 (2013).
- [3] Bierbrauer, J., Edel, Y. Quantum twisted codes, *J. Comb. Designs* **8** (2000) 174-188.
- [4] Blackmore, T., Norton, G.H. Matrix-product codes over \mathbb{F}_q , *Appl. Algebra Eng. Comm. Comp.* **12** (2001) 477-500.
- [5] Bosma, W., Cannon, J., Playoust, C. The Magma algebra system. I. The user language, *J. Symbolic Comput.* **24** (1997) 235-265.
- [6] Bras-Amorós, M., O'Sullivan, M.E. Duality for some families of correction capability optimized evaluation codes, *Adv. Math. Commun.* **2** (2008) 15-33.
- [7] Calderbank, A.R., Rains, E.M., Shor, P.W., Sloane, N.J.A. Quantum error correction via codes over $\text{GF}(4)$, *IEEE Trans. Inf. Theory* **44** (1998) 1369-1387.
- [8] Calderbank A.R., Shor, P. Good quantum error-correcting codes exist, *Phys. Rev. A* **54** (1996) 1098-1105.
- [9] Delsarte, P. On subfield subcodes of modified Reed-Solomon codes, *IEEE Trans. Inform. Theory* **IT-21** (1975) 575-576.
- [10] Delsarte, P. Goethals, J.M., MacWilliams, F.J. On generalized Reed-Muller codes and their relatives, *Inf. Control* **16** (1970) 403-442.
- [11] Ekert, A., Macchiavello, C. Quantum Error Correction for Communication, *Phys. Rev. Lett.* **77** (1996) 2585.
- [12] Edel, Y. *Some good quantum twisted codes*. Online available at <http://www.mathi.uni-heidelberg.de/~yves/Matritzen/QT BCH/QT BCHIndex.html>.
- [13] Feng, K., Ma, Z. A finite Gilbert-Varshamov bound for pure stabilizer quantum codes, *IEEE Trans. Inf. Theory* **50** (2004) 3323-3325.
- [14] Feng, G.L., Rao T.R.N. Improved geometric Goppa codes, part I: basic theory, *IEEE Trans. Inform. Theory* **41** (1995) 1678-1693.
- [15] Fitzgerald, J., Lax, R.F. Decoding affine variety codes using $\text{Gr}_{i, \frac{1}{2}}$ bner bases, *Des. Codes Cryptogr.* **13** (1998) 147-158.
- [16] Galindo, C., Hernando, F. Quantum codes from affine variety codes and their subfield-subcodes. *Des. Codes Cryptogr* **76** (2015) 89-100.
- [17] Geil, O. *Evaluation codes from an affine variety code perspective*. Advances in algebraic geometry codes, Ser. Coding Theory Cryptol. 5 (2008) 153-180. World Sci. Publ., Hackensack, NJ. Eds.: E. Martinez-Moro, C. Munuera, D. Ruano.
- [18] Geil, O., Hi $_{\frac{1}{2}}$ holdt, T. On hyperbolic codes, *Lect. Notes Comp. Sc.* **2227** (2001) 159-171.
- [19] Grassl, M. *Bounds on the minimum distance of linear codes*. Online available at <http://www.codetables.de> (2007).
- [20] Hamada, M. Concatenated quantum codes constructible in polynomial time: Efficient decoding and error correction, *IEEE Trans. Inform. Theory* **54** (2008) 5689-5704.
- [21] Hernando, F., Hi $_{\frac{1}{2}}$ holdt, T., Ruano, D. List Decoding of matrix-product codes from nested codes: an application to quasi-cyclic codes, *Adv. Math. Commun* **6** (2012) 259-272.

- [22] Hernando, F., Lally, K., Ruano, D. Construction and decoding of matrix-product codes from nested codes, *Appl. Algebra Eng. Comm. Comp.* **20** (2009) 497-507.
- [23] Hernando, F., Ruano, D. New linear codes from matrix-product codes with polynomial units, *Adv. Math. Commun.* **4** (2010) 363-367
- [24] Hernando, F., Ruano, D. Decoding of matrix-product codes, *J. Algebra Appl.* **12** (2013) 1250185.
- [25] Høholdt, T., van Lint, J.H., Pellikaan, R. *Algebraic geometry codes*. Handbook of coding theory, vol. I (1998) 871-961. Elsevier, Amsterdam. Eds.: V.S. Pless, W.C. Huffman, R.A. Brualdi.
- [26] Jungnickel, D., Beth, T., Geiselmann, W. A note on orthogonal circulant matrices over finite fields, *Arch. Math.* **62** (1994) 126-133.
- [27] Kabatiansky, G. Two generalizations of product codes, *Proc. of Academy of Science USSR, Cybernetics and Theory of Regulation* **232** (1977) 1277-1280 (in Russian).
- [28] Kasami, T., Lin, S., Peterson, W.W. New generalization of Reed-Muller codes. Part 1: primitive codes, *IEEE Trans. Inform. Theory* **14** (1968) 189-199.
- [29] Ketkar, A., Klappenecker, A., Kumar, S., Sarvepalli, P.K. Nonbinary stabilizer codes over finite fields, *IEEE Trans. Inform. Theory* **52** (2006) 4892-4914.
- [30] Knill, E., Laflamme, R. Theory of quantum error-correcting codes, *Phys. Rev. A* **55** (1997) 900-911.
- [31] La Guardia, G.G. Construction of new families of nonbinary quantum BCH codes, *Phys. Rev. A* **80** (2009) 042331.
- [32] La Guardia, G.G. On the construction of nonbinary quantum BCH codes, *IEEE Trans. Inform. Theory* **60** (2014) 1528-1535.
- [33] La Guardia, G.G., Palazzo, R. Constructions of new families of nonbinary CSS codes, *Discrete Math.* **310** (2010) 2935-2945.
- [34] MacWilliams, F.J. Orthogonal circulant matrices over finite fields, and how to find them, *J. Comb. Theory* **10** (1971) 1-17.
- [35] Massey, J., Costello, D.J., Justesen, J. Polynomial Weights and Code Constructions, *IEEE Trans. Inform. Theory* **19** (1973) 101-110.
- [36] Matsumoto, R., Uyematsu, T. Lower bound for the quantum capacity of a discrete memoryless quantum channel, *J. Math. Phys.* **43** (2002) 4391-4403.
- [37] Özbudak, F., Stichtenoth, H. Note on Niederreiter-Xing's propagation rule for linear codes. *Appl. Algebra Eng. Comm. Comp.* **13** (2003) 53-56.
- [38] Rains, E.M. Nonbinary quantum codes, *IEEE Trans. Inf. Theory* **45** (1999) 1827-1832.
- [39] Ruano, D. On the structure of generalized toric codes, *J. Symbolic Comput.* **44** (2009) 499-506.
- [40] Saints, K., Heegard, C. On hyperbolic cascaded Reed-Solomon codes, *Lect. Notes Comp. Sc.* **673** (1993) 291-303.
- [41] Sarvepalli, P.K., Klappenecker, A. Nonbinary quantum Reed-Muller codes. In Proc. 2005 Int. Symp. Information Theory, 1023-1027.
- [42] Shor, P.W. Algorithms for quantum computation: discrete logarithm and factoring, in Proc. 35th Ann. symp. foundations of computer science, *IEEE Computer Society Press* 1994, 124-134.
- [43] Shor, P.W. Scheme for reducing decoherence in quantum computer memory, *Phys. Rev. A* **52** (1995) 2493-2496.
- [44] Smith, G., Smolin, J. Putting "Quantumness" to the test, *Physics* **6** 105 (2013).
- [45] Steane, A.M. Simple quantum error correcting codes, *Phys. Rev. Lett.* **77** (1996) 793-797.
- [46] Steane, A.M. Quantum Reed-Muller codes, *IEEE Trans. Inform. Theory* **45** (1999) 1701-1703.
- [47] Steane, A.M. Enlargement of Calderbank-Shor-Steane quantum codes, *IEEE Trans. Inform. Theory* **45** (1999) 2492-2495.

Email address: Galindo: galindo@uji.es; Hernando: carrillf@uji.es; Ruano: diego@math.aau.dk