



New construction of quasi-twisted two-weight codes and related strongly regular graphs

Research Article

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Abstract: Two-weight codes can be used to construct secret sharing systems and to obtain strongly regular graphs. To construct new two-weight codes is a difficult problem. In this paper, a mixed integer programming model is presented to find quasi-twisted two-weight codes. A lot of quasi-twisted two-weight codes have been obtained. The new two-weight codes and their corresponding strongly regular graphs are presented.

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1. Introduction

A linear q -ary $[n, k, d]_q$ code over the finite field with q elements $GF(q)$ is a k -dimensional subspace of $GF(q)^n$, where q is a prime or prime power, n is the block length, k is the dimension of the code, while d is the minimum distance between any two codewords. One of the most important problems is to optimize one of the parameters n , k and d for given values of the other two: to find $d_q(n, k)$, the largest

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value of d , or to find $n_q(k, d)$, the smallest value of n , for which there exists an $[n, k, d]_q$ code. A code that achieves the $d_q(n, k)$ value or $n_q(k, d)$ value is called optimal. A fundamental challenge in coding theory is finding optimal codes. Due to the complexity of this problem, researchers often focus on cyclic and constacyclic codes, as well as their generalizations, including quasi-cyclic (*QC*) and quasi-twisted (*QT*) codes. It has been shown that the *QC* and *QT* codes contain many good linear codes. With the help of modern computers, many record-breaking *QC* and *QT* codes have been constructed [1, 2, 8, 9, 11, 13, 15–20, 26, 27].

The weight of a codeword is the number of nonzero coordinates in the codeword. In a two-weight code, the nonzero codewords have only two different weights, w_1 and w_2 , with $w_1 < w_2$. Two-weight codes have many applications. For example, they can be used to implement secret sharing schemes [28] and to construct strongly regular graphs [7]. The connection between two-weight codes and strongly regular graphs was presented by Delsarte [14]. An important survey on two-weight codes and related strongly regular graphs was presented by Calderbank and Kantor in [7], where families of two-weight codes were listed. In [4], the classification and construction of projective two-weight codes with relatively small parameters over small finite fields were presented. For such small parameters, back-track search techniques can be applied to find all two-weight codes and obtain a complete classification of these codes. The parameters of the classified two-weight codes can be found in [4] and [23]. In [21], a family of q -ary projective two-weight linear codes defined via trace functions was introduced, and several of their properties as well as applications were discussed. In [5], the fundamental properties, necessary conditions, lower and upper bounds, and constructions of two-weight codes with two distances d and $d + \delta$ were presented. The emphasis was on their existence criteria, bounds on their size, and geometric and algebraic structures. Similarly, in [25], the properties, classifications, and geometric representations of non-projective two-weight codes were discussed, with exhaustive enumeration used for codes with small parameters. Gulliver, in his search for good *QT* codes, found 3 new *QT* two-weight codes [15, 16]. In [24], Kohnert constructed new two-weight codes by solving Diophantine systems. One of the key references on strongly regular graphs is the book by Brouwer and Van Maldeghem [6], which offers more detailed information on two-weight codes, strongly regular graphs, and their constructions. Additionally, an online database of two-weight codes is also available [10], with entries mainly from [7].

In this paper, a new construction of *QT* two-weight codes is formulated as a mixed integer programming problem, and the IBM ILOG CPLEX Optimizer [22] is used to solve this optimization problem. The remainder of the paper is organized as follows. In Section 2, the definition of *QT* codes, and the relation to the strongly regular graphs are presented. In Section 3, a construction of *QT* two-weight codes is modelled as a mixed integer programming problem. In Section 4, new *QT* two-weight codes and their corresponding strongly regular graphs are presented.

2. Quasi-twisted codes, two-weight codes and strongly regular graphs

A linear $[n, k, d]_q$ code is called constacyclic if, whenever a codeword $(a_0, a_1, \dots, a_{n-1})$ is in the code, then so is $(\alpha a_{n-1}, a_0, \dots, a_{n-2})$, where α is a non-zero element in the field $GF(q)$ and is called the shift constant. A constacyclic code can be defined by its generator polynomial. Therefore, the cyclic code is a constacyclic code with $\alpha = 1$. A code is said to be quasi-twisted (*QT*) if a constacyclic shift of any codeword by p positions is also a codeword. Therefore, a constacyclic code is a *QT* code with $p = 1$, and a quasi-cyclic (*QC*) code is a *QT* code with $\alpha = 1$. The length n of a *QT* code is a multiple of p , i.e., $n = pm$, for some positive integer m .

A constacyclic matrix C is an $m \times m$ matrix:

$$C = \begin{bmatrix} c_0 & c_1 & c_2 & \dots & c_{m-1} \\ \alpha c_{m-1} & c_0 & c_1 & \dots & c_{m-2} \\ \alpha c_{m-2} & \alpha c_{m-1} & c_0 & \dots & c_{m-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha c_1 & \alpha c_2 & \alpha c_3 & \dots & c_0 \end{bmatrix}. \quad (1)$$

The algebra of $m \times m$ constacyclic matrices over $GF(q)$ is isomorphic to the algebra in the ring $GF(q)[x]/(x^m - \alpha)$, if C is mapped onto the polynomial formed by the elements of its first row, $c(x) = c_0 + c_1x + \dots + c_{m-1}x^{m-1}$, with the least significant coefficient to the left. The polynomial $c(x)$ is also called the defining polynomial of the matrix C . The generator matrix of a QT code can be transformed into rows of $m \times m$ constacyclic matrices by suitable permutation of columns and rows. A 1-generator QT code has the following form of the generator matrix [11, 26]:

$$G = [G_1 \ G_2 \ G_3 \ \dots \ G_p], \quad (2)$$

where G_i (for $i = 1, 2, \dots, p$) are $m \times m$ constacyclic matrices with defining polynomials $g_1(x), g_2(x), \dots, g_p(x)$. Due to the structure of the generator matrix, a QT code can be easily encoded. A lot of efforts have been made to construct good QT codes. In this paper, the QT structure is used to construct two-weight codes.

A linear code is called projective, if any two of its coordinates are linearly independent, or in other words, if the minimum distance of its dual code is at least three. According to Delsarte [14], for two-weight projective code over $GF(q)$, where $q = p^e$, and p is prime, the weights are of the form $w_1 = up^t$, and $w_2 = (u+1)p^t$, for suitable integers u and t , $u \geq 1$, $t \geq 0$. The two-weight codes discussed in this paper are projective.

A strongly regular graph is a K -regular graph with N vertices, where each pair of adjacent vertices has λ common neighbours, and each pair of non-adjacent vertices has μ common neighbours ($\lambda, \mu \geq 0$). Given a two-weight projective $[n, k]_q$ code of weights w_1 and w_2 , a strongly regular graph can be constructed [7] with the following parameters:

$$\begin{aligned} N &= q^k, \\ K &= n(q-1), \\ \lambda &= K^2 + 3K - q(w_1 + w_2) - Kq(w_1 + w_2) + q^2w_1w_2, \\ \mu &= q^2w_1w_2/q^k = K^2 + K - Kq(w_1 + w_2) + q^2w_1w_2. \end{aligned}$$

3. Constructions of two-weight codes by mixed integer programming

By eliminating the equivalent defining polynomials, and eliminating all redundant information polynomials, an $s \times s$ weight matrix A is used in the constructions [17, 18], as given below, where $g_t(x)$ is the t -th defining polynomial, $i_j(x)$ is the j -th information polynomial, a_{jt} is the Hamming weight of

$i_j(x)g_t(x) \pmod{(x^m - \alpha)}$, where m is the size of the constacyclic matrix and α is the shift constant.

$$A = \begin{array}{c|cccccc} & g_1(x) & g_2(x) & \dots & g_t(x) & \dots & g_s(x) \\ \hline i_1(x) & a_{1,1} & a_{1,2} & \dots & a_{1,t} & \dots & a_{1,s} \\ i_2(x) & a_{2,1} & a_{2,2} & \dots & a_{2,t} & \dots & a_{2,s} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ i_j(x) & a_{j,1} & a_{j,2} & \dots & a_{j,t} & \dots & a_{j,s} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ i_s(x) & a_{s,1} & a_{s,2} & \dots & a_{s,t} & \dots & a_{s,s} \end{array} \quad (3)$$

In [9], it was shown that the weight matrix can be obtained from a constacyclic simplex code of composite length. The weight matrices have been used to search for good QT codes [9, 15–19]. In this paper, the weight matrices are used to construct two-weight projective codes. To construct a QT two-weight $[pm, k]_q$ code, it is necessary to examine all combinations of the defining polynomials and find p defining polynomials such that the row sums of the corresponding p columns have values of w_1 or w_2 . This problem can be formulated as a mixed-integer programming problem [12].

Let $X = (x_1, x_2, \dots, x_s)$ be variables in the mixed-integer programming problem. To find a QT two-weight $[pm, k]_q$ code with non-zero weights w_1 and w_2 , ($w_1 < w_2$), it is sufficient to find an integer solution subject to the following constraints:

$$\sum_{t=1}^s a_{j,t}x_t = w_1 \text{ or } w_2, j = 1, 2, \dots, s \quad (4)$$

and

$$\sum_{t=1}^s x_t = p \quad (5)$$

with bounds $0 \leq x_t \leq 1$, $t = 1, 2, \dots, s$.

4. New QT two-weight codes and related strongly regular graphs

By solving the mixed integer programming formulated in the last section, a lot of QT two-weight projective codes have been found. As an example, let $q = 5$, $\alpha = 2$, $k = 6$ and $m = 21$. A weight matrix of 186×186 can be constructed. For $p = 18$, a new QT two-weight projective $[378, 6]_5$ or $[18 \times 21, 6]_5$ code with $w_1 = 300$ and $w_2 = 325$ is obtained. The 18 defining polynomials of the code are given below, with the lowest degree coefficient on the left, i.e. 24001 corresponds to the polynomial $2 + 4x + x^4$. The code has been checked with the Magma algebraic system [3]. No code with the same parameters was reported in literature [6].

14000110132243124113, 20121320443221223124, 331420211231001123002,
343421211420031200211, 11422413320313000212, 312442032004012224123,
441211023200340322102, 221444101013002012341, 31302112442323430112,
0331114241313210104, 301034123021214411104, 444040113242442302023,
14244140214402100111, 040441442322112040042, 224310320114203221313,
43442332434404003143, 242232410001040422121, 141014021022022211241.

For a weight matrix of small size, it is feasible to conduct the exhaustive search. As the size increases, it is impossible to solve it by using exhaustive search. For the above example with a weight matrix of size 186×186 and number of defining polynomials of $p = 18$, an exhaustive search requires the investigation of $\binom{186}{18} = 4.74 \times 10^{24}$ combinations in the worst case.

In [17, 18], Gulliver found 3 new two-weight codes when he conducted the search for good QC codes. In [24], the point sets in the projective geometry were used and Diophantine system of linear equations was modelled to construct two-weight codes. The mixed integer programming approach presented in this paper is new.

Table 1 lists QT two-weight codes and their corresponding strongly regular graphs, found by exhaustive search and mixed integer programming. In the table, it is noted that some QT two-weight codes found have the same parameters as ones in [6]. The two-weight codes with the same parameters as given in [7] are not given in the table. Among the new codes, the QT two-weight $[585, 6]_4$ code with $w_1 = 432$ and $w_2 = 448$, and the QT two-weight $[595, 4]_{13}$ code with $w_1 = 546$ and $w_2 = 559$ were constructed using exhaustive search during the early stage of this work, and they were included in [6]. The rest of the codes are constructed after the book [6] was published.

It is interesting to note that many QC two-weight codes for $q = 2$, $k = 16$, $m = 771$ have been found by solving the mixed integer programming problem, as shown in Table 2. For $p = 5, 10, 15, 16, 17, 20, 21, 22, 25, 27, 28, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41$ and 42 , the QC two-weight $[p \times 771, 16]_2$ codes are found. Among them, codes found with $p = 5t$, $p = 17$ and $p = 34$, where $t = 1, 2, 3, \dots, 8$, have the same parameters as the cyclotomic (CY) examples given in [7]. The code with $p = 16$ has the same parameter as one in [6]. Let $g_{1,5}(x), g_{2,5}(x), \dots, g_{5,5}(x)$ be the defining polynomials for the found QC two-weight $[5 \times 771, 16]_2$ code with $p = 5$, and $g_{1,16}(x), g_{2,16}(x), \dots, g_{16,16}(x)$ be the defining polynomials for the found QC two-weight $[16 \times 771, 16]_2$ code with $p = 16$. Then for $p = 21 = 5 + 16$, a QC two-weight $[21 \times 771, 16]_2$ code can be constructed by the defining polynomials of both codes, that is $g_{1,5}(x), g_{2,5}(x), \dots, g_{5,5}(x)$ and $g_{1,16}(x), g_{2,16}(x), \dots, g_{16,16}(x)$. This construction is an example of unions and differences construction in [6]. Table 2 shows that many QC codes can be obtained through the union construction. Column *Union Constructions* presents the union constructions, column *No Union Constructions* presents the given union construction is not applicable, and column *Note* gives the references where the codes of the same parameters can be found. The new codes are marked as *New*. No union constructions for codes with $p = 28$, and $p = 31$ are found. Therefore, the QC two-weight $[p \times 771, 16]_2$ codes for $p = 28$ and $p = 31$ are new. Furthermore, the QC two-weight $[p \times 771, 16]_2$ codes for $p = 36$, $p = 38$ and $p = 41$ are new, since no construction methods (including union construction) are known.

5. Conclusions

QT codes have good algebraic structures and have been shown to contain good linear codes. In this paper, we attempted to construct QT two-weight projective codes by formulating the construction as a mixed-integer programming problem. This approach is the first in the literature to construct two-weight codes with the quasi-twisted structure. Many QT two-weight codes have been found. From these two-weight codes, the corresponding strongly regular graphs can be obtained. New two-weight codes and their strongly regular graphs have been listed in the paper. These two-weight codes belong to the sporadic two-weight codes, since they do not fit in known families of two-weight codes [7]. Even if QT two-weight codes found have the same parameters as the known families of codes or existing codes, the construction methods are not the same and they might not be equivalent. As more and more sporadic two-weight codes and their corresponding strongly regular graphs are found, it may motivate further work on the subject and lead to the discovery of new families of two-weight codes.

Table 1. New QT two-weight codes and related strongly regular graphs

q	α	k	m	p	n	w_1	w_2	N	K	λ	μ	Note
2	1	16	771	16	12336	6144	6272	65536	12336	2192	2352	[6]
			771	21	16191	8064	8192	65536	16191	3902	4032	[6]
			771	22	16962	8448	8576	65536	16962	4298	4422	[6]
			771	27	20817	10368	10496	65536	20817	6548	6642	[6]
			771	28	21588	10752	10880	65536	21588	7052	7140	New
			771	31	23901	11904	12032	65536	23901	8672	8742	New
			771	32	24672	12288	12416	65536	24672	9248	9312	[6]
			771	33	25443	12672	12800	65536	25443	9842	9900	[6]
			771	36	27756	13824	13952	65536	27756	11732	11772	New
			771	37	28527	14208	14336	65536	28527	12398	12432	[6]
			771	38	29298	14592	14720	65536	29298	13082	13110	New
			771	39	30069	14976	15104	65536	30069	13784	13806	[6]
			771	41	31611	15744	15872	65536	31611	15242	15252	New
			771	42	32382	16128	16256	65536	32382	15998	16002	[6]
			1285	16	20560	10240	10368	65536	20560	6384	6480	New
			1285	19	24415	12160	12288	65536	24415	9054	9120	New
3	2	10	671	10	6710	4455	4536	59049	13420	2947	3080	New
			671	12	8052	5346	5427	59049	16104	4311	4422	New
			671	20	13420	8910	8991	59049	26840	12187	12210	New
3	2	12	3796	2	7592	5022	5103	531441	15184	427	434	New
			2920	10	29200	19440	19683	531441	58400	5911	6480	New
			4088	20	81760	54432	54675	531441	163520	50119	50400	New
			4745	21	99645	66339	66582	531441	199290	74619	74802	New
			4088	25	106288	70713	70956	531441	204400	78511	78680	New
			4745	23	109135	72657	72900	531441	218270	89569	89700	New
			4745	25	118625	78975	79218	531441	237250	105871	105950	New
			4088	30	122640	81648	81891	531441	245280	113175	113232	New
			4745	27	128115	85293	85536	531441	256230	123525	123552	New
4	1	6	13	45	585	432	448	4096	1755	746	756	New
				50	650	480	496	4096	1950	926	930	New
5	2	6	21	18	378	300	325	15625	1512	55	156	New
			42	30	1260	1000	1025	15625	5040	1595	1640	New
			42	33	1386	1100	1125	15625	5544	1943	1980	New
			42	36	1512	1200	1225	15625	6048	2323	2352	New
5	2	8	626	25	15650	12500	12625	390625	62600	9675	10100	New
			626	32	20032	16000	16125	390625	80128	16143	16512	New
			626	38	23788	19000	19125	390625	95152	22935	23256	New
			626	44	27544	22000	22125	390625	110176	30879	31152	New
			626	50	31300	25000	25125	390625	125200	39975	40200	New
			626	51	31926	25500	25625	390625	127704	41603	41820	New
			626	56	35056	28000	28125	390625	140224	50223	50400	New
			626	58	36308	29000	29125	390625	145232	53895	54056	New
			626	62	38812	31000	31125	390625	155248	61623	61752	New
			626	64	40064	32000	32125	390625	160256	65679	65792	New

Table 1. New QT two-weight codes and related strongly regular graphs (Continued)

q	α	k	m	p	n	w_1	w_2	N	K	λ	μ	Note
			626	68	42568	34000	34125	390625	170272	74175	74256	New
			1878	23	43194	34500	34625	390625	172776	76379	76452	New
			626	70	43820	35000	35125	390625	175280	78615	78680	New
			626	74	46324	37000	37125	390625	185296	87879	87912	New
			626	75	46950	37500	37625	390625	187800	90275	90300	New
			626	76	47576	38000	38125	390625	190304	92703	92720	New
7	5	4	5	25	125	105	112	2401	750	221	240	New
7	5	6	129	16	2064	1764	1813	117649	12384	1061	1332	New
			258	16	4128	3528	3577	117649	24768	5057	5256	New
			129	48	6192	5292	5341	117649	37152	11645	11772	New
			258	28	7224	6174	6223	117649	43344	15911	16002	New
			258	30	7740	6615	6664	117649	46440	18287	18360	New
			258	32	8256	7056	7105	117649	49536	20825	20880	New
			258	34	8772	7477	7546	117649	52632	23525	23562	New
			258	36	9288	7938	7987	117649	55728	26387	26406	New
13	6	4	119	5	595	546	559	28561	7140	1721	1806	New

Table 2. Union constructions of QC two-weight code for $q = 2$, $k = 16$, $m = 771$ from two QC two-weight codes

p	$[p \times 771, 16]$ code	Union Constructions	No Union Constructions	Note
1 – 4	no			
5	found			CY [7]
6 – 9	no			
10	found	5 + 5		CY [7]
11 – 14	no			
15	found	5 + 10		CY [7]
16	found			[6]
17	found			CY [7]
18	no			
19	no			
20	found	5 + 15, 10 + 10		CY [7]
21	found	5 + 16		[6]
22	found	5 + 17		[6]
23	no			
24	no			
25	found	5 + 20, 10 + 15		CY [7]
26	no			
27	found	10 + 17		[6]
28	found			New
29	no			
30	found	5 + 25, 10 + 20, 15 + 15		CY [7]

Table 2. Union constructions of QC two-weight code for $q = 2$, $k = 16$, $m = 771$ from two QC two-weight codes (Continued)

p	$[p \times 771, 16]$ code	Union Constructions	No Union Constructions	Note
31	found			New
32	found	$5 + 27, 16 + 16$		[6]
33	found	$5 + 28, 16 + 17$		[6]
34	found	$17 + 17$		[6]
35	found	$5 + 30, 10 + 25, 15 + 20$		CY [7]
36	found	$5 + 31$	$15 + 21$	New
37	found	$5 + 32, 10 + 27, 15 + 22, 16 + 21$		[6]
38	found	$10 + 28$	$5 + 33, 16 + 22, 17 + 21$	New
39	found	$5 + 34, 17 + 22$		[6]
40	found	$5 + 35, 10 + 30, 15 + 25, 20 + 20$		CY [7]
41	found	$5 + 36$	$20 + 21$	New
42	found	$5 + 37, 20 + 22$	$10 + 32$	[6]

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Declarations

Author contributions

All authors contributed equally to the conception, mathematical modeling, computational experiments, and writing of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest or competing interests.

Data availability

The dataset and database of two-weight codes are accessible online at <http://databases.cs.hkr.se/2weightcodes/search.php>.

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The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript, except for tools used solely for spelling, grammar, language editing, reference formatting, or similar routine editorial corrections.

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