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# Regular Hadamard Matrices, Maximum Excess and SBIBD

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# Regular Hadamard Matrices, Maximum Excess and SBIBD \*

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## Abstract

When  $k = q_1, q_2, q_1 q_2, q_1 q_4, q_2 q_3 N, q_3 q_4 N, q_1, q_2$  and  $q_3$  are prime power, where  $q_1 \equiv 1 \pmod{4}$ ,  $q_2 \equiv 3 \pmod{8}$ ,  $q_3 \equiv 5 \pmod{8}$ ,  $q_4 = 7$  or  $23$ ,  $N = 2^a 3^b t^2$ ,  $a, b = 0$  or  $1$ ,  $t \neq 0$  is an arbitrary integer, we prove that there exist regular Hadamard matrices of order  $4k^2$ , and also there exist  $SBIBD(4k^2, 2k^2 + k, k^2 + k)$ . We find new  $SBIBD(4k^2, 2k^2 + k, k^2 + k)$  for 233 values of  $k$ .

## 1 Preliminaries

An  $n \times n$  matrix  $H$  is called Hadamard matrix (or H-matrix) if every entry of the matrix is 1 or  $-1$ , and

$$HH^T = nI_n,$$

where  $I_n$  is an  $n \times n$  identity matrix. In this paper we use  $H^T$  to denote the transpose of a matrix  $H$ .

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We denote the excess of a  $H$ -matrix  $H = [a_{ij}]$  by  $\sigma(H)$ , where

$$\sigma(H) = \sum_{1 \leq i, j \leq n} a_{ij}.$$

Let  $\sigma(n) = \max\{\sigma(H)\}$ . The weight of a  $H$ -matrix  $H$ , denoted by  $W(H)$ , is the number of ones in the  $H$ . We define  $W(n) = \max\{W(H)\}$ . Note that the maximums are taken over all  $n \times n$   $H$ -matrices  $H$ . It is obvious that  $\sigma(H) = 2W(H) - n^2$  and  $\sigma(n) = 2W(n) - n^2$  (see [4], [5], [6], [7] for details).

M. R. Best [1] proved that

$$\sigma(n) \leq n\sqrt{n} \tag{1}$$

**Definition 1** (*Regular Hadamard Matrix*) A regular Hadamard matrix has the sum of each column of the matrix and the sum of each row of the matrix constant.

**Definition 2** (*SBIBD*) A symmetric balanced incomplete block design, called a  $SBIBD(v, k, \lambda)$ , is defined by a  $v \times v$  matrix  $M$ , which has every entry 0 or 1. The sum of each column and the sum of each row of the matrix is  $k$ . For any two columns  $c_i, c_j$  (and two rows  $r_i, r_j$ ),  $1 \leq i \neq j \leq v$ , the inner product of  $c_i$  and  $c_j$  ( $r_i$  and  $r_j$ ) is  $\lambda$  (see [10]).

With the result of this paper and those of [4], [9] the status of the existence of  $4k^2$ -Hadamard matrix and  $SBIBD(4k^2, 2k^2 + k, k^2 + k)$  becomes that they exist for  $k \in \{1, 3, 5, \dots, 45, 49, \dots, 69, 73, 75, 81, \dots, 101, 105, 107, 109, \dots, 125, 129, 131, 135, 137, 139, 143, \dots, 149, 153, \dots, 165, 169, \dots, 175, \dots, 189, 193, \dots, 197, 201, \dots, 207, 211, 215, 219, 221, 225, 227, 229, 233, 235, 241, \dots, 251, 257, 259, 261, 267, 269, 273, 275, 277, 281, \dots, 299, 303, 307, 313, \dots, 327, 331, \dots, 339, 343, \dots, 353, 361, 363, 371, 373, 375, 379, 387, 389, 391, 393, 397, 401, 405, \dots, 411, 415, 417, 419, 421, 427, 429, 433, 441, 443, 447, 449, 451, 457, 461, 467, 471, 475, 477, 489, 491, 495, 499, 507, 509, 511, 513, 519, 521, 523, 525, 529, 531, \dots, 543, 547, 549, 551, 557, 559, 563, 567, 569, 571, 575, 577, 579, 583, 587, 591, 593, 601, 603, 605, 609, 613, 617, \dots, 625, 633, 637, 641, 643, 645, 653, 655, 659, 661, 667, 671, 673, 675, 677, 679, 683, 687, 691, 695, 699, 701, 703, 707, 709, 723, 725, 729, 731, 733, 735, 739, 741, 747, 753, 757, 761, 763, 767, 769, 771, 773, 777, 779, 783, 787, 791, 797, 803, 807, 809, 811, 815, 819, 821, 827, 829, 831, 841, \dots, 859, 865, 867, 871, 875, 877, 879, 881, 883, 885, 891, 895, 897, 907, 909, 921, 925, 929, 931, 937, 939, 941, \dots, 947, 951, 953, 957, 959, 961, 963, 971, 975, 977, 979, 981, 993, 997, 999, q_1, q_2, q_1q_2, q_1q_4, q_2q_3N, q_3q_4N\}$ , where  $q_1, q_2$  and  $q_3$  are prime power,  $q_1 \equiv 1 \pmod{4}$ ,  $q_2 \equiv 3 \pmod{8}$ ,  $q_3 \equiv 5 \pmod{8}$ ,  $q_4 = 7$  or  $23$ ,  $N = 2^a 3^b t^2$ ,  $a, b = 0$  or  $1$ ,  $t \neq 0$  is an arbitrary integer,  $r \geq 0$ . This means we find 233 new values  $< 1000$ .

Let  $G$  be an *Abelian* group with the addition  $\oplus$  and the subtraction  $\ominus$ . We denote by  $\theta$  be the zero element in  $G$ . Consider the polynomials in the elements

of  $G$  over the field of rational number,  $\sum_{g \in G} a(g)g$ , where the integer  $a(g)$  is the number of occurrences of  $g$ , and define the addition by

$$\sum_{g \in G} a(g)g + \sum_{g \in G} b(g)g = \sum_{g \in G} (a(g) + b(g))g.$$

We denote  $\sum_{g \in A} g$  as  $A$ ,  $G = \sum_{g \in G} g$  and  $G^* = G - \theta$ . For any two subsets  $A, B \subset G$ , we define

$$A \ominus B = \sum_{a \in A, b \in B} (a \ominus b), \quad \Delta A = A \ominus A,$$

$$\Delta(A, B) = (A \ominus B) + (B \ominus A).$$

It is obviously that  $\Delta(A, A) = 2\Delta A$ . We define  $\Delta\phi = 0$ ,  $\Delta(\phi, A) = 0$  for any  $A \subset G$ .

**Definition 3 (DS)** Let  $D = \{a_1, \dots, a_k\}$  be a subset of a group  $G$  of order  $v$ . If for every non-zero element  $g \in G$  there are  $\lambda$  pairs  $(a_i, a_j)$ ,  $a_i, a_j \in D$ , such that

$$a_i \oplus a_j = g,$$

we call  $D$  a  $(v, k, \lambda)$ -difference set (DS).

**Definition 4 (Incidence matrix)** The incidence matrix  $A = (a_{ij})$  of a  $(v, k, \lambda)$ -difference set  $D$  is defined by ordering the elements of the group  $G = \{g_i\}$ ,  $i = 1, \dots, v$ . and defining

$$a_{ij} = \begin{cases} 1, & g_j \ominus g_i \in D, \\ 0, & \text{otherwise} \end{cases}$$

**Definition 5 (SDS)** Let  $D_i \subset G$ ,  $|D_i| = k_i$ ,  $i = 1, \dots, r$ . If

$$\sum_{i=1}^r \Delta D_i = \left( \sum_{i=1}^r k_i - \lambda \right) \theta + \lambda G,$$

$\lambda \geq 0$ , then  $D_1, \dots, D_r$  are  $r - \{v; k_1, \dots, k_r; \lambda\}$  supplementary difference sets (SDS), where  $v = |G|$ .

If  $k_1 = \dots = k_r = k$ , we simplify  $D_1, \dots, D_r$  to  $r - \{v; k; \lambda\}$  SDS. When  $r = 1$ , the SDS become the difference set (DS).

We only consider  $r = 4$ . Then we define  $\lambda = \sum_{i=1}^4 k_i - v$  in this paper. In this case, we call  $D_1, D_2, D_3, D_4$  type  $H$ -SDS.

**Definition 6 (Type  $H_1$ )** Let  $D_1, D_2, D_3, D_4 \subset G$  be SDS of order  $v$ .  $|D_i| = k_i$ ,  $i = 1, 2, 3, 4$ .  $D_1, D_2, D_3, D_4 \in H_1$  iff

$$\sum_{i=1}^4 \Delta D_i = v\theta + \lambda G,$$

and

$$\Delta(D_1, D_2) + \Delta(D_3, D_4) = \lambda G,$$

where  $\lambda = k_1 + k_2 + k_3 + k_4 - v$ .

**Definition 7** (*T-matrix*) Let  $T_1, T_2, T_3, T_4$  be  $n \times n$  matrices with entries  $(0, \pm 1)$ . Let  $I_n$  be an  $n \times n$  identity matrix. Then we call  $T_1, T_2, T_3, T_4$  *T-matrices* if

- (i)  $T_i T_j = T_j T_i$ ,  $1 \leq i, j \leq 4$ ,  $i \neq j$ ,
- (ii) there exists an  $n \times n$  monomial matrix  $R$  with  $R^T = R$ ,  $R^2 = I_n$ , such that  $(T_i R)^T = T_i R$ ,  $i = 1, 2, 3, 4$ ,
- (iii) if  $T_i = (t_{jk}^{(i)})$ ,  $1 \leq j, k \leq n$ ,  $i = 1, 2, 3, 4$ , then  $\sum_{i=1}^4 |t_{jk}^{(i)}| = 1$ ,  $i \leq j, k \leq n$ ,
- (iv)  $\sum_{i=1}^4 T_i T_i^T = n I_n$ ,

We use condition (i) and (ii) to replace the condition of circulant *T-matrices*, and matrix  $R$  may easily be found in *Abelian groups*.

**Definition 8** (*C-partitions*)  $A_1, A_2, \dots, A_8$  are called *C-partitions* of an abelian group  $G$  of order  $v$ , if the following three conditions are satisfied:

- (i)  $A_i \cap A_j = \phi$ ,  $i \neq j$ ;
- (ii)  $\bigcup_{i=1}^8 A_i = G$ ;
- (iii)  $\sum_{i=1}^8 \Delta A_i = v\theta + \sum_{i=1}^4 \Delta(A_i, A_{i+4})$ .

**Lemma 1** (*J. Seberry [7]*) The following conditions are equivalent:

- (i) There exists a Hadamard matrix of order  $4k^2$  with maximum excess  $8k^3$ .
- (ii) There exists a regular Hadamard matrix of order  $4k^2$ .
- (iii) There exists SBIBD( $4k^2, 2k^2 + k, k^2 + k$ ).

Some very useful methods to construct *Hadamard* matrices with maximum excess from *Willamson* matrices and *T-matrices* are given in [7].

**Lemma 2** (*M. Y. Xia and G. Liu [11]*) Let  $q$  be a prime power, if  $q \equiv 1 \pmod{4}$ , there exist  $4 - \{q^2; \frac{1}{2}q(q-1); q(q-2)\}$  supplementary difference sets.

**Lemma 3** (*M. Y. Xia and G. Liu [14]*) Let  $q$  be a power of a prime,  $q \equiv 3 \pmod{8}$ , then there exist  $4 - \{q^2; \frac{1}{2}q(q-1); q(q-2)\}$  supplementary difference sets.

**Lemma 4** (*Y. Q. Chen [2], M. Y. Xia [12]*) Let  $q = 2^a 3^b N^2$ ,  $a, b = 0$  or  $1$ ,  $N$  is an arbitrary integer, then there exist  $(4q^2, 2q^2 + q, q^2 + q)$  difference sets and Williamson type matrices (type 1)  $A_1, A_2, A_3$  and  $A_4$  of order  $q^2$  that satisfy

$$\begin{aligned} \sigma(A_1) = \sigma(A_2) = \sigma(A_3) = q^3, \quad \sigma(A_4) = -q^3, \\ A_1^2 + A_2^2 + A_3^2 + A_4^2 = 4q^2 I_{q^2}, \\ A_i A_j + A_k A_l = 0, \quad \{i, j, k, l\} = \{1, 2, 3, 4\}. \end{aligned} \quad (2)$$

**Lemma 5** (*M. Y. Xia and T. Xia [13]*) Let  $q_1$  be a prime power,  $q_1 \equiv 5 \pmod{8}$ ,  $q_2 = 2^a 3^b N^2$ ,  $a, b = 0$  or  $1$ ,  $N$  is an arbitrary integer, then there exist  $(1, -1)$  Williamson type matrices (type 1)  $A_1, A_2, A_3$  and  $A_4$  of order  $(q_1 q_2)^2$  that satisfy:

$$\begin{aligned} \sigma(A_1) = \sigma(A_2) = \sigma(A_3) = (q_1 q_2)^3, \quad \sigma(A_4) = -(q_1 q_2)^3, \\ A_1 A_1^T + A_2 A_2^T + A_3 A_3^T + A_4 A_4^T = 4(q_1 q_2)^2 I_{(q_1 q_2)^2}, \\ A_1 A_2^T + A_2 A_1^T + A_3 A_4^T + A_4 A_3^T = 0. \end{aligned} \quad (3)$$

**Proposition 1** Let  $p \equiv 5 \pmod{8}$  be a prime,  $q \equiv 2^a 3^b N^2$ ,  $a, b = 0$  or  $1$ ,  $N$  be an arbitrary integer, for any integer  $r \geq 1$ , there exist  $(1, -1)$  matrices  $A_1, A_2, A_3$  and  $A_4$  of order  $(p^r q)^2$  that satisfy

$$\begin{aligned} \sigma(A_1) = \sigma(A_2) = \sigma(A_3) = (p^r q)^3, \quad \sigma(A_4) = -(p^r q)^3, \\ \sum_{i=1}^4 A_i A_i^T = 4(p^r q)^2 I_{(p^r q)^2}, \\ A_1 A_2^T + A_2 A_1^T + A_3 A_4^T + A_4 A_3^T = 0 \end{aligned} \quad (4)$$

**Proof.** When  $q_1 = p^{2r+1}$ , then  $q_1 \equiv 5 \pmod{8}$ . Then from lemma 5, the result is true.

When  $q_1 = p^{2r} = (p^r)^2$ , from lemma 4 we have the result. This completes the proof.  $\square$

**Remark.** By using definition 6 we can say when  $p \equiv 5 \pmod{8}$ ,  $q = 2^a 3^b N^2$ ,  $a, b = 0$  or  $1$ ,  $N$  is an arbitrary integer, for any integer  $r \geq 1$ , there exist SDS  $D_1, D_2, D_3$  and  $D_4$  of order  $p^{2r} q^2$  and type  $H_1$ . We say  $H_1(p^{2r} q^2) \neq \phi$ , wherever such SDS exist for order  $p^{2r} q^2$ .

In section 2 we use SDS to construct SBIBD In section 3 we use SDS and  $T$ -matrices to construct SBIBD. We find new results which give many new SBIBDs.

## 2 Construct SBIBD from SDS

**Theorem 1** If there exist  $4 - \{q^2; \frac{1}{2}q(q-1); q(q-2)\}$  SDS on an Abelian group  $G$  of order  $q^2$ , then there exist SBIBD  $(4q^2, 2q^2 + q, q^2 + q)$ .

**Proof.** Let  $D_1, D_2, D_3, D_4$  be  $4 - \{q^2; \frac{1}{2}q(q-1); q(q-2)\}$  SDS on  $G$ , since we have

$$|D_1| = |D_2| = |D_3| = |D_4| = \frac{1}{2}q(q-1), \quad \sum_{i=1}^4 \Delta D_i = q^2 \theta + q(q-2)G.$$

Let  $g_1, \dots, g_{q^2}$  be the arbitrary order of  $G$ , set

$$A_i = (a_{jk}^{(i)})_{1 \leq j, k \leq q^2}, \quad a_{jk}^{(i)} = \begin{cases} -1 & \text{if } g_k \ominus g_j \in D_i, \\ 1 & \text{otherwise,} \end{cases} \quad i = 1, 2, 3, 4, \quad (5)$$

$$R = (r_{jk})_{1 \leq j, k \leq q^2}, \quad r_{jk} = \begin{cases} 1 & \text{if } g_j \oplus g_k = 0, \\ 0 & \text{otherwise.} \end{cases} \quad (6)$$

It is obvious that  $A_1, A_2, A_3, A_4$  are matrices of type 1. In this case

- (i)  $A_i A_j = A_j A_i, i \neq j, i, j = 1, 2, 3, 4,$
- (ii)  $(A_i R)^T = A_i R, i = 1, 2, 3, 4,$
- (iii)  $\sum_{i=1}^4 A_i A_i^T = 4q^2 I_{q^2}.$

Since  $|D_i| = \frac{1}{2}q(q-1)$ , there exist  $\frac{1}{2}q(q+1)$  ones and  $\frac{1}{2}q(q-1)$  negative ones in each row of  $A_i, i = 1, 2, 3, 4,$  so  $\sigma(A_i) = q^3, i = 1, 2, 3, 4.$  Set

$$H = \begin{pmatrix} -A_1 & A_2 R & A_3 R & A_4 R \\ A_2 R & A_1 & A_4^T R & -A_3^T R \\ A_3 R & -A_4^T R & A_1 & A_2^T R \\ A_4 R & A_3^T R & -A_2^T R & A_1 \end{pmatrix}. \quad (7)$$

It is easy to verify that  $HH^T = 4q^2 I_{4q^2}, \sigma(A_i) = \sigma(A_i R) = \sigma(A_i^T R), i = 1, 2, 3, 4.$  So we have

$$\sigma(H) = 2\{\sigma(A_1) + \sigma(A_2) + \sigma(A_3) + \sigma(A_4)\} = 8q^3.$$

From lemma 1,  $\frac{1}{2}(H + J)$  is a  $SBIBD(4q^2, 2q^2 + q, q^2 + q).$  This completes the proof.  $\square$

**Proposition 2** *Let  $q$  be a prime power,  $q \equiv 1 \pmod{4}$  or  $q \equiv 3 \pmod{8}.$  There exist  $SBIBD(4q^2, 2q^2 + q, q^2 + q).$*

**Proof.** From lemma 2, lemma 3 and theorem 1 the conclusion is true.  $\square$

**Remark.** When  $q \equiv 1 \pmod{4}$  is a prime power, there exist *Williamson* type matrices  $A_1, A_2, A_3$  and  $A_4$  of order  $q^2,$  that make the matrix  $H$  of (7) have maximum excess and the form

$$H = \begin{pmatrix} -A_1 & A_2 & A_3 & A_4 \\ A_2 & A_1 & A_4 & -A_3 \\ A_3 & -A_4 & A_1 & A_2 \\ A_4 & A_3 & -A_2 & A_1 \end{pmatrix}. \quad (8)$$

**Lemma 6** *Let  $q = 2^a 3^b N^2, a, b = 0$  or  $1, N$  be arbitrary integer. There exists  $SBIBD(4q^2, 2q^2 + q, q^2 + q).$*

**Proof.** From lemma 4, there exist  $DS$  of type  $(4q^2, 2q^2 + q, q^2 + q)$ , the  $(0, 1)$  incidence matrix  $B$  of the  $DS$  is an  $SBIBD(4q^2, 2q^2 + q, q^2 + q)$ . The proof is completed.  $\square$

**Remark.** From lemma 4 we know that there exist *Williamson* type matrices  $A_1, A_2, A_3, A_4$  of order  $q^2$  that satisfy (2). In this case, the matrix  $H$  of order  $4q^2$  with maximum excess has the following form

$$H = \begin{pmatrix} A_1 & A_2 & A_3 & A_4 \\ A_2 & A_1 & A_4 & A_3 \\ A_3 & A_4 & A_1 & A_2 \\ A_4 & A_3 & A_2 & A_1 \end{pmatrix}, \quad (9)$$

or

$$H = \begin{pmatrix} A_1 & A_2 & A_3 & A_4 \\ A_2 & A_3 & A_4 & A_1 \\ A_3 & A_4 & A_1 & A_2 \\ A_4 & A_1 & A_2 & A_3 \end{pmatrix}. \quad (10)$$

**Lemma 7** Let  $p \equiv 5(\text{mod } 8)$  be a prime,  $q = 2^a 3^b p^c N^2$ ,  $a, b, c = 0$  or  $1$ ,  $N$  be an arbitrary integer. Then there exists  $SBIBD(4q^2, 2q^2 + q, q^2 + q)$ .

**Proof.** When  $c = 0$ , from lemma 6, the lemma 7 is true. When  $c = 1$ , from lemma 5 that there exist  $(1, -1)$  matrices (type 1)  $A_1, A_2, A_3$  and  $A_4$  of order  $q^2$  that satisfy (3). Let

$$H = \begin{pmatrix} A_1 & A_2 & A_3 & A_4 \\ A_2 & A_1 & A_4 & A_3 \\ -A_3^T & -A_4^T & A_1^T & A_2^T \\ -A_4^T & -A_3^T & A_2^T & A_1^T \end{pmatrix}, \quad (11)$$

then  $HH^T = 4q^2 I_{4q^2}$ ,  $\sigma(H) = 4(\sigma(A_1) + \sigma(A_2)) = 8q^3$ . So the matrix  $H$  of (11) is an *Hadamard* matrix with maximum excess. In this case, from lemma 1 there exists  $SBIBD(4q^2, 2q^2 + q, q^2 + q)$ . The proof is completed.  $\square$

**Proposition 3** Let  $q = 2^{r_1} 3^{r_2} p^{r_3} N^2$ ,  $p \equiv 5(\text{mod } 8)$  be a prime,  $r_1, r_2, r_3$  be integers and  $r_1, r_2, r_3 \geq 0$ ,  $N$  be an arbitrary integer. Then lemma 7 still holds.

**Proof.** Let  $r_i = 2m_i + a_i$ ,  $0 \leq a_i \leq 1$ ,  $i = 1, 2, 3$ , then  $q = 2^{a_1} 3^{a_2} p^{a_3} (2^{m_1} 3^{m_2} p^{m_3} N)^2$ . From lemma 7 the result is true.  $\square$

### 3 Construct SBIBD from SDS and T-matrices

More details of *T-matrices* are discussed in [3]. In this paper we refer to the paper [15].

**Theorem 2** *If there exist  $4 - \{q^2; \frac{1}{2}q(q-1); q(q-2)\}$  SDS  $D_1, D_2, D_3, D_4$  of order  $q^2$  in an Abelian group  $G$ , and every entry of  $G$  appears an even number of times in  $D_1, D_2, D_3, D_4$ , then there exist *T-matrices*  $T_1, T_2, T_3, T_4$  that satisfy*

$$\sigma(T_1) = q^3, \quad \sigma(T_2) = \sigma(T_3) = \sigma(T_4) = 0.$$

**Proof.** Let

$$\begin{aligned} E_1 &= G \setminus (D_1 \cup D_2 \cup D_3 \cup D_4), & E_2 &= (D_1 \cap D_2) \setminus E_5, \\ E_3 &= (D_1 \cap D_3) \setminus E_5, & E_4 &= (D_1 \cap D_4) \setminus E_5, \\ E_5 &= D_1 \cap D_2 \cap D_3 \cap D_4, & E_6 &= (D_3 \cap D_4) \setminus E_5, \\ E_7 &= (D_2 \cap D_4) \setminus E_5, & E_8 &= (D_2 \cap D_3) \setminus E_5. \end{aligned}$$

From [15] we know

$$\begin{aligned} E_i \cap E_j &= \phi, \quad i \neq j, \quad 1 \leq i, j \leq 8, \\ G &= \cup_{i=1}^8 E_i, \\ \sum_{i=1}^8 \Delta E_i &= q^2\theta + \sum_{i=1}^4 \Delta(E_i, E_{i+4}), \end{aligned}$$

and

$$\begin{aligned} D_1 &= E_5 \cup E_2 \cup E_3 \cup E_4, & D_2 &= E_5 \cup E_2 \cup E_7 \cup E_8 \\ D_3 &= E_5 \cup E_3 \cup E_6 \cup E_8, & D_4 &= E_5 \cup E_4 \cup E_6 \cup E_7. \end{aligned}$$

Set  $|E_i| = e_i, i = 1, \dots, 8$ , we have

$$\begin{aligned} |D_1| &= e_2 + e_3 + e_4 + e_5, & |D_2| &= e_2 + e_5 + e_7 + e_8, \\ |D_3| &= e_3 + e_5 + e_6 + e_8, & |D_4| &= e_4 + e_5 + e_6 + e_7. \end{aligned}$$

Since  $|D_1| = |D_2| = |D_3| = |D_4| = \frac{1}{2}q(q-1)$ , then

$$e_2 - e_6 = e_3 - e_7 = e_4 - e_8 = 0.$$

Since

$$\begin{aligned} q^2 &= |G| = |\cup_{i=1}^8 E_i| = \sum_{i=1}^8 e_i = e_1 + e_5 + 2(e_2 + e_3 + e_4) \\ &= e_1 - e_5 + 2(e_2 + e_3 + e_4 + e_5) = e_1 - e_5 + q(q-1), \end{aligned}$$

then  $e_1 - e_5 = q$ . Let  $g_1, \dots, g_{q^2}$  be an arbitrary order of entries of  $G$ , and

$$T_i = \left( t_{jk}^{(i)} \right)_{1 \leq j, k \leq q^2}, t_{jk}^{(i)} = \begin{cases} 1 & \text{if } g_k \ominus g_j \in E_i, \\ -1 & \text{if } g_k \ominus g_j \in E_{i+4}, \quad i = 1, 2, 3, 4. \\ 0 & \text{otherwise,} \end{cases}$$

$T_1, T_2, T_3, T_4$  are T-matrices of order  $q^2$  and

$$\sigma(T_1) = q^3, \quad \sigma(T_2) = \sigma(T_3) = \sigma(T_4) = 0.$$

This completes the proof.  $\square$

**Proposition 4** *Let  $q$  be a prime power and  $q \equiv 3 \pmod{8}$ , then there exist T-matrices  $T_1, T_2, T_3$  and  $T_4$  of order  $q^2$  that satisfy theorem 2.*

**Theorem 3** *If there exist T-matrices  $T_1, T_2, T_3$  and  $T_4$  of order  $t^2$ , and  $\sigma(T_1) = t^3$ ,  $\sigma(T_2) = \sigma(T_3) = \sigma(T_4) = 0$ , then there exists SBIBD( $4k^2, 2k^2 + k, k^2 + k$ ),  $k = tq$ , where  $q \equiv 1 \pmod{4}$  is any prime power.*

**Proof.** When  $q \equiv 1 \pmod{4}$  is a prime power, from lemma 2 we know there exist  $4 - \{q^2; \frac{1}{2}q(q-1); q(q-2)\}$  SDS. In this case from theorem 1 we have Williamson type (type 1) matrices  $A_1, A_2, A_3$  and  $A_4$  of order  $q^2$  which are satisfy

- (i)  $A_i = A_i^T, A_i A_j = A_j A_i, 1 \leq i, j \leq 4, i \neq j,$
- (ii)  $\sum_{i=1}^4 A_i^2 = 4q^2 I_{q^2},$
- (iii)  $\sigma(A_1) = \sigma(A_2) = \sigma(A_3) = \sigma(A_4) = q^3.$

Let

$$\begin{aligned} B_1 &= T_1 \times A_1 + T_2 \times A_2 + T_3 \times A_3 + T_4 \times A_4, \\ B_2 &= T_1 \times A_2 - T_2 \times A_1 + T_3 \times A_4 - T_4 \times A_3, \\ B_3 &= T_1 \times A_3 + T_2 \times A_4 - T_3 \times A_1 - T_4 \times A_2, \\ B_4 &= T_1 \times A_4 - T_2 \times A_3 - T_3 \times A_2 + T_4 \times A_3, \end{aligned} \tag{12}$$

where  $\times$  is Kronecker product. It is obvious that  $B_i B_j = B_j B_i, i \neq j, i, j = 1, 2, 3, 4,$  and

$$\sum_{i=1}^4 B_i B_i^T = \left( \sum_{i=1}^4 T_i T_i^T \right) \times \left( \sum_{i=1}^4 A_i^2 \right) = 4(tq)^2 I_{(tq)^2}.$$

Since  $\sigma(T_i \times A_i) = \sigma(T_i) \sigma(A_i), i = 1, 2, 3, 4,$

$$\sigma(B_1) = \sigma(B_2) = \sigma(B_3) = \sigma(B_4) = (tq)^3.$$

Let

$$Q = R \times I_{q^2}, \quad (13)$$

where  $R$  is a monomial matrix of order  $t^2$  that satisfies  $R = R^T$ ,  $R^2 = I$ , and  $(T_i R)^T = T_i R$ ,  $i = 1, 2, 3, 4$ . It is easy to show that  $Q$  is a permutation matrix and  $(B_i Q)^T = B_i Q$ ,  $i = 1, 2, 3, 4$ . Let

$$H = \begin{pmatrix} B_1 & B_2 Q & -B_3 Q & B_4 Q \\ B_2 Q & -B_1 & B_4^T Q & B_3^T Q \\ B_3 Q & B_4^T Q & B_1 & -B_2^T Q \\ -B_4 Q & B_3^T Q & B_2^T Q & B_1 \end{pmatrix} \quad (14)$$

Then  $HH^T = 4k^2 I_{4k^2}$ , and  $\sigma(H) = 2(\sum_{i=1}^4 \sigma(B_i)) = 8k^3$ . In this case, the matrix  $H$  of order  $4k^2$  defined from (12), (13), (14) has the maximum excess. There exist  $SBIBD(4k^2, 2k^2 + k, k^2 + k)$ ,  $k = tq$ . The proof is complete.  $\square$

**Proposition 5** *When  $k = q_1 q_2$ , where  $q_1 = 1 \pmod{4}$ ,  $q_2 = 3 \pmod{8}$  are prime powers, there exist  $SBIBD(4k^2, 2k^2 + k, k^2 + k)$ .*

**Proof.** From [15] we know that there exist  $T$ -matrices  $T_1, T_2, T_3, T_4$  satisfying theorem 3. This completes the proof.  $\square$

**Theorem 4** *Suppose*

1. *there exist  $T$ -matrices  $T_1, T_2, T_3, T_4$  of order  $t^2$  that satisfy*

$$\sigma(T_1) = t^3, \quad \sigma(T_2) = \sigma(T_3) = \sigma(T_4) = 0,$$

*and*

2. *there exist  $(1, -1)$  matrices (type 1)  $A_1, A_2, A_3$  and  $A_4$  of order  $q^2$  that satisfy*

$$(i) \quad \sum_{i=1}^4 A_i A_i^T = 4q^2 I_{q^2},$$

$$(ii) \quad A_1 A_2^T + A_2 A_1^T + A_3 A_4^T + A_4 A_3^T = 0,$$

$$(iii) \quad \sigma(A_1) = \sigma(A_2) = \sigma(A_3) = q^3 = -\sigma(A_4).$$

*Then there exist  $SBIBD(4k^2, 2k^2 + k, k^2 + k)$ ,  $k = tq$ .*

**Proof.** Let

$$\begin{aligned} B_1 &= T_1 \times A_1 + T_2 \times A_2 + T_3 \times A_3 + T_4 \times A_4, \\ B_2 &= T_1 \times A_2 + T_2 \times A_1 + T_3 \times A_4 + T_4 \times A_3, \\ B_3 &= T_1 \times A_3^T + T_2 \times A_4^T - T_3 \times A_1 T - T_4 \times A_2^T, \\ B_4 &= -T_1 \times A_4^T - T_2 \times A_3^T + T_3 \times A_2^T + T_4 \times A_1^T, \end{aligned}$$

It is easy to verify that

$$\sum_{i=1}^4 B_i B_i^T = \left( \sum_{i=1}^4 T_i T_i^T \right) \times \left( \sum_{i=1}^4 A_i A_i^T \right) = 4k^2 I_{k^2},$$

and

$$\sigma(B_1) = \sigma(B_2) = \sigma(B_3) = \sigma(B_4) = k^3.$$

Set

$$H = \begin{pmatrix} B_1 & B_2 R & -B_3 R & B_4 R \\ B_2 R & -B_1 & B_4^T R & B_3^T R \\ B_3 R & B_4^T R & B_1 & -B_2^T R \\ -B_4 R & B_3^T R & B_2^T R & B_1 \end{pmatrix},$$

where  $R = R_1 \times R_2$ ,  $R_1, R_2$  are monomial matrices of order  $t^2$  and  $q^2$ , and  $(T_i R_1)^T = T_i R_1$ ,  $(A_i R_2)^T = A_i R_2$ ,  $i = 1, 2, 3, 4$ . In this case  $HH^T = 4k^2 I_{4k^2}$ , and  $\sigma(H) = 2 \sum_{i=1}^4 \sigma(B_i) = 8k^3$ . Then  $H$  is a *Hadamard* matrix with maximum excess, and  $\frac{1}{2}(H + J)$  is a *SBIBD*( $4k^2, 2k^2 + k, k^2 + k$ ).  $\square$

**Proposition 6** *Let  $k = 2^{a_1} 3^{a_2} p_1^{a_3} p_2^{a_4} N^2$ ,  $a_1, a_2, a_3, a_4 = 0$  or  $1$ ,  $p_1 = 5 \pmod{8}$ ,  $p_2 = 3 \pmod{8}$  are primes and  $N$  be an arbitrary integer. Then there exist *SBIBD*( $4k^2, 2k^2 + k, k^2 + k$ ).*

**Proof.** When  $a_4 = 0$ , from lemma 7, the result is true. When  $a_4 = 1$ , set  $t = p_2$ ,  $q = 2^{a_1} 3^{a_2} p_1^{a_3} N^2$ . From lemma 5, proposition 4 and theorem 3, we can prove the result is correct.  $\square$

**Remark.** Let  $k = 2^{a_1} 3^{a_2} p_1^{a_3} p_2^{a_4} N^2$ , where  $a_1, a_2, a_3, a_4 \geq 0$ ,  $p_1 \equiv 5 \pmod{8}$ ,  $p_2 \equiv 3 \pmod{8}$ , then proposition 6 is still true.

Let  $a_i = 2s_i + r_i$ , where  $s_i \geq 0$ ,  $0 \leq r_i \leq 1$ ,  $i = 1, 2, 3, 4$ . Then  $k = 2^{r_1} 3^{r_2} p_1^{r_3} p_2^{r_4} (2^{s_1} 3^{s_2} p_1^{s_3} p_2^{s_4} N)^2$  satisfies the condition of proposition 6.

**Proposition 7** *If  $q \equiv 1 \pmod{4}$  is a prime power, there exist *SBIBD*( $4(7q)^2, 2(7q)^2 + 7q, (7q)^2 + 7q$ ).*

**Proposition 8** *When  $p_2^{a_4}$  in proposition 6 is replaced by 7, the conclusion of proposition 6 is still true.*

**Proof.** Let  $g = x \oplus 2$  be a generator of  $GF(7^2)$ , set

$$F_i = \{g^{16j+i} \pmod{x^2 \oplus 1, \pmod{7}} : j = 0, 1, 2\}, \quad i = 0, 1, \dots, 15.$$

$$\begin{aligned} E_1 &= \{0\} \cup F_{11} \cup F_{12} \cup F_{15}, & E_2 &= F_0 \cup F_{13}, & E_3 &= F_3 \cup F_6, & E_4 &= F_4 \cup F_{14}, \\ E_5 &= F_{10}, & E_6 &= F_1 \cup F_2, & E_7 &= F_7 \cup F_8, & E_8 &= F_5 \cup F_9. \end{aligned}$$

It is easy to verify that

$$\sum_{i=1}^8 \Delta E_i = 49\theta + \sum_{i=1}^4 \Delta(E_i, E_{i+4}).$$

Without loss of generality, let  $g_1, \dots, g_{49}$  be an arbitrary order on the elements of  $GF(7^2)$ . Set

$$T_i = \left( t_{jk}^{(i)} \right)_{1 \leq j, k \leq 49}, \quad t_{jk}^{(i)} = \begin{cases} 1, & \text{if } g_k \ominus g_j \in E_i, \\ -1, & \text{if } g_k \ominus g_j \in E_{i+4}, \\ 0, & \text{otherwise,} \end{cases} \quad i = 1, 2, 3, 4.$$

The matrices  $T_1, T_2, T_3, T_4$  are T-matrices of order 49, and

$$\sigma(T_1) = 7^3, \quad \sigma(T_2) = \sigma(T_3) = \sigma(T_4) = 0.$$

From theorem 3 and theorem 4, we know the proposition 7 and 8 are all true. This completes the proof.  $\square$

From proposition 8 we know, for any integer  $r \geq 1$ , there exist  $SBIBD(4 \cdot 7^{2r}, 2 \cdot 7^{2r} + 7^r, 7^{2r} + 7^r)$ . When  $r$  is even,  $q = 7^r = 1 \pmod{4}$ , from proposition 7 we know the conclusion is true. When  $r$  is odd, then  $7^{r-1} = 1 \pmod{4}$ . In this case let  $q = 7^{r-1}$ , then from proposition 7, the conclusion is true. For any integer  $a, b \geq 1$ ,  $p \equiv 5 \pmod{8}$  a prime, from proposition 8 we know there exist  $SBIBD(4(7^a p^b)^2, 2(7^a p^b)^2 + 7^a p^b, (7^a p^b)^2 + 7^a p^b)$ . From proposition 8 we conclude that for  $a, b, c \geq 0$ ,  $p \equiv 5 \pmod{8}$  a prime, there exist  $SBIBD(4(3^a 7^b p^c)^2, 2(3^a 7^b p^c)^2 + 3^a 7^b p^c, (3^a 7^b p^c)^2 + 3^a 7^b p^c)$ .

**Lemma 8** *There exist  $4 - \{23^2; 23 \cdot 11, 23 \cdot 21\}$  SDS of order  $23^2$ .*

**Proof.** Let  $g = x + 2$  be a generator on  $GF(23)^2$ . Set

$$E_i = \{g^{48j+i} \pmod{x^2 + 1, \pmod{23}} : j = 0, 1, \dots, 10\}, \quad i = 0, \dots, 47.$$

Put

$$\begin{aligned} A_1 &= \{0\} \cup E_9 \cup E_{12} \cup E_{13} \cup E_{28} \cup E_{41} \cup E_{44} \cup E_{45}, \\ A_2 &= E_0 \cup E_{16} \cup E_{17} \cup E_{29} \cup E_{32} \cup E_{33}, \\ A_3 &= E_2 \cup E_4 \cup E_{18} \cup E_{20} \cup E_{34} \cup E_{36}, \\ A_4 &= E_3 \cup E_8 \cup E_{19} \cup E_{24} \cup E_{35} \cup E_{40}, \\ A_5 &= E_1 \cup E_5 \cup E_6 \cup E_{22} \cup E_{38}, \\ A_6 &= E_{10} \cup E_{21} \cup E_{25} \cup E_{26} \cup E_{37} \cup E_{42}, \\ A_7 &= E_7 \cup E_{11} \cup E_{23} \cup E_{27} \cup E_{39} \cup E_{43}, \\ A_8 &= E_{14} \cup E_{15} \cup E_{30} \cup E_{31} \cup E_{46} \cup E_{47}. \end{aligned} \tag{15}$$

Let  $g_1, \dots, g_{23^2}$  be an arbitrary order on the elements of  $GF(23)^2$ . Set matrix

$$T_i = (t_{jk}^{(i)})_{1 \leq j, k \leq 23^2}, \quad t_{jk}^{(i)} = \begin{cases} 1, & \text{if } g_k - g_j \in A_i, \\ -1, & \text{if } g_k - g_j \in A_{i+4}, \\ 0, & \text{otherwise.} \end{cases} \quad i = 1, 2, 3, 4, \quad (16)$$

Then  $T_1, T_2, T_3$  and  $T_4$  defined in (16) are  $T$ -matrices of order  $23^2$  and

$$\sigma(T_1) = 23^3, \quad \sigma(T_2) = \sigma(T_3) = \sigma(T_4) = 0.$$

In this case the set  $\{A_i\}_{i=1}^8$  defined in (15) is the  $C$ -Partitions (see [15] for details). The set

$$\begin{aligned} D_1 &= A_5 \cup A_2 \cup A_3 \cup A_4, & D_2 &= A_5 \cup A_2 \cup A_7 \cup A_8, \\ D_3 &= A_5 \cup A_3 \cup A_6 \cup A_8, & D_4 &= A_5 \cup A_4 \cup A_6 \cup A_7. \end{aligned} \quad (17)$$

is the  $4 - \{23^2; 23 \cdot 11, 23 \cdot 21\}$  SDS. This complete the proof.  $\square$

**Proposition 9** *There exist SBIBD( $4 \cdot 23^2; 2 \cdot 23^2 + 23, 23^2 + 23$ ).*

Proposition 9 follows easily from Theorem 1.

**Proposition 10** *When 7 in proposition 7 is replaced by 23, there exist SBIBD( $4 \cdot (23q)^2, 2 \cdot (23q)^2 + 23q, (23q)^2 + 23q$ ).*

**Proposition 11** *There exist SBIBD( $4 \cdot 23^{2r}, 2 \cdot 23^{2r} + 23^r, 23^{2r} + 23^r$ ).*

**Proof.** For any integer  $r \geq 1$ , when  $r$  is even,  $q = 23^r \equiv 1 \pmod{4}$ , from proposition 7, there exist SBIBD( $4 \cdot 23^{2r}, 2 \cdot 23^{2r} + 23^r, 23^{2r} + 23^r$ ). When  $r$  is odd, then  $q = 23^{r-1} \equiv 1 \pmod{4}$ , in this case the conclusion is again true.  $\square$

**Remark.** For any integer  $a, b \geq 1$ ,  $p \equiv 5 \pmod{8}$  be a prime, there exist SBIBD( $4 \cdot (23^a p^b)^2, 2 \cdot (23^a p^b)^2 + 23^a p^b, (23^a p^b)^2 + 23^a p^b$ ).

For any  $a, b, c \geq 0$ ,  $p \equiv 5 \pmod{8}$  a prime, there exist SBIBD( $4 \cdot (3^a 23^b p^c)^2, 2 \cdot (3^a 23^b p^c)^2 + 3^a 23^b p^c, (3^a 23^b p^c)^2 + 3^a 23^b p^c$ ).

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