

Self-Orthogonal Designs

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1 Introduction

It is well-known that for any positive integer t , a nontrivial t -(v, k, λ) design exists for some v, k, λ . However, it seems that there are very few self-orthogonal t -designs known for large t . Recall that a t -(v, k, λ) design $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ is said to be self-orthogonal if the parity of the size of intersection of any two blocks is the same as the parity of k .

The purpose of this talk is to formulate a conjecture on the nonexistence of self-orthogonal designs for large t with $t \geq \lfloor \frac{k}{4} \rfloor + 1$, where k is even. We show that the conjecture is true for $(t, k) = (6, 20)$, for example. The method employed is the same as the one developed in [1], where a self-orthogonal 5-(72, 36, 78) design is investigated.

2 Saturated designs

Definition 1. Let $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ be a self-orthogonal t -(v, k, λ) design. Assume that k is even, so that the binary code C generated by the rows of the block-point incidence matrix of $\mathcal{D}$ is self-orthogonal. We call the design $\mathcal{D}$ saturated, if C is self-dual, C has minimum weight k , and every minimum weight codeword of C is the support of a block of $\mathcal{D}$.

Let $\mathbf{k} = (k_1, \dots, k_t)$ be a nonzero left null vector of the $t \times (t-1)$ matrix

$$A_t = \begin{pmatrix} 2 & 4 & \dots & 2(t-1) \\ \binom{2}{2} & \binom{4}{2} & \dots & \binom{2(t-1)}{2} \\ \vdots & \vdots & \ddots & \vdots \\ \binom{2}{t} & \binom{4}{t} & \dots & \binom{2(t-1)}{t} \end{pmatrix} \quad (1)$$

Since the matrix A_t has rank $t-1$, the vector $\mathbf{k}$ is unique up to a scalar multiple.

Lemma 1.

$$\sum_{i=1}^t i(-2)^{i-1} \binom{2t-i-1}{t-1} \binom{2j}{i} = (-1)^{t-1} 2^{2t-1} t \binom{j}{j-t}.$$

Proof. Induction on j . □

Proposition 2. Let $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ be a self-orthogonal t -(v, k, λ) design. Assume that k is even, so that the binary code C generated by the rows of the block-point incidence matrix of $\mathcal{D}$ is self-orthogonal. If C has minimum weight k and

$$t \geq t_0 := \left\lceil \frac{k}{4} \right\rceil + 1, \quad (2)$$

then

$$\lambda_s = \frac{(-1)^{t_0-1} 2^{2t_0-1} t_0 \binom{k/2}{k/2-t_0}}{\sum_{i=1}^{t_0} i(-2)^{i-1} \binom{2t_0-i-1}{t_0-1} \binom{k}{i} \prod_{j=i}^{t_0-1} \frac{v-j}{k-j}} \prod_{j=s}^{t_0-1} \frac{v-j}{k-j} \quad (3)$$

is an integer for $s = 0, 1, \dots, t_0$.

Proof. Fix a block B_0 of $\mathcal{D}$. Since X is a t_0 -design, we have

$$\sum_{B \in \mathcal{B}} \binom{|B \cap B_0|}{i} = \lambda_i \binom{k}{i} \quad (i = 1, 2, \dots, t_0), \quad (4)$$

where

$$\lambda_i = \lambda_{t_0} \prod_{j=i}^{t_0-1} \frac{v-j}{k-j}. \quad (5)$$

Put

$$n_j = |\{B \in \mathcal{B} \mid 2j = |B \cap B_0|\}| \quad (j = 0, 1, 2, \dots).$$

Since C has minimum weight k , $|B \cap B_0| \leq k/2$ unless $B = B_0$. Thus

$$r_j = 0 \quad \text{for } j > \lfloor \frac{k}{4} \rfloor, j \neq \frac{k}{2},$$

and obviously $r_{k/2} = 1$. Now (4) can be written as

$$\sum_{j=0}^{t_0-1} \binom{2j}{i} r_j = (\lambda_i - 1) \binom{k}{i} \quad (i = 1, 2, \dots, t_0). \quad (6)$$

Let $\mathbf{k} = (k_1, \dots, k_{t_0})$ be the vector defined by

$$k_i = i(-2)^{i-1} \binom{2t_0 - i - 1}{t_0 - 1}. \quad (7)$$

Then $\mathbf{k}$ is a left null vector of A_{t_0} by Lemma 1, and hence we have

$$\sum_{i=1}^{t_0} k_i \lambda_i \binom{k}{i} = \sum_{i=1}^{t_0} k_i \binom{k}{i}. \quad (8)$$

By (6) we have

$$\lambda_{t_0} \sum_{i=1}^{t_0} k_i \binom{k}{i} \prod_{j=i}^{t_0-1} \frac{v-j}{k-j} = \sum_{i=1}^{t_0} k_i \binom{k}{i}.$$

Applying (5) again, we obtain

$$\lambda_s = \frac{\sum_{i=1}^{t_0} k_i \binom{k}{i}}{\sum_{i=1}^{t_0} k_i \binom{k}{i} \prod_{j=i}^{t_0-1} \frac{v-j}{k-j}} \prod_{j=s}^{t_0-1} \frac{v-j}{k-j}$$

The result then follows from (7) and Lemma 1. $\square$

As a special case of (3), we have

$$\lambda_{t_0} = \frac{(-1)^{t_0-1} 2^{2t_0-1} t_0 \binom{k/2}{k/2-t_0}}{\sum_{i=1}^{t_0} i(-2)^{i-1} \binom{2t_0-i-1}{t_0-1} \binom{k}{i} \prod_{j=i}^{t_0-1} \frac{v-j}{k-j}}. \quad (9)$$

Observe that the denominator is a polynomial in v of degree $t_0 - 1$ with positive leading coefficient. Thus, for a given t_0 , there are only finitely many v for which λ_{t_0} is an integer.

Proposition 3. Let $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ be a self-orthogonal t -(v, k, λ) design, where $k < v$. Assume that k is even, so that the binary code C generated by the rows of the block-point incidence matrix of $\mathcal{D}$ is self-orthogonal. If C has minimum weight k and

$$t \geq t_0 := \left\lfloor \frac{k}{4} \right\rfloor + 1 \text{ and } k \leq 24, \quad (10)$$

then

$$\begin{aligned} (t_0, v, k, \lambda) = & (1, v, 2, 1), \\ & (2, 7, 4, 2), (2, 8, 4, 3), (2, 9, 4, 6), \\ & (2, 16, 6, 2), (2, 21, 6, 4), (2, 22, 6, 5), (2, 24, 6, 10), (2, 25, 6, 20), \\ & (3, 16, 8, 3), (3, 22, 8, 12), (3, 23, 8, 16), (3, 24, 8, 21), \\ & (3, 26, 8, 28), (3, 29, 8, 16), (3, 30, 8, 12), (3, 32, 8, 7), \\ & (3, 26, 10, 3), (3, 42, 10, 9), (3, 46, 10, 8), (3, 50, 10, 6), \\ & (4, 47, 12, 15), (4, 48, 12, 36), (4, 51, 12, 2640), \\ & (5, 56, 16, 42), (5, 64, 16, 91), (5, 72, 16, 78), \\ & (7, 120, 24, 231). \end{aligned}$$

Proof. If $k = 2$, then clearly $\lambda = 1$.

If $k = 4$, then

$$\lambda = \frac{6}{10 - v},$$

hence $v = 7, 8$ or 9 .

If $k = 6$, then

$$\lambda = \frac{20}{26 - v},$$

hence $v = 16, 21, 22, 24, 25$.

If $k = 8$, then

$$\begin{aligned} 0 & \geq 336 \left(\frac{1}{\lambda} - 1 \right) \\ & = (v - 8)(v - 44), \end{aligned}$$

hence $8 < v \leq 44$. Since $\lambda_3, \dots, \lambda_0$ are also integers, we have $v = 16, 22, 23, 24, 26, 29, 30$ or 32 .

If $k = 10$, then

$$0 \geq 1152\left(\frac{1}{\lambda} - 1\right) - (v - 10)(v - 74),$$

hence $10 < v \leq 74$. Since $\lambda_3, \dots, \lambda_0$ are also positive integers, we have $v = 10, 26, 42, 46$ or 50 .

If $k = 12$, then

$$\lambda = \frac{31680}{v^3 - 127v^2 + 5456v - 80592},$$

hence

$$\begin{aligned} 0 &\geq v^3 - 127v^2 + 5456v - 80592 \\ &= v^2(v - 127) + 5456(v - 15) + 1248. \end{aligned}$$

This implies $v < 127$. Since $\lambda_4, \dots, \lambda_0$ are also positive integers, we have $v = 12, 36, 47, 48, 51, 52$ or 57 .

If $k = 14$, then

$$\lambda = -\frac{549120}{5v^3 - 875v^2 + 52952v - 1132668},$$

hence

$$\begin{aligned} 0 &\geq 5v^3 - 875v^2 + 52952v - 1132668 \\ &= 5v^2(v - 175) + 52950(v - 22) + 32232. \end{aligned}$$

This implies $v \leq 174$. Since $\lambda_4, \dots, \lambda_0$ are also positive integers, we have $v = 14$.

If $k = 16$, then

$$\lambda = \frac{4193280}{v^4 - 235v^3 + 20960v^2 - 848000v + 13292544},$$

hence,

$$\begin{aligned} 0 &\geq 4193280\left(\frac{1}{\lambda} - 1\right) \\ &= (v - 16)(v^2(v - 219) + 17456(v - 33) + 7344). \end{aligned}$$

Thus $v < 219$. Since $\lambda_5, \dots, \lambda_0$ are also positive integers, we have $v = 16, 56, 64$ or 72 .

If $k = 18$, then

$$\begin{aligned} 0 &\geq 102359040\left(\frac{1}{\lambda(18)} - 1\right) \\ &= 7v^3(v - 299) + 240404v(v - 53) + 37200v + 162256464. \end{aligned}$$

Thus $16 \leq v < 299$. Since $\lambda_5, \dots, \lambda_0$ are also positive integers, we have $v = 18$.

If $k = 20$, then

$$\begin{aligned} 0 &> \frac{5000970240}{\lambda} \\ &\quad - 7v^4(v - 376) + 399861v^2(v - 78) + 1215608048(v - 17) \\ &\quad + 350602v^2 + 887460016, \end{aligned}$$

hence $v < 376$. Since $\lambda_6, \dots, \lambda_0$ are also positive integers, we have $v = 20$.

If $k = 22$, then

$$\begin{aligned} 0 &> -\frac{2500485120}{\lambda} \\ &\quad = v^4(v - 456) + 84659v^2(v - 96) + 394932588(v - 21) \\ &\quad + 79328v^2 + 200001388, \end{aligned}$$

hence $v < 456$. Since $\lambda_6, \dots, \lambda_0$ are also positive integers, we have $v = 22$.

If $k = 24$, then

$$\begin{aligned} 0 &\geq 148852408320\left(\frac{1}{\lambda} - 1\right) \\ &= (v - 24)((v - 526)(v^4 + 114511v^2 + 47117192v + 25600739920) \\ &\quad + 13441571438560), \end{aligned}$$

hence $v < 526$. Since $\lambda_7, \dots, \lambda_0$ are also positive integers, we have $v = 24$ or 120 . $\square$

3 Unsaturated designs

In this section we let $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ be a self-orthogonal t -(v, k, λ) design with k even, so that the binary code C generated by the rows of the block-point

incidence matrix of $\mathcal{D}$ is self-orthogonal. We assume that the design $\mathcal{D}$ is unsaturated, i.e., either C is not self-dual, or C has a codeword of weight at most k different from the support of a block of $\mathcal{D}$. This implies that there exists a coset $x + C$, possibly equal to C , such that it contains a nonzero vector with minimal weight other than the support of any block of $\mathcal{D}$. Let S be the support of such a vector, put $m = |S|$. Then

$$|B \cap S| \leq \frac{k}{2}$$

for any block B . Since

$$\sum_{B \in \mathcal{B}} \binom{|B \cap S|}{i} = \lambda_i \binom{m}{i} \quad (i = 1, 2, \dots, t),$$

putting

$$n_j = |\{B \in \mathcal{B} \mid 2j = |B \cap B_0|\}| \quad (j = 0, 1, 2, \dots),$$

we have

$$\sum_{j=0}^{\lfloor k/4 \rfloor} \binom{2j}{i} n_j = \lambda_i \binom{m}{i}.$$

Assume

$$t \geq t_0 := \left\lfloor \frac{k}{4} \right\rfloor + 1.$$

Then, as in the previous section, we have

$$\sum_{i=1}^{t_0} i(-2)^{i-1} \binom{2t_0 - i - 1}{t_0 - 1} \lambda_i \binom{m}{i} = 0$$

By (5), we have

$$\sum_{i=1}^{t_0} i(-2)^{i-1} \binom{2t_0 - i - 1}{t_0 - 1} \binom{m}{i} \prod_{j=i}^{t_0-1} \frac{v-j}{k-j} = 0 \quad (11)$$

If k is given, then this is a Diophantine equation in m, v . The only integer solutions of equation (11) in the range $0 < m < v \leq 1000$, $k = 8, 10, \dots, 20$

are

$$\begin{aligned}
k = 8, (v, m) &= (16, 4), (16, 6), (22, 6), (22, 7), (23, 7), \\
k = 10, (v, m) &= (20, 4), (22, 6), (26, 6), \\
k = 12, (v, m) &= (24, 8), (36, 8), (47, 11), (68, 16), (156, 36), (311, 71), \\
k = 14, (v, m) &= (80, 16), (159, 31), \\
k = 16, (v, m) &= (32, 8), (43, 8), (43, 11), (48, 12), (56, 12), (58, 13), \\
k = 18, (v, m) &= (36, 8).
\end{aligned}$$

Therefore, we obtain the following result.

Proposition 4. *Let $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ be a self-orthogonal t -(v, k, λ) design. Assume that k is even, and $t \geq \lfloor \frac{k}{4} \rfloor + 1$, and $8 \leq k \leq 20$, $2k \leq v \leq 1000$. The binary code C generated by the rows of the block-point incidence matrix M of $\mathcal{D}$ is self-dual and the codewords of C of weight k are precisely the rows of M , unless (k, v) is one of the pairs listed above, in which case, either $C^\perp/C$ contains a coset of weight m whose values are listed above.*

References

- [1] M. Harada, M. Kitazume and A. Munemasa, On a 5-design related to an extremal doubly-even self-dual code of length 72, J. Combin. Theory, Ser. A, 107 (2004), 143–146.