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SOME INEQUALITIES FOR t-DESIGNS

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1. Introduction

D.K. Ray-Chaudhuri and R.M. Wilson [3] proved $b\geqq\binom{v}{s}$ for 2s-designs with $v\geqq k+s$, generalizing Fischer's inequality $b\geqq v$ for 2-designs, and Petrenjuk's inequality $b\geqq\binom{v}{2}$ for 4-designs. In this note we introduce a notion of rank s tactical decompositions of 2s-designs, and generalize some of well known results for 2-designs.

DEFINITION. *A rank s tactical decomposition* of a 2s-design $(X, \mathcal{B})$ is a partition of the set $X^{(s)}$ of all s-element subsets of X into s-point classes $X_1, X_2, \cdots, X_m$, together with a partition of $\mathcal{B}$ into block classes $\mathcal{B}_1, \mathcal{B}_2, \cdots, \mathcal{B}_{m'}$, such that the number of elements of X_i contained in a block B of $\mathcal{B}_j$ depends only in i and j, (and does not depend on the choice of B in $\mathcal{B}_j$) and the number of blocks in $\mathcal{B}_h$ containing an element $\{p_1, p_2 \cdots p_s\}$ *of* X_g depends only on h and g.

Our first result is:

Theorem 1. *Let a 2s-(v, k, λ) design $(X, \mathcal{B})$ with $v\geqq k+s$ admit a rank s tactical decomposition with m s-point classes and m′ block classes. Then $m\leqq m'$.*

The case $s=1$ in the above was proved by W.M. Kantor (Theorem 4.1 [2]). Our proof, which will be given in section 2, seems to be more elementary.

If G is a group of automorphisms of a 2s-design $(X, \mathcal{B})$, then the orbits of G on $X^{(s)}$, together with the orbits of G on $\mathcal{B}$, form a rank s tactical decomposition of $(X, \mathcal{B})$. Therefore, by Theorem 1, we have

Corollary 2. *A group of automorphisms of a 2s-(v, k, λ) design $(X, \mathcal{B})$ with $v\geqq k+s$ has at least as many orbits on $\mathcal{B}$ as on $X^{(s)}$. In particular a block transitive automorphism group of $(X, \mathcal{B})$ is s-homogeneous on points.*

The following is a slight extension of a theorem of D.K. Ray-Chaudhuri and R.M. Wilson (Theorem 2 [3]).

Theorem 3. *Let a 2s-$(v, \mathcal{B}, \lambda)$ design $(X, \mathcal{B})$ with $v\geqq k+s$ admit a rank* *s tactical decomposition with m s-point classes and m′ block classes. Then b* $(=|\mathscr{B}|)\geqq\binom{v}{s}+m'-m$.

Extending the notion of parallelsms of 2-designs we also introduce the following.

DEFINITION. *A rank s parallelism* of a 2*s*-design $(X, \mathscr{B})$ is an equivalence relation on $\mathscr{B}$ with the property that each element of $X^{(s)}$ lies in a unique member of each equivalent class. Equivalently a rank *s* parallelisms of a 2*s*-design $(X, \mathscr{B})$ is a partition of $\mathscr{B}$ into "rank *s* parallel classes", each of which is a partition of $X^{(s)}$.

It is easy to see that a rank *s* parallelism of a 2s-design is a rank *s* tactical decomposition with one *s*-point class and λ_s block classes, each of which consists of $\binom{v}{s}\Big/\binom{k}{s}$ blocks. Here, as usual, λ_s denotes the number of blocks containing given *s* points. Thus, by Theorem 3 (or by Theorem 2 of [3]), we have

Corollary 4. *Let a* 2*s*-(v, k, λ) *design with* $v\geqq k+s$ *have a rank s parallelism. Then* $b\geqq\binom{v}{s}+\lambda_s-1$.

Corollary 4 is a generalization of Bose's inequality $b\geqq v+r-1$ for 2-designs with a parallelism [1]. The author does not know whether there exist 2*s*-designs, $s\geqq 2$, with a rank *s* parallelism. But the following is true.

Theorem 5. *If* $s\geqq 2$, *there exist no* 2*s*-(v, k, λ) *designs,* $v\geqq k+s$, *with a rank s parallelism having the smallest rumber* $b=\binom{v}{s}+\lambda_s-1$ *of blocks.*

In the case $s=1$, as is well known, there exist infinitely many 2-designs with a parallelism having $v+\lambda_1-1$ blocks.

2. Proof of Theorem 1

Let N be the $\binom{v}{s}\times b$-matrix whose rows are numbered by elements of $X^{(s)}$ and columns by elements of $\mathscr{B}$, and whose $(\{i_1, i_2, \cdots, i_s\}, B)$ entry is 1 or 0 according as $\{i_1, i_2, \cdots, i_s\}\subset B$ or not. Then N has rank $\binom{v}{s}$ by (the proof of) Theorem 1 [3]. So our Theorem 1 is an immediate consequence of the following.

Lemma. *Let M be a (real)* $n\times b$*-matrix with rank n. Assume that M can be decomposed into mm′ rectangular submatrices* M_{ij}, $1\leqq i\leqq m$, $1\leqq j\leqq m'$, *such that* M_{ij} *is an* $n_i\times b_j$*-matrix with constant column sum* k_{ij}. *Then* $m\leqq m'$.

Proof. Let x_i $(1 \leqq i \leqq n)$ denote the i-th row vector of M. Set $y_1 = x_1 + \cdots + x_{n_1}$, $y_2 = x_{n_1+1}, + \cdots + x_{n_1+n_2}, \cdots$, $y_m = x_{n_1+n_2\cdots+n_{m-1}+1} + \cdots + x_{n_1+n_2+\cdots+n_m}$.

Then y_i is the vector of the form:

$$y_i = (\overbrace{k_{i_1} \cdots k_{i_1}}^{b_1},\ \overbrace{k_{i_2} \cdots k_{i_2}}^{b_2}, \cdots,\ \overbrace{k_{im'} \cdots, k_{im'}}^{b_{m'}}), \qquad 1 \leqq i \leqq m_i .$$

Then since the m vectors y_i are linearly independent, it follows that $m \leqq m'$.

3. Proof of Theorem 3

We make use of an argument of D.K. Ray-Chaudhuri and R.M. Wilson [3]. Let V_s denote the free vector space over the rationals generated by $X^{(s)}$. Claerly V_s is $\binom{v}{s}$ dimensional over rationals. Now for each $A \in \mathcal{B}$, define a vector $\hat{A} \in V_s$ as the sum of all s-subsets of A, *i.e.*

$$\hat{A} = \sum(S\colon S \in X^{(s)},\ S \subseteq A) .$$

D.K. Ray-Chaudhuri and R.M. Wilson showed that the vectors $\{\hat{A}\colon A \in \mathcal{B}\}$ span V_s. Put $\hat{X}_j = \sum(S\colon S \in X_j)$. Then, by our assumption

$$\sum\{\hat{A}\colon A \in \mathcal{B}_i\} = \sum_{j=1}^{m} \lambda_{ij} \sum(S\colon S \in X_j) = \sum_{j=1}^{m} \lambda_{ij} \hat{X}, \text{ for some } \lambda_{ij}, \qquad 1 \leqq i \leqq m'$$

So, if we choose one block A_i from each $\mathcal{B}_i$, then

$$\{\hat{A}\colon A \in \mathcal{B} - \{A_1, \cdots, A_{m'}\}\} \cup \{\hat{X}_1\, \hat{X}_2 \cdots, \hat{X}_m\}$$

spans V_s. The stated inequality follows.

4. Proof of Theorem 5

Assume by way of contradiction that there exists a $2s$-(v, k, λ) design $(X, \mathcal{B})$, $s \geqq 2$, $v \geqq k+s$ with a rank s parallelism having the smallest number $b = \binom{v}{s} + \lambda_s - 1$ of blocks. Then we have

$$\frac{\binom{v}{s}}{\binom{k}{s}} \lambda_s = \binom{v}{s} + \lambda_s - 1 ,$$

$$\lambda_s \left\{ \frac{\binom{v}{s}}{\binom{k}{s}} - 1 \right\} = \binom{v}{s} - 1 \tag{4.1}$$

Case 1. $s=2r$ is even.

Applying the theorem of D.K. Ray-Chaudhuri and R.M. Wilson (Theorem 1 [3]), to a contracted s-$(v-s,\ k-s,\ \lambda)$ design of $(X, \mathcal{B})$, we have

$$\lambda_s \geqq \binom{v-s}{r} \tag{4.2}$$

Then (4.1) and (4.2) yield

$$\binom{v-s}{r}\left\{\frac{\binom{v}{s}}{\binom{k}{s}}-1\right\} \leqq \binom{v}{s}-1\,, \tag{4.3}$$

Now let $\mathcal{B}_1$ be a rank s parallel class of $(X, \mathcal{B})$. Then $(X, \mathcal{B}_1)$ is a s-$(v, k, 1)$ design, and hence, again by the theorem of D.K. Ray-Chaudhuri and R.M. Wilson, we have

$$\frac{\binom{v}{s}}{\binom{k}{s}} \geqq \binom{v}{r} \tag{4.4}$$

Then (4.3) and (4.4) imply

$$\binom{v-s}{r}\left\{\binom{v}{r}-1\right\} \leqq \binom{v}{s}-1$$

$$\left\{\binom{v-s}{r}-1\right\}\binom{v}{r} \leqq \binom{v-s}{r}\left\{\binom{v}{r}-1\right\} \lneqq \binom{v}{s}$$

$$\binom{v-s}{r}-1 \lneqq \frac{\binom{v}{s}}{\binom{v}{r}} = \frac{(v-r)(v-r-1)\cdots(v-2r+1)}{2r\quad(2r-1)\quad\cdots\quad(r+1)} \tag{4.5}$$

On the other hand, since $v \geqq 6r$, we have

$$\frac{v-s-i}{r-i} \gneqq \frac{v-r-i}{2r-i}, \qquad 0 \leqq i \leqq r-2 \tag{4.6}$$

and

$$v-3r+1 \geqq \frac{v-2r+1}{r+1}+1\,. \tag{4.7}$$

Then (4.6) and (4.7) yield

$$\binom{v-s}{r}-1 = \frac{(v-s)}{r}\cdot\frac{(v-s-1)}{r-1}\cdots\frac{(v-3r+2)}{2}\cdot(v-3r+1)-1$$

$$\gneqq \frac{(v-r)}{2r}\cdot\frac{(v-r-1)}{2r-1}\cdots\frac{(v-2r+2)}{r+2}\left\{\frac{v-2r+1}{r+1}+1\right\}-1$$

$$=\frac{\binom{v}{s}}{\binom{v}{r}}+\frac{(v-r)}{s}\frac{\binom{v}{s-1}}{\binom{v}{r+1}}-1$$

$$\geqq\frac{\binom{v}{s}}{\binom{v}{r}}.$$

This contradicts (4.5).

Case 2. $s=2r+1$ $(r\geqq 1)$ is odd.

Applying the theorem of D.K. Ray-Chaudhuri and R.M. Wilson to a contracted $2(s-1)$-$(v-2,\ k-2,\ \lambda)$ design of $(X,\ \mathscr{B})$, we have

$$\lambda_2=\frac{\binom{v-2}{s-2}}{\binom{k-2}{s-2}}\lambda_s\geqq\binom{v-2}{s-1} \tag{4.8}$$

Then (4.1) and (4.8) yield

$$\frac{\binom{k-2}{s-2}(v-s)}{s-1}\left\{\frac{\binom{v}{s}}{\binom{k}{s}}-1\right\}\leqq\binom{v}{s}-1$$

$$\frac{s(v-s)}{k(k-1)}\left\{\binom{v}{s}-\binom{k}{s}\right\}\leqq\binom{v}{s}-1 \tag{4.9}$$

On the other hand applying Fischer's inequality to a contracted 2-$(v-s+2, k-s+2, 1)$ design of a s-$(v, k, 1)$ design $(X, \mathscr{B}_1)$, where $\mathscr{B}_1$ is a rank s parallel class of $(X,\ \mathscr{B})$, we have

$$(k-s+2)\,(k-s+1)\leqq v-s+1\,. \tag{4.10}$$

We shall now show that

$$\binom{v}{s}-\binom{k}{s}\geqq\frac{4}{5}\left\{\binom{v}{s}-1\right\} \tag{4.11}$$

Deny (4.11). Then

$$\frac{1}{5}\binom{v}{s}\lneqq\binom{k}{s}$$

$$v(v-1)\cdots(v-s+1)\lneqq k(k-1)\cdots(k-s+1)\,5 \tag{4.12}$$

Then (4.10) and (4.12) give

$$v(v-1)\cdots(v-s+2) \lneqq k(k-1)\cdots(k-s+3)\,5$$
$$v(v-1)\cdots(v-s+3) \lneqq k(k-1)\cdots(k-s+3)$$
$$v \lneqq k, \text{ a contradiction.}$$

Now by (4.9) and (4.11) we obtain

$$s(v-s) \leqq \frac{5}{4}k(k-1)$$

Combining this with (4.10) gives

$$(k-s+2)(k-s+1) \leqq \frac{5k(k-1)}{4s}+1 \tag{4.13}$$

Then since $k \geqq 2s$ (4.13) implies

$$\left(\frac{1}{2}k+2\right)\left(\frac{1}{2}k+1\right) \geqq \frac{5k(k-1)}{4s}+1 \tag{4.14}$$

If $s \leqq 5$ then (4.14) gives

$$\left(\frac{1}{2}k+2\right)\left(\frac{1}{2}k+1\right) \leqq \frac{k(k-1)}{4}+1$$

$$\frac{3}{2}k+2- \leqq -\frac{1}{4}k+1\,, \text{ a contradiction.}$$

So we must have $s=3$. But then (4.13) gives

$$(k-1)\,(k-2) \leqq \frac{5}{12}k(k-1)+1$$

$$7k^2-31k+12 \leqq 0$$

$$k \leqq 4, \text{ a contradiction.}$$

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