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Jacobsen, Søren B.

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The Rearrangement Process in a Two-Stage Broadcast Switching Network

SØREN B. JACOBSEN

Abstract—This paper considers the rearrangement process in the two-stage broadcast switching network presented by F. K. Hwang and G. W. Richards in IEEE TRANSACTIONS ON COMMUNICATIONS, October 1985. By defining a certain function it is possible to calculate an upper bound on the number of connections to be moved during a rearrangement. When each inlet channel appears twice, the maximum number of connections to be moved is found. For a special class of inlet assignment patterns in the case where each inlet channel appears three times, the maximum number of connections to be moved is also found. In the general case, an upper bound is given when the number of outlets at each second-stage switch is kept below a certain bound.

I. THE KNOWN PROPERTIES OF THE NETWORK

The network to be considered here (see Fig. 1) is identical to the one presented in [1], and it is described by the three parameters \( n_1, n_2, \) and \( M \) where

- \( n_1 \) is the number of inlet channels at each first-stage switch,
- \( n_2 \) is the number of outlets at each second-stage switch, and
- \( M \) is the number of times each inlet channel appears in the first stage.

The number of crosspoints in the network divided by the number of crosspoints in the corresponding rectangular switch is called the reduced number of crosspoints and is given by

\[
C_{\text{red}} = M \left( 1/n_1 + 1/n_2 \right).
\]

To minimize \( C_{\text{red}} \), the fraction \( M/n_2 \) has to be made as close to zero as possible but the rearrangement requirement puts a lower bound on the fraction.

Hall’s theorem on a system of distinct representatives [2] ensures that the network is rearrangeable, if and only if, the following condition is fulfilled.

**The Rearrangement Condition:** For any \( n \leq n_2 \), there are at least \( n \) first-stage switches containing appearance of any \( n \) inlet channels.

To ensure that the \( n_1 \) inlet channels are effectively rotated in the \( M \) blocks the following condition is assumed to be fulfilled.

**The Pair Condition:** No pair of inlet channels appears on the same first-stage switch more than once throughout the \( M n_1 \) first-stage switches.

All the inlet assignment patterns presented in [1] fulfill the pair condition, but instead of working with some explicit patterns, it is more advantageous in a general approach just to assume the pair condition to be fulfilled.

II. AN UPPER BOUND ON THE NUMBER OF CONNECTIONS TO BE MOVED DURING A REARRANGEMENT BY MEANS OF THE FUNCTION \( S_{M,n_1} \)

As it will be seen later, the rearrangement condition as well as an upper bound on the number of connections to be moved during a rearrangement can be given by means of a function whose values are in general unknown. The function will be called \( S_{M,n_1} \), and it is defined by means of another function \( T_{M,n_1} \). Let \( E \) be a subset of the set of inlet channels. Then,

\[
T_{M,n_1}(E) = \text{The number of first-stage switches having elements from } E \text{ amongst its inlet channels.}
\]

Now \( S_{M,n_1} \) is defined by

\[
S_{M,n_1}(n) = \min \{ T_{M,n_1}(E) | \text{E has } n \text{ elements} \}.
\]

**Now \( S_{M,n_1} \) is an increasing function, it depends on the inlet assignment pattern chosen, and \( S_{M,n_1}(n) \) denotes the smallest number of first-stage switches that \( n \) inlet channels can appear on.**

In terms of \( S_{M,n_1} \), we have

**The network is rearrangeable if and only if**

\[
\forall n \leq S_{M,n_1}(n) \text{ for all } n \leq n_2.
\]

This means that the optimal choice for \( n_2 \) is

\[
n_2 = \max \{ n | n \leq S_{M,n_1}(n) \}.
\]

An upper bound on the number of connections to be moved during a rearrangement can be found in terms of a sequence
\{s_k\} defined recursively from \(S_{M,n_l}\) by

\[
s_1 := S_{M,n_l}(1) \text{ and } s_{k+1} := S_{M,n_l}(s_k + 1).
\] (2.4)

The main result of this section is as follows.

Result 2.1: Let \(r\) denote the integer with the property: \(s_r \leq n_2 - 1\) and \(s_{r+1} \geq n_2\). Then the number of connections to be moved during a rearrangement will never exceed \(r\).

Proof: To prove the result, consider the rearrangement algorithm given in [1]. It is characterized by the blocking relationship tree and its associated levels. The development of the tree stops at the first level where an idle switch arises. See Fig. 2. The important fact, given in [1], is

The number of connections to be moved is one less than the number of the level where the first idle switch arises.

Now the idea is to step through all levels of the blocking relationship tree, and in each level, keep an eye on the total number of inlet channels that have appeared so far, and to see how many first-stage switches they necessarily have appearance on. Sooner or later a level is reached where so many inlet channels have appeared, that the number of switches they demand, exceed the number of busy lines, which is, at most, \(n_2 - 1\). When this occurs, at least one switch is idle.

The sequence \(\{s_k\}\) is defined so that \(s_k\) is a lower bound on the number of first-stage switches that have appeared in the first \(k\) levels of the blocking relationship tree. This fact is explained in Fig. 3. Therefore, an idle switch must arise in the first level where \(s_k \geq n_2\), which according to the definition of \(r\) is level \(r + \). This concludes the proof of Result 2.1.

To use Result 2.1 on a given network, it is sufficient to know \(S_{M,n_l}(n)\) for \(n = 1, 2, \ldots, n_2 + 1\). In the case \(M = 2, S_{M,n_l}\) is independent of \(n_l\) and for \(n \leq 6\) it takes the following values:

\[
S_2(1) = 2, \quad S_2(2) = 3, \quad S_2(3) = 4, \quad S_2(4) = 5, \quad S_2(5) = \Delta, \quad S_2(6) = 5.
\]

This means that the optimal choice for \(n_2\) is 5, as given in [1]. The sequence \(\{s_k\}\) takes for \(k \leq 3\), the values

\[
s_1 = 2, \quad s_2 = S_2(3) = 4, \quad s_3 = S_2(5) = 5 - n_2
\]

from which we see that the integer \(r\) defined in Result 2.1 equals 2 proving.

Result 2.2: The number of connections to be moved during a rearrangement will never exceed 2, when \(M = 2\).

Fig. 2 shows a situation where two connections must be moved. This means that the maximum number of connections to be moved is two.

III. THE MAXIMUM NUMBER OF CONNECTIONS TO BE MOVED DURING A REARRANGEMENT FOR A SPECIAL CLASS OF INLET ASSIGNMENT PATTERNS WHEN \(M = 3\)

In this section, we consider the case \(M = 3\). Fix an inlet assignment pattern and let the switches in each of the 3 blocks be numbered 0, 1, \(\ldots\), \(n_l - 1\). We will show that this inlet assignment pattern induces a latin square of order \(n_l\). Define the \(n_l \times n_l\) matrix \(Z\) by

\[
ij\text{'e element in } Z \text{ is the number of the switch in block 3, containing the common element of switch } i \text{ from block 1 and switch } j \text{ from block 2.}
\]

This definition is taken from [3] and the pair condition ensures that \(Z\) is a latin square. We restrict the calculation of \(S_{M,n_l}\) to inlet assignment patterns where the induced latin square is the multiplication table of a group. Result 4.1 applied to the case.
$M = 3$ together with the upper bound $U_3$ given in Appendix A yields

\[ S_{3,n_1}(1) = 3, \quad S_{3,n_1}(2) = 5, \quad S_{3,n_1}(3) = 6, \]
\[ S_{3,n_1}(5) = 8, \quad S_{3,n_1}(7) = 9, \quad S_{3,n_1}(10) = 11, \]
\[ S_{3,n_1}(4) = 6 \text{ or } 7, \quad S_{3,n_1}(6) = 8 \text{ or } 9, \quad S_{3,n_1}(8) = 9 \text{ or } 10, \]
\[ S_{3,n_1}(9) = 9, \quad 10 \text{ or } 11, \quad S_{3,n_1}(11) = 11 \text{ or } 12, \]
\[ S_{3,n_1}(13) = 12 \text{ or } 13 \quad S_{3,n_1}(14) = 12 \text{ or } 13. \]

We will now determine when $S_{3,n_1}(4) = 6$. If $S_{3,n_1}(4) = 6$ then there must exist four inlet channels appearing in two switches in block 1, in two switches in block 2, and in two switches in block 3. (If all four inlet channels appeared on the same switch in one of the blocks then they would appear on four different switches in the remaining two blocks.) In the language of Latin squares this means we can find four entries appearing in two rows and two columns so that these four entries contain only two different element which we call $x_1$ and $x_2$. Since the Latin square corresponds to the multiplication table of a group, we have proved

\[ \{a_1, a_2\} \times \{b_1, b_2\} \]

This yields $a_1 = x_1 b_1^{-1}$ and $a_2 = x_2 b_2^{-1}$ and therefore $x_1 b_1^{-1} b_2 = x_2$ and $x_2 b_2^{-1} b_1 = x_1$ implying $(b_1^{-1} b_2)^2 = 1$. Since an element of order 2 exist, if and only if, 2 divides the order of the group, we have proved

\[ S_{3,n_1}(4) = \begin{cases} 6 \text{ when } 2 \text{ divides } n_1, \\ 7 \text{ else.} \end{cases} \]

In Appendix A, similar methods are used to find $S_{3,n_1}(n)$ when $n = 11$ and 13. The remaining values can be calculated the same way. We therefore have the following.

**Result 3.1:** Assume $M = 3$ and $n_1 \geq 4$. For all inlet assignment patterns where the induced Latin square is the multiplication table of a group, we have:

1) $S_{3,n_1}$ takes the values in Table I.
2) The optimal choice for $n_1$ (assuming $S_{3,n_1}(14) \leq 13$ for all inlet assignment patterns), and the maximum number of connections to be moved during a rearrangement are the numbers given in Table II.

When $n_1$ is a multiple of four or five, it is easy to construct states where a rearrangement requires 3 connections to be moved. Figs. 4 and 5 show a state where 4 (5) connections has to be moved. The upper bounds given in Table II are therefore the maximum number of connections to be moved.

Can the results in this section be extended so that they include arbitrary Latin squares? The answer is no. Consider the following Latin square:

\[
\begin{array}{cccc}
0 & 1 & 2 & 3 \\
1 & 0 & 3 & 4 \\
2 & 4 & 0 & 1 \\
3 & 2 & 4 & 0 \\
4 & 3 & 1 & 2 \\
\end{array}
\]

Select the four entries in the two upper rows and the two left columns and conclude that $S_{3}(4) = 6$ in this case where 2 does not divides $n_1(=5)$.

1 For Latin squares corresponding to some special groups of order a power of 3, it is in doubt whether $S_{3,n_1}(14) = 13$ or 14. If $S_{3,n_1}(14) = 14$ there exist inlet patterns where best $n_1$ is 14.

**IV. AN UPPER BOUND ON THE NUMBER OF CONNECTIONS TO BE MOVED DURING A REARRANGEMENT WHEN $M$ IS ARBITRARY**

When $n_1$ and $M$ grow, it becomes very time consuming to calculate the values of $S_{3,n_1}$. It would, therefore, be advantageous if upper and lower bounds could be given. In Appendix A we prove the following.

**Result 4.1:** For all inlet assignment patterns fulfilling the pair condition the following estimate is valid:

\[ S_{M,n_1}(n) \geq G_M(n) \text{ for any } n \leq n_1^2 \] (4.1)

where

\[ G_M(n) = \begin{cases} (p+1)M-1 & \text{when } p^2+1 \leq n \leq p^2+p+1 \\
(p+1)M & \text{when } p^2+p+1 \leq n \leq (p+1)^2. \end{cases} \] (4.2)

Since $G_M(n) \leq S_{M,n_1}(n)$, the network is rearrangeable as long as $n_2 \leq \max \{n|n \leq G_M(n)\}$. But (4.2) gives that max $\{n|n \leq G_M(n)\} = M(M+1) - 1$ so

\[ n_2 = M(M+1) - 1 \] (4.3)

well known from [1].

To get an upper bound on the number of connections to be moved during a rearrangement the following sequence $\{g_k\}$ [compare to (2.4)] is defined

\[ g_k := G_M(1) \text{ and } g_{k+1} = G_M(g_k + 1). \] (4.4)

$g_k$ has the following two obvious properties:

1) $g_k \leq g_k$ for any $k$ and $g_k$ is therefore a lower bound on the number of first-stage switches that have appeared in the first block levels of the blocking relationship tree.

2) Let $m$ be the integer with the property $g_m = n_2 - 1$ and $g_{m+1} \geq n_1$. Then $m$ is an upper bound on the number of connections to be moved during a rearrangement.

It is now easy to verify the following.

**Result 4.2:** If $n_2 \leq M(M+1) - 1$ then the number of
connections to be moved during a rearrangement will for $M = 2^l$ never exceed the numbers given in Table III.

In Appendix C it is proven that:

Result 4.3: If $n_2 \leq M(M + 1) - 1$, then the number of connections to be moved during a rearrangement will never exceed $3 + \lceil (l/\ln 2) \ln(M^2 \ln M) \rceil$ where $\lceil x \rceil$ is the smallest integer bigger than or equal to $x$.

Result 4.3 is not the best obtainable but it shows that the number of connections to be moved grow at most logarithmic in $M$.

V. THE INLET ASSIGNMENT PATTERN AND FINITE GEOMETRY

In this section, results from the theory of finite geometries is used to examine the inlet assignment pattern.

According to the definition [4, p. 251], a geometric $k$ net is a set of points together with a set of lines appearing in $k$ different parallel classes such that:

1) each point belongs to exactly one line of each parallel class
2) if $l_1$ and $l_2$ are lines of different parallel classes, then $l_1$ and $l_2$ have exactly one point in common
3) there are at least two points on each line.
Consider a network with $n_1$, $M$, and an inlet assignment pattern given. The $n_1^2$ inlet channels correspond to the set of points. Each of the $M$ blocks corresponds to a parallel class, and each switch in a block corresponds to a line in this parallel class. Since each inlet channel is present exactly once in each block, 1) is fulfilled. The pair condition ensures that 2) is fulfilled, and for $n_1 \geq 2$ the inlet assignment pattern given is a geometric $M$-net of order $n_1$.

This connection to $k$ net can be used to find the highest possible value of $M$ before the pair condition is violated. For $n_1 \leq 9$, we have [4, ch. 8].

The function $S_{M,n_1}$ is known in general to depend on the inlet assignment pattern chosen. To be more precise an equivalence relation is introduced. Let $P_1$ and $P_2$ be two inlet assignment patterns in the same network, i.e., $M$ and $n_1$ is fixed. Then,

$$P_1 \sim P_2 \iff S_{M,n_1}(P_1) = S_{M,n_1}(P_2).$$

The equivalence relation splits the set of inlet assignment patterns for the network into classes and in order to obtain the best network an inlet pattern that makes $S_{M,n_1}$ as big as possible has to be chosen.

When $M = 2$, there is for any $n_1$ only one class, and it is therefore impossible to improve the network by using inlet patterns different from the one used in the Fig. 2.

When $M = 3$, the results in Section III prove that $S_{3,n_1}$ depends on $n_1$ and for $n_1 \geq 5$ there are in general more than one class. From lemma 1 in [3], it can be seen that for $n_1$ a prime all inlet assignment patterns made from the subarrays given in [1] are contained in only one class.

For a general $M$ and $n_1$, it seems very difficult to determine the classes. Then it seems more practical to find an useful upper bound $U_M$ on $S_{M,n_1}$, which can be used to decide whether or not a given inlet pattern makes $S_{M,n_1}$ big enough. In [4] and [5], geometric nets are used to construct projective planes, and it is not unlikely that methods and results there can be helpful in finding an useful upper bound.

VI. CONCLUSIONS

In this paper, an upper bound on the number of connections to be moved during a rearrangement in a two-stage broadcast switching network is found. In general, the bound is given in terms of the function $S_{M,n_1}$, which means that when the values of $S_{M,n_1}$ are known, then the upper bound is easily calculated.

When $M = 2$ the function $S_{M,n_1}$ is independent of $n_1$ and of the inlet assignment pattern, and two is the maximum number of connections to be moved during a rearrangement.

When $M = 3$ the function $S_{M,n_1}$ depends on $n_1$. For a special class of inlet patterns the values of $S_{3,n_1}$ is found, and the optimal choice for $n_1$ is 11 when $n_1$ is a multiple of 4, it is 12 when $n_1$ is a multiple of 5 but not 4, and it is 13 in the other cases. The maximum number of connections to be moved during a rearrangement is 3 when $n_1$ is a multiple of 4 or 5. When $n_1$ is not a multiple of 4 or 5, the maximum number of connections to be moved is 5 and when $n_1$ is a prime it is 4.

In the case where $M$ is arbitrary the pair condition is used to find a lower bound $G_M$ on $S_{M,n_1}$, and this lower bound yields that the number of connections to be moved during a rearrangement grows, at most, logarithmic as a function of $M$ when the number of outlets at each second-stage switch is not exceeding $M(M + 1) - 1$.

Finally, the close connection between the inlet assignment pattern and finite geometry is considered.

APPENDIX A

THE CALCULATIONS OF $S_{3,n_1}$

We first find an upper bound $U_3$ for $S_{3,n_1}$. Let for $1 \leq n \leq 14$, $U_3$ be defined by Table V.

<table>
<thead>
<tr>
<th>$n_1$</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>$p$ prime</th>
</tr>
</thead>
<tbody>
<tr>
<td>highest</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>$p^n + 1$</td>
</tr>
</tbody>
</table>

Result A.1: Assume $n_1 \geq 4$. For all inlet assignment patterns where the induced latin square is the multiplication table of a group we have $S_{3,n_1}(n) \leq U_3(n)$, $n = 1, 2, \ldots, 13$. $S_{3,n_1}(14) \leq 13$ when the induced latin square
We only prove the lemma in the case where $|C_i \cap C_j| \geq 3$ for $j = 2, 3$. Then there are three possibilities to consider: 1) $ab$ is the unknown element, i.e., we do not know whether or not $ab \in \{1, a, b, c\}$, 2) $b^2$ is the unknown, or 3) $cb$ is the unknown element.

Assume that $ab$ is the unknown element: Then $b^2 = a$ or $b^2 = 1$. If $b^2 = a$ then $b$ has order 4 and the subgroup generated by $b$ is a subgroup of order 4. If $b^2 = 1$ we have $cb = a$ implying $c = b^3 = ab$. But then $a^2 = 1$, $b^2 = 1$, $c = ab = ba$ and therefore $\{1, a, b, c\}$ is the Klein Four Group $(Z_2 \times Z_2)$.

Assume that $b^2$ is the unknown element; then $ab = c$. Multiplying by $a$ from left gives $b = acl. Now cb = 1$ or $cb = a$. If $cb = 1$ then $a = abc = b^2$ implying that $b$ has order four. If $cb = a$ then $a = a^2 = acb = b^2$ and then $ab = ba = c$ implying that $\{1, a, b, c\}$ is the Klein Four Group.

Assume that $c$ is the unknown element; then $ab = c$ and therefore $b^2 = 1$ or $b^2 = a$. If $b^2 = 1$, $\{1, a, b, c\}$ is the Klein Four Group and if $b^2 = a, b$ has order 4. Since we have now covered all cases the proof of lemma A.1 is completed.

We now proceed with the calculation of $S_{3,n_1}$. The fact that no element appears more than once in a row (column) will be used without comment.

$n = 11$: Assume $S_{3,n_1}(11) = 11$. If the 11 inlet channels appeared on only two switches in one of the blocks then they would have to appear on at least six switches in each of the remaining two blocks and the 11 inlet channels would then appear on at least 14 switches. Because of the symmetry in rows and columns, we only have to consider the following two cases: 1) when the 11 inlet channels appear on four switches in block 1, four switches in block 2, and three switches in block 3; 2) when the 11 channels appear on four switches in block 1, three switches in block 1, and four switches in block 3.

Case 1: In the language of latin squares we have 11 entries containing only three different elements $(x_1, x_2, x_3)$ and appearing in four rows and four columns. The four rows (columns) correspond to four group elements $a_1, a_2, a_3, a_4 (b_1, b_2, b_3, b_4)$. Since it is 11 entries containing only $x_1, x_2, x_3$, three of the rows and three of the columns contain all the elements $x_1, x_2, x_3$ and the remaining row and column contains two of these three elements. After possible remapping of the group elements we may assume that we have the following table:

<table>
<thead>
<tr>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$x_1$</td>
<td>$x_2$</td>
<td>$x_3$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$x_2$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$x_3$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$a_4$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

where row 1, 2, and 3 and column 1, 2, and 3 or 4, contain $x_1, x_2, x_3$ while row 4 and column 4 or 3 contain two of these three elements. Multiply the row elements by $a_i$ from the left and the column elements by $b_i$ from the right and obtain

<table>
<thead>
<tr>
<th>$a$</th>
<th>$b$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1$</td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>$a$</td>
<td>$a$</td>
<td>$a$</td>
</tr>
<tr>
<td>$b$</td>
<td>$b$</td>
<td>$b$</td>
</tr>
<tr>
<td>$c$</td>
<td>$c$</td>
<td>$c$</td>
</tr>
</tbody>
</table>

where $a := a_1^2 = a_2, b := b_2 b_1^{-1}, c := a_3^2 = a_4, d := b_3 b_2^{-1}$ and where it is row 4 and column 3 or 4 that have only two of the elements 1, $a, b$.

Assume $a^2 \in \{1, a, b\}$. Since row 2 and column 2 both contains 1, a, b, we have $ba = 1$, $ca = b$, and $ab = 1$ and $ad = b$. This implies $b = a^{-1}$ and $c = d = a^2$. Since 1, a, b, c are distinct a has order at least four. Use that row 3 has all
three elements 1, a, a⁻¹ to conclude that a has order 4 and, therefore, 4 divides n₁. Assume that a² ∈ {1, a, b, c}; then a² = 1 or a² = b. If a² = 1 then ca = b and therefore c = ba. Since row 2 contains 1, a, b, we get ad = b and therefore d = ab. The same argument is applied to row 3 giving b² = 1 and bd = a or b² = a and bd = 1. If b² = a then b is an element of order 4. If b² = 1 then d = b² = (b(bd)) = ba = c and then {1, a, b, c} = {1, a, b, d} is the Klein Four Group.

Assume a² = b then ba = 1 or ca = 1, ba = 1 implies a² = 1 and b² = a and makes it impossible for row 4 and column 4 to contain more than one of the elements 1, a, b, c. Therefore, ca = 1 and in row 2, we get ad = 1. Then c = a⁻¹ = d and {1, a, b, c} = {1, a, a², a⁻¹} and it follows as before that a has order 4.

Case 2): Assume that we have 11 inlet channels appearing on four switches in block 1, on three switches in block 2, and on four switches in block 3. In the induced latin square, we can find 11 entries appearing in four rows and four columns so that the 11 entries contains only four different elements. By appropriate multiplication as in the former case, we may assume that the row elements are 1, a, b, c and the column elements are 1, a, b, c. Since only four different elements are present in the 11 entries, we have C₁ = C₂ = C₃, and |C₁ ∩ C₂| ≥ 3 for j = 2, 3. We assume that C₁ = C₂. If a² = 1, we conclude by lemma A.1 that 4 divides n₁. If a² = b, then ba = 1 or ba = c. Since ba = 1 forces ca = c, we conclude that ba = c. Then ca = 1 forcing b² = a² = a⁴. Therefore, a is an element of order 4 and 4 divides n₁. When a² = c the same argument yields that a has order 4.

n = 13: Assume Sₙ₋₁(n₁) = 12. If the 13 inlet channels appeared on only three switches in one of the blocks this would force the inlet channels to appear on at least five switches in each of the remaining blocks. We may, therefore, assume that in the induced latin square, there exist 13 entries containing only four different elements x₁, x₂, x₃, x₄ and appearing in four rows and four columns. There exists at least one row and one column containing all the elements x₁, x₂, x₃, x₄. By appropriate multiplication as in Case 1) of n = 11, we may assume that the four rows and the four columns correspond to the elements 1, a, b, c. If there exist two columns both containing four different elements, we can proceed exactly as in Case 2) of n = 11 and conclude that 4 divides n₁. We may, therefore, assume that |C₁ ∩ C₂| = 3 for f = 2, 3, 4. From this we see that if a² = 1 then by lemma A.1, we conclude that 4 divides n₁.

If ba = c then ca = b or ca = 1, ca = b implies a² = c implying a² = 1 and by lemma A.1, we conclude that 4 divides n₁. ca = a⁻¹ implies a² = 1 and by lemma A.1, we conclude that 4 divides n₁.

Assume that ab is unknown. Then a² = 1 or a² = c. If a² = 1, we have a contradiction. Therefore, ca = b, implying b = a, i.e., {1, a, b, c} = {1, a, a², a⁻¹}. As in the case a² unknown, this yields 4 divides n₁ or 5 divides n₁.

Since ac unknown proceeds the same way and gives the same result, it will be omitted. The calculation of S₉₋₁(13) is therefore completed.

Appendix B

A Lower Estimate for S₉₋₁

In this Appendix, a proof of Result 4.1 is given. The M blocks in the first stage are denoted by B₁, B₂, · · · , B₉ and the M₁ first-stage switches are denoted I₁, · · · , I₉₁.

Let E be a subset of the set of inlet channels, assume that E has n elements and put

\[ k(E) = \text{Number of switches in } B \text{ having elements from } E \text{ among their inlet channels}. \]

\[ a_j(E) = \text{The number of elements from } E \text{ appearing on } I_j. \]

\[ a(E) = \max \{ a_j(E) | j = 1, 2, \cdots, M \}. \]

\[ a(E) = \min \{ k(E) | i = 1, 2, \cdots, M \}. \]

\[ a(E) = \max \{ a_j(E) | j = 1, 2, \cdots, M_1 \}. \]

\[ a(E) = \min \{ k(E) | i = 1, 2, \cdots, M_1 \}. \]

The definition of k(E) and T₉₋₁(2.1) ensures

\[ T₉₋₁(2.1) \text{ ensures} \]

\[ T₉₋₁(E) = k(E)M. \]

The pair condition gives

\[ T₉₋₁(E) = a(E)(M - 1) + k(E). \]

From 2.2, B.1, B.2, and B.3, we get

\[ S₉₋₁(n) \geq \min \left\{ \left. \left( \frac{n}{k(E)} \right) \right| k(E) \right\} \left( (M - 1) + k(E) \right) \]

When E runs through all subsets with n elements, k(E) runs through a subset of \{1, 2, \cdots, n₁\} yielding

\[ S₉₋₁(n) \geq \min \left\{ \left( \frac{n}{k(E)} \right) \left( (M - 1) + k(E) \right) \right\} \left( (M - 1) + k(E) \right) \]

Put \[ f_j(k) = kM \text{ and } f_{n₁}(k) = \left[ \frac{n}{k(E)} \right] (M - 1) + k. \]

To finish the proof of Result 4.1, it is enough to show that

\[ \min \{ f_j(k), f_{n₁}(k) \} = G_m(n) \text{ for any } n \leq n₁. \]

Choose p as the integer having the property

\[ n = p^2 + x \text{ where } 1 \leq x \leq 2p + 1. \]
First assume that $1 \leq x \leq p$. Then for $k = 0, 1, \cdots, p - 1$, we have
\[
f_{2,n}(p-k) = \left\lfloor \frac{p^2 + x}{p-k} \right\rfloor (M-1) + p - k \geq (p+k+1)(M-1) + p - k = (p+1)M + k(M-2) - 1 \geq (p+1)M - 1.
\]
Since $f_{2,n}(p) = (p+1)M - 1$ and $f_1(k) \geq (p+1)M$ for $k \geq p + 1$, it is now proved that
\[
\min_k \{ \max \{ f_1(k), f_{2,n}(k) \} \} = (p+1)M - 1.
\]
Assume now that $p + 1 \leq x \leq 2p + 1$. Then for $k = 0, 1, \cdots, p - 1$ we have
\[
f_{2,n}(p-k) = \left\lfloor \frac{(p-k)(p+k+1)+k^2+k+x-p}{p-k} \right\rfloor (M-1) + p - k \geq (p+k+2)(M-1) + p - k = (p+1)M + (k+1)(M-2) \geq (p+1)M.
\]
Since $f_{2,n}(p+1) = (p+1)M$ and $f_1(k) \geq (p+1)M$ for $k \geq p + 1$ it is proved that
\[
\min_k \{ \max \{ f_1(k), f_{2,n}(k) \} \} = (p+1)M
\]
when $n = p^2 + x$ and $1 \leq x \leq p$. (B.7)
Assume now that $p + 1 \leq x \leq 2p + 1$. Then for $k = 0, 1, \cdots, p - 1$ we have
\[
f_{2,n}(p-k) = \left\lfloor \frac{(p-k)(p+k+1)+k^2+k+x-p}{p-k} \right\rfloor (M-1) + p - k \geq (p+k+2)(M-1) + p - k = (p+1)M + (k+1)(M-2) \geq (p+1)M.
\]
Since $f_{2,n}(p+1) = (p+1)M$ and $f_1(k) \geq (p+1)M$ for $k \geq p + 1$ it is proved that
\[
\min_k \{ \max \{ f_1(k), f_{2,n}(k) \} \} = (p+1)M
\]
when $n = p^2 + x$ and $1 \leq x \leq p$. (B.7)
B.5, B.7, and B.8 concludes the proof of Result 4.1.

APPENDIX C

PROOF OF RESULT 4.3

In this Appendix, we prove Result 4.3. It is enough to show if $k \geq 3 + 1/(ln2ln(M^2lnM))$ then $g_k \geq M^2$. The following lemma will be helpful.

Lemma C.1: For $k \geq 2$ and $M \geq 2$ the following estimate is valid:
\[
g_k \geq M^{2-2^{-k}} \left( 1 + \left( \sum_{i=0}^{k-2} 3^i \right) M^{-2} \right). \quad (C.1)
\]

Proof: We have $g_2 = G_0(M + 1) \geq M(M + 1)^{1/2} \geq M^{3/2}(1 + 1/3M) \geq M^{3/2}(1 + 1/3M^2)$. This proves the lemma for $k = 2$. Assume the lemma is true for some $k$. Then,
\[
g_{k+1} = G_0(g_k + 1) \geq M(g_k + 1)^{1/2} \geq M \left( M^{2-2^{-k}} \left( 1 + \left( \sum_{i=0}^{k-2} 3^i \right) \right)^{1/2} \cdot 3^{1-k}M^{-2} \right) = M^{2-2^{-k}} \left( 1 + \left( \sum_{i=0}^{k-2} 3^i \right) \right) \cdot 3^{1-k}M^{-2} + M^{2-2^{-k}} \cdot 3^{1-k}M^{-2}.
\]
which concludes the proof of the lemma.

REFERENCES


Soren B. Jacobsen received the M.Sc. in mathematics from Aarhus University, Denmark, in January 1986. During 1986, he was employed at Electromagnetics Institute, Technical University of Denmark. In 1987 he was temporarily with the Mathematics Departments at UCLA and M.I.T. He returned to Electromagnetics Institute, Technical University of Denmark in January 1988. His interests include switching networks, combinatorics, ATD, and queueing systems.