ABSTRACT
A calculational method is presented for evaluating blocking probabilities for multislot calls in the time-division multistage switching networks of digital exchanges, which will be required to handle such calls in the future ISDN. The study shows the importance of the global peakedness factor resulting from mixing different classes of traffic within the same switching network. It explains how this factor can be used to define a reduced networks carrying equivalent average calls constituting ordinary (single-slot) Poisson traffic flows. And it demonstrates the increased importance of the stochastic dependence between switching stages in the case of multislot calls. Lastly, it is shown how to apply the reduced network method to evaluate, in a simple manner, the real blocking probabilities for the various classes of traffic.

1 - INTRODUCTION
Performance evaluation [1] as well as surveys on the grade of service [2] are more and more essential for large modern telephone exchanges offering more and more complex and varied facilities.

In the planned integrated services digital network (ISDN), digital exchanges will be required to establish MULTISLOT CALLS alongside ordinary single-slot calls.

Studies on such mixed traffic streams offered to a single group of circuits were performed some 20 years ago [3], and an algorithm for simplifying the numerical calculations was described recently by Roberts [4].

Mixed traffic handling in a multistage switching network (link system) with end-to-end path finding has also been analyzed, notably in [5].

This said, the calculational methods proposed to date do not permit simple evaluation of the impact of mixed traffic on blocking. Moreover, they assume stochastic independence between the various switching stages, an assumption first made by Jacobaeus [6].

In this paper, we show how the PEAKEDNESS FACTOR can be used to model the effects of traffic mixing; and how it is possible to take into account the DEPENDENCIES between stages due to the existence of multislot connections and to the structures of large digital switching networks. The basic idea is to simplify analysis to that of ordinary (single-slot) Poisson traffic flows, obviating the need for special algorithms. For this, we introduce the concept of EQUIVALENT AVERAGE CALLS carried by a network having a reduced number of paths, termed the REDUCED NETWORK, but without altering the offered traffic loads. It is then explained how the blocking probabilities in the real network can be simply calculated.

For preliminary calculations relative to the reduced network, use is made of the general method described in [8] and [9], which is valid for all switching networks.

After eliminating the effects of multislot connections on interstage dependencies, by translating the problem to the reduced network, we analyze the specific effects of the structures of digital switching networks, which tend to be large, have a small number of stages, and be heavily loaded.

Our results are also applicable to digital exchanges carrying only single-slot calls. In respecting grade-of-service specifications, it is necessary to consider the least-favorable case of "local" calls between lines or circuits connected at the same switch elements (e.g. at the same input and output switches of a TST network). Within the latter, each such local call occupies two time slots, even though it is an ordinary single-slot call.

2 - SINGLE CIRCUIT GROUP
2.1 - Basic assumptions and notation
We consider a group of N circuits offered x Poisson traffic streams labelled by an index (i = 1, 2, ..., x). For the ith stream, the offered traffic intensity is denoted ai and is expressed as a number of calls; the number of channels (time slots) used for each call is di; and the average call duration is equal to time unit. The latter duration is the same for all classes of traffic (any differences between classes would have no influence because each stream is Poissonian and can conserve its own time scale). Also, stationary conditions are assumed, meaning that the distribution of holding times has little importance, and the model is the lost call model.

The total offered traffic (expressed as a number of circuits) is:

\[ M = \sum_{i=1}^{x} a_i d_i \]  

(1)

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Its variance is:

\[ \text{var} = \sum_{i=1}^{x} a_i^2 \]

(2)

And its peakedness factor is:

\[ Z = \text{var}/M \]

(3)

We denote by \( P_k(N;M) \) the probabilities of finding \( k \) circuits occupied, and by \( B_i \) the call congestion for the \( i \)th traffic stream.

2.2 - Occupancy distribution function

J. Roberts [4] has given the following algorithm for numerically calculating probability \( P_k \):

\[ P_k = \frac{N^x}{k!} \prod_{i=1}^{x} a_i \]

(4)

with:

\[ P_k - 0 \text{ if } k < d_1. \]

\[ P_0 \]

is determined by the normalization formula below:

\[ \sum_{k=0}^{N} P_k = 1 \]

(5)

It can then be shown that:

\[ B_i = \sum_{k=N-d_1+1}^{N} P_k \]

2.3 - Equivalent average calls and reduced circuit groups

Because all traffic is supposed Poissonian, the traffic mixing distribution takes a product form. To simplify, we can assume the circuit group to be of infinite size. This only changes the normalization factor in the expression of \( P_k(N;M) \), which becomes \( P_k(x;N) \).

The first two moments of \( e^\Psi(u) \) are zero and hence the associated random number usually has a low value, oscillating around the origin. From (8) and (9), the circuit group can therefore be considered as virtually occupied by a single class of traffic made up of EQUIVALENT AVERAGE CALLS each occupying \( Z \) channels (with \( Z \) an integer).

We denote:

\[ M_0 = N/Z, \quad N_0 = N/Z \]

(10)

defining a "REDUCED CIRCUIT GROUP" carrying equivalent average calls.

For equivalent average calls, the probability of finding \( K = K_0 \cdot Z \) circuits occupied (with \( K_0 \) integer) is:

\[ P_{k_0}(N_0;M_0) = \frac{M_0^{N_0} N_0!}{K_0!} \]

(11)

In time interval \( dt \), the probability of arrival of a call finding this occupancy state is:

\[ (M_0 dt)(1/P_k) \]

In other words, for integer \( K_0 \):

\[ P_k = \frac{1}{Z} P_{K_0} \]

(12)

Now, notice that \( e^\Psi(u) \) defines a step function in which, for integer \( Z > 0 \) and \( N \) a multiple of \( Z \):

\[ P_{N-(y-1)Z} = P_{N-(y-1)Z-1} = \cdots = P_{N-(y-1)Z-(Z-1)} \]

The purpose of function \( e^\Psi(u) \) is to smooth the distribution with respect to \( e^\Psi(u) \) without changing (12) for integer \( K_0 \). We can write with \( n < Z \):

\[ P_{N-(y-1)Z-n} = P_{N-(y-1)Z} \]

(13)

For \( n = Z \) (integer), this expression must be equal to

\[ P_{N-Z} \]

Hence:

\[ K_y = \frac{P_{N-Z}}{P_{N-(y-1)}} \]

(14)

Finally, for an integer \( y > 0 \) not too large and an integer \( n (0<n<Z) \), we can write:

\[ P_{N-Z-n} = P_{N(K_y)^n} \]

(15)
When N is not an integer multiple of Z, we shall also use this approximation. Formulas (11) and (12) then give the following expression for the TIME CONGESTION, taking into account (10);

\[ P_j = \frac{1}{Z} E_{N_0} \left( \frac{M}{Z} \right) \]  \hspace{1cm} (16)

where \( E_{N_0} \left( \frac{M}{Z} \right) \) is the Erlang loss formula. Also, the CALL CONGESTION B for an equivalent average call is:

\[ B = \frac{E_N \left( \frac{M}{Z} \right)}{Z} \]  \hspace{1cm} (17)

This is Hayward's loss formula [7].

2.4 - Loss formulas

When \( d/Z \) is not too large, (13) becomes:

\[ E_j = K \left[ \frac{P_{N-1}}{P_{N_0}} \right]^{1/Z} = \left( \frac{N}{M} \right)^{1/Z} \]  \hspace{1cm} (18)

Formulas (5), (15), and (16) then give the loss value for the ith traffic stream:

\[ B_i = \frac{E_N \left( \frac{M}{Z} \right)}{Z} \left[ \frac{1}{Z} \right]^ {d-1} \]  \hspace{1cm} (19)

Table 1 shows the excellent accuracy of this formula compared with the results of calculations using algorithm (4). And our formula has the advantage of permitting fast, easy calculations.

<table>
<thead>
<tr>
<th>( a_j )</th>
<th>( d_j )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( N )</th>
<th>( Z )</th>
<th>( E_1 )</th>
<th>( E_2 )</th>
<th>( E_3 )</th>
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<tr>
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<td>1</td>
<td>22</td>
<td>2</td>
<td>86.2</td>
<td>1.51</td>
<td>6.1 \times 10^{-4}</td>
<td>1.4 \times 10^{-4}</td>
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<tr>
<td>42.2</td>
<td>1</td>
<td>11</td>
<td>4</td>
<td>86.2</td>
<td>2.53</td>
<td>2.3 \times 10^{-3}</td>
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<td>42.2</td>
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<td>26</td>
<td>2</td>
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<td>2.8 \times 10^{-2}</td>
<td>1.3 \times 10^{-2}</td>
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<tr>
<td>51</td>
<td>1</td>
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<td>1.5 \times 10^{-2}</td>
</tr>
</tbody>
</table>

Table 1 - Mixing of two classes of traffic (on \( N = 120 \) circuits). Comparison of exact values and approximate values.

When \( N \) is an integer multiple of \( Z \), expression (17) for \( B \) corresponds to the average blocking probability. If, however, \( N \) is not an integer multiple of \( Z \), (17) does not give exactly the average blocking probability. Perturbations to the quasi-congested states result in a slight discrepancy from the exact result given by (19).

3 - SWITCHING NETWORK

We consider the multistage switching network of a digital exchange, operating as a link system in which the assumption of symmetry is valid [6]. The issue of stochastic dependence between the network's stages is examined further on.

This network carries a mixture of different classes of traffic, using the same assumptions and notation as for a single circuit group in paragraph 2.

3.1 - The reduced network method

For establishment of a \( d \)-slot call, conventional point-to-point conditional selection involves looking for \( d \) free paths between the concerned input switch and output switch, out of \( N \) possible 'geographically' distinct paths.

Even when inter-stage stochastic dependencies exist, we assure almost symmetrical operation and selection for these \( N \) paths, which can be used indifferently for ordinary (single-slot) calls and multislot calls.

We denote respectively by \( N \) and \( Z \) the average values and the peakedness factor of the global traffic carried by the switching network.

We also assume that all point-to-point traffic streams have the same value and the same characteristics. In [10], formula (160), it is shown that, for single-slot calls and taking the interstage dependencies into account, the probability of finding \( j \) channels (links) occupied per stage is:

\[ P_j = P_0 \cdot W(N;j) \cdot \frac{M_j}{j!} \]  \hspace{1cm} (20)

\( W(N;j) \) is the probability of being able to place \( j \) single-slot calls in the empty network independently of the nature of the random processes, with the random and independent draws taking place in proportion to the intensities of the partial traffic streams and respecting the symmetrical conditional selection rules.

For a mixture of different classes of traffic, (12) can be used to write, for any \( j \) which is an integer multiple of \( Z \):

\[ P_j = P_0 \cdot W(N;j) \cdot \frac{M_j}{(j/Z)!} \]  \hspace{1cm} (21)

In view of the symmetry in hunting, \( W(N;j) \) virtually depends only on \( j \) and not on the distribution between the various classes of traffic. As the global random distribution is that of the equivalent average call, the latter has only \( (N/Z) \) paths available. It follows that:

\[ W(N;j) = \frac{W(N)}{Z} \]  \hspace{1cm} (22)

For a (point-to-point) series-parallel graph, in which all the paths are "geographically" disjoint, the above reasoning is strict. In the case of a 'spider' graph, the analysis differs but only very slightly (because blocking takes place above all in the two end stages). Finally, formula (21) becomes:

\[ P_j = P_0 \cdot W \left( \frac{N}{Z}; \frac{j}{Z} \right) \cdot \frac{(M/Z)_j}{(j/Z)!} \]  \hspace{1cm} (23)

even when \( j \) is not an integer multiple of \( Z \). Thus, the concept of the equivalent average call can again be used to express the occupancy of internal links, and to translate the problem to the case of ordinary (single-slot) Poisson traffic streams carried by a reduced network in which the number of possible paths is \( (N/Z) \), without altering the loading of the internal links.
For a mixed point-to-point traffic stream, we define \( S_y(N;M) \) as the probability of finding exactly \( y \) free paths, where \( M \) is the global traffic intensity. \( S_y(N;M) \) is the counterpart of \( P_{N-y}(N;M) \) in the case of a circuit group (see paragraph 2).

We also denote:

\[
N_0 = \frac{M}{Z}, \quad N = \frac{N}{Z}
\]

by analogy with (10). And for the corresponding reduced network denote by:

\[
R_y(N_0;M_0)
\]

the probability of finding exactly \( y \) free point-to-point paths. This is the counterpart for the reduced network of \( S_y(N;M) \) for the real network.

If we write \( y_0 \) the integer part of \( y/Z \) then

\[
R_{y_0}(N_0;M_0)
\]

is the counterpart of \( P_{N-y}(N_0;M_0) \) by analogy with (10).

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Lastly, formula (15) becomes:

\[
B_i = \sum_{y=0}^{d_i-1} R_y(N_0;M_0)
\]

because of the coefficient \((1/Z)\) in (12).

This smoothing approximation allows us to evaluate the point-to-point call congestion for each of the \( i \) classes of traffic:

\[
B_i = \left[ \frac{K_0}{R_0(N_0;M_0)} \right]^{1/Z}
\]

We now write \( d_i \) the integer part of \( d_i/Z \)

Taking account of (24) and (25), formulas (26) and (27) finally give:

\[
B_i = \sum_{u=0}^{d_i-1} R_u(N_0;M_0) \left[ \frac{K_0}{R_0(N_0;M_0)} \right] \frac{1}{Z K_u+1-1}
\]

with \( v = Z \) for \( u < d_0 \) and \( v = d_0 \) for \( u = d_0 \)

As a first approximation, for \( d_i/Z \) not too large we can take

\[
K_i = K = (B_i/R_0)^{1/Z}
\]

in which case:

\[
B_i = R_0 \frac{1}{Z} \frac{K_i-1}{K-1} = B_i \frac{K_i-1}{K-1}
\]

analogous to (19).

In the case of a SINGLE-SLOT CALL, the point-to-point call congestion is:

\[
B_1 = \frac{1}{Z} R_0(N_0;M_0)
\]

By simplifying the problem to a single class of traffic offered to a reduced network, formulas (30) and (31) allow us to take into account the effects of multislot calls on the stochastic dependence between stages.

3.2 - Calculation of blocking in the reduced network

It is now necessary to evaluate probability \( R_0 \). This is quite straightforward, involving the conventional case of single-slot calls, offered to the reduced network. As a first step, we make the usual assumption of stochastic independence between the stages [6], and we introduce the generating function for the network:

\[
G(s) = \sum_{y=0}^{\infty} R_y(N_0;M_0) s^y
\]

Section III of [8] shows how to apply the Bernoulli distribution to occupancy in order to determine this generating function, and then conveniently extend the analysis to the case of arbitrary distributions at each stage.

For simplicity, we again assume that the \( N \) possible point-to-point paths are geographically independent of one another, referring to the discussion in paragraph 3.1. With the Bernoulli distribution at all stages, each path has a probability \( Q \) of being free. It follows that:

\[
R_y(N_0;M_0) = (N_0)^y (1-Q)^{N_0-y}
\]

The network is assumed to have \( E \) stages, with a loading \( p_i \) on the links of the \( i \)th stage \((i = 1, 2, \ldots, E)\).

Denoting \( q_i = 1 - p_i \), we have:

\[
Q = q_1 q_2 \cdots q_E
\]

Inserting this expression in (33), we next expand the resulting polynomial function of \((p_1, p_2, \ldots, p_E)\) and then make the necessary substitutions to take into account the real occupancy distributions, using the method explained in [8]. This approach thus avoids the laborious manipulations of approaches based on combinatorial analysis.

In what follows, we apply our approach to the important case of a two stages link system.

4 - BLOCKING IN A TWO-STAGE LINK SYSTEM

We once again assume stochastic independence between the stages in the reduced network.

4.1. - "Exact" formulas

The Lee graph for paths from a point \( A \) to a point \( B \) is shown below in Figure 1:

\[
A \quad B
\]

By simplifying the problem to a single class of traffic offered to a reduced network, formulas (30) and (31) allow us to take into account the effects of multislot calls on the stochastic dependence between stages.
Expanding the second term in brackets, we find:

\[ R_y = \sum_{\lambda_1=0}^{N_0} \sum_{\lambda_2=0}^{\lambda_2} [p_{\lambda_1}] [p_{\lambda_2}] q_{\lambda_1} + q_{\lambda_2} \]

To bring out the equivalent influence of each stage, the second term in brackets can also be written:

\[ \left( N_0 - \lambda_2 \right) \left( N_0 - \lambda_1 \right) \left( \lambda_1 + \lambda_2 \right) \]

From which it follows, with Bernoulli's model:

\[ R_y = \sum_{\lambda_1=0}^{N_0} \sum_{\lambda_2=0}^{\lambda_2} \left[ \left( \lambda_1 + \lambda_2 \right) \left( \lambda_1 + \lambda_2 \right) \right] \]

where:

\[ N(y;\lambda_1,\lambda_2) = \left( \frac{N_0 - \lambda_1}{\lambda_2} \right) \frac{N_0 - \lambda_2}{\lambda_2} \]  \hspace{1cm} (36)

In (35), it is now sufficient to replace each term in brackets by the real distribution. In practice, the ith stage corresponds to a group of circuits that must carry a traffic \( Mo \) which is Erlang distributed. We can therefore make the substitution:

\[ R_y = \sum_{\lambda_1=0}^{N_0} \sum_{\lambda_2=0}^{\lambda_2} [p_{\lambda_1}] [p_{\lambda_2}] q_{\lambda_1} + q_{\lambda_2} \]

with:

\[ P_{\lambda_1} = \frac{N_0 - \lambda_1}{\lambda_2} \left( \lambda_2 \right) \left( \lambda_1 + \lambda_2 \right) \]

Expressions of the sort are presented in [5] for real networks.

Table 2a shows the very high accuracy of the reduced network method applied with the formula (28) to the case of a two-stage link system and \( N = 120 \) channel internal highways (groups of 120 links), as compared to the results obtained by using Roberts' algorithm.

### Table 2

<table>
<thead>
<tr>
<th>Algorithm of Roberts</th>
<th>Reduced Network</th>
</tr>
</thead>
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<tr>
<td>Exact</td>
<td>Approximates</td>
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<td>( A_2 )</td>
</tr>
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</tr>
<tr>
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<tr>
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<td>1.6</td>
</tr>
<tr>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

5.4B-2-5
Table 2b shows the close correspondence between results obtained with the above approximation and formula (30) and those obtained with Roberts' algorithm.

Formulas (30), (46), and (47) can thus be used to calculate the individual loss values \( B_i \), provided the structure of the switching network permits the assumption of stochastic independence between stages. However, as shown by the simulation results in Table 3a, this assumption is not very well respected in the case of digital networks. We now tackle this problem for the case of multislot call traffic, again using the reduced network approach.

4.3 - Stochastic dependence between stages

In digital (time-division) switching networks the elementary switches are large, the number of stages is small, and internal loads are high. This is incompatible with the assumption of stochastic independence between stages. To take into account the perturbations due to inter-stage dependencies, we use the MODEL WITH BALKING. For a transition to occur within a given stage from state \((N-A-1)\) to state \((N-A)\), the given links in the other stage capable of being used to set up an additional call must not all be busy. Using the Palm-Jacobaeus formula, the probability of this can be written:

\[
1 - \frac{E_{N_0}(M_0)}{E_{N_0}(M_0) - \lambda}(N_0)
\]

This multiplication factor is applied to the previous birth rate in the reduced network, and the substitution thus becomes:

\[
P_{N_0} \cdot D(N_0, M_0) = \frac{E_{N_0}(M_0)}{E_{N_0}(M_0) - \lambda}(N_0)
\]

with:

\[
D(N_0, M_0) = \prod_{\lambda=0}^{N_0} (1 - \frac{E_{N_0}(M_0)}{E_{N_0}(M_0) - \lambda}(N_0))
\]

This expression can be calculated using the recursive formula:

\[
D(N_0, M_0) = D(N_0, M_0) \cdot (1 - \frac{E_{N_0}(M_0)}{E_{N_0}(M_0) - (N_0+1)}(N_0))
\]

Table 3b shows the close correspondence between the results of calculation and simulation.

In multi-slot calls, the lowest sensitivity to the dependence phenomenon is noticeable and comes from the following:

Denoting

\[
D(N_0, M_0) = \prod_{\lambda=0}^{N_0} (1 - \lambda^+)
\]

where Bernoulli's approximation is used for not too high load values, as here only \( \lambda' \) low values are influential. (40) becomes:

\[
H_y(\lambda) = \frac{\lambda}{\lambda' \cdot y} \left[ (\lambda^+ \cdot y) \sum_{\lambda=0}^{N_0} \frac{D(\lambda^+ \cdot y, N_0)}{N_0} \right]
\]

which allows formula (39) to be kept.

In practice, as \( N_0 \) is large, the formula analogous to (42) becomes:

\[
H_y(\lambda) = \frac{\lambda}{\lambda' \cdot y} \sum_{\lambda=0}^{N_0} \frac{D(\lambda^+ \cdot y, N_0)}{N_0}
\]

Similarly (39) becomes:

\[
R_y(N_0, M_0) = E_{N_0}(M_0) \cdot \frac{E_{N_0}(M_0)}{y!} \sum_{\lambda=0}^{N_0} \frac{E_{N_0}(M_0) - \lambda}{E_{N_0}(M_0) - \lambda} \cdot D(\lambda^+ \cdot y, N_0)
\]

Table 3 - Comparison between calculation and simulation

5 - LOCAL CALLS THROUGH THE SAME TERMINAL SWITCH

To complete this study of digital switching networks carrying multislot call traffic, we now examine the case of calls between two lines or circuits connected at the same terminal switch. The latter must then carry "local" calls each occupying two times \( d_j \) channels.

We consider the simple case of single-slot calls. The formulas for multislot calls can be derived quite easily.

Symmetrical path selection is again assumed. We denote by \( C \) the number of input switches (and output switches) in the network. And we denote by \( N \) the traffic in circuits offered to a single
switch. Because calls are equally distributed, we can write:

\[ M = x \left( \frac{C-1}{C} \right) + \frac{x}{C} \cdot 2 \]  

(54)

Where \( x \) is the traffic intensity in calls on the switch.

Hence:

\[ x = \frac{M}{C} \]  

(55)

and because \( M = a_1 + a_2 \cdot 2 \) it becomes:

\[ a_1 = \frac{M}{C+1}, \quad a_2 = \frac{M}{C+1} \]  

(56)

It is then possible to calculate blocking for the "local" calls and for "non-local" calls in the same way as for multislot calls in previous sections. Calculation of \( Z \) gives:

\[ V \cdot \frac{C+3}{M} \cdot \frac{C+1}{C+1} \]  

(57)

This result correctly reflects the relative influence of the number of switches.

6 - SOME PRACTICAL RESULTS

In conclusion to our study, you will find hereunder results showing coefficient \( K \) variations in formula (30) depending on opening \( N \) of TST network, and on coefficient of reduction \( Z \) for internal load value \( p = 0.7 \).

In brackets we give the corresponding blocking probability \( B_1 \) for ordinary calls.

These results are obtained by the exact calculation of section 4.3 taking into account the dependency between stages.

![Figure 2 - K and B1 in TST network, with p = 0.7.](image)

Thus we show that the blocking characteristics for multislot connections can be calculated by the simple use of formula (30) applied to the reduced network whose parameters \( B_1 \) and \( K \) may be obtained by calculation or by simulation in the case of very high loads.

7 - CONCLUSION

We have shown how the REDUCED NETWORK METHOD resulting from the EQUIVALENT AVERAGE CALL concept, based on the PEAKEDNESS FACTOR \( Z \), is applied to evaluate the real blocking probabilities for the multislot connections in the digital connection networks. As it allows the reference to single-slot connections, the general results already obtained on the networks can be used. The impact of the multislot calls on the ordinary traffic can thus be evaluated and the blocking probabilities derived for all types of traffic by using a simple relationship.

The increased importance of the dependencies between stages in the connection networks using large switching unit and a small number of stages has been stressed. It can be noticed that the phenomenon is less sensible for multislot connections than for ordinary connections. We have showed how to take into account the dependencies in the calculation.

Some practical results are given referring to a TST network such as those used in the French digital switching systems.

Finally, for the standards relating to the blocking of calls presented to a circuit group of a network handling mixed multislot connections, it can be referred to the blocking of ordinary single-slot calls in the reduced network defined by its parameters: \( N_0, Z, K \).

References :


