Design of Mixed Analogue and Digital Switching Networks

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ABSTRACT

Modern common control switching systems invariably use link trunking within individual exchanges whereas step-by-step operation is still the normal way of working in complete multi-exchange networks. The introduction of common-channel signalling by means of inter-processor data links, together with integrated digital switching and transmission, provides a convenient opportunity to review the arrangements for trunking multi-exchange switching networks.

An approach to the design of efficient link trunking arrangements and its application to multi-exchange switching networks is described. The impact of introducing digital switching into such networks is considered and possibilities for providing efficient multi-exchange networks having blocking probabilities substantially independent of the number of switching stages, are discussed.

1. INTRODUCTION

Switching networks in current exchange designs are frequently based on the two-stage, line and group selection units used in crossbar systems which in turn have evolved from and been considerably influenced by step-by-step switching techniques. This approach provides convenient building blocks from which complete switching systems may be constructed and is thus valuable from the points of view of manufacture, installation and possibly, extension. The approach does, however, seem to have impeded the design of switching networks as an integrated whole. The design of switching networks as a complete entity should result in configurations which are flexible and economical when associated with modern control techniques, whilst retaining good modularity.

This paper describes such an approach to switching network design and its extension to multi-exchange networks, particularly as applied to the mixed space-division and time-division switching environment which is likely to be the norm during the coming years.

2. FUNDAMENTALS

The essential function of a telecommunications switching network is to enable any one subscriber's line termination to be connected to any other. The simplest arrangement to perform this function is a single crosspoint matrix. This becomes very inefficient as the number of subscribers increases. Its use is thus restricted to small PAXs, where it does provide the benefit of non-blocking access.

Multi-stage networks are necessary to maintain crosspoint efficiency as the number of subscribers increases. Such networks do, however, introduce the possibility of congestion on the links between switching stages. If acceptable blocking probabilities are to be achieved several alternative paths must be available for a connection between any pair of network terminals. The design of efficient switching networks is concerned very much with the provision of an adequate number of paths and with their arrangement.

In considering the traffic handling characteristics of multi-stage switching networks, it is helpful to clearly distinguish between two fundamental switch functions. 'Line selection' is the means of providing access, either directly or via other switching stages, to the required one out of a number of switching networks terminals. The blocking characteristics are only indirectly affected by the line selection function in that the number of terminals affects the number of switching stages required and also the distribution of the occupancy states of the inter-stage links. 'Group selection' is the means of providing access to an adequate number of paths through the switching network, any one of which may be selected for a connection between a particular pair of network terminals. The blocking characteristics of a switching network are to a large degree determined by the extent and disposition of the group selection function.

It should be noted that, particularly in link systems where the trunking is effectively bi-directional, the switches may be considered to perform a particular switching function with respect to their outlets and a similar or quite different function with respect to their inlets. Thus the terminals of switches which lead away from the centre of the switching network towards the switching network terminals are generally concerned with the line selection function. The switch terminals which lead towards the centre of the switching network, are, on the other hand, generally concerned with the group selection function.

Note that the commonly used terms 'line selection unit' and 'group selection unit', although convenient in practice, are somewhat misleading. A line selection unit, for example, performs a group selection function for subscriber originated traffic.

A suitable convention for showing these switch functions on simplified trunking diagrams is suggested in figure 1. The switches or switching stages are indicated by points. An oblique line above the horizontal indicates line selection (L), whilst one below the horizontal identifies group selection (G). The L and G indications are obviously optional and may usefully be replaced by figures indicating the switch access size or, in the case of a combined function, by the number of groups and the number of links per group. Figure 1 (c) shows a commonly seen 4-stage arrangement in which the B- and C-switches perform a combined line and group selection function on one side of the switch.

3. LINK SYSTEMS

3.1 INTRODUCTION

The Clos non-blocking networks1 form a class of networks which provide a useful starting point in the design of efficient practical link systems. Another important class of networks, the rearrangeable non-blocking networks, may be derived from the Clos configurations by the omission of, in the 3-stage case, almost 50% of the paths and thus the same proportion of crosspoints. Even greater crosspoint savings are obtainable in networks with more than 3 stages, albeit at the cost of the control complexity necessary for rearrangement of established connections.

Economical switching networks, for the interconnection of two subscribers anywhere on a normal national network, cannot have an overall non-blocking property. Non-blocking networks, if they are to be used at all, can only apply to a part of the overall network.

Networks identical to the rearrangeable networks but without rearrangement of established connections provide acceptable blocking probabilities with reasonably high terminal loadings. With the much lower loadings normally found on subscriber line terminations, the number of paths provided may be still further reduced. The result is something approximating to the efficient subscriber switching networks which we seek to achieve in practice.

Such networks, whether blocking or non-blocking, have simple series-parallel channel graphs as shown in figures 2 (a) and 2 (b). Given optimisation of switch sizes, the crosspoint efficiency of the three-stage network or its folded counterpart cannot be bettered within the network size range for which a three-stage network is minimal. This is not, however, true of networks with more than three stages, as a fundamental difference between non-blocking networks and their blocking derivatives arises.
3.2 EFFECT OF INTERCONNECTION PATTERN

In a network with the simple series-parallel interconnection pattern, a free first-stage link must be matched by the equivalent final-stage link also being free, for a connection to be possible. This condition is guaranteed in non-blocking networks. In blocking networks, however, a free first-stage link not being matched by free final-stage links is considerably higher than the probability of either set of links being completely unavailable. This effect is also apparent on the second-stage and penultimate-stage links of networks with more than five stages.

A second source of inefficiency is apparent on the links adjacent to the centre stages. Consider, by way of example, the five-stage network shown in figure 2(b). The limited number of second-stage switches in one section all have access to the same small set of fourth-stage switches. This results in strong dependences between the occupancy states of the second- and third-stage links, so as to increase the probability of blocking. This effect is also present, though in diluted form, on other links of networks with more than five stages.

Both of these deleterious effects result from a lack of unity of the series-parallel switching network. Both effects may be minimised by a suitable choice of switch interconnection pattern at the centre of the switching network. The principle may be seen in figure 2(c), which shows a fully interleaved trunking pattern. Each first-stage link now has access to all final-stage links, so minimising the mismatch problem. At the same time, the traffic from each B-switch is now distributed over a much larger number of central switches, so that the dependences between the link occupancy states are minimised. This does not alter the functions of the individual switches but merely improves the group selection function within the overall network.

The same principle may be easily extended to networks with more than five stages where the benefits are available to the links in all stages. See figure 2(d). It should be noted that unity is given to the complete network, regardless of the number of stages, by a suitable interconnection pattern at the centre of the network only. The simplicity of the series-parallel networks can be otherwise retained.

Figure 3 shows the calculated approximate blocking performances of three- and five-stage series-parallel networks and five-stage interleaved networks, having a switch access size of k = 8 at all stages. Identical link loadings with independent binomial distributions at all stages are assumed.

The five-stage interleaved network is seen to be able to handle link loadings 25% higher than the series-parallel networks (3-stage included), at 1% loss probability. This excludes the effect of the more peaksy traffic on the links adjacent to the centre stage in the series-parallel networks. The blocking contribution of these links is in any case seen to be negligible at the low loadings available. This reflects inefficiency in crosspoint and link utilisation resulting from the use of first-stage only concentration. Multi-stage concentration enables efficient link loadings to be achieved at the centre of the network, whilst the low first-stage link load allows point-to-group selection losses (and corresponding dial tone delays) to be minimised.

The factors contributing to the attainment of an efficient switching network for the interconnection of subscribers may now be perceived. Firstly, the channel graph should 'fan out' as rapidly as possible from the network terminals towards the centre-stage switches, so as to permit efficient link loads with reasonable contribution to the overall blocking. This implies that the switches should perform only a group selection function on their 'inner' terminals, that is to say, be no 'cross-linking' in either half of the channel graph, nor any parallelising of links. The latter two desirata result in what is sometimes known as 'link alignment'; the provision of only a single path from any individual centre-stage switch to any single network termination.

The second major factor in the achievement of switching network efficiency is the use of a suitable interconnection pattern to link the two halves of the channel graph so as to obtain a unified trunking, as already discussed.

3.3 EXTENT OF THE GROUP SELECTION FUNCTION

If the switches perform only a group selection function on their inner terminals, then the number of paths available increases rapidly with the number of stages and hence with network size.

This may be partially exploited by using increasingly high link loadings at the centre of the network is approached. The effect on overload performance is likely to set a limit to the value of this technique.

An alternative approach for large networks is to restrict the availability of links after the first few stages. In this way a sufficient number of paths to achieve the required loss probability is obtained after a minimum number of stages and this number of paths then remains substantially constant throughout the central part of the network. The function of the concentration stages is now seen to be two-fold. In addition to establishing efficient link loadings, they simultaneously build up the link availability so that it can sustain those loadings.

The redundancy in switch terminals, which results from the restriction of link availability, can be used to increase the number of network terminals. The switches affected now perform a line selection or combined line and group selection function on their inner terminals.

In references 2 and 3, Feiner and Kappel describe a method of deriving efficient link systems, with and without line concentration, which is relevant to the present discussion. In concluding that switch access sizes and link loadings of non-concentrating networks should be equal at all stages and dependent only upon the link associated cost, they use an access factor (A) defined in such a way that it correlates reasonably well with the loss probability of arbitrary network sizes and forms.

The access factor

\[ A = m \cdot \frac{k^s}{N} \cdot (1-a)^s \]

where \( m \) = number of paths accessible between every inlet-outlet terminal pair, 
\( q \) = the link idle probability (1-a), 
\( a \) = average link occupancy, 
\( s \) = number of switching stages, 
\( k \) = individual switch access size, 
\( N \) = number of network inlets (and outlets).

The extension to include the effects of line concentration does not affect the basic premise.

Table 1 shows the relationship between optimal switch access size \( k \) and link loading \( a \) and the cost per switch outlet \( n \) expressed in crosspoint units, as derived in reference 2. It also shows a parameter \( 1/q^2 \), which is the factor by which the number of paths \( m \) must be increased for every two stages added to the network, in order to maintain \( A \) (and thus the loss probability approximately) constant.

Table 1 Optimal Network Parameters

<table>
<thead>
<tr>
<th>n</th>
<th>k</th>
<th>a</th>
<th>1/q^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.4</td>
<td>.5</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>.58</td>
<td>5.7</td>
</tr>
<tr>
<td>8</td>
<td>13.5</td>
<td>.62</td>
<td>6.9</td>
</tr>
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<td>12</td>
<td>16</td>
<td>.64</td>
<td>7.7</td>
</tr>
<tr>
<td>16</td>
<td>18.5</td>
<td>.65</td>
<td>8.2</td>
</tr>
</tbody>
</table>

The addition of two stages to a symmetrical link system enables the number of paths to be increased by a maximum factor equal to the switch access size \( k \). This is seen from table 1 to be approximately double the factor \( 1/q^2 \) required to maintain the blocking performance for practical values of \( n \) (reference 2 suggests \( n = 5 \) to 15). In the central part of large networks therefore, only about one-half of the stages are required to provide the group selection function. The remainder can provide a line selection function on both sets of terminals.
The foregoing gives a feel for the way in which the line and group selection functions might be distributed in an efficient very large link system. All stages perform line selection on their outer terminals and the first few and last few stages give group selection on their inner terminals. A minority of stages in the opinion of the network provide line selection on their inner terminals also.

4. TERMINAL EXCHANGES

Switching networks within individual terminal exchanges are rarely large enough to allow the pattern described in the previous paragraph to be clearly established and there are several other reasons why line selection is performed on the inner terminals of switches should, in the author's opinion, be avoided in practice. Some form of junctor is frequently provided in each link at or adjacent to the centre of the switching network. This may be a supervisory bridge, a type junctor or merely a crosspoint holding 'through' type device. In either case it will increase the link associated cost in that part of the network and justify traffic concentration to provide higher link occupancies. This will require the group selection function to be continued further into the heart of the network.

A switching network which performs the line selection function only on the outer terminals of switches, has the total switching network traffic passing through its centre stage. This avoids the problems of traffic imbalance, which can occur when separate link groups interconnect the switching network modules.

The separate link groups also present an extension problem and considerable ingenuity has been devoted to simplifying the process of line selection. Such arrangements are only necessary when line selection is performed on inner switch terminals and is frequently restrictive on the growth range of the switching network.

The alternative arrangement, which in its symmetrical form always uses an odd number of stages, allows extension by addition rather than by rearrangement. If the simplest extension arrangement, shown in figure 4 (a), requires excessively large switching modules or provides an inadequate growth range then the alternative of figure 4 (b) may be used.

Subscribers' lines are generally bothway terminations and therefore need to be connected to both an inlet and an outlet of the two-sided type of network discussed thus far. Since the network is symmetrical, the inlets and outlets may be treated identically and two sets of 'm' paths are available for the interconnection of any pair of subscribers (except on intra-module connections). The redundancy which this represents is clearly seen from the fact that each subscriber's terminal has access to two sets of first-stage links. The first-stage switches are therefore effectively twice the size that they appear to be and should be redimensioned accordingly.

By combining the final-stage switches of such a symmetrical network with those of the first stage, the network may be redrawn as a single-sided or folded version. The link interconnection pattern is now seen to provide access from any one of the first-stage links to only half of the total but may be extended to restore full interleaving.

This approach to folded networks demonstrates the very close affinity between folded and two-sided forms and suggests that the distinction drawn in practical networks is largely a matter of physical realisation rather than a difference in trunking principles.

5. MULTI-EXCHANGE NETWORKS

Switching networks of the type described in section 3 may be "grown" to any size by the provision of additional switching stages. Feiner and Kappel have shown that optimum switch size is not dependent on switching network size but only on effective link cost, at least beyond the concentration stages. Thus the optimum way to grow such a network is to increase the number of switching stages. This finding is of particular significance if we consider the switching network to extend beyond the confines of a single geographical location since multi-exchange networks are, in effect, of variable size dependent on call routing.

In theory it is possible to expand and distribute such a network to serve a large city or even a whole country, but additional factors now arise which make the economics of the network more complicated. Primarily the link costs become a very much more significant factor and secondly, the community of interest of subscribers generally diminishes with distance. These two factors make it very inefficient to route all traffic via a single central point and the majority of traffic needs to be "folded back" after a limited number of stages. Thus the normal hierarchical pattern of exchanges is arrived at, not by working upwards from the individual exchanges but rather by working downwards from an overall switching network concept.

A simple form of multi-exchange link system might have a channel graph as shown in figure 2 (d). One terminal exchange consists of the A-, B- and C- stages, whilst the other has the E-, F- and G- stages. The two terminal exchanges are connected to each other and to other exchanges via the single-stage transit exchange connecting all the D-switches. This might be an economical way of arranging a number of small link concentrators but has the following major disadvantages for the interconnection of larger terminal exchanges.

Firstly, all traffic is routed via the transit exchange, including local traffic which must be folded back via the D-stage. Secondly, the exchange to which a called subscriber is connected will need to signal to the originating exchange the identity of all free D-E links which have access to the called line in order that a subscriber to subscriber path may be selected. This is likely to represent an excessive load on the signalling channel except in very small configurations. Finally, the single-stage transit switch is likely to be restrictive on the number of terminal exchanges which may be served.

The potential benefits are however, clear from figure 2 (d). The terminal exchanges are only required to provide a pure group selection function between a subscriber and the inter-exchange links. Such simplifies path selection and ensures that the provision of crosspoints is minimal. The major benefit, however, is seen in the transit exchange where independent switches each interconnect only a single link from each terminal exchange. It is clear that, in addition to the control simplicity of such an arrangement, the quantity of switching equipment required is very considerably less than in an orthodox transit exchange where every inlet needs to have access to every outlet. It seems desirable that these benefits should be made available to the general case.

The routing of own-exchange traffic via the transit exchange can be avoided by making provision for folding back of traffic via the C-stage and (and E-stage). The channel graph for own-exchange traffic will now be as figure 2 (c). If own-exchange traffic is a significant proportion of the total, then it may no longer be possible to justify the quantity of inter-exchange links required to maintain the performance necessary on calls via the transit exchange. This situation will be exacerbated if routes from a terminal exchange to several other exchanges are justified by network planning considerations. Many junction routes will be too small to form part of a multi-exchange link system and will need to be terminated on the A-stage and treated in the orthodox manner.

The introduction of integrated digital transmission and switching techniques into transit exchanges will provide solutions to the problems raised in this section.

6. DIGITAL NETWORKS

A major benefit expected from the widespread use of integrated digital techniques is a reduction in transmission impairments on long distance calls. In particular such impairments should become substantially independent of the number and length of transmission links involved in a call. It is interesting to consider whether congestion probabilities might similarly be made substantially independent of the number of switching stages traversed.

A terminal exchange concentrates traffic from a large number of subscribers' lines onto a much smaller number of junctions to other exchanges. In these circumstances some blocking is inevitable. If the remainder of the network could be part of a self-contained link system, then it need not necessarily introduce any additional blocking. In practice however, as mentioned earlier, a proportion of the traffic must be folded back at each level of the exchange hierarchy. This results in unavoidable additional blocking at each step up the hierarchy. Some increase in blocking probability with number of switching stages is thus inevitable as long as transmission and switching costs are other than negligible.

Rapidly reducing transmission cost, at least for large circuit bundles, has been the trend for many years and is likely to continue with any introduction of integrated digital techniques. This will also extend the trend to switching costs. The effect of this in the future is likely to be a tendency towards routing more
traffic via main switching centres and a diminution in the provision of direct routes, especially small ones. This will favour the concept of multi-exchange link systems and may justify a reduction in the number of levels in the exchange hierarchy, hence reducing the spread in loss probabilities. The liberal provision of inter-exchange links due to modularity constraints and service security considerations will also tend to reduce blocking probabilities.

By suitable planning of integrated digital networks, it might be possible to ensure that the number of paths available in a multi-exchange link system increases with the number of stages involved, as discussed in section 3. This would provide the simplest trunking concept, though not necessarily the most economical nor easiest to control. A more reasonable assumption is that the number of paths required to handle the traffic between exchanges at efficient loadings will vary considerably between the various parts of the network. As a result, the linking patterns must be capable of dealing with this variation and should be based on a reasonable minimum number of paths, at all points in the network. Figure 5 shows how this might be arranged.

A medium-size terminal exchange provides the A1-, B1-, C1- and DI-stages, with own-exchange traffic and traffic to small side-routes (if any) folded back via the DI-stage.

Inter-exchange links are shown by broken lines. Three levels of transit exchange (T1, T2 and T3) are shown. The right-hand side of figure 5 (a) (A2-, B2- and C2-stages) shows the way in which a small terminal exchange could be connected. The terminal exchanges are assumed to employ space-division switching (although the use of digital switching is not excluded), whilst the transit exchanges use digital switching to interconnect digital transmission links. Figure 5 (b) shows how a fairly small route on a large or medium-size terminal exchange might possibly be connected.

To allow for a wide variation in junction and trunk route size, a transit exchange has, say, 6 or 8 switching network sections, each terminating a number of links from every exchange to which it is connected. This is in contrast to the switch-per-path arrangement of a straightforward link system and obviously uses more crosspoints. It does, however, enable the blocking contribution of the inter-exchange links to be kept low even when their number is smaller than the quantity of paths provided in the terminal exchanges. The quantity of transit sections is chosen to match the first-stage switch access size most commonly used in the terminal exchanges, although this does not appear to be critical. The transit sections are thus seen to perform a similar trunking function to that of the B1- and C1-switches of the terminal exchange.

Each transit section will normally terminate at least one 30-channel PCM system from each terminal exchange served; the individual channels being distributed over the D1-switches as shown. In the case of links to small terminal exchanges and between transit exchanges, a PCM system may need to be divided between the transit sections. The means of doing this is beyond the scope of this paper but may affect the overall economics.

Although the transit sections are shown as being composed of a single switch, they may in practice be multi-stage non-blocking or nearly non-blocking networks, which are economical to provide using digital switching techniques. In this way, the transit exchanges can handle links from a large number of other exchanges. The economics of digital switching techniques favours the use of large switches and it is unlikely that more than 3-stages will be needed for an optimal practical result.

Figure 6 compares the minimum virtual crosspoint quantities required for 8-section transit exchanges using a time-space-time (T-S-T) configuration with those required for non-sectionalised exchanges of T-S-T non-blocking and nearly non-blocking forms. The time-switch sizes are restricted to multiples of 30 input channels. The discontinuities in the curves reflect this. No attempt has been made to take account of link associated costs or the cost relationship of time- and space-switch virtual crosspoints.

The reduction in virtual crosspoint quantities is substantial if non-blocking configurations are assumed for both sectionalised and non-sectionalised networks. This also applies if nearly non-blocking networks are acceptable for both. A thorough analysis of the sectionalised network forms has not yet been undertaken but such a study might indicate a necessity for completely non-blocking sections, whereas it would appear that nearly non-blocking networks are becoming generally accepted for non-sectionalised digital transit exchanges. In these circumstances the crosspoint savings from the sectionalised approach will be substantially reduced. Other factors such as security against the effects of equipment failure may, however, weigh in favour of the sectionalised form.

The discontinuities in the curves for non-sectionalised digital exchanges in figure 6, indicate a practical growth problem which only shows itself in the sectionalised approach at very large sizes. This tends to result in the use of time-switches in non-sectionalised exchanges which are larger than optimal, in order to allow easy extension to the largest sizes.

The practical realisation of multi-exchange link systems is dependent upon the existence of common-channel signalling (CCS) systems linking the control processors of the exchanges involved. By limiting the number of transit exchange sections to not more than about 8, it is only necessary to signal that number of link-group availability signals between exchanges, for path selection. These can easily be accommodated within a single common-channel signalling message and should therefore contribute little if any additional CCS data-link traffic.

7. CONCLUSION

An attempt has been made to describe some of the factors to be taken into account in the design of efficient switching networks. The approach has been to treat the switching network as an integrated whole, rather than as a set of separate trunking elements.

The concept of multi-exchange link systems has been introduced as a means of providing efficient total networks in a mixed analogue and digital environment. It has only been possible to skim the surface of this aspect and further studies are necessary to fully evaluate the economic implications of the approach. The technology of digital transmission and switching is evolving at a rapid pace and the eventual outcome is far from clear. The concept of applying rearrangeable non-blocking link systems to the multi-exchange case, where the non-expansion nature of the configuration would allow the several stages to occupy separate geographical locations, is a fascinating, if currently rather unlikely, possibility.

ACKNOWLEDGEMENTS

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REFERENCES

FIG. 1 CONVENTION FOR SHOWING SWITCH FUNCTIONS

(a) SINGLE-STAGE

(b) 3-STAGE

(c) 4-STAGE

FIG. 2 NETWORK CHANNEL GRAPHS

(a) 3-STAGE NETWORK

(b) 5-STAGE SERIES-PARALLEL NETWORK

(c) 5-STAGE INTERLEAVED NETWORK

(d) 7-STAGE INTERLEAVED NETWORK

FIG. 3 BLOCKING CHARACTERISTICS OF SERIES-PARALLEL AND INTERLEAVED NETWORKS

FIG. 4 EXCHANGE EXTENSION ARRANGEMENTS
FIG. 5 MULTI-EXCHANGE LINK SYSTEM

FIG. 6 COMPARISON OF MINIMAL VIRTUAL CROSSPOINT QUANTITIES FOR SECTIONALISED AND NON-SECTIONALISED T-S-T SWITCHING NETWORKS