A PERFORMANCE AND TRAFFIC COMPARISON OF ALTERNATIVE ATM TANDEM SWITCHING NETWORK ARCHITECTURES

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Networking alternatives for providing ATM connectivity between pairs of local ATM switches are described and compared on the basis of traffic-handling capacity, flexibility, and technological complexity. The advantages of providing some ATM tandem switching capability in local switches are demonstrated.

1. INTRODUCTION

This paper describes and compares alternative ATM (Asynchronous Transfer Mode) network architectures for interconnecting "local" ATM switches of a fixed size, e.g., \( M \times M \), where each of the \( M \) switch ports is assumed to terminate a "standard" 150 Mbps B-ISDN link. The principal issue is one of devising a flexible and efficient means for interconnecting all pairs of ATM switches at the ATM layer, and this will require that at least some pairs of local ATM switches be interconnected at the physical layer. Thus, we will need to consider both physical layer and ATM layer connectivity. While the possibilities for interconnecting two \( M \times M \) local ATM switches are simple (the only consideration is the required inter-switch bandwidth, and thus the number of inter-switch links), fundamentally different alternatives are introduced for the interconnection of three or more local ATM switches. In particular, an interconnection scheme where at least one 150 Mbps link connects each pair of local ATM switches can quickly exhaust the local ATM switch ports, leaving little or no switch ports for connecting to ATM end-devices.

To avoid such local ATM switch port depletion, it becomes essential, as the number of local ATM switches requiring interconnection increases, to introduce some form of "tandem switching" into the interconnection scheme. In this paper we describe four basic alternatives for providing such ATM tandem switching capability, and compare these alternatives on the basis of traffic-handling capacity, flexibility, and technological complexity.

The remainder of this paper is organized as follows. Section 2 contains the description of the four alternatives for interconnecting local ATM switches. The comparison of these alternatives on the basis of the technological complexity, flexibility, and traffic-handling capacity are presented in Section 3-5, respectively. Our closing remarks are given in Section 6.

2. ALTERNATIVES FOR INTERCONNECTING LOCAL ATM SWITCHES

Here we describe four alternative families of ATM networking architectures. Our classification of the architectures into these four families is based on the type of tandem switching scheme to be used. Throughout our discussion, we will assume that our goal is to provide ATM connectivity between \( N \) local ATM switches, each of size \( M \times M \). We also assume that a wide spectrum of point-to-point traffic matrices needs to be accommodated, but that at each local ATM switch, \( M-k \) links are designated to provide network access to end-terminals, while \( k \) links are designated to provide physical connectivity to the community of the remaining \( N-1 \) local ATM switches. Clearly, the parameter \( k \) is itself "engineerable," but to help in better examining and comparing the alternatives, we think of \( k \) as being fixed. Full ATM connectivity between pairs of local ATM switches is the goal, but how ATM connectivity can be provided will depend on how the physical connectivity is achieved.

1. Direct links connecting selected pairs of local switches (Fig. 1): Here the network does not employ any tandem switch per se, i.e., a switch whose sole function is to provide the required tandem switching. Rather, the network provides direct links between selected ports of selected local ATM switches (with \( k \) ports of each local ATM switch connected to some of the other \( N-1 \) local switches), and the tandem switching capability is provided in the local ATM switches themselves. This family of architectures includes the case where all pairs of local ATM switches are directly connected at the physical layer, if \( N-1 \leq k \). But, as \( N \) increases, it becomes necessary to abandon full physical interconnectivity, and to rely instead on ATM connectivity between pairs of local switches by "multi-hopping" through a chain of ATM local switches that are connected at the physical layer.

Under such scenarios, pairs of local ATM switches communicate either directly (without hopping) or after their cells have been routed through one or more other local ATM switches (with hopping). This idea of multi-hopping is not new in telecommunication networks. For example, it has been used in packet radio networks [1,2] and has also been proposed for high-speed and lightwave networks [3,4]. Similar multi-hopping ideas have also proven advantageous in time-multiplexed switching [5].

We note that relying on tandem switching at local ATM switches introduces at least two penalties that must be considered: (i) the ATM switching capacity that remains for handling local traffic is diminished, and (ii) multi-
hopping through multiple local ATM switches increases the end-to-end ATM switching delays.

This family of architectures can be characterized by the following design parameters:

a. the subset of local ATM switch pairs that are to be physically interconnected,
b. for each physically interconnected switch pair, number of connecting 150 Mbps links (keeping the total number of links to/from each local ATM switch at k),
c. for each pair of local ATM switches, whether physically interconnected or not, a set of alternate routes connecting them at the ATM layer.

2. ATM interconnectivity via a pure ATM tandem switch (Fig. 2): Here a \((kN) \times (kN)\) ATM tandem switch is used. There are \(k\) 150 Mbps links between the tandem ATM switch and each of the local switches. This is the most flexible architecture, since it allows the full \(k \times 150\) Mbps bandwidth from any local ATM switch to be directed towards any combination of the remaining local ATM switches, with no constraints imposed by physical interconnectivity parameters. However, it requires a potentially very large ATM tandem switch, and thus introduces considerable technological complexity and cost.

3. Physical interconnectivity via a pure circuit tandem switch (Fig. 3): Here a \((kn) \times (kn)\) broadband circuit switch is used to interconnect the \(N\) local switches. Each local ATM switch is connected to the tandem circuit switch via multiple 150 Mbps links. This architecture achieves tandem switching at the physical layer by setting up "ATM super-highways," reconfigurable through circuit switching. This alternative can also be thought of as a reconfigurable version of Alternative #1 above, and can be used to establish both single-hop ATM networks (i.e., full interconnection between local ATM switches at the physical layer, if \(N-1 \leq k\), or all the required connectivity between local switch pairs when the point-to-point traffic matrix over any time interval is sufficiently sparse) and multi-hop ATM networks (where ATM tandem switching in the local ATM switches is required to achieve ATM connectivity between most pairs of local switches). The idea of utilizing circuit switching capabilities to reconfigure the physical layer connectivity of a "packet" network is not new; see, e.g., [6] for some earlier work in this area.

4. Both pure ATM and pure circuit tandem switches (Fig. 4): In this alternative, reconfigurability of physical interconnectivity between ATM switches is achieved by a circuit tandem switch, as in Alternative #3 above, but additional ATM tandem switching capacity is provided by one or more pure ATM tandem switches. Inclusion of these ATM tandem switches reduces the amount of ATM tandem switching required by the local ATM switches. However, since physical connectivity between some pairs of local ATM switches can be provided via the circuit tandem switch, a smaller total ATM pure tandem switching capacity than is provided by the \((kn) \times (kn)\) ATM tandem switch in Alternative #2 would be required.

In particular, to be specific, we shall assume that \(n\) ATM tandem switches of the same size \((M \times M)\) as the local ATM switches are used. We also assume that each of the \(N\) local ATM switches is connected to the circuit tandem switch via \(k\) links (as in Alternative #3), and that each of the \(n\) \((M \times M)\) ATM tandem switches is connected to the circuit tandem switch via \(M\) links. This architecture thus requires a \((kN+nM) \times (kN+nM)\) circuit tandem switch.

3. TECHNOLOGICAL COMPLEXITY COMPARISON

3.1 What Each Alternative Needs

Before comparing the four alternatives with respect to technological complexity, it is beneficial to list the number and the size of ATM and circuit switch fabrics needed to their implementation. Such a list is given in the following table.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>No. of Sw. Needed</th>
<th>Size of ATM Sw. Needed</th>
<th>No. of ckt Sw. Needed</th>
<th>Size of ckt Sw. Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>#2</td>
<td>1</td>
<td>(kN \times kN)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>#3</td>
<td>---</td>
<td>---</td>
<td>1</td>
<td>(kN \times kN)</td>
</tr>
<tr>
<td>#4, (n=0)</td>
<td>---</td>
<td>---</td>
<td>1</td>
<td>(kn \times kN)</td>
</tr>
<tr>
<td>#4, (n=1)</td>
<td>1</td>
<td>(M \times M)</td>
<td>1</td>
<td>((kN+M) \times (kN+M))</td>
</tr>
<tr>
<td>#4, (n=i)</td>
<td>(i)</td>
<td>(i)</td>
<td>1</td>
<td>((kN+iM) \times (kN+iM))</td>
</tr>
<tr>
<td>#4, (n=M)</td>
<td>(kn)</td>
<td>(M)</td>
<td>1</td>
<td>(2kn \times 2kn)</td>
</tr>
</tbody>
</table>

TABLE 1: What each ATM tandem switching architecture needs

3.2 Technological Complexity and Cost

Here we assume that "technological complexity" of a particular alternative refers to how difficult would it be to develop and implement it. We further assume that it is technologically "easier" today to build an \(N\times N\) circuit switch at 150 Mbps than an \(N\times N\) ATM switch at 150 Mbps.

Under the above assumptions, Alternative #1 is clearly the least complex. Alternative #2 has the most complex piece, i.e., the \(kn \times kN\) ATM switch. Therefore, Alternative #2 could be considered the most complex. As far as technological complexity is concerned, Alternative #3 and #4 fall somewhere between Alternative #1 and Alternative #2. Since Alternative #4 generally uses a larger circuit switch than does Alternative #3, it could be considered more complex. Therefore, the architectures are ordered with respect to increasing technological complexity as: #1, #3, #4, #2. We may assume that the alternatives would tend to be similarly ordered with respect to cost.

4. TRAFFIC-HANDLING FLEXIBILITY COMPARISON

There is much uncertainty about the type, mix, and amount of expected broadband ATM traffic. This uncertainty, along with the difficulty to foresee, with any amount of accuracy the new services, and the wish to transport different signals through one integrated network, leads one to require much flexibility in traffic handling capabilities in broadband related design and developments. By traffic handling flexibility we mean the ease of accommodating the widest range of types and mixes of traffic scenarios and point-to-point traffic matrices.

Some architectures will naturally perform better under particular traffic scenarios than others. The task is to determine which architecture performs well or at least...
adequately under the largest set of traffic patterns and scenarios.

There are many phenomena that result in different traffic patterns and scenarios. To illustrate this, consider the following. At a high level of classification, the 150 Mbps ATM input traffic streams can be classified into two categories: Type A -- Uni-destination: This category represents all the 150 Mbps ATM input trunks for which all (or at least the majority of) the cells are destined to the same local ATM switch. That is, although these streams carry ATM cells, they do not require ATM cell switching at the tandeming switch.

Type B -- Multi-destination: This category represents all the 150 Mbps ATM input trunks whose cells are to be routed to many different local ATM switches. Considering the magnitude and the time variability of the fraction of the Type A v.s. Type B trunks leads to different traffic scenarios. For example, if the majority of the input trunks are known to be to Type A, then all four alternatives will do relatively well. Under such circumstances, however, Alternative #1 would be preferred since it is the least costly. On the other hand, if the majority of the input trunks are of Type B, then Alternatives #2 and #4 would be preferred since they provide ATM cell switching capability at the tandeming switch, which minimizes multi-hopping overhead at the local ATM switches. Moreover, if the time variability of the fraction of the Type A v.s. Type B traffic is high, then Alternative #1 is never suitable.

In summary, Alternative #1 is the least flexible. Any traffic matrix must be accommodated by establishing appropriate point-to-point paths, and tandeming through appropriate local ATM switches, subject to very strict constraints imposed by the physical switch interconnectivity. Alternative #3 becomes more flexible than #1 since it removes these physical constraints by introducing circuit switching at the tandeming office. Note that this is only true if the dynamic changes in the traffic matrix are slow enough so that the circuit tandem switch can effectively reconfigure. Alternative #4 removes the constraints in #3 that entire 150 Mbps ATM trunks must interconnect local ATM switches at any time. This allows Alternative #4 to exhibit greater flexibility than #3. Finally, Alternative #2 which provides the maximum ATM interconnectivity at all times, is the most flexible. Thus, with respect to increased traffic handling flexibility, the four alternatives are ordered as: #1, #3, #4, #2.

5. CAPACITY QUANTIFICATION COMPARISON

5.1 Summary of capacity Comparisons

The major quantitative comparison provided in this paper is a one of the total ATM transport demand that can be satisfied by these architecture alternatives. To perform this comparison, we assume a normalized point-to-point traffic matrix, subject to very strict constraints imposed by the physical switch interconnectivity. The scalar multiplier thus is a measure of total usable ATM transport capacities for the four architecture alternatives. We specifically consider the case where \( N = 8 \) local ATM switches, where the size of each ATM switch is \( M = 8 \), and where there are \( k = 4 \) links per local ATM switch for inter-switch traffic. The number of ATM tandem switches for Alternative #4 is allowed to vary in the range \( 0 \leq n \leq 4 \), and it can be shown that the case \( n = 0 \) reduces to Alternative #3, while the case \( n = 4 \) reduces to Alternative #2.

Two traffic scenarios are considered: a balanced-traffic situation, and an unbalanced-traffic situation, represented by \( N \times N \) normalized traffic matrices \( \pi_s \) and \( \pi_u \), respectively. For each normalized traffic matrix, the \((i,j)\) element, \( \pi_{i,j} \), represents the fraction of the total inter-switch traffic originating at local ATM switch \( i \) that is destined for local ATM switch \( j \). Since none of the intra-local-switch traffic occupies the connecting links, we observe that \( \pi_{i,j} = 0 \) for all \( i \).

To investigate the unbalanced-traffic case, the following normalized traffic matrix was used:

\[
\pi_u = \begin{bmatrix}
0.0 & 0.18 & 0.14 & 0.08 & 0.10 & 0.12 & 0.16 & 0.22 \\
0.22 & 0.00 & 0.18 & 0.14 & 0.08 & 0.10 & 0.12 & 0.16 \\
0.16 & 0.22 & 0.00 & 0.18 & 0.14 & 0.08 & 0.10 & 0.12 \\
0.12 & 0.16 & 0.22 & 0.18 & 0.14 & 0.08 & 0.10 & 0.10 \\
0.10 & 0.12 & 0.16 & 0.22 & 0.08 & 0.18 & 0.14 & 0.08 \\
0.08 & 0.10 & 0.12 & 0.16 & 0.22 & 0.08 & 0.18 & 0.14 \\
0.14 & 0.08 & 0.10 & 0.12 & 0.16 & 0.22 & 0.08 & 0.18 \\
0.18 & 0.14 & 0.08 & 0.10 & 0.12 & 0.16 & 0.22 & 0.00
\end{bmatrix}
\]

This matrix resulted from "randomly" choosing the fractions \( \pi_{i,j} \), for \( 2 \leq j \leq 8 \), and then imposing a cyclically-symmetric structure on \( \pi_u \). This choice for \( \pi_u \) is clearly arbitrary, but serves as a vehicle for investigating some of the effects of traffic imbalances on transport capacity.

Having defined a normalized traffic matrix, \( \pi_u \), the capacity of an architecture alternative is defined as the largest scalar multiplier, \( \alpha \), of this matrix such that the architecture can provide \( \pi_{i,j} \) 150 Mbps links worth of ATM transport capacity from local ATM switch \( i \) to local ATM switch \( j \), for all \( i \) and \( j \). In Figures 5 and 6, we plot the networking throughput \( \eta \) vs. traffic load \( \alpha \) for balanced and unbalanced traffic, respectively. Networking throughput, \( \eta \), is defined as the amount of traffic carried by the network for each local ATM switch. Therefore, \( \eta \) is always less than or equal to \( \alpha \). If \( \eta < \alpha \), then certain fraction of traffic is buffered at the local switches. The point where the networking throughput deviates...
Many simplifying assumptions were made in the model. For the two normalized traffic matrices given above, this capacity measure for the four alternatives is summarized in Table 2.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>#1</th>
<th>#3</th>
<th>#4</th>
<th>#2</th>
</tr>
</thead>
<tbody>
<tr>
<td>balanced traffic</td>
<td>n=0</td>
<td>n=1</td>
<td>n=2</td>
<td>n=3</td>
</tr>
<tr>
<td>2.36</td>
<td>2.36</td>
<td>3.02</td>
<td>3.51</td>
<td>3.77</td>
</tr>
<tr>
<td>unbalanced traffic</td>
<td>2.08</td>
<td>2.85</td>
<td>3.11</td>
<td>3.52</td>
</tr>
</tbody>
</table>

TABLE 2: Networking capacities with different architecture alternatives (N=8, k=4)

Note that the networking capacity is smaller for all architecture alternatives except #1 when the traffic is balanced. For Alternative #1, unbalanced traffic results in smaller networking capacity since the capacity is determined by the worst possible traffic permutation. Moreover, the reconfiguration provided by a tandem switch (Alternatives #2 through #4) does not gain us anything when the traffic is balanced, but begins to allow the majority of traffic to take shorter more efficient routes, and hence results in increased capacity, as the traffic becomes more unbalanced. As more and more tandem ATM switches are added (in Alternative #4), the networking capacity increases from the reduction of multi-hopping required in local ATM switches. If we use Alternative #3 (n=0) as a reference point, then the increment of networking capacity as the number of tandem ATM switches increases is shown in Table 3.

<table>
<thead>
<tr>
<th>n=1</th>
<th>n=2</th>
<th>n=3</th>
<th>n=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>balanced traffic</td>
<td>28.0</td>
<td>48.7</td>
<td>59.7</td>
</tr>
<tr>
<td>unbalanced traffic</td>
<td>9.1</td>
<td>23.5</td>
<td>37.9</td>
</tr>
</tbody>
</table>

TABLE 3: Percentage capacity increase in Alternative #4 beyond that of Alternative #3.

5.2 Description of the model and capacity estimation methodology

Many simplifying assumptions were made in the model. The goal of the work is not to generate precise performance calibrations, but rather to compare the performance of the different alternatives. For example, we assume that each ATM link can be loaded 100 percent, to its full capacity. In practice, a more realistic assumption is to allow the ATM links to be loaded up to, say, 80 percent, assuming there are enough buffers to absorb fluctuations in traffic load due to bursty sources. But, for comparison purposes, as long as links in all architecture alternatives are loaded the same, the exact utilization at which the links are loaded should not change the outcome of the comparison of alternatives. We also assume that physical connectivity between each pair of local ATM switches is provided by at most one 150 Mbps link, precluding the possibility of multiple 150 Mbps links. This assumption turns out to be reasonable because it fits well with the balanced traffic scenario, which is of most interest. All of these simplifying assumptions can be relaxed in follow-up studies.

The model is executed in the following sequence:

i. Select a traffic matrix: Both balanced and unbalanced normalized traffic matrices, as described above, were considered.

ii. Configure the physical inter-local-switch connectivity topology (applies only to Alternatives #3 and #4): The concept of topology reconfiguration applies to Alternatives #3 and #4, in which circuit switches are involved. For Alternative #1, the links are physically connected to a pair of local ATM switches. For Alternative #2, the ATM tandem switch, by its nature, effectively reconfigures the network topology in each cell slot (via certain contention resolution algorithms or buffering). For Alternatives #3 and #4, the network topology is reconfigured to best accommodate the traffic matrix. First, the source-destination pairs (there are $N^2$ of them) are sorted by their (unidirectional) traffic intensity in decreasing order. Then a uni-directed link (an ATM super-highway) is assigned to a source-destination pair according to the sorted list if both the source and the destination nodes have the ports available. In Alternative #4, symmetric connections from the local ATM switches to all the tandem ATM switches via the circuit switch are assumed, regardless of traffic intensity, and these do not require reconfiguration.

iii. Routing tables and ATM traffic assignment: For a pair of local ATM switches that do not have a direct link (i.e., an ATM super-highway) between them, traffic has to multihop through other ATM switches, either local or tandem. A routing table is set up every time the network topology is reconfigured. From each local ATM switch, up to $J$ ($J<k$) outgoing links are available for traffic destined for each of the other local ATM switches. The rank of the each outgoing link is determined by the hop-number of the shortest path which passes through each outgoing link. The outgoing link which provides smallest hop-number is the primary choice. A path through the circuit switch (e.g., local/tandem ATM switch - circuit switch - local/tandem ATM switch) is labeled as a one-hop path. That is, circuit switch is viewed as part of the facility network providing interconnection and does not count as a node in a ATM network. The primary routing link to a destination is the direct link to that destination, if such a link exists. Otherwise, the primary link will be the link leading to the tandem ATM switches. If there is a direct link to a given destination, the link leading to the tandem ATM switches will be the secondary routing link. Lower rank routing links are the links connected to other local ATM switches. Their ranks are determined by how close the local switches they connect to are to the destination ATM switch. The setup of routing tables is thus distributed among each local ATM switches and it may not be optimal since it relies solely on the exchange of routing information with its immediate neighbors. However, since routing tables are determined after each topology reconfiguration, which provides direct links between heaviest traffic pairs, this distributed routing table setup mechanism may not be too far from optimum.

The last step is to assign source-destination traffic to the available shortest paths. We assume that each source-destination traffic can be broken in any granularity and routed through different paths. Traffic is carried by the network in the following way: A given source-destination traffic will fill the direct links (ATM super-highway) first. If the capacity of the direct links is used up, the next choice is the ATM links through tandem ATM switches.
If the capacity of the corresponding links to/from the tandem ATM switches are used up, multi-hop paths via other local ATM switches are then taken based on their relative ranks, subject to the maximum-hop (L; a parameter) constraint. Therefore, up to \( J \) alternate paths exist for each source-destination pair. The path assignment is done in a way that short-hop source-destination traffic is assigned before long-hop source-destination traffic. This will ensure a near-optimum realization of carrying most source-destination traffic in the network.

5.3 Some additional results and discussions

From the results summarized in Section 5.1, it is seen that a major capacity increase above that of Alternative #1 is achieved from full ATM tandem switching capability (Alternative #4), but that a circuit tandem switching capability provides significant gains in the ability to better handle unbalanced traffic. Moreover, inclusion of \( M \times N \) ATM switches in the tandem switch quickly provides much of the capacity that full ATM tandem switching would yield.

We have also considered as a second example the problem of interconnecting \( N=16 \) local ATM switches. Each local ATM switch has \( k=6 \) links to communicate with the remaining 15 local ATM switches. The size of the tandem ATM switch is \( M=16 \). Only the balanced traffic case is considered since we learned from the previous example that it is the worst case scenario for architectures #2, #3, and #4 (we neglect Alternative #1 from now on since it cannot adapt to traffic changes). The networking throughput vs. traffic load curves are shown in Figure 7, for \( n=0, 1, 2, 3 \). It is surprising that the architecture with \( n=1 \) delivers the least networking throughput. Initial examination of the problem suggests that some traffic cannot be delivered possibly due to the two constraints: (1) that a path is limited to a maximum of \( L=4 \) hops and (2) that only \( J=4 \) out of the 6 possible outgoing links are available for alternate routing. Relaxing this two constraints individually, it is found that increasing \( L \) from 4 to a larger number does not improve the networking throughput of the architecture with \( n=1 \), whereas allowing all 6 outgoing links for alternate routing does. Although networking throughput improves significantly for \( n=1 \) (however, not very much for \( n=0 \)), its networking capacity is not any better than Alternative #3 (\( n=0 \)), as shown in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>( n=0 )</th>
<th>( n=1 )</th>
<th>( n=2 )</th>
<th>( n=3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>balanced</td>
<td>3.48</td>
<td>3.47</td>
<td>3.99</td>
<td>4.39</td>
</tr>
</tbody>
</table>

**TABLE 4: Networking capacities with different architectures (N=16, k=6)**

This phenomenon could be explained as follows: Alternative #4 with \( n=i, i=1,2,\ldots,k \), is logically equivalent to an overlay of two subnetworks, one being Alternative #3 with \( k-i \) networking links and the other being Alternative #2 with an \( N \times N \) tandem ATM switch. Define network connectivity as the inverse of the average number of hops between a pair of source-destination nodes. The latter subnetwork (the ATM subnetwork) has connectivity equal to \( \frac{1}{2} \) because a source can always reach a destination in two hops. The connectivity of the former subnetwork (the circuit-switched subnetwork) is variable depending on how many networking links are used in what patterns. Since the links leading to the tandem ATM switches are either the primary or the secondary choice for routing, capacity of the ATM subnetwork is used up long before the capacity of the circuit-switched subnetwork is. Two important factors thus affect the networking capacity: (1) the amount of traffic flows through the circuit switched subnetwork and (2) the connectivity of the circuit-switched subnetwork.

As the number of tandem ATM switches increases, the amount of traffic flows through the circuit switched subnetwork decreases and the connectivity of the circuit-switched subnetwork also decreases. The reasons that the case for \( n=1 \) has the smallest networking capacity are: when compared with \( n=1 \), (A) the case for \( n=0 \) has more traffic flowing through the circuit-switched subnetwork, but the larger connectivity of the circuit-switched subnetwork sort of makes up for the increase in the traffic; and (B) the cases for \( n>1 \) have most of their traffic carried by the ATM subnetwork, and the smaller connectivity of their circuit-switched subnetworks is not a dominant factor.

6. CONCLUSIONS

We have provided a comparison, on several different levels, between alternative means for achieving ATM connectivity between a set of local ATM switches. The ideal, most flexible, and highest capacity approach would be to use a single ATM tandem switch, but this alternative may involve considerable technological complexity and cost. We have shown that simpler tandem switching architectures, involving a mix of circuit and ATM switching capabilities, can come close to the capacity of this ATM tandem switching ideal, but will typically involve reduced complexity and cost.

REFERENCES

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5. N=8, k=4, balanced traffic, L=4, J=4.

Figure 6. N=8, k=4, imbalanced traffic, L=4, J=4.

Figure 7. N=16, k=6, balanced traffic, L=4.