# Dimensioning of Large-Scale Hybrid Optoelectronic Networks with Modular Switch Costs and Grooming

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***Abstract*— We examine in this paper the problem of dimensioning large hybrid optoelectronic networks with grooming when switch costs are highly modular. Using a new heuristic, we are now able to investigate networks of a size much larger than what was previously possible. We show that the impact of grooming and modular switch costs on the design process is very significant for large networks as well. Increasing the number of alternate paths decreases the network cost while increasing the path length increases it. We also show that the modular switch costs produce solutions where the switches are nearly always fully utilized. Finally, we also show that the relative size of the demands offered to the network can have a significant effect on the cost, a feature that cannot be captured by other models.**

## I. INTRODUCTION

With the recent advances in optical communication technologies, it is now possible to transmit information at the rate of Gigabits and even Terabits per second in the core network. There is however a large gap between the capacity of these optical technologies and the bandwidth required by the vast majority of networks users where most demands are in the range of kilobits or Megabits per second, at least 1000 times lower than optical capacity. There is obviously a need to use this abundant capacity as efficiently as possible.

One technique that can provide a better utilization of the optical resources is traffic grooming where many connections with low traffic requirements and similar paths are electronically multiplexed onto a single optical lightpath. By doing so, optical channels are used more efficiently, resulting in less expensive networks with higher throughput. However, grooming small demands onto an optical channel requires fast electronic multiplexers and these are expensive network elements, the more so when their speed is in the Gigabits per second. This fundamental tradeoff between cost and efficiency is the subject of the present work.

The problem of dimensioning and designing a network based on hybrid optoelectronic technology and grooming has been described previously in [1] and some preliminary results were obtained in [2] for small networks. In this paper, we use a new heuristic described in detail in [3] to compute solutions for optoelectronic networks whose size is much larger than what was previously possible. The heuristic exploits grooming possibilities to minimize the total cost of electronic and optical components while dimensioning optical links and router capacity to meet all the traffic requirements. We then use it to investigate how we can route traffic and assign capacity to key components while keeping the cost of the network at a minimum. We also examine the effect of the size of the demands on the grooming cost.

In section II, we present a brief literature review. In section III, basic concepts of grooming are presented followed by a mathematical description of the problem. The heuristic is briefly described in section IV and results are presented in section V. Finally, we conclude in section VI with a summary of some important results and a brief look at future work.

## II. LITERATURE REVIEW

There has been a plethora of mathematical models on routing and capacity assignment for traffic networks. In [4]–[6], the authors proposed optimization models that assign capacity to the links to minimize the total network cost, expressed as the sum of the delay and capacity costs. Delay was based on M/M/1 queues and the solution method was Lagrangian relaxation. A similar routing and dimensioning problem was examined in [7] where the authors used another model based on m-M/M/1 queues. These classical routing and capacity assignment models did not take into account the capacity of the nodes, which is a major element in our problem.

Dimensioning of WDM optical networks also received a lot of attention in the past few years where the objective was to minimize the average delay [8] or the blocking probability [9] or to increase the throughput [10]. These references are just a small part of a very vast number of publications on WDM networks. Most of these models only considered SONET rings or all-optical networks. A small part of this research, as in [10], did take into account grooming in the WDM network. This work however did not consider the cost of the electronic components required for grooming. An accurate model for these costs is a central feature in our approach.

The literature on traffic grooming, which is also part of our problem, is also growing fast. For a good overview of previous works on grooming, we refer the reader to [11]. We note however that there is very little work which combines

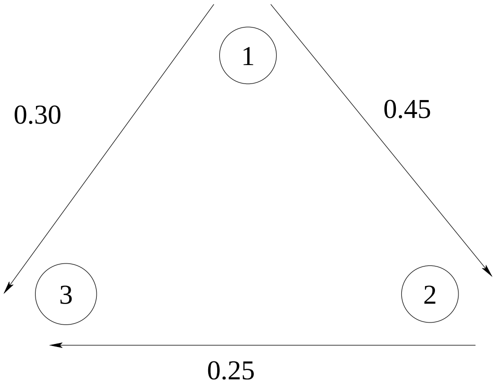

Fig. 1. All-optical 3-node network

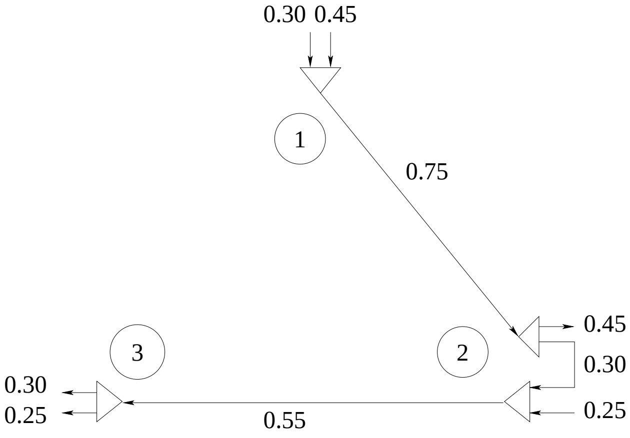

Fig. 2. Network with grooming

network design and grooming. Most models try to reduce the number of add-drop multiplexers (ADM) or the number of wavelengths or transceivers or try to improve throughput in SONET rings. Others also discuss the placement of grooming nodes. Nevertheless, in all these cases, the cost induced by grooming is not taken into account, which is a fundamental feature of our model. An exception is the work presented in [12] where the authors propose a model that minimizes three types of costs: links, wavelength ports and subwavelength ports. They also provide a heuristic that considers connections with dedicated links as different from connections with shared links as we do here. However, the model presented in [12] assumes that the cost of grooming is based only on the port count, an assumption that we think is too simple to reflect correctly the cost of grooming and that is being more accurately modeled in our work.

## III. MODEL

First we recall some basic notions about grooming and their relation with network dimensioning. Next, we define the variables of the problem and the assumptions that were made. Finally, for the sake of completeness, we state formally the mathematical optimization problem that we want to solve.

### A. *Dimensioning and Grooming*

As we mentioned in section I, grooming is a technique that offers a higher utilization of optical channels by concentrating traffic on optical paths. Even though grooming can make networks more efficient, we must still find the best trade-off between the increase in efficiency and the cost of the grooming equipment. This tradeoff is explained on Figure 1 for a 3-node optical network. There is a demand of 0.45, expressed as a fraction of the capacity of an optical channel, between nodes 1 and 2, of 0.25 between nodes 2 and 3 and of 0.3 between nodes 1 and 3. In this figure, each demand is met with a dedicated optical channel so that the channels are not fully loaded and there is a waste of bandwidth.

In Figure 2, we have the same 3-node network with the same demands between the nodes. However, in this network, we decide to add grooming capabilities to the nodes. Demand between nodes 1 and 3 is electronically multiplexed (groomed) at node 1 with the demand between nodes 1 and 2 and both demands are sent on the same optical channel between 1 and 2. At node 2, these groomed demands are demultiplexed; Demand 1-2 has reached its destination and is extracted and demand 1-3 is remultiplexed with demand 2-3. At node 3, both demands are demultiplexed since they both have reached their destination. In this scenario, we have one less optical channel and the remaining two are used more efficiently. However, three multiplexers were added to the design.

The question is then: *Has the addition of grooming nodes made the network less expensive even though it has made it more efficient?* The answer to this question is not obvious since many parameters must be taken into account such as the cost of optical and electronic components, the size of each demand, the total number of demands and the routing possibilities.

A mathematical model was developed in [1], [2] to solve this problem. It uses as input the bandwidth of an optical channel, a demand matrix, the cost of an optical channel and the capacity and cost of each switch type that can be installed at a node.

Its solution describes whether a demand should be assigned directly to an optical channel upon entry into the network or whether it should go through an electronic multiplexing stage. The solution also provides the best path to route each demand. In addition to this, the model computes the optimal number of optical channels to install between the routers and the optimal type of router to install at each network node. Note that the topology of the optical network is an *output* of the model and is determined by the set of values $n_{k,l} > 0$. We do not consider the problem of routing these optical channels over a fiber network.

### B. *Notation*

In the following model, superscripts and subscripts $i$, $j$, $k$ and $l$ indicate nodes. The variable $t$ denotes the type $t$ of traffic carried between two nodes where a type is defined by its bandwidth requirement. The variable $p$ is used to indicate which path a demand takes. Finally, $r$ indicates the type of

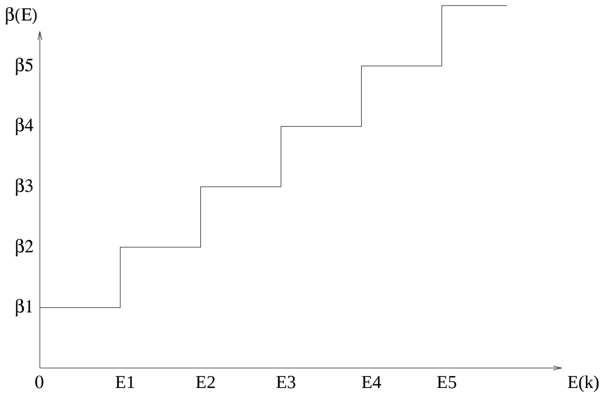

Fig. 3. Cost function of electronic routers.

router installed at any given node and is defined by the traffic processing capacity of the switch.

In this model, some variables are known prior to the optimization process. The parameters that are given as input to the problem are defined as

| | |
|---|---|
| $B$ | the bandwidth of an optical channel, |
| $\alpha_{k,l}$ | the cost of an optical channel between nodes $k$ and $l$, |
| $\beta_r$ | the cost of a router of type $r$, |
| $\Gamma_r$ | the capacity of a router of type $r$ and |
| $d^{i,j}(t)$ | the traffic demand of type $t$ between nodes $i$ and $j$ expressed as a fraction of the capacity of an optical channel. |

We also define the auxiliary variable $E(k)$ the total electronic traffic going through node $k$. The decision variables that are calculated by the solution algorithm are

| | |
|---|---|
| $n_{k,l}$ | the number of optical channel to install between nodes $k$ and $l$, |
| $y_r^k$ | the presence of a router of type $r$ at node $k$. These variables can take only the values 1, to indicate that the router is installed, or 0 otherwise, |
| $\delta_{i,j}(t)$ | the decision to have demand $d^{i,j}(t)$ enter the network via an electronic router ($\delta_{i,j}(t) = 1$) or directly on a dedicated optical channel ($\delta_{i,j}(t) = 0$) and |
| $x_p^{i,j}(t)$ | the fraction of the traffic demand of type $t$ between nodes $i$ and $j$ routed on path $p$. |

### C. Cost Model

A basic feature of the model is the modular structure of the switch costs, an element that is not taken into account in other work. We assume a step cost as a function of the traffic $E(k)$ through switch $k$, as shown on Figure 3. This is fundamentally different from a network cost based only on the interface cost since we believe that when a router has exhausted its processing capacity, a faster but more expensive router must be installed, not just a new card. In that case, the jumps in the function are much larger than would be the case with a cost function based only on the cost of interfaces and as we will see, this has a significant effect on the solution.

In practice, a step cost function is equivalent to having a given set of switch types $r$, each with its capacity and cost, and adding decision variables to decide whether to install a particular switch type at each location.

The mathematical model allows for the cost of optical channels to be different for each nodes pair. However, for the sake of simplicity, we assume throughout the rest of this article that the cost of an optical channel $\alpha_{k,l}$ between nodes $k$ and $l$ is the same for every node pair so that $\alpha_{k,l} = \alpha \ \forall k, l$. This assumption is based on the hypothesis that the cost of an optical channel is dominated by the cost of optical transceivers.

We also assume that the capacity $\Gamma_r$ of a router of type $r$ is equal to $r$ times the bandwidth $B$ of an optical channel. As for the cost $\beta_r$, we take it equal to $r^2$. Thus, for example, a router $\Gamma_3$ will have a capacity of $3B$ and will cost $\beta_3 = 9$. These assumptions can easily be modified to fit real-world data. Work is currently in progress to determine the effect of the step size on the solution.

### D. Routing

In our model, the routing is fixed since there is for each demand a given set of paths that can be used to route it. There are two kinds of routing variables in the model. For each demand, we first have to decide whether it will enter the network in the optical or the electronic layer. Demands that enter the network on an optical channel are routed directly to their destination node without going through any electronic processing. Demands that enter via the electronic multiplexers can be routed on a number of paths. There is a set of decision variables $\boldsymbol{\delta}$ associated with this first decision.

For the demands that enter the network via the electronic layer, a number of paths are available to route these demands and there is another set of routing variables $\mathbf{x}$ associated to this decision. In all cases, however, the direct link between the two routers is available. The other paths are also selected a priori. For the results presented here, they are either made up of a varying number of two-link alternate paths, or a single alternate path but with a varying number of tandem nodes.

### E. Optimization Problem

We now present a mathematical optimization model that defines the optimal design problem. It was formulated as an Integer Linear Programming (ILP) problem so that it could be solved by standard techniques, at least for small instances.

$$\min_{\delta,x,n,y} Z = \sum_{k,l} \alpha_{k,l} n_{k,l} + \sum_k \sum_r \beta_r y_r^k \tag{1}$$

subject to

$$d^{i,j}(t)\delta_{i,j}(t) = \sum_p x_p^{i,j}(t) \tag{2}$$

$$\begin{aligned} n_{k,l} \geq \; & \frac{1}{B} \sum_{i,j,p,t} x_p^{i,j}(t) \mathcal{I}_{(k,l),(i,j,p,t)} + \\ & \sum_{i,j,p^*,t} [1 - \delta_{i,j}(t)] \mathcal{I}_{(k,l),(i,j,p^*)} \end{aligned} \tag{3}$$

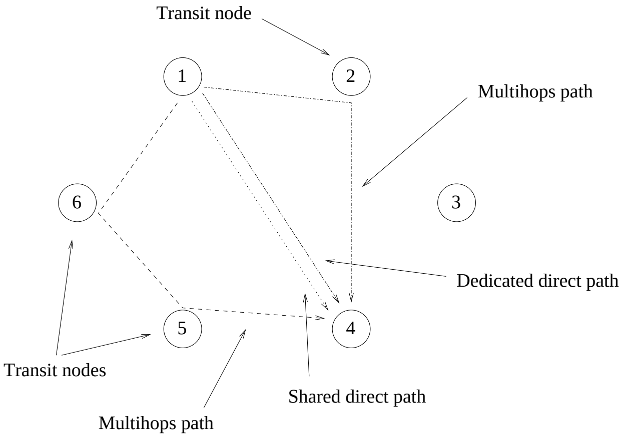

Fig. 4. Example of alternate paths

$$\sum_r y_r^k \Gamma_r \geq E(k) \quad (4)$$

$$\sum_r y_r^k = 1 \quad (5)$$

$$x_p^{i,j}(t) \geq 0 \quad (6)$$

$$n_{k,l} \in \{0,1,2,...\} \quad (7)$$

$$\delta_{i,j}(t) \in \{0,1\} \quad (8)$$

$$y_r^k \in \{0,1\} \quad (9)$$

where $\mathcal{I}_{(k,l),(i,j,p,t)}$ is the arc-path incidence matrix and is equal to 1 if the $p^{\text{th}}$ path available to route an electronic demand of type $t$ from $i$ to $j$ uses link $(k,l)$ and 0 otherwise. It has the same meaning for path $p^*$ for optical demands. There are 3 important constraints in this model. The flow conservation constraint (2) stipulates that all bifurcated flows must total the original demand. Capacity constraint (3) forces the number of optical channel to be greater or equal to the required capacity between 2 nodes. Constraint (4) forces the installation of a router with a capacity greater or equal to the total electronic traffic in a given node. The other constraints are mostly non-negativity and integrality constraints.

## IV. THE HEURISTIC

The results obtained in [2] using a standard ILP algorithm show a solution structure that is strongly influenced by the modular cost structure of the switches. However, problems become intractable beyond 10 nodes because of computer memory and computation time. We have developed a fast and accurate heuristic inspired from two well-known combinatorial optimization methods: Tabu Search and Genetic Algorithms. In what follows, we first provide some notions about the structure of the solutions and then briefly explain the core of the heuristic. A complete description of the heuristic along with extensive results on its performance and accuracy can be found in [3].

### *A. Solution Structure*

In our model, the set of paths that each demand can take is known *a priori*. We can see an example of these paths in Figure 4. A demand between nodes 1 and 4 can use 4 possible paths: a direct dedicated optical link between nodes 1 and 4, a direct shared optical link, a multihop path using nodes 1, 2 and 4 and another multihop path using nodes 1, 6, 5 and 4. The dedicated optical link does not use grooming whereas the shared direct link and the multihop paths do. Summarizing, the set of available paths for demand 1-4 are: dedicated 1-4, shared 1-4, 1-2-4 and 1-6-5-4.

The number of multihop paths and the number of nodes in these multihop paths are not constrained. However, each demand has always the option of a dedicated optical channel and a shared direct link.

A *solution* is defined by allocating a path to each demand. When this is done, we can compute the capacity required on each link and in each node. We then assign the smallest number of optical channels to each link and the smallest type of router to each node so that the capacity constraints are met. Finally, we can compute the total cost of the network from the cost functions.

It can be noted that the *solution* we described above assumed that no demand is split between two or more paths: there is no *bifurcation*. This assumption was made even if the mathematical model allows bifurcation since previous tests [2] have shown that bifurcation occurs only rarely and also, permitting bifurcation would make the heuristic much more complicated and slower without giving significantly better results.

### *B. Heuristic Principle*

The heuristic is based both on Tabu Search and Genetic Algorithms. The main idea behind the heuristic was the observation that *good solutions share a good number of paths*. This property helps us restrict the search for good solutions. If we can find those common paths, we can freeze them and concentrate (intensify) the search on the rest of the paths. By freezing some paths, we are also reducing the size of the search space. If too many paths get frozen, we can unlock some of them and thus diversify the search.

To find those common paths, we need the concept of a *population*. The idea is to start with a population of initial solutions and use a descent method for each individual initial solution. After a number of iterations, we sort the minimized (but not yet optimal) solutions based on their cost. A subset of the initial population which showed the lowest cost are taken and compared demand by demand. When a demand uses the same path in all solutions part of the subset, the path is locked. Then, a new population of initial solutions is constructed where the paths that were previously locked are frozen to this specified value and the rest of the paths are chosen randomly. After a while, most paths will be locked. This can lead to a too narrow search space. To avoid this problem, we add the possibility of unlocking paths when the search space seems to be too small. This is a process of diversification which helps to find new good solutions elsewhere in the search space. The block diagram of Figure 5 summarizes the main heuristic.

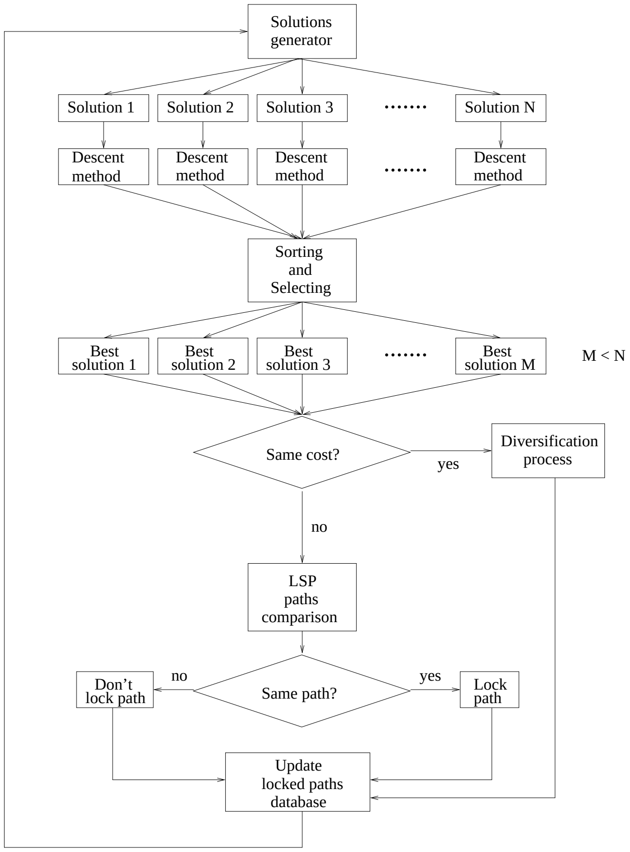

Fig. 5. Diagram of the heuristic

As we can see in that figure, there is a box called *Descent method* which is also a heuristic in itself. This inner heuristic is a relatively simple descent technique similar to Simulated Annealing in which bad solutions can be kept for some iterations in order the get out of local minima. A box diagram of this inner heuristic is shown in Figure 6.

## V. RESULTS

The mathematical model is a large integer linear program which can be solved to optimality by standard algorithms, CPLEX in our case. This method was used to examine the impact of modular switch costs on the network structure. Results have been reported in [2] but only for small networks no larger than 10 nodes. It was not possible to compute solutions for larger networks because the computation times or the size of the enumeration tree would become too large to solve to optimality. Recent work [3], however, has provided us with a fast and accurate heuristic so that it is now possible to check whether the results obtained for small networks do hold out in more realistic cases.

The heuristic was programmed in C++ and the tests were performed on a 2.4 GHz Pentium 4 computer. Results are presented here for a 20-node network but we have designed a number of networks, up to 50 nodes, with conclusions similar to the ones presented here. The traffic matrix was generated from a uniform distribution in the interval $[0, 0.4]$ for *all* o-d pairs. As we said, the topology of the network came out as a by-product of the solution. The tests correspond to 5 different runs of the heuristic where each one uses a different random stream to explore the solution space.

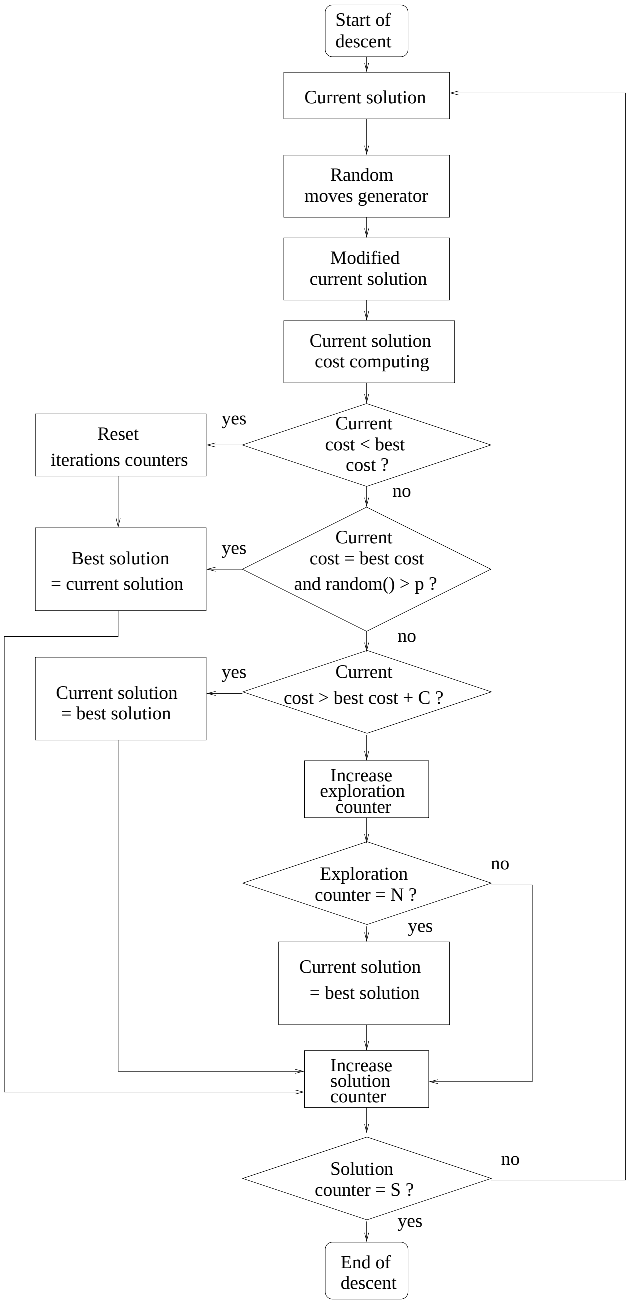

Fig. 6. Diagram of the descent method

### A. CPU Time

The computation times for a 20-node network over 5 different runs of the heuristic are shown in Table I. They increase with the number of alternate routes available, which is expected since the solution space is getting much larger. The largest values run somewhat over 1 hour, while an exact

TABLE I

CPU TIME IN SECONDS, 20-NODE NETWORK

| Test No | No Alternate Paths | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 242 | 376 | 547 | 774 |
| 2 | 322 | 441 | 585 | 659 |
| 3 | 295 | 401 | 572 | 734 |
| 4 | 270 | 434 | 547 | 849 |
| 5 | 262 | 392 | 571 | 776 |
| Avg. | 278 | 409 | 564 | 758 |

TABLE II

TOTAL COST, 20-NODE NETWORK

| Test No | No Alternate Paths | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 1407 | 1369 | 1343 | 1345 |
| 2 | 1415 | 1373 | 1356 | 1345 |
| 3 | 1406 | 1367 | 1358 | 1348 |
| 4 | 1403 | 1385 | 1354 | 1342 |
| 5 | 1400 | 1379 | 1354 | 1338 |
| Avg | 1406.2 | 1374.6 | 1353.0 | 1343.6 |
| All-optical cost | 1520 | 1520 | 1520 | 1520 |
| Gain | 0.0749 | 0.0957 | 0.1099 | 0.1161 |

solution technique was totally unable to reach a solution after 24 hours of CPU time. These results and similar ones not reported here to reduce space show that the heuristic is capable of solving reasonably large networks up to 50 nodes in a few hours, small enough for design studies. The optimality gap is under 7% in all cases and the heuristic often finds the optimal solution for small networks for which the optimum is known.

### *B. Effect of Number of Alternate Paths*

Here we investigate the structure of the networks produced by the algorithm when we increase the number of two-link alternate paths available to each demand. The number of paths is increased equally for all demands.

The first results on the cost of the network are shown in Table II. We see that increasing the number of alternate paths does decrease the network cost, as it should, since there are more routes available for the demands. We also show the cost of an all-optical solution, computed by routing each demand on a dedicated optical channel, and on the last row, the relative savings brought about by the grooming, which increases with the number of paths available.

The impact of modular switch cost is more obvious in Table III, where we present the average switch utilization for a 20-node network as a function of the number of alternate two-link paths. The switch utilization is defined as the amount of traffic actually going through the switch divided by the total traffic carrying capacity of this switch type. In all cases, these values are very close to 1 showing a high utilization because of the large switch cost.

TABLE III

AVERAGE SWITCH UTILIZATION, 20-NODE NETWORK

| Test No | No Alternate Paths | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 0.9076 | 0.9288 | 0.9560 | 0.9144 |
| 2 | 0.8970 | 0.9182 | 0.9475 | 0.9317 |
| 3 | 0.9212 | 0.9587 | 0.9295 | 0.9392 |
| 4 | 0.9127 | 0.9218 | 0.9274 | 0.9392 |
| 5 | 0.9375 | 0.9264 | 0.9339 | 0.9422 |
| Avg | 0.9266 | 0.9426 | 0.9409 | 0.9350 |

A more detailed description of this utilization is given in Table IV showing the results obtained from the first test. Here we see the amount of traffic through each of the 20 switches in the network. We see that once a switch is installed, the algorithm will try to fill it as much as possible, e.g., values of 1.8 or 1.9, but will avoid exceeding the capacity by a small amount, e.g., will avoid traffic values like 2.1 or 2.2. This effect is directly tied to the high modularity of the cost and would not appear in a model with interface costs only.

Recall that the capacity of each router type $r$ is a multiple $rB$ of the capacity of an optical channel. For instance, we see that switch 4 is of type 2 in the solutions with 1, 3 and 4 alternate paths but of type 3 in the solution with 2 alternate paths and that in each case, it is fairly well filled. We would expect a much wider range of utilization if the cost was simply the interface cost with a correspondingly smaller step size.

TABLE IV

SWITCH UTILIZATION VS NO OF ALTERNATE PATHS, 20-NODE NETWORK

| Switch No | No Alternate Paths | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 1.5192 | 1.9296 | 1.9188 | 1.9388 |
| 2 | 1.9516 | 1.7576 | 1.9320 | 1.9304 |
| 3 | 1.8116 | 1.9556 | 2.8824 | 1.7732 |
| 4 | 1.9212 | 2.6916 | 1.8904 | 1.9768 |
| 5 | 1.4048 | 1.9396 | 1.6456 | 1.7448 |
| 6 | 1.9408 | 1.9612 | 2.9668 | 1.9020 |
| 7 | 1.9608 | 1.6588 | 2.9448 | 1.9556 |
| 8 | 1.6988 | 1.7960 | 1.9984 | 1.9320 |
| 9 | 0.9656 | 1.7000 | 1.8232 | 1.7052 |
| 10 | 1.6672 | 1.9128 | 1.9372 | 1.9728 |
| 11 | 0.9740 | 1.6592 | 1.9484 | 1.8152 |
| 12 | 1.8384 | 1.9160 | 1.9772 | 1.9352 |
| 13 | 1.9324 | 1.8936 | 1.9176 | 1.8428 |
| 14 | 1.9248 | 1.9948 | 1.9552 | 1.8068 |
| 15 | 1.8412 | 1.9348 | 1.9768 | 1.8296 |
| 16 | 1.8596 | 1.9212 | 1.6624 | 1.5904 |
| 17 | 2.8992 | 1.9552 | 1.9800 | 2.5236 |
| 18 | 1.8132 | 1.8392 | 1.8132 | 1.9352 |
| 19 | 1.7436 | 1.6968 | 1.9476 | 1.9896 |
| 20 | 1.7288 | 1.9680 | 1.9892 | 1.3920 |
| Avg | 0.9076 | 0.9288 | 0.9560 | 0.9144 |

The utilization of the optical channels, on the other hand, is much lower, as can be seen from Table V. Here again the utilization of a channel is defined as the ratio of the traffic on the channel to the channel capacity. This is due to the fact that the cost of the channels is much smaller than that of the switches so that it is better to use optical channels with a lower utilization than to groom more traffic and be forced to install larger switches.

This interpretation is reinforced by Table VI which shows the maximum, minimum and average in- and out-degree of the nodes in these solutions. We see that all the nodes have a very high degree and that the graph is nearly complete. For

TABLE V

AVERAGE OPTICAL CHANNEL UTILIZATION, 20-NODE NETWORK

| Test No | No Alternate Paths | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 0.2380 | 0.2497 | 0.2574 | 0.2545 |
| 2 | 0.2359 | 0.2527 | 0.2550 | 0.2536 |
| 3 | 0.2396 | 0.2489 | 0.2546 | 0.2568 |
| 4 | 0.2402 | 0.2454 | 0.2550 | 0.2620 |
| 5 | 0.2361 | 0.2476 | 0.2539 | 0.2608 |
| Avg | 0.2380 | 0.2489 | 0.2552 | 0.2575 |

the cost values used in this example, the best solution is to spread traffic as much as possible in order to avoid the high cost of installing the next router type.

TABLE VI

NODE DEGREE

| Degree | No alternate paths | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | |
| | In | Out | In | Out | In | Out | In | Out |
| Max | 18 | 19 | 18 | 18 | 19 | 18 | 18 | 18 |
| Avg | 16.5 | 16.5 | 15.95 | 15.95 | 15.5 | 15.5 | 15.6 | 15.6 |
| Min | 14 | 13 | 13 | 14 | 13 | 13 | 13 | 12 |

### *C. Effect of Number of Tandem Nodes*

We have also examined the effect of the path length on the solution. In this case, the routing options are the direct link and a single alternate path, which is made increasingly longer for all demands at the same time. This has a definite effect on the network cost, as can be seen from Table VII, where the cost increases with the path length. In the case where there are 4 tandem nodes, the heuristic finds a solution that is even slightly worse that the all-optical solution, indicating that in this case, there is probably little to be gained by grooming. This confirms the well-known traffic engineering principle that one should avoid long paths whenever possible since they are less efficient than short ones.

We also see in Table VIII the effect of increasing the number of tandem nodes on the utilization of the switches. There is a clear decrease as the tandem path gets longer, a result that confirms what was also obtained for smaller networks.

TABLE VII

NETWORK COST VS NO TANDEM NODES, 20-NODE NETWORK

| Test No | No Tandem Nodes | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 1414 | 1477 | 1501 | 1522 |
| 2 | 1416 | 1467 | 1506 | 1519 |
| 3 | 1414 | 1472 | 1502 | 1524 |
| 4 | 1413 | 1477 | 1499 | 1519 |
| 5 | 1408 | 1473 | 1497 | 1521 |
| Avg | 1413.00 | 1473.20 | 1501.00 | 1521.00 |
| All-optics cost | 1520 | 1520 | 1520 | 1520 |
| Grooming gain | 0.0704 | 0.0308 | 0.0125 | $-0.0007$ |

TABLE VIII

SWITCH UTILIZATION VS NO TANDEM NODES, 20-NODE NETWORK

| Test No | No Tandem Nodes | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 0.9243 | 0.8630 | 0.8573 | 0.7591 |
| 2 | 0.9092 | 0.8976 | 0.7661 | 0.7440 |
| 3 | 0.9213 | 0.8275 | 0.7932 | 0.7193 |
| 4 | 0.9261 | 0.8325 | 0.8595 | 0.7896 |
| 5 | 0.9365 | 0.8894 | 0.8208 | 0.8224 |
| Avg | 0.9235 | 0.8620 | 0.8194 | 0.7669 |

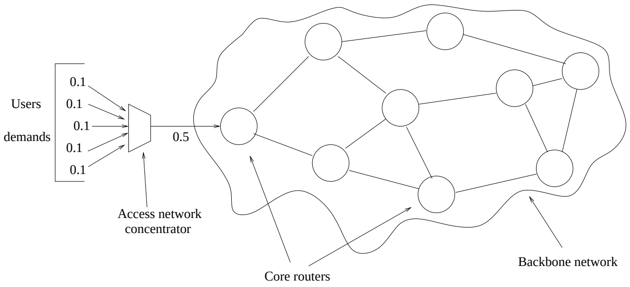

Fig. 7. Concentration in the access network

### *D. Effect of Traffic Mix*

Finally, we have used the heuristic to examine the effect of the composition of the traffic on the network. For a given value of the total traffic offered to the network we have compared a situation where this traffic is made up mostly of a large number of low-bandwidth connections to the opposite situation where we have a small number of connections with a larger bandwidth. This could happen for instance when the demand from a number of users is concentrated on the customer network, as shown in Figure 7 as opposed to being offered as individual demands to the network, as shown in Figure 8. In the latter case, it is the network that will do the traffic concentration through grooming with a corresponding increase in cost.

The traffic matrices were generated as follows. First, a base matrix was calculated by generating demands from a uniform distribution in the range $[0, 0.1]$. These demands were assigned type 1. To model the situation of Figure 7, we simply *multiplied* demand $d_{i,j}(1)$, initially set at 0.05, by a factor 2, 3, 4, 6, 8 and 10 so that we had in the first case one demand $d_{i,j}(1) = 0.1$ and then one demand $d_{i,j}(1) = 0.15$ and so on until $d_{i,j}(1) = 0.5$. On the other hand, to model the situation of Fig. 8, where a large number of small demands are offered to the network, each demand of type 1 was *replicated* 2, 3, $\ldots$ 10 times. If for example we had a demand $d_{i,j}(1) = 0.05$ in the base matrix, then we would create a new demand of the same size $d_{i,j}(2) = 0.05$ and then $d_{i,j}(3) = 0.05$ and so on up to $d_{i,j}(10) = 0.05$.

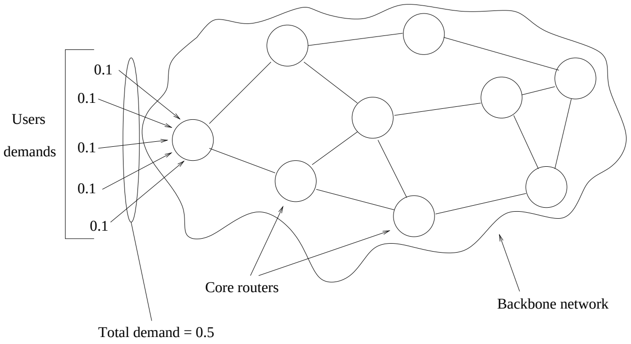

Fig. 8. Concentration in the core network

We have computed the optimal network cost in both cases of user and network concentration as explained above and the result is compared in Table IX. The results show that grooming a large number of small demands can lead to large cost increases as opposed to the case where the demands are already groomed by the user. This is a result that cannot be obtained by other models that do not have an accurate modular switch cost.

This raises an important issue for the network operators. If the grooming of the small demands is done in the core network, there will be a large grooming cost which must somehow be passed back to the user. If the grooming is done on the customer premises, the network grooming will be much smaller with a correspondingly small cost. This grooming by the users will also incur some cost and the question is whether it is more economical to do this in the core or in the access. It is not possible to answer this question without a realistic model for the access grooming but the results presented here clearly indicate that this question must be examined seriously.

TABLE IX

EFFECT OF TRAFFIC MIX ON NETWORK COST

| | Total Network Cost | | | | | | |
|---|---|---|---|---|---|---|---|
| Total traffic | 19 | 38 | 57 | 76 | 114 | 152 | 190 |
| User grooming | 852 | 1145 | 1273 | 1342 | 1411 | 1442 | 1462 |
| Network grooming | 852 | 1405 | 2065 | 2775 | 4578 | 6689 | 9492 |

## VI. CONCLUSION

We have used a heuristic tool that dimensions the capacity of optical and electronic components of optoelectronic networks while minimizing the total cost. We have been able to extend results previously obtained for small networks only to significantly larger networks. Numerical results show that adding grooming in the dimensioning process has a significant impact on the final cost in those cases as well and should be taken into consideration in the design procedure. We have also confirmed that the choice and the number of routes is an important factor affecting the total cost. We have also found that small demands are much more expensive to carry than demands that have already been grouped in large bundles before being offered to the network. This is an effect that shows up only if we model the switch cost accurately as was done here. This is an important issue for network operators who must decide whether it is more economical to encourage users to bundle their demands or to do it themselves in their network.

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