Virtual Topology Design For A Hypothetical Optical Network*

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Abstract- In this paper a study of the design of wide area optical networks is presented, more specifically the problem of design of the virtual topology in optical networks. A network with a small number of nodes was analysed through a Mixed-Integer Linear Programming (MILP) formulation for the problem of the virtual topology design. Heuristic methods were then applied for a hypothetical optical network with a larger number of nodes plausibly located on the Brazilian territory. The work resulted in some suggested guidelines for the design of virtual topologies.

Index terms- Optical Networks, Virtual Topology, Optimization.

I. INTRODUCTION

The last decades have brought an enormous growth in the data transport capacity of fiber optic networks, which has now exceeded the Terabit-per-second milestone. However, the speed in which it is possible to generate electronic modulated signals in commercial equipments barely reaches 20Gb/s (with a foreseeable expansion to 40Gb/s). Such large difference between the speeds of optical transmission and electronic processing is commonly called the *electronic bottleneck*.

Although the combination of the emerging ATM technology with the new SDH (Synchronous Digital Hierarchy) transport network constitutes a widening of this bottleneck, it is not enough to eliminate it. At this moment, it seems that the viable technology to bridge this speed gap is *wavelength division multiplexing* (WDM), in which several wavelengths are electronically modulated by different signals and multiplexed in the same fiber. In a networking environment, enabled by optical crossconnects and a whole new family of emerging photonic devices, such wavelengths may then be all-optically routed to different destinations in the network [7], [8], [10], [13].

WDM offers an important new dimension to increase the transmission capacity on substantial fiber lengths, at a reasonable cost. As the demand for capacity in wide areas networks (WANs) scales up, WDM technology emerges as an attractive, cost-effective solution for upgrading [9].

Modulated on different wavelengths, different packets can share the fiber without any risk of collision, but requiring a coordination of the wavelength tunings of transmission at the source node and of reception at the destination node, so that connectivity is provided between them. For this purpose, wavelength conversion may also have to be provided and dynamically assigned at intermediate nodes.

In order to engineer such wavelength coordination, many studies are being accomplished for design of optical WANs, especially in the problem of designing the virtual topology to be overlayed on optical networks. The architectural framework assumes transparent clear channels called *lightpaths*, so named because they traverse several physical links without ever leaving the optical domain from end to end [1], [3], [11], [13].

Lightpath networks are designed to be reconfigured when traffic patterns change, as opposed to the physical topology, which can only be changed in response to long-term needs.

All intermediate nodes in a lightpath are traversed without any electronic processing, thus creating a virtual link in the client layer. In the optical layer, the ligthpath uses one or several wavelengths in tandem, according with the availability of costly wavelength conversion capabilities in the intermediate nodes. Because of the limited number of wavelengths in the optical spectrum (the so called *wavelength bottleneck*), a major concern of the optical network design is the reuse of wavelengths.

The objective of this paper is to analyze the efficiency of some heuristic algorithms to generate a virtual topology design to be implemented by a lightpath network. Section 2 (a brief overview) describes a virtual topology and its elements in full detail. Section 3 describes an optimization method based on the Mixed Integer – Linear Programming (MILP) technique, and discusses the resulting topologies. Section 4 describes some heuristic methods and explains why they are needed. Section 5 discusses a hypothetical optical network over the Brazilian territory. The results are presented in Section 6. Section 7 states some conclusions and suggests directions for future studies.

II. VIRTUAL (OR LOGICAL) TOPOLOGY (A BRIEF OVERVIEW)

A. Definition

The set of all unidirectional lightpaths set up among the access nodes is the virtual topology. Fig.1 shows an example in which the virtual topology is represented by the full lines with arrows. The virtual topology design is constrained by the resources of the

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access nodes (node degree, traffic processing capability).

Note also that each access node is connected to a router node. Besides, each lightpath is labeled by a wavelength (λ1 and λ2 in Fig. 1) taken from a finite, usually small, pool. No two paths with the same label may share a physical link. Such physical – layer constraints will constrain the lightpath network design, and may limit its ability to implement the desired virtual topology.

At the ends of a lightpath, packets may be terminated or store-and-forwarded. This architecture is a combination of the systems known as "single-hop" and "multihop", and it explores the characteristics of both.

In Fig. 1, the access node A communicates with the access node C through "single-hop". However, for communicating with B, the information has to be processed in nodes C and D, forming, in this case, a "multihop" system.

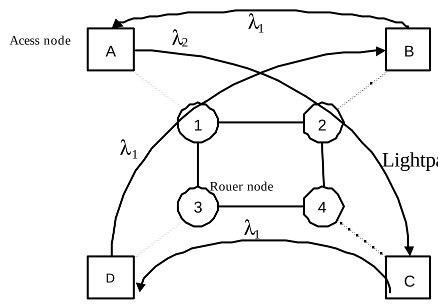

Figure 1 - *Virtual topology over a physical topology for a network of four nodes*

Ideally in a network with N nodes, we would like to set up lightpaths betweeen all the *N(N-1)* pairs. However this is usually not possible because of two reasons. First, the number of available wavelengths imposes a limit on how many lightpaths can be set up (this is also a function of the traffic distribution). Secondly, each node can be the source and sink of a limited number of lightpaths. This is determined by the amount of optical hardware that can be provided (transmitters and receivers) and by the total amount of information the node can handle [11].

B. Reconfiguration

The virtual topology is usually designed based on the estimated average traffic flow between the node pairs in a specific time frame.The length of this time frame depends on whether the planning is long-term or short-term. The traffic flow between the nodes is not constant and is subject to change with time. The underlying virtual topology may be not be optimum for all the different patterns of traffic flow.

Reconfiguring the virtual topology to be in tune with the changing traffic pattern would help maximize the performance. Reconfiguration requires that a few lightpath in the existing virtual topology be removed and a few lightpaths be added to form a new virtual topology. The flexibility in wavelength crossconnect to dynamically change the switching patterns of wavelengths from the incoming fibers to be outgoing fibers aids the process of reconfiguration [14].

C. Transmission Impairment

Developing network-layer solutions to counter physical-layer impairments, such as laser shift, dispersion in fiber, and also impairment that affects optical components such as amplifiers, switches, and wavelength converters, is another important issue. For example, the routing and assignment of wavelengths for lightpaths assume an ideal physical layer. However, in practice, a signal degrades in quality due to physical-layer impairment as it travels through switches (picking up crosstalk) and EDFAs (picking up noise). This may cause a high bit error rate (BER) at the receiving end of a lightpath [8], [14].

D. Signaling and Resource Reservation

In order to set up a lightpath, a signaling protocol is required to exchange control information among nodes and to reserve resources along the path. In many cases, the signaling protocol is closely integrated with the routing and wavelength assignment protocols. Signaling and reservation protocols may be categorized based on whether the resources are reserved on each link in parallel, reserved on a hop-by-hop basis along the forward path, or reserved on a hop-by-hop basis along the reverse path. Protocols will also differ depending on whether global information is available or not [13].

E. IP over WDM

With the rapid growth of the Internet, it is becoming apparent that IP traffic will soon become the dominant type of traffic in emerging networks; thus, there is much interest in optimizing the underlying optical network to handle IP traffic. In IP over WDM networks, lightpaths are established between any two IP routers (higher-layer equipment). The routers between wich a lightpath exists become neighbors, changing the network topology perceived by all participating IP routers. The traffic on a lightpath connecting two routers can be monitored continuosly and appropriate changes can be made to the virtual topology. This is strong on with the reconfiguration [14].

III. OPTIMIZATION OF VIRTUAL TOPOLOGY

Although lightpaths underly SDH networks in a natural way, packet- and cell-switching client networks, like ATM and IP, would be better served by more packet-oriented WDM layer mechanisms and protocols. However, current optical packet-switching technologies do not yet deliver the same performance that is possible in electronic networks. By looking for the best possible circuit configuration for the traffic demand at any given time, optimizing the virtual topology mitigates the impairments caused by the inability to switch packets on an individual basis.

One of the great advantages of the high speed networks is the flexibility to support several types of services. An individual connection can accommodate a heterogeneous traffic with different characteristics and objectives. But if a virtual link arrives to its superior load limit, the control of the traffic and congestion should be activated.

In the virtual topology the traffic that traverses a virtual link *i-j* is denoted by l_{ij}. Then, the maximum link traffic over all links is given by $l_{max} = \max l_{ij}$. Each l_{ij} is a heterogeneous traffic that traverses the *i-j* virtual link; in other words, it is the sum of several types of traffics: $l_{ij} = \sum_{sd} l_{ij}^{sd}$, where l_{ij}^{sd} is the specific part of the traffic from a source *s* to a destination *d* that goes through the *i-j* virtual link. The lightpath will be denoted by b_{ij} and it can assume two values; $b_{ij} = 1$, if there is a lightpath from node *i* to node *j*, and $b_{ij} = 0$ otherwise. The optical hardware (transmitters and receivers) will determine the maximum number of lightpaths (b_{ij}*'s*) that may originate and terminate in that end-node, i.e. the virtual degree of the node, denoted by *D*.

Primarily, in a high-speed network, one aims at minimizing the congestion to guarantee some specified quality of service (QoS). To optimize the virtual topology means to allocate lightpaths so that the congestion is minimized. Then:

Data:	#Matrix of distances #Matrix of traffic
Objective:	#Minimize congestion λ_{max}
Variables:	#Traffic flow #Lightpaths
Constraints:	#Flow conservation #Total flow on a lightpath (constrained by link capacities) #Virtual degree of nodes

Table 1 - *Statement Problem*

A. Mathematical Formulation

Objective Function:

Min l_{max} (minimize the congestion) (1)

Subject to:

Flow conservation at each node:

$$\sum_j l_{ij}^{sd} - \sum_j l_{ji}^{sd} \begin{cases} = l^{sd} & \text{if s=i} \\ = - l^{sd} & \text{if d=i } \forall \text{ s,d,i} \\ = 0 & \text{otherwise} \end{cases} \quad (2)$$

Total flow on a logical link (lightpath):

$$l_{ij} = \sum_{s,d} l_{ij}^{sd}, \quad \text{for all } i,j \quad (3)$$

$$l_{ij} \le l_{max}, \quad \text{for all } i,j \quad (4)$$

$$l_{ij}^{sd} \le b_{ij} l^{sd}, \quad \text{for all } i,j,s,d \quad (5)$$

Degree constraints:

$$\sum_i b_{ij} \le \Delta \quad \text{for all } j \quad (6)$$

$$\sum_j b_{ij} \le \Delta \quad \text{for all } i \quad (7)$$

Non-negativity constraints:

$$l_{ij}^{sd}, l_{ij}, l_{max} \ge 0, \quad \text{for } i,j,s,d$$

$$b_{ij} \in \{0,1\} \quad \text{for all } i,j$$

Table 2 - *Mathematical Formulation in MILP*

B. Application

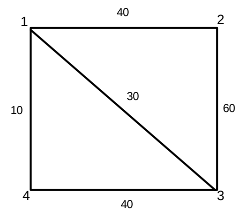

Figure 2 - *Pilot network of four nodes with respective distance (out of scale) among the nodes (each edge represents a bidirectional fiber link).*

s,d	1	2	3	4
1	0	0,58	0,14	0,27
2	0,92	0	0,2	0,19
3	0,41	0,81	0	0,11
4	0,89	0,01	0,6	0

Table 3 – *Traffic matrix T for the network of Fig. 2*

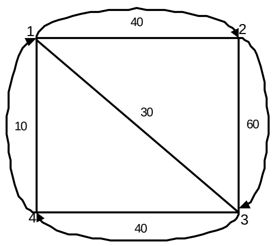

Figure 3 - *Virtual Topology obtained with MILP, with D=1, congestion =2.81.*

The MILP problem was solved for a network of four nodes, as displayed in Fig.2. The traffic matrix was given by Table 3; it was randomly generated from a uniform distribution between 0 and 1.

With virtual degree equal to "one" (Δ=1), a value of 2.81 was obtained for traffic congestion. The variables b_{ij}*'s* assumed the following values: $b_{12}=b_{23}=b_{34}=b_{41}=1$; $b_{13}=b_{14}=b_{21}=b_{31}=b_{32}=b_{43}=0$. For this particular case, the links of the virtual topology correspond to some (but not all) links of the physical topology, as displayed in Fig. 3.

It is observed that, in the analysis above, the design of the virtual topology included the routing subproblem; in other words, all offered traffic will be routed through the generated virtual links (which means finding the values of the variables l_{ij}^{sd}) so that congestion is minimized. Notice that physical link 1-3 (3-1) was not used in the optimizing solution.

IV. ALGORITHMS FOR VIRTUAL TOPOLOGY DESIGN

The problem discussed in the previous section implies the determination of an optimal virtual topology among many (usually hundreds, often thousands) feasible arrangements.

The complete enumeration of all viable solutions of a problem of discrete optimization will lead to the optimal solution in a finite number of steps. Unfortunately it is shown that for problems of high dimensions the number of steps will be so large that the most advanced computer would take centuries in the calculation process. This implies, as an alternative solution, the use of heuristic algorithms, as a way to obtain a good solution (not necessarily optimal) with reduced computational cost [2].

For the MILP problem, some heuristics should be used, on account of its intractability for networks with a great number of nodes and larger virtual degrees. The basic approach is to decompose the design of the virtual topology into the following two subproblems:

Topology Subproblem: Determine the virtual topology to be imposed on the physical topology, i.e. determine a set of lightpaths in terms of their source and destination nodes.

Traffic Routing Subproblem: Route packet traffic between source and destination nodes over the virtual topology obtained in the previous step.

A. Explanation

In terms of the formulation provided in section 3, the topology subproblem consists of the determination of the values of the variables b_{ij}*'s*, and the routing subproblem consists of the determination of the values of the variables l_{ij}^{sd} . Note that in the decomposition the problem is solved sequentially, using the solution of the virtual topology subproblem as input to the routing subproblem. Once the b_{ij}*'s* (discrete values) are found through some heuristics, the routing subproblem can be easily solved, since only continuous variables (flow of traffic) will remain in the mathematical formulation, reducing MILP to an LP (Linear Programming) problem.

The heuristic algorithms HLTD (Heuristics for the Logical Topology Design), LPLTD (Linear Programming LTD) and RLTD (Random LTD) are proposed to solve the topology subproblem[11]. In those cases, the term LTD means "Logical Topology Design Algorithm ".

HLTD: This algorithm attempts to place logical links between nodes in order of descending traffic. The idea behind this heuristic is that routing most of the traffic in one hop may lower the congestion.

LPLTD: It considers the relaxation of the variables b_{ij}*'s* of the formulation of the section 3, in other words, the b_{ij}*'s* may now take any value between 0 and 1. We organize the relaxed b_{ij}*´s* (obtained from linear programming formulation) in the decreasing order and, starting with the largest b_{ij}, we round each sucessive value of b_{ij} to one, if degree constraints are not violated, and to zero otherwise.

RLTD: For comparison, the random algorithm (RLTD) can be used; it places the virtual links entirely at random, subject to finding a lightpath for each edge and not violatiung degree constraints, but ignoring the traffic matrix altogether.

V. CASE . STUDY

So that the study of a network with larger number of nodes approaches of known data, the 12-node hypothetical network of Fig. 4 was considered.

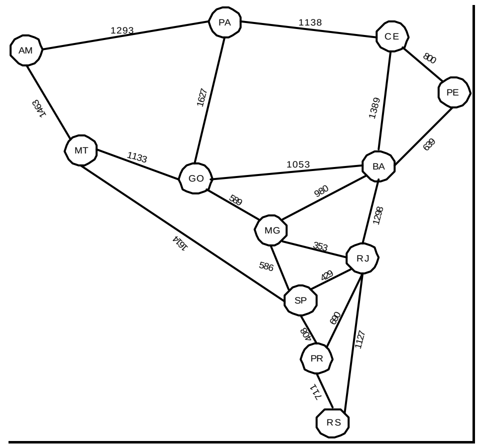

Figure 4 - *A WAN with 12 nodes. The numbers in the links represent distances among the nodes in km.*

Each node corresponds to one of 12 States in Brazil, chosen for their economic regional importance.

$$T_{ij} = k\frac{P_i F_i P_j F_j}{d_{ij}} \quad (8)$$

Where :

P_i	Population of State i
P_j	Population of State j
F_i	Utilization factor in State i
F_j	Utilization factor in State j
d_{ij}	Distance between States i e j
k	Proportionality factor

A plausible mesh was assumed for the physical links. The distances among nodes were based on the geographical positions of the States capitals. The traffic matrix A, seen in the table 5, was based on statistical data [6], and was obtained through the following expression [12]: distances among the nodes in km.

The utilization factor F_i is some measure of the use of Telecommunications in State i. In the network under study, it will be the level of services of telecommunications disputed by a State [6]. The traffic matrix A, generated in this way, is seen in table 5. Observe that (8) implies a symmetrical matrix.

For comparison, a traffic matrix with random values was also generated in which the distribution was in the interval between zero and 1. It is shown in table 6 (matrix B).

	0,92	2,50	0,97	0,80	0,20	0,19	0,08	0,06	0,08	0,03	0,1
0,92		6,4	1,49	1,27	0,28	0,23	0,1	0,08	0,09	0,03	0,08
2,50	6,40		10,2	9,29	1,62	0,90	0,39	0,31	0,40	0,13	0,36
0,97	1,49	10,2		6,06	0,56	0,54	0,18	0,13	0,14	0,05	0,11
0,8	1,27	9,29	6,06		1,36	0,88	0,31	0,25	0,20	0,1	0,21
0,20	0,28	1,62	0,56	1,36		0,25	0,09	0,08	0,08	0,04	0,08
0,19	0,23	0,90	0,54	0,88	0,25		0,26	0,11	0,09	0,02	0,03
0,08	0,1	0,39	0,18	0,31	0,09	0,26		0,11	0,05	0,01	0,02
0,06	0,08	0,31	0,13	0,25	0,08	0,11	0,11		0,09	0,02	0,01
0,08	0,09	0,40	0,14	0,20	0,08	0,09	0,05	0,09		0,04	0,02
0,03	0,03	0,13	0,05	0,1	0,04	0,02	0,01	0,02	0,04		0,02
0,1	0,08	0,36	0,11	0,21	0,08	0,03	0,02	0,01	0,02	0,02	

Table 5 - *Traffic matrix A*

	0,92	0,13	0,84	0,3	0,49	0,83	0,17	0,28	0,52	0,41	0,32
0,23		0,2	0,52	0,29	0,89	0,56	0,97	0,46	0,64	0,3	0,96
0,6	0,17		0,2	0,19	0,82	0,37	0,27	0,06	0,2	0,87	0,72
0,48	0,4	0,6		0,68	0,64	0,7	0,25	0,98	0,37	0,01	0,41
0,89	0,93	0,27	0,83		0,81	0,54	0,87	0,58	0,78	0,76	0,74
0,76	0,91	0,19	0,01	0,54		0,44	0,73	0,42	0,68	0,97	0,26
0,45	0,41	0,01	0,68	0,15	0,34		0,13	0,51	0,46	0,99	0,43
0,01	0,89	0,74	0,37	0,69	0,28	0,62		0,33	0,56	0,78	0,93
0,82	0,05	0,44	0,83	0,37	0,34	0,79	0,89		0,79	0,43	0,68
0,44	0,35	0,93	0,5	0,86	0,53	0,95	0,19	0,22		0,49	0,21
0,61	0,81	0,46	0,7	0,85	0,72	0,52	0,29	0,57	0,6		0,83
0,79	0,01	0,41	0,42	0,59	0,3	0,88	0,66	0,76	0,05	0,64	

Table 6 - *Traffic matrix B*

VI. NUMERICAL RESULTS

It is observed that the algorithm HLTD and LPLTD obtains good results for the matrix A, with the congestion decreasing as the degree is increased, indicating the reach of a value approximately great. However, the application of HLTD, for the degree two, is not interesting, because a loop is formed (closed cycle) among SP, RJ and MG.

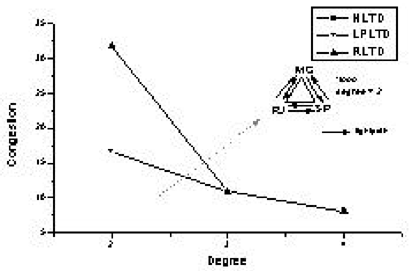

Figure 5 - *Minimum obtained congestion (in arbitrary units) in function of the virtual degree for the matrixof* traffic A.

For instance, assuming a degree two, SP would create two virtual links, one for MG and other for RJ. The same would happen with the creation of the virtual links on the part of MG and RJ, since the high concentration of symmetrical traffic existing will provoke the use of all entrance degrees and exit, of those three nodes, only among them (see Fig.5 *).

For the matrix B, RLTD obtained smaller congestion values. HLTD and LPLTD didn't obtain a good acting, being overcome even by RLTD. Before that, those, they should just be used for networks in that some we have high concentration of traffic.

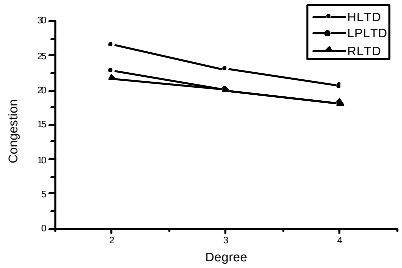

Figure 6 - *Minimum obtained congestion (in arbitrary units) in function of the virtual degree for the matrixof traffic B.*

VII. CONCLUSIONS AND FUTURE DIRECTIONS

It was seen that the usual goal of the design of the lightpath topology is to improve the performance of the network, such that congestion is reduced. An exact formulation of the design problem was applied for a network with four nodes, resulting in a virtual topology with efficient allocation of virtual links, reduced electronic processing and optimized routing. This is s good procedure for a network with a few nodes, since it obviates the need to separate the design into two subproblems.

Interesting results were obtained with the application of the algorithms HLTD and LPLTD for the network of 12 nodes, with high traffic concentration in some source-destination pairs, resulting in small, closely packed values of congestion as the virtual degree is increased.

It was checked the application of the HLTD for a symmetrical traffic matrix should be done carefully, because closed cycles can be generated, depending on the virtual degree.

For the randomly generated traffic, inefficient results were observed from the HLTD and LPLTD algorithms, showing that their application is effective only for demands with high traffic concentration in some source-destination pairs.

While the technological limitations (mainly associated to the tuning agility of the lasers and optical filters) hinder the switching of optical packets, it is likely that emerging systems will work with entities at intermediate levels of granularity between the optical path and the individual optical packet. An example would be *flow switching,* set up by intermediate nodes as they detect that certain thresholds are exceeded by the flows of bits addressed to the same exit point in the optical layer. Another example would be *burst switching,* in the which the source of a *burst* (for instance, a big file to be lowered) will originate signaling to schedule an ad-hoc path for the *burst* along an appropriate chain of nodes, liberating the resources soon after they are used for this purpose.

Intermediate granularity protocols should evolve toward switching of optical packets in the future: hence the interest in studies leading to the use of the *lambda-labeling*, that treats wavelengths as labels in MPLS - *multiprotocol label-switching*.

In a general way, such schemes try to take into account the dynamics of the traffic in IP routers and their limitations, especially the need for distributed control. Some new technologies, such as *wavelength merging* to set up optical trees in the WDM layer, will be needed.

The main focus of the architectural solutions is still the elimination of unnecessary electronic processing, but now in ATM nodes and IP routers. Consequently, the solutions need to adapt to the volatile and explosive nature of Internet (IP) and *multi-service* (ATM) traffics.

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