An Integrated Design for Topologies of Optical Networks, Part II: Resources of Wavelength Conversion

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Abstract— **Traditional approaches to wavelength-routing network design divide it into two separate problems: virtual topology design (VTD) and routing-and-wavelength assignment (RWA). We propose an iterative linear programming approach to solve both problems jointly under multiple objectives. Our formulation allows for any kind of wavelength conversion.**

***Index Terms*— RWA, Optical networks, wavelength conversion.**

I. Introduction

PLANNING real world telecommunications networks is a task of growing complexity. The complexity results not only from the fact that the networks are large and functionally complex, subject to continuous technological evolution and growth, but also that network planning is a multidimensional techno-economic optimization problem.

Optical Networks planning draws an increasing amount of attention nowadays. The Wavelength Division Multiplexing (WDM) technique splits the the large bandwidth available in optical fibers into multiple channels, each one operating at a different wavelength and a specific data rate (up to 40 Gbps). Due to current advances in WDM and high-speed eletronic routing/switching, it is likely that next-generation broadband networks will employ a hybrid, layered architecture, using both optical WDM and electronic switching technologies. In such networks, a significant gap exists between the huge transmission capacity of WDM fibers and the eletronic switching capacity, generating an *eletronic routing bottleneck* [2], [3]. Notice that WDM itself has evolved to address an electronic transmission bottleneck, as per-channel bit rates reached 10 Gbps and were found not to scale up cost-efficiently above this level.

At this moment, it is already clear that the available technology to bridge this speed gap is WDM. In a networking environment, enabled by optical crossconects and a whole new family of emerging photonic devices, the wavelengths may then be photonically routed to different destinations in the network. 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 [6].

In general, the network design problem can be formulated as an optimization problem aimed at maximizing network throughput or other performance measures of interest. Typically, the exact solution can be shown to be NP-hard, and heuristic approaches are needed to find realistic good solutions. For this purpose, the problem can be decomposed into two subproblems. The first is to decide what virtual topology to embed on a given physical topology, that is, what are the lightpaths to be implemented, as seen from the client layer: this is the virtual topology design (VTD) or lightpath topology design (LTD) problem. The second is the RWA for these lightpaths at the physical layer, this is the physical topology design (PTD). The routing of packet traffic on the lighpaths is also usually seen to be a part of the VTD problem, since its objective function is usually some parameter function of the traffic routing [5], [6], [7].

In our previous paper, [1], in the design of the physical topology, lightpath routing normally requires that the same wavelength be allocated on all of the links in the path. This requirement is know as the wavelength continuity. The entire bandwidth available on this lightpath is allocated to the connection during its "holding time". The wavelength continuity constraint distinguishes the wavelength-continuous network from a traditional circuit-switched network which blocks calls only when there is no capacity along any of the links in the path assigned to the call. Thus, a wavelength-continuous network may suffer from higher blocking as compared to a circuit-switched network.

It is easy to eliminate the wavelength continuity constraints if we are able to *convert* the data arriving on one wavelength along a link into an other wavelength at an intermediate node and forward it along the next link. Such a technique is referred to as wavelength conversion.

A. *Previous Work*

Virtual topology problem can therefore be decomposed into subproblems. Since the virtual topology problem is very complex to solve, the subproblems can be solved individually. Although this results in a suboptimal solution, it is well acceptable for complexity reasons. Some of the existing work solves only a few among of the subproblems, with the

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assumption that other subproblems have already been solved by some means [6].

In [8] the authors formulate the virtual topology design problem as a nonlinear optimization problem. The objective considered was either delay minimization or minimizing the maximum offered load. The authors subdivide the problem into four subproblems. The drawbacks of the above approach are follow. 1) If the network is large then using the heuristics approach will be computationally very expensive. 2) It is not an integrated approach to solve the subproblems; rather, it considers subproblems independently. In [9] the authors formulated the virtual topology design problem as a linear program when the nodes were equipped with wavelength changers. However, to assume changes this previous work only serves to relax the restriction of continuity of wavelength. The model does not allow to define kinds of conversion. In [7] the problem of virtual topology design is considered but the number of wavelengths that the fiber supports is not a constraint. The drawback in this approach is that the physical topology becomes irrelevant for designing a virtual topology. In [10] is present an exact linear formulation for designing a virtual topology, but with no wavelength changers. In [1] is present an iterative linear programming to solve the subproblems jointly, but with no wavelength changers too.

B. *Contribution of this work*

We propose an iterative linear programming approach to solve the subproblems jointly under multiple objectives such as congestion avoidance, fiber load and wavelength pool minimization. Our formulation allows for any kind (partial or full, sparse or ubiquitous) of wavelength conversion, thus providing a tool for the allocation of conversion resources in the network. To the best of our knowledge, this is the first time a linear formulation has been stated wich provides an solution to the virtual topology design problem with resources of any kind of conversion.

C. *Outline*

In the following we present the solution approach. Section II shows a precise formulation for the VTD and RWA with resources of conversion. Section III explains a heuristic for an integrated virtual and physical topology design. Section IV exemplifies the application on two kinds of network. Section V shows some statistics, and finally section VI draws some conclusions.

II. STATIC PROBLEM STATEMENT

A physical layer (topology) is a graph representing the physical interconnection of the wavelength routing nodes by means of fiber-optic cables. Fig. 1 shows a physical layer of a six-node- wide-area network. The wavelength routing nodes are numbered from 0 to 5. We consider an edge in the physical topology to represent a pair of fibers, one in each direction

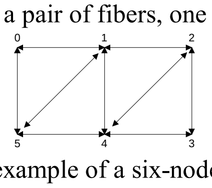

Fig. 1. Illustrative example of a six-node network, physical topology.

The set of all unidirectional lightpaths set up among the access nodes is the virtual topology. For example, Fig. 2 shows a possible virtual interconnection. There is an edge in the virtual topology between node 2 and node 0 when the data or packets from node 2 to node 0 traverse the optical network in the optical domain only, i.e., undergo no electronic conversion in the intermediate wavelength routing nodes. Edges in a virtual topology are called virtual links.

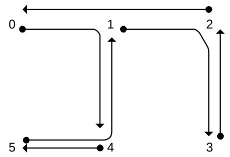

Fig. 2: Virtual topology

For example, in Fig. 2 data from node 2 to node 0 are sent on lightpath l_{20} through the wavelength routing node at 1. Simultaneously, we can send a packet from node 1 to node 3 through the wavelength routing node at 2. We see that even though in the physical topology there is a fiber connection between node 2 and node 4, to send a packet from node 2 to node 4 we would have to use two virtual links l_{20} and l_{04} . We say that the physical *hop length* of virtual link l_{20} is two as it traverses two physical edges, (2,1) and (1,0). On the other hand, the virtual *hop length* of connection (2-4) in the virtual topology is also two, (2,0) and (0,4).

A. *Mathematical Formulation*

We formulate the joint VTD and PTD (same as RWA) problems as an optimization problem. The problem of embedding a desired virtual topology on a given physical topology (fiber network) was formally stated as an **exact linear programming** formulation.

1) *Notation:*

- *i and j* denote *originating* and *terminating* nodes, respectively, in a lightpath.
- *m* and *n* denote endpoints of a physical link that might occur in a lightpath.

2) *Given:*

- Number of nodes in the network: *N*.
- Number of transmitters at node *i*: T_i ($T_i \geq 1$). Number of receiver at node *i*: R_i ($R_i \geq 1$).
- Traffic matrix Λ_{sd}: Which denotes the average rate of traffic flow from *s* to node *d*.
- Capacity of each channel: *C* (normally expressed in bits/second).
- Maximum loading per channel: β, $0<\beta<1$. β restricts the queuing delay on a lightpath from getting unbounded by avoiding excessive link congestion.
- Number of wavelengths available: $\zeta = 1, 2.... W$
- Physical Topology (P_{mn}): Denotes the number of fibers interconnecting node *m* and *n*. $P_{mn} = 0$ for nodes which are note physically adjacent to each other. $P_{mn} = P_{nm}$ indicates that there are equal number of fibers joining two nodes in different directions. Note that there may be more than one fiber link connecting adjacent nodes in the network. $\sum_{mn} P_{mn} = M$ denotes the total number of fiber links in the network.

- Set $C_l(\varsigma)$: Set of the wavelengths into which ς can be converted in node *l*.
- Set $D_l(\varsigma)$: Set of the wavelengths that can be converted to ς in node *l*.

3) Variables:

- Maximum load fiber: *L* is the maximum number of wavelength channels supported per fiber.
- Lightpath: The variable: $b_{ij} = 1$ if there exists a lightpath from node *i* to node *j* in the virtual topology; $b_{ij} = 0$ otherwise. Note that this formulation is general since lightpaths are not necessarily assumed to be bidirectional, i.e., $b_{ij} = 1 \nRightarrow b_{ji} = 1$. Moreover, there may be multiple lightpaths between the same source-destination pair, i.e., $b_{ij} > 1$, for the case when traffic between nodes *i* and *j* is greater than a single lightpath capacity.
- Traffic routing: The variable λ_{ij}^{sd} denotes the amount of traffic flowing from source node *s* to destination node *d* through a virtual link from node *i* to node *j*.
- Physical topology route: The variable p_{mn}^{ij} denotes the number of lightpaths between nodes *i* and *j* being routed though fiber link *m-n*.
- $c_{ij\varsigma}$ = Number of lightpaths between node *i* and node *j* that start in the wavelength ς; for $\varsigma = 1,2,3,...,W$.
- $d_{ij\varsigma}$ = Number of lightpaths between node *i* and node *j* that finish in the wavelength ς; for $\varsigma = 1,2,3,...,W$.
- Wavelength assignment variables: $p_{mn\varsigma}^{ij} = 1$, if a lightpath between node *i* and *j* uses wavelength ζ, and is routed through physical link *m-n*.

4) Virtual Topology Design (VTD)

- Objective:

Minimize: $$\frac{1}{\sum_{sd} \Lambda_{sd}} \sum_{ij} \sum_{sd} \lambda_{ij}^{sd} \quad (1)$$

- Constraints on virtual topology connection matrix:

$$\sum b_{ij} \le T_i, ...\forall_i \quad (2)$$
$$\sum b_{ij} \le R_i, ...\forall_i \quad (3)$$

- Constraints on virtual topology traffic variables:

$$\sum \lambda_{sj}^{sd} = \Lambda_{sd} \quad (4)$$
$$\sum \lambda_{id}^{sd} = \Lambda_{sd} \quad (5)$$
$$\sum \lambda_{ik}^{sd} = \sum \lambda_{kj}^{sd} ....if....k \ne s, d \quad (6)$$
$$0 \le \lambda_{ij}^{sd} \le \Lambda_{sd}.\{1 + \text{sgn}(b_{ij} - 0,5)\}/2 \quad (7)$$
$$\sum \lambda_{ij}^{sd} \le \beta.C.b_{ij} \quad (8)$$

Int b_{ij}

5) Physical Topology Design (PTD)

- 5.1) Routing on physical topology p_{mn}^{ij}:

$$\sum p_{mk}^{ij} = \sum p_{kn}^{ij}, ...if....k \ne i, \quad (9)$$
$$\sum p_{in}^{ij} = b_{ij} \qquad \forall i,j,\zeta \quad (10)$$
$$\sum p_{mj}^{ij} = b_{ij} \qquad \forall i,j,\zeta \quad (11)$$
$$\sum p_{mn}^{ij} \le L.P_{mn} \qquad \forall i,j,\zeta \quad (12)$$

Int p_{mn}^{ij}

- 5.2) On coloring lightpaths:

$$\sum_n p_{in\varsigma}^{ij} = c_{ij\varsigma} \quad (13)$$
$$\sum_m p_{mj\varsigma}^{ij} = d_{ij\varsigma} \quad (14)$$
$$\sum_m p_{ml\varsigma}^{ij} \le \sum_n \sum_{t \in C_l(\varsigma)} p_{lnt}^{ij}, \qquad if\ l \ne i,j \quad (15)$$
$$\sum_n p_{ln\varsigma}^{ij} \le \sum_m \sum_{t \in D_l(\varsigma)} p_{mlt}^{ij} \qquad if\ l \ne i,j \quad (16)$$
$$\sum_\varsigma c_{ij\varsigma} = \sum_\varsigma d_{ij\varsigma} = b_{ij} \quad (17)$$
$$\sum_\varsigma p_{mn\varsigma}^{ij} = p_{mn}^{ij} \quad (18)$$
$$\sum_{ii} p_{mn\varsigma}^{ij} \le P_{mn} \quad (19)$$

Int $p_{mn\varsigma}^{ij}$, $c_{ij\varsigma}$, $d_{ij\varsigma}$.

6) Explanation

In VTD, subsection 4, the objective function (1) minimizes the average packet hop distance in the network, and is a linear constraint. Eqs. (2) and (3) ensure that the number of lightpaths emerging from a node is constrained by the number of transmitters at that node, while the number of lightpaths terminating at a node are constrained by the number of receivers at that node. Eqs. (4)-(6) are multicommodity-flow equations governing the flow of traffic through the virtual topology; (7) ensures that traffic can only flow through an existing lightpath, while (8) specifies the capacity constraint in the formulation.

In PTD, subsection 5.1, (9)-(11) are multicommodity-flow equations governing the routing of lightpaths from source to destination. Eq. (12) ensures that the number of lightpaths flowing through a fiber link does not exceed *L*.

In PTD, subsection 5.2, equations (13) and (14) allow for a lightpath to start in wavelength ς and be finished in another wavelength. Equation (17) guarantees that the number of lightpaths that start in node *i* is equal to the number of lightpaths that finish in node *j*, but not necessarily in the same wavelength.

Constraint (18) guarantees that the number of wavelengths present in each physical link is equal to the number of lightpaths traversing it. In (19) we are assured that there is no wavelength clash at physical link, i.e., no two virtual links traversing through the physical link will be assigned the same wavelength.

Equations (15) and (16) guarantee that a wavelength that arrives in node *l* in color ς can be converted to another wavelength in accordance with definition of the $C_l(\varsigma)$ and $D_l(\varsigma)$ sets. Notice that if no conversion is allowed in node *l*, then $C_l(\varsigma) = D_l(\varsigma) = \{\varsigma\}$, and therefore:

$$\sum_m p_{ml\varsigma}^{ij} \le \sum_n \sum_{t \in C_l(\varsigma)} p_{lnt}^{ij} = \sum_m p_{ml\varsigma}^{ij} \le \sum_n p_{ln\varsigma}^{ij}$$

and

$$\sum_n p^{ij}_{ln\varsigma} \le \sum_m \sum_{t \in D_l(\varsigma)} p^{ij}_{mlt} = \sum_n p^{ij}_{\ln\varsigma} \le \sum_m p^{ij}_{ml\varsigma},$$

which implies that: $\sum_n p^{ij}_{ln\varsigma} = \sum_m p^{ij}_{ml\varsigma}$. This equality expresses a flow conservation of ς-colored paths through node l that is valid when no conversion is allowed.

A) Examples

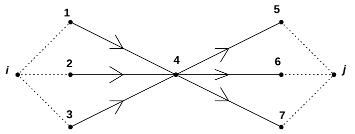

Fig. 3. Optional physical links that they arrive and they leave of node 4 for a lightpath from *i* to *j*.

For the graph above, the conservation of lightpaths from node *i* to node *j* at intermediate node 4 is expressed for the examples to follow:

- *A1)* There is no resource for conversion at 4.

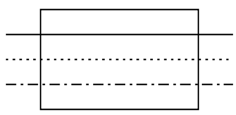

Fig. 4. No conversion for example A1.

- Then, $C_4(\varsigma)=D_4(\varsigma)=\{\varsigma\}$.W=$\varsigma$, for $\varsigma = \varsigma_1, \varsigma_2, \varsigma_3$. Applying (15) and (16), we get to:

$$p^{ij}_{14\varsigma} + p^{ij}_{24\varsigma} + p^{ij}_{34\varsigma} \le p^{ij}_{45\varsigma} + p^{ij}_{46\varsigma} + p^{ij}_{47\varsigma}$$

and

$$p^{ij}_{45\varsigma} + p^{ij}_{46\varsigma} + p^{ij}_{47\varsigma} \le p^{ij}_{14\varsigma} + p^{ij}_{24\varsigma} + p^{ij}_{34\varsigma}$$

$$\Rightarrow p^{ij}_{14\varsigma} + p^{ij}_{24\varsigma} + p^{ij}_{34\varsigma} = p^{ij}_{45\varsigma} + p^{ij}_{46\varsigma} + p^{ij}_{47\varsigma}$$

$$\Rightarrow \sum p^{ij}_{ln\varsigma} = \sum p^{ij}_{ml\varsigma},$$

- *A2)* Now, with conversion fixed at node 4, from $\varsigma_1 \rightarrow \varsigma_2$ and $\varsigma_2 \rightarrow \varsigma_1$, but without conversion for ς_3.

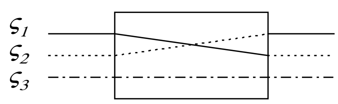

Fig. 5. Types of conversion for example A2.

Then, $C_4(\varsigma_1)=\{\varsigma_2\}$, $D_4(\varsigma_1)=\{\varsigma_2\}$ *and* $C_4(\varsigma_2)=\{\varsigma_1\}$, $D_4(\varsigma_2)=\{\varsigma_1\}$ and $C_4(\varsigma_3)=D_4(\varsigma_3)=\{\varsigma_3\}$. Applying these sets for inequalities (restrictions) 15 and 16, we get to equalities:

$$\Rightarrow p^{ij}_{14\varsigma 1} + p^{ij}_{24\varsigma 1} + p^{ij}_{34\varsigma 1} = p^{ij}_{45\varsigma 2} + p^{ij}_{46\varsigma 2} + p^{ij}_{47\varsigma 2}$$

$$\Rightarrow p^{ij}_{14\varsigma 2} + p^{ij}_{24\varsigma 2} + p^{ij}_{34\varsigma 2} = p^{ij}_{45\varsigma 1} + p^{ij}_{46\varsigma 1} + p^{ij}_{47\varsigma 1}$$

$$\Rightarrow p^{ij}_{14\varsigma 3} + p^{ij}_{24\varsigma 3} + p^{ij}_{34\varsigma 3} = p^{ij}_{45\varsigma 3} + p^{ij}_{46\varsigma 3} + p^{ij}_{47\varsigma 3}$$

- *A3)* Now, with parcial conversion at 4, as illustrated for the figure below.

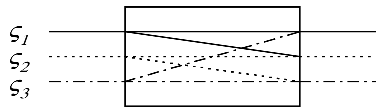

Fig.6. Types of conversion for example A3.

Then, $C_4(\varsigma_1)=\{\varsigma_1,\varsigma_2\}$, $D_4(\varsigma_1)=\{\varsigma_1,\varsigma_3\}$ *and* $C_4(\varsigma_2)=\{\varsigma_2,\varsigma_3\}$, $D_4(\varsigma_2)=\{\varsigma_1,\varsigma_2\}$ *and* $C_4(\varsigma_3)=\{\varsigma_1,\varsigma_3\}$, $D_4(\varsigma_3)=\{\varsigma_2,\varsigma_3\}$. Applying (15) and (16), we get to:

$$\Rightarrow p^{ij}_{14\varsigma 1} + p^{ij}_{24\varsigma 1} + p^{ij}_{34\varsigma 1} = p^{ij}_{45\varsigma 1} + p^{ij}_{46\varsigma 1} + p^{ij}_{47\varsigma 1} + p^{ij}_{45\varsigma 2} + p^{ij}_{46\varsigma 2} + p^{ij}_{47\varsigma 2}$$

$$\Rightarrow p^{ij}_{14\varsigma 2} + p^{ij}_{24\varsigma 2} + p^{ij}_{34\varsigma 2} = p^{ij}_{45\varsigma 2} + p^{ij}_{46\varsigma 2} + p^{ij}_{47\varsigma 2} + p^{ij}_{45\varsigma 3} + p^{ij}_{46\varsigma 3} + p^{ij}_{47\varsigma 3}$$

$$\Rightarrow p^{ij}_{14\varsigma 3} + p^{ij}_{24\varsigma 3} + p^{ij}_{34\varsigma 3} = p^{ij}_{45\varsigma 1} + p^{ij}_{46\varsigma 1} + p^{ij}_{47\varsigma 1} + p^{ij}_{45\varsigma 3} + p^{ij}_{46\varsigma 3} + p^{ij}_{47\varsigma 3}$$

Through the example above we evidence that the definition of the sets $C_l(\zeta)$ and $D_l(\zeta)$ allows for any kind of the conversion in a network: partial, full, sparse, ubiquitous, etc.

III. Approach for Integrated Design

The full problem was decomposed into two subproblems, VTD and RWA. The algorithm below, explained in [1], (Min W) solves the fully integrated problem:

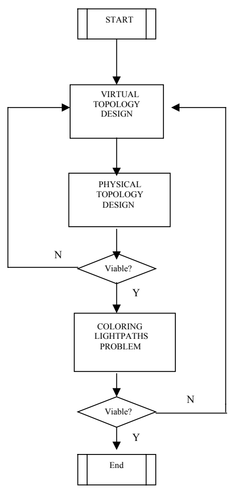

Fig. 7. Heuristic MinW

IV. Simulations

For simulation, we use the described strategy in the previous section of the following way:

1.) VTD: In order to avoid the complexity associated with the mixed-integer-linear programming (MILP) approach whenever appropriate, we have decided to solve the VTD problem using the HVTD heuristic, instead of applying Eqs. (1) to (8) and looking for integer approximations for the b_{ij}`s variables. HVTD is a classic heuristic [7] that attempts to establish attempts to lightpaths between source-destination pairs with the highest Λ_{sd} values, subject to constraints of the virtual degree. The traffic can easily be routed through b_{ij}´s obtained in this step through multicommodity flow Eqs. (1)-(8).

2.) PTD: Solve (9)-(12) with a objective function: Min *L*. *Our objective is to minimize the maximum load needed in any fiber in the network in order to establish a certain set of lightpaths for a given physical topology*. This step yields only a temporary solution, to be validated in the next step.

3.) Coloring: Given *L*, re-optimize (9)-(19) with objective function: Min $\Sigma\, p_{mn}^{ij}$ (number of hops), keeping *L* constant at the minimal value found in the previous step. It is need because maximum fiber load may be oblivious to the persistence of cycles in paths, which may even be dismembered from the source-to-destination link sequence. Re-optimizing the solution using the total number of hops as a new objective function may eliminate these anomalies. Moreover the coloring is carried through. Therefore we add the equations (13)-(19). We assume a certain availability of wavelengths and get the minimum number of wavelengths necessary to color the lightpaths.

A) Multifiber Networks

Multifibers networks are useful when the number of available wavelengths is small and the traffic is high. They are also useful for designing survivable networks. In this work we consider that a multifiber network is one with two links unidirectional fibers (one in each direction) binding two nodes of the network, fig.8 (same fig.1).

Consider the traffic matrix from [1]. Fig. 8 shows the cycles formed for virtual degree "1". This justifies the need for the re-optimization previously proposed in step 3. Moreover the shortest path always is the chosen one, for example b_{34} only needs a physical hop after of the re-optimization. These two factors guarantee a minimum number of physical *hop length* in the network. Therefore, the success of the re-optimization is guaranteed.

In fig. 9, for virtual degree 2, the wavelengths are shown separately as subnetworks for better visualization. For example, there are two parallels lightpaths from node 0 to node 1, implying that b_{011}=1 and b_{012}=1.

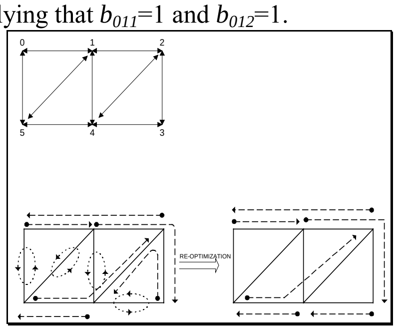

Fig. 8: Re-optimization, for virtual degree "1" . Only a wavelength is necessary.

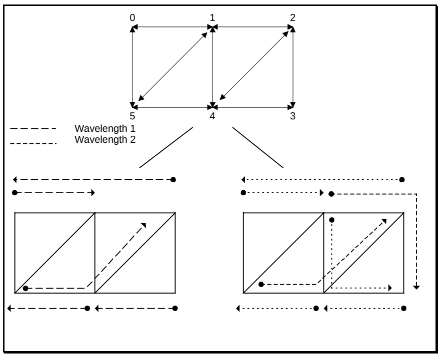

Fig. 9. Virtual degree "2".

B) Unidirectional fiber networks

The efficiency of the conversion of wavelength can better be visualized in a unidirectional network, Fig.10. However, all-optical converters any very expensive.

Therefore, more practical and cost-effective solution is to use only a few converting nodes. In the next simulations (W=3), only node "0", Fig. 10.c, will possess conversion (sparse conversion). We will compare the gotten topologies en relation with the network with no conversion in any node, Fig.10.b.

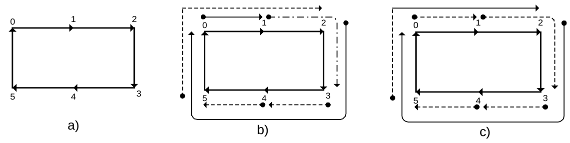

Fig.10. a) Physical Topology, b) Lightpath topology without conversion, c) Lightpath topology with conversion

C) Commentaries

Notice that: 1) Fig.10.b required 3 wavelengths, while 10.c required only 2. That is, without any type of conversion and W=2 the network would suffer blocking. 2) The availability of converters in all nodes is not necessary, but if making the topology will be similar of Fig.10c. That is, the reduction of pool of wavelengths is found with sparse conversion only in one node. 3) In addition to sparse conversion, the converting node could use partial conversion of wavelength instead of total conversion. This would not change the final configuration. 4) It is well know that VTD/PTD problem optimization problem is NP-hard. For large networks, efficient heuristics can be used. Our results had been obtained from a commercial ILP solver, the CPLEX.

V. SOME STATISTICS

For comparasion with [1], we apply Min W, with resources of conversion for the network of fig.1

Table 1 shows that for virtual degree 5 the wavelength pool size decreased with availability of converters, as expected for large virtual degrees.

In table 1 we observe the efficiency of the re-optimization to eliminate the cycles of the network and to find shorter paths for lightpaths, sufficiently decreasing the *physical hop length*. For the topology and matrix of connection that we study the number of hops with conversion in all nodes, it was similar to the number of *hop length* without conversion in no node.

Evidently this number of hops will be able to diminish with conversion of wavelength, since that let us have topologies and matrices of more complex connections.

TABLE* . Some statics

Δ_l	*L*	W_{min} *Without conversion*	W_{min} *With Conversion*	*HL*	*HL/O*
1	1	1	1*	9	18
2	2	2	2	18	27
3	2	2	2	34	34
4	3	3	3	41	51
5	4	5	4	50	72

Legend:

- Δ_l : Virtual degree
- *L*: Maximum fiber load
- W_{min} : Minimum number of wavelengths necessary
- *HL*: *hop length* with the re-optimization
- *HL/O*: *hop length* without the re-optimization

VI. CONCLUSIONS

In this paper we propose an iterative linear programming approach to solve virtual and physical topology design with wavelength conversion resources.

The solution of the VTD problem generates a request for a set of paths to be supplied by the physical topology. Physical paths are then allocated in order to minimize the maximum fiber load. This may be oblivious to the persistence of cycles in paths (in the multifiber networks), which may even be dismembered from the source-to-destination link sequence. These anomalies may be eliminated and the mean *hop length* reduced by re-optimizing the solution using the total number of hops as a new objective function, subject to the minimal value of maximum fiber load that was determined in the previous optimization step. The final design phase is the assignment of wavelengths to paths.

An important new feature of the proposed formulation is that any kind of conversion can be made in each node of the network. This is obtained by the substitution of the traditional conservation of wavelength constraints by the more general constraint formulation of (15) and (16).

These new constraints open new perspectives of works for RWA that use linear programming in topics as reconfiguration, survivability, etc.

The results suggest that it is feasible to approach the VTD and the RWA problems jointly. However, new features must be incorporated in the formulation in order to take into account the resources and limitations of current and future optical networks:

a) networks must scale up in order to serve a scaling traffic. New traffic models must be considered that include a growing traffic demand and at least a dynamic traffic component, and new approaches are required to solve the VTD/RWA problems under this model;
b) as the need for QoS and traffic engineering leads to the aggregation of traffic into LSP's in MPLS networks, there is a need to route LSP traffic into the lightpath topology. Appropriate solutions for LSP routing must then be discussed;
c) as more and more integration between the control planes of optical and IP layers is achieved, appropriate solutions for routing under distributed control must also be discussed.

Appropriate algorithmic solutions are under investigation to support the incorporation of new features in the integrated approach presented in this paper, in order to enable it to deal with these new environments.

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* It is notice that for virtual degree 1, no simulation with conversion is needed, because W=1.