Practical models for design and reconfiguration of virtual topology in optical transport networks

Jovan Stosic[1], Boris Spasenovski[2]

Abstract: **In this paper we deal with reconfiguration of virtual topology. Routing of traffic through virtual and physical topology is investigated. Practical model for minimizing the difference between initial and reconfigured virtual topology is presented. The results show the utilization of the links and augmentation of the number of the lightpaths for two types of networks with different line system and different optical channel capacities.**
Keywords: **WDM, SDH, optimization, reconfiguration, virtual topology**

I. INTRODUCTION

Present optical transport networks are mainly based on SDH (Synchronous Digital Hierarchy), WDM (Wavelength Division Multiplexing) or a combination of these technologies. Today, we are witnessing the appearance of new network operators and expansion of already established operators on new markets. Operators start to develop their business by having in mind two main parameters: intended geographical coverage of the network and expected traffic patterns within the network. By taking in account these input parameters they are trying to find most lucrative solution for encapsulation of required traffic matrix. Two common possibilities could be chosen, ether deploying private network or leasing required telecommunication services from other network operators.

In this paper, we consider the first possibility, i.e. the challenge is construction of cheapest network by knowing the traffic matrix and the geographical coverage. It includes choice of technology (SDH, WDM), type of network nodes (e.g. number of transceivers), capacity of links, encapsulation of best virtual topology in required physical topology, and routing of traffic through chosen virtual topology. For this purpose, two mathematical models are developed: model for design of the virtual topology and routing of lower order traffic, and model for minimal reconfiguration of already deployed virtual topology due to change of traffic pattern. It is assumed that the price would be minimized if number of optical-electrical-optical conversions is minimal. This assumption is complementary with the objective of the models to minimize the average hop distance of lower order traffic that should be routed over the designed virtual topology. Considering that average hop distance is inversely proportional to the network throughput by its minimization more traffic could be accommodated in the future. The model for reconfiguration of the virtual topology takes inputs from previously solved model for virtual topology design. It minimizes both average hop distance of traffic routing through new virtual topology and the difference between old and new virtual topology. Given a relatively small changes of the traffic matrix, we would prefer for the new virtual topology to be largely similar to the previous virtual topology, in terms of the constituent lightpaths and the routes for these lightpaths, i.e. we would prefer to minimize the changes in the number of WRS (Wavelength Routing Switch) configurations needed for adaptation from existing virtual topology to the new virtual topology.

Models are written in MPL (Mathematical Programming Language) and solved by CPLEX 7.1 MIP (Mixed Integer Programming) solver. For successful evaluation of the influence of different network parameters (e.g. node type, link capacities, channel capacities and traffic matrix) to traffic and virtual topology routing, a tool called IOE (Integrated Object Environment) for object modeling of the initial and new network is developed. By using this environment, one can design the network graphical model, introduce all necessary network parameters, control the optimization process, and analyze the obtained results.

II. MODEL FOR MINIMAL RECONFIGURATION OF VIRTUAL TOPOLOGY

The developed models are special in several items compared to the models already described in the literature (e.g. [1]). For example, generated lightpaths and traffic routes are loop-less. Moreover, the greater number of simultaneous lightpaths is allowed between same nodes and these lightpaths are appropriately indexed for straightforward analysis. Proposed reconfiguration model is simple yet very powerful. Objective is minimizing the difference between virtual topology routing in initial and upgraded network.

In the model we use the following decision variables that have to be adapted by means of optimization technique:

$V^{c}_{i,j}$ Binary variable with value *1* if in the virtual topology a lightpath exists between nodes *i* and *j*, otherwise 0. If there are more lightpaths between this pair of nodes they would be indexed by *c*;

$\lambda^{s,d}_{i,j,c}$ Integer variable representing the traffic routing through the virtual topology. It gets value equal to the part of the traffic demand of the *s,d* pair of nodes that is routed through the virtual path $V_{i,j,c}$.

$p1^{i,j,c}_{m,n}$ Binary variable that represents the routing of the reconfigured virtual paths through the physical

[1]Jovan Stosic is with Macedonian Telecommunications, MTcom, Orce Nikolov BB, 1000 Skopje, Macedonia, E-mail: jstosic@mt.net.mk
[2]Boris Spasenovski is with Faculty of Electrical Engineering, University "Ss. Cyril and Methodious", Karpos 2, 1000 Skopje, Macedonia, E-mail: boriss@etf.ukim.edu.mk

topology. It takes value 1 if lightpath $V_{i,j,c}$ is passing through span m,n, otherwise 0.

Following parameters are given from the graphical model or derived from output of previous mathematical model:

- $P_{m,n}$ — Parameter representing the physical topology, i.e. the number of the optical fibers in the span m,n. If between nodes m and n the direct physical link exists then $P_{m,n} > 0$, otherwise $P_{m,n} = 0$. $P_{m,n}$ is also equal to 0 for non-adjacent nodes.
- T_i — Number of optical transmitters in node i ($T_i \geq 1$)
- R_i — Number of optical receivers in node i ($R_i \geq 1$)
- $\Lambda_{s,d}$ — Traffic demand of the s,d traffic pair, expressed as required number of AU-4 trails.
- $W_{m,n}$ — Number of the wavelengths per optical fiber.
- C — Capacity of the optical channel, i.e binary rate. WDM channel capacity could be 1, 4, 16, 64, 256 AU-4 channels, i.e. binary rates of 155 Mb/s, 622Mb/s, 2,4 Gb/s, 10Gb/s, 40Gb/s, respectively.
- $p_{m,n}^{i,j,c}$ — Parameter denoting encapsulation of the initial virtual topology in the physical topology. Its values are taken from the previously solved model for traffic routing through the virtual topology for a given physical topology (elaborated in [5] and [1]).

Indices used in the model are:

- *s,d* — Indices representing the source (*s*) and destination (*d*) of the lower order path (e.g. AU-4 trail)
- *i,j* — Indices designating the origination and termination of the lightpath i.e. high order connection.
- *m,n* — Indices denoting the origination and termination nodes of the physical link (span).
- *node* — Index representing the nodes in the network (node=1,2,…N).
- *k* — Index representing the intermediate nodes in the low and high order connections.
- *c* — If there are more lightpaths between same *i,j* pair this index enumerates them.

The objective function which should be minimized in the reconfiguration model is given with following equation:

$$\text{MIN}\ \frac{1}{\sum_{s,d}\Lambda_{s,d}}\sum_{s,d}\sum_{i,j,c}\lambda_{i,j,c}^{s,d} + \sum_{i,j,c}\sum_{m,n}(p1_{m,n}^{i,j,c} - p_{m,n}^{i,j,c}) \quad (1)$$

As could be observed, besides minimizing the difference between initial and reconfigured virtual topology the objective function minimizes the average hop distance of the low order traffic paths. The objective is linear function considering that $\sum_{s,d}\sum_{i,j,c}\lambda_{i,j,c}^{s,d}$ is a linear sum of the variables, while $\sum_{s,d}\Lambda_{s,d}$ is constant for the given traffic matrix. It would be preferable if large number of $p_{m,n}^{i,j,c}$ variables retain same values in solutions for old and new virtual topology, without compromising the quality of solution. Decision variables are bounded by number of constraints which define the dependence between these variables and the given input parameters.

1) Eqs. (2) through (4) represent constraints relating to the connection of the virtual topology:

$$\sum_{j,c} V_{i,j,c} \leq T_i \quad \forall i \quad (2)$$

$$\sum_{i,c} V_{i,j,c} \leq R_j \quad \forall j \quad (3)$$

$$V_{i,j,c} \in \{0,1\} \quad (4)$$

First two constraints ensure that the number of the lightpaths originating from a node is bounded by the number of node's optical transmitters, while number of lightpats that terminate in a node is bounded by the number of the optical receivers. The $V_{i,j,c}$ variable could receive only binary values. In [1] it is allowed for this variable to receive integer values. This approach is not chosen as suitable in our models due to the specificity of posed network problem. Existence of several virtual paths between same two nodes is possible and in that case they would be indexed by *c*.

2) The constraints that relates to the connection of the physical topology, i.e. routing of the virtual through physical topology are given with Eqs. (5) through (11). They are based on the principle for conservation of flow and resources.

$$\sum_m p1_{m,k}^{i,j,c} = \sum_n p1_{k,n}^{i,j,c} \quad \forall i,j,c,k \quad k \neq i,j \quad (5)$$

$$\sum_n p1_{i,n}^{i,j,c} = V_{i,j,c} \quad \forall i,j,c \quad (6)$$

$$\sum_m p1_{m,j}^{i,j,c} = V_{i,j,c} \quad \forall i,j,c \quad (7)$$

$$\sum_{i,j,c} p1_{m,n}^{i,j,c} \leq W_{m,n}P_{m,n} \quad \forall m,n \quad (8)$$

$$\sum_n p1_{j,n}^{i,j,c} + \sum_m p1_{m,j}^{i,j,c} = 0 \quad \forall i,j,c \quad (9)$$

$$p1_{m,n}^{i,j,c} \in \{0,1\} \quad \forall i,j,c,m,n \quad (10)$$

Eqs. (5) through (7) are based on the theory for multi-commodity flow and they define the routing of the lightpaths from the source to the destination. Eq. (8) assures that the number of lightpaths passing through a given span don't exceed the maximal number of wavelength allocated for that span. By means of experiments using the MPL implementation appearance of cycles (paths that return to the previously traversed nodes) is found especially in *i,j* nodes. Constraint represented with Eq. (9) is used for avoidance of cycles. It states that virtual path $V_{i,j,}$ should not contain span whose origination is *j* nor span whose termination is *i*. It should be noticed that the equations don't follow the wavelength continuity constraint. Therefore the solution obtained from this formulation might require usage of wavelength converters.

The first three constraints might be sublimated in one statement:

$$\sum_{\substack{m \\ IF\ k\neq i,j}} p1_{m,k}^{i,j,c} - \sum_{\substack{n \\ If\ k\neq i,j}} p1_{k,n}^{i,j,c} + \sum_{\substack{n \\ IF\ k=i}} p1_{k,n}^{i,j,c} + \sum_{\substack{m \\ IF\ k=j}} p1_{m,k}^{i,j,c} = \begin{cases} V_{i,j,c}; & k = i,j \\ 0; & k \neq i,j \end{cases} \quad \forall i,j,k,c \quad (11)$$

In the MPL implementation of the model we have used the Eq. (11) instead Eqs. (5) through (7). From the experiments we've discovered that results are accurate only in this case.

3) The constraints that relates to the traffic routing through the virtual topology are given with Eqs. (12) through (17).

$$\sum_{j,c} \lambda_{s,j,c}^{s,d} = \Lambda_{s,d} \quad \forall s,d \tag{12}$$

$$\sum_{i,c} \lambda_{i,d,c}^{s,d} = \Lambda_{s,d} \quad \forall s,d \tag{13}$$

$$\sum_{i,c} \lambda_{i,k,c}^{s,d} = \sum_{j,c} \lambda_{k,j,c}^{s,d} \quad \forall s,d,k \quad k \neq s,d \tag{14}$$

$$\sum_{c} \lambda_{i,j,c}^{s,d} \leq \Lambda_{s,d} \sum_{c} V_{i,j,c} \quad \forall i,j,s,d \tag{15}$$

$$\sum_{s,d} \lambda_{i,j,c}^{s,d} \leq C \cdot V_{i,j,c} \quad \forall i,j,c \tag{16}$$

The Eq. (12) point out that the traffic originating in node s might be split and be routed through different virtual paths, provided that aggregated traffic routed through these virtual paths is equal to the traffic demand of the s,d pair. Similar constraint is applicable for the termination node. Eq. (14) represents the flow conservation principle for the intermediate nodes, and Eq. (15) indicates that traffic might be routed only through the existing lighpaths. Last constraint assures that the traffic passing through lightpath $V_{i,j,c}$ is not larger than optical channel capacity. The constraints given with Eqs. (12) through (14) could be compounded in one statement:

$$\sum_{\substack{i,c \\ IF\ k\neq s,d}} \lambda_{i,k,c}^{s\,d} - \sum_{\substack{j,c \\ IF\ k\neq s,d}} \lambda_{k,j,c}^{s\,d} + \sum_{\substack{j,c \\ IF\ k=s}} \lambda_{k,j,c}^{s\,d} + \sum_{\substack{i,c \\ IF\ k=d}} \lambda_{i,k,c}^{s\,d} = \begin{cases} \Lambda_{s,d} & k = s,d \\ 0 & k \neq s,d \end{cases} \quad \forall s,d,k \tag{17}$$

In the MPL formulation we used this statement and only in that case we obtained accurate results.

4) The constraints for symmetrical routing are given in Eqs. (18) through (20). First equation makes the lighpaths bidirectional, i.e if the lightpath from i to j exists then the lightpath from j to i should also exist. Routing of lighpaths through physical topology should be symmetrical i.e. lightpaths $V_{i,j,c}$ and $V_{j,i,c}$ should pass through same links but in opposite direction. The last constraint imposes symmetrical traffic routing.

$$V_{i,j,c} = V_{j,i,c} \quad \forall i,j,c \tag{18}$$

$$p_{1\,c,m,n}^{i,j} = p_{1\,c,n,m}^{j,i} \quad \forall i,j,c,m,n \tag{19}$$

$$\lambda_{i,j,c}^{s,d} = \lambda_{j,i,c}^{d,s} \quad \forall s,d,i,j,c \tag{20}$$

III. RESULTS

Fig. 1 depicts the network that is studied. We have chosen an arbitrary physical topology. By means of IOO other physical topologies could easily be constructed. Two types of networks are investigated. First type is WDM network with 8 channels per fiber and STM-64 channel capacity (Fig. 1 illustrates such type of network). Second type is WDM network with 32 channels per fiber and STM-16 channel capacity. It would be concluded which of these architectures gives better performance for a given traffic matrix. The augmentation of the number of lightpaths in the new virtual topology would be presented for linear increase of traffic demands. It would also be shown that number of optical-electrical-optical conversions is minimal and most of the traffic is routed in optical domain.

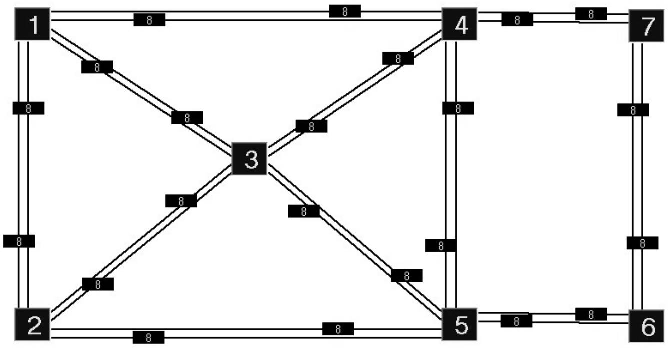

Fig. 1. Evaluated network architecture

For the evaluated network, arbitrary traffic matrix for the initial virtual topology is chosen as shown with Eq. (21). Virtual topology for the initial network has 26 lightpaths for WDM-8/STM-64 and 78 lightpaths for WDM-32/STM-16 design. Corresponding average link utilizations for initial network are 21,4% and 4,9%.

$$T = \begin{bmatrix} 0 & 60 & 77 & 56 & 21 & 0 & 0 \\ 60 & 0 & 28 & 42 & 56 & 7 & 7 \\ 77 & 28 & 0 & 60 & 109 & 0 & 0 \\ 56 & 42 & 60 & 0 & 0 & 0 & 0 \\ 21 & 56 & 109 & 0 & 0 & 0 & 0 \\ 0 & 7 & 0 & 0 & 0 & 0 & 0 \\ 0 & 7 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{21}$$

Fig. 2 shows traffic routing over initial topology and Fig. 3 traffic routing over reconfigured virtual topology with 80% larger traffic demands. There are 10 more lightpaths in the reconfigured network. Lightpaths from the initial virtual topology are retained in the reconfigured one.

	1,2	1,3	1,4	1,5	2,1	2,3	2,4	2,5	2,6	2,7	3,1	3,2	3,4	3,5	4,1	4,2	4,3	5,1	5,2	5,3	6,2	7,2
1,2,3	60																					
1,3,2		64																				
1,3,3		13																				
1,4,1			56																			
1,5,2				21																		
2,1,3					60																	
2,3,3						28																
2,4,3							42															
2,5,2								56														
2,6,1									7													
2,7,1										7												
3,1,2											64											
3,1,3											13											
3,2,3												28										
3,4,1													60									
3,5,1														64								
3,5,2														45								
4,1,1															56							
4,2,3																42						
4,3,1																	60					
5,1,2																		21				
5,2,2																			56			
5,3,1																				64		
5,3,2																				45		
6,2,1																					7	
7,2,1																						7

Fig. 2. Traffic routing through initial virtual topology

Fig. 2 shows that entire traffic is routed in optical domain due to small traffic demands in initial network. In the case depicted on Fig. 3 most of the traffic is optically routed and minimal number of electronic switching is required.

	1,2	1,3	1,4	1,5	2,1	2,3	2,4	2,5	2,6	2,7	3,1	3,2	3,4	3,5	4,1	4,2	4,3	5,1	5,2	5,3	6,2	7,2
1,2,2	64																					
1,2,3	44															10						
1,3,1		64																				
1,3,2		64																				
1,4,1			54				10															
1,4,3		11	47																			
1,5,3				38																		
2,1,2					64																	
2,1,3					44		10															
2,3,2						50	2													4		
2,4,1							64															
2,5,1								64														
2,5,3								37						4								
2,6,3									13													
2,7,3										13												
3,1,1											64											
3,1,2											64											
3,2,2												50		4		2						
3,4,1													64									
3,4,3							2				11		44									
3,5,1														64								
3,5,2														64								
3,5,4														64								
4,1,1															54	10						
4,1,3											11				47							
4,2,1																64						
4,3,1																	64					
4,3,3		11														2	44					
5,1,3																		38				
5,2,1																			64			
5,2,3																			37	4		
5,3,1																				64		
5,3,2																				64		
5,3,4																				64		
6,2,3																					13	
7,2,3																						13

Fig. 3. Traffic routing through reconfigured virtual topology

Fig. 4 depicts the augmentations of the number of lightpaths due to the linear increase of traffic demands for the two types of the considered network. Chart on Fig. 5 depicts average utilization of physical links. We conclude that WDM-8/STM-64 design needs considerably lesser reconfiguration for accommodation of new traffic in the network i.e. it imposes introduction of lesser number of new lightpaths in the network. This is desirable because it incurs fewer changes in WRS configurations.

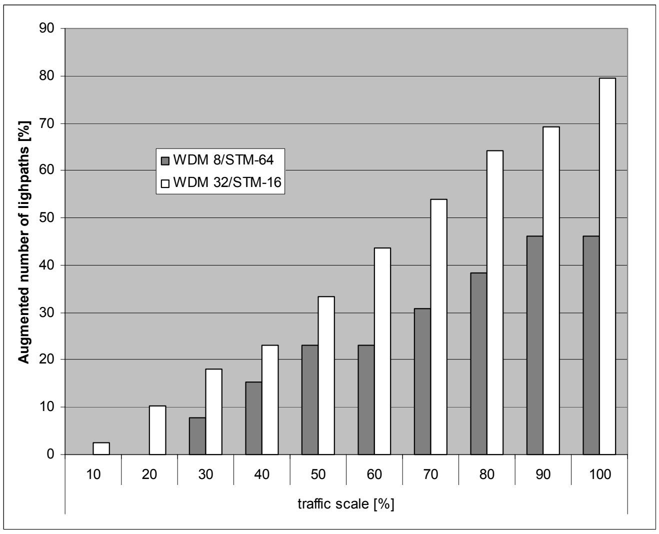

Fig. 4. Augmentation of number of lightpaths due to linear increase of traffic demands.

However, WDM-32/STM-16 design has much lower and uniform utilization of the links. It depends on the operator to assume what would be preferable in future operation of the network. Authors' opinion is that putting a bit more effort in more WRS reconfigurations for WDM-32/STM-16 design is worth of having better utilization and more balanced network, however if time for implementation of new traffic demands is an issue WDM-8/STM-64 is better choice. This choice has to be done before network is going to be implemented, because changing the line system of already implemented network is a challenging task.

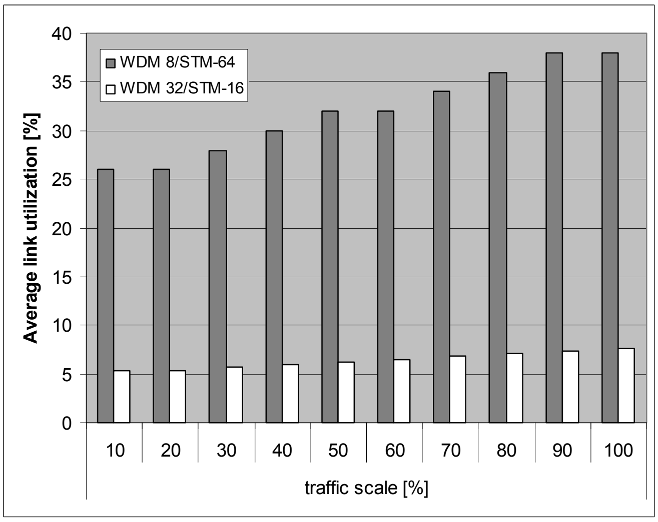

Fig. 5. Average link utilization for linear increase of traffic demands

IV. CONCLUSIONS

In this paper practical model for reconfiguration of virtual topology in SDH/WDM networks was presented. The model minimizes the difference between initial and reconfigured network. Furthermore, under these conditions it minimizes the average hop distance of routed traffic. Results show that most of the traffic is routed in optical domain due to the requirement for minimal average hop distance routing. Also from the results we found that networks with smaller optical channel capacity needs more WRS reconfigurations but it is worth using them for having better link utilization and more balanced network.

REFERENCES

[1] Biswanath Mukherjee, "Optical Communication Network", *McGraw-Hill*, 1997

[2] Biswanath Mukherjee, Dhritiman Banerjee, S. Ramamurthy, and Amarnath Mukherjee, "Some Principles for Designing a Wide-Area WDM Optical Network", *IEEE/ACM Transactions On Networking*, vol 1. No. *5.* October 1996

[3] Keyao Zhy and Biswanath Mukherjee, "Traffic grooming in an optical WDM mesh network", *Proc. IEEE ICC, 2001*, pp. 721 - 725, June 2001

[4] O. Gerstel, P. Lin, and G. Sasaki, "Combined WDM and SONET network design," *Proc. IEEE INFOCOM, 1999*, pp. 734 - 743, March 1999.

[5] Jovan Stosic, "Modeling, planning and optimization of survivable WDM networks"- Masters thesis, *Faculty of Electrical Engineering, University "Ss. Cyril and Methodious", Skopje, Macedonia*, November 2002