IVTD - Iterative Virtual Topology Design to Maximize the Traffic Scaling in WDM Networks

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Abstract *– We propose an iterative algorithm for the Virtual Topology Design (VTD) in optical networks. The algorithm eliminates lighter traffic lightpaths and rearranges the traffic through the remaining lightpaths. This tries to preserve the open capacity for the accommodation of future unknown demands. The results suggest that it is feasible to preserve enough open capacity to avoid blocking of future requests in networks with scarce resources, this is, maximize the traffic scaling.*

1. Introduction

The evolution of optical networks is driven by traffic growth, which is sustained by the emergence of new applications and the engagement of new users. This process is now well established, leading to an expectation of steady growth in the coming years.

Data traffic is going to overcome traditional telephone traffic in volume. Statistical modeling of network load has to be modified to describe a new reality with less regular flows, more and more independent from geographical distances [Barbado and Maier, 2003]. The change is also reflected by the evolution of WDM protocol standardization. The simple static Optical Transport Network (OTN) is already well-defined by the main standard bodies, while the new model known as Automatic Switched Optical Network (ASON) is currently under development [ITU-T, 2001], [ITU-T, 1990]. Its main feature is the ability to accommodate on-line connection requests issued to the network operating system, which is responsible of the activation of new lightpaths in real time [Barbado and Maier, 2003], [Gencata and Mukherjee, 2002].

It is however likely that the evolution from OTN to ASON is going to happen as a gradual process in order to preserve the investments of the network operators. In this transition phase static and dynamic traffic will co-exist and share the same WDM network infrastructure [Barbado and Maier, 2003], [Ozdalgar and Bertsekas, 2003].

In general, the network design problem in static phase 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 sub-problems [Ramaswami and Sivarajan, 1996].

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 routing–and-wavelength assignment (RWA) for these lightpaths at the physical layer. The routing of packet traffic on the lightpaths 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.

Ideally in a network with N nodes, we would like to set up lightpaths between all the $N.(N-1)$ pairs. However this is usually not possible because of two reasons. First, the number of wavelengths available imposes a limit on how many lightpaths can be set up. (This is also a function of the traffic distribution). Second, each node can be source and sink of only a limited number of lightpaths. This is determined by the amount of optical hardware that can be provided (transmitters and receivers) and by the amount of information the node can handle in total [Ramaswami and Sivarajan, 1996].

The goals in the research of the virtual topology design include maximizing the single-hop traffic [Zhang and Acampora, 1995], minimizing the number of wavelengths required [Waters and Demester, 1995] or minimizing the maximum load in a lightpath [Ramaswami and Sivarajan, 1996]. A review can be found in [Dutta and Rouskas, 1999]. This paper studies a particular situation in which the new on-line connection requests are generated as an expansion of the original static traffic. The key point is the iterative formulation of the well-known VTD problem for the elimination of the least congested lightpaths λ_{min} in the virtual topology, allowing a degradation of the objective function in VTD until one predefined bound C. In other words, we have used an iterative (modified) VTD algorithm to configure the lightpaths, which is oriented towards preservation of open capacity for the accommodation of future unknown demands [Kodialam and Laksshman, 2004], [Assis *et al*, 2004].

The maximum congestion λ_{max} determines the viability of the solution in iterative routing VTD. If after eliminating the lightpath with traffic λ_{min} and re-arranging the traffic through the remaining lightpaths the λ_{max} is still supported by the system, i.e., $\lambda_{max} < C$, then the solution is feasible. Whenever this happens, the rollback to the routing problem of the virtual topology asks for the next best solution, thus implying objective function degradation. Our work is inspired in the papers [Barbado and Maier, 2003] and [Assis and Waldman, 2004]. However, [Barbado and Maier, 2003] compares several algorithms in dynamic phase for maximize the traffic scaling while [Assis and Waldman, 2004] compares Linear Programming techniques in static phase. In this paper, we investigate the traffic scaling behavior for two cases of Virtual Topology Design: 1) the traditional VTD and 2) the Iterative VTD.

Section 2 describes in detail the VTD and its main variables. In Section 3 we show the iterative VTD proposed and simulations for a small network. Section 4 shows simulations for a hypothetical large network over Brazilian territory and in Section 5 we finish the paper with some conclusions.

2. Static Problem Statement

It is well known there are two topologies associated with such WDM optical networks. They are: 1) Physical topology, determined by set of physical links, and 2) Virtual topology, determined by set of lightpaths or logical links.

2.1. Physical Topology

A physical topology (G_p) is a graph representing the physical interconnection of the wavelength routing nodes by means of fiber-optic cables. Fig. 1 shows a physical topology 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.

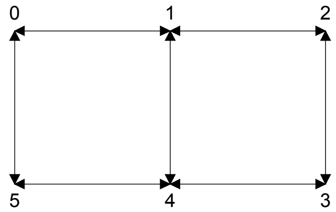

Figure 1. Illustrative example of a six-node network, physical topology.

2.2. Virtual Topology

Let $T = (\lambda^{sd})$ be the traffic matrix, i.e., λ^{sd} is the arrival rate of packets (or Gb/s) at s that are destined for d. We try to create a virtual topology G_v and route the given traffic in this G_v minimizing $\lambda_{max} = \max_{ij}\lambda_{ij}$ where λ_{ij} denotes the offered load on link (i,j) of the virtual topology. λ_{max} is the maximum offered load to a virtual link and is called the *congestion*. Let G_p be the given physical topology of the network , Δ the degree of the virtual topology (number of transceivers) , and W the number of wavelengths available. An informal description of the virtual topology design problem is as follow (a precise definition as a mixed-integer linear program (MILP) is given in [Ramaswami and Sivarajan, 1996]):

$$\text{Min } \lambda_{max}$$

Such that:

- Each virtual link in G_v corresponds to a lightpath and two lightpaths that share an edge in the physical topology are assigned different wavelengths.
- The total number of wavelengths used is at most W.
- Every node in G_v has Δ incoming edges and Δ outgoing edges.
- Traffic is routed so that flow of traffic from each source-destination pair is conserved at each node.

Note that the topology design problem includes routing as a sub-problem.

The set of all unidirectional lightpaths set up among the access nodes is the virtual topology G_v or lightpath topology. For example, Fig. 2 shows a possible virtual interconnection with $\Delta=1$, in which arrows are bent so as to show their physical routing. Notice, however, that physical routing of the lightpaths is actually not visible in the virtual or lightpath topology. 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, and are defined only by their source and destination nodes (i.e., they are shapeless, or straight, arrows, unlike in Fig. 2). Note that to send a packet from node 2 to node 4 we would have to use two virtual links (or lightpaths) *2-0* and *0-4*. The logical connection would then use two virtual hops.

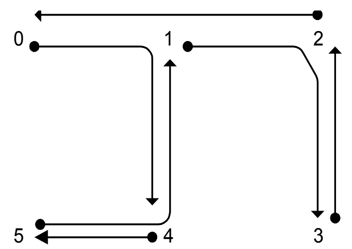

Figure 2. Virtual topology (G_v)

Note that several virtual topologies can be implemented on a physical topology and that not all virtual topologies are supported by a given physical topology. Moreover, the number of transceivers Δ in a network depends only on the virtual topology, whereas other system parameters like performance, number of wavelengths, etc., depend on how the lightpaths are implemented on the physical topology.

3. Iterative Virtual Topology Design (IVTD)

In this section we propose a *loose topology*, i.e. a multi-client physical topology that must accommodate both a static and a dynamic traffic demands. An iterative formulation of the well-known VTD problem is used for the elimination of the least congested lightpaths, i.e., with traffic λ_{min} in the virtual topology, allowing a degradation of the objective function in VTD until one predefined bound *C*. After, all available wavelengths may be used to solve the static RWA problem. The wavelengths are then re-used to set up lightpaths adaptively to dynamic traffic demands by dynamic RWA. Blocking probability of dynamic path requests is to be minimized while allowing a degradation of the objective function in the static traffic demand. The objective function degradation in VTD until system supported capacity orients towards preservation of open capacity for the accommodation of future unknown demands.

3.1. Heuristic Algorithm for Iterative VTD *(IVTD)*

Here we present a heuristic algorithm based on VTD design. Note that our algorithm (from the **step 1** to the **step 6**) prescribes only an iterative virtual topology. It does not describe how the virtual topology is realized on the physical network.

Step 1: Given a static traffic matrix and the system capacity *C*, find the virtual links (original G_v);

Step 2: Route the given static traffic on the virtual links and find λ_{max};

Step 3: (If $\lambda_{max} \geq C$ and it is the first iteration, then stop. Or if $\lambda_{max} \geq C$ and any virtual links has already been removed, go to step 6). Else continue;

Step 4: Remove the least congested virtual link (λ_{min});

Step 5: If all nodes remain virtually connected, return to the step 2. If any node becomes disconnected, continue.

Step 6: Re-add the last removed virtual link, so that the last network state is recovered, and continue;

Step 7: Solve the RWA problem.

3. 2. Example

We solve the above heuristic for the 6-node network shown in figure 1, for a Δ=2 with linear programming, using the routine CPLEX in static phase The traffic matrix used is shown in table I and is the same as in [Ramaswami and Sivarajan, 1996].

With *C*=5 Gb/s, there are 5 possible virtual topologies {(a),(b),(c),(d) and (e)}. The table (a) is the original virtual topology (fig.3a) with λ_{max} =2,04 and λ_{min}=1,4 in virtual link 5-0. The table (e) is optimized topology (fig.3b) with λ_{max} =4,96 and λ_{min} =2,28. Note that table (f) is not a viable topology, because virtual link 0-4 would have λ_{max} =7,04 and the system capacity is 5, besides one more elimination would lead to a node disconnection. After, the static RWA problem was solved for original and optimized topologies with shortest path routing.

Table 1. Traffic matrix for 6-node network, [Ramaswami and Sivarajan, 1996]

-	0,537	0,524	0,710	0,803	0,974
0,391	-	0,203	0,234	0,141	0,831
0,06	0,453	-	0,645	0,204	0,106
0,508	0,660	0,494	-	0,426	0,682
0,480	0,174	0,522	0,879	-	0,241
0,950	0,406	0,175	0,656	0,193	-

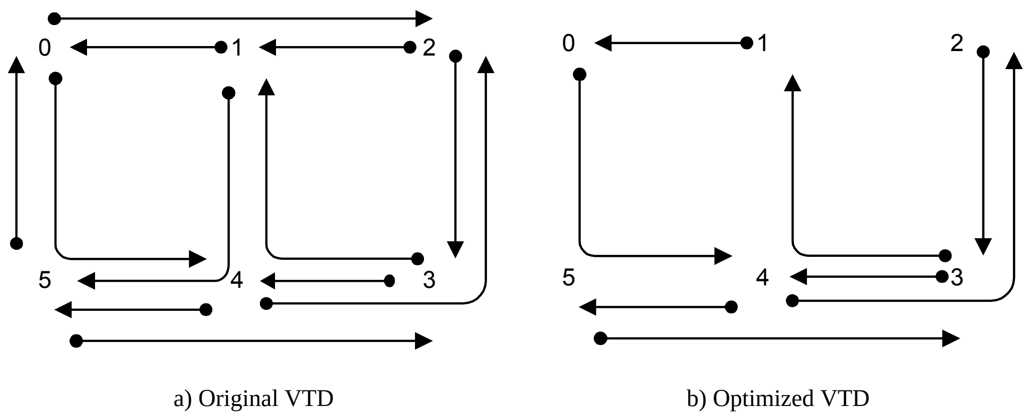

Figure 3. a) original virtual topology and b) optimized virtual topology with IVTD.

-		2,04		2,04	
1,53	-				1,85
	1,77	-	1,87		
	2,04		-	1,51	
		2,04		-	2,04
1,4			2,04		-

(a) Original Topology

-		2,07		1,78	
2,69	-				**1,38**
	1,81	-	2,5		
	2,69		-	2,15	
		2,69		-	1,76
			2,69		-

(b) 1 lightpath eliminated

-		2,35		2,61	
3,8	-				
	1,94	-	3,79		
	2,32		-	3,8	
		3,8		-	3,14
			2,68		-

(c) 2 lightpaths eliminated

-		**1,44**		3,52	
3,79	-				
		-	4,23		
	4,23		-	3,1	
		3,2		-	3,9
			3,4		-

(d) 3 lightpaths eliminated

-				4,96	
3,8	-				
		-	3,4		
	4,2		-	**2,28**	
		3,88		-	3,89
			3,43		-

(e) Optimized Topology

				7,24	
6,08					
			4,48		
	6,5				
		4,9			2,8
			2,4		

(f) Inviable Topology

Figure 4. Tables (Iterative VTD)

3.3. Traffic Scaling

In the second phase the network with all static lightpaths pairs set up is fed to a discrete-event simulator, whose basic event is the provisioning of a connection in the network keeping the current resources occupancy state into account at the arrival of a new request. It should be noted that for the purpose of this work the time instant of arrival of a new request does not matter, since all the connections are supposed to be permanent (There are no death events). The only relevant aspect is the sequence of the requests. To simulate a homogeneous procedure a couple of source and destination nodes are randomly and uniformly chosen among all the couple of nodes having a static traffic relation. One new connection is requested for that couple. If available resources are not sufficient to satisfy the request, then it is blocked and lost forever. If instead resources are sufficient, the connection is set up by allocating the WDM channel for an indefinite time. Then, independently of the result of the previous allocation, a new couple is chosen and another request is issued, and so on.

As more and more extra lightpaths are set up in the simulation, resources for the new connections continue to decrease, as no reconfiguration of already active extra lightpaths is admitted.

The chance of being able to accept a new connection is measured by the blocking probability parameter P. At a given simulation event, P is defined as the ratio between the number of unsuccessful events (requests which could not have been satisfied) and the total number of events occurred so far. At the beginning of the traffic-growth phase a threshold value *P* is given to the simulator. The simulation is stopped when *P* reaches the pre-fixed threshold value of blocking probability. For example, a threshold value *P*=0 implies that the simulation is stopped at the first connection refusal. At the end of the simulation the scaling factor is defined as the ratio between the number of extra connection requests accepted during the traffic-growth phase and the total number of static connection in the network. Therefore, the next step for heuristic proposed is:

Step 8: Find the Traffic Scaling for a future dynamic traffic.

3.3. Routing and Wavelength Assignment

One particular aim of this work is to compare the effectiveness of VTD and IVTD strategy in terms of maximum scaling obtained in the traffic-growth phase, given a threshold on the average blocking probability. However, it is important to use a good RWA algorithm. This consists in the identification of the route (sequence of links) from the source to the destination and in the selection of a WDM channel.

Several first-fit algorithms have been studied and compared in the literature [Ramaswami and Sivarajan, 1998, Chap. 8]. The simplest one uses an *a priori* wavelength list: the algorithm will then look up the list and pick the first wavelength under which the path can be accommodate. This will be called the *fixed priority algorithm* (FP). Other algorithms favor the use of the wavelength that is being most used in the network at assignment time.

A good performance has been observed with the MaxSum (MS) algorithm, which chooses the wavelength which minimizes the number of routes that will become blocked with the wavelength assignment.

Combining the decision rules of MS with route allocation algorithms leads to a JRW (*Joint Routing and Wavelength Assignment*) algorithm; hence in this case the algorithm must compare, according to some criterion, all the *route-wavelength* pairs.

In this paper, for dynamic environments, JRW algorithms were used in which a shortest path route is always chosen, i.e., JRW_SP.

4. L arge Optical Networks

A moderately large network, the 12-node hypothetical Brazilian network of Fig. 5 was considered. Each node corresponds to one of 12 states in Brazil, chosen for their economic regional importance, with 4 transceptors per node. In phase I a certain virtual degree Δ=2 (bold lines) is initially assigned for the static configuration and *R*=2 (dotted lines) is the remaining virtual degree could be used for a dynamic traffic. However with IVTD the number of transceivers remaining *R* grows, therefore we expect the open capacity of the network grows too.

4.1 Simulations

We studied the IVTD procedure with *W*=2 wavelengths and *W*= 4, 8 and 16 wavelengths. Using the proposed algorithm with traffic matrix from [10] (shown in table II), and system capacity C=10Gb/s, there are 7 possible virtual topologies, the original with λ_{max} =6,5 (VTD) and the last (optimized) with λ_{max} =9,955 (IVTD).

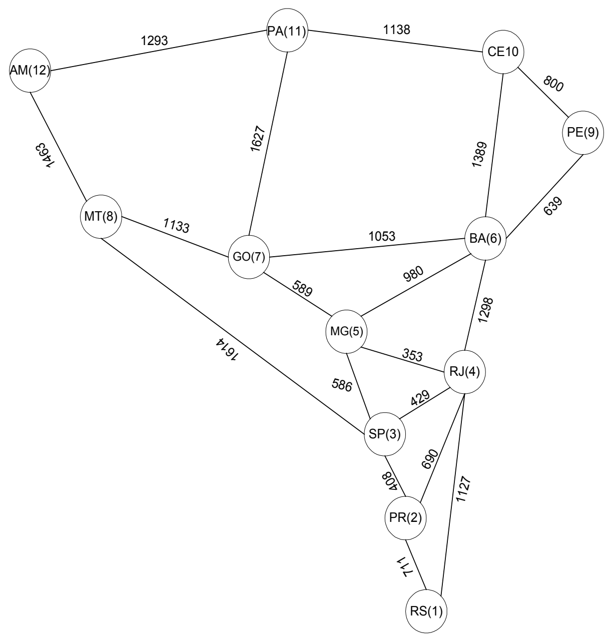

Figure. 5. Brazilian Hypothetical Network

Table II: Matrix Traffic for Brazilian Network (Gb/s)

.	0.37	1.00	0.39	0.32	0.08	0.08	0.03	0.02	0.03	0.01	0.04
0.37	.	2.56	0.60	0.51	0.11	0.09	0.04	0.03	0.04	0.01	0.03
1.00	2.56	.	4.08	3.72	0.65	0.36	0.16	0.12	0.16	0.05	0.14
0.39	0.60	4.08	.	2.42	0.22	0.22	0.07	0.05	0.06	0.02	0.04
0.32	0.51	3.72	2.42	.	0.54	0.35	0.12	0.10	0.08	0.04	0.08
0.08	0.11	0.65	0.22	0.54	.	0.10	0.04	0.03	0.03	0.02	0.03
0.08	0.09	0.36	0.22	0.35	0.10	.	0.10	0.04	0.04	0.01	0.01
0.03	0.04	0.16	0.07	0.12	0.04	0.10	.	0.04	0.02	0.01	0.01
0.02	0.03	0.12	0.05	0.10	0.03	0.04	0.04	.	0.04	0.01	0.01
0.03	0.04	0.16	0.06	0.08	0.03	0.04	0.02	0.04	.	0.02	0.01
0.01	0.01	0.05	0.02	0.04	0.02	0.01	0.01	0.01	0.02	.	0.01
0.04	0.03	0.14	0.04	0.08	0.03	0.01	0.01	0.01	0.01	0.01	.;

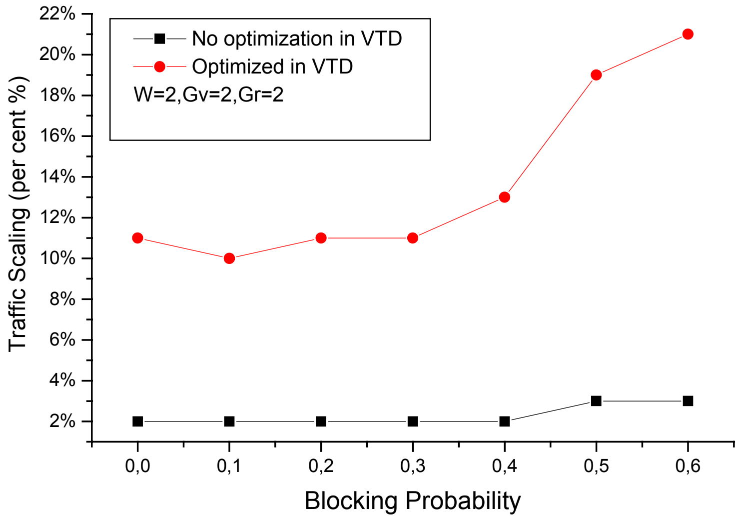

Figure 6. Traffic Scaling without optimization and with optimization (IVTD), for *W*=2.

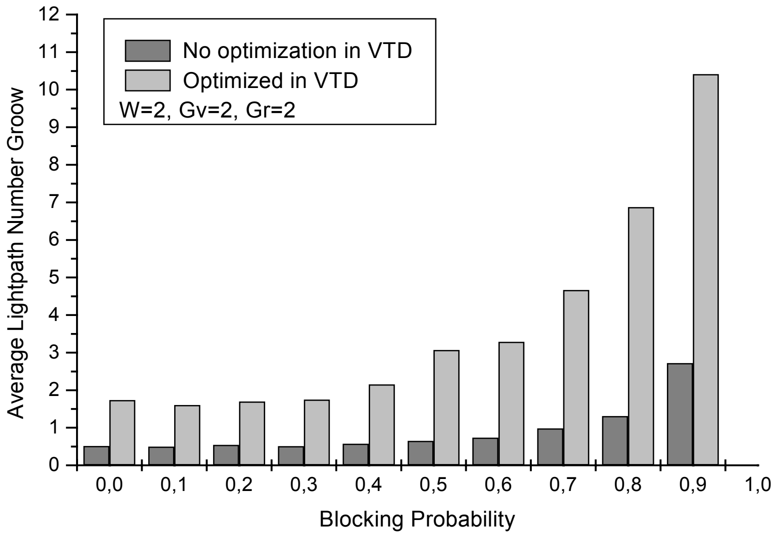

Figure 7. Average Lightpath Number

In Fig. 6, note that for *W*=2 and *R*=2 the best topology in relation to the open capacity is the optimized with IVTD, e.g,. for P=0.1 the traffic scaling is 10%, while the traditional VTD is 2%. Figures 7 show the average number of lightpaths that can be added using the strategy proposal. Clearly, we see that the performance of IVTD is better that traditional VTD.

However, if we increase the number of available wavelengths in the network to *W*=3 (Fig.8) the scaling grows, but it is the upper bound, because the limitations is the number of transceivers. Therefore the traffic expansion will be the same for the 4, 8 and 16 wavelengths cases. So, there is a saturation curve, showing that there is almost no gain in adding additional wavelengths in the network after a certain number have already been deployed. This suggests that IVTD is required if the system has scarce resources (for example, only a few wavelengths). Figure 9 show the average number of lightpaths that can be added using the strategy proposal. Clearly, we see that the performance of IVTD is better that traditional VTD.

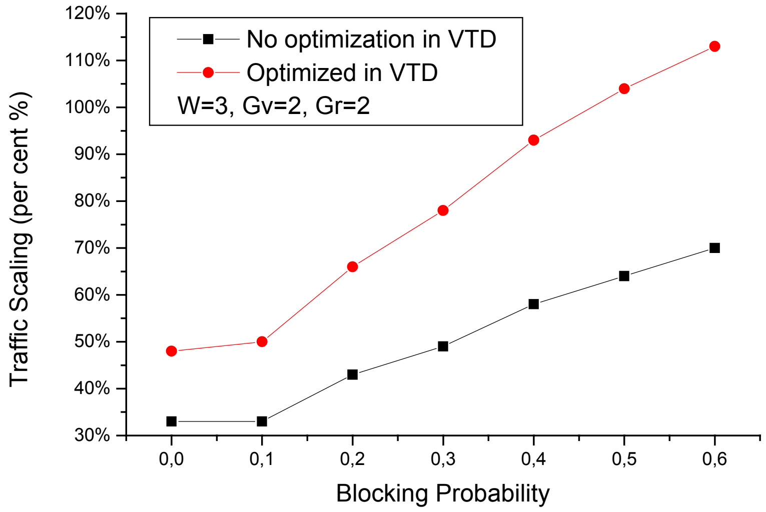

Figure 8. Traffic Scaling without optimization and with optimization (IVTD), for *W*=3.

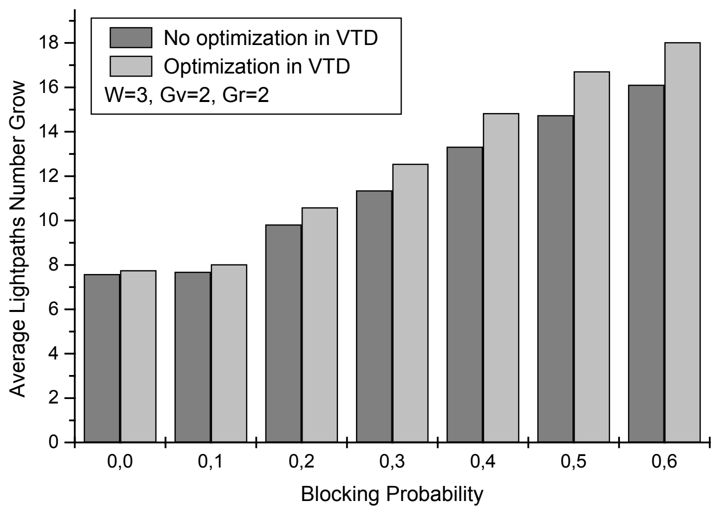

Figure 9. Average Lightpath Number

4.2 Some comments

Integer Linear Programming models are popular in the literature as they provide formal descriptions of the problem. In practice, however, scalability to networks with at least 10´s of nodes, with 100´s of demands is required. In many cases all but trivial instances of theses ILP´s are computationally difficult with current state-of-the-art software. The complexity of our formulation grows as demonstrated in [Ramaswami and Sivarajan, 1996]. For the first iteration (to find VTD) in our 6-node mesh network, on average our strategy run be the optimization software CPLEX© took around 20 seconds on an Intel Pentium IV/1.6Ghz.

5. Conclusions

The computational experiments clearly show that our algorithm does give good solutions to maximize the traffic scaling. Besides, the paper shows that careful aggregation of low speed traffic streams on to lightpaths in VTD can decrease the number of the transceivers (cost) used in the network planning. This reduction in cost, compared to the cost of obvious solutions, can be substantial in large networks. 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) wavelength conversion may be available in many nodes, either all-optically or through some OEO processing;

b) new traffic models must be considered and new approaches are required to solve the VTD/RWA problems under this perspective.

c) 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;

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

Acknowledgment

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