Linear Formulation to Avoid Adjacent Channel Interference in LTD of Optical Networks

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ABSTRACT

A strategy is implemented for solving the Logical Topology Design (LTD) based on a Linear Formulation (LP) with channel interference constraints. The formulation is able to provide excellent solutions. In traditional LTD Problem there is no a-priori knowledge of channel use and once the solution has been implemented the interference cannot be avoided. Taking into consideration the effects of adjacent channel interference, we extend the traditional formulation as a set of analytical formulas as additional constraints on LTD.

Keywords: Optical Networks, Virtual Topology Design, Logical Topology Design, Channel Interference

1. INTRODUCTION

Many papers have already addressed the Logical Topology Design (LTD) problem alone or the Virtual Topology Design (VTD) and Routing and Wavelength Assignment RWA (RWA) problems together. Many mathematical formulation and heuristic method under different assumption and traffic standards were proposed. See the surveys of Dutta and Rouskas [1] and Zang, Jue and Mukherjee [2] for a summary of the works until 2000. The most studied aims are: the minimization of congestion and the reduction of electronic processing, in relation to the RWA, the reduction of wavelengths (called min-RWA) and the maximization of connections which can be established (called max-RWA).

However, in WDM transparent networks, the quality of the signal degrades subject to physical impairments. For example, channel interference depends on the use of adjacent channels along the lightpath [3]. Moreover, the effects of other impairments, such as XPM Cross-Phase Modulation and FWM four-wave mixing, are highly dependant on the use of adjacent channels or channels next to adjacent. Therefore, avoiding adjacent channel interference is a key issue in efficiently designing transparent WDM networks.

In [3] presents an interference limitation algorithm for dynamic RWA and [4] presents another interference limitation algorithm for static RWA. The first algorithm is based on the enumeration of interference introduced by sources over the lightpath, considering that the virtual topology (established light paths) is known. The second algorithm is based on a linear formulation programming subject to a static traffic requirement. Other approaches, such as [5], try to avoid four waves mixing and cross phase modulation.

In this work, we propose a new optimization LP – complete formulation to block channel interference in links of optical fiber. To the best of our belief, the first linear formulation of a partial solution to the RWA problem avoiding the use of adjacent channels has been stated in [4], where constraints are created using path formulation, where all possible paths are known beforehand. In this work, we propose a link formulation. Therefore, we do not know beforehand the set of alternative routes for any node pair. With all possible routes, the linear formulation that we propose can find effective results to avoid channel interference. Furthermore, our formulation is to the full logical topology design, similar to [6]. We observe the effect of physical impairments in a higher layer, i.e, in virtual topology configuration.

2. TRADITIONAL LOGICAL TOPOLOGY DESIGN

Although lightpaths underlie SDH networks in a natural way, cell- and packet-switching client networks, like ATM and IP, would be better served by more packet-oriented WDM layer mechanisms and protocols. However, current optical

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packet-switching technologies do not yet deliver the same performance that is possible in electronic networks. For this reason, lightpath provision is still the best available service the optical layer can offer today to its client layers, including those which would probably benefit from optical packet switching, such as IP.

As IP becomes the dominant client in most environments, the integration between the control planes of the client (IP) and server (optical) layers becomes attractive, generating the so called peer-to-peer framework. In this framework, the VTD and RWA problems would be solved by the same entity (the IP router), so there is no need to separate them anymore.

A physical topology is a graph representing the physical interconnection of the wavelength routing nodes through fiber-optic cables. Figure 1 shows a physical topology of a six-node wide-area network. The wavelength routing nodes are numbered from 1 to 6. We consider an edge in the physical topology to represent a pair of fibers, one in each direction.

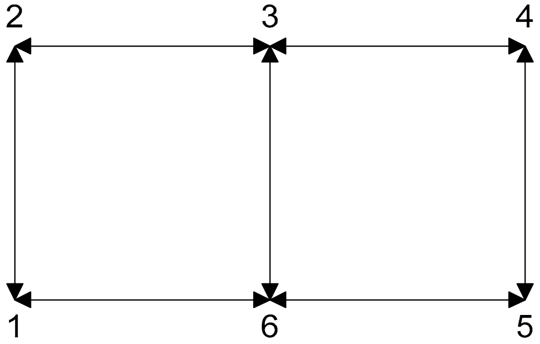


Figure 1. Illustrative example of a six-node network, physical topology.

The set of all unidirectional lightpaths set up among the access nodes is the virtual topology or lightpath topology. For example, Figure 2 shows a possible virtual interconnection in which arrows are bent in order to show their physical routing. Note, 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 4 and node 2 when the data or packets from node 4 to node 2 cross the optical network in the optical domain only, i.e., there is 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 Figure 2).

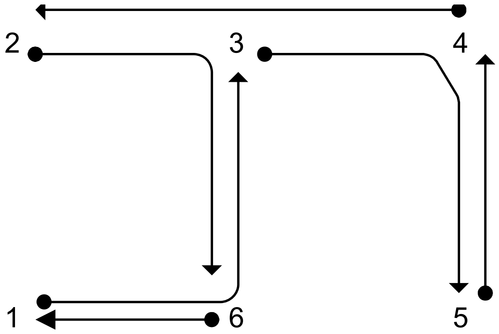


Figure 2. Virtual topology

The virtual topology may be specified by the integer variables b_{ij}, $i = 1, 2, \ldots, N$; $j = 1, 2, \ldots, N$, where N is the number of nodes. We define $b_{ij} = 1$ if there is a virtual link (i.e. a lightpath) from node i to node j; otherwise $b_{ij} = 0$. For example, in Figure 2 data from node 4 to node 2 are sent on a single lightpath through the wavelength routing node at 1; thus $b_{42} = 1$. Simultaneously, we can send a packet from node 2 to node 6 through the wavelength routing node at 3. We see that even though in the physical topology there is a fiber connection between node 4 and node 6, to send a packet from node 4 to node 6 we would have to use two virtual links (or lightpaths) *4-2* and *2-6*. The logical connection would then use two hops. In the same way, we say that *hop length* of virtual link b_{42} is two, as it crosses two physical edges, (4,3) and (3,2), in the physical path topology. See [2] for a detailed explanation of this type of 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 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 [7] because of its limited port count, as most of its cost is usually associated with its ports.

3. FORMULATION OF THE PROBLEM

We formulate the joint VTD and 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.

A) Notation:

- *i and j* are the starting node and the ending node, respectively, in a lightpath.
- *m* and *n* denote of a physical links from m to n in which it is possible to have one or more lightpath.

B) 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 ($R_i \geq 1$). In this work, $\Delta = T_i = R_j$ is the virtual degree.
- Traffic matrix $\Lambda = (\lambda^{sd})$: Which denotes the average rate of traffic flow from *s* to node *d*.
- Each fiber is able to support *W* distinct wavelengths, where ς.=1,2....*W*.
- Physical Topology (P_{mn}): Denotes the number of fibers interconnecting node *m* and *n*. $P_{mn} = 0$ for nodes which are not physically adjacent to each other. $P_{mn} = P_{nm}$ indicates that there are equal number of fibers joining two nodes in different directions.

C) Variables:

- Lightpath: The variable: $b_{ij} = 1$ if there is 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., $b_{ij} = 1 \nRightarrow b_{ji} = 1$. In this work $b_{ij} \in \{0,1\}$.
- Traffic routing: The variable λ_{ij}^{sd} denotes the amount of traffic flowing from node *s* to node *d* and employing b_{ij} as an intermediate virtual link.
- Physical topology route: The variable p_{mn}^{ij} denotes the lightpaths between nodes *i* and *j* being routed though fiber link *m-n*.
- $b_{ij\varsigma} = 1$, if a logical link between node *i* and node *j* uses wavelength ς.
- Wavelength assignment variables: $p_{mn\varsigma}^{ij} = 1$, if the lightpath between node *i* and *j* uses wavelength ς, and is routed through physical link *m-n*.

3.1 Logical Topology

Let $\Lambda = (\lambda^{sd})$ be the traffic matrix, i.e., λ^{sd} is the arrival rate of packets (or Gb/s) from node *s* to node *d*. We try to create a virtual topology G_v and route the given traffic in G_v minimizing $\lambda_{max} = \max_{ij} \lambda_{ij}$, where λ_{ij} denotes the offered load on link (*i,j*) on the virtual topology. λ_{max} is the maximum load offered to a virtual link b_{ij} and is called the *congestion*. Let G_p be the given physical topology of the network, $\Delta=T_i=R_j$ the degree of the virtual topology (number of transceivers at each node), and W the number of wavelengths available. An informal description of the virtual topology design problem is as follows (a precise definition as a mixed-integer linear program (MILP) is given in [7]):

$$\min \lambda_{\max} \tag{1}$$

Such that:

- Each *virtual* link b_{ij} 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 at each fiber 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.

3.2 Routing and wavelength Assignment

Adding the routing and wavelength assignment constraints in the formulation above (from [7]) the objective from equation (1) guarantees the routing and wavelength assignment to the lightapth b_{ij} to be set up. We add to the formulation the following constraints:

- Routing on physical topology p^{ij}_{mn} :

$$\sum_m p^{ij}_{mk} = \sum_n p^{ij}_{kn} \quad \textit{if} \quad k \neq i, j \tag{2}$$

$$\sum_n p^{ij}_{in} = b_{ij} \quad \textit{for all } i, j \tag{3}$$

$$\sum_m p^{ij}_{mj} = b_{ij} \quad \textit{for all } i, j \tag{4}$$

$p^{ij}_{mn} \in \{0,1\}$, $b_{ij} \in \{0,1\}$

- On coloring lightpaths, $\varsigma \in C$:

$$\sum_n p^{ij}_{\ln\varsigma} = \sum_m p^{ij}_{ml\varsigma}, \quad \textit{if} \quad l \neq i, j \tag{5}$$

$$\sum_n p^{ij}_{in\varsigma} = b_{ij\varsigma} \quad \textit{for all } i, j, \varsigma \tag{6}$$

$$\sum_m p^{ij}_{mj\varsigma} = b_{ij\varsigma} \quad \textit{for all } i, j, \varsigma \tag{7}$$

$$\sum_\varsigma b_{ij\varsigma} = b_{ij} \quad \textit{for all } (i, j) \tag{8}$$

$$\sum_\varsigma p^{ij}_{mn\varsigma} = p^{ij}_{mn} \quad \textit{for all } (m,n),(i,j) \tag{9}$$

$p^{ij}_{mn\varsigma} \in \{0,1\}$, $b_{ij\varsigma} \in \{0,1\}$

Equations (2)-(4) are multi-commodity flow equations governing the routing of lightpaths from source to destination. Equations (5)-(7) ensure that a wavelength ς is conserved at every node for a lightpath. Equation (8) requires a lightpath to be one color only and in (9) the number of wavelengths being used in a physical link is equal to the number of lightpaths on this link.

4. INTERFERENCE IN RWA

In WDM transparent networks the signal quality degrades due to physical impairments [4]. These impairments depend on the physical characteristics of the fibers used, but some of them also vary according to the network use. For example, inter-channel and intra-channel crosstalk, cross-phase modulation and four-wave mixing not only depend on the fiber characteristics, but also on the utilization of other wavelengths on the same link. Therefore, in this case, we have to consider how the wavelengths interferes in the solution for RWA problem.

In this section, we enhance LP formulation presented in the previous section to take into consideration the interference among adjacent channels on the same fiber. Therefore, we describe the effect of adjacent channel interference with an analytical formula applied to the links that compose the path. Then, we constrain the total adjacent channel interference over a link so as to be less than a predefined threshold.

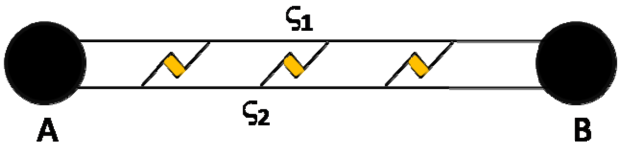


Figure 3. Interference example

4.1 Definitions

- Distance of two wavelengths:

  $d(\varsigma_a, \varsigma_b) = | \varsigma_a - \varsigma_b |$
- Adjacent wavelengths:

  Two wavelengths are called adjacent, if the distance between them is:

  $d(\varsigma_a, \varsigma_b) = 1$
- Interference of two wavelengths in the same link:

  Two wavelengths interfere with each other if they are adjacent. This occurs, if the distance between them is 1.
- To know if ς is active in link m-n, the binary variable $I_{mn\varsigma}$ was created and added it to the formulation from section II (RWA problem), so:

$$I_{mn\varsigma} = \begin{cases} 1 & if \quad \sum_{ij} p^{ij}_{mn\varsigma} \geq 1 \\ 0 & otherwise \end{cases} \qquad (10)$$

The constraint of adjacent channel interference to the RWA was imposed to be lower then a predefined threshold for each channel in each fiber, in order to ensure an acceptable OSNR at the final destination. For this purpose, the following constraint is implemented for each fiber:

$$I_{mn(\varsigma+1)} + I_{mn(\varsigma-1)} + \alpha * I_{mn\varsigma} \leq D_{mn} + \alpha \qquad (11)$$

Where:

- α= constant (taking large values, e.g. *a*=100).
- D_{mn} = maximum acceptable interference of adjacent channel that can be tolerated in each link.
- $I_{mn(\varsigma+1)} + I_{mn(\varsigma-1)}$: sum of wavelengths that affects the wavelength ς. Only adjacent wavelengths contribute to the interference, so:
- $\alpha * I_{mn\varsigma} = \begin{cases} \alpha & if \ \varsigma = 1 \, (active) \\ 0 & otherwise \end{cases}$

If we further analyze the cases above, we have

1. In case $I_{mn\varsigma} = 1$ constraint (11) becomes $I_{mn(\varsigma+1)} + I_{mn(\varsigma-1)} \leq D_{mn}$ and the number of wavelengths affecting the signal is constrained to be less than the predefined threshold.

In case $I_{mn\varsigma} = 0$, the wavelength was not selected and the constraint for adjacent channels is not taken into account. As $\varsigma = \{1 \ldots W\}$, $I_{mn0} = I_{mn(W+1)} = 0$.

The following example illustrates the operation of the formulation above (Figure 4). Suppose that there is a request from *A* to *E*. A potential path is *p={A,B,C,D,E}*. Figure 4 shows the case in which a lightpath from *A* to *E* is established over path *p* and wavelength 2 is selected to serve it. In this case, we have the interference of adjacent channel introduced at each intermediate link over the whole path. Since wavelength 2 is used, $\alpha * I_{mn\varsigma} = \alpha$ for ς =2 and thus the constraint for each link becomes $I_{mn\varsigma_{(i+1)}} + I_{mn\varsigma_{(i-1)}} \le D_{mn}$.

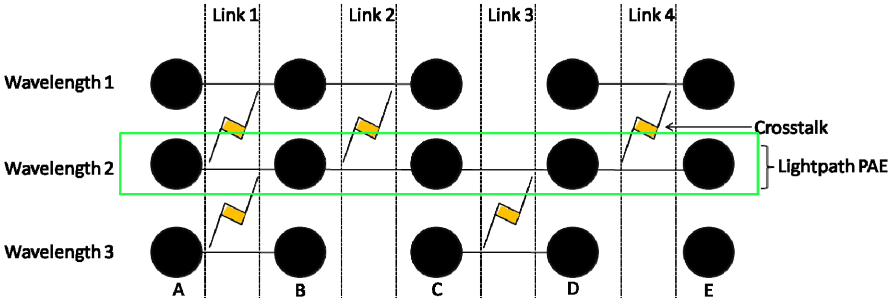


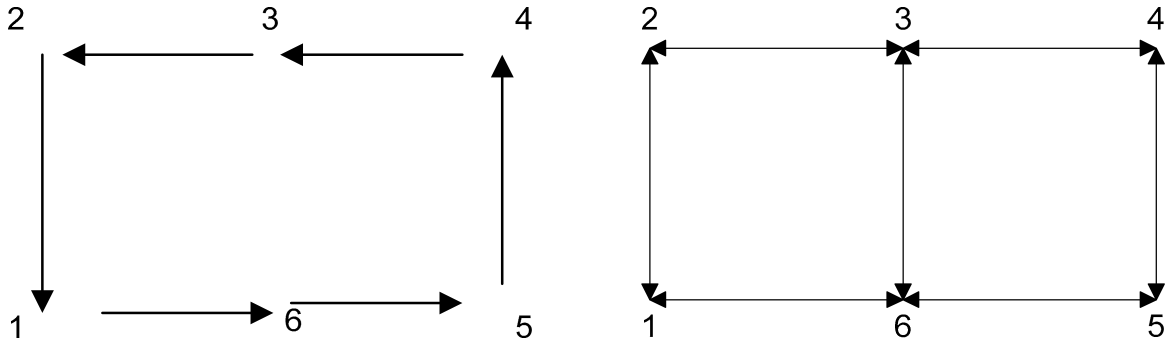
Figure 4: A used wavelength is represented by a line connecting 2 OXCs. Path from *A* to *E* uses wavelength 2. Adjacent channel interference can be computed as the sum of adjacent used wavelengths over the path, which is equal to 5 in this specific example.

In order to ensure an acceptable OSNR at the final destination, we can define $D_{OSNR}=D_{mn}.H$, where *H* is the maximum number of hops that a lightpath may have. In example above, the maximum D_{mn} is 2 and the maximum number of hops is 4, therefore the possible maximum D_{OSNR} is 8.

5. SIMULATIONS AND NUMERICAL RESULTS

Here, we consider two small networks (Figure 4). A ring-shaped network with six nodes (to show a simple simulation) and a six-node mesh network (comparing with with [6], [7]). We also consider a larger network: the 14-node network of National Science Foundation Network (also from [6] and [7]), which is planned through heuristics due to its complexity.

5.1 Small Networks



a) Ring network

b) Mesh network

Figure 4. Small Networks

Table II: Traffic matrix Λ_k for 6-node network, [7]

-	0.537	0.524	0.710	0.803	0.974
0.391	-	0.203	0.234	0.141	0.831
0.060	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	-

For small networks (Figure 4a) we solved the MILP and the exact results are given in Tables III and IV. To solve the MILP we used ILOG´s CPLEX on a Pentium IV, 2Ghz.

We solved the MILP formulation of section II for this network with W=4, Δ=2 for the case without allowing link interference, D_{mn} = 0. Table III shows a possible virtual topology and RWA. The congestion is 3.67 and some possible virtual links (b_{26} and b_{64}) were not possible to be set up. This is due to the fact that for virtual degree 2, we need more wavelengths or we need to allow some interference in order to setup all possible lightpaths. For the same network, for virtual degree 2 with unlimited interference, the congestion is 2.45 (Table IV). In this case all lightpaths were set up. Considering that impairments are blocked in case 1, it may be a good solution for networks with high lightpath capacity C (see [7], for definition of capacity). For this case without interference we need $C>\lambda_{max}$=3.67 or more wavelengths.

Table III. LTD without interference

W=4, Δ=2 , $D_{mn}=0$			
b_{ij}	*Route*	ς_i	λ_{max}
1-5	1-6-5	3	3.67
1-6	1-6	1	
2-1	2-1	3	
2-6	X	X	
3-1	3-2-1	1	
3-2	3-2	4	
5-3	5-4-3	3	
4-3	4-3	1	
5-3	5-4-3	3	
5-4	5-4	1	
6-4	X	X	
6-5	6-5	1	

Table IV. LTD with unlimited interference

W=4, Δ=2 , unlimited interference			
b_{ij}	*Route*	ς_i	λ_{max}
1-5	1-6-5	2	2.45
1-6	1-6	1	
2-1	2-1	1	
2-6	2-1-6	4	
3-1	3-2-1	2	
3-2	3-2	1	
4-2	4-3-2	4	
4-3	4-3	2	
5-3	5-4-3	1	
5-4	5-4	2	
6-4	6-5-4	1	
6-5	6-5	4	

For Figure 4b the traffic matrix from table II also was considered. We considered four parameters: the link bound interference, the hop-length (hop bound), the number of wavelengths and the degree of the logical topology. Table ′*′ indicates no restriction for that particular column parameter. With theses parameters, many combinations are possible. We present results for some combinations and compare with results from [6]. For degree 2, in the case the unconditional interference and the unconditional hop bound (traditional formulation), the congestion is 2.042. For degree=2, without interference, 2 wavelengths and hop bound=2, the congestion grow, it is 2.21. For degree 3 (traditional formulation) the congestion is 1.183. However, with *W*=2, unconditional hop bound and without interference, the congestion with the new formulation is 2.21. However if more one wavelength, *W*=3 is available, the congestion is similar in two formulations. Degrees 4 and 5 have similar explanation as degree 3.

Table IV. Comparison with [6]

			New Formulation		*[6], Traditional Formulation*	
Δ	W	HB	D_{mn}, D_{OSNR}	λ_{max}	D_{OSNR}	λ_{max}
2	2	2	0	2.21	*	2.21
2	*	*	0	2.042	*	2.042
3	2	*	0	2.21	*	1.183
3	*	*	0	1.183	*	1.183
4	3	*	0	1.105	*	0.887
4	*	*	0	0.887	*	0.887
5	4	*	0	1.105	*	0.710
5	*	*	0	0.710	*	0.710

5.2 Larger Network (NSFNET)

Since the decision problem (feasibility problem) for the MILP is NP-hard and the network sizes are not small, we propose the following two heuristics: Heur I and Heur II.

Heur I (without interference):

Step 1: Given a static traffic matrix Λ_k, find the set up virtual links (b_{ij}) with a heuristic (LP relaxation, rouding heuristics etc. In this work we use tabu search).

Step 2: With MILP from [8], only flow constraints, route the traffic Λ through b_{ij}*'s* and find $\min\lambda_{max}$.

Step 3: Solve the RWA with the new formulation, only with RWA constraints and interference constraints). Choose the objective function (in this work, to minimize the total number of hops).

Heur II (with unlimited interference):

Step 1: Given a static traffic matrix Λ_k, find the set up virtual links (b_{ij}) with a heuristic (LP relaxation, rouding heuristics etc. In this work we use tabu search).

Step 2: With MILP from [8], only flow constraints, route the traffic Λ through b_{ij}*'s* and find $\min\lambda_{max}$.

Step 3: Solve the RWA with shothest path in physical topology and find the wavelengths need (unlimited interference, traditional RWA).

Note:

-The b_{ij} solutions for the two heuristics are the same. Therefore, we hope similar results for the congestion.

- $D_{mn} = 0$ is parameter in Heur I and unlimited in Heur II.

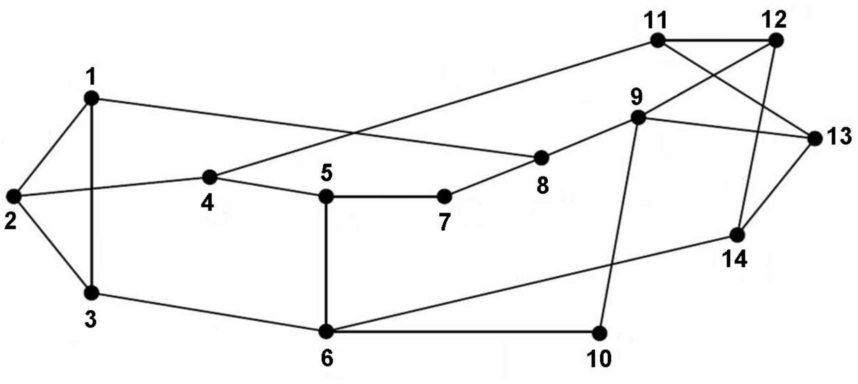


Figure 5. NSFNET

NSFNET shown in Figure 5 is a 14-node network with 21 edges. The pair of directional edges represents a pair of fibers, one in each direction. We consider the number of wavelengths and the degree of the logical topology as parameters for this case. We do not consider the hop bound constraint. Table V gives the heuristics results for the traffic matrix P1 from (Ramaswami, 1996, [7]).

In Table V under the Heur I heading there are four columns, viz., degree, wavelength, upper bound on interference and congestion. The degree Δ specifies the degree of the logical topology to be designed. The wavelength denotes the number of wavelengths available, which is the parameter. The upper bound on interference denotes the solution parameter that we use in MILP formulation (in this work it is 0). For example in degree 2, in the first line, case with 2 wavelengths, without link interference, the solution (congestion value) is impracticable. However, for degree 2, in the second line, case with 3 wavelengths the congestion value is 553.757. We can observed also than for 3 or more wavelengths (*=unlimited) we take a viable solution. So, in order to take viable solutions without interference we need take more wavelengths. Column (Heur II) shows the results that we take with Heur II. We observed the link interference to take a solution. For the other degree the discussion is similar. Figure 6 shows the number of wavelengths needed to take viable solutions for several degrees. In this figure, for Heur I we have considered without link interference. For example, for degree 5 we need 7 wavelengts to take a viable solution with Heur I. With Heur II, for same degree, we take 5 wavelengths, but the unlimited interference. We also take the results from HLDA [7] and computing the number of wavelengths with unlimited interference for comparasion with the heuristics here presented. The good solutions from our MILP with Heur I can be seen in Figure 6, because it shows the results without interference to take viable solutions.

Table V. Solution for larger networks, NSFNET.

Degree	Number of wavelengths	*Heur I*		*Heur II*	
Δ	W	$D_{OSNR_{mn}}$	λ_{max}	$D_{OSNR_{mn}}$	λ_{max}
2	2	0	X	unlimited	553.757
2	3	0	553.757		
2	*	0	553.757		
5	5	0	X	unlimited	63.205
5	6	0	X		
5	7	0	63.205		
5	*	0	63.205		
7	7	0	X	unlimited	43.727
7	8	0	X		
7	9	0	X		
7	10	0	X		
7	11	0	43.727		
7	*	0	43.727		
10	11	0	X	unlimited	28.353
10	12	0	X		
10	13	0	X		
10	14	0	X		
10	15	0	X		
10	16	0	X		
10	17	0	X		
10	18	0	X		
10	19	0	28.353		
10	*	0	28.353		

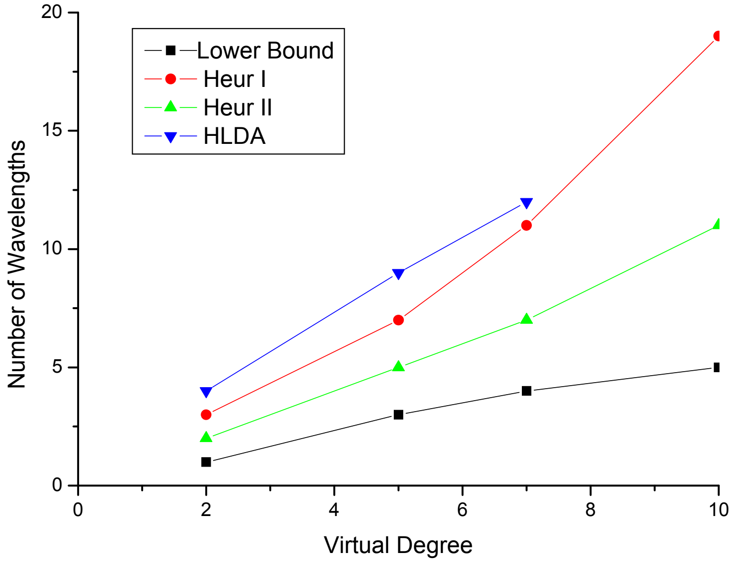


Figure 6. Number of wavelengths needed, lower bound from [7].

CONCLUSIONS

The computational experiments clearly show that our linear formulation for the traffic optimization does give good solutions to minimize the congestion without link interference in RWA. Therefore it is a complete design. Due to lack of space, results for more complex networks were not included, but will be certainly included in later works.

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