A Heuristic Algorithm for Designing Logical Topologies in Packet Networks with Wavelength Routing

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Abstract: **By introducing optical telecommunication networks with WDM (Wavelength Division Multiplexing), the capacity of network becomes very high and the price more acceptable then with pure electronic processing. Major part of traffic in these networks is IP, a packet switched traffic. On the other hand, contemporary optical networks are basically circuit switched. A promising solution for interfacing different network levels is a logical topology for IP that is transported over wavelength path established in WDM network. Optimal design of such logical topology has been the goal of many algorithms. In this paper a new heuristic algorithm, LLHS (*Low Traffic Largest Hops High Traffic Smallest Hops*) is proposed to design optimal logical topology aimed at minimizing packet congestion.**

1. INTRODUCTION

The progress in optical technology made WDM (Wavelength Division Multiplexing) system one of the most promising transport technologies due to its high capacities that satisfy the increasing bandwidth requirements. At the same time, IP protocol (Internet Protocol) is becoming dominant network layer protocol in today's networks. As a consequence, the problem of IP over WDM integration attracts considerable interest. In the past years, various scenarios were proposed for integration, but most of them were too complicated. The best solution seams to be in sending IP traffic directly to the WDM layer (with PPP/HDLC framing). The IP protocol uses wavelength paths for transmission. The wavelength paths established through WDM network, make direct connections between IP routers. Figure 1 depicts this concept.

Physical network is built of optical links and optical nodes. Logical topology (layer 2) is built of IP routers with interfaces connected through wavelength paths. Wavelength path is a set of wavelength channels that establish direct connection between IP routers. A packet sent on a path is not electronically processed except in the end points. When an IP router has a packet to transmit, it uses the established wavelength path for transmission. If there is no direct connection to the destination router, the packet has to travel through several wavelength paths to reach the destination. Whenever the packet is changing wavelength path, it undergoes electronic processing in the intermediate router. This situation is not desirable because it may produce a bottleneck in the network. For IP protocol, from the performance point of view, the best solution would be full meshed logical topology, but often this is not possible due to the lack of available wavelengths. Chapter 1 gives formal description of the problem. Chapter 2 describes LLHS algorithm. A comparison to other algorithms and conclusion are given in Chapters 3 and 4.

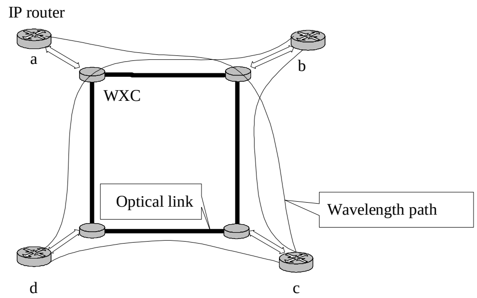


Figure 1 – An example of physical and logical topology

2. PROBLEM DEFINITION

The aim of the paper is to build up optimal logical topology. Optimization of logical topology can comprise the set of actions. Some of them are:

- minimization of logical link congestion,
- minimization of the required number of wavelengths per fiber,
- minimization of end-to-end delays and
- maximization of routing stability.

Many works and papers have been made on these topics [1-3]. Our goal was to optimize logical topology in order to minimize congestion of logical links. Therefore, we proposed the algorithm that is derived by a deductive method

Let us first introduce the assumptions used in resolving stated problem. We assumed that physical topology had been given, i.e. that the placement of optical nodes and optical links had been known and that the number of wavelengths on the optical fiber had been limited by the logical degree of nodes (denoted by Δ), where logical degree was the number of logical links connected to the node.

The input traffic matrix of order N is denoted by T **[**λ^{sd}**]**, where N is the number of nodes in physical topology. λ^{sd} is the long term average traffic demand between the nodes s and d. Binary variable b_{ij} (0,1) denotes the presence of logical links in topology. The number of variables b_{ij} is $N(N-1)/2$. For large networks it necessarily leads to heuristic method in looking for optimal logical topology.

Traffic demand λ^{sd} between the nodes s and d does not necessarily travel over the single wavelength path. This means that logical link is not loaded only with traffic that belongs to traffic demands between the edge nodes of that path, but also with other traffic passing through that link. So, let us denote the offered traffic demand on the logical link between nodes i and j by λ_{ij}:

$$\lambda_{ij} = \sum_{sd} a_{ij} \lambda^{sd} \tag{1}$$

Variable a_{ij} is also binary type like b_{ij} and indicates whether the traffic between the nodes s and d passes through the logical link i j or not.

Now, we can formulate the goal of optimization with

$$\min\left\{\lambda_{\max}\right\} \tag{2}$$

where

$$\lambda_{\max} = \max\left\{\lambda_{ij}\right\}. \tag{3}$$

λ_{max} represents the congestion of logical topology.

Assume that the arrival process of packets to the network is Poisson and assume that transmission time of packets is distributed exponentially with intensity μ. Also assuming that the offered load on one link is independent of the offered loads on others links, we can use M/M/1 queuing system model to evaluate the delay caused by processing. Figure 2 shows the simplified structure of electronic router. We can see that the delay consists of processing, queuing and transmission delays.

According to M/M/1 queuing system, the delay is:

$$\frac{1}{\mu - \lambda_{ij}} \tag{4}$$

The throughput of a network is defined as minimum value of the offered load that will cause an infinite delay. This case happens if

$$\lambda_{\max} = \max\left\{\lambda_{ij}\right\} = \mu\ . \tag{5}$$

Eq. (5) shows that finding the algorithm that minimizes congestion is important because it improves network throughput.

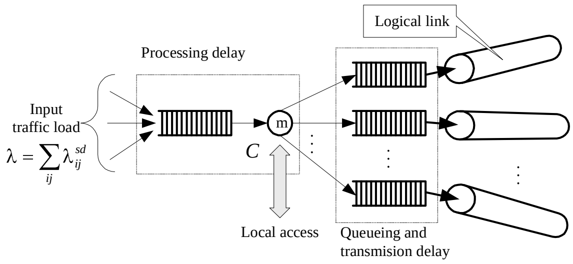


Figure 2 - Simplified structure of electronic router

The packet belonging to the connection to which there is no direct logical link is passing of several links through on its transport to the destination node. In the intermediate nodes the packet is converted to electrical domain, then processed and converted back to the optical domain. Because of the demanding electronic processing, the number of logical links connected to a node is limited to logical degree (Δ).

To complete the problem definition, we introduce additional limitations:

- Flow conservation at each node:

$$\sum_j \lambda_{ij}^{sd} - \sum_j \lambda_{ji}^{sd} = \begin{cases} \lambda^{sd} & if\ \ s = i, \\ -\lambda^{sd} & if\ \ d = i, \quad for\ \forall\ s,d,i. \\ 0 & otherwise, \end{cases} \tag{6}$$

- Total traffic flow for logical link:

$$\lambda_{ij} = \sum_{s,d} \lambda_{ij}^{sd}, \quad for\ \forall\ i,j \tag{7}$$

Constraints are:

$$\lambda_{ij} \le \lambda_{\max} \ \ \text{for}\ \forall\ i,j$$

$$\lambda_{ij}^{sd} \le b_{ij}\lambda^{sd}\ \ \text{for}\ \forall\ i,j,s,d.$$

- Constraints on the logical degree of nodes:

$$\begin{aligned} &\sum_i b_{ij} \le \Delta,\ for\ \forall\ j \\ &\sum_j b_{ij} \le \Delta,\ for\ \forall\ i. \end{aligned} \tag{8}$$

3. LLHS ALGORITHM

The algorithm was developed by successive analysis of traffic congestion in small networks.

We started our analysis with small topologies with the input and output logical degree of network nodes equal to 1 ($\Delta = 1$), i.e. each node in logical topology could have one ingress and egress logical link attached. Because of that, in creating logical topology we could place the nodes on the edge of the circle (Figure 3) and interconnect them in one direction. It gave starting logical topology. Each node permutation represented one logical topology, hence, there were $(N-1)!$ possible topologies.

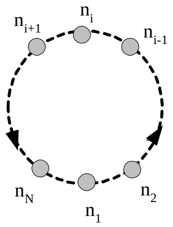


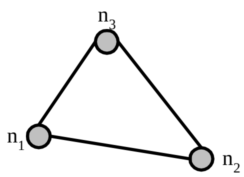
Figure 3 – The placement of nodes on ring

The traffic load on logical link between nodes *i* and *i+1* for starting logical topology could be calculated using the formula (9):

$$\lambda_{ij} = \sum_{j=1}^{N-1} T(i, i+j) + \sum_{j=1}^{i-1} T(i, j) + \\ + \sum_{j=0}^{N-i-1} \sum_{k=1}^{i-1} T(i-k, i+j+1) + \sum_{j=1}^{i-k-1} \sum_{k=1}^{i-1} T(i-k, j) + \\ + \sum_{s=0}^{N-i-2} \sum_{j=0}^{N-s-i-2} T(N-s, i+j+1), \quad (9)$$

We started with small network composed of three nodes.

Case N3: Physical topology, composed of 3 nodes and traffic matrix are shown on Figure 4. That case was taken from [2].

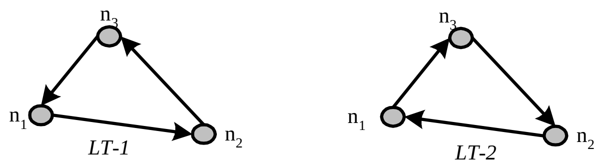


Traffic matrix:

node	1	2	3
1	0,000	0,537	0,524
2	0,391	0,000	0,203
3	0,060	0,453	0,000

Figure 4 – An example network composed of three nodes

In that case, only two logical topologies were possible, as shown on Figure 5. Traffic loads on corresponding wavelength paths are also shown.



Traffic load of logical links:

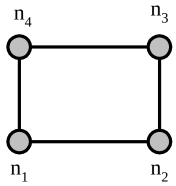
$$\lambda_{ij,1} = \begin{bmatrix} 0 & 1{,}514 & - \\ - & 0 & 1{,}118 \\ 0{,}904 & - & 0 \end{bmatrix}, \quad \lambda_{ij,2} = \begin{bmatrix} 0 & - & 1{,}264 \\ 0{,}654 & 0 & - \\ - & 1{,}050 & 0 \end{bmatrix}$$

$$\lambda_{\max,1} = \max \lambda_{ij,1} = 1{,}514. \qquad \lambda_{\max,2} = \max \lambda_{ij,2} = 1{,}264.$$

Figure 5 - Possible logical topologies and load of their links

Due to $\lambda_{\max,1} > \lambda_{\max,2}$, *LT-2* topology is optimal.

Case N4: We considered a network with the 4 nodes. Figure 6 shows the network and traffic demands.



Traffic matrix

node	1	2	3	4
1	0,000	0,537	0,524	0,710
2	0,391	0,000	0,203	0,234
3	0,060	0,453	0,000	0,645
4	0,508	0,660	0,494	0,000

Figure 6 - Case N4 - A network composed of four nodes

In this case there are six possible logical topologies shown in Figure 7.

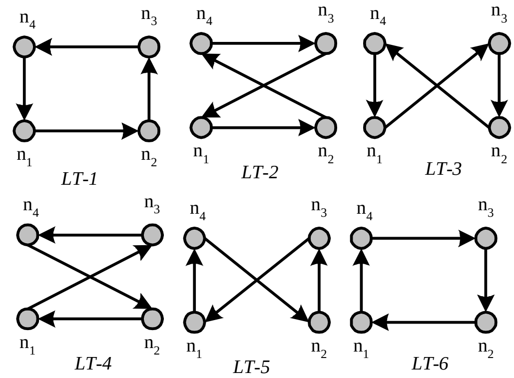


Figure 7 - Possible logical topologies for 4 nodes network

Maximum traffic loads of the logical topologies are shown in Figure 8.

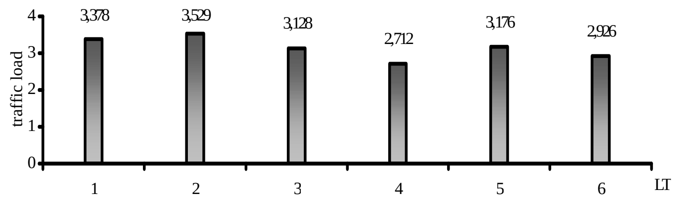


Figure 8 – Congestion of logical topologies in case N4

Figure 8 shows that optimal topology is LT-4. The advantages in percentage of logical topologies with respect to the worst one (topology LT-2) are given in Table 1**.**

Table 1 Advantages of logical topologies over the worst one

LT	1	**2**	3	4	5	6
Adv. %	4,27	**0**	11,36	23,15	10,00	17,09

3.1 Analysis of Optimal Logical Topology

Let us analyze optimal topologies obtained in the cases *N*3 and *N*4. What makes them optimal?

Let us focus on the maximum traffic load on these topologies. At the *LT-2* of the network case *N*3, the wavelength path *1-3* is congested the most. At the *LT-4* of the network case *N*4 the most congested path is *4-2*. The traffics on these paths are given in Table 2:

Table 2 Traffic load on congested link of optimal topology

Path 1-3 on LT-2	
Node pair	*Traffic load*
1-3	0,524
1-2	0,537
2-3	0,203

Path 4-2 on LT-4	
Node pair	*Traffic load*
4-2	0,660
4-1	0,508
4-3	0,494
3-2	0,453
3-1	0,060
1-2	0,537

We see that the lightest traffic goes the longest way (Figure 5 and 7). From these facts we come to the rule 1:

Rule 1: The lightest traffic goes the longest way (highest number of hops)

Applying this rule, optimal topology can be built for the network in case *N*3 (Figure 9 a).

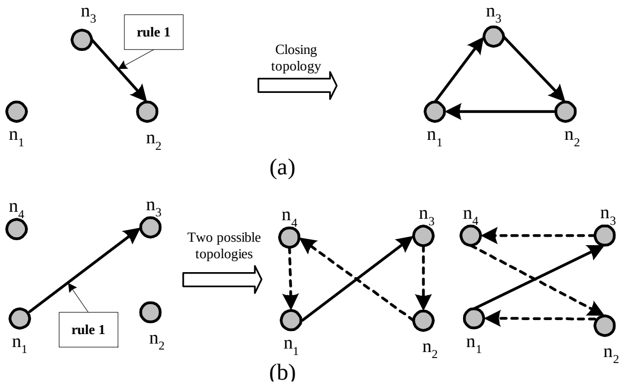


Figure 9 - Building logical topology by rule 1

In case *N*4 we cannot create logical topology (Figure 9 b). So, let us see where the heaviest traffic in optimal logical topology goes. From Table 2 we see that the traffic goes the shortest way. Consequently, we come to the rule 2:

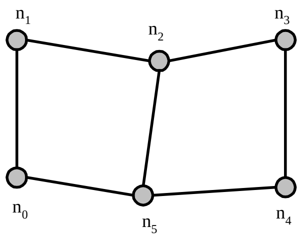
Rule 2: The heaviest traffic goes the shortest way (smallest number of hops)

The rules are so understandable that we took them as the basis for heuristic algorithm for any network size. We call this algorithm LLHS (**L**ow traffic **L**argest hops **H**igh traffic **S**mallest hops).

Case N6: In order to verify the algorithm, we applied the rules to the network of 6 nodes [2]. Physical topology and traffic matrix are given in Figure 10.

With rules 1 and 2 we have built optimal topology shown on Figure 11.

The congested link in this topology is 4-3 and the load on this link is 7,077. This topology was also obtained in [2] by the mixed integer linear programming, which verified the rules 1 and 2.



Traffic matrix

node	0	1	2	3	4	5
0	0,000	0,537	0,524	0,710	0,803	0,974
1	0,391	0,000	0,203	0,234	0,141	0,831
2	0,060	0,453	0,000	0,645	0,204	0,106
3	0,508	0,660	0,494	0,000	0,426	0,682
4	0,480	0,174	0,522	0,879	0,000	0,241
5	0,950	0,406	0,175	0,656	0,193	0,000

Figure 10 – Case N6 - A network composed of six nodes

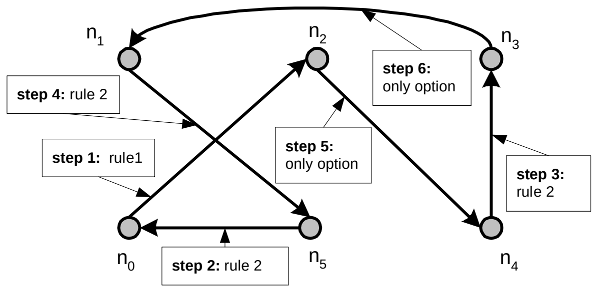


Figure 11 - Building of optimal topology with LLHS algorithm

Hence, the whole LLHS algorithm is:

(1) Sort traffic demands from the highest to the lowest.

(2) Create a wavelength path between the nodes with the lowest traffic demand having opposite to the traffic flow, if logical degrees of the nodes allow. Remove that demand from the list.

(3) Create a wavelength path between nodes with highest traffic demand having direction equal to traffic flow, if logical degrees of the nodes allow. Remove that demand from the list.

(4) Keep repeating steps 2 and 3 as long as possible, i.e. until logical topology is closed.

3.2 Higher logical degree

In the networks with logical degree above one, we applied LLHS algorithm in the following way: First we created as many images of physical topology as was the degree of nodes (Δ) (Figure 12).

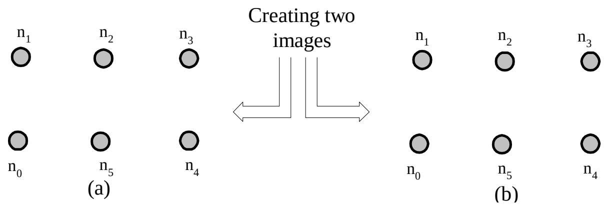


Figure 12 – The creation images of physical topology

Then, we applied the LLHS algorithm step by step with respect to all created images. In other words, we started creating wavelength paths on the first image. If it was not possible, we tried to create that path in the second image, or third, or Δ image. If none of Δ created images can accept that path, it is rejected. Figure 13 shows this procedure for $\Delta = 2$, N6.

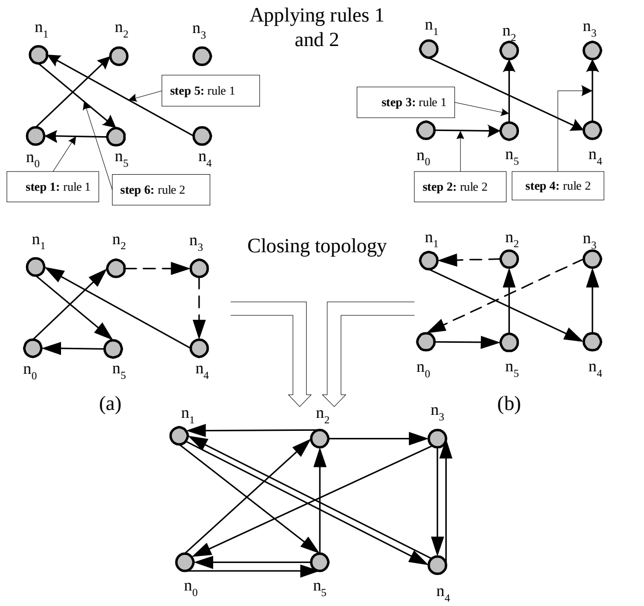


Figure 13 - Building higher degree logical topology with LLHS

Traffic demands, for which there is no direct wavelength path, are also routed by the rules 1 and 2. If, for example, there are two paths between two nodes, traffic is split between them relevant to the number of hops in these paths. The congested link in topology in Figure 13 is 0-2. The load is 3,347 which is about 2 times better than in topology with logical degree 1.

4. COMPARISON TO OTHER ALGORITHMS

We compared LLHS algorithm to other algorithms [1-5] on the examples of small networks (cases *N*3 and *N*4).

HLDA (Heuristic Logical Design Algorithm) algorithm [1] creates wavelength paths in accordance with decreasing traffic. For the network from Figure 6 its logical topology is shown in Figure 14 a, which equals LT-5 in Figure 7.

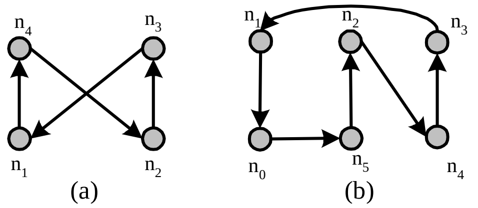


Figure 14 - Optimal topology built with HLDA algorithm

We see that LT-5 topology is inferior to LT-4 topology built with LLHS algorithm. Application of HLDA to the network in case N6 (Figure 10) yields topology (b) in Figure 14. This topology is inferior to LT-3. Thus, we conclude that, in this case, LLHS algorithm is better than HLDA.

MLDA [2] (Minimum-delay Logical Topology Design Algorithm) creates wavelength paths according to physical topology and then uses HLDA algorithm to place the rest of wavelength paths. By applying MLDA on 4-node topology we get two possible solutions shown in Figure 15.

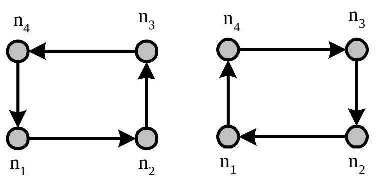


Figure 15 - Optimal topology built with MLDA algorithm

These topologies are LT-1 and LT-6 topologies shown in Figure 7. They are inferior to LT-4 too. Hence, we conclude that in this case LLHS is better then MLDA. This situation is similar to other algorithms [4][5].

5. CONCLUSION

We conclude that LLHS algorithm is simple, clear, understandable, deductive and applicable. When applied to small networks, LLHS algorithm gives better results than other considered algorithms. Relation between traffic matrix and optimal logical topology is left for future work.

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