Optimal Solution for Routing and Wavelength Assignment Problem in Optical WDM Networks

Goran Marković[1], Vladanka Aćimović-Raspopović[2]

Abstract - **We consider the routing and wavelength assignment *(RWA)* problem in multi-hop optical WDM networks with static traffic demands. In the case of static traffic, the connection requests are given in advance, and the objective is typically to minimize the number of used wavelengths in a network. Since the number of available wavelengths per a fiber is limited by technological reasons, *RWA* problem solution is crucial for improvement of optical WDM network efficiency. In this paper, the routing and wavelength assignment is considered as the optimization problem based on integer linear programming resolving. We developed the software that gives the optimal solution of the RWA problem. The simulations of the RWA problem on a ring, mesh and fully connected network with six routing nodes are performed and the network performances are compared.**

Keywords – **optical WDM network, routing and wavelength assignment (RWA), optimal solution, integer programming**

I. INTRODUCTION

The ever increasing demands for higher transmission bandwidth require new design solutions for future telecommunication networks. Optical networks employing *Wavelength Division Multiplexing (WDM)* technique are believed to be the next generation networks that can meet the agile future requirements. Recent developments in *WDM* technology have led to a tremendous research interest in WDM-based optical network designing [2,3,4].

In *WDM* networks several optical signals using different wavelengths are carried over a single optical fiber. Thus the huge available capacity of an optical fiber can be used more efficiently. Each wavelength is a separate, signal-carrying communication channel called a lightpath. A *lightpath* is simply a high bandwidth circuit-switched communication channel, carrying data at up to several gigabits/second. It is set up by assigning a dedicated wavelength to it on each physical link on its path between the end nodes in a network.

WDM technique brings out new problems in coordination of wavelengths usage in network [1,4,5]. In particular, when it is needed to establish a connection between a node pair, a route must be found and a wavelength has to be assigned to carry the information. The problem is known as the *routing and wavelength assignment (RWA)*. Resolving the *RWA* problem has received a lot of attention in optical WDM networks researching. The current well-known routing approaches, such as fixed routing, fixed-alternate routing and adaptive routing are the basic routing strategies that are widely used for the resolving this problem.[1,6,7].

Ones the route has been chosen for a connection request (or a lightpath), the wavelengths have to be assigned to each lightpaths in such a manner that any two lighpaths traverse over the same physical link are assigned a different wavelength. If wavelength conversion cannot be performed at network nodes, the lightpaths must be established on the same wavelength over all physical links along the path between two end nodes. This is known as the wavelength continuity constraint. Different wavelength assignment approaches have been extensively researched in the literature [1-7]. The wavelength assignment algorithms can be broadly classified into most-used, least used, fixed order and random order depending on the order in which the wavelengths are searched.

In this paper the optimal solution for routing and wavelength assignment problem in multi-hop optical *WDM* network with static traffic demands and without the wavelength conversion possibility is considered.

With static traffic demands, the entire set of connection requests are known in advance and the routing and wavelength assignment problem is performed off-line. In such situation, the objective is to minimize the required network resources such as the number of wavelengths needed to set up a certain set of lightpaths or the number of fibers in network for a given physical topology. An alternative of minimizing the number of wavelengths is to maximize the number of connections that can be established (blocking minimization) for a given fixed number of available wavelengths.

An exact optimal solution for a given *RWA* problem can be obtained by solving the corresponding combinatorial *RWA* using the integer linear programming. Such an approach, especially when applied to large problem solving, may be computationally expensive. In spite of using sophisticated techniques such as branch-and-bound methods, the computation time may be an exponential function of the number of source-destination pairs and the network connectivity degree. However, for a practical network, an optimal solution for RWA problem could be obtained in reasonable time. The proposed approach could be applied for solving the RWA problem in different network topologies.

II. PROBLEM STATEMENT

Consider a given physical network that has *N* routing nodes connected in any topology. Two end nodes may require a

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[1] Goran Marković is with the Faculty of Transport and Traffic Engineering, Vojvode Stepe 305, 11000 Belgrade, Serbia and Montenegro, e-mail:g.markovic@sf.bg.ac.yu

[2] Vladanka Aćimović-Raspopović is with the Faculty of Transport and Traffic Engineering, Vojvode Stepe 305, 11000 Belgrade, Serbia and Montenegro, e-mail: v.acimovic@sf.bg.ac.yu

number of connection requests between them and all of those requests are known *a priori*. We assume that the network resources, such as the available number of wavelengths per fiber links or the number of optical transmitters and receivers in optical nodes are also given. The objective of the RWA problem is to select the routes throughout the network for all required connections with the wavelengths assignment such that no two lightpaths using the same wavelength traverse through the same physical link. The objective is to minimize the number of required wavelengths in the network. This goal can be achieved using *integer linear programming (ILP) optimization.* A total number of lighpaths that are established over one physical link defines a congestion of a particular link.

Analytical formulation of the RWA *ILP* optimization problem is given as follows:

$$F = min \sum_{w=1}^{W} \lambda_w \tag{1}$$

where *F* is the objective function in terms of required number of wavelengths that has to be minimized. With *W* the maximum available number of wavelengths in the network that is assumed to be large enough to establish all the required connections is denoted. It is assumed that all the links in a network have the same value of *W*. Wavelength λ_w is the binary decision variable that has the value 1, if the wavelength *w* is used at any link in the network, otherwise $\lambda_w=0$.

Two constraints that have to be satisfied for the observed optimization problem can be formulated as follows:

$$\sum_{w=1}^{W} x_w^k = r_k , \forall k \in K = \{i, j\}, i, j \in \{1,2,...,N\}, i \neq j \tag{2}$$

$$\sum_k x_{w,l}^k \leq \lambda_w, \forall\, w \in W, l \in L \tag{3}$$

$$\begin{gathered} x_{w,l}^k \in \{0,1\}, \forall k \in K, w \in W \\ \lambda_w \in \{0,1\}\ \forall w \in W \end{gathered} \tag{4}$$

where the used symbols have next notations:
W - total number of available wavelengths in network,
K- set of node pairs in network,
L - set of all physical links in network,
N - number of routing nodes in network,
r_k - the number of connections required between node pair *k*,
$x_{w,l}^k$ - binary decision variable that has the value 1, if the wavelength *w* is used at all links *l* along the path between node pair *k*, otherwise it has the value 0.

The constraint formulated by (2) is considered with traffic demand requirements. For all node pairs, $k \in K$, the number of required connections, r_k, between two end nodes has to be satisfied. With the constraint (3) we obtain that only one lightpath on particular wavelength *w* can pass over a link *l*. In other words, no two lightpaths using the same wavelength *w* can be established over one physical link *l*.

To resolve the described RWA optimization problem we developed the software that is based on binary integer programming. Its application gives the optimal solution of RWA problem for particular network topology. Input parameters of this software are the traffic demands matrix, the physical network topology and the maximal available number of wavelengths in the network. For resolving the routing problem, we assume that the fixed-alternate routing strategy is applied. In fixed-alternate routing, multiple fixed routes, that are computed off-line, are considered as the candidate paths for a connection that need to be established. In this approach, each node in the network forms its routing table that contains an ordered list of a number of fixed routes to each destination node. These routes could be, for example, the first shortest path, the second shortest path, etc. For all connection requests, optimization model try to find a route-wavelength pair, so that the total number of required wavelengths is minimized. All of the candidate paths and available wavelengths are considered simultaneously until the required set of connection requests is satisfied. We assume that the number of available wavelengths is large enough to establish all the required connection requests. Then the total number of wavelengths for all of the established lightpaths is determined as the objective function value.

III. NETWORK MODEL

We consider the optical WDM transport network with 6 routing nodes, interconnected by a single fiber links for each direction. Simulations of routing and wavelength assignment problem are performed for network topologies with various degree of connectivity, beginning with the simplest variant of a ring network, via a mesh to fully connected architecture. Figure 1 illustrates considered topologies in our simulation.

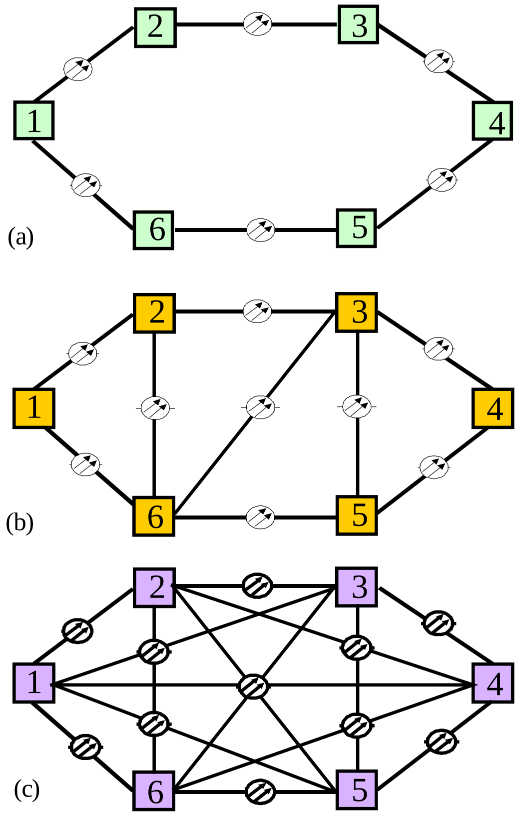

Fig. 1 Considered network topologies: a) ring, b) mesh, c) fully connected network

IV. SIMULATION RESULTS

For the simulation purposes, we assumed that the traffic demand matrix R is given in the form of requests of required number of connections between end nodes with the randomlyy distributed values between 1 and 3. The matrix R is symmetric, which means that connection requests in both directions are the same. An example of a generated traffic matrix R, which is considered throughout the simulation, is given as:

$$R = \begin{bmatrix} - & 2 & 1 & 1 & 2 & 2 \\ 2 & - & 1 & 3 & 1 & 3 \\ 1 & 1 & - & 1 & 2 & 1 \\ 1 & 3 & 1 & - & 2 & 3 \\ 2 & 1 & 2 & 2 & - & 1 \\ 2 & 3 & 1 & 3 & 1 & - \end{bmatrix} \qquad (5)$$

By running developed software for the ring network topology given in Fig. 1-a and for the traffic demands given by (5), we obtain the optimal solution for routing and wavelength assignment design, as given in Table I.

TABLE I
Optimal RWA solution for ring network topology

Node pair	Selected route(s)	Assigned wavelength(s)	Lightpath # (wavelengths)
1-2	1→2	λ_7, λ_8	8
1-3	1→2→3	λ_6	-
1-4	1→2→3→4	λ_2	-
1-5	1→6→5	λ_6, λ_7	-
1-6	1→6	λ_2, λ_8	8
2-3	2→3	λ_8	8
2-4	2→3→4	λ_3, λ_4, λ_5	-
2-5	2→3→4→5	λ_7	-
2-6	2→1→6	λ_3, λ_4, λ_5	-
3-4	3→4	λ_1	8
3-5	3→4→5	λ_6, λ_8	-
3-6	3→2→1→6	λ_1	-
4-5	4→5	λ_1, λ_5	8
4-6	4→5→6	λ_2, λ_3, λ_4	-
5-6	5→6	λ_1	6

We can see that each of the total offered 26 connection requests could be satisfied in this network by using the routes and wavelengths as it is shown in Table I. Note that in these network topology only two possible routes between each node pair exists and that it is required to use minimum of 8 different wavelengths in the network to satisfy all the connection requests. All the lighhtpaths are established over corresponding shortest path. The obtained results for used wavelengths on each physical link are given in the last column of Table I. We can see that for all links in the ring network, except for the link 5-6, minimum number of different wavelengths to satisfy all the connection requests is 8. Therefore, the link congestion is equal to 75% for the link 5-6 and 100% for other links in the network.

The results of simulation for routing and wavelength assignment optimization problem in mesh network topology, given by Figure 1-b are shown in Table II. We assumed the same traffic demand matrix, as it is given by equation (5). We assumed also that maximum 8 wavelengths are available over each link in the network.

From the obtained results, we can see that all connection requests can be also successfully satisfied, but in this case with less number of wavelengths over links compared to the previously analyzed ring network for the same traffic demands. For resolving the RWA problem in this network topology, we limited the possible routes between end nodes in network on those that contain maximum three hopes. Therefore, for the given network topology, it can be seen that each node pair has not the same number of candidate paths such that the assumed constraint is satisfied. Maximum number of possible paths between two nodes, for observed mesh network is 5 and this is only a case between nodes 2 and 5. For other node pairs the number of candidate paths that satisfy chosen hop constraint is either three or four. We sorted possible routes in routing table in increasing order of their hop number, such as the first shortest path(s), the second shortest path(s), etc. From the results given in the last column of Table 2, we can obtain the optimal (minimum) number of wavelengths over all links in the network such that all of the connection requests can be successfully satisfied.

TABLE II
Optimal RWA solution for mesh network topology

Node pair	Selected route(s)	Assigned wavelength(s)	Lightpath # (wavelengths)
1-2	1→2	λ_6,λ_7	4
1-3	1→2→3	λ_1	-
1-4	1→2→3→4	λ_8	-
1-5	1→6→5	λ_3, λ_4	-
1-6	1→6	λ_1, λ_2	2
2-3	2→3	λ_3	7
2-4	2→3→4	λ_5, λ_6, λ_7	-
2-5	2→3→5	λ_2	-
2-6	2→6	λ_1, λ_2, λ_3	3
3-4	3→4	λ_4	8
3-5	3→5	λ_1, λ_3	3
3-6	3→6	λ_4	4
4-5	4→5	λ_1, λ_2	2
4-6	4→3→6	λ_1, λ_2, λ_3	-
5-6	5→6	λ_1	3

For the fully connected network topology, we assumed maximum 2 available wavelengths over each link. For the routing problem we limited the candidate paths on those that contain maximum two hops. As the result, we have total of 5 candidate paths (1 direct and 4 two-link alternate paths) for each node pair. For this network topology, the optimization model gives a solution of the RWA problem that is shown in Table III. We can see that all of the connection requests can be satisfied with maximum 2 wavelengths over each fiber.

TABLE III
Optimal RWA solution for fully connected topology

Node pair	Selected route(s)	Assigned wavelength(s)	Lightpath # (wavelengths)
1-2	1→2	λ_1, λ_2	2
1-3	1→3	λ_1	2
1-4	1→4	λ_2	2
1-5	1→5	λ_1, λ_2	2
1-6	1→6 1→3→6	λ_2 λ_2	2
2-3	2→3	λ_2	2
2-4	2→4 2→3→4	λ_1, λ_2 λ_1	2
2-5	2→5	λ_1	2
2-6	2→6 2→5→6	λ_1, λ_2 λ_2	2
3-4	3→4	λ_2	2
3-5	3→5	λ_1, λ_2	2
3-6	3→6	λ_1	2
4-5	4→5	λ_1, λ_2	2
4-6	4→6 4→1→6	λ_1, λ_2 λ_1	2
5-6	5→6	λ_1	2

From the results obtained by performed simulations we can leave out the fact that the network connectivity greatly respond to the required number of wavelengths over physical links. The results presented in this paper show that in the case of great network connectivity such as in extremely considered example of fully connected network topology, the required optical resources or number of wavelengths could be significantly reduced. We developed the software that can simulate the routing and wavelength assignment problem in any optical WDM network topology. By using this software we can obtain the optimal results for the RWA problem in concrete network example and so minimize the required network resources for given traffic demand scenario.

We also performed a lot of simulations for the considered network topologies with various traffic demands that may represent the forecasted traffic in future period. By carrying out these simulations we obtained the results that are similar to those represented in this paper. The general conclusion is that the required number of wavelengths for given traffic demands is greatly dependent on degree of network connectivity and the applied route selection principle. Therefore, the software that is developed for simulation purposes is able to provide the best results for the complex optimisation RWA problem for any topology and for concrete values of traffic demands in particularly considered real optical communication network.

V. CONCLUSION

The optical WDM networks employing wavelength routing are considered as the most promising solution for future telecommunication infrastructure. The routing and wavelength assignment problem is one of the most significant problems in designing such networks. Efficiently resolved RWA problem can greatly improve the using of network resources. Therefore, the optimal resolving of RWA problem is crucial task. With this aim, we developed the software that simulates the routing and wavelength assignment problem, based on integer linear programming optimisation. The input parameters of our software are the traffic demand matrix in the form of the required number of connection requests and the concrete physical network topology. The software outputs are the routes and assigned wavelengths for established connections. The objective of applied optimisation model is to minimize the required number of wavelength in the given WDM network topology. We tested our model on different network topologies to illustrate how the network connectivity affects to the network resources utilisation. Developed software can be efficiently applied on any given network topology in the case of small network dimensions.

ACKNOWLEDGEMENT

This paper is a result of researching project sponsored by the Ministry of Science and Environment Protection of Republic of Serbia.

REFERENCES

[1] C. S. Ram Murthy, M.Gurusamy, *WDM Optical Networks - Concepts, Design and Algorithms*, Prentice Hall, 2002.

[2] B. Mukherjee, “WDM Optical Communication Networks: Progress and Challenges” *IEEE Journal on Selected Areas in Communications*, Vol.18, No.10, pp. 1810-1824. October 2000.

[3] A. Marinčić, V. Aćimović-Raspopović, »Evolution of WDM Optical Networks«, Facta Universitatis, Series: electronic and energetics, Vol.14, No. 2, August 2001.

[4] P. Kaminow et al., “A Wideband All-Optical WDM Network”, IEEE J.Select. Areas Commun., vol.14, no.6, pp.780-799, June 1996.

[5] Rajiv Ramaswami, Kumar N. Sivarajan,”Design of Logical Topologies for Wavelength-Routed Optical Networks”, *IEEE J. Select. Areas Commun.*, vol.14, no.6, pp.840-851, June 1996.

[6] R. Ramaswami, K.N. Sivarajan, “Routing and Wavelength Assignment in All-Optical Networks”, *IEEE/ACM Transaction on Networking*, vol.3, no.5, pp.489-500, October 1995.

[7] V. Aćimović-Raspopović, G. Marković, „ Routing in Optical WDM Network“, *Proc. of TELFOR Conference*, 2003, (original in Serbian), available at www.telfor.org.yu