Solving the RWA Problem in WDM Optical Networks Using the BCO Meta-Heuristic

Goran Z. Marković and Vladanka S. Aćimović-Raspopović

Abstract — **This paper researches the *routing and wavelength assignment* (*RWA*) problem in wavelength routed optical *WDM* networks with the wavelength conversion capability at different network nodes. We studied the static case in which all connection requests are known in advance, thus a routing decision can be made based on the complete knowledge of the traffic to be served by the network. The *Bee Colony Optimization* (*BCO*) metaheuristic is applied to solve the *RWA* problem. We carried out a comprehensive simulation study of the performance of the proposed *BCO-RWA* algorithm for different network topologies and traffic scenarios. The obtained simulation results are analyzed and compared.**

Keywords — **lightpath, optical *WDM* network, routing and wavelength assignment (*RWA*), wavelength conversion.**

I. INTRODUCTION

THE emerging demand for advanced broadband Internet applications requires excessive network capacities which can be effectively achieved by Wavelength Division Multiplexing (*WDM*) technique. *WDM* brings out new problems in coordination of wavelengths usage in optical network [1]. Each wavelength represents the independent communication channel, called a lightpath, carrying the information with data rates up to 40 Gb/s. When it is necessary to establish a lightpath between two network nodes, a route has to be chosen and the particular wavelength has to be assigned. This problem is known as the routing and wavelength assignment (*RWA*). If the wavelength conversion is not available in network nodes, a lightpath has to be set up by assigning the same wavelength over each physical link along the route. This is known as the wavelength continuity constraint. Wavelength conversion in a node allows the lightpaths to be established by using different wavelengths along the route sections between end nodes.

The *RWA* problem takes two forms: static and dynamic [1]. In the static case, all connection requests are known in advance, thus a routing decision can be made based on the complete knowledge of the traffic to be served by the network. The static *RWA* problem is found to be NP-complete that cannot be solved exactly in a polynomial

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time. In the dynamic case, a connection request has to be routed and wavelengths assigned independently of other connections, which either have already been assigned or will be assigned [1]-[3].

We concentrate here on the static version of the *RWA* problem in which the objective is to maximize the number of established lightpaths, also known as the *Max-RWA* problem. The *Max-RWA* problem could be formulated as an integer linear program (ILP). The optimal solution is difficult to reach, especially in the cases of large network dimensions [4], [5]. A number of papers devoted to the *RWA* problem proposed various both exact and heuristic approaches. A detailed survey of different *RWA* methods can be found in [6].

In this paper, we used heuristic *RWA* algorithm, based on the *Bee Colony Optimization (BCO)* meta-heuristic, recently proposed in [7]. The *BCORWA* heuristic algorithm is tailored for the *Max-RWA* problem in all-optical *WDM* mesh networks. The proposed algorithm has been able to produce high quality solutions in a reasonable computation time.

The paper is organized as follows. In section II, we state the problem. Section III gives a concise description of proposed *BCO-RWA* algorithm. Section IV is devoted to the numerical experiments and the obtained simulation results. Finally, the conclusion is given in Section V.

II. PROBLEM STATEMENT

The *Max-RWA* problem that we solved in [8] can be defined in the following way: for a given traffic demand matrix (the number of requested lightpaths between network node pairs) and a given number of available wavelengths, maximize the number of established lightpaths in a given physical optical *WDM* network. We assumed that the wavelength conversion is allowed at one network node. It means that a lightpath can operate on the same wavelength across all fiber links along the route (a lightpath satisfies the wavelength continuity constraint) or on different wavelengths before and after the node equipped with the wavelength converter (if the wavelength conversion is performed).

We assume that a given optical *WDM* network is a single fiber which means that each physical link has one separate fiber for each direction of transmission. Each fiber supports the same number of wavelengths W. An optical *WDM* network composed of N nodes and L physical links can be represented by a corresponding graph with N nodes and L undirected edges. No two lightpaths traversing through the same physical link (i, j)

will have the identical wavelength assigned to them. The goal of this research is to study the impact that converter placement at one node has on the number of established lightpaths in a given optical network topology.

We solve the defined problem using the heuristic *RWA* algorithm based on *BCO* (bee colony optimization) metaheuristic, which is concisely described in Section III. The artificial bee colony behaves partially alike, and partially differently from bee colonies in nature and represents the new metaheuristic capable of solving difficult combinatorial optimization problems. For a more detailed explanation about the *BCO* metaheuristic see [9].

III. THE BCO-RWA ALGORITHM

In this section, we describe the *BCO* metaheuristic *RWA* algorithm, tailored for the Max-*RWA* problem [8]. We call the proposed algorithm the *BCO-RWA*. The agents that we call- *artificial bees* collaborate in order to solve the Max-*RWA* problem. Let us represent every requested lightpath by a node in artificial network, as shown in Figure 1. We have grouped all the requested lightpaths in stages. The first lightpath to be established represents the first stage, the second lightpath to be established represents the second stage, etc. We determine in advance the number of bees B and the number of iterations I. All artificial bees are located in the hive (square shown in Figure 1) at the beginning of the search process. When flying through the space (by visiting artificial nodes in the network shown in Figure 1) our bees perform *a forward pass* or *a backward pass*. During one forward pass every bee visits s unvisited nodes (bee tries to establish s new lightpaths) and create its partial solution. After that, bees perform *a backward pass*, i.e. they return to the hive. The number of nodes s to be visited during one forward pass is prescribed by the analyst at the beginning of the search process.
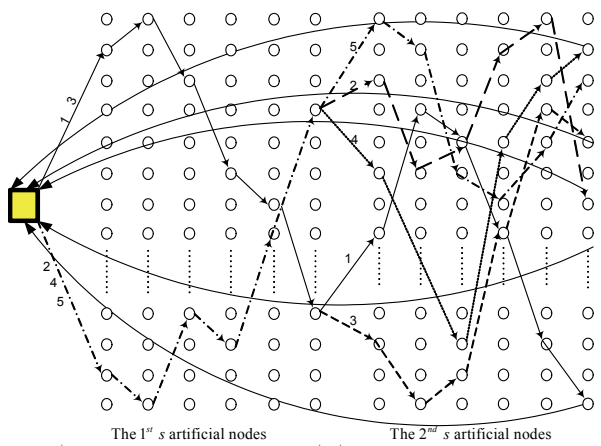

Fig. 1. Bee's flying through the artificial network.

In the hive, all bees participate in a *decision-making* process. Bees *exchange* information about quality of the partial solutions created and compare all generated partial solutions. Based on the quality of the partial solutions generated, every bee decides whether to abandon the created partial solution (bees B_2, B_3, and B_4 in the example illustrated in Figure 1), and become again an uncommitted follower, or dance (bees B_1 and B_5) and thus recruit the nestmates before returning to the created partial solution. Depending on the quality of the partial solutions generated, every bee possesses a certain level of *loyalty* to the path leading to the previously discovered partial solution. Figure 1 illustrates the situation in which bee B_3 joined bee B_1, and bees B_2, and B_4 joined bee B_5. During the second forward pass bees B_3, and B_1 fly together along the path generated by the bee B_1, while bees B_2, and B_4 fly together along the path generated by the bee B_5. When followers reach the end of the previously generated path, they are free to make individual decisions about the next node to be visited. During the second forward pass, bees expand previously created partial solutions (establish additional lightpaths), and after that perform again the backward pass and return to the hive. In the hive bees again participate in a decision-making process, perform the third forward pass, etc.

The *iteration* ends when one or more feasible solutions of the Max-*RWA* problem are created. The best discovered solution during the first iteration is saved, and then the second iteration begins. Within the second iteration, bees again incrementally construct solutions of the problem, etc. There are one or more created partial solutions at the end of each iteration. Parameter s reflects the granularity of the search process.

A. Bees node and route choice mechanisms

Bees choose some of the artificial nodes (not previously visited) in a random manner. Probability p that a specific unvisited artificial node will be chosen by the bee equals $1/n_{tot}$, where n_{tot} is the total number of unvisited artificial nodes. By visiting a specific artificial node in the network shown in Figure 1 bees attempt to establish the requested lightpath between one real source-destination node pair in optical network. Let us assume that the specific bee decided to consider the lightpath request between the node s and the node d. In the next step, it is necessary to choose the route and to assign an available wavelength along the route between these two real nodes. In this paper, we defined for every node pair (s,d), the subset R^{sd} of allowed routes that could be used when establishing the lightpath. We defined these subsets by using the k shortest path algorithm. We calculated for every of the k alternative routes the bee's utility when choosing the considered route. The shorter the chosen route and the higher the number of available wavelengths along the route, the higher is the bee's utilities. We define the bee's utilities V_r^{sd} when choosing the route r between the node pair (s,d) in the following way:

$$V_r^{s,d} = \left\{ a \frac{1}{h_r - h_{r\min} + 1} + (1-a) \frac{W_r}{W_{\max}} \right. \tag{1}$$

where:
r – the route ordinary number for the node pair (s,d),
$r=1,2,...k,\ r \in \left\{ R^{sd} \right\}$,
h_r – the route length expressed in the number of physical hops (or links),
$h_{r\min}$ – the length of the shortest route r,

W_r – the number of available wavelengths along the route r,

$W_{\max} = \max\limits_{r \in R^{sd}} \{W_r\}$ – the maximum number of the available wavelengths among all the routes $r \in R^{sd}$,

a – weight (importance of the criteria), $0 \le a \le 1$.

Bees decide to choose a physical route in optical network in a random manner. Inspired by the well-known Logit model (one of the most successful and widely accepted discrete choice models), we have assumed that the probability p_r^{sd} of choosing route r in the case of origin-destination pair (s,d) equals:

$$p_r^{sd} = \begin{cases} \dfrac{e^{V_r^{sd}}}{\sum\limits_{i=1}^{\left|R^{sd}\right|} e^{V_i^{sd}}}, & \forall r \in R^{sd} \ \text{i} \ W_r > 0 \\[4mm] 0, \forall r \in R^{sd} \ \text{i} \ W_r = 0 \end{cases} \qquad (2)$$

where $\left|R^{sd}\right|$ is the total number of available routes between pair of nodes (s,d). The route r is available if there is at least one available wavelength on all links that belong to the route r. The random number is generated from the interval $[0, 1]$ for every route of the node pair (s,d). Using these random numbers and the equation (2), bee is assigned to one of the considered routes. In the next step, the available wavelength is assigned to the lightpath along the route chosen by the bee, using the *random* strategy. If the lightpath cannot be established using the same wavelength along the route, after that the wavelength conversion is tried at one network node in order to establish it.

B. Bee's partial solutions comparison mechanism

In the hive every bee makes the decision about abandoning the created partial solution or expanding it in the next forward pass. The probability that the bee b will at the beginning of the $u + 1$ forward pass use the same partial tour that is defined in forward pass u equals:

$$p_b^{u+1} = e^{-\frac{C_{\max} - C_b}{u}} \qquad (3)$$

where:
C_b – the total number of established lightpaths from the beginning of the search process by the b-th bee,
C_{max} – the maximal number of established lightpaths from the beginning of the search process by any bee,
u – ordinary number of forward pass, $u=1,2,...,U$.

The smaller the number of the established lightpaths by the bee, the smaller is the probability that the bee will fly again along the same path. The smaller the ordinary number of the forward pass u (beginning of the search process) the higher the bees "freedom of flight".

The random number z is generated from the interval $[0, 1]$. When $z \le p_b$ bee will fly along the same partial tour. In the opposite case, when $z > p_b$ bee will abandon the created partial solution and become an uncommitted follower.

C. Recruiting process

After making the decision to continue flight along the previously generated path, the bee flies to the dance floor area in the hive and starts dancing. Within the dance area, the bee dancers "advertise" different partial solutions. In the case when at the beginning of stage $u + 1$, bee does not want to fly along the same path, the bee will go to the dancing area and will follow another dancing bee. In this way, two groups of bees are formed in the dancing area – *uncommitted followers* ready to join some of the dancing bees, and *dancing bees* ready to recruit uncommitted followers. The probability p_P that the P-th advertised partial solution will be chosen by any of the uncommitted follower equals:

$$p_P = \frac{e^{C_P}}{\sum\limits_{p=1}^{P} C_p}, \qquad (4)$$

where:
C_P – the total number of the established lightpaths in the case of the P-th advertised partial solution,

The random number is generated from the interval $[0, 1]$ for every uncommitted follower. Using these random numbers and the equation (4) every uncommitted follower is «assigned» to one of the dancing bees. In this way, the number of bees flying along a specific path is changed before the beginning of the new forward pass. Using collective knowledge and sharing information among themselves, bees concentrate on more promising search paths, and slowly abandon less promising paths.

IV. NUMERICAL EXPERIMENTS AND RESULTS COMPARISON

The proposed *BCO-RWA* algorithm is used to solve the *Max-RWA* problem in *WDM* optical network in a case of static traffic demands with the wavelength conversion capability at one network node. Since the reasonable goal is to minimize the total number of conversions at a network node, the wavelength conversion is allowed only for the lightpaths, otherwise cannot be established with the wavelength continuity constraint satisfied. For this purpose, a particular program code was developed in MATLAB software package.

The *BCO-RWA* algorithm was tested for various optical network physical topologies and traffic demand scenarios. In this section, we present some computational and comparative results for 2 different network topologies. For both networks, we assumed that each edge (link) represents a pair of directed fiber, one for each direction. We assumed also that the maximal number of available wavelengths W is the same for each fiber link. We run the *BCO-RWA* program code in both cases by assuming that the total number of engaged bees is $B=10$ and the number of independent algorithm iterations is $I=10$. The best results obtained throughout these iterations are used.

A. Case study #1

The first considered optical *WDM* network topology is a mesh network shown in Fig. 2.

Traffic demands between node pairs are randomly generated numbers chosen between the boundaries values $[1, 10]$ with the uniform probability. A randomly generated traffic scenario used in this numerical
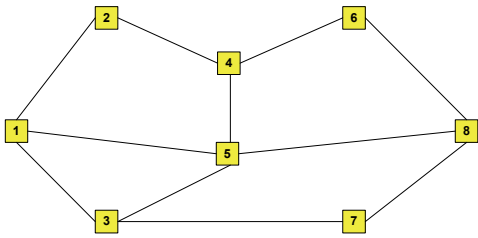
Fig. 2. The optical network topology with 8 routing nodes.

experiment, with the total number of requested lightpaths equal to 300 is given by the following matrix D^1:

$$D^1 = \begin{array}{c|cccccccc} i/j & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 0 & 2 & 6 & 6 & 1 & 10 & 7 & 4 \\ 2 & 4 & 0 & 9 & 5 & 1 & 2 & 8 & 6 \\ 3 & 5 & 5 & 0 & 1 & 9 & 10 & 4 & 6 \\ 4 & 5 & 6 & 5 & 0 & 8 & 4 & 7 & 8 \\ 5 & 5 & 4 & 6 & 5 & 0 & 3 & 3 & 7 \\ 6 & 8 & 9 & 3 & 3 & 9 & 0 & 2 & 10 \\ 7 & 3 & 2 & 3 & 7 & 2 & 7 & 0 & 6 \\ 8 & 5 & 1 & 6 & 9 & 4 & 8 & 6 & 0 \end{array}$$

We assumed that the number of alternative routes between each node pair is limited to $\left|R^{sd}\right|$=5. The alternative routes for each node pair are specified in advance by using the shortest path algorithm. The routes are sorted in an increasing order according to the number of hopes (links).

The optimization results for the considered network topology are given by Fig. 3 to Fig. 8. Fig 3 illustrates the total number of established lightpaths in a given network for various numbers of available wavelengths W and different numbers of alternative routes R, if the wavelength conversion is not allowed at network nodes.

It can be seen that the total number of established lightpaths depends to a great extent on the number of available wavelengths as well as on the number of alternative routes between a node pair. The smaller the number of alternative routes, the greater is the number of established lightpaths. The reason is the lightpaths are allowed to use shorter routes (with a smaller number of links) if the number of alternative routes is smaller.

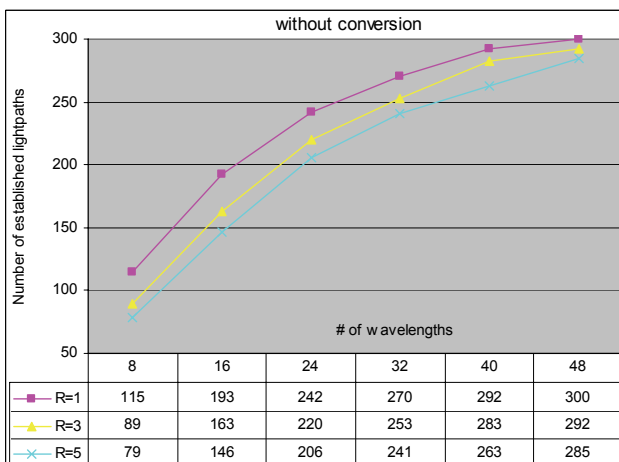| without conversion						
# of wavelengths	8	16	24	32	40	48
R=1	115	193	242	270	292	300
R=3	89	163	220	253	283	292
R=5	79	146	206	241	263	285

Fig. 3. The number of established lightpaths without wavelength conversion.

In addition, a similar conclusion can be found when the wavelength conversion is performed at a network node.

Fig. 4 illustrates such results in a case of wavelength conversion at node 5.

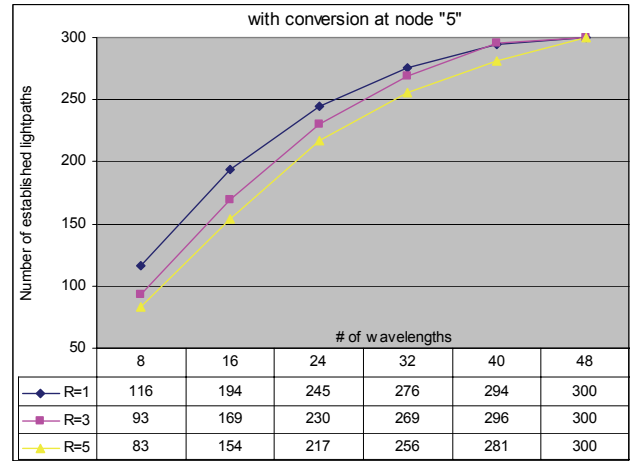| with conversion at node "5"						
# of wavelengths	8	16	24	32	40	48
R=1	116	194	245	276	294	300
R=3	93	169	230	269	296	300
R=5	83	154	217	256	281	300

Fig. 4. The number of established lightpaths with wavelength conversion at node 5.

The comparison of the total number of established lightpaths in the considered network, with and without the wavelength conversion at node 5 for different values of available wavelengths can be obtained from Fig 5.

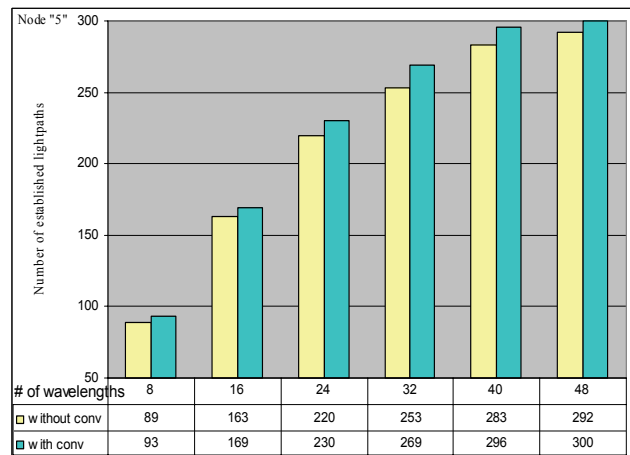| # of wavelengths	8	16	24	32	40	48
without conv	89	163	220	253	283	292
with conv	93	169	230	269	296	300

Fig 5. Total number of established lightpaths with and without wavelength conversion at node 5.

Fig. 6 illustrates more evidently the variation between the number of established lightpaths (or conversion gain) when the conversion is performed at node 5.

Furthermore, the location of the converter in a given network also has the influence on the number of established lightpaths. Therefore, one of the crucial problems is to find the best node(s) location for the converter placement. This is an optimization problem that has to be solved additionally. For simplicity, we restricted here to the instance of only one node equipped with a converter in order to investigate the potential effects of the wavelength conversion practice in an optical *WDM* network.

Fig. 7 shows the comparative results for the established number of lightpaths when the converter is placed at different routing nodes in the considered network. It can be seen that significant upgrading could be obtained by locating a wavelength converter at every network node. The best results (the maximum number of established lightpaths) for the assumed traffic scenario could be

obtained in the case of node 3. The differences between the cases without wavelength conversions (for different considered nodes) are the result of independent individual simulations. More precisely, each simulation for a considered node (integrating the cases with and without the converter) is performed fully separately, one by one. The percentage conversion gain obtained throughout these simulations is given by Fig. 8.
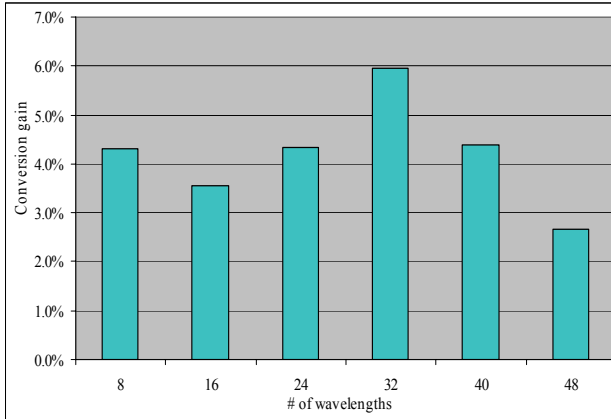

Fig. 6. The conversion gain with converter placement at node 5.

B. Case study #2

The second considered *WDM* network topology, illustrated by Fig. 9, could reflect on a part of national backbone telecommunication infrastructure. We try also to solve the *Max-RWA* problem for this network topology by using the *BCO-RWA* algorithm and to investigate the wavelength conversion effects on the number of established lightpaths in a given network. We predefined at most 2 possible shortest routes for each node pair.

The traffic demands between node pairs are assumed to be as given by the following matrix D^2.

i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	5	1	1	1	3	1	1	1	1	1	1	1	1	3	1	1	1
2	5	0	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1
3	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
$D^2 =$ 9	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
15	3	3	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

The optimization results for this network example are illustrated by Fig. 10. to Fig. 13.

It can be seen from the obtained results that the conversion gain of a few percent could be achieved by placing a converter in only one network node. In all performed numerical experiments, the number of conversions is to be minimized. Therefore, the obtained results represent only the minimal possible conversion gain that could be achieved. The improvements could be still enhanced if the conversion would be allowed in more than one node, which will be the topic of our future research.
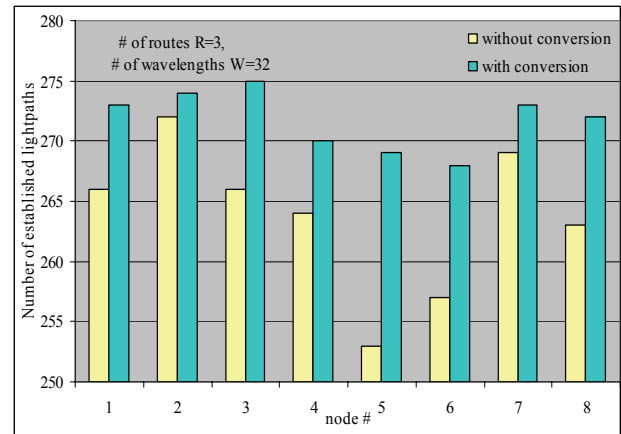

Fig. 7. The number of established lightpaths with and without wavelength conversion at various network nodes.
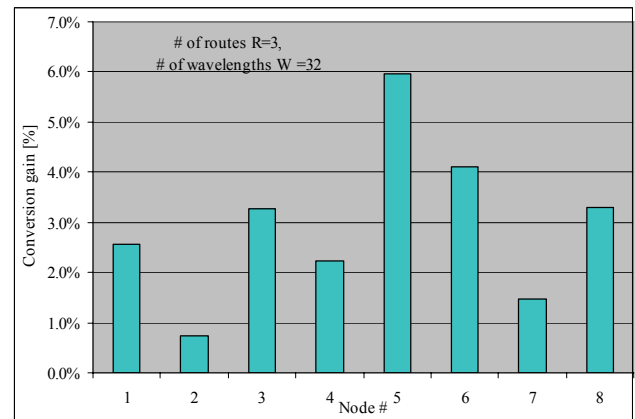

Fig. 8. Conversion gain obtained with a converter placement at different network nodes.
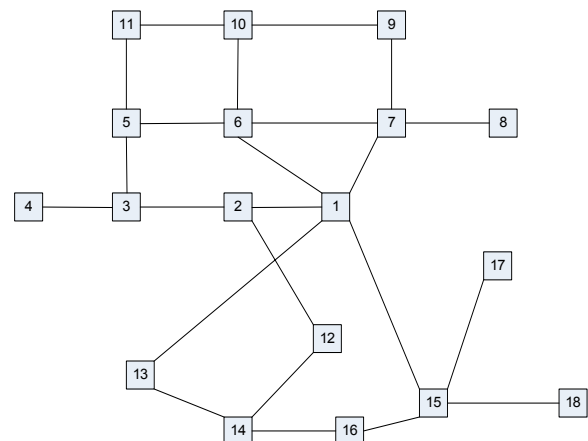

Fig. 9. A mesh WDM optical network with 18 nodes.

V. CONCLUSION

RWA problem belongs to a class of difficult combinatorial optimization problems. The proposed *BCO-RWA* algorithm has been able to produce optimal or near-optimal solutions in a reasonable computation time. The results obtained by applying this algorithm show that the number of established lightpaths could be improved significantly compared to other previously proposed algorithms.
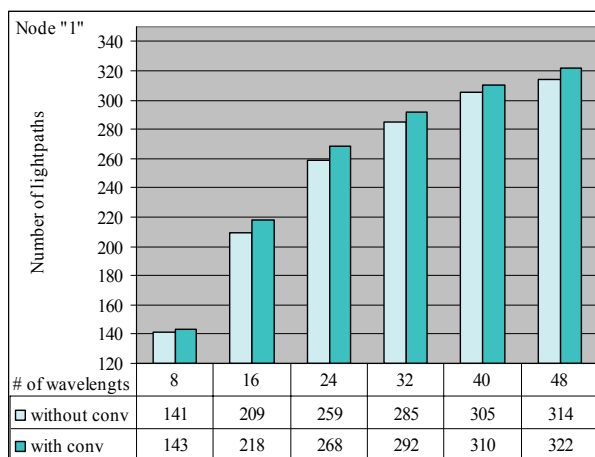
Fig. 10. The total number of established lightpaths with and without the conversion at node 1.
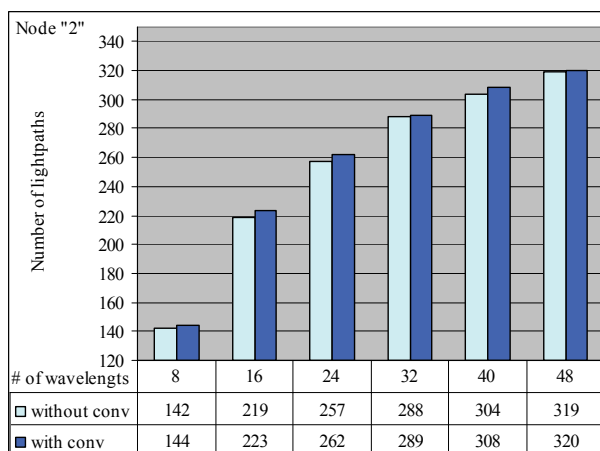
Node "1" # of wavelengts	8	16	24	32	40	48
□ without conv	141	209	259	285	305	314
■ with conv	143	218	268	292	310	322

Fig. 12. The total number of established lightpaths with and without the conversion at node 6.

Node "6" # of w avelengts	8	16	24	32	40	48
□ w ithout conv	142	211	264	289	308	319
■ w ith conv	144	216	264	289	308	319

Fig. 11. The total number of established lightpaths with and without the conversion at node 2.

Node "2" # of wavelengts	8	16	24	32	40	48
□ without conv	142	219	257	288	304	319
■ with conv	144	223	262	289	308	320

Fig. 13. Conversion gain for various numbers of available wavelengths.

Moreover, this paper researches the effects of wavelength conversion procedure at different node locations. Many simulations are performed and the obtained results are compared in the case of two network examples. The simulation results show that wavelength conversion at one network routing node could improve slightly the network traffic performances. Our further investigations would be focused on solving the optimization problem concerned with the determination of the best node locations for placing more than one converter, which also stands for challenge one.

REFERENCES

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

[2] A. E. Ozdaglar and D. P. Bersekas. "Routing and wavelength assignment in optical networks," *IEEE/ACM Trans on Netw*, vol. 11, no. 2, pp.259–272, Apr. 2003.

[3] V. Aćimović-Raspopović, G. Marković "Routing in Optical *WDM* Networks," *Invited paper, Proceedings of X TELFOR Conference* (CD), Belgrade, Nov 2003.

[4] B. Jaumard, C. Meyer, B. Thiongane, Y. Xiao, "ILP formulations and optimal solutions for the *RWA* problem," *Proc. IEEE GLOBECOM'04 Conf.*, vol.3, pp. 1918-1924, Dec. 2004.

[5] G. Marković, V. Aćimović-Raspopović, D. Teodorović, "Optimal routing and wavelengt assignment in optical networks," *Proc. of the 50-th ETRAN Conf.*, pp. 120-123, Belgrade 2006.

[6] H. Zang, J. P. Jue, and B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical
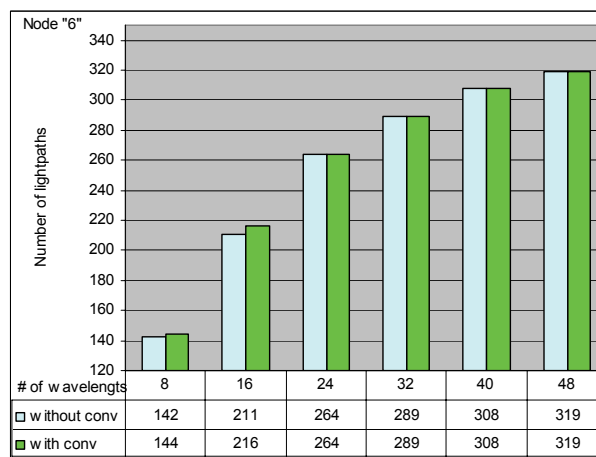
WDM networks," *SPIE Opt. Netw. Mag.*, vol.1, pp.47–60, Jan. 2000.

[7] G. Marković, D. Teodorović, V. Aćimović, "Routing and Wavelength Assignment in All-Optical Networks Based on the Bee Colony Optimization," *AI Communications – Special Issue: Network Analysis in Natural Sciences and Engineering*, Vol.20, No.4, pp. 273-285, Nov. 2007.

[8] G. Marković, V. Aćimović-Raspopović „Solving the *RWA* problem in *WDM* networks using the *BCO* metaheuristic," *XVII TELFOR Conferene, CD Proceedings*, pp.720-723, nov 2009, Belgrade.

[9] D. Teodorović, P. Lučić, G. Marković, Mauro Dell' Orco, "Bee Colony Optimization: Principles and Applications," *Proc. on 8th NEUREL Conference* 2006, pp.151-156. Belgrade, Sept. 2006.

[10] R. Ramamurthy and B. Mukherjee, "Fixed-alternate routing and wavelength conversion in wavelength-routed optical networks," *IEEE/ACM Trans. Netw*, vol. 10, no. 3, pp. 351–367, Jun. 2002.

[11] X. Chu, B. Li, and I. Chlamtac, "Wavelength converter placement under different *RWA* algorithms in wavelength-routed all-optical networks," *IEEE Trans. Commun.*, vol. 5, no. 4, pp. 607–617, Apr. 2003.

[12] E. Karasan and E. Ayanoglu, "Effects of wavelength routing and selection algorithms on wavelength conversion gain in *WDM* optical networks," *IEEE/ACM Trans. Netw.*, vol. 6, no. 2, pp. 186–196, Apr. 1998.

[13] V. Aćimović-Raspopović, "A procedure of wavelength rerouting in optical *WDM* networks," *Proc. of IEEE TELSIKS Conference,* Vol. 1, pp. 303-306, Nis, 2005.

[14] G. Marković "*Optimization of the resource usage in optical wavelength routing networks*," PhD thesis, University of Belgrade – Faculty of Trafic and Transport Engineering, Belgrade 2007.

[15] M. Pioro, D. Medhi, Routing, *Flow, and Capacity Design in Communication and Computer Networks*, Elsevier, 2004.