TSCP: A Tabu Search Algorithm for Wavelength Converting Node Placement in WDM Optical Networks

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Abstract **Sparse wavelength conversion can increase the performance of all-optical wavelength division multiplexing (WDM) networks signi cantly by relaxing the wavelength continuity constraint. In this paper, we study the wavelength converter placement problem in multi- ber networks with static traf c demands. We present a tabu search based heuristic algorithm. The objective of the algorithm is to satisfy all the traf c demands with the minimum total cost of bers achieved in the full conversion case, by placing minimum number of wavelength converting nodes. We also implement a greedy algorithm and compare the performances of these converter placement algorithms with the optimum solutions on a sample network. The Tabu search based algorithm achieves the optimum solution in 72% of the test cases and it increases the average number of wavelength converting nodes by less than 10% with respect to the optimum solution. The effect of the utilized routing scheme on the generated solutions and the correlation between the converter node locations and the amount of traf c passing through the nodes are also investigated.**

I. Introduction

All-optical Wavelength Division Multiplexing (WDM) Networks offer a solution to the growing requirement of high speed data transmission. By carrying the routing and switching functions into the optical domain, the need for optical-to-electrical conversion and electronic processing of data is eliminated. Thus, faster switching times, cost reduction and transparency are achieved in the network. In all-optical networks, the data is transmitted along lightpaths and each lightpath should occupy the same wavelength on all the fibers along its path. This restriction is known as the wavelength continuity constraint, and it degrades the performance of the network by causing wavelength mismatch blockings. Due to this constraint, a request will be blocked if there is no wavelength which is free on every link along the path, even though the capacities of the links are not exceeded.

The wavelength continuity constraint can be eliminated using wavelength converters, which are devices that can translate the incoming optical signal on one wavelength to another wavelength at the outgoing port. For transparent all-optical networks, use of optical wavelength converters that can achieve the wavelength translation completely in the optical domain is necessary. However the high cost of these devices makes it inefficient to equip each node in the network with wavelength converters, called full wavelength conversion. One solution to this problem is placing wavelength converters at only some of the nodes in the network, and the resulting architecture is called sparse wavelength conversion.

The converter placement in networks with sparse wavelength conversion addresses the problem of determining the best locations for placing wavelength converting nodes. This problem can be classified into two main classes according to the traffic type: static and dynamic traffic.

For the dynamic traffic case, the objective is generally to minimize the overall blocking probability in the network. In [1] and [2], it is shown that the minimum blocking probability can be achieved with the uniform placement of the wavelength converting nodes, if the link loads are uniform. For independent link loads, the end-to-end blocking probability on a path is minimized when the path is divided into segments with equal blocking probabilities and heuristic algorithms to accomplish this are presented in [2]. In [3] and [4], the relationship between RWA and converter placement algorithms is considered and heuristic converter placement and wavelength assignment algorithms are presented. Different heuristics for placing the converters according to the traffic statistics are proposed [5], [6] and [7]. There are also proposed solutions employing genetic algorithms in [8], [9].

Most of the studies investigating wavelength converter placement under static traffic consider single-fiber networks. In these studies, the objective is either to reduce the number of wavelengths required to satisfy all the connection requests

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by placing a fixed number of converters or to satisfy all the requests using the same number of wavelengths required in the full conversion case, which is equal to the maximum link load. The problem of satisfying any traffic demand matrix that can be routed under full wavelength conversion using the same number of wavelengths by employing sparse wavelength conversion is studied in [10]–[12]. It is assumed in these studies that the routing of the lightpaths is known. The optimum converter placement problem is proven to be NP-complete for general topologies, but in [10], it is shown that it can be solved in polynomial time for bi-directed networks with tree of rings topology. This result is generalized also to directed networks of tree of rings [11]. The same problem is studied in [12] for networks with general topologies, and it is shown that for duplex communication channels, it can be solved in polynomial time. An approximation algorithm for unidirectional channels, for which the problem is NP-complete, is also proposed.

In [13], an ILP model including path protection is presented to minimize the number of converters necessary to route all the demands with a number of wavelengths equal to the maximum link load. For the same objective, heuristic algorithms are proposed in [14] and [15]. In [14], the converters are placed one by one to the nodes with highest transit traffic until the target number of wavelengths is reached. A greedy method is proposed in [15], the lightpaths are processed one-by-one and if no available wavelength is found for a lightpath, the wavelength assignment is achieved by placing converters. [16] investigates the problem of placing a given number of converters in ring networks and compares the performances od three algorithms using Genetic Algorithms (GA), Simulated Annealing (SA) and Tabu Search (TS). It is stated that the algorithm using GA method gives the best performance amon all three.

All the studies mentioned above considers single fiber links and ignores the benefits of using multiple fibers. In [17] and [18], multi-fiber networks are considered and the total cost of the fibers is minimized. In these studies, the objective is to satisfy all the demands using the same number of fibers with the minimum total cost as in the full conversion case. A heuristic method is presented in [17], placing the converters to the end nodes of the links which contain more fibers than needed in the full conversion case. In [18], a similar approach to the one used in this paper is proposed. First, the routing problem is solved by ignoring the wavelength continuity constraint with the objective that total fiber cost in the network is minimized. Then, wavelength assignment and converter placement problems are solved by utilizing ILP. However, as the network size, the number of wavelengths and the number of demands increase, the number of variables in the ILP formulation increase quickly and it may not be possible to obtain the optimum solution for large networks.

Using multiple fibers on the links can significantly increase the performance of the network [19]–[21]. In this paper, we assume multi-fiber networks with a fixed number of wavelengths per fiber and static traffic demands. Our objective is to find the locations of the minimum number of wavelength converting nodes necessary to satisfy all the demand requests with the same total cost of fibers obtained in a network having full wavelength conversion capability. We assume that the wavelength converting nodes have complete wavelength conversion capability where each port of the optical cross-connect is assigned with a dedicated wavelength converter. We propose a Tabu Search (TS) based heuristic algorithm for this problem. In our solution technique, the routes and number of fibers needed on each link are calculated first by Integer Linear Programming (ILP), assuming that all nodes have wavelength conversion capability. The Tabu Search Converter Placement (TSCP) algorithm uses these routes and the proposed Reordered Longest Path First (RLPF) wavelength assignment algorithm. TSCP algorithm places the wavelength converting nodes in a way to satisfy all the demand requests by utilizing the same number of fibers with the minimum total cost as calculated assuming full conversion. We also implement a simple converter placement algorithm using greedy search method which generates solutions for comparison. The performances of these algorithms are compared with the optimum solutions presented in [18] for a mesh network. The effect of the routing algorithm is also investigated by considering different ILP formulations for the routing subproblem. The relationship between the amount of traffic passing through each node and the likelihood of placing a converter at that node is also investigated.

The remainder of the paper is organized as follows. Section II describes the routing and wavelength assignment algorithms used. The greedy and tabu search algorithms proposed for the wavelength converting node placement are introduced in Section III. In Section IV, numerical results are given on a sample network and comparison of the two wavelength converter algorithms with the optimum solutions is made. Finally, we make the concluding remarks in Section V.

II. Routing and Wavelength Assignment (RWA)

Since our objective is to determine the minimum number of wavelength converting nodes that are necessary to achieve the minimum fiber cost with full conversion, we just solve the routing subproblem once assuming full wavelength conversion for obtaining the optimum routing configuration achieving the minimum fiber cost. On the other hand, the wavelength assignment problem is solved at each iteration of the TSCP algorithm for different combinations of the wavelength converting nodes.

A. Routing Problem - ILP Formulation

Our objective in this work is to use the same number of fibers obtained with the full wavelength conversion. Therefore, the routing problem is solved assuming full conversion, without the consideration of the wavelength continuity constraint. We use the optimum routes calculated by a flow-based formulation presented in [18]. We also utilize a path-based ILP formulation for this problem.

In our formulation, the undirected graph $G = (N, L)$ represents the network topology with N being the set of nodes and L being the set of links. C_l denotes the cost of installing a fiber on link l, and the decision variable f_l denotes the number of fibers that will be installed on link l. The set of the first k shortest paths (the length of link l is taken as C_l) between the node pair z is denoted as P_z. The paths in P_z can be computed by using the algorithm by Yen and Lawler [22], which has a computational complexity of $O(k|N|^3)$ where $|N|$ denotes the number of nodes in G. Let Z represent the node pairs with at least one lightpath request between them and D represent the set of lightpath demands. For a node pair z, d_z stands for the number of lightpath demands between the node pair z. The number of lightpaths used by the node pair z and lying on path $p \in P_z$ is represented by the decision variable X_{pz}. The number of wavelengths supported by each fiber is W, and j_{lp} is an element of the link-path incidence matrix where

$$j_{lp} = \begin{cases} 1 & if\ link\ l\ is\ on\ path\ p \\ 0 & otherwise \end{cases}$$

The path-based ILP formulation minimizing the total cost of fibers is given by

$$\text{Minimize} \sum_{l \in L} f_l \times C_l$$

Subject to

$$\sum_{p \in P_z} X_{pz} = d_z \quad \forall z \in Z, d_z \in D \quad \text{(demand constraints)}$$

$$\sum_{z \in Z} \sum_{p \in P_z} X_{pz} j_{lp} \leq W \times f_l \ \forall l \in L \ \text{(capacity constraints)}$$

$$f_l \in Z^+ \quad \forall l \in L$$

$$X_{pz} \in Z^+ \quad \forall z \in Z, \forall p \in P_z$$

The routes corresponding to lightpaths in the optimum solution are represented by the routing variables X_{pz}'s.

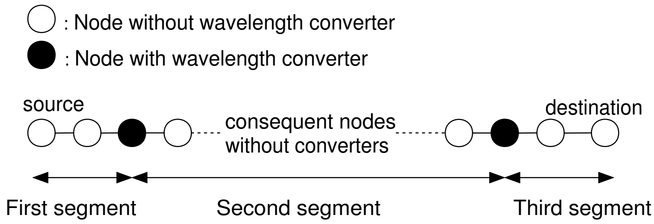

Fig. 1. Division of a lightpath into segments

B. Reordered Longest Path First (RLPF) Wavelength Assignment Algorithm

As mentioned in the previous section, at each step of the TSCP algorithm, the wavelength assignment is done from the beginning. Considering this fact, we utilize a heuristic algorithm, for the solution of the wavelength assignment problem. In the RLPF algorithm, first the number of fibers on each link is initialized to the number of fibers in the full conversion case, which is obtained from the solution of the routing subproblem. Then, all the lightpaths, for which the routes are obtained from the solution of the routing algorithm, are divided into segments between the source node, each subsequent wavelength converting node and the destination node as illustrated in Figure 1. For the full-conversion case, each segment corresponds to an individual link and for the no-conversion case, each segment corresponds to a lightpath.

These segments are then sorted according to their hop lengths in a descending order. Starting from top of the list, the first available wavelength is assigned to each segment. If there is no available wavelength for a segment, then this segment is moved to the top of the list, and all wavelength assignments are done from the beginning. This reordering is repeated for a maximum number of iterations denoted by $reorder\_number$. After $reorder\_number$ repetitions, if there is no available wavelength for a segment, the assignment of the wavelength to that segment is achieved by installing additional fibers. In order to achieve the wavelength assignment with a minimum increase in the total fiber cost, the wavelength which is not available on the links with minimum total cost is determined. The numbers of fibers on these links are incremented by one, the calculated wavelength is assigned to the segment, and the wavelength assignment is continued with the next segment in the list. The flowchart of the RLPF algorithm is shown in Figure 2.

The value of $reorder\_number$ has an important effect on the total cost of fibers in the solution. However, there is no simple relationship between this value and the cost of fibers. Reordering the list for a number of times may produce a worse solution (higher total cost of fibers) as it may produce better solution (lower total cost of fibers). To attain the best result, in our proposed solution for the wavelength assignment problem, this algorithm is run with

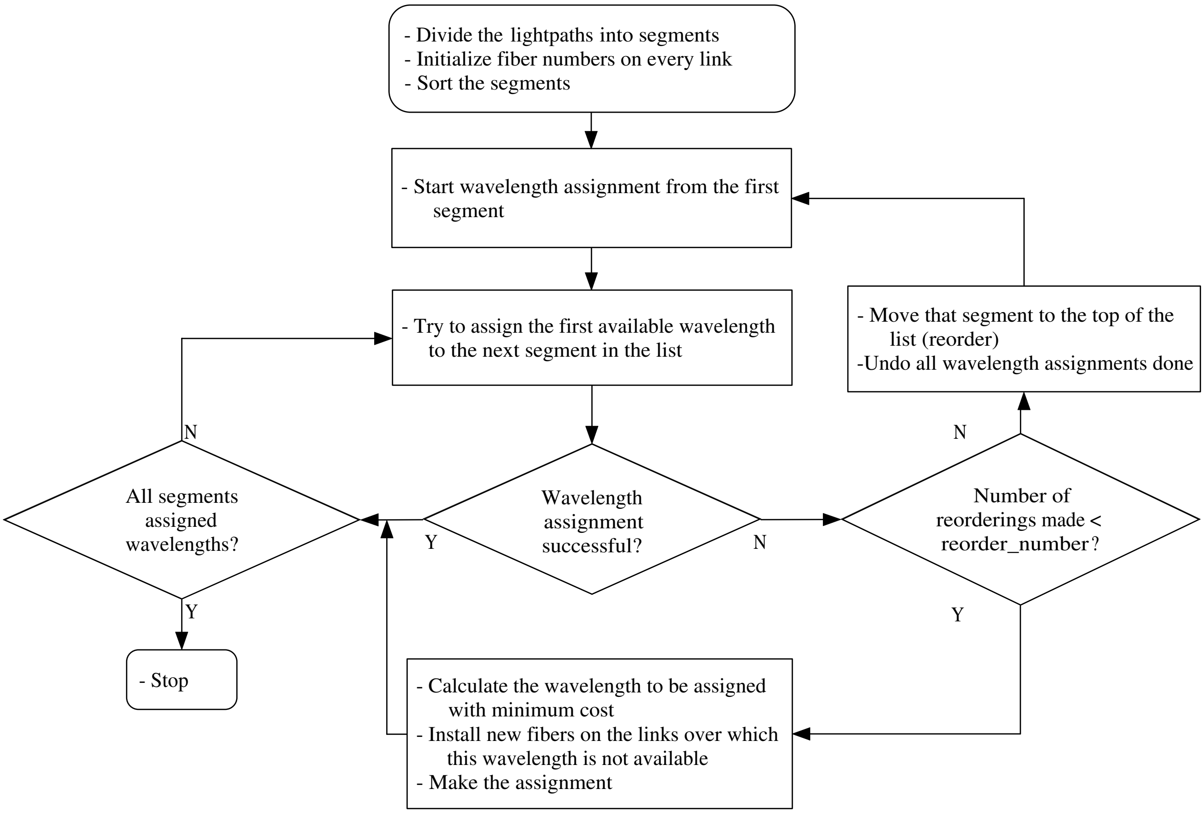

Fig. 2. Flowchart of the RLPF wavelength assignment algorithm

different values of $reorder\_number$ starting from 0 to a specified number called $reorder\_limit$. The flowchart for RLPF wavelength assignment algorithm is shown in Figure 2.

III. Wavelength Converting Node Placement

In this study, our objective is to satisfy a given set of lightpath requests using the same total cost of fibers as required in the case of full conversion by placing the minimum number of wavelength converting nodes. The routes of the lightpaths and the number of fibers required on each link in the full conversion case are obtained from the outputs of the routing solution described in Section II-A. For the converter placement problem, we propose a tabu search algorithm and also implement a simpler greedy search algorithm whose solutions are used for comparison. Both placement algorithms use the RLPF wavelength assignment algorithm.

A. Greedy Search Converter Placement (GSCP) Algorithm

The algorithm starts with no converting nodes in the network and places the converters one by one at each iteration. Each move in the algorithm consists of placing a converter at one of the non-converting nodes. For each non-converting node, the total cost of fibers required to satisfy all lightpath requests if a converter is placed at that node in addition to existing converting nodes, is calculated. The node for which the calculated total cost of fibers is the lowest is chosen for placing the next converting node. When there are multiple such nodes, one of them is chosen randomly. When the minimum cost of fibers with full conversion is attained, the algorithm stops. The GSCP algorithm is executed a number of times in order to generate multiple solutions, and the best one is reported.

B. Tabu Search Converter Placement (TSCP) Algorithm

Tabu Search is an iterative search procedure which was proposed by Glover [23] and has been used for a wide range of hard optimization problems from resource planning to telecommunications. Its distinctive feature is that, the non-improving moves are also allowed in order to escape the local optima. For avoiding entrapment in cycles, previously visited solutions are declared tabu for a number of iterations and the moves leading to tabu solutions are forbidden.

In TSCP algorithm, the search space consists of all possible converter placement configurations capable of satisfying all lightpath demand requests with the target minimum cost of fibers which corresponds to the optimum cost obtained assuming full conversion. The objective function is the number of converting nodes in the network. There are three types of possible moves in the TSCP algorithm: add move, drop move and exchange move. In an add move, a converter is placed to one of the non-converting nodes, a drop move consists of removing the converter from one of the converting nodes and an exchange move is a combination of these two moves: a converter is removed from a converting node and is placed at a non-converting node.

The initial solution of the TSCP algorithm can be any converter placement configuration achieving the target minimum cost of fibers. In this study, we use the full conversion configuration. At each step of the algorithm, the list of all feasible moves, that result in a converter placement configuration giving the target minimum cost of fibers and are not tabu, is created. If there are drop moves in the list, next move is chosen randomly among them. If there exists no possible drop move, the next move is chosen among the feasible exchange moves. If neither a drop nor an exchange move is feasible, the next move is chosen among the add moves. Improvement of the objective function is achieved by giving priority first to the drop moves and then to the exchange moves. Whenever a move is made, the move together with the existing configuration of converting nodes and a tenure value, is added to the tabu list. The tenure value is chosen randomly. At each step, after the move is made, the tenure values of the entries in the tabu lists are decreased by one, and the entries with 0 tenure value are removed from the lists. The best solution, which is the configuration with the minimum number of converting nodes found so far, is stored in the memory and updated when a better solution is found. There are two stopping conditions for the algorithm: the conditions of no feasible moves and no improvement in the objective function for a maximum number of iterations.

Prioritizing the drop moves causes the algorithm to have a tendency to return to the best solution produced. In order to find the other solutions that are not in the close neighborhood of the previously visited solutions, a diversification step is introduced so that unvisited regions of the solution space are also visited. This step is executed when no improvement is achieved in the objective function for a certain number of iterations. In the diversification step, the drop and exchange moves are not considered for a number of iterations, only add moves are made and a solution with a larger number of converting nodes is attained. After the diversification step ends, other local optima can be achieved by a series of moves also including drop and exchange moves.

The flowchart of the TSCP converter placement algorithm is presented in Figure 3. There are three important parameters mentioned in the flowchart: no_imp_limit, $diverse\_start$ and $diverse\_limit$. The algorithm stops if

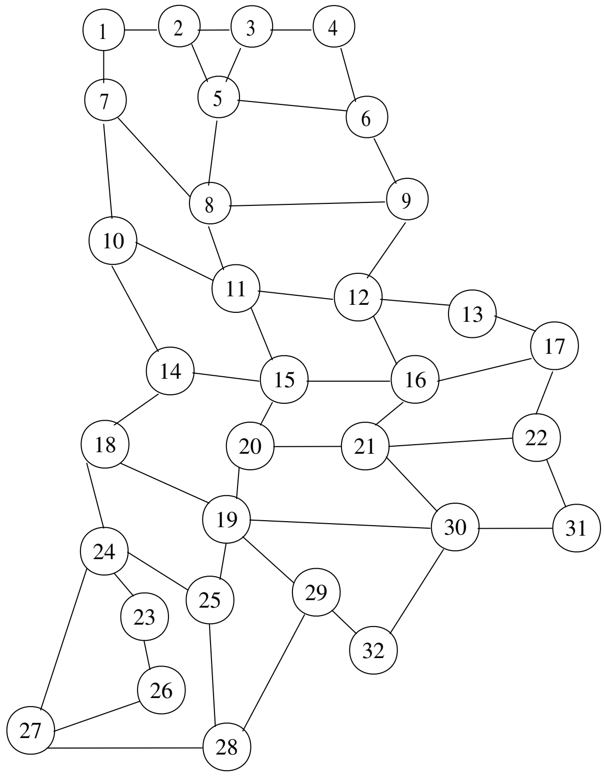

Fig. 4. The 32 node mesh network

no improvement is obtained in the objective function for no_imp_limit iterations. $diverse\_start$ represents the number of non improving iterations before the diversification step starts, and $diversification\_limit$ is the number of iterations during which the diversification step lasts.

IV. Numerical Results

A. Performance Comparison with Optimum Solutions

We run the GSCP and TSCP algorithms on a sample 32-node mesh network shown in Figure 4. For this network, the optimum solutions for the wavelength assignment and converter placement problems were presented in [18] for different demand patterns. In order to compare the converter placement algorithms with the optimum solution, we used the routes which are calculated by the flow-based ILP formulation used in [18].

The algorithms are compared for two different numbers of wavelengths, $W = 8$ and $W = 16$, and nine different demand sets for each value of W. For each demand set, the GSCP algorithm is run 10 times, and the best solution among all runs is reported. The number of converting nodes placed with each algorithm for each demand set is shown in Table I for $W = 8$ and Table II for $W = 16$. As it is observed from the results, the TSCP algorithm produces the optimum solutions in 5 out of 9 demand patterns for $W = 8$

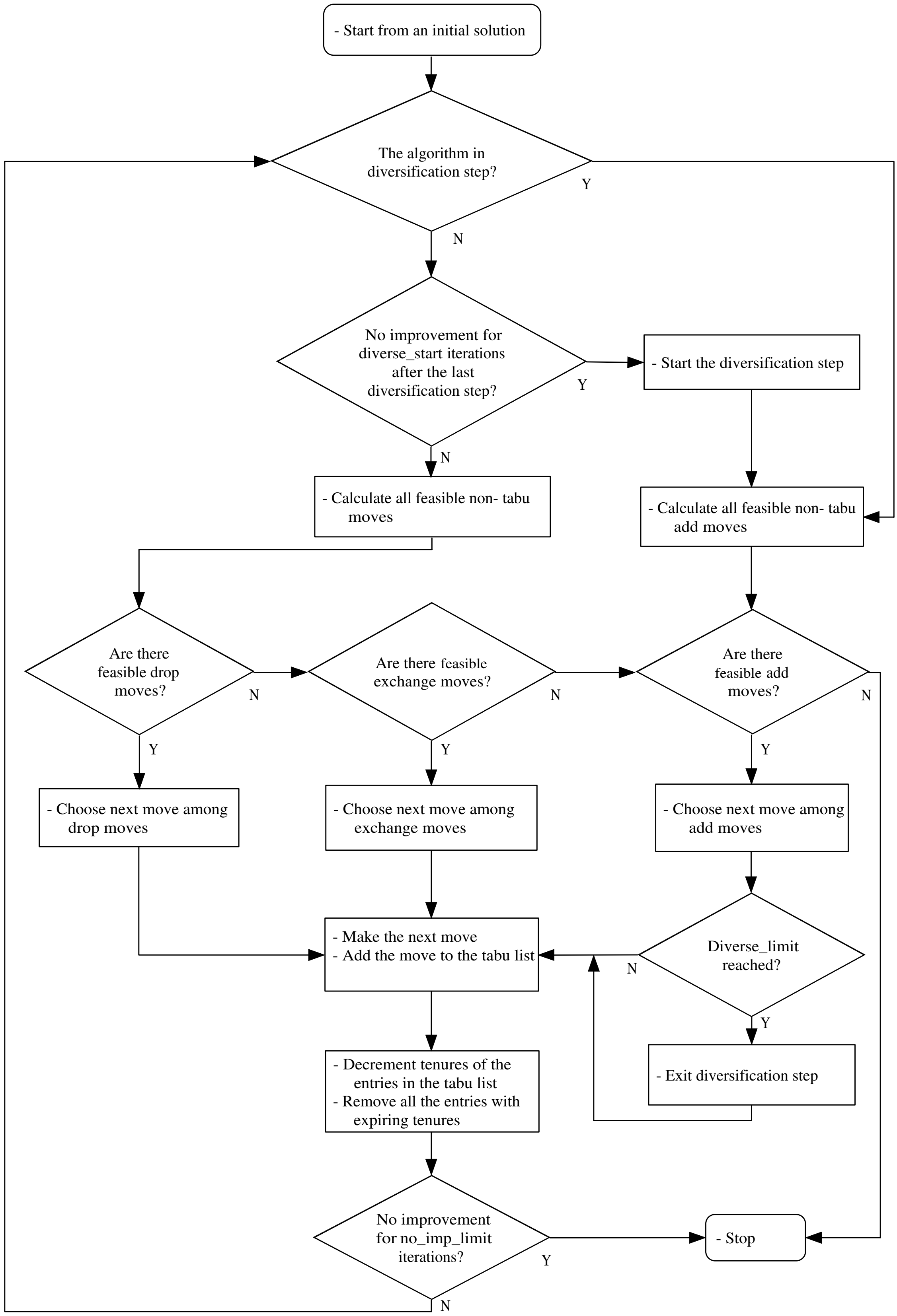

Fig. 3. Flowchart of the TSCP algorithm

Demand Set	GSCP	TSCP	Optimum
1	6	6	6
2	10	9	7
3	5	4	4
4	4	4	4
5	10	4	4
6	12	3	2
7	6	4	3
8	9	2	2
9	1	1	0
Total	63	37	32

TABLE I
THE NUMBER OF CONVERTING NODES IN THE SOLUTIONS GENERATED BY THE GSCP AND TSCP ALGORITHMS USING OPTIMUM ROUTING, AND THE OPTIMUM SOLUTIONS FOR $W = 8$

Demand Set	GSCP	TSCP	Optimum
1	2	2	2
2	2	2	2
3	1	1	1
4	5	5	5
5	4	4	4
6	4	4	4
7	6	6	6
8	11	6	5
9	3	3	3
Total	65	33	32

TABLE II
THE NUMBER OF CONVERTING NODES IN THE SOLUTIONS GENERATED BY THE GSCP AND TSCP ALGORITHMS USING OPTIMUM ROUTING, AND THE OPTIMUM SOLUTIONS FOR $W = 16$

and 8 out of 9 demand patterns for $W = 16$, i.e., in 72% of all runs. The number of converting nodes in the optimum solutions corresponds to 8.6% less than the total number of converting nodes placed by the TSCP algorithm. For all demand patterns where the TSCP algorithm fails to find the optimum solution, the RLPF wavelength assignment algorithm cannot achieve the target minimum number of fibers when the optimum converter locations are used. The failure of the TSCP algorithm in finding the optimum solution is not due to the inefficiency of the converter placement algorithm, but it is a consequence of the suboptimum RLPF wavelength assignment algorithm.

We observe that in 39% of the solutions, the TSCP algorithm improves the solution provided by the GSCP algorithm. The GSCP algorithm achieves the optimum solution in 56% of the cases, however the main drawback of the algorithm is that, in some cases it generates extremely inefficient solutions containing much more converting nodes than the optimum solution. The reason of this inefficiency is that, placing a converter at a node alone may not decrease the number of fibers much, but when two or more such nodes are equipped with converters together, their combination may give a much better result and the greedy approach fails to reach that combination since it places the converters one-by-one.

B. Performance Comparison under Different Wavelength Assignment Algorithms

In this part, we investigate the performances of the GSCP and the TSCP algorithms using three different wavelength assignment algorithms and optimum paths.

The first of these algorithms, denoted as Heuristic Wavelength Assignment (HWA), is an adaptation of the heuristic wavelength assignment algorithm proposed in [24], for single-fiber networks without converters. In this algorithm, first an initial lightpath l_0 (having k links) is chosen randomly and assigned a wavelength. For each link e_i along l_0, other lightpaths sharing e_i are grouped in a set L_{e_i} and assigned wavelengths. Then the same procedure is repeated replacing l_0 with the fiberspan of L_{e_i} for $i = 1, 2, ..., k$ and this is continued until all the wavelength assignments are done. The aim of this algorithm is to minimize the number of wavelengths needed to satisfy all of the lightpath requests. In our modification of the algorithm, the number of wavelengths is fixed to the specified value and the wavelength assignment is achieved by installing additional fibers when the number of wavelengths is not sufficient. Furthermore, instead of lightpaths, segments that are obtained by dividing the lightpaths, as shown in Section II-B, are used.

The Second algorithm used for comparison is the simple Longest Path First (LPF) algortihm [21]. The segments are sorted in a decreasing order according to their hop lengths and assigned wavelengths one by one starting from top of the list. When two segments have equal lengths, one is chosen in a random manner. The third algorithm is the proposed RLPF algorithm which is explained in Section II-B and is an iterative version of the LPF algorithm.

It can be seen from tables III and IV that the RLPF wavelength assignment algorithm gives the best results for both wavelength converter placement algorithms. The superiority of RLPF to LPF is an expected result because RLPF starts first using the LPF algorithm and tries to improve its solution by reordering the segments. RLPF provides 33.7% improvement for the GSCP algorithm and a 25.6% improvement for the TSCP algorithm in terms of number of wavelength converting nodes placed compared to LPF. We also observe that the wavelength assignment algorithm proposed in [24] does not perform well in multi-fiber networks since it gives similar results to LPF for the GSCP algorithm and even worse results for the TSCP algorithm.

Dem. Set	GSCP HWA	GSCP LPF	GSCP RLPF	TSCP HWA	TSCP LPF	TSCP RLPF
1	10	27	6	7	7	6
2	17	10	10	11	9	9
3	8	24	5	8	6	4
4	22	7	4	12	6	4
5	13	7	10	12	7	4
6	9	20	12	9	5	3
7	13	8	6	11	7	4
8	14	15	9	8	6	2
9	8	4	1	5	4	1
Total	114	122	63	83	57	37

TABLE III

THE NUMBER OF CONVERTING NODES IN THE SOLUTIONS GENERATED BY THE GSCP AND THE TSCP ALGORITHMS USING OPTIMUM ROUTING WITH THREE DIFFERENT WAVELENGTH ASSIGNMENT ALGORITHMS FOR $W = 8$

Dem. Set	GSCP HWA	GSCP LPF	GSCP RLPF	TSCP HWA	TSCP LPF	TSCP RLPF
1	3	2	2	3	2	2
2	3	3	2	3	2	2
3	5	2	2	3	2	1
4	5	5	5	5	5	5
5	5	7	4	5	4	4
6	8	6	4	7	5	4
7	11	10	6	9	6	6
8	8	22	11	8	6	6
9	11	5	3	9	5	3
Total	59	62	39	52	37	33

TABLE IV

THE NUMBER OF CONVERTING NODES IN THE SOLUTIONS GENERATED BY THE GSCP AND THE TSCP ALGORITHMS USING OPTIMUM ROUTING WITH THREE DIFFERENT WAVELENGTH ASSIGNMENT ALGORITHMS FOR $W = 16$

	$k = 3$		$k = 5$		$k = 8$		Optimum Routing	
Dem. Set	TS	GS	TS	GS	TS	GS	TS	GS
1	3	4	5	5	6	7	6	6
2	6	7	3	4	4	5	9	10
3	5	6	5	5	8	8	4	5
4	4	5	5	7	1	1	4	4
5	3	4	3	5	2	6	4	10
6	1	1	2	2	3	4	3	12
7	2	3	3	4	3	4	4	6
8	1	1	1	1	2	2	2	9
9	1	1	1	1	2	2	1	1
Tot.	26	32	28	34	31	39	37	63
Avg.	2.9	3.6	3.1	3.8	3.4	4.3	4.1	7.0

TABLE V

THE AVERAGE NUMBER OF CONVERTING NODES PLACED BY THE TS CONVERTER PLACEMENT AND GS CONVERTER PLACEMENT ALGORITHMS FOR DIFFERENT ROUTING SCHEMES FOR $W = 8$

	$k = 3$		$k = 5$		$k = 8$		Optimum Routing	
Dem. Set	TS	GS	TS	GS	TS	GS	TS	GS
1	0	0	1	1	0	0	2	2
2	2	2	4	4	3	3	2	2
3	0	0	1	1	1	1	1	1
4	1	1	6	6	6	6	5	5
5	1	1	1	1	2	2	4	4
6	1	1	3	3	4	4	4	4
7	2	3	5	5	6	7	6	6
8	4	5	4	4	7	8	6	11
9	4	5	6	18	4	6	3	3
Tot.	15	18	31	43	33	37	33	38
Avg.	1.7	2.0	3.4	4.8	3.7	4.1	3.7	4.2

TABLE VI

THE AVERAGE NUMBER OF CONVERTING NODES PLACED BY THE TS CONVERTER PLACEMENT AND GS CONVERTER PLACEMENT ALGORITHMS FOR DIFFERENT ROUTING SCHEMES FOR $W = 16$

C. Performance Comparison under Different Routing Schemes

To observe the effect of the routing algorithm used, we executed the TSCP and GSCP algorithms for the same demand patterns under different routing schemes. The routes are calculated by solving the path-based ILP formulation presented in Section II-A, considering the first 3, 5 and 8 shortest paths, and the RLPF algorithm is used for wavelength assignment. The number of converting nodes in the solutions produced by the two algorithms for each demand set, and the averages are given in Tables V and VI for $W = 8$ and $W = 16$, respectively.

When the average over all four routing schemes is taken, the TSCP algorithm outperforms the GSCP algorithm in 58% of the test cases for $W = 8$ and in 22% for $W = 16$. The GSCP algorithm performs well in the cases when there are smaller number of converting nodes in the solution, but when a large number of converting nodes are needed, it tends to diverge from the optimum solution significantly.

As shown in Table VII, the average number of converting nodes in the solutions generated by the TSCP and GSCP algorithms is lower for $W = 16$ than for $W = 8$. When the converter placement solutions for $W = 16$ are examined, it can be observed that most of the solutions contain one or two converting nodes. This is because, when there is a larger number of wavelengths per fiber, the number of wavelength mismatch blockings decreases and a smaller number of wavelength converting nodes are needed. Consequently, the performance difference between the two algorithms is higher for $W = 8$. An important fact to take into consideration is that, in these simulations the number of demands is approximately the same for the two values of W. For the cases where the number of demands is increased with W, these conclusions may not be valid.

It can be observed from Tables V and VI that, as the

W	TSCP	GSCP
8	3.39	4.67
16	3.11	3.78
Overall	3.25	4.24

TABLE VII
THE AVERAGE NUMBER OF CONVERTING NODES PLACED BY THE TSCP AND GSCP ALGORITHMS OVER ALL ROUTING SCHEMES

	$k=3$	$k=5$	$k=8$	Opt. routes
Ave. fiber cost	23109.89	22721.56	22453.67	22222.78
Ave. fiber number	59.78	59.78	58.67	58.22
Ave. path length	4.31	4.38	4.41	4.44

TABLE VIII
AVERAGE FIBER COST, NUMBER OF FIBERS AND PATH LENGTHS WITH ALL THE ROUTING SCHEMES FOR $W = 8$

number of shortest paths considered while solving the routing problem increases, the total number of converting nodes placed by the TSCP algorithm also increases. The increase in the average number of converting nodes continues when optimum routes are considered for $W = 8$. There are two main reasons for the increase in the number of placed converters. First, as more paths are considered in the routing the the total number of fibers decreases as with the total fiber cost. Second, when a larger number of shortest paths are considered, longer paths can be utilized, and the average number of hops on the lightpaths generally tends to increase. These observations are verified in Tables VIII and IX. With smaller number of fibers (i.e., less space switching) and longer paths (i.e., more possibilities for wavelength conflicts), the number of wavelength mismatch blockings increase, and larger number of converting nodes are needed.

	$k=3$	$k=5$	$k=8$	Opt. routes
Ave. fiber cost	15348.11	14107.11	13386.22	12708.89
Ave. fiber number	39.22	36.89	36.11	34.78
Ave. path length	4.52	4.78	4.85	5.09

TABLE IX
AVERAGE FIBER COST, NUMBER OF FIBERS AND PATH LENGTHS WITH ALL THE ROUTING SCHEMES FOR $W = 16$

D. Traf c Statistics and Converting Node Placement Distribution

We investigate the correlation between the total amount of traffic passing through a node (transit traffic) and the likelihood that a converter is placed at that node in the solution generated by the TSCP algorithm. Our purpose is to find out whether this parameter can be utilized in making the converter placement decisions.

Figure 5 presents the percentage of the cases each node is placed a converter and Figure 6 shows the average amount of transit traffic passing through each node for $W = 8$. These values are calculated taking the average over all four routing schemes mentioned in the previous part. The distribution of the same parameters for $W = 16$ are shown in Figures 7 and 8, respectively. As seen from the graphics, the first five nodes with the highest percentage of placing a converter are nodes 15, 14, 16, 12 and 25 for $W = 8$ and nodes 14, 25, 16, 15 and 28 for $W = 16$. For both values of W, these five nodes are among the first twelve nodes with the highest amount of transit traffic among all the 32 nodes. These results show that the nodes with higher transit traffic may have a higher likelihood for placing a converter. However, this correlation is not sufficient alone to place the converters according to transit traffic parameter since for some of the nodes the two distributions diverge significantly, e.g., although there is a large amount of traffic passing through node 19 for both values of W, that node does not have a high percentage of converter placement (below 15% for W=8 and 10% for $W = 16$).

We also observe from Figures 5 and 7 that there is a high correlation between the locations of the wavelength converting nodes obtained using different sets of traffic demands and different values of W. Although each set of wavelength converting node placements is optimized for a specific traffic pattern and a specific value of W, this high correlation shows that the optimum configuration can be adapted to a different set of traffic demands by making just a few changes in the current configuration of converting node locations.

V. CONCLUSION

In this paper, a tabu search based algorithm (TSCP) for sparse placement of wavelength converting nodes on a multi-fiber network under static traffic demands is presented. The main objective is to place the minimum number of wavelength converting nodes necessary for achieving the minimum total fiber cost which is obtained in a network having full wavelength conversion capability. We use flow and path-based ILP formulations for the routing problem. We propose a heuristic wavelength assignment algorithm (RLPF) to be used in the converter placement algorithm. RLPF performs well compared to two other heuristic wavelength assignment algorithms proposed earlier in the literature. A heuristic

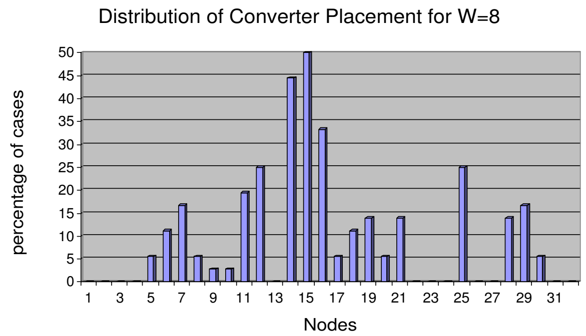

Fig. 5. The percentage of the cases that a converter is placed at the node for each node for $W = 8$

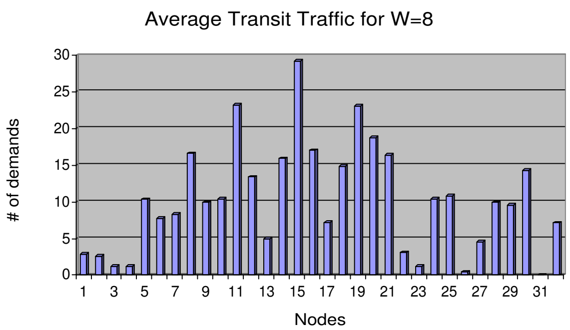

Fig. 6. The average transit traffic for each node for $W = 8$

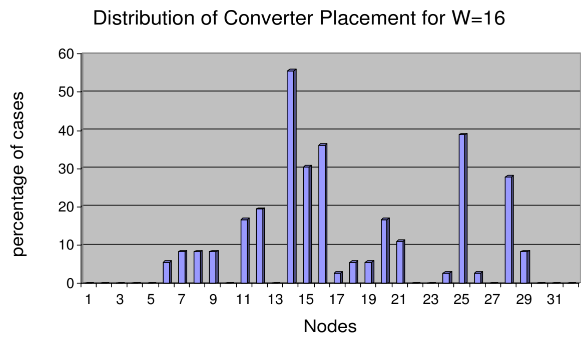

Fig. 7. The percentage of the cases that a converter is placed at the node for each node for $W = 16$

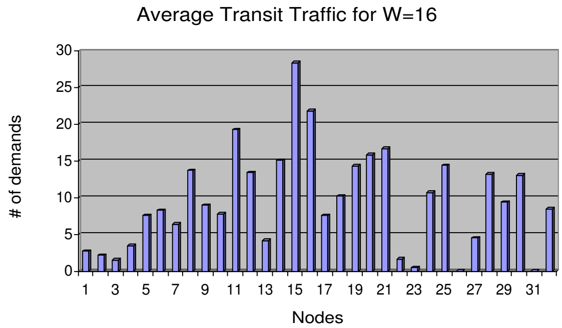

Fig. 8. The average transit traffic for each node for $W = 16$

converter placement algorithm (GSCP) is also implemented for performance comparison.

The TSCP algorithm achieves the optimum solutions in 72% of the cases, and it places 9.3% more converting nodes on the average than the optimum solutions. TSCP improves the solutions generated by the GSCP algorithm in 40% of the results. We observe that as the number of considered paths for routing increases, the target minimum cost of fibers decreases and the number of converting nodes in the generated solutions increases.

The relationship between the number of demands passing through a node and the likelihood that a converter is placed at that node is also investigated. The nodes with higher amount of transit traffic have a higher likelihood of being chosen as a converting node location. This information can be used as an auxiliary parameter in the converter placement decisions. The TSCP algorithm can be modified such that the nodes with higher amount of transit traffic can be given a higher probability of placing the converters. The performance of the TSCP algorithm can also be investigated using different wavelength assignment algorithms.

ACKNOWLEDGMENT

This work is partially supported by FP6 IST e-Photon/ONe NoE project.

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