A Heuristic Converter Placement Scheme for Wavelength-routed Optical Networks

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Abstract – **In optical networks with sparse wavelength conversion, the optimal converter placement (OCP) problem is one of the most important considerations. In this paper, we propose a heuristic OCP algorithm, called the Optimized Utilization Placement (OUP), to determine proper numbers of converters that should be placed at selected nodes. Performances of the OUP are evaluated by simulations when fixed routing and fixed-alternate routing are used. The simulations justify that the OUP can significantly increase converter gains.**

I. INTRODUCTION

Wavelength-division multiplexing (WDM) combined with wavelength routing is the enabling technology for next generation optical networks [1, 2, 3]. In simple optical networks, a lightpath must satisfy the wavelength-continuity constraint, i.e. a unique wavelength must be used along the path, and the blocking probability is thus very high. To remove this constraint, wavelength converters are incorporated into the optical cross-connects (OXCs). Many literatures [4-7, 9, 11] show that wavelength converters can significantly improve the blocking performance. However, all-optical wavelength converters are likely to remain expensive and they significantly increase the complexity of OXCs [4, 8-10, 16, 19, 20]. Therefore, networks with sparse wavelength conversion where converters are place at a limited number of nodes have been extensively studied in [9, 10, 16]. In such networks, the problem of optimal converter placement (OCP) has aroused much interest: given a network topology with a certain number of converters and traffic statistics, how should converters be distributed among nodes so that the average blocking is minimized?

The OCP was first introduced by S. Subramaniam *et al.* [12] and then studied by many other authors [13-18]. Exhaustive searching is the straightforward and simplest approach to get the optimal placement (OP). First, performance of all possible ways to place converters must be obtained by numerical calculations or simulations. Then, the best placement is the one which gives the minimum blocking probability. However, this approach is impractical because it is prohibitively time-consuming [12-18]. Therefore, numerous heuristic algorithms have been proposed. S. Subramaniam *et al.* [12] obtained the optimal placement for single paths, bus and ring topologies for different traffic statistics. Considerable gains in blocking could be obtained when the optimal placement is used, compared to random or uniform placement. Ling Li and Arun K. Somani [13] suggested that to minimize the end-to-end performance, converters should be placed so that the path is split into equal-blocking segments. However, it is very hard to obtain such an optimal solution when overall performance of a network is considered. Some other algorithms were proposed for arbitrary topologies. S. Thiagarajan and Arun K. Somani [14] relieved the exhaustive search process by creating auxiliary graphs using each node in the network as the destination nodes and then evaluating the blocking for only some combinations. The numerical results showed that, in most cases, their algorithm could give near-optimal solution with more than 95% time efficiency. K.R. Venugopal *et al.* [15] insisted that converters should be placed at nodes that have higher nodal degree, transit large amount of traffic and convert a large number of optical signals. Similarly, A.S. Arora and S. Subramaniam [17] proposed the total out-going traffic (TOT) algorithm. The TOT placed converters at nodes that have the high out-going traffic. The simulation results showed that the TOT could perform almost as well as optimal scheme in different network topologies.

We observe that all of the above-mentioned literatures have made an important assumption to reduce the complexity of their algorithms: nodes that are selected for converter placement are uniformly implemented with only one converter or unlimited number of converters to have full-conversion capability. This assumption may oversimplify the OCP and may be thus impractical. Firstly, consider a WDM network using fibers of high capacity, e.g. 64 or 128 wavelength channels, a node having one converter can support only a wavelength translation for a lightpath while there are several tens or hundreds of lightpaths. This implies that a certain number of converters, e.g. 10 or 20 or more converters, should be placed at a node to minimize blocking. Secondly, full-conversion capacity is rarely necessary for a desired performance [9]. Therefore, our main contribution in this paper is that we solve the OCP problem by placing a proper limited number of converters at each of a limited number of nodes in networks with arbitrary topologies. Nodes requiring more wavelength translation should receive more converters. To our knowledge, this consideration has not been addressed earlier.

The remainder of this paper is organized as follows. In part II, some important terminologies to specify a network are defined. Next, our OCP algorithm, called Optimized Utilization Placement (OUP), is introduced and explained in details. Performances of the OUP and other algorithms obtained from simulations are discussed in part III. And finally, part IV concludes this paper.

II. NOTATIONS

- A network consists of n nodes, $V=\{v_1, v_2, \ldots, v_n\}$, interconnected by m fiber links, $E=\{e_1, e_2, \ldots, e_m\}$.

- *Link capacity vector*: shows the capacity of each fiber link, given by

$$W = (w_1, w_2, \ldots, w_m)$$

where w_i is the capacity of link e_i, the maximum number of wavelength channels that it can support. In this paper, assume that all links have the same capacity, i.e. $w_1 = w_2 = \ldots = w_m = w$ (is selected to be 64).

- *Converter placement vector*: shows the total number of converters placed at each node, given by

$$C = (c_1, c_2, \ldots, c_n)$$

where c_i is the number of wavelength converters implemented in node v_i. The sum $c_T = c_1 + c_2 + \ldots + c_n$ is the total number of converters employed in the whole network.

Besides, in this paper, we consider the converter utilization in the whole network, therefore a converter utilization vector are defined as follows:

- *Converter utilization vector*: shows the usage of converters at each node, relative to each other, given by

$$U = (u_1, u_2, \ldots, u_n)$$

where u_i is the normalized converter utilization at node v_i, calculated by $u_i = \hat{u}_i / \max_{\forall v_i \in V}\{\hat{u}_i\}$ where $\hat{u}_i$ is the number of wavelength translation performed at node v_i during a period of time.

III. OPTIMIZED UTILIZATION PLACEMENT

It is observed that each node in the network requires different wavelength translating, therefore, when converters are uniformly placed, some nodes may be usually lack of converters, while the others may be usually redundant of converters. To maximize the efficiency, more converters should be implemented in nodes that require more translating. For each node, its requirement for wavelength translation can be estimated by examining its converter utilization measured by simulation when all nodes are assumed to have full-conversion capability. Therefore, we suggest that

$$\text{If } u_{k_1} \le u_{k_2} \le \ldots \le u_{k_n}, \text{ then } c_{k_1} \le c_{k_2} \le \ldots \le c_{k_n} \quad (1)$$

Our proposed algorithm attempts to make (1) satisfied to expect that the utilization efficiency of converters in each node can be optimized. Therefore, it is called Optimized Utilization Placement (OUP). In this paper, the converter utilization vector U is used to determine not only the best nodes to place converters but also the most proper numbers of converters should be incorporated at each selected node.

To implement the OUP, at first, all nodes are arranged in non-decreasing order in terms of their converter utilization, i.e.

$$V = \{v_{k_1}, v_{k_2}, \ldots, v_{k_n}\} \text{ so that } u_{k_1} \le u_{k_2} \le \ldots \le u_{k_n} \quad (2)$$

Next, the placement is determined as follows:

- n_1 nodes of highest converter utilizations, $V_1 = \{v_{k_{n_2}}, v_{k_2}, \ldots, v_{k_n}\}$, will be implemented with converters, where $n_1 = \lfloor n \times \xi \rfloor$, $0\% \le \xi \le 100\%$, $\lfloor x \rfloor$ is the largest integer smaller than the real number x, and $n_2 = n - n_1 + 1$. The sparseness, ξ,, is defined to show to the fraction of nodes in the network that have converters and it is inversely proportional to the complexity of the network. Note that the number of converters placed at each node in V_1 should be proportional to its converter utilization.
- Remaining nodes in $V_2 = V \setminus V_1 = \{v_{k_1}, v_{k_2}, \ldots, v_{k_{n_2-1}}\}$ have no converter.

Therefore, we have

$$c_{k_i} = 0, \ \forall i \in \{1, 2, \ldots, n_2 - 1\} \quad (3)$$

and

$$c_{k_i} = \left\lfloor \frac{u_{k_i}}{u_T} \times c_T \right\rfloor, \ \forall i \in \{n_2, n_2 + 1, \ldots, n\} \quad (4)$$

$$\text{where } u_T = u_{k_{n_2}} + u_{k_{n_2+1}} + \ldots + u_{k_n} \quad (5)$$

Assume that, on average, c_{avg} converters are placed at each node in V_1, thus the total number of converters is $c_T = n_1 \times c_{avg}$. After converters are placed to V_1 following (3),(4), and (5), we have

$$\begin{aligned} \sum_{i=1}^{n} c_i &= \sum_{i=n_2}^{n} c_i = \sum_{i=n_2}^{n} \left\lfloor \frac{u_{k_i}}{u_T} \times c_T \right\rfloor \\ &\le \sum_{i=n_2}^{n} \left(\frac{u_{k_i}}{u_T} \times c_T \right) = c_T \times \frac{1}{u_T} \left(\sum_{i=n_2}^{n} u_{k_i} \right) = c_T \end{aligned} \quad (6)$$

Therefore, residue converters are then added to the most converter-utilized node, v_{k_n}. As a result, (4) is rewritten as follows:

$$c_{k_i} = \left\lfloor \frac{u_{k_i}}{u_T} \times c_T \right\rfloor, \ \forall i \in \{n_2, n_2 + 1, \ldots, n - 1\} \quad (7a)$$

$$\begin{aligned} c_{k_n} &= \left\lfloor \frac{u_{k_n}}{u_T} \times c_T \right\rfloor + \left\{ c_T - \sum_{i=n_2}^{n} \left\lfloor \frac{u_{k_i}}{u_T} \times c_T \right\rfloor \right\} \\ &= c_T - \sum_{i=n_2}^{n-1} \left\lfloor \frac{u_{k_i}}{u_T} \times c_T \right\rfloor \end{aligned} \quad (7b)$$

IV. SIMULATION RESULTS

This part compares the blocking performance obtained by the OUP versus the TOT algorithm [17] in a 111-node mesh network, which is present in typical North American carriers, as shown in Fig.1. The dynamic traffic model is used in the simulations. The call rate is assumed to follow the Poisson distribution with mean λ. The call-holding time is assumed to follow the exponential distribution with unit mean. The rate of calls is thus denoted in units of Erlangs where 1 Erlang means 1 call per call-holding time. A path to route a lightpath is determined by the Fixed shortest path Routing (FR) or Fixed-Alternate Routing (FAR) and then the wavelengths on the selected path are assigned by the first-fit wavelength assignment algorithm. It is also assumed that every fiber can carry 64 wavelength channels, and on average 16 converters are placed in each of 50 candidate nodes ($\xi \approx 45\%$).

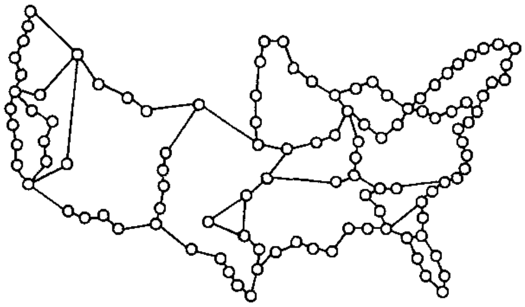

Fig. 1. A mesh network with 111 nodes, 125 links

First, we compare the blocking performances given by the TOT and the OUP when the FR is used. The two extreme cases when no converter is used (no conversion) and when all nodes have full conversion capability (full conversion) are also investigated. Positions of candidate nodes selected by the OUP are illustrated in Fig.2, and the blocking performances in four different cases are plotted in Fig. 3. We can observe from Fig. 3 that the OUP can decrease the blocking probability by 4.47% up to 27.00% (12.11% on average), compared to the TOT. It is also noted that when only 50 nodes (about 45% of all nodes) are incorporated with converters, the OUP can achieve almost the same performance as that in the case of full conversion. This verifies that our converter utilization-based placement specified by (7) can achieve significant gains. Another observation is that when the network is more loaded, the OUP offers more gains since at light loads, most lightpaths can be established with a single wavelength continuously available from source to destination, the converter gain itself is thus very small.

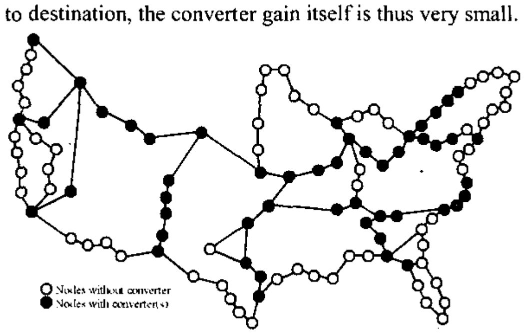

Fig. 2. Candidate nodes (black-colored) determined by the OUP when the FR is used

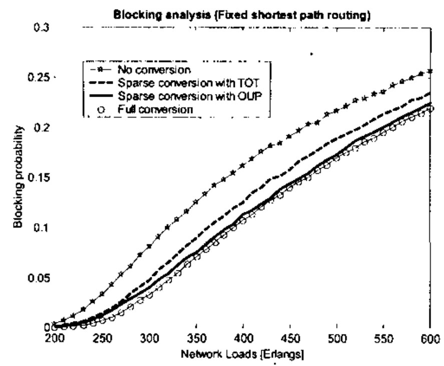

Fig. 3. Blocking performance of the TOT and the OUP versus network loads when the FAR is used

Second, we compare the blocking performances given by the TOT and the OUP when the FAR is used. Assume that two edge-disjoint shortest routes are provided for each source-destination pair. Positions of candidate nodes selected by the OUP are illustrated in Fig. 4. As can be seen in Fig. 5, in this case, the OUP can also perform better than the TOT, however, its gain is smaller (up to 10.00%, and 5.05% on average). This can be explained as follows: when the FAR is used, converter requirements per node are more balanced, numbers of converters per candidates nodes are less differentiated, and therefore our placement is less beneficial.

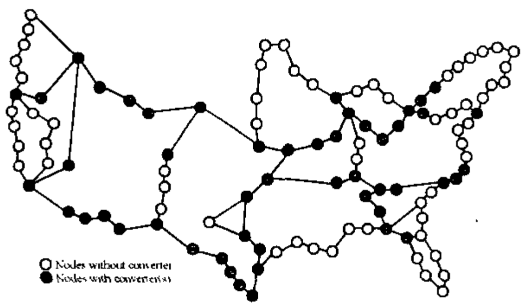

Fig. 4 Candidate nodes (black-colored) determined by the OUP when the FAR is used

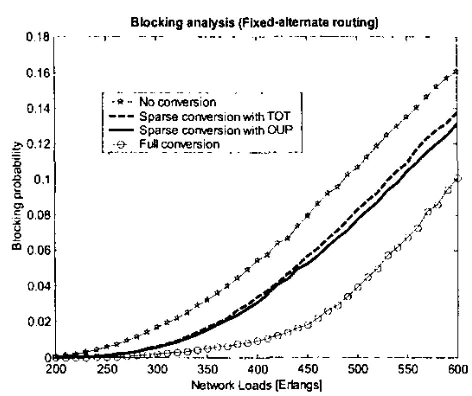

Fig. 5 Blocking performance of the TOT and the OUP versus network loads when the FAR is used

V. CONCLUSIONS

We analyzed the problem of wavelength converter placement in all-optical WDM networks. Our heuristic algorithm, the Optimized Utilization Placement (OUP), can enhance the converter gain significantly in terms of blocking probability, especially when fixed shortest path routing is used and when the network is more loaded. When the fixed-alternate routing is used, its gains are moderate because the routing algorithm makes converter requirements per node tend to be similar, the numbers of converters per candidate nodes are thus less differentiated. We found from simulations that with fixed shortest path routing and in the load range of interest, the OUP can outperform the TOT by more than 12% on average. Besides, we can see that the OUP can be applied to place an arbitrary number of converters for networks with arbitrary topologies. Therefore, our proposed algorithm can be more efficient and practical for converter placement, especially when a large number of converters are used in networks with high capacity fibers along with advancements in nowadays technology.

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