Routing and Wavelength Assignments in Optical WDM Networks with Maximum Quantity of Edge Disjoint Paths*

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Abstract. In the present paper routing and wavelength assignment (RWA) in optical WDM networks is discussed. Previous techniques on based on the integer linear programming and graph coloring are complex and require extensive use of heuristics which makes them slow and sometimes practically not reasonable. Another approach employs the greedy algorithm for obtaining available edge disjoint paths. Even though it is fast, it produces a solution for any connection request which is far from the optimal utilization of wavelengths. We propose a novel algorithm which is based on the maximum flow to have the maximum quantity of edge disjoint paths. Comprehensive computer simulation shows that the proposed method outperforms previous ones significantly in terms of running time. Furthermore, it shows compatible or better performance comparing to others in number of wavelengths used.

1 Introduction

Among various research areas in optical networks, efficient source-destination routing and assigning a wavelength on the route selected are quite important for the network performance [1]. Their objectives include the minimization of the required number of wavelengths [2,3,4], the minimization of the blocking probability under fixed number of wavelengths [5], and the minimization of the network costs [6].

Routing and wavelength assignment (RWA) problem for the lightpaths of virtual topology in any WDM network is **NP** complete and many heuristic approaches [2,3,4,5,6] have been proposed in the literature. It has been studied for various criteria. One criterion of them is how to set up and release optical paths. Here we assume the static path assignment that optical paths are not released after once established. In static wavelength assignment the lightpaths and their routes are known in advance and we need to assign wavelengths to each lightpath such that the lightpath on a given link must have different wavelengths.

* This paper was supported in part by Brain Korea 21 and University ITRC project.

That is practically more achievable with the current technology than the dynamic path assignment, where optical paths are randomly set up and released.

Another criterion is the existence of wavelength converters. Physical constraints in the RWA problem include wavelength channel spacing in a fiber link, the number of optical transceivers, and the number of wavelength converters. Actually they determine the number of wavelengths available on fiber links and thus the number of source-to-destination connections. Each wavelength is assumed to be assigned to a single channel and the bandwidth granularity of the channel is usually not considered for the simplicity of the problem. This paper investigates the case that no wavelength converters exist in the topology based on the static path assignment. It is predictable that the proposed scheme can easily apply to the case with wavelength converters. And the goal of this work is either to reduce the number of used wavelengths or to maintain the similar number with shorter running time. This can be achieved based on the maximum number of edge disjoint paths. The comprehensive computer simulation shows that the proposed scheme significantly outperforms other schemes in terms of the running time.

Basically there are two approaches for solving the RWA problem. The first approach is based on the *lpsolver* [7], which is a program to solve a linear program using the idea of multicommodity flows, to obtain the optimal solution for RWA. And the second one uses path selection based graph algorithms to minimize the number of wavelengths used heuristically. We briefly mention three popular RWA algorithms in the literature.

Lpsolver: Routing Heuristic Algorithm with Graph Coloring - Rounding heuristic algorithm based on *lpsolver* is used in lightpath routing and graph coloring is used in wavelength assignment phase [2]. *Graph Algorithm: BGA for EDP* - A simple edge disjoint paths scheme based on shortest path algorithm to identify available paths is used in [3]. Here authors investigate the performance of rounding heuristic algorithm and their scheme in terms of the number of wavelengths used and the actual running time. The result shows that the number of wavelengths used in two schemes is almost same, however, rounding heuristic algorithm consistently takes more time than that of *BGA for EDP*. Therefore we just compare the proposed scheme with *BGA for EDP* in our work. *Graph Algorithm: RWA with Lookup Table - LTB-RWA* is based on disjoint path set selection protocol (DPSP) [4,8]. Here authors investigate the performance of *BGA for EDP* and their scheme in terms of the number of wavelengths used and the running time. The simulation result shows that the number of wavelengths used in *BGA for EDP* is almost same. However, *LTB-RWA* yields better solutions for the running time.

2 The Proposed RWA Scheme

Let $G(V, E)$ denote a simple graph that models a network, where V is the vertex set and E is the edge set. Let $|V| = n$, i.e. a network contains n hosts. The demand set D is a set of pairs $\{(s_1, t_1), \dots, (s_k, t_k)\}$, where $s_i, t_i \in V, i = 1, \dots, k$. Here k is the total number of requests for connections, s_i is a host-sender, and t_i

Fig. 1. The sample topologies for RWA

is a host-receiver. For the request (s_i, t_i) it is necessary to assign a wavelength λ_i and a lightpath $L_i \subseteq E$ (which means that edges in the lightpath are elements in E). Let us remark the lightpaths that are assigned the same wavelength *simultaneously* will not traverse the same physical link, i.e. these paths are edge disjoint. Let $l = \max_i \lambda_i$. The aim of RWA problem is to minimize l under the condition $L_i \cap L_j = \emptyset, \forall i, j \in \{1, \dots, k\}$. If the condition is false, then we say the assignment is not admissible.

If $s_1 = s_2 = \dots = s_k = s$ and $t_1 = t_2 = \dots = t_k = t$, then the optimal solution for the problem is defined as k over the maximal number of edge disjoint paths between s and t , i.e. k divided by the *cardinality* of the *edge cut set* between s and t , $Card(s, t)$. i.e., *Optimal number of wavelengths* = $\lceil \frac{k}{Card(s, t)} \rceil$

Let us assume an optical network (refer to Fig. 1 (a)). Shortest path is assigned to the connection request. Let the demand set be $\{(1,4), (4,1), (2,3)\}$. First random selected request is $(1,4)$. The shortest path between node 1 and 4 is $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$. Hence the request $(1,4)$ receives wavelength $\lambda = 1$ and uses path $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$. We remove this path from graph and get unconnected graph. Paths for other connections do not exist (see Fig. 1 (b)). Now we return to the original graph and increase the number of wavelength, i.e. $\lambda = 2$. Let a second random selected request be $(4,1)$. Shortest path is $4 \rightarrow 3 \rightarrow 2 \rightarrow 1$. Hence connection $(4,1)$ uses this path with wavelength 2. We have no path for the demand $(2,3)$. So we use wavelength 3 for this request. As a result, we use different wavelength for each connection, i.e. $\max \lambda = 3$. However, if connection $(1,4)$ uses path $1 \rightarrow 5 \rightarrow 6 \rightarrow 3 \rightarrow 4$, $(4,1)$ uses $4 \rightarrow 8 \rightarrow 7 \rightarrow 2 \rightarrow 1$, $(2,3)$ use $2 \rightarrow 3$, then $\max \lambda = 1$.

As we all know, ring topology is one of important network architectures. Let a network be as in Fig. 1 (c). Let a demand set be $\{(1,2), (6,2)\}$. The graph diameter is 3. Hence the second request $(6,2)$ cannot use a path $6 \rightarrow 5 \rightarrow 4 \rightarrow 3 \rightarrow 2$ because the length of this path is more than the diameter. The resulting assignment by the method in [3] is as follows. The request $(1,2)$ uses path $1 \rightarrow 2$ and wavelength $\lambda = 1$. The request $(6,2)$ uses path $6 \rightarrow 1 \rightarrow 2$ and wavelength $\lambda = 2$. However, only one wavelength can be enough if all edge disjoint paths are used.

Fig. 2 shows a strategic comparison between the conventional approach and the proposed one. The conventional approach is done by selecting routes for the set of connection requests. This will be repeated for the subsequent sets of requests. However the proposed approach finds maximum number of EDPs for all possible connections and stores them in a lookup table for lightpath assignments.

Fig. 2. Comparison of strategies between two approaches

To solve the RWA problem based on the table, just refer to the table without reselecting a route for the same connection request and assign a wavelength to the route as far as the network topology does not change. The optical network is a technology that is employed in core backbone networks. In general they are not changed frequently with fixed connection requests. Hence the proposed algorithm can be efficient in terms of time. If the same connection request occurs concurrently the probability that the proposed algorithm minimizes the number of wavelengths comparing to others is relatively high. In the simulation for the number of wavelength used, we generate random graphs and random demand sets. First we obtain a random graph for the physical topology by specifying the number of nodes in the graph and the probability of an edge existence (P_e) for any node pair. The demand set is also generated randomly by populating the matrix with the number of same requests, which is less than or equal to N_c , where the probability of the request is specified by P_l . After obtaining the table and we assign a path for a request of the demand set in order. Table 1 summarizes the notation used in this section.

Table 1. Notation

<i>Variables</i>	<i>Meaning</i>
G	The directed graph that models the network
V	The set of vertices
E	The set of edges
d	$\max(\text{diam}(G), \sqrt{ E })$
τ	The demand set, $\tau = \{(s_1, t_1), \dots, (s_k, t_k)\}$
P_l	The probability of request
P_e	The probability of edge existence between any node pairs
N_c	The multiplicity of a single request

In order to find a set of edge disjoint paths for effective wavelength assignment we solve the maximal flow problem from s to t in G , where any edge is undirected and all capacities are equal to one. Generally (s_i, t_i) and (s_j, t_j) for arbitrary i and j ($i \neq j$) are different. Here we can get an optimal solution for RWA for the traffic between any couple of nodes as above. If the union of these solutions is acceptable, then the optimal common solution is found. Otherwise,

some wavelengths assigned to edge common paths should be replaced by some other wavelength assignments. We do not necessarily get the optimal solution by this approach, furthermore the assignment is not trivial as in examples earlier, when $\lambda_i \neq \lambda_j, \forall i, j$.

As a network topology is usually fixed we offer to calculate a set of edge disjoint paths for all possible pairs in advance before investigation of the demand set. For this purpose the procedure **Get_Table**(G) has been implemented and used in the our method. By $P(s, t, i)$ denote the result of **Get_Table**(G), here $s = 1, 2, \dots, n-1$; $t = s+1, s+2, \dots, n$; $i = 1, 2, \dots, \text{Card}(s, t)$. Entire edge disjoint paths and their maximal quantity between nodes s and t can be found from the solution of maximal unit flow in G from s to t . Here the unit flow corresponds to one path. As we know, a straightforward implementation of the maximal unit flow algorithm runs in time $O(|E| \cdot \text{Card}(s, t))$.

The network topology can be altered due to link-host failures and network expansions. In this situation, we reconfigure the set of edge disjoint paths $P(s, t, i)$ and continue the RWA process. Now we provide the description of the method.

Algorithm **Max_EDP_RWA**

Get_Table(G)

while (the same G) **do**

 retrieve a new D

$\lambda = 0$

while ($D \neq \emptyset$) **do**

$\lambda = \lambda + 1$

for $j = 1$ **to** k **do**

if $\exists$ empty path $P(s_j, t_j, i)$ **then**

 Assign $P(s_j, t_j, i)$ and λ to (s_j, t_j)

$D = D - (s_j, t_j)$

end if

end for

end while

end while.

Usually network problems can be classified into two parts. The first part takes a serious view of path, and the other for taking a serious view of flow. Representative instance of the former is shortest path problem and the latter is source and destination pair. The mechanism that searches the maximum flow is based on the famous Ford-Fulkerson algorithm. The two sets of elements divided by an edge cut set are S and T , edge cut set is $e_1, \dots, e_{\text{Card}(s,t)}$. **Get_Table**(G) obtains maximum possible edge disjoint paths for each (s, t) pair based on the mechanism discussed above.

In Fig. 3 shows the graph of a network topology. And demand set is $\{(1,8), (4,6), (1,8), (6,9)\}$. So the reasonable value d is 4.1. First we make the Table through **Get_Table**(G). For each demand pair, we obtain the maximum number of EDPs. The demand pair $(1,8)$ which is requested at first and third has

Fig. 3. Random Network Topology

$1 \rightarrow 2 \rightarrow 7 \rightarrow 6 \rightarrow 8$ and $1 \rightarrow 4 \rightarrow 3 \rightarrow 5 \rightarrow 8$. The second pair (4,6) has $4 \rightarrow 6$, $4 \rightarrow 2 \rightarrow 7 \rightarrow 6$, and $4 \rightarrow 3 \rightarrow 5 \rightarrow 6$. And the last demand (6,9) has $6 \rightarrow 8 \rightarrow 9$ and $6 \rightarrow 5 \rightarrow 9$. We select one at random $1 \rightarrow 2 \rightarrow 7 \rightarrow 6 \rightarrow 8$. For the second pair (4,6), assign the shortest EDP in the Table $4 \rightarrow 6$. And for the third one (1,8), we take the path $1 \rightarrow 4 \rightarrow 3 \rightarrow 5 \rightarrow 8$ because the other one is used for the first demand (1,8). At the last demand (6,9), assign the path $6 \rightarrow 5 \rightarrow 9$ since edge (6,8) is used for the first demand. The total number of wavelengths used is 1. We need 2 wavelengths for *BGA for EDP* based algorithm in this topology, i.e. $1 \rightarrow 4 \rightarrow 6 \rightarrow 8$ and $4 \rightarrow 3 \rightarrow 5 \rightarrow 6$ for wavelength 1, and $1 \rightarrow 4 \rightarrow 6 \rightarrow 8$ and $6 \rightarrow 5 \rightarrow 9$ for wavelength 2.

3 Performance Evaluation

We now describe some numerical results with which we compare the performance of the proposed scheme, the *LTB_RWA* algorithm [4], and the *BGA for EDP* based *Greedy_EDP_RWA* described in [3]. We compare the number of wavelengths used and the running time. We use NSFNET for the running time as done earlier and random graphs for the number of wavelengths used to test them in various network topologies. The demand set is also generated randomly by populating the $n \times n$ matrix with the number of requests, which is less than or equal to N_c , where the probability of the request is specified by P_l . We simulate 1,000 times for each n , P_e , and P_l , and obtain the average number of wavelengths used. Table 2 shows the number of wavelengths used for each combination of the graph G and the demand set. Note that the proposed scheme (denoted as ‘New’ in the Table 2) consistently requires the number of wavelengths which is quite similar to those of *BGA for EDP* based *Greedy_EDP_RWA* (denoted as ‘BGA’) and *LTB_RWA* (denoted as ‘LTB’).

We measure the running time for three algorithms on NSFNET with the demand set as obtained earlier. We generate 100 to 1,000 demand sets separately and take the average running time. Fig. 4 shows the average running time when $P_l = 0.6$ and $N_c = 5$, and other P_l values present the similar trends. As a result, the proposed scheme uses almost same number of wavelengths when the multiplicity of a pair is close to 1, meanwhile it is better than other schemes when the multiplicity becomes higher. Furthermore, the proposed scheme takes significantly less running time than others.

Table 2. Performance comparison: the number of wavelengths

n	P_e	P_l	$N_c = 1$			$N_c = 3$			$N_c = 5$		
			BGA	LTB	New	BGA	LTB	New	BGA	LTB	New
10	0.6	0.4	2.02	2.09	2.1	5.44	5.38	5.39	8.81	9.04	8.63
10	0.6	0.6	2.69	2.78	2.75	8.1	7.66	7.86	13.22	13.27	12.74
10	0.6	0.8	3.49	3.54	3.53	10.55	10.34	10.2	17.34	17.69	16.7
10	0.8	0.4	1.25	1.33	1.34	3.6	3.56	3.57	5.88	5.86	5.74
10	0.8	0.6	1.92	1.94	1.94	5.24	5.11	5.11	8.6	8.68	8.26
10	0.8	0.8	2.15	2.17	2.18	6.8	6.68	6.6	11.44	11.52	10.93
14	0.6	0.4	1.99	2.06	2.05	5.36	5.23	5.2	8.95	8.99	8.58
14	0.6	0.6	2.74	2.79	2.8	8.03	7.53	7.68	13.19	13.18	12.5
14	0.6	0.8	3.44	3.42	3.46	10.37	10.05	9.88	17.34	17.6	16.21
14	0.8	0.4	1.22	1.31	1.34	3.68	3.64	3.6	6.05	6.0	5.82
14	0.8	0.6	1.97	1.99	1.98	5.33	5.21	5.19	8.95	8.96	8.55
14	0.8	0.8	2.2	2.23	2.27	7.1	6.84	6.79	11.87	11.89	11.16
18	0.6	0.4	2.06	2.03	2.06	5.45	5.21	5.33	8.9	8.82	8.42
18	0.6	0.6	2.67	2.84	2.73	7.86	7.53	7.5	13.08	13.09	12.24
18	0.6	0.8	3.38	3.0	3.38	10.48	9.85	9.81	17.88	17.57	16.61
18	0.8	0.4	1.15	1.21	1.26	3.73	3.74	3.67	6.09	6.16	5.86
18	0.8	0.6	1.97	2.0	1.98	5.47	5.27	5.26	9.12	9.13	8.58
18	0.8	0.8	2.28	2.24	2.35	7.27	6.98	6.91	12.2	12.17	11.4

Fig. 4. The average running time (NSFNET, $P_l = 0.6$, and $N_c = 5$)

4 Conclusion

In this paper we present an RWA method in optical networks to minimize the number of wavelengths needed with shorter running time than others. It is studied in the static path assignment and without wavelength converters. The method obtains the maximum edge disjoint paths for each and every possible source-destination pair, and stores them in a table in advance. And for each demand pair of the demand set, we assign any available path from the table. The table obtained is again directly used for other demand sets unless the network

topology changes. The comprehensive computer simulation results show that our scheme uses almost same number of wavelengths when the multiplicity of a pair is close to 1, meanwhile it is much better than others when the multiplicity becomes higher. Furthermore, the proposed scheme takes significantly less running time than others.

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