Dynamic Lightpath Protection in WDM Mesh Networks under Wavelength Continuity Constraint

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***Abstract*-- Path protection requires finding a working path and a protection path that are link disjoint. In this paper, we consider the dynamic lightpath protection problem in WDM mesh networks under the wavelength continuity constraint. Existing polynomial time algorithms can be applied to find a pair of link-disjoint lightpaths on a single wavelength; however, such algorithms fail if the working and protection lightpaths are on two different wavelengths. We prove the problem is NP-complete for both dedicated protection and shared protection. We develop an ILP formulation and heuristic solutions for the problem. Computer simulations are conducted to evaluate the performance of the heuristic algorithms.**

***Index terms*-- Lightpath protection, wavelength continuity constraint, optical network, integer linear program (ILP)**

I. Introduction

In wavelength division multiplexing (WDM) networks, end users can communicate with one another via all-optical WDM channels called lightpaths [1][2]. Because of the high data rate on lightpaths, it is imperative to develop appropriate protection and restoration schemes [3] [4] to prevent or reduce data loss.

In protection schemes, backup resources are pre-computed and reserved for each connection before a failure occurs [5][6]. In restoration schemes, an alternate route is discovered dynamically for each interrupted connection after a failure occurs [7][8]. Compared to restoration schemes, protection schemes have faster recovery time and provide guaranteed recovery ability but require more network resources.

Protection schemes can be divided into path protection and link protection based on the level of network resources involved in the protection. In path protection, a working path and a disjoint protection path are established for each connection. In link protection, separate backup resources are reserved for each individual link on the working path. Path protection usually has lower resource requirements and lower end-to-end propagation delay for the recovered route [5][7].

Protection schemes can be further divided into dedicated protection and shared protection based on whether backup resources are shared by more than one connection. In dedicated protection, each link or node can be reserved as a backup resource for at most one connection. In shared protection, a link or node can be reserved as a backup resource for multiple connections, as long as those connections do not fail simultaneously. Dedicated protection requires more network resources but is simpler to implement, while shared protection is more resource efficient but requires more complex signaling and network management [2].

The path protection problem can be considered under either static or dynamic traffic. Under static traffic, the entire set of connection requests is known. The routes and the wavelengths for the working and protection lightpaths of all connection requests must be determined[5][9][10][11][12]. Under dynamic traffic, connection requests arrive one at a time and each connection exists for only a finite duration. Routes and wavelengths must be determined individually for the working and protection lightpaths of each connection request.

In an optical network without wavelength conversion capability [13][14], the establishment of a lightpath is subject to the wavelength continuity constraint, i.e., a lightpath is required to be on the same wavelength channel throughout its entire path in the network. Under this constraint, the working lightpath and its protection lightpath may both be on the same wavelength, or each may be on a different wavelength.

A network failure may be caused by either a link failure or a node failure. Most modern node devices have built-in redundancy which greatly improves their reliability. Therefore link failure is more of a concern than node failure, and we only consider link failure in this paper. In order to find the two link-disjoint lightpaths, we may intuitively use a simple two-step solution, i.e., we find one shortest path on one wavelength first, then remove all links on that path and find the second shortest path on the same wavelength or on a different wavelength. These two paths are guaranteed to be link disjoint. However, this solution fails in so-called “trap” topologies (Fig. 1).

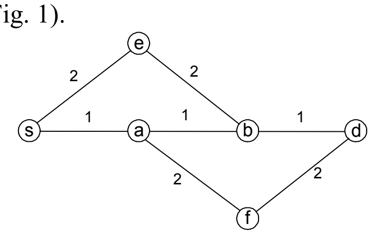

Figure 1. A single-wavelength WDM network.
The numbers indicate link costs.

For single-wavelength networks, a feasible solution can be found using Suurballe's algorithm and its variations [15][16]. The total cost of the resulting two link-disjoint lightpaths is minimal among all such path pairs. The algorithm runs in $O(n^2\log\ n)$ time, where n is the number of nodes. For networks with multiple wavelengths, we can apply this algorithm on every wavelength in order to find the two lightpaths on the same wavelength. However, if such paths do not exist, the problem is to find two link-disjoint lightpaths on two different wavelengths. In [17], it is proven that, for the special case in which the total cost of the two lightpaths is to be minimal, the problem is NP-complete. In this paper, we prove that in a more general case, the problem is still NP-complete for both dedicated protection and shared protection, regardless of the total path costs.

To solve the Routing and Wavelength Assignment (RWA) problem of lightpath protection, fixed alternate paths heuristics have been proposed in [18] and [19]. With these heuristics, alternate routes are predefined for each source-destination pair. When a connection request arrives, the predefined routes are searched to find a working path and a protection path with free bandwidth on the entire route. In this paper, we develop heuristic algorithms that select routes and wavelengths based on the real-time network status.

The rest of the paper is organized as follows. Section II proves that, under the wavelength continuity constraint, the problem of finding a working lightpath and its protection lightpath, each on a different wavelength, is NP-complete, regardless of the lightpaths' total cost. Section III formulates the problem as an ILP and gives heuristic solutions. Section IV presents computer simulations results for the heuristic solutions and compares the performance of the heuristics. Section V concludes the paper.

II. NP-Completeness of the Dynamic Lightpath Protection Problem under the Wavelength Continuity Constraint

For dedicated protection, the problem is formally defined as follows. Given optical network $G = (N, L)$, where N is the set of optical switching nodes and L is the set of fiber links, and given the number of wavelengths on each fiber link, find two link disjoint lightpaths from source node s to destination node d such that each lightpath is on a different wavelength.

A. Proof of NP-Completeness for Dedicated Protection

We reduce the 3SAT problem, which is known to be NP-complete [20], to the target problem. The 3SAT problem is stated as follows. Given a collection $C = \{C_1, C_2, ..., C_M\}$ of clauses on a finite set $V = \{v_1, v_2, ..., v_N\}$ of variables such that $|C_j| = 3$ for $1 \le j \le M$, where clause C_j is the boolean "or" of three literals (a literal is either a variable or the boolean "not" of a variable) and is satisfied by a truth assignment if and only if at least one of the three literals is true, is there a truth assignment for V that satisfies all the clauses in C?

We construct a graph G for an arbitrary instance of 3SAT C, such that the graph contains two link-disjoint lightpaths, P_1 on wavelength λ_1 and P_2 on wavelength λ_2, from node s to node d if and only if there is a truth assignment satisfying all clauses in C. In this proof, the graph contains only two wavelengths, λ_1 and λ_2, but it can easily be expanded to the case of more wavelengths. Following are the steps for the graph construction:

1. Create source node s and destination node d.
2. Corresponding to the N variables in V, create N+1 nodes z_i, $0 \le i \le N$. There is a link from s to z_0 and from z_N to d. Between z_{i-1} and z_i, there are nodes $x_i^1, y_i^1, x_i^2, y_i^2, ..., x_i^M, y_i^M$, and $\bar{x}_i^1, \bar{y}_i^1, \bar{x}_i^2, \bar{y}_i^2, ..., \bar{x}_i^M, \bar{y}_i^M$, which correspond to the M clauses in C. There are links $z_{i-1}x_i^1$, $x_i^1y_i^1$, $y_i^1x_i^2$, $x_i^2y_i^2$, ... , $x_i^My_i^M$, $y_i^Mz_i$ and links $z_{i-1}\bar{x}_i^1$, $\bar{x}_i^1\,\bar{y}_i^1$, $\bar{y}_i^1\,\bar{x}_i^2$, $\bar{x}_i^2\,\bar{y}_i^2$, ... , $\bar{x}_i^M\,\bar{y}_i^M$, $\bar{y}_i^M z_i$. Links $x_i^jy_i^j$ and $\bar{x}_i^j\,\bar{y}_i^j$ each contain two wavelengths, λ_1 and λ_2. All other links created in this step contain only wavelength λ_1.
3. Corresponding to each clause C_j, create nodes u_j and w_j, $1 \le j \le M$. There is a link from s to u_1 and from w_M to d. There is also a link from w_j to u_{j+1}. Other links are formed according to the following rules:
   a. A link from u_j to x_i^j exists, and a link from y_i^j to w_j exists, if and only if variable v_i is in clause C_j.
   b. A link from u_j to $\bar{x}_i^j$ exists, and a link from $\bar{y}_i^j$ to w_j exists, if and only if variable $\bar{v}_i$ is in clause C_j.

   All links constructed in this step only contain wavelength λ_2.

An example is given in Fig 2. In this example, we construct graph G for a 3SAT instance $C = \{C_1, C_2\}$, $V = \{v_1, v_2, v_3\}$, $C_1 = v_1 \vee \bar{v}_2 \vee v_3$, $C_2 = \bar{v}_1 \vee v_2 \vee v_3$. The dotted links contain wavelength λ_1 and the dashed links contain wavelength λ_2. The solid links contain both wavelengths λ_1 and λ_2. For a truth assignment v_1=1, v_2=1, v_3=1, the corresponding disjoint paths are: p_1 (s-z_0-$\bar{x}_1^1$-$\bar{y}_1^1$-$\bar{x}_1^2$-$\bar{y}_1^2$-z_1-$\bar{x}_2^1$-$\bar{y}_2^1$-$\bar{x}_2^2$-$\bar{y}_2^2$-z_2-$\bar{x}_3^1$-$\bar{y}_3^1$-$\bar{x}_3^2$-$\bar{y}_3^2$-z_3-d) on wavelength λ_1 and p_2 (s-u_1-x_1^1-y_1^1-w_1-u_2-x_2^2-y_2^2-w_2-d) on wavelength λ_2.

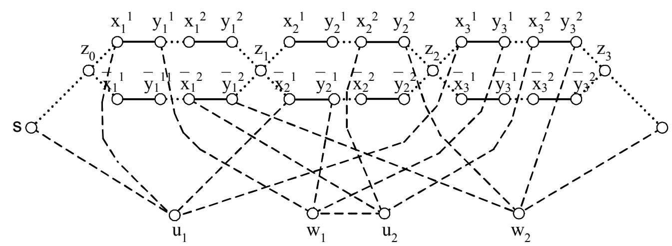

Figure 2. A graph constructed from a 3SAT instance.

Lemma 1: If C is satisfiable, then there exist two link-disjoint lightpaths of different wavelengths from node s to node d in graph G.

Proof: Let boolean values be assigned to $v_1, v_2, ..., v_N$ that satisfy C. The two paths should be routed as follows:

- P_1 is on wavelength λ_1. It traverses all z_i nodes for $0 \le i \le N$. Between node z_{i-1} and z_i, the path is routed via nodes x_i^j and y_i^j ($1 \le j \le M$) if and only if $v_i = 0$. Otherwise it is routed via nodes $\bar{x}_i^j$ and $\bar{y}_i^j$.
- P_2 is on wavelength λ_2. It traverses all u_j, w_j nodes for $1 \le j \le M$. Between node u_j and w_j, the path is routed as follows. By construction, link u_jw_j corresponds to clause C_j which has three literals. Each of the literals corresponds to a path from u_j to w_j that goes either through nodes x_i^j and y_i^j if the literal is in the form of v_j, or through nodes $\bar{x}_i^j$ and $\bar{y}_i^j$ if the literal is in the negation form, $\bar{v}_j$.

Because C is satisfied, at least one of the three literals in C_j must be 1. Let the variable in that true literal be v_j. Then

- if the literal is in the form of v_j, then $v_j = 1$, and route P_2 passes through nodes x_i^j, y_i^j;
- if the literal is in the form of $\bar{v}_j$, then $v_j = 0$, and route P_2 passes through nodes $\bar{x}_i^j$, $\bar{y}_i^j$.

If more than one literal is true, then randomly pick one of the true literals and route P_2 accordingly.

Thus, P_1 doesn't traverse any of the nodes u_j, w_j for $1 \le j \le M$, and P_2 doesn't traverse any of the nodes z_i for $0 \le i \le N$. Furthermore, if P_2 traverses node x_i^j, y_i^j, then P_1 traverses $\bar{x}_i^j$, $\bar{y}_i^j$, and vice versa. Therefore P_1 and P_2 are link disjoint, and each is on a different wavelength.

Lemma 2:If there exist two link-disjoint lightpaths of different wavelengths from s to d in the constructed graph G, then C can be satisfied.

Proof:

1. Since there are only two links originating from the source node s, the two links must each belong to a separate path. Let sz_0 be part of P_1 and su_1 be part of P_2.
2. Since P_2 is already on wavelength λ_2, P_1 must not traverse any of the nodes u_j, w_j for $1 \le j \le M$, otherwise it would also be on wavelength λ_2 and violate the wavelength continuity constraint. Therefore, if P_1 traverses x_i^1 for $1 \le i \le N$, then it must also traverse y_i^1, x_i^2, y_i^2, … , x_i^M, y_i^M, z_i. Similarly if P_1 traverses $\bar{x}_i^1$ for $1 \le i \le N$, then it must also traverse $\bar{y}_i^1$, $\bar{x}_i^2$, $\bar{y}_i^2$, … , $\bar{x}_i^M$, $\bar{y}_i^M$, z_i.
3. Since P_1 is already on wavelength λ_1, P_2 must not traverse any of the nodes z_i for $0 \le i \le N$, otherwise it would also be on wavelength λ_1 and violate the wavelength continuity constraint. Furthermore, if P_2 traverses node u_j ($1 \le j \le M$) and x_i^j ($1 \le i \le N$), it must also traverse y_i^j and then back to w_j. Similarly, if P_2 traverses node u_j and $\bar{x}_i^j$, it must also traverse $\bar{y}_i^j$ and then back to w_j.
4. Loops are not allowed. Therefore once P_2 reaches w_j ($1 \le j \le M$), it must go to u_{i+1} if $j < M$, or to d if $j = M$.
5. If P_2 traverses nodes x_i^j, y_i^j, $1 \le j \le M$, $1 \le i \le N$, it must not also traverse nodes $\bar{x}_i^k$ and $\bar{y}_i^k$, $k \ne j$, and vice versa; otherwise P_1 is "blocked" and cannot reach the destination node d without violating the link disjoint constraint.
6. If P_2 traverses nodes x_i^j, y_i^j, $1 \le j \le M$, $1 \le i \le N$, then P_1 must traverses nodes traverses $\bar{x}_i^1$ for $1 \le i \le N$, then it must also traverse $\bar{x}_i^1$, $\bar{y}_i^1$, $\bar{x}_i^2$, $\bar{y}_i^2$, ..., $\bar{x}_i^j$, $\bar{y}_i^j$, …, $\bar{x}_i^M$, $\bar{y}_i^M$. Similarly if P_2 traverses nodes $\bar{x}_i^j$, $\bar{y}_i^j$, then P_1 must traverses nodes x_i^1, y_i^1, x_i^2, y_i^2, …, x_i^j, y_i^j, … , x_i^M, y_i^M.
7. Assign values to v_1, v_2, … , v_N as follows:
   - If P_2 traverses nodes x_i^j, y_i^j, $1 \le j \le M$, $1 \le i \le N$, then assign $v_i = 1$, making clause C_j to be true.
   - If P_2 traverses nodes $\bar{x}_i^j$, $\bar{y}_i^j$, $1 \le j \le M$, $1 \le i \le N$, then assign $v_i = 0$, making clause C_j to be true.
   - Variables that are not assigned a value in the first two steps are randomly assigned either 1 or 0.
   - This assignment satisfies C.

Combining *Lemma 1* and *Lemma 2*, we see that the 3SAT problem is reducible to the problem of finding disjoint lightpaths on different wavelengths. Therefore this problem is NP-complete, regardless of the paths costs.

B. *Proof of NP-Completeness for Shared Protection*

With shared protection, one or more protection lightpaths may traverse a common wavelength on a fiber link. If the problem with shared protection is solvable, then the problem with dedicated protection can also be solved since it is a special case of that with shared protection.

III. ILP Formulation and Heuristic Algorithms

We now develop ILP formulation and heuristic solutions for the NP-complete problem of finding link-disjoint lightpaths on different wavelengths.

A. *ILP Formulation*

The ILP formulation should be solved for each incoming connection request. The objective is to find any two link-disjoint lightpaths. An alternative objective is to minimize the total hop count of the two link-disjoint lightpaths.

The following are given as inputs to the problem.

- N: number of nodes in the network
- L: collection of all fiber links in the network.
- Λ_{ij}: collection of all free wavelengths on fiber link $ij \in L$.
- s, d: source node and destination node.

The ILP solves for the following variables:

- α_{ij}^{sdw} : 1 if wavelength w on link ij is taken by the working lightpath from source s to destination d; 0 otherwise.
- β_{ij}^{sdw} : 1 if wavelength w on link ij is taken by the protection lightpath from source s to destination d; 0 otherwise.

Objective: Find a working lightpath and a protection lightpath that satisfy the wavelength continuity constraint.

$$\sum_{\forall ij \in L} \sum_{\forall w \in \Lambda_{ij}} \alpha_{ij}^{sdw} + \sum_{\forall ij \in L} \sum_{\forall w \in \Lambda_{ij}} \beta_{ij}^{sdw} > 0 \qquad (1)$$

Constraints:

Flow-conservation constraint:

$$\sum_{i=1}^{N} \alpha_{il}^{sdw} - \sum_{j=1}^{N} \alpha_{lj}^{sdw} = \begin{cases} 1, & \text{if } l = d \\ -1, & \text{if } l = s \\ 0, & \text{otherwise} \end{cases}$$

$$1 \le l \le N,\ 1 \le w \le W, \qquad (2)$$

$$\sum_{i=1}^{N} \beta_{il}^{sdw} - \sum_{j=1}^{N} \beta_{lj}^{sdw} = \begin{cases} 1, & \text{if } l = d \\ -1, & \text{if } l = s \\ 0, & \text{otherwise} \end{cases}$$

$$1 \le l \le N,\ 1 \le w \le W, \qquad (3)$$

Link disjoint constraint:

$$\sum_{\forall w \in \Lambda_{ij}} \alpha_{ij}^{sdw} + \sum_{\forall w \in \Lambda_{ij}} \beta_{ij}^{sdw} \leq 1, \ \forall ij \in L \tag{4}$$

B. Heuristic Algorithms

In this section we introduce heuristic algorithms for finding link-disjoint lightpaths in WDM networks. The first algorithm is named the Route-First Algorithm. In this algorithm, we use a standard routing and wavelength assignment (RWA) approach. We first try to find two disjoint routes, and then assign free wavelengths to them. The second algorithm is named the Wavelength-Scan Algorithm. In this algorithm, we first scan through each wavelength for a pair of link-disjoint lightpaths using Suurballe's algorithm. If Suurballe's algorithm fails, we search through each pair of wavelengths for a pair of link-disjoint lightpaths on different wavelength using a two-step approach.

At the beginning of both algorithms, we scan all fiber links and increase the cost of a link linearly to the number of wavelengths already in use on the link. This step increases the likelihood of finding free wavelengths on selected routes. It also balances traffic load among the network links, thus improves the blocking probability.

For the Route-First Algorithm, the running time is $O(n^2\log n + Wn)$, where n is the number of nodes and W is the number of wavelengths in the network. The pseudo code is given in Fig 3.

```
Initialize c_l on every link to the cost of the link;
for ( all network  links)
   increase c_l on link l according to the number of wavelengths in
use on l;

if ( Suurballe's algorithm(s, d) succeeds and finds two routes r_1
and r_2 )
{
   for ( all wavelengths λ_i and  λ_j  in the network and λ_i ≠ λ_j )
      if ( a wavelength λ_i  is available on route r_1
          and a wavelength λ_j is available on route r_2 )
      {
         assign λ_i  to  r_1 and make it the working lightpath p_1;
         assign λ_j to r_2 and make it the protection lightpath p_2;
         return( p_1 and p_2);
      }
}
return(FAILURE);
```

Figure 3. Route-First Algorithm

For the Wavelength-Scan Algorithm, the running time is $O(W{\cdot}n^2\log n)$, where n is the number of nodes and W is the number of wavelengths in the network.. The pseudo code is given in Fig 4.

Comparing the two algorithms, the Route-First Algorithm obtains the routes first before it assigns free wavelengths to the routes. If the algorithm returns successfully, the total cost of the two lightpaths is minimal among all link-disjoint paths from s to d. On the other hand, the Wavelength-Scan Algorithm scans through all available wavelengths, searching for the two link-disjoint paths, first on a single wavelength then on different wavelengths. Thus the running time of this algorithm is higher. When the traffic load is low, the Route-First Algorithm should have lower blocking probabilities because free wavelengths are readily available and the routes are optimal in total cost. When the traffic load is high, the Wavelength-Scan Algorithm should have lower blocking probability because it searches through all available wavelengths.

```
Initialize c_l on every link to the cost of the link;
for ( all network  links)
   increase c_l on link l according to the number of wavelengths in
use on l;

for ( all the wavelengths )
   run Suurballe's algorithm and return the two disjoint paths with
the minimum total cost if they are found;

//If the previous step fails
for ( all wavelength λ_i in the network )
{
   if ( Dijkstra's algorithm(s, d) on λ_i succeeds and finds the first
shortest path p_1 from s to d)
   {
      for ( all λ_j in the network and λ_j ≠ λ_i )
      {
         remove links on the first shortest path p_1;
         if ( Dijkstra's algorithm(s, d) on λ_j succeeds and finds the
second shortest path p_2 from s to d)
            return( p_1 and p_2 ); //Return the lightpaths
      }
   }
}
return(FAILURE);
```

Figure 4. Wavelength-Scan Algorithm

To increase resource utilization and thus reduce blocking probability, we can modify these two algorithms to support shared protection [21]. The tradeoffs are complex network management and additional signaling protocol.

IV. Simulations

We have discussed two heuristic algorithms for the dynamic path protection problems under the wavelength continuity constraint, i.e., the Route-First Algorithm and the Wavelength-Scan Algorithm. We can also develop shared protection support for each of the algorithms. Computer simulations were developed to evaluate the performance of these four algorithms. In these simulations, the primary performance metric is the blocking probability.

We use the 16-node, 25-link NSFNET backbone topology (Fig. 5) for the simulations. Other network topologies are also used and yield similar results. The cost of every link is assumed to be 1, and the capacity on each link is 8 units. Working paths and protection paths each takes one unit of capacity. Connection requests arrive according to a Poisson process, and holding times are exponentially distributed.

In the simulation, we compare the blocking probabilities of the Route-First Algorithm and the Wavelength-Scan Algorithm. For each of the algorithms, we run the simulation for an extended period of time, under various traffic loads, and compare their blocking probabilities. The results are obtained with confidence level between 90% to 95% and confidence interval around 5%. The results are depicted in Fig.6.

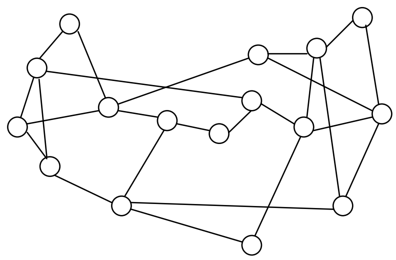

Figure 5. 16-node NSFNET backbone network.

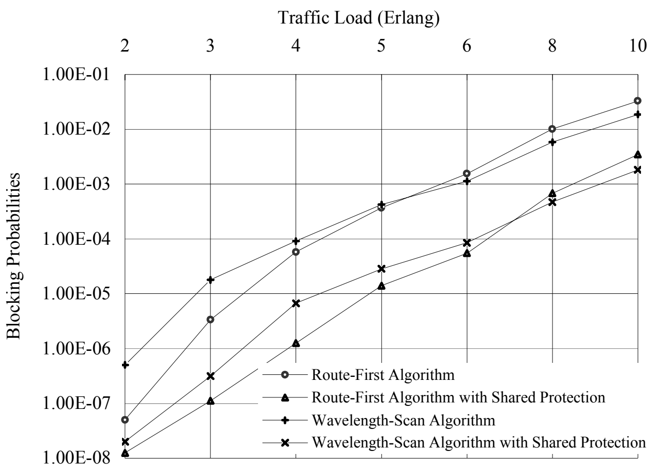

Figure 6. Blocking probability versus load. The trends continue for traffic load higher than 10 Erlangs.

The simulation results confirm our analysis in Section III. From the simulation, we first observe that shared protection significantly improves blocking probability, regardless of the traffic load. Secondly, when the traffic load is very low, the Route-First Algorithms perform better than the Wavelength-Scan Algorithms. While the traffic load increases, the Wavelength-Scan Algorithms become better than the Route-First Algorithms.

V. CONCLUSION

In this paper we considered the problem of dynamic lightpath protection in optical networks under the wavelength continuity constraint. We proved that the problem is NP-complete. We then developed an ILP formulation and heuristic algorithms to solve the problem. We conducted computer simulations to evaluate the heuristic algorithms and compared their blocking probabilities under various traffic loads. The simulation reveals that, when network load is low, the Route-First Algorithm performs better. When network load is higher, the Wavelength-Scan Algorithm performs better. The simulations also confirmed that shared protection significantly improves blocking probability over dedicated protection.

One possible area of future work would be to further improve the performance of the Wavelength-Scan Algorithm at higher load. In addition to traffic balancing, we may also adjust the link costs based on other factors such as the number of free wavelengths on a link that are reachable to the destination. This type of adjustments may have a positive impact on the algorithm's performance.

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