Dynamic Lightpath Protection in WDM Mesh Networks under Risk-Disjoint 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 where a single risk factor may cause multiple links to fail simultaneously. The objective is to find link-disjoint lightpaths that are also risk disjoint. A similar problem has recently been proven to be NP-Complete. We give an alternative proof of the NP-completeness, and formulate the problem as an Integer Linear Program. We then develop heuristic algorithms and evaluate the performance of the algorithms through computer simulation. We show that we can achieve satisfactory performance using the heuristic techniques.**

Index terms-- **Optical network, lightpath protection, shared risk link group, risk disjoint, integer linear program (ILP)**

I. INTRODUCTION

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

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 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 connections 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. Subsequently, routes and wavelengths are 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 this paper, we address the dynamic lightpath protection problem in WDM networks with full wavelength conversion. In this case, a lightpath may consist of different wavelengths on each link.

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 two link-disjoint lightpaths, we may intuitively use a simple two-step solution, i.e., we find one shortest path first, then remove all links on that path and find the second shortest path. These two paths are guaranteed to be link disjoint. However, this solution fails in so-called "trap" topologies[15].

The correct approach is to use Suurballe's algorithm and its variations [16][17], if the probabilities of link failures are independent. 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. However, in a network where a single factor can cause more than one link failure, the two lightpaths found with this approach may still fail simultaneously. For instance, in optical transport networks, multiple fiber links are bundled into the same underground conduit, or span. A cut to the conduit can cause all the fiber links to fail. To describe this type of network phenomenon, transport network carriers use the notation of Shared Risk Link Group (SRLG) [18][19]. The fiber links in the same conduit belong to the same SRLG because they all share the same risk of a conduit cut. Therefore, in addition to being link disjoint, the path protection problem in optical transport networks has the extra constraint of being SRLG disjoint.

For some special SRLG configurations, such as forks and express links, there exist algorithms with polynomial time complexity [15][17]. If the configurations are arbitrary, it has been recently proved that the problem of finding two SRLG-disjoint paths is NP-complete [20][21]. In this paper, we give an alternative proof using 3SAT reduction. Since the risk-disjoint constraint also applies to path protection in WDM networks and other path-routed networks, we introduce the concepts of Risk ID and Risk Set to extend the NP-completeness result beyond the scope of fiber span failure.

The work in [12] proposes a heuristic to solve the path protection problem under the optical fiber duct-layer constraint, which is a special case of the SRLG-disjoint constraint. The heuristics in [22] and [23] use a simple two-step approach. The solution proposed in [24] selects the working and protection lightpaths for each incoming connection request from the predefined alternate paths. In this work, we develop heuristic algorithms for the case in which risks are arbitrarily distributed. The heuristics are adaptive to the real-time network status.

The rest of the paper is organized as follows. Section II gives an alternative 3SAT reduction to prove the NP-completeness of the dynamic path protection problem under the SRLG-disjoint constraint. The result is then extended to WDM mesh networks and general path-routed networks. In Section III, we formulate the problem as an ILP and develop 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 Risk-Disjoint Constraint

For dedicated protection, the problem is formally defined as follows. Given network $G = (N, L)$, where N is the set of nodes and L is the set of fiber links, and given the SRLGs on all links in L, find two paths from source node s to destination node d such that the two paths are SRLG-disjoint and do not share any links on the paths of existing connections.

A. Proof of NP-Completeness for Dedicated Protection

We reduce the NP-complete 3SAT problem [25] 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 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 SRLG-disjoint paths P_1 and P_2 from node s to node d, if and only if there is a truth assignment satisfying all clauses. 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 belongs to a unique SRLG other than SRLG-1 and SRLG-2. All other links created in this step belong to SRLG-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 belong to SRLG-2.

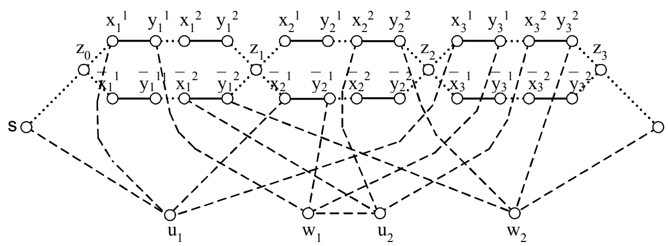

Figure 1. A graph constructed from a 3SAT instance.

An example is given in Fig 1. 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 belong to SRLG-1 and the dashed links belong to SRLG-2. Each solid link belongs to a unique SRLG other than SRLG-1 and SRLG-2. For a truth assignment v_1=1, v_2=1, v_3=1, the corresponding risk-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) 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).

Lemma 1: If C is satisfiable, then there exist two SRLG-disjoint paths 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 traverses all z_i nodes for $0 \le i \le N$. Between node z_{i-1} and z_i, the path is routed via x_i^j-y_i^j ($1 \le j \le M$) if and only if $v_i = 0$; It is routed via $\bar{x}_i^j$-$\bar{y}_i^j$ otherwise.
- P_2 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 x_i^j-y_i^j if the literal is in the form of v_j, or through $\bar{x}_i^j$-$\bar{y}_i^j$ 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 each belongs to a different set of SRLGs.

Lemma 2:If there exist two SRLG-disjoint paths 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 already belongs to SRLG-2, P_1 must not traverse any of the nodes u_j, w_j for $1 \le j \le M$, otherwise it would also belong to SRLG-2 and violate the SRLG disjoint constraint. Therefore, if P_1 traverses x_i^1 for $1 \le i \le N$, then it must also traverse $y_i^1, x_i^2, y_i^2, \ldots, x_i^M, y_i^M, z_i$. 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 already belongs to SRLG-1, P_2 must not traverse any of the nodes z_i for $0 \le i \le N$, otherwise it would also belong to SRLG-1 and violate the SRLG disjoint 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 $x_i^1, y_i^1, x_i^2, y_i^2, \ldots, x_i^j, y_i^j, \ldots, x_i^M, y_i^M$.
7. Assign values to $v_1, v_2, \ldots, v_N$ 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 SRLG-disjoint paths. Therefore this problem is NP-complete.

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

With shared protection, one or more protection paths may traverse a common 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.

C. *Dynamic Path Protection in WDM Mesh Networks and General Path-Routed Networks*

In WDM mesh networks, a single risk factor may cause multiple lightpaths to fail simultaneously in situations such as the case in which portions of several lightpaths are on the same fiber link when the link is cut. Therefore the risk-disjoint constraint is applicable and the NP-completeness persists. This is true for MPLS networks as well. To expand the concept of SRLG to the general path-routed networks, we propose the following concepts:

- Risk ID: For each risk factor that may cause a failure in a network, we assign a unique integer number called the Risk ID.
- Risk Set: The collection of Risk IDs of the links on a path is called the Risk Set of that path. The Risk Set represents all the factors that may cause a path to fail. The risk-disjoint constraint requires that a working path and its protection path contain no common Risk Ids in their Risk Sets.

The concepts of Risk ID and Risk Set are a generalization of SRLG. Now the dynamic path protection problem under the risk-disjoint constraint in a general path-routed network can be defined as follows. Given network $G = (N, L)$, where N is the set of nodes and L is the set of links, and given the Risk IDs of each link, find two risk-disjoint paths from source node s to destination node d. The proof in Section II.A and Section II.B can be easily generalized to prove the NP-completeness of this problem.

III. ILP Formulation and Heuristic Algorithms

A. *ILP Formulation*

For the ILP formulation, the objective is to find two risk-disjoint lightpaths for a connection request. An alternative objective is to minimize the total hop count of the two risk-disjoint lightpaths. The following are given as inputs to the problem.

- N: number of nodes in the network.
- L: collection of all links in the network.
- W_{ij}: number of free wavelengths on link $ij \in L$.
- $S = \{ s_1, s_2, \ldots, s_k, \ldots, s_T \}$: collection of all Risk IDs in the network. T is the number of Risk IDs in the network.
- r_{ij}^k: 1 if link ij has Risk ID s_k; 0 otherwise.
- 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 risk-disjoint constraint.

$$\sum_{\forall ij \in L} \sum_{w}^{W_{ij}} \alpha_{ij}^{sdw} + \sum_{\forall ij \in L} \sum_{w}^{W_{ij}} \beta_{ij}^{sdw} > 0 \tag{1}$$

Constraints:

Flow-conservation without the wavelength continuity constraint:

$$\sum_{i=1}^{N} \sum_{w}^{W_{il}} \alpha_{il}^{sdw} - \sum_{j=1}^{N} \sum_{w}^{W_{lj}} \alpha_{lj}^{sdw} = \begin{cases} 1, & \text{if } l = d \\ -1, & \text{if } l = s \\ 0, & \text{otherwise} \end{cases} \quad 1 \leq l \leq N \tag{2}$$

$$\sum_{i=1}^{N} \sum_{w}^{W_{il}} \beta_{il}^{sdw} - \sum_{j=1}^{N} \sum_{w}^{W_{lj}} \beta_{lj}^{sdw} = \begin{cases} 1, & \text{if } l = d \\ -1, & \text{if } l = s \\ 0, & \text{otherwise} \end{cases} \quad 1 \leq l \leq N \tag{3}$$

Link-disjoint constraint:

$$\sum_{w}^{W_{ij}} \alpha_{ij}^{sdw} + \sum_{w}^{W_{ij}} \beta_{ij}^{sdw} \leq 1, \quad 1 \leq i, j \leq N \tag{4}$$

Risk-disjoint constraint:

$$r_{ij}^{k} \sum_{w}^{W_{ij}} \alpha_{ij}^{sdw} + r_{mn}^{k} \sum_{w}^{W_{mn}} \beta_{mn}^{sdw} \leq 1, \quad \forall k \leq T, \ \forall ij \in L, \ \forall mn \in L \tag{5}$$

B. Heuristic Algorithms

We discussed the simple two-step heuristic in Section I. This solution may fail in the "trap" topologies because the first shortest path is obtained without considering the disjoint path being routed next. We develop the Joint-Search Two-Step Algorithm (JSTSA) to overcome this problem by using Suurballe's algorithm to jointly route both paths. As the first step of this algorithm, we increase the cost of those links with high-occurring Risk IDs; hence those links are avoided whenever possible, which makes it more likely to find risk-disjoint paths. In order to further reduce blocking probability, we also increase the cost of the links with high traffic load so that traffic load is better balanced across all links. The remaining steps are included in the pseudo code in Fig. 2 and Fig. 3.

Compared to the simple two-step heuristic and other existing heuristic solutions, the Joint-Search Two-Step Algorithm is superior not only because it may find two disjoint paths in topologies where the simple two-step algorithm fails, but also because it is fully adaptive to network status and works on networks with arbitrary risk distribution. If every Risk ID occurs only once in the network, this algorithm is equivalent to Suurballe's algorithm. It also has the same order of time complexity as Suurballe's algorithm.

We can further improve the performance of the Joint-Search Two-Step Algorithm with shared protection [26]. With shared protection, a network can accommodate more connections, and the blocking probability is reduced.

```
find_protection_path(working path p_w)
{
    remove the network links along p_w;
    remove the network links used by other working paths;
    remove the links that have common Risk IDs with p_w;
    run Dijkstra's algorithm(s, d). If Succeeds, return path p_p.
    Otherwise return FAILURE;
}
```

Figure 2. Subroutine find_protection_path()

```
for (all network links)
{
   for (all Risk ID r that occurs more than once in the network)
       increase cost c_l on link l if l contains r;
   Adjust link cost based on its traffic load;
}

if ( run Suurballe's algorithm(s, d) and find two routes r_1 and r_2)
{
    r_1p = find_protection_path(r_1);
    r_2p = find_protection_path(r_2);
    compare the total cost of the two path pairs, i.e., (r_1, r_1p) and
    (r_2, r_2p), and choose the one with smaller total cost;
}
else
   return(FAILURE);
```

Figure 3. Joint-Search Two-Step Algorithm (JSTSA)

IV. SIMULATIONS

Computer simulations were conducted to evaluate the performance of the algorithms proposed in Section III. We use the 16-node, 25-link NSFNET backbone topology (Fig. 4) 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. Every node has full wavelength conversion capability. A working lightpath and a protection lightpath each take one unit of capacity. Connection requests arrive according to a Poisson process, and holding times are exponentially distributed. The primary performance metric is the blocking probability.

Since an optimal solution is infeasible due to the NP-completeness of the problem, we run Suurballe's algorithm without the risk-disjoint constraint and use the resulting blocking probabilities as a lower bound. Note that the disjoint lightpaths obtained from Suurballe's algorithm may not be risk disjoint. The results are obtained with confidence level between 90% to 95% and confidence interval around 5%. The results are depicted in Fig. 5.

The simulation results show that, first of all, shared protection significantly improves the blocking probabilities, regardless of the traffic load. Secondly, when the traffic load is low, the Joint-Search Two-Step Algorithm is significantly better than the simple two-step algorithm. As the traffic load increases, the blocking probabilities of the two algorithms converge. The performance of the Joint-Search Two-Step Algorithm stems from its incorporation of Suurballe's algorithm and the minimization of the total cost of the working lightpath and its protection lightpath.

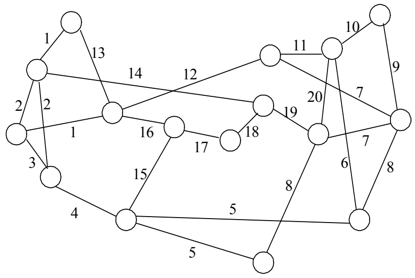

Figure 4. 16-node NSFNET backbone network. The numbers indicate Risk IDs.

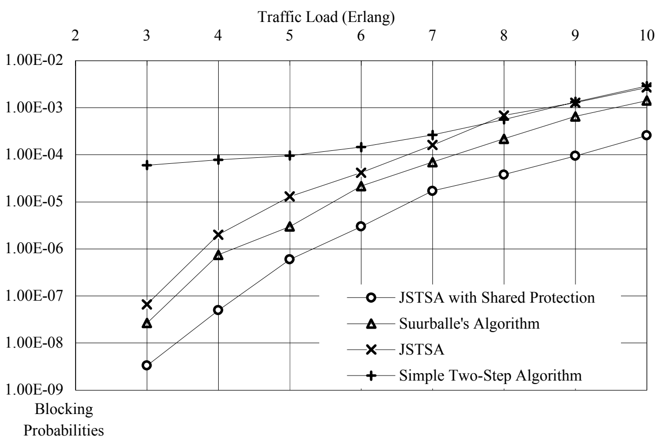

Figure 5. Blocking probability versus load under low traffic load. The blocking probabilities of the simple two-step algorithm and the JSTSA converge at higher load.

V. Conclusion

In this paper we first considered the problem of dynamic path protection in optical transport networks under the SRLG-disjoint constraint. We proved that the problem is NP-complete. The problem was then generalized to WDM mesh networks and general path-routed networks with the introduction of two new concepts - Risk ID and Risk Set.

To solve the NP-complete problem, we developed an ILP formulation and heuristic algorithms. We conducted computer simulations to evaluate the heuristic algorithms and compared their blocking probabilities under various traffic loads. The simulation reveals that, the Joint-Search Two-Step Algorithm is superior to the simple two-step algorithm. The simulations also confirm 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 Joint-Search Two-Step Algorithm. The algorithm currently adjusts the link costs based on the occurrences the Risk IDs of the network links. We may include other factors to make the adjustment more intelligent. Another area of improvement might be using traffic grooming on the working lightpaths and protection lightpaths to reduce network complexity and cost.

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