Joint Topology Control and Path-Oriented Protection in Free Space Optical Networks

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***Abstract*— We consider the problem of optimizing the topology of free-space optical networks jointly with path-oriented protection. Our proposed scheme is based on a mixed integer linear programming formulation. In this problem, candidates of working paths and protection paths are found for each origin-destination (OD) pair, and the optimization algorithm chooses the optimal working path and protection path for every OD pair such that the congestion in the network is minimized. Numerical results demonstrate the efficiency of our proposed approach in terms of the number of constraints and solution time.**

I. INTRODUCTION

Free-space optical (FSO) wireless communication has been continuously growing as an attractive solution for high data rates communications over short distances in the recent years [1]. A direct line-of-sight is imperative in an FSO link, which consists of a transmitter, the propagation channel and a receiver. Invisible, eye-safe light beams are used between FSO links to provide optical bandwidth connections that can send and receive voice, video, and data information [1]. In an FSO network, end users are connected by installing optical transceivers on windows, building rooftops or exterior walls. An example of an imaginary urban FSO network of five nodes, employed in the Melbourne central business district (CBD) area, is illustrated in Fig. 1.

Commercially available FSO equipments can provide high-speed data rates in the range of 100 Mbps to 2.5 Gbps, and a data rate as high as 160 Gbps has been reported in demonstration systems [2]. Potential applications of the FSO technology include last mile network access, enterprise connectivity, fiber backup, disaster recovery, etc.

The main challenges for FSO communication are to combat atmospheric disturbances and building sway. Examples of the former include fog, absorption, scattering, and scintillation, which may result in high bit-error rate and long transmission delay. The latter usually leads to the difficulty to maintain the strict line-of-sight requirement [3]. The design of dynamic logical topologies has been widely studied for wavelength-division multiplexed optical networks (e.g., [4]–[7]). In [8], Desai and Milner extended similar topology control techniques to autonomous reconfigurable FSO networks. They formulated a congestion minimization problem in the form of a mixed integer program (MIP) to dynamically make decisions about the choice of network topology in response to link failures, and a range of heuristics were proposed to solve the problem in a more efficient manner.

On the other hand, to design survivable networks, protection and restoration schemes in different network layers have been extensively studied to combat network failures [9]–[11]. When a network failure on the working path is detected, protection schemes are able to immediately re-route data onto the pre-allocated backup path. In contrast, an alternative path is dynamically established in real time in restoration schemes upon the detection of a network failure. As such, protection schemes can react faster to network failures at the cost of reserving more spare capacity. While restoration schemes usually take longer to recover connections, they are more efficient in terms of the utilization of network resources. Protection and restoration can be implemented using two techniques: path-oriented or link-oriented [11].

In this paper, we jointly consider topology control and path-oriented protection for FSO networks. The remainder of the paper is organized as follows. In Section II, the network model and notation are described. The problem formulation of topology control without assuming routing is introduced in Section III. In Section IV, our scheme in which we combine topology control and path-oriented protection for FSO networks is presented. Numerical evaluation and discussion appear in Section V.

II. NETWORK MODEL AND NOTATION

Consider a network of N nodes as a digraph $G =< V, E >$, where V is the set of nodes in the network and E is the set of potential links in the network. A link between two nodes i and j is represented as (i, j). It is assumed that the traffic matrix R of size $N \times N$ (the $[s, d]$th entry R_{sd} denotes the average traffic flow from source node s to destination node d) is known *a priori*. In addition, we introduce the following important notation.

- λ_{ij}^{sd} : the amount of traffic on link (i, j) from the origin destination (OD) pair $[s, d]$.
- b_{ij} : binary decision variable represents the selection of link (i, j).
- Δ_i : degree constraint of node i.
- W^{sd} : set of working path candidates for OD pair $[s, d]$.

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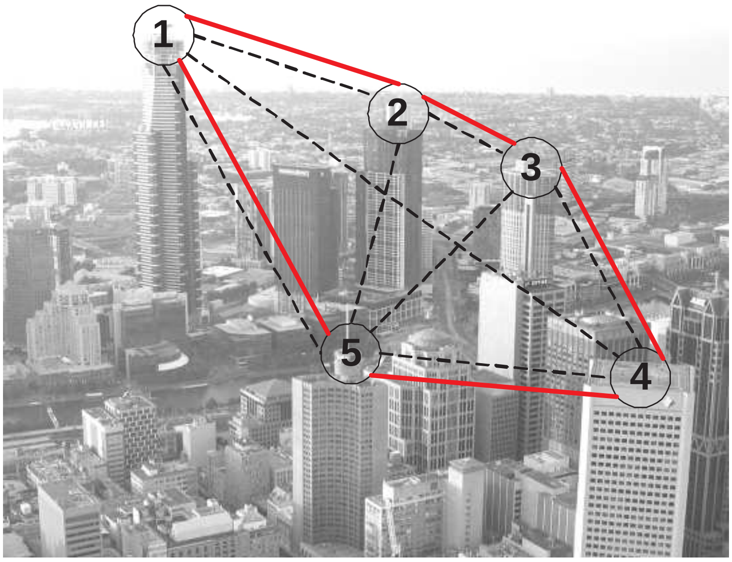

Fig. 1. An FSO network of five nodes in the Melbourne CBD area. Dashed lines represent potential links and solid lines show an example of the resultant topology after optimization.

- W_w^{sd} : an arbitrary working path candidate in set W^{sd}.
- P^{sd} : set of protection path candidates for OD pair $[s,d]$.
- P_p^{sd} : an arbitrary protection path candidate in set P^{sd}.
- $\lambda_{ij}^{sd,W}$: the amount of traffic on link (i,j) from working path candidates of OD pair $[s,d]$.
- $\lambda_{ij}^{sd,P}$: the amount of traffic on link (i,j) from protection path candidates of OD pair $[s,d]$.
- λ_{ij} : total traffic on link $(i,j) \in E$.

In Fig. 1, the dashed lines represent the potential links, through which it is possible for nodes to communicate with each other. While the number of transceivers installed on each node (i.e., the degree of node) is limited, the actual network topology can be optimally decided by minimizing certain optimization metrics, (e.g., congestion, communication delay, bit error rate, etc.). The solid lines in Fig. 1 demonstrate an optimal solution where the degree of nodes is constrained to two. In the following, we will describe optimization schemes to make decisions about the choice of the optimal topology for FSO networks.

III. THE NODE-ARC FORMULATION

In general, network flow problems can be formulated as "node-arc" or "arc-path" models. The former means the flow variables are associated with each link of the network, while they are assigned to eligible routes in "arc-path" models [11].

In wavelength-routed optical networks, the problem of congestion minimization has been formulated to design logical topologies. Recently, the same problem in the form of a non-linear MIP formulated as a "node-arc" model has been extended to FSO networks with ring topologies [8]. In this section, we re-formulate the problem in a simpler manner where the objective function is linearized. First let us define the indicator function δ_{ij} as follows:

$$\delta_{ij} = \begin{cases} 1 & \text{if nodes } i \text{ and } j \text{ can see each other,} \\ 0 & \text{otherwise.} \end{cases}$$

The objective function:

$$\min z$$

Subject to:

1) Flow conservation at node i:

$$\sum_j \delta_{ij}\lambda_{ij}^{sd} - \sum_j \delta_{ji}\lambda_{ji}^{sd} = \begin{cases} +R_{sd} & \text{if } i = s; \\ -R_{sd} & \text{if } i = d; \\ 0 & \text{otherwise.} \end{cases}$$

$\forall i \in V, \forall [s,d]$.

2) Bound on variable z:

$$z \geq \sum_{[s,d]} \lambda_{ij}^{sd}, \qquad \forall (i,j) \in E.$$

3) Bound on traffic flow variables:

$$0 \leq \lambda_{ij}^{sd} \leq R_{sd} b_{ij}, \qquad \forall (i,j) \in E, \forall [s,d].$$

4) Degree of each node constrained:

$$\sum_j \delta_{ij} b_{ij} \leq \Delta_i, \qquad \forall i \in V.$$

5) Bound on decision variables b_{ij}:

$$b_{ij} \in \{0,1\}, \qquad \forall (i,j) \in E.$$

As in [8], no routing is assumed in the above problem and the formulation searches the optimal topology and optimal routing simultaneously. In practice, one might be more interested in finding the optimal topologies when the set of possible routes for each OD pair is given.

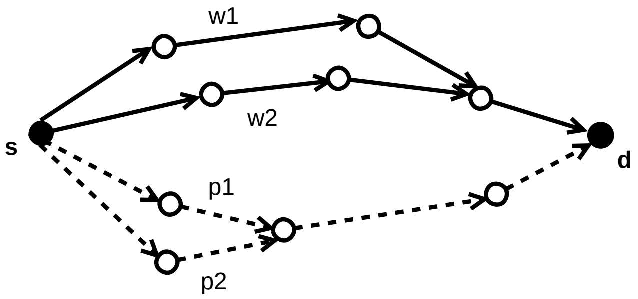

Fig. 2. Work/protection path candidates example.

IV. OUR PROPOSED SCHEME

In this section, we describe our joint topology control and path protection scheme, in which the problem is formulated as an arc-path model.

A. Finding Working/Protection Path Candidates

First, we show a solution to find the set of working and protection path candidates for each OD pair. Any path in the set of working path candidates W^{sd} must be link-disjoint with any path in the set of protection path candidates P^{sd}. Fig. 2 illustrates a simple example of two working path candidates and two protection path candidates. Assuming it is required to find $k_W \in \mathbb{Z}^+$ working path candidates and $k_P \in \mathbb{Z}^+$ protection path candidates for each OD pair $[s, d]$ in the network $G =< V, E >$, we propose the following solution.

Step 1: Use the Dijkstra's algorithm to find the shortest path for OD pair $[s, d]$;
Step 2: Disable all the links on the shortest path found in step 1;
Step 3: Use the k shortest path (ksp) algorithm to find k_P protection path candidates for OD pair $[s, d]$, and store them to P^{sd};
Step 4: Disable all the links on all the k_P paths found in step 3;
Step 5: Restore the shortest path found in step 1;
Step 6: Use the ksp algorithm to find k_W working path candidates for OD pair $[s, d]$, and store them to W^{sd}.

The above procedure is repeated for each OD pair to find the required number of working and protection path candidates. The shortest paths are searched in terms of number of hops and we used the ksp algorithm proposed in [12].

B. Joint Topology Control and Path-Oriented Protection

We model the problem in a manner that only one path in the two sets to be selected as working path and protection path for each OD pair, respectively, while the objective function of our problem is still to minimize congestion in the network. In the normal conditions, the two paths for a particular OD pair can operate either in $1+1$ protection or load sharing manner. For a specific OD pair $[s, d]$, in the $1 + 1$ protection mode, original data are being sent on the working path and duplicate data are being sent on the protection path. If a link failure occurs on the working path, the receiver is still able to retrieve the data from the protection path. In the load sharing mode, the proportions of data sending on the working and on protection paths can be pre-determined. When a failure happens, all the data of a particular OD pair can be temporarily sent on the unaffected path until the failed path is recovered. In this paper, we use the $1 + 1$ protection mode. The MIP program in our scheme is formulated as follows.
Objective function:

$$\text{minimize } z \tag{1}$$

1) Flow constraints: To address the flow conservation constraints, we first define Ω_W^{sd} and Ω_P^{sd} as the set of nodes that appear as the second node on a path in W^{sd} and P^{sd}, respectively. Thus for the working path candidates,

$$\Omega_W^{sd} = \{v : (s, v) \in W_w^{sd} \in W^{sd}\}.$$

Similarly, for the protection path candidates, we have

$$\Omega_P^{sd} = \{v : (s, v) \in P_p^{sd} \in P^{sd}\}.$$

The flow conservation constraints for working path candidates are as follows:

$$\sum_{v \in \Omega_W^{sd}} \lambda_{sv}^{sd,W} = R_{sd}, \quad \forall [s, d]. \tag{2}$$

and similarly, for protection path candidates:

$$\sum_{v \in \Omega_P^{sd}} \lambda_{sv}^{sd,P} = R_{sd}, \quad \forall [s, d]. \tag{3}$$

If a path candidate is selected as the working/protection path for a specific OD pair, the traffic flow on an arbitrary link of this path is the same as on any other link of the path. Therefore, on any working path candidate $W_w^{sd} = \{s, e_{sv}, v, e_{vg}, g, \cdots, u, e_{ud}, d\}$, (where e_{ij} denotes the link between node i and j), we have the following flow conservation constraints for working path candidates:

$$\lambda_{sv}^{sd,W} = \lambda_{vg}^{sd,W} = \cdots = \lambda_{ud}^{sd,W}. \tag{4}$$

Similarly on any protection path candidate $P_p^{sd} = \{s, e_{sv}, v, e_{vg}, g, \cdots, u, e_{ud}, d\}$, we have,

$$\lambda_{sv}^{sd,P} = \lambda_{vg}^{sd,P} = \cdots = \lambda_{ud}^{sd,P}. \tag{5}$$

2) Bound on traffic flow variables: The following binary decision variables are defined:

$$\phi_w^{sd} = \begin{cases} 1 & \text{if path } W_w^{sd} \text{ is selected as the} \\ & \text{working path for OD pair [s, d];} \\ 0 & \text{otherwise,} \end{cases}$$

and

$$\gamma_p^{sd} = \begin{cases} 1 & \text{if path } P_p^{sd} \text{ is selected as the} \\ & \text{protection path for OD pair}[s, d]; \\ 0 & \text{otherwise.} \end{cases}$$

Because we only choose one working path and one protection path for each OD pair, the following constraints hold:

$$\sum_{w} \phi_w^{sd} = 1, \quad \forall [s,d]. \tag{6}$$

and

$$\sum_{p} \gamma_p^{sd} = 1, \quad \forall [s,d]. \tag{7}$$

If a working path candidate is not selected as the working path, all the traffic flow decision variables associated with that are set to zero. Therefore,

$$\lambda_{ij}^{sd,W} \le \phi_w^{sd} R_{sd}, \qquad \text{for any OD pair } [s,d], \tag{8}$$

where $(i,j) \in W_w^{sd} \in W^{sd}$. Similarly, for protection path candidates,

$$\lambda_{ij}^{sd,P} \le \gamma_p^{sd} R_{sd}, \qquad \text{for any OD pair } [s,d], \tag{9}$$

where $(i,j) \in P_p^{sd} \in P^{sd}$.

3) Bound on variable z: The total traffic amount on link (i,j) is given by:

$$\lambda_{ij} = \sum_{[s,d]} \lambda_{ij}^{sd,W} + \sum_{[s,d]} \lambda_{ij}^{sd,P} \text{ for all } (i,j) \in E.$$

The bound on variable z is given by:

$$z \ge \lambda_{ij}, \text{ for all } (i,j) \in E. \tag{10}$$

$$\sum_{j} b_{ij} \le \Delta_i, \quad \forall i \in V. \tag{11}$$

4) Bound on decision variables: The decision variables are binary, thus we have

$$b_{ij} \in \{0,1\}, \quad \forall (i,j) \in E. \tag{12}$$

Let us assume link (i,j) is an arbitrary link on the path candidate W_w^{sd}. If W_w^{sd} is chosen as the working path, ϕ_w^{sd} is set to one and the decision variable b_{ij} of link (i,j) will be set to one. On the other hand, if W_w^{sd} is not chosen as the working path, ϕ_w^{sd} is set to zero, but it is still possible that the selected working paths for other OD pairs include link (i,j). Therefore, we have the following constraint:

$$\phi_w^{sd} \le b_{ij} \text{ for all } (i,j) \in W_w^{sd}. \tag{13}$$

and similarly for protection paths:

$$\gamma_p^{sd} \le b_{ij} \text{ for all } (i,j) \in P_p^{sd}. \tag{14}$$

Thus we have formulated an MIP program in which we jointly consider topology control and path-oriented protection for FSO networks. The objective function is given by (1), and the constraints are from (2) to (14).

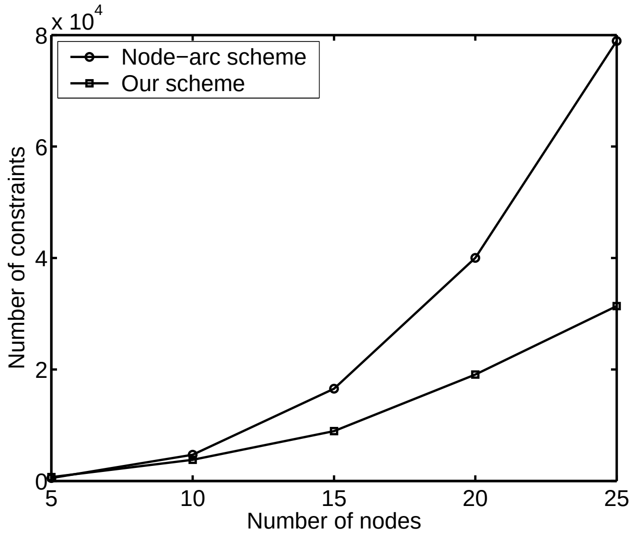

Fig. 3. Comparisons of number of constraints.

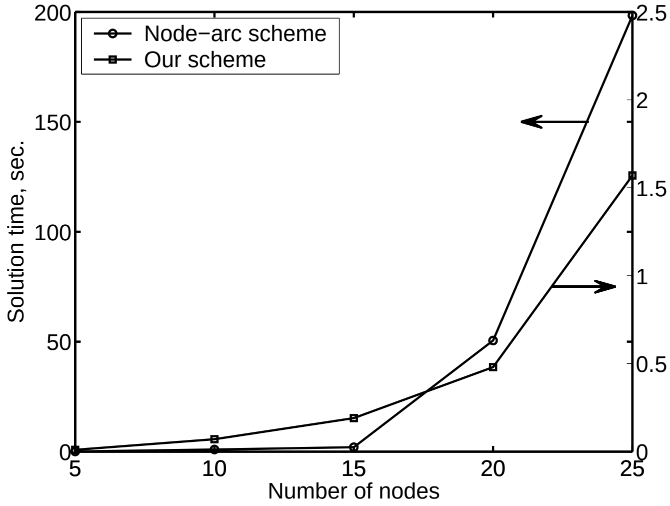

Fig. 4. Comparisons of solution time.

V. NUMERICAL EVALUATION AND DISCUSSION

We evaluated the performance of our scheme using CPLEX 6.0 on a 3 GHz Pentium 4 with 1-GB RAM. The degree constraint Δ_i of node i is uniformly set to three for all nodes in the networks. The numbers of working and protection path candidates, k_W and k_P, were both set to three. The networks of 5, 10, 15, 20 and 25 nodes with potential links were randomly generated. For such a randomly generated network of N nodes, we also randomly generated five $N \times N$ traffic matrices, whose entries were uniformly chosen from $[0,1]$. Results in Fig. 3 and 4 were averages over five. Fig. 3 illustrates an comparison of the no routing scheme and our scheme in terms of the number of constraints. It shows that the number of constraints in our scheme is significantly reduced. For example, When $N = 20$ and $N = 25$, the number of constraints of our scheme is less than half of the no routing scheme. The solution time of the proposed scheme is also dramatically decreased compared to the no routing one, as depicted in Fig. 4. For relatively large networks, (e.g., containing more than 25 nodes), our scheme may also be slow for certain applications. In such cases further heuristics may be needed.

VI. CONCLUSION

To combat link failures, survivable FSO networks need to be designed. In this paper, we proposed a scheme, in which we jointly consider topology control and path-oriented protection for FSO networks. We formulated an MIP program, in which the optimal network topology is established such that the congestion is minimized, and at the same time, a working path and a protection path are found for each OD pair. Numerical results demonstrated the efficiency of our scheme in terms of the number of constraints and solution time.

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