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A Shared Backup Path Protection Scheme for Optical Mesh Networks

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***Abstract*— We propose a new heuristic ILP model for share backup path protection (SBPP) scheme of mesh networks, which used the sets of disjoint-joint primary-backup path candidates of using path-pair candidates. The solution of the model is near optimal and provides all the routing details of demands as well as the sharing information between backup paths, and also simplifies the wavelength assignment problem if the wavelength continuity is a consideration. The new entities are introduced into this model that allow to control the the resource utilization as well as congestion level of the network for optimization purposes and the pre-processing of data offers more control in properties of the path candidates.**

I. INTRODUCTION

Protecting Networks against the failures of physical components is a crucial task in network design and development. This is particularly important with networks employing wavelength division multiplexing (WDM), which offers terabit/second data channels over the fiber infrastructure. Survivable networks can be defined as networks that can continue functioning correctly in the presence of the failures of network components [1].

Optical mesh networks are becoming more wide spread due to the facts that they use much less resource compared to ring networks, and can satisfy the growth in demand of data communication, by integrating new technologies into the networks that help reduce the response time gap between mesh and ring networks.

The survivability at optical layer in mesh networks is based on two paradigms: *path protection/restoration* and *link protection/ restoration*. Protection and restoration are generally different in the timing of when the alternative paths are established, statically in design time for protection mechanism or dynamically after the failure has occurred for restoration. There are basically two types of resource allocation in network protection schemes: dedicated or shared. Studies of survivable mesh networks have shown that SBPP schemes offer the highest resource efficiency compared to others [1], [2], [3], [4]. However, due to the capacity sharing between backup paths, SBPP schemes generally have greater complexity in term of modeling and computation. Currently, there are three different approaches to the capacity allocation modeling for SBPP: *non-joint SBPP* , *joint SBPP* and *joint SBPP design with wavelength assignment* [5], [6]. In the first approach, the Non-Joint SBPP has to admit the possibility of the infeasibility in finding the backup routes for the given primary routes. The third approach involves wavelength assignment problem, thus the model is very complex and has a large number of variables/ constraints, especially, due to the wavelength continuity requirements absence of wavelength converters, large number of wavelength channels may have to be installed. Therefore, this model can practically be applied only to networks with no more than 10 nodes [6].

In this paper, we propose a new alternative joint SBPP model, which employs a minimum set of disjoint-joint primary-backup paths set of demands. The solution of this model provides all the routing details for each connection in a given demands as well as sharing details between backup paths of demands. The rest of this paper is organized as follows: in Sec. II, we describe the general ILP model for link-path formulation; Sec. III, introduces the heuristic SBPP model based on minimum set of disjoint-joint primary-backup path pairs; simulation results are presented in Sec. IV; Sec. V summarizes some remarks and conclusion from our work.

II. BACKGROUND

An optical mesh network using a large number of wavelengths, usually includes Optical Cross Connects (OXCs). Each OXC switches the optical signal coming from the input fiber link on a wavelength to an output fiber link with the same wavelength (or different wavelength if the OXC is equipped with a wavelength-converter). Thus an optical channel established over the network of OXCs is the lightpath, in some papers referred to as λ-channel, which may span over a number of fiber links (physical hops). In the absence of wavelength converters, a lightpath is associated with the same wavelength on all hops that the light pass through (referred to as *wavelength continuity constraint*). If wavelength converters are used, different wavelengths may be used on each hop to create the lightpath. In this paper, we assume that the system either has enough wavelengths or wavelength converters are installed, hence wavelength continuity constraint is not considered.

A. General mathematical model for network's traffic routing

There are two basic types of network routing models known as Link-Path formulation and Node-Link formulation [7], [8]. The Node-Link model usually has a larger number of variables and constraints than the Link-Path model, thus has a greater complexity. However, the Link-Path model requires preprocessing of data before being implemented, such as computing sets of candidate paths for the traffic demands. More details about Link-Node model can be found in [8]. The new SBPP model introduced in this paper will be based on the above Link-Path formulation due to the following advantages it provides:

- The pre-processing data allows the properties of path candidates to be controlled , eg. limited number of hops, path cost.
- The model can easily be extended further for dedicated protection, SBPP application.
- The size of the model is small in terms of variables and constraints.

Typical Link-Path model is as bellows:

Model 1: General Link-Path model and Notations for ILPs.

- **Notation**
  - Network notation

    A network physical topology can be modeled as an undirected graph $G(V, E)$, where V is a set of network nodes and E is a set of physical links.
    $V = \{v_1, v_2, \ldots, v_N\}$, where N is the number of network nodes.
    $E = \{e_1, e_2, \ldots, e_M\}$, where M is the number of network links.
  - Indices

$d = 1, 2, \ldots, D$	demands
$b = 1, 2, \ldots, P^d$	candidate paths pair between end nodes of demand d
$e = 1, 2, \ldots, M$	links
  - Constants

$\delta_{edp} = 1$	if link e belongs to path p of demand d; 0, otherwise
h_d	volume of demand d
ξ_e	unit cost of link e
c_e	upper bound on the capacity of link e
  - Variables

x_{dp}	flow variable allocated to path p of demand d
y_e	capacity on link e
- **ILP model**
  - Objective

$$\text{Minimize :} \qquad \Sigma_e \xi_e y_e \tag{1}$$

  - Constraints

$$\Sigma_p x_{dp} = h_d \ , \quad d = 1, 2, \ldots, D \tag{2}$$

$$\Sigma_d \Sigma_p \sigma_{edp} x_{dp} \leq y_e \ , \quad e = 1, 2, \ldots, E \tag{3}$$

$$y_e \leq c_e \ , \quad e = 1, 2, \ldots, E \tag{4}$$

Form the above model, the number of variables and constraints are as in Tab. I. Where $\bar{P}$ is the average of candidate paths, $N' \times (N' - 1)$ is the demand D, with N' is the number of nodes generating demand, N is the network's nodes and $\bar{k}$ is the average node degree.

TABLE I
NO. OF VARIABLES & CONSTRAINTS.

Number of Variables	Number of Constraints
$\bar{P}N'(N'-1) + \frac{1}{2}\bar{k}N$	$N'(N'-1) + \frac{1}{2}\bar{k}N$

B. Data pre-processing for SBPP

Using Link-Path formulation for modeling the SBPP requires pre-processing of data to bring them into suitable forms. This generally includes finding *disjoint paths* for each demand; the capacity constraint for each link; defining the cost related to a physical link; and the physical topology of the network is checked for survivable before any further implementation. Following are typical processes involved when modeling SBPP:

1) Survivable physical topology: A physical topology is considered to be survivable if it can cope with any single failure of network components by allows rerouting the connections that are affected by the failure through an alternative path. This requires some degree of capacity redundancy in the network, and the network physical topology must be in the form of a 2-connected or bi-connected graph. More details about this can be found in [5], [2], [9], [10]. In this paper, we assume that the given network can be presented by a 2-connected graph, thus it is survivable.

2) Finding k-disjoint paths pair: In path protection routing, for each connection, two disjoint paths must be provided between the source and the destination nodes. The primary path is provisioned to serve the request under normal operation while the backup path is reserved in case of failure of the corresponding primary path. There are various well developed techniques for finding disjoint path pairs [11], [12], [13], [14]. Alg. 1 describes the technique of finding K pairs of disjoint paths adopted from [15], [16]. The outcomes form this will be used for generating K set of disjoint-joint path pairs. Alg. 2 presents the general algorithm for finding disjoint-joint primary-backup paths. This algorithm, however, won't provide all possible candidates because there would be a large number of them, and thus the model become impractical with the present of an enormous number of variables. Therefore, we address the following model as an heuristic model for SBPP. The reader can refer to [15] for more details and the proof of Alg. 1.

III. SBPP MODELING WITH K-MINIMUM SETS OF JOINT-DISJOINT PATHS

Definition 1: Let $S(P, R)$ be the set of candidate path-pairs, where
$P = \{P_1, \ldots, P_D\}$ is the set of candidate primary paths.
$R = \{R_1, \ldots, R_D\}$ is the set of candidate backup paths.
$P_d = \{p_d^1, p_d^2, \ldots, p_d^K\}$ is the set of K candidate primary paths for connection d, where p_d^{th} denotes the th primary path of connection d.
$R_d = \{r_d^1, r_d^2, \ldots, r_d^K\}$ is the set of K candidate backup paths for connection d, where r_d^{th} denotes the th backup path of connection d disjoint with p_d^{th}.

The set of Joint-Disjoint path-pairs of group demands denote as $H = \{H^l_{d,g,k}\}$, where $H^l_{d,g,k}$ is the set of joint- disjoint path pairs of the k^{th} candidate primary of demand d in group demand g at share level l, with: $H^l_{d,g,k} = \{S'(P', R')|S' \subseteq S(P, R)\}$ satisfying the following conditions:

$a)$ $\forall p'_i, p'_j \in P', p'_i \bigcap p'_j = \emptyset, i \neq j$: primary paths disjoint.

$b)$ $\forall r'_i, r'_j \in R', r'_i \bigcap r'_j \neq \emptyset, i \neq j$: backup paths joint.

$c)$ $\exists e_i \in E, \sum_{p \in P'} e_i = l$: shared level.

Model 2: Proposed new ILP model for Joint SBPP

- **Notation**
  - Network notation

    Similar to Model 1.
  - Indices

H	set of disjoint-joint path-pair candidates
$d = 1, 2, \ldots, D$	demands
$e = 1, 2, \ldots, M$	links
$p = 1, 2, ..., n$	$p \in H$

  - Constants

$\delta_{edb} = 1$	if link e belongs to path b of demand d; 0, otherwise.
$\sigma_{egp} = \Sigma_{b \in p} \delta_{edb}$	if path-pair b^{th} in S uses link e belongs to set p of group demand $g = \{d_i\}$; 0, otherwise.
h_d	volume of demand. d
ξ_e	unit cost of link. e
W	upper bound on the amount of capacity of link e.

  - Variables

x_{dgp}	flow variable allocated to set p demand d of group g
y_e	capacity on link e

- **ILP model**
  - Objective

$$\text{Minimize} \qquad \Sigma_e \xi_e y_e \tag{5}$$

  - Constraints

$$\Sigma_p x_{dgp} = h_d \ , \quad d \in D \tag{6}$$

$$\Sigma_d \Sigma_p \sigma_{egp} x_{dgp} \leq y_e \ , \quad e = 1, 2, \ldots, E \tag{7}$$

$$y_e \leq c_e \ , \quad e = 1, 2, \ldots, E \tag{8}$$

The number of variables and constraints that are introduced in the new SBPP model are given in Tab. II.

TABLE II

NO. OF VARIABLES & CONSTR. IN JOINT SBPP

Number of Variables	**Number of Constraints**
$\bar{P}N'(N'-1) + \frac{1}{2}\bar{k}N$	$N'(N'-1) + \frac{1}{2}\bar{k}N$

Algorithm 1 : K disjoint-path pairs

Input : An indirected graph $G(V, E)$, a pair of source and destination nodes (s, d), and the number of shortest disjoint-path pairs required.

Output: A set of K-shortest disjoint-path pairs.

1: Take a shortest path between the source s and destination d, using one of the shortest path algorithms, eg. modified Dijkstra or BFS [13], [8]. Denote this as p.

2: Define the direction of each link traversed in p from s toward d as positive direction.

3: Remove all directed links on the shortest path p and replace them with reverse direction and negative weight of each such link (eg. by multiplying the original link's cost with -1).

4: Find K least cost paths from s to d in the modified graph using the algorithm in [17]. Denote these as the set of paths $S = \{s_1, s_2 \ldots, s_K\}$.

5: For each pair of paths (p, s_i), remove any link of the original graph traversed by both p and s_i. These are called *interlacing links*. Identify all path segments by the link removal from path p and s_i. Such path-pairs form the K-disjoint path pairs $(Ppairs) = \{(w_1, r_1), (w_2, r_2), \ldots, (w_K, r_K)\}$.

Routing cost vs. network congestion:
Optimization models for wavelength routing currently have objective functions aimed at reducing either the network congestion level (referred to as *CongMin*) or the total wavelength channels used (referred to as *CapMin*) [15]. The purpose of the *CongMin* scheme is balancing the network load, thus lowering the number of wavelength channels needed and reducing the blocking probability for future connections. However, the total cost or capacities used by *CongMin* is usually higher compared to the *CapMin* scheme. In contrast, when the objective function has employed the *CapMin* scheme, the total network capacities used may be reduced, but the utilized wavelength channels on some links in the network can reach their upper limit, thus no future demands can be served via those links.

By combining the above two schemes into the objective function of the ILP model, we can control and balance the capacity utilization and congestion level of the network. To do that, we need to introduce some new identities into the model as follows:

- Constants

  $f_p = \Sigma_p \sigma_{egp}$ total capacity used by set p
- Variables

  α max congestion of the network
- The modified ILP model: If we define $f_{sum} = \sum_p f_p$ and $f_{max} = k\alpha$, where k is the controlling factor, then:
  - Objective

$$\text{Minimize} \qquad f_{sum} + f_{max} \tag{9}$$

  - Constraints

$$\Sigma_p x_{dgp} = h_d \ , \quad d \in D \tag{10}$$

$$\Sigma_d \Sigma_p \sigma_{egp} x_{dgp} \leq \alpha \tag{11}$$

$$\alpha \leq W \tag{12}$$

Algorithm 2 Finding Joint-Disjoint Primary-Backup paths

Input : An undirected graph $G(V,E)$, $T = \{t_1, t_2, \ldots, t_D\}$ is the set of connection demands D over the network, where t_i denotes the connection between node pair $\{s_i, d_i\}$ required for each demand d. A set of candidate disjoint path-pairs $S = (P, R)$ as in Definition 1

Output: Set of Joint-Disjoint path pairs H of demand D at different share levels.

```
1: Finding primary disjoint path of K shortest path-pair for each demand d ∈ D:
init. i ← 1
for every p_d^i do
    dP_d^i ← {p_d^i}
end for
while i < D do
    for j = 1 → K do
        for t = i + 1 → D do
            for s = 1 → K do
                if p_i^j ⋂ p_t^s = ∅ ∧ b_i^j ⋂ b_t^s ≠ ∅
                    dP_i^j ← dP_i^j + {p_t^s}
                end if
            end for
        end for
    end for
    i ← i + 1
end while
2: Generate H
α ← Sharefactor
for d = 1 → D do
    for i = 1 → K do
        for j = 2 → α do
            N ← C^j_{dP_d^i}
            if ∀n ∈ N, ∃e ∈ E, Σ_b e_b = i then
                H^j_{{d},i} ← {n}
            end if
        end for
    end for
end for
```

IV. Simulation and Discussion

In this section, we illustrate the performance of our proposed model through an example using a small randomly generated network. Note that our purpose is to demonstrate the abilities of the new ILP model, therefore a small number of traffic demands are used for the simulation. Fig. 1 shows the randomly generated network which has 7 nodes and 8 links, and has the link configuration and connection demands as shown in tables III, IV and V. In table III, each physical link of the network is assigned an index. For simplicity, all links have the same capacity and cost. In table V, each traffic is also assigned an index. By indexing the network links and demands, the implementation of the model is much easier and we can create the cross reference table for the translation of the solution from the ILP solver. Table IV contains information about the number of k shortest path-pair candidates that the program generates and is used in the model, and the maximum allowable sharing per physical link in the network. Note that the number of candidates k for each demand are not necessarily the same; they can have different values, eg. demand 1 of connection (1-4) may have the $k = 3$ candidate path-pairs due to the limits of the physical network, while demand 4 of connection (2-4) can have the $k = 5$ candidate path-pairs. The details of the solution given by

TABLE III

Link configuration

Link index	end nodes	capacity	cost
1	1-2	12	1
2	1-6	12	1
3	2-3	12	1
4	3-4	12	1
5	3-5	12	1
6	4-7	12	1
7	5-7	12	1
8	6-7	12	1

TABLE IV

Other configuration

Description	value
Number of candidate path pairs	5
Max. allowable of shared per link	3

TABLE V

Connection demands

Traffic index	Source	Destination
1	1	4
2	1	5
3	6	4
4	2	4
5	2	4
6	6	5

the ILP solver are shown in tables VI and VII. Table VI contains the routing details of each demand for both primary path (indicated by letter **P**) and backup path (indicated by the letter **B**). The last column of the table gives the indices of the corresponding demands used for cross referencing with

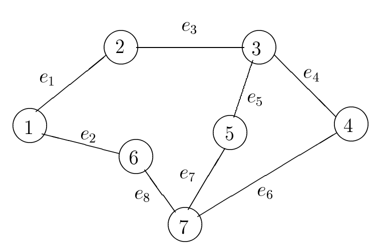

Fig. 1. An arbitrary network

table VII, which shows the sharing details between backup paths of demands. Assigning wavelength for paths selected, and placement of wavelength converters can simply be done by using the information provided in these two tables. From the routing details, the two demands with indices 4 and 5 have the same source and destination, and also have the same primary and backup paths assigned to them as in table VI. However, this is not always the case as the primary-backup paths can be different between such demands.

TABLE VI
ROUTING DETAILS

Demand		e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	Traffic index
(1 - 4)	P	1	0	1	1	0	0	0	0	1
	B	0	1	0	0	0	1	0	1	
(1 - 5)	P	1	0	1	0	1	0	0	0	2
	B	0	1	0	0	0	0	1	1	
(6 - 4)	P	0	0	0	0	0	1	0	1	3
	B	1	1	1	1	0	0	0	0	
(2 - 4)	P	0	0	1	1	0	0	0	0	5
	B	1	1	0	0	0	1	0	1	
(2 - 4)	P	0	0	1	1	0	0	0	0	4
	B	1	1	0	0	0	1	0	1	
(6 - 5)	P	0	0	0	0	0	0	1	1	6
	B	1	1	1	0	1	0	0	0	

(Header "Link used" spans columns e_1–e_8.)

TABLE VII
SHARING DETAILS BETWEEN BACKUP PATHS OF TRAFFICS

Connection	Sharing
1	0
2	0
3	4
4	3
5	6
6	5

The limits of the conventional SBPP model compared to the heuristic one are that they can only give the optimal solution in capacity usages, congestion of the network. Further processing of results to get the sharing details.

If the network can support wavelength converters as needed at each node, then the model can be applied directly. At the other extreme is that placing wavelength converters is another objective of the optimization problem. Hence, wavelength assignment will be the next task if this model is employed. In contrast, the proposed model although having less advantages in terms of size of variables and requires data pre-processing, it provides all the routing details for each connection in the demands such as which path is selected for the corresponding connection and how the links are shared between backup paths. In addition, due to the candidates in Model 2 are sets of Disjoint-Joint primary-backup paths, hence assigning wavelengths for each path selected, and placing the wavelength converters at suitable nodes is just the matter of translate from the solution details and can be done via a simple program algorithm. However, Model 2 can only provide an heuristic solution because of the limit of candidates. Furthermore, this model can be extended to support multi-failure scenarios by the use of k disjoint paths for the candidates.

V. CONCLUSION

In this paper, we have reviewed the survivability of the optical networks with particular focus on the SBPP at the optical layer because of its resource efficiency due to the fact that the backup paths can share wavelength channels on links while their corresponding primary paths are link disjoint. We presented a new heuristic ILP model for SBPP problem based on the general link-path formulation and compared our model with the conventional models. The total number of constraints in the our model is lager than the conventional one, but has less constraints. The new SBPP model gives near optimal solution, assures 100% protection under single link failures, and gives full routing details for each connection sharing in the demand set, thus simplifying the wavelength assignment problem in the network design phase. In addition, the new model can be extended to solve SBPP with multiple link failures by using k-disjoint path candidates instead of path pair candidates.

REFERENCES

[1] D. Zhou and S. Subramanian, "Survivability in optical networks," *IEEE Networks*, 2000.

[2] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh networks. part i-protection," in *Proceedings of Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies. INFOCOM'99*, vol. 2, (New York, NY, USA), pp. 744–751, 1999.

[3] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh network.ii. restoration," in *IEEE International Conference on Communications*, vol. 3, (Vancouver, BC Canada), pp. 2023 – 2030, 1999.

[4] P. Arijs, B. V. Caenegem, P. Demeester, and P. Lagasse, "Design of ring and mesh based wdm transport networks," *Optical Networks Magazine*, vol. 1, no. 3, pp. 27–41, 2000.

[5] W. D. Grover, *Mesh-based Survivable Networks: Options and Strategies for Optical, MPLS, SONET/SDH, and ATM networking*. Prentice Hall PTR, 2004.

[6] S. Ramamurthy, L. Sahasrabuddhe, and B. Mukherjee, "Survivable WDM mesh network," *Journal of Lightwave Technology*, vol. 21, no. 4, pp. 870–883, 2003.

[7] R. Kalaba and M. Juncosa, "Optimal desing and utilization of communication networks," *Management science*, vol. 3, no. 1, pp. 33–44, 1956.

[8] M. Pioro and M. Deepankar, *Routing, Flow, and Capacity Design in Communicatio and Computer Networks*. Morgan Kaufman, 2004.

[9] O. Crochat and J.-Y. LeBoudec, "Design protection for WDM optical networks," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 7, pp. 1158–1165, 1998.

[10] R. Diestel, *Graph Theory*. New York: Springer-Verlag, 2000.

[11] J. McHugh, *Algorithmic Graph Theory*. Prentice Hall PTR, 1990.

[12] D. Xu, Y. Chen, Y. Xiong, C. Quia, and X. He, "On finding disjoint paths in single and dual link cost networks," in *Proceedings of the 23rd Conference of the IEEE Communications Society*, (Hong Kong), 2004.

[13] R. Bhandari, *Survivable Networks: Algorithms for Diverse Routing*. Kluwer Academic Publishers, 1999.

[14] J. Zhang, K. Zhu, L. Sahasrabuddhe, and S. B. Yoo, "On the study of routing and wavlength assignment approaches for survivable wavelength-routed WDM mesh networks," *Optical Networks Magazine*, vol. 4, no. 6, pp. 16–28, 2003.

[15] Q. V. Phung, D. Habibi, H. N. Nguyen, and K. Lo, "Capacity utilization versus network congestion level in wavelength routing problem in wdm network," *Submited to APCC*, 2005.

[16] Q. V. Phung, D. Habibi, H. N. Nguyen, and K. Lo, "K-pairs of two-disjoint paths algorithm for protection in wdm optical networks," *Submited to APCC*, 2005.

[17] Q. V. Phung, D. Habibi, H. N. Nguyen, and K.-M. Lo, "An efficient approach to optimal wavelength routing in WDM optical networks," in *The 12th IEEE ICON*, vol. 2, (Singapore), pp. 600–604, 2004.