Shared Backup Path Protection (SBPP) in Elastic Optical Transport Networks
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Abstract: We consider the share backup path protection (SBPP) and 1+1 protection techniques for CO-OFDM-based elastic optical networks. We develop mixed integer linear programming (MILP) models to minimize required protection capacity and used link spectrum in the network.

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1. Introduction
The coherent optical orthogonal frequency division multiplexing (CO-OFDM)-based elastic optical networks receive much attention due to its flexibility in bandwidth allocation and efficiency of fiber spectrum utilization [1]. Though many studies have been carried out for the design and performance evaluation on this type of network, most of them considered unprotected lightpath services. Only few studies considered the issue of network protection [2-3]. Network protection is of paramount importance for an optical transport network since it carries a large amount of traffic demand and any network failure such as a fiber cut can cause a significant number of network services terminated.

Among many network protection techniques, share backup path protection (SBPP) is considered as one of the most promising schemes due to its combined advantages of operational simplicity, speed, and efficiency [4]. SBPP is a failure-independent path-oriented scheme where the protection route is identified in advance, and protection capacity is cross-connected on the protection route in real time. Its protection capacity efficiency is realized by protection capacity sharing on the common links of protection lightpaths whose corresponding working lightpaths do not share any common link.

Most of the prior works on SBPP focused on the SONET/SDH networks and recently on the dense wavelength division multiplexing (DWDM) optical networks [4]. In this paper, for the first time we apply the SBPP scheme to the CO-OFDM elastic optical networks [5]. As the unique and challenging features of this study, we need to ensure the special constraints of spectrum continuity along a lightpath route and frequency slot neighboring in the spectrum domain for each lightpath connection. We develop a mixed integer linear programming (MILP) model for the SBPP scheme. Also, in order to evaluate the capacity efficiency of the SBPP scheme, we compare the results of SBPP with those of the 1+1 scheme in terms of protection capacity and used link spectrum in the network.

2. Shared backup path protection (SBPP) and 1+1 protection
This section introduces the concept of SBPP in contrast to the 1+1 protection scheme in the context of CO-OFDM-based elastic optical network. As shown in Figs. 1 and 2, when a span fails, both of the techniques find a replacing path directly between the two path end-nodes. For example, if span (6-8) fails, working path (1-3-6-8) gets affected and a switch-over is performed onto a predefined protection route (0-2-4-7-8) for failure recovery. Similarly, if span (0-1) fails, working path (0-1-4) gets affected and a switch-over is performed onto a predefined route (0-2-4) for failure recovery. Under the 1+1 protection technique, to enable 100% failure recovery, the same amount of capacity should be reserved on each protection path as that of its corresponding working path. Thus, as shown in Fig. 1, seven frequency slots (FSs) are reserved on the common spans (0-2) and (2-4) that are shared by the two protection routes.

Fig. 1. An example of 1+1 protection  Fig. 2. An example of SBPP protection
In contrast, SBPP is advantageous of allowing protection capacity sharing on the common spans traversed by multiple protection paths if their corresponding working paths do not share any common link. For example, in Fig. 2, spans (0-2) and (2-4) are commonly traversed by two protection paths (0-2-4-7-8) and (0-2-4). As the two working paths do not share any common link, the two protection paths can share protection capacity on the spans to reserve only four FSs, which is sufficient to guarantee full recovery of non-simultaneous failures of spans (0-1) and (6-8).

3. MILP design models for SBPP and 1+1 protection

In this section, we present the MILP models for the above-mentioned two protection schemes. We first introduce the model for SBPP. Given a set of lightpath traffic demands with each requiring a predefined number of FSs, we minimize required protection capacity and used link spectrum in the network. We assume that the elastic optical networks are operated under the flexi-grid mode which assumes that each fiber spectrum is divided into many FSs with a constant small granularity [4]. We also assume that between each pair of nodes there is only a single shortest route employed to establish the working lightpath, while there are multiple routes (link-disjoint from the working route) that can be selected to establish the protection lightpath. The sets and parameters of the model are as follows.

**Parameters:**
- $S$ is the set of links.
- $R$ is the set of node pairs.
- $B_r$ is the set of backup routes of node pair $r$.
- $\eta^r_i = 1$ if failure span $i$ hits the working path of node pair $r$; 0, otherwise.
- $\zeta^b_{ij} = 1$ if the $b^{th}$ eligible backup route for node pair $r$ crosses span $j$; 0, otherwise.
- $x^r_j = 1$ if the working path for node pair $r$ and the working path for node pair $t$ share a common span; 0, otherwise.
- $y^r = 1$ if the working path for node pair $r$ and backup path $b$ of node pair $t$ share a common span; 0, otherwise.
- $s_j$ is the number of required FSs between node pair $r$. $\forall$ is a large value. $\alpha$ is a weight factor.

**Variables:**
- $\rho^r_{b,r} = 1$ if the $b^{th}$ backup route of node pair $r$ is chosen; 0, otherwise.
- $f^r$ is an integer variable denoting the index of starting FS of the working lightpath between node pair $r$.
- $e^r_j$ is an integer variable denoting the index of starting FS of backup path $b$ of node pair $r$. $a^r_j = 1$ if $f^r$ is larger than $j$; 0, otherwise.
- $\delta^b_{a,r}$ is the maximum index of the used FSs on all the fiber links in the network of node pair $r$.
- $\delta^b_{a,r} = 1$ if the working path for node pair $r$ has only $a$ FSs.

**Objective:** Minimize $\sum_{j \in S} s_j + \alpha \cdot c$  

Subject to:
\[
\begin{align*}
    c & \geq f^r + d^r & \forall r \in R \quad (1) \\
    \sum_{b \in B_r} \rho^r_{b,r} & = 1 & \forall r \in R \quad (2) \\
    \sum_{r \in R} \sum_{b \in B_r} \eta^r_i \cdot \rho^r_{b,r} \cdot \zeta^b_{ij} \cdot d^r & \leq s_j & \forall i,j \in S, i \neq j \quad (3) \\
    f^r + d^r - f^r & \leq \nu \cdot (a^r_j + 1 - x^r_j) & \forall r \in R, r \neq t \quad (4) \\
    f^r + d^r - e^r_j & \leq \nu \cdot (1 - a^r_j + 1 - x^r_j) & \forall r \in R, r \neq t \quad (5) \\
    \sum_{r \in R} \sum_{b \in B_r} \rho^r_{b,r} \cdot \zeta^b_{ij} \cdot d^r & \leq s_j & \forall i,j \in S, i \neq j \quad (6) \\
    f^r + d^r - f^r & \leq \nu \cdot (1 - a^r_j + 1 - x^r_j) & \forall r \in R, r \neq t \quad (7) \\
    f^r + d^r - e^r_j & \leq \nu \cdot (1 - a^r_j + 1 - x^r_j) & \forall r \in R, r \neq t \quad (8) \\
    \forall b \in B_t, \forall r \in R, r \neq t & \quad (9) \\
    e^r_j & \leq \nu \cdot (1 - a^r_j + 1 - x^r_j) & \forall r \in R, r \neq t \quad (10) \\
    \forall b \in B_t, \forall r \in R, r \neq t & \quad (11) \\
    \forall a \in A_r, \forall b \in B_t, \forall r \in R, r \neq t & \quad (12) \\
    \forall a \in A_r, \forall b \in B_t, \forall r \in R, r \neq t & \quad (13)
\end{align*}
\]

The MILP model for 1+1 protection can be extended from that of SBPP. The differences are as follows: (i) Parameter $\eta^r_i$ is not required, and constraint (6) becomes $\sum_{r \in R} \rho^r_{b,r} \cdot \zeta^b_{ij} \cdot d^r \leq s_j$ since spare capacity
sharing is not allowed under the 1+1 protection; (ii) Under 1+1 protection, $z_{a,r}^{b,t} = 1$ if backup path $b$ of node pair $r$ and backup path $t$ of node pair $a$ share a common span; 0, otherwise.

4. Results and discussions

To evaluate the performance of the SBPP and 1+1 protection schemes in the CO-OFDM-based elastic optical networks, we consider three test networks: (a) a six-node eight-link network (n6s8, average nodal degree = 2.7), (b) the 11-node and 26-link COST239 network (average nodal degree = 4.7), and (c) the 14-node 21-link NSFNET network (average nodal degree = 3.0). For all the networks, the traffic demand on each node pair is random with a uniform distribution within a certain range. We set a maximum number of FSs, $X$, and each node pair can choose any number (between 1 and $X$) of FSs. Without losing generality, this study sets $X$ to be five. In addition, we employed the K-disjoint shortest path algorithm to find all eligible protection routes for each node pair. All these routes are link-disjoint from the shortest working route.

Fig. 3 shows the working and spare capacity and used spectrum in unit of FS for the three test networks. We can see that SBPP can achieve better capacity efficiency than the 1+1 protection scheme in both terms of protection capacity and used link spectrum for all the test networks. This is attributed to the fact that SBPP allows protection capacity sharing among multiple protection lightpaths whose corresponding working lightpaths do not share any common link. Fig. 4 shows the results of spare capacity redundancy which is defined as a ratio of total protection capacity to total working capacity. Again, we can see that the SBPP scheme shows to have much lower spare capacity redundancy in all the test cases. In addition, comparing the spare capacity redundancies of the three test networks, we find that the redundancy of the COST239 network is lower than those of the n6s8 and NSFNET networks. This is because the COST239 network has a higher average nodal degree, which increases spare capacity sharing opportunities and thus helps reduce spare capacity redundancy. For the 1+1 scheme, we have a similar observation, i.e., a network with a higher nodal degree tends to have a lower spare capacity redundancy. This is attributed to the fact that a denser network provides more shorter protection routes, which therefore help reduce the sum of link protection capacity.

5. Conclusion

We considered the SBPP and 1+1 protection schemes in the context of CO-OFDM-based elastic optical networks. Under the assumption of spectrum continuity, we developed MILP models to minimize required spare capacity and used link spectrum in the network. Due to the spare capacity sharing feature, our results indicate that the SBPP scheme requires much lower spare capacity compared to the traditional 1+1 protection scheme. In addition, it was observed that a higher nodal degree can help improve spare capacity redundancy for SBPP, which is attributed to the fact that a denser network provides more opportunities for spare capacity sharing.

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