Applying Ring Cover Technique to Elastic Optical Networks

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Abstract: We apply the ring cover technique to elastic optical networks. We develop an Integer Linear Programming (ILP) model to minimize the required protection capacity and the overall link spectra used in the entire network.

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1. Introduction

Elastic optical networks have received much attention recently due to their flexibility in bandwidth allocation and efficiency of fiber spectrum utilization [1]. Though many studies have been carried out for the design and performance evaluation of this type of network [2], only few studies considered the issue of network protection [3-6]. Network protection is important for an optical network since it carries a large amount of traffic demand and any network failure such as a fiber cut can cause a significant amount of traffic to be affected.

Ring networks are popular in the carrier world. This is because a ring is the simplest topology offering an alternate route around a failure. When a link fails, the affected service can be restored within 50 ms after the failure. Ring architectures are inherently suitable for sparse physical topologies and in situations where most of the traffic is confined within the ring. Unlike ring networks, mesh networks are more suitable for most backbone networks which typically show irregular mesh topologies. The ring cover technique applies ring protection to the mesh networks [7].

In particular, we need to find enough rings to cover the whole mesh network so that whenever a link fails, this covering system can quickly find a corresponding restoration path. This ensures that the entire network would be able to survive any single link failure.

Most of the prior works on ring cover focused on the SONET/SDH networks [7]. This paper, for the first time, applies this technique to the elastic optical network. For this, a unique and challenging requirement is to ensure special constraints of spectrum continuity along a lightpath route and frequency slot neighboring in the spectrum domain for each lightpath connection [2]. We develop an Integer Linear Programming (ILP) model for the ring cover scheme to minimize both the additional protection capacity required and the link spectra used in the entire network.

2. Ring cover in the elastic optical network

This section introduces the concept of ring cover in the context of the elastic optical network. Specifically, whenever a link traversed by different rings fails, the ring cover technique finds eligible rings that traverse the link to recover all the affected working flows on it. Due to the constraint of frequency slot neighboring of each lightpath, all the frequency slots (FSs) of a restored working flow must travel together along the same ring, which requires each working flow to be recovered only by a single eligible ring. This requirement is one of the key differences of the current restoration from the traditional ring cover where the restored capacity units are allowed to be split onto different eligible rings. In addition, under the ring cover technique, all the protection capacity deployed for a ring is dedicated; different rings cannot share spare capacity on common spans as in span restoration [5] or path protection [6]. Lastly, due to the constraint of spectrum continuity of a lightpath, two pairs of opposite fibers should be deployed on each physical link so as to ensure that the allocated spectra for rings and working flows do not conflict (since a working flow must be covered by a ring if it is protected by the ring).
We consider an example of ring cover for the elastic optical network of Fig. 1. Here two rings are pre-deployed in the network, i.e., (2-6-5-3-2) and (2-1-6-5-3-2). Failure of link (2-3) affects both the two working flows between node pairs (2-3) and (2-4). Rings (2-6-5-3-2) and (2-1-6-5-3-2) can recover both the affected flows. Subject to the constraint of spectrum continuity, spectrum slots from 3 to 4 on ring (2-6-5-3-2) are used to recover the flow between node pair (2-3) and spectrum slots from 5 to 7 on ring (2-1-6-5-3-2) are used to recover the flow between node pair (2-4). In addition, because the rings have to allocate the same spectra to recover their corresponding protected working flows, two pairs of opposite fibers must be placed on each link (e.g., as shown for link 4-5 in Fig. 1) so as to use the same spectra on different fibers to establish both the working flow and the protecting ring.

3. ILP design model for ring cover in elastic optical networks

Given a set of lightpath requests with each requiring a predefined number of FSs, we minimize the required protection capacity and the link spectra used in the entire network. We assume that each fiber spectrum is divided into many FSs with a constant small granularity. We also assume that between each node pair there is only a single shortest route employed to establish the working lightpath. The sets and parameters of the model are as follows.

**Sets and Parameters:**
- \( S \): the set of network links.
- \( R \): the set of node pairs in the network.
- \( P \): the set of rings in the network.
- \( P_i \): the set of eligible rings for the recovery of the \( i^{th} \) link failure.
- \( R_{IN} \): the set of node pairs whose working routes cross link \( i \).
- \( d^r \): the demand units in (FS) between node pair \( r \). \( \delta_{i,p} = 1 \) if ring \( p \) includes link \( i \); 0, otherwise. \( \delta_{i,p} = 1 \) if working path between node pair \( r \) and working path between node pair \( r \) share at least one common link; 0, otherwise. \( \delta_{i,p} = 1 \) if rings \( p \) and \( q \) share common links; 0, otherwise. \( \alpha \) is a weight factor.
- \( \beta \): the number of spare capacity units (in FS) assigned for ring \( p \). \( \beta_p = 1 \) if the starting frequency of ring \( p \) is larger than the starting frequency of ring \( q \), i.e., \( e_p > e_q \); 0, otherwise.
- \( n_p \): the maximum index of the used FSs on all the fiber links in the network.
- \( \alpha \): the weight factor.
- \( \gamma_{p}^q \): the maximum index of the used FSs on all the fiber links in the network.
- \( \alpha_c \): the weight factor.
- \( \alpha_c \): the weight factor.

**Objective:** Minimize \( \sum_{i \in S} s_i + \alpha \cdot c \) (1)

**Subject to:**
1. \( c \geq f^r + d^r - 1 \quad \forall r \in R \) (2) \( c \geq e_p + n_p - 1 \quad \forall p \in P \) (3)
2. \( \sum_{p \in P_i} x_{p,r}^{i} = 1 \quad \forall i \in S, \forall r \in R_{IN} \) (4) \( d^r \cdot x_{i}^{p,r} \leq n_p \quad \forall i \in S, \forall r \in R_{IN}^r, \forall p \in P_i \) (5)
3. \( s_i = \sum_{p \in P} \delta_{i,p} \cdot n_p \quad \forall i \in S \) (6) \( e_p = f^r \quad \forall r \in R, r \neq t \) (7)
4. \( f^r + d^r - (e_p + n_p) \leq \gamma \cdot (1 - x_{i}^{p,r}) \quad \forall i \in S, \forall r \in R_{IN} \) (8) \( f^t - f^r \leq \gamma \cdot (1 - z_i^r + 1 - \phi_i^r) - 1 \quad \forall r, t \in R, r \neq t \) (9)
5. \( f^r + d^r - 1 - f^t \leq \gamma \cdot (1 - x_{i}^{p,r}) \) (10) \( e_q = e_p \quad \forall p, q \in P, p \neq q \) (11)
6. \( e_p + n_p - 1 - e_q \leq \gamma \cdot (1 - z_i^r + 1 - \phi_i^r) - 1 \quad \forall p, q \in P, p \neq q \) (12)

Objective (1) is to minimize the total required protection capacity in units of FS and the maximal index of used link FSs in the entire network. In the study, we set \( \alpha \) to be a small value 0.01 so that minimizing the total spare capacity becomes the first objective. Constraints (2) and (3) tell that the maximal FS index in the entire network should be always greater than the ending FS index of any working lightpath and protection ring in the network. Constraint (4) ensures that there is only one eligible ring chosen for any node pair whose working lightpath is affected by link failure. Constraint (5) ensures that the protection capacity provided by ring \( p \) is sufficient to recover the failure of lightpath between node pair \( r \) upon link failure \( i \). Constraint (6) counts the total number of spare capacity units in FS that should be reserved on link \( j \). Constraint (7) is chosen; 0, otherwise. Constraint (8) ensures that the protection capacity provided by ring \( p \) is sufficient to recover the failure of lightpath between node pair \( r \) upon link failure \( i \). Constraint (9) ensures that the protection capacity provided by ring \( p \) is sufficient to recover the failure of lightpath between node pair \( r \) upon link failure \( i \). Constraint (10) ensures that the protection capacity provided by ring \( p \) is sufficient to recover the failure of lightpath between node pair \( r \) upon link failure \( i \). Constraint (11) ensures that the protection capacity provided by ring \( p \) is sufficient to recover the failure of lightpath between node pair \( r \) upon link failure \( i \). Constraint (12) ensures that the protection capacity provided by ring \( p \) is sufficient to recover the failure of lightpath between node pair \( r \) upon link failure \( i \).
physical link). More specifically, if the starting FS index of working lightpath A is larger than that of working lightpath B, then the starting FS index of lightpath A should also be larger than the ending FS index of lightpath B. Constraints (11) and (12) are a version of constraints (9) and (10) for the rings that share common link(s).

4. Results and performance analyses

To evaluate the performance of the ring cover technique, we consider three test networks: (1) a six-node eight-link network (n6s8) shown in Fig. 1, (2) the 10-node and 22-link SmallNet network shown in Fig. 2(a), and (3) the 11-node and 26-link COST239 network shown Fig. 2(b). For all the networks, the traffic demand between each pair of nodes is random with a uniform distribution within a certain range between 1 and \( X \) FSs. We set \( X \) to be three, four, and five. For the SmallNet and COST239 networks, because the numbers of candidate rings are very large, we restricted the maximal number of hops of the rings to be four to limit the number of rings used for evaluation.

Fig. 3 shows the results of spare capacity redundancy which is defined as the ratio of total protection capacity to total working capacity in the entire network. Comparing spare capacity redundancies of the three test networks, we find that the redundancy of the COST239 network is the lowest and that of the n6s8 network is the highest, while the SmallNet network lies in between. This phenomenon is attributed to the link working capacity distribution in the networks. On computing the standard deviation of link working capacity distribution, we found that the COST 239 network has the smallest standard deviation, which means the most balanced link working capacity distribution, while the n6s8 network has the largest standard deviation, which corresponds to the most unbalanced link working capacity distribution. As the ring cover technique needs to deploy a number of protection capacity units that is equal to the largest number of working units on the links covered by the ring, a more balanced link working capacity distribution tends to achieve better spare capacity efficiency. This therefore explains the different spare capacity redundancies of the three test networks. Figs. 4 show the maximal number of FSs required for accommodating all the protected traffic demands for the three test networks. We can see that the test network of COST239 requires the largest number of FSs, the test network of n6s8 requires the smallest number of FSs, and the test network of SmallNet lies in between. This is because the COST239 network has the largest number of node pairs and the n6s8 network has the smallest number of node pairs. Under the assumption that each node pair has the traffic demand with the same random distribution, the COST239 is expected to have the highest total traffic demand, which therefore leads to largest number of FSs required on the links. For the n6s8 network, it is the opposite situation.

5. Conclusion

We applied the ring cover technique to the elastic optical network. We developed an ILP optimization model to minimize the required protection capacity and the link spectra used in the network. Results indicate that the spare capacity redundancy of the ring cover technique is typically much higher than 100% due to the dedication of protection capacity of the deployed rings. In addition, the protection redundancy of this technique is highly dependent on the working traffic demand distribution on each link in a network. A network with a more balanced working capacity distribution tends to show a lower spare capacity redundancy.

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