Novel models for efficient shared-path protection

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Abstract: The proposed models combines two simple modifications to existing ILP models so as to *not only* significantly reduce restoration time, *but also* reduce total bandwidth consumption.

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1. Introduction

As widespread deployment of high-capacity dense wavelength-division multiplexing (DWDM) systems is envisioned, achieving efficient *shared-path protection*, which protects a bandwidth guaranteed connection from a single link (node) failure using a link (node) disjoint pair of *active path* (AP) and *backup path* (BP), becomes a key design consideration. Since the restoration time (the BP set-up signaling delay) mainly depends on the BP length, long BPs will not only violate a given restoration time guarantee, but also introduce negative effects on the optical signal transmission quality (in terms of SNR, BER, etc).

In a dynamic provisioning environment under the bandwidth-on-demand paradigm, connection requests arrive one by one and future demands are unknown. So online algorithms that determine the AP and BP for a new request without disturbing existing APs and BPs are desirable. In [1], such an online scheme, named *Sharing with Complete Information* (SCI), was proposed, which determines an optimal pair of AP and BP by solving an Integer Linear Programming (ILP) model. The ILP model, however, focuses only on minimizing the total cost, in terms of total bandwidth (TBW) consumption but does not consider the need to limit the BP length. As a result, a BP may contain many links of *zero* (0) cost in terms of *additional* backup bandwidth (or BBW) the BP incurs due to BBW sharing among this BP and existing BPs. In [2-4] (where fixed APs are used), the tradeoff between the BP length and BBW sharing was investigated, and found that in order to reduce the BP length, one has to sacrifice BBW sharing or in other words, increase TBW consumption.

In this paper, we will devise a novel ILP model based on the SCI model in [1], which can be used to significantly reduce the BP length while reducing the TBW consumption as well. This model is applicable when complete aggregate (or per-flow) information on all existing APs and BPs is available to a centralized controller as in [1]. We will also devise a corresponding model for the case where only *partial aggregate* information is available and *distributed control* is adopted, based on the DPIM model in [5] (DPIM is chosen because it is the most efficient shared-path protection scheme requiring only partial information and distributed control). Note that since one only needs to obtain an optimal solution for the new request, instead of all requests as in the off-line case, the time required to solve the ILP models in the on-line case becomes not so unreasonable. Besides, the ILP models can also be solved by using speedy algorithms that take advantage of the proposed improvements to yield a solution that is even closer to the optimal one than what is possible using speedy algorithms based on the original ILP models.

2. Improving over existing ILP models

We now describe two proposed modifications to the existing ILP models, one for SCI [1] and the other for DPIM [5]. Both modifications affect only the objective functions (i.e., the cost function which is to be minimized) in the ILP models, and hence we will not describe the rest of the ILP formulation (which can be found in [1] [5]).

To facilitate the informal description of the objective function, let w be the bandwidth requested by the new connection to be established. In addition, let a and b denote an link along an AP and BP, respectively, and |AP| and |BP| denote the length of the AP and BP, respectively. Finally, let BC_b denote the cost of link b (i.e., additional BBW to be reserved on link b for the new BP). It is clear that the total cost (TBW consumption) is

$$w \cdot |AP| + \sum_{b \in BP} BC_b \qquad (1)$$

The objective function used in SCI is to minimize Eq. (1). To explain the second term in more detail, let S_a^b be the total amount of ABW required by the existing connections whose APs traverse link a and whose BPs traverse link b, and B_b be the amount of BBW already reserved on link (for these as well as possible other connections whose APs do not use link a). Then the additional BBW needed on link b for the new connection, in order to protect against the failure of link a, is $BC_a^b = \max\{S_a^b + w - B_b, 0\}$ [1][5]. Since link b needs to be used to restore all the traffic affected by the failure of any one of the links along the AP, we have [1]:

$$BC_b = \max_{\forall a \in AP} \{S_a^b + w - B_b, 0\} \tag{2}$$

It is clear that if the objective function in Eq. (1), which focuses only on the TBW, the ILP solver will not (and cannot) distinguish between two pairs of AP and BP with the same TBW, but the first pair has a longer AP (and hence a larger ABW) and a shorter BP (and hence a smaller BBW) than the second pair. In other words, the ILP solver may end up choosing the first pair. Since the BP is shorter, such a choice may affect BBW sharing among this BP and future BPs, thus increase the TBW consumption in the end.

Based on the above observation, the first improvement is to introduce parameter ε (where $0<\varepsilon<1$) in the objective function in order to assign less weight to BBW. More specifically, the objective function can be improved as follows:

$$\text{minimize}: \quad w \cdot |AP| + \varepsilon \sum_{b \in BP} BC_b \tag{3}$$

This objective function makes the second pair containing a shorter AP and a longer BP more appealing to the ILP solver because the TBW of the second pair is now smaller than that of the first pair. Note that $\varepsilon=1$ in the original model. In addition, if $\varepsilon=0$, the objective function becomes simply the minimization of ABW, which is equivalent to finding a shortest AP.

As mentioned earlier, a BP chosen by an ILP solver, based on the objective function in Eq. (3) (or Eq. (1)), may contain many links with zero cost. In order to reduce the BP length, and also in part, compensate for the effect of using $0<\varepsilon<1$, the second improvement is made, which introduces parameter μ (where $0<\mu\leq1$) in Eq. (2) to assign a non-zero (virtual) cost to links that would otherwise have zero (actual) cost. That is, we will plug in the following value, instead of the value given in Eq. (2) to the objective function in Eq. (3) (or Eq. (1)):

$$BC_b = \max_{\forall a \in AP} \{S_a^b + w - B_b, \mu w\} \tag{4}$$

Because every link will now have a non-zero cost, virtual or actual, an ILP solver may favor a BP consisting of a fewer links, most or all of which have a non-zero (actual) cost, instead of a longer BP consisting of many links which have a non-zero (virtual) cost of μw because the former now has a lower total cost (virtual or actual). Note that $\mu = 0$ in the original ILP model, and μ never needs to be larger than 1 as the additional BBW to be reserved never needs to exceed w.

We now describe the ILP model for DPIM. Define $P_{A_a} = \max_{\forall b} S_a^b$ which is part of the partial aggregated information maintained by each node. The only significant difference in the objective function between DPIM and SCI is that here, the BBW is estimated as follows [5]:

$$BC_b = \min\{\max_{\forall a \in AP}(P_{A_a} + w - B_b, 0), w\} \tag{5}$$

Since the original ILP model for DPIM used the same objective function as Eq. (1), it can be firstly improved by introducing parameter $0 < \varepsilon < 1$ as in Eq. (3). In addition, Eq. (5) can be improved as follows:

$$BC_b = \min\{\max_{\forall a \in AP}(P_{A_a} + w - B_b, \mu w), w\} \tag{6}$$

Note that, by definition, $P_{A_a} + w - B_b$ in Eq. (5) is no smaller than $S_a^b + w - B_b$ in Eq. (2), that is, the former gives an over-estimation of the BBW cost. Therefore, as to be shown next, the effect of having $\mu > 0$ in increasing the BBW cost is less significant in DPIM than in SCI. Also, having $0 < \varepsilon < 1$ will help compensate for the overly estimated BBW cost in DPIM.

3. Simulation results

We have simulated a randomly generated 15-node network (with 26 bi-directed edges) used in [1][5] and a larger network called USnet (with 46 nodes and 76 bi-directed edges [6]) to study the effect of ε and μ. One of the performance metrics is the *bandwidth saving ratio (or BSR)* which is defined to be the percentage of the reduction in the TBW consumption due to the use of SCI, DPIM or their improved models with respect to the TBW consumption with no BBW sharing at all (as in the case of dedicated path protection). Other performance metrics include the number of hops along a BP and an AP.

We first investigate the effect of ε only (i.e., by setting μ=0). Fig.1 (a) shows the BSR for various ε (0~1.9). It is clear that when $0<\varepsilon<1$, the BSR improves over that when $\varepsilon=1$ (or $\varepsilon=0$), especially for DPIM in the 15-node network (up from about 28% to about 33%). At the same time, Fig.1 (b) shows that using $0<\varepsilon<1$ does not increase the BP length (or decrease the AP length) too much when comparing to the case where $\varepsilon=1$. The results for the 15-node network are similar but will be omitted hereafter (even though they make the proposed models look even better). Also to be omitted are other results for the cases where ε >1 and ε =0 as these values of ε result in reduced BSR and thus are not so interesting.

We now study the effect of μ (and ε). Fig.1(c) and (d) show the BSR for SCI and DPIM, respectively. It is clear that the decrease in BSR in DPIM due to the use of 1 > μ > 0 is not as much as that in SCI (this is because, as mentioned earlier, DPIM over-estimates the BBW cost). An interesting observation is that in DPIM, the BSR with ε ≤0.5 and μ ≤0.8 is higher than that using the original model (i.e., ε = 1.0 and μ = 0), while the BP length is shorter as can be seen from Fig.1(f). Even in SCI, the BSR with ε ≤0.5 and μ ≤0.2 is still higher than that using the original model, while the BP length is much shorter (down from 10.75 hops to 7.5 hops) as can be seen from Fig.1(e).

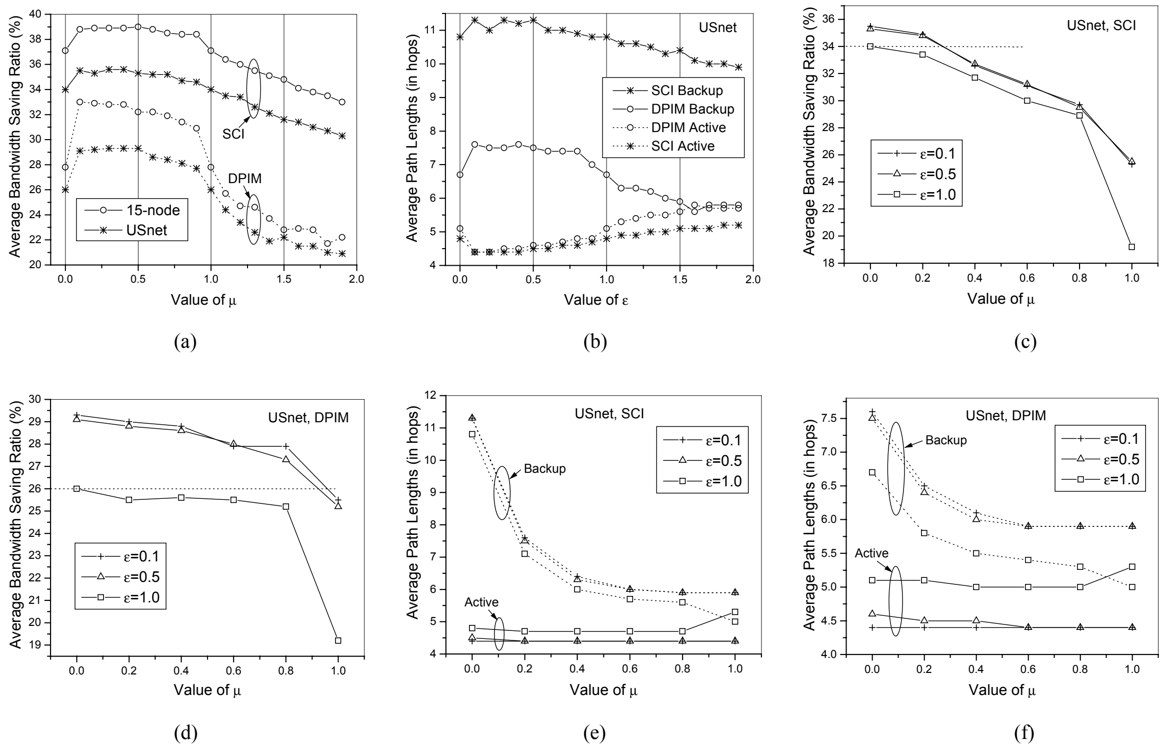

Fig.1 The effect of ε and μ on network performance

4. Conclusions

We have introduced two parameters (ε and μ) into the objective function of ILP models for dynamic provisioning of restorable, bandwidth guaranteed connections using shared-path protection. By using ε (0<ε <1), we can obtain a lower total bandwidth (TBW) consumption than using ε =1 as in the existing models. In addition, using 1 ≥ μ > 0 can avoid the pitfall of choosing very long backup paths (BPs) that is common in existing models (where μ =0), thus reducing the BP length and consequently restoration time. One of the pleasantly surprising results is that, by combining an appropriate ε (e.g., 0.1) and μ (e.g., 0.2), the proposed models can achieve a lower TBW consumption with shorter BPs than the existing ones.

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