Efficient Shared Subconnection Protection in Mixed-Line-Rate Optical WDM Networks

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Abstract: Employing Mixed Line Rates (MLR) in optical WDM networks enables new paradigms for protection. We propose to design transparent MLR networks with shared subconnection protection and achieve significant cost reduction.

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1. Introduction

Mixed-Line-Rate (MLR) network [1-3] is a recent evolution of optical transparent networks. In such a network, the wavelength channels of optical paths (i.e., lightpaths) can have a variety of capacities (10/40/100 Gbps), so that the network designer can exploit the volume discount of high-bit-rate transponders when serving large amount of traffic. But, because of accumulating signal impairments, the reach of some high-bit-rate lightpaths are limited, based on a threshold signal quality (e.g., bit-error rate (BER)). Nonetheless, equipping the network with different bit rates over different wavelengths allows us to (1) efficiently groom low-bandwidth connections onto high-capacity optical paths; (2) use the optimal combination (number/rate) of wavelengths on each link, to satisfy traffic and network asymmetry.

In optical networks, the failure of a network element (e.g., a fiber cut) can cause huge data loss, resulting in the failure of several lightpaths. Hence, protection in MLR networks is very important, but so far it is a rather unexplored research field. In [2], we have preliminarily dealt with transparent MLR network design with dedicated protection, demonstrating the beneficial interaction among MLR and protection. While dedicated protection has fast protection switching, shared protection (considered here) is more resource efficient due to backup sharing.

Shared protection in a transparent network can exploit optical bypass, but enforcing wavelength continuity (as required in a transparent network) limits the sharing opportunities and its resource efficiency. A more-effective shared-protection scheme is based on pre-deploying "subconnections" [5] (essentially pre-"lit" lightpaths), so that, when a failure occurs on a working connection, these subconnections are concatenated to form a backup path. It addresses the cost-vs.-capacity tradeoff [5]: the shorter the backup subconnections (the extreme case is that each subconnection traverses only one fiber link), the more the chances for sharing. But shorter backup subconnection also means more transmission equipment and optical-electrical-optical (OEO) conversions are needed in the network, leading to higher network cost. On the other hand, the longer the subconnections (the extreme case is that each working lightpath is protected by only one backup subconnection), the less transmission equipment is required, but this will also limit the opportunity to share capacity in the subconnections.

Shared subconnection protection (in this paper, we use the term SSP) is an excellent candidate for protection in MLR networks for the following reasons. (1) MLR networks allow operation of different lightpaths at different rates; in SSP, both working lightpaths and backup subconnections can take advantage of rate heterogeneity. (2) Since backup subconnections are pre-deployed, we can avoid power transients, which arise when the power level on a link is suddenly changed, due to the provisioning of backup paths in reaction to a failure, as it happens in shared path protection, where the backup paths are not pre-crossconnected. It is worth reminding that, in a MLR network, the management of physical impairments at the optical layer is very challenging, e.g., due to the careful dispersion management required to address self-phase modulation and cross-phase modulation. So maintaining a stable lightpath pattern in the network even in case of failure is a very desirable feature. (3) SSP enables very low restoration time [4] which is crucial when transporting very high bit rates (e.g., 100 Gbps).

In this paper, we study the problem of MLR network design with SSP, which is discussed next.

2. Shared Subconnection Protection (SSP) in Mixed-Line-Rate (MLR) Networks

We show the operation of SSP in MLR networks in Fig. 1. Let us consider five lightpaths, whose feasible bit rates (i.e., higher bit rates will result in unacceptable BER) are shown in Table I. Let l_1 be a working lightpath serving 80 Gbps of traffic and is protected by subconnections l_3 and l_5. Two wavelengths are used to support l_1, each at 40

Gbps; both l_3 and l_5 need one wavelength at 100 Gbps, and the two protection wavelengths are always lit. When a failure occurs on l_1, the cross-connects at node 4 is configured so that l_3, l_5 are concatenated to form a protection path from node 1 to 6, to which the flow on l_1 is switched. After the failure is repaired, the flow reverts to l_1 such that subconnection l_3 and l_5 can be used to protect other working flows. Let l_2 be a working lightpath carrying 40 Gbps of traffic, protected by subconnection l_3 and l_4. Since l_1 and l_2 are link disjoint, they can share transponders of l_3, and 40 Gbps backup capacity reserved on l_3. Based on feasible rates, one wavelength is needed on both l_2 and l_4, each at 40 Gbps. When a failure occurs on l_2, l_3 and l_4 will be connected to form a protection path.

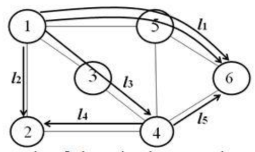

Fig. 1. Example of shared subconnection protection.

TABLE I FEASIBLE BIT RATE OF LIGHTPATHS IN FIG 1

Lightpath	Feasible bit rate (Gbps)
1	10, 40
2	10, 40, 100
3	10, 40, 100
4	10, 40, 100
5	10, 40

Our objective is to minimize the network cost in terms of transponders at various bit rates. (Note that other costs, e.g., cost of switches, multiplexers, demultiplexers, etc., are not considered. We consider the simplifying hypothesis of a single fiber network with a fixed number of wavelengths per fiber.) The steps of our analysis are as follows. (1) Determine the *k*-shortest paths between each *s-d* pair of the network as candidate lightpaths. (2) Calculate the BERs for candidate lightpaths at all bit rates and check if the calculated BER is less than a given threshold (10^{-3} used in this study). (3) With preprocessed feasible lightpaths at each rate as input, together with traffic demands, available line rates (i.e., 10/40/100 Gbps), and cost of associated transponders, we assign rates and wavelengths to lightpaths while minimizing the overall network cost. This is a routing/wavelength/rate assignment (RWRA) problem.

3. A Quasi-Heuristic Approach

We solve the RWRA problem in a quasi-heuristic manner. First, by relaxing wavelength-continuity constraint, we solve the routing/rate assignment (RRA) via an integer linear program (ILP). This relaxation reduces the number of variables and constraints are reduced, so we can get results on reasonable study cases. Then, we use well-known wavelength assignment (WA) approaches [6] (e.g., First-Fit) to assign a wavelength to each lightpath.

Given: (1) $G(V,E)$: physical topology of the network with *V* nodes and *E* links; (2) *W*: number of wavelengths on a link; (3) $T=[\Lambda_{sd}]$: traffic matrix with aggregated demands Λ_{sd} in Gbps between a *s-d* pair; (4) $R=\{r_1,r_2,\dots,r_k\}$: set of available bit rates; (5) D_k: cost of a transponder at rate r_k; (6) L_{ij}^l: l_{th} lightpath from node *i* to node *j*; (7) P_e: set of lightpaths passing through link *e* (8) *B*: threshold BER; (9) BER_{ijk}^l: BER of L_{ij}^l at rate r_k; (10) α_{ijk}^l=1, if $BER_{ijk}^l<B$; α_{ijk}^l=0 otherwise.

Variables: (1) W_{ijk}^l: number of wavelengths used by L_{ij}^l at rate r_k as a working lightpath; (2) B_{ijk}^l: number of wavelengths used by L_{ij}^l at rate r_k as a backup subconnection; (3) $f_{ij,l}^{sd}$: working traffic from *s* to *d* routed on L_{ij}^l; (4) $\nu_{i'j'l'}^{ijl}$: amount of flow that will be rerouted on $L_{i'j'}^{l'}$, if any link on L_{ij}^l fails.

Objective:

Minimize: $\sum_{(i,j)}\sum_l\sum_k(W_{ijk}^l+B_{ijk}^l)\,D_k$ (1)

Constraints:

$\sum_k r_k\,\alpha_{ijk}^l W_{ijk}^l \ge \sum_{sd} f_{ij,l}^{sd}$ $\quad\forall(i,j),l$ (2)

$\sum_k r_k\,\alpha_{i'j'k}^{l'} B_{i'j'k}^{l'} \ge \sum_{L_{ij}^l\in P_e}\nu_{i'j'l'}^{ijl}$ $\quad\forall(i',j'),l',e$ (3)

$\sum_{L_{ij}^l\in P_e}\sum_k\alpha_{ijk}^l(W_{ijk}^l+B_{ijk}^l)\le W$ $\quad\forall e$ (4)

$0\le W_{ijk}^l,\,B_{ijk}^l\le W\in\mathbf{Z}$ $\quad\forall(i,j),l,k$ (5)

$f_{ij,l}^{sd}\ge 0$ $\quad\forall(s,d),(i,j),l$ (6)

$\nu_{i'j'l'}^{ijl}\ge 0$ $\quad\forall\,(i,j),l,(i',j'),l'$ (7)

$\nu_{i'j'l'}^{ijl}=0$ $\quad\forall\,L_{ij}^l,L_{i'j'}^{l'}$ which are not link disjoint (8)

$$\sum_i\sum_l f_{ij,l}^{sd}-\sum_i\sum_l f_{ji,l}^{sd}=\begin{Bmatrix}-\Lambda_{sd} & \text{if } s=j\\ \Lambda_{sd} & \text{if } d=j\\ 0 & \text{otherwise}\end{Bmatrix}\qquad\forall\,j,(s,d)\qquad(9)$$

$$\sum_{i'}\sum_{l'}\nu_{i'j'l'}^{ijl}-\sum_{i'}\sum_{l'}\nu_{j'i'l'}^{ijl}=\begin{Bmatrix}-\sum_{sd}f_{ij,l}^{sd} & \text{if } i=j'\\ \sum_{sd}f_{ij,l}^{sd} & \text{if } j=j'\\ 0 & \text{otherwise}\end{Bmatrix}\qquad\forall\,j',(i,j),l\qquad(10)$$

The objective function in Eqn. (1) computes the overall cost of transponders at various bit rates. Eqns. (2) and (3) set capacity constraints at the logical layer: total traffic of all connections routed on a lightpath/subconnetion must be bounded by its capacity, considering only those for which $\alpha_{ijk}^l=1$. Eqn. (4) is the physical layer capacity constraint (i.e., relaxed wavelength-continuity constraint). Eqn. (8) forces a working lightpath to be protected by link-disjoint backup subconnection(s). Eqns. (9) and (10) satisfy the flow-conservation constraint at the logical level. The bounds of the variables are written as Eqn. (5)-(7).

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4. Results and Discussions

We consider a typical backbone network topology as in Fig. 2, and a typical traffic demand matrix as in Table II, which sums to a total traffic of 1 Tbps. Different traffic loads are generated applying scale factor of (1, 2, 3, 4, 5, 6, 7) to this traffic demand. Normalized costs of 10 Gbps, 40 Gbps, and 100 Gbps transponders are, respectively, 1×, 2.5×, and 3.75× [7] (note the volume discount). Number of wavelengths on a link is 80. BER parameters are same as in [1].

TABLE II BASE TRAFFIC DEMAND MATRIX (EACH ELEMENT IN GIGABIT PER SECOND)

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	2	1	1	1	4	1	1	2	1	1	1	1	1
2	2	0	2	1	8	2	1	5	3	5	1	5	1	4
3	1	2	0	2	3	2	11	20	5	2	1	1	1	2
4	1	1	2	0	1	1	2	1	2	2	1	2	1	2
5	1	8	3	1	0	3	3	7	3	3	1	5	2	5
6	4	2	2	1	3	0	2	1	2	2	1	1	1	2
7	1	1	11	2	3	2	0	9	4	20	1	8	1	4
8	1	5	20	1	7	1	9	0	27	7	2	3	2	4
9	2	3	5	2	3	2	4	27	0	75	2	9	3	1
10	1	5	2	2	3	2	20	7	75	0	1	1	2	1
11	1	1	1	1	1	1	1	2	2	1	0	2	1	61
12	1	5	1	2	5	1	8	3	9	1	2	0	1	81
13	1	1	1	1	2	1	1	2	3	2	1	1	0	2
14	1	4	2	2	5	2	4	4	1	1	61	81	2	0

Figure 3 reports cost in terms of transponders for the following three scenarios: single-line-rate (SLR) network equipped only with 10G transponders providing SSP, MLR network providing SSP, and MLR network without protection. As expected, MLR approach can carry more traffic and achieve significant cost reduction (up to 32%) compared to SLR. As traffic grows, cost reduction between SLR and MLR becomes more significant. The network, if equipped only with 10Gbps transponders, cannot carry a traffic larger than 4×, because of the limited number of wavelengths. Also note that the cost of providing SSP in MLR network is less than two times (typically between 1.7 and 1.8) of that without protection, which shows it offers a good opportunity to share backup capacity.

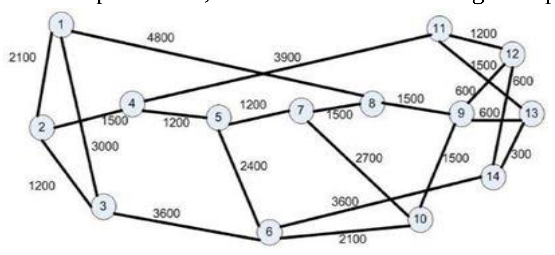

Fig. 2. 14-node NSF network (link length in kilometers).

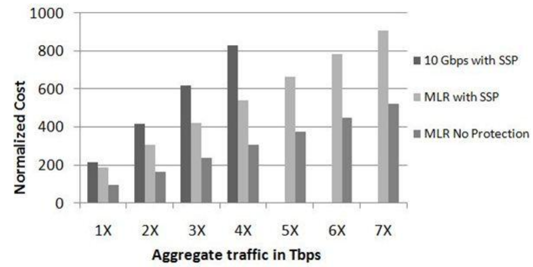

Fig. 3. Comparison of transponder costs for SLR and MLR networks.

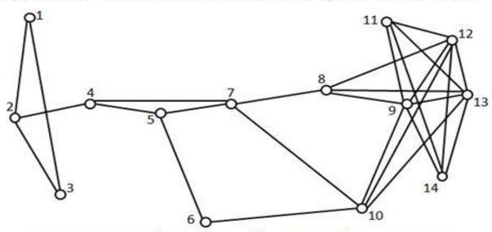

Fig. 4. Logical topology of SLR 40 Gbps NSFNET.

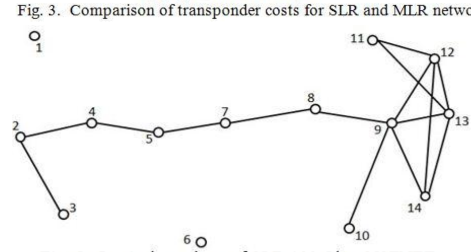

Fig. 5. Logical topology of SLR 100 Gbps NSFNET.

Figures 4 and 5 are the logical topology obtained from BER calculation considering Fig. 2 as a SLR network equipped with only 40-Gbps and 100-Gbps transponders. A link in Fig. 4 (5) represents a lightpath feasible at 40 (100) Gbps between a node pair. Note that in Fig. 4 there is only one path (the direct link) between node 2 and 4, while to provide protection, there must be at least two link-disjoint paths. Similar cases exist for Fig. 2 as a MLR network with dedicated protection in [2]: there is no feasible working and backup lightpath *pair* connecting node 4 and any other node, leading to the failure to provide protection. In Fig. 5, the network is not even connected, not to mention protection infeasibility. This is why we do not have results for these scenarios. Also, this confirms that MLR network with shared protection enables a survivable, cost-efficient and flexible network design.

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