New and Improved Strategies for Optical Protection in Mixed-Line-Rate WDM Networks

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Abstract: Employing Mixed Line Rates (MLR) in optical WDM networks enables new paradigms for protection at lightpath level. We design transparent MLR networks with dedicated protection and achieve significant cost reduction.

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1. Introduction

To cope with the increasing amount and heterogeneity of traffic, optical backbone networks employ wavelength-division-multiplexing (WDM) to multiplex multiple data flows over different WDM channels on a single fiber. The transmission rate of each WDM channel is quite high (typically, 10-40 Gbps) and expected to become higher (e.g., 100 Gbps). New technological solutions that allow mapping higher rates over WDM channels are being developed: solutions for 40 Gbps have been commercialized [1], while solutions for 100 Gbps are under R&D [2].

High bit rates are desirable because they can carry a huge amount of traffic, but signal impairments significantly limit the regenerator-free optical distance. To maximize retrofit with existing network equipment (switches, ports, filters), it is desirable to maintain the same channel spacing of legacy 10 Gbps systems (typically 50 GHz), which provides a narrow transmission spectrum for higher-bit-rate signals. So, increasing the channel capacity to 40/100 Gbps presents a tradeoff between capacity and reach. In [3], an analytical model that evaluates the maximum transmission range to satisfy a BER target, and considering physical impairments and channel spacing, has been presented and it is applied also here to identify feasible paths.

However, since most connections run at sub-10Gbps rates, the problem of efficiently multiplexing low-bandwidth connections onto high-capacity optical transmission path or lightpaths (i.e., *traffic grooming*) is very challenging. Thus, optical networks with mixed line rates (MLR), e.g., 10/40/100 Gbps over different wavelength channels, is becoming a new networking paradigm. Equipping a network with different bit rates over different wavelengths allows us to (1) use the optimal combination (number/rate) of wavelengths on each link, which addresses both traffic and network asymmetry, (2) support multi-rate transport protocols and hence avoid complex multiplexing schemes, and (3) add design flexibility by avoiding low-bandwidth connections over high-capacity lightpaths. With MLR, one can design a cost-effective network by exploiting volume discount of 40 and 100 Gbps transponders [3].

However, survivability, which is a key concern in optical network design, has not been addressed yet in MLR networks. The opportunities that MLR enables to support effective protection are largely unexplored. For example, consider a 100-Gbps lightpath with dedicated protection in a single-line-rate (SLR) network. Even if the primary path is feasible, it may be the case that no feasible backup path can be provisioned in the network due to the signal impairment at 100 Gbps. Now, a possible solution enabled by MLR is to protect the 100-Gbps lightpath with two lightpaths each at 40 Gbps and two lightpaths each at 10 Gbps.

In this paper, for the first time and to the best of our knowledge, we deal with the problem of *protection in MLR optical networks*. In particular, we study how to design a cost-effective transparent MLR network that provides dedicated protection at lightpath (PAL) level using three approaches, which are discussed next.

2. Problem Statement

We now formally state the problem: given the network topology (including the number of wavelengths on each link), the set of candidate *p*-lightpaths (a *p*-lighpath is defined as a pair of link-disjoint lightpaths between two nodes), the traffic demands, the available line rates (i.e., 10/40/100 Gbps), and the costs of the associated transponders. We need to assign rates and wavelengths to the working and backup lightpaths while minimizing the overall network design cost measured in terms of the cost of transponders. The problem is a Routing/Wavelength/Rate assignment (RWRA).

The constraints are: (1) number of a lightpaths on a link must be bounded by the number of wavelengths supported by that link; (2) total traffic of all connections routed on the lightpath must be less than the capacity of that lightpath; (3) traffic demand between each source-destination pair must be supported; and (4) BER constraints, namely, a lightpath can be set only at rates compatible with the transmission-range constraint.

3. Proposed Schemes

In this section, we first illustrate three schemes for dedicated protection in MLR networks: via a few examples on the network in Fig. 1. Then, we provide mathematical models for these approaches: MLR-at-*p*-lightpath protection (MLR-*p*), MLR-at-lightpath protection (MLR-*l*), and MLR-with-backup-traffic-packing protection (PMLR).

Table 1 Candidate *p*-lightpaths from node 1 to 2 in Fig. 1.

p-lightpath	working	backup
No. 1	1→2	1→3→4→2
No. 2	1→3→4→2	1→2
No. 3	1→5→4→2	1→2

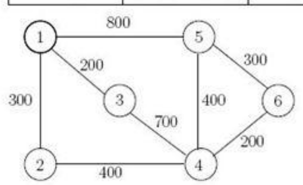


Fig. 1. Six-node network (link lengths in km).

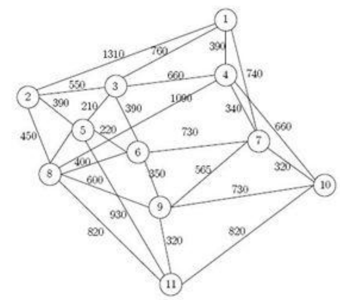
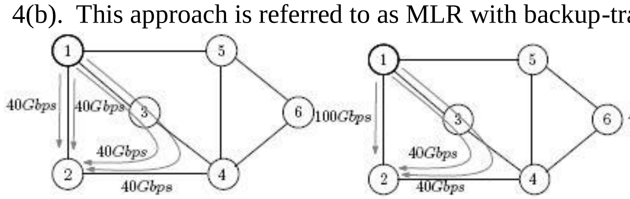


Fig. 2. COST239 network (link lengths in km).

In MLR-*p*, the bit rates of the working and the backup lightpath of a *p*-lightpath are the same (this rate is "the rate of the *p*-lightpath"), but the rates of different *p*-lightpaths can be different. For example, for the network in Fig. 1, three candidate *p*-lightpaths from node 1 to node 2 are shown in Table 1. According to the BER estimation, let lightpath 1→2 be feasible up to 100 Gbps, while lightpaths 1→3→4→2 and 1→5→4→2 be feasible only for bit rates up to 40 Gbps. Let us assume that 80 Gbps of traffic has to be routed on No. 2 *p*-lightpath from node 1 to 2; the rate of this *p*-lightpath has to be 40 Gbps even if its backup lightpath is feasible on 100 Gbps. So both of its working and backup lightpaths will consume two wavelengths, as shown in Fig. 3(a).

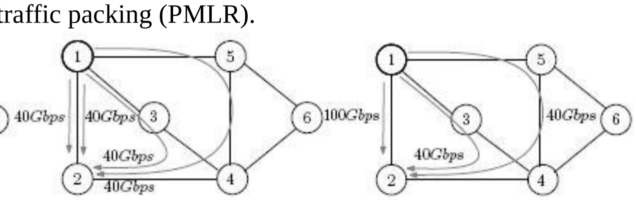
In case of MLR-*l*, the rates of the working and the backup lightpath in a *p*-lightpath can be different. Let us consider the same example as before: since transponders with higher rates provide volume discount, (i.e. the higher the capacity, the lower the cost per unit of capacity), in order to minimize the cost, the backup lightpath 1→2 may operate on 100 Gbps, as shown in Fig. 3(b), so that the backup lightpath will consume only one wavelength.

Let us describe a third potential approach to provide dedicated protection in a MLR network. Assume the physical links of 1-3 and 3-4 now have only one free wavelength, but still we have to serve 80 Gbps traffic from node 1 to 2. A way to satisfy the traffic using MLR-*l* is to allocate 40 Gbps on No.2 *p*-lightpath in Table 1 and other 40 Gbps on No.3 *p*-lightpath, as shown in Fig. 4(a). Note that the backup lightpath (1→2) of these two *p*-lightpaths is exactly the same, and it can support up to 100 Gbps bit rate. In other words, now, to minimize the cost of transponders, we can pack the backup traffic of two different lightpaths onto one single backup lightpath from 1 to 2, as shown in Fig. 4(b). This approach is referred to as MLR with backup-traffic packing (PMLR).



(a) MLR-*p* (b) MLR-*l*

Fig. 3. Comparison between MLR-*p* and MLR-*l*.



(a) MLR-*l* (b) PMLR

Fig. 4. Comparison between MLR-*l* and PMLR.

We propose to solve the RWRA problem in a quasi-heuristic manner. First, by relaxing wavelength-continuity constraint, we solve the routing-rate-assignment problem via a relaxed Integer Linear Programming (ILP) formulation. Second, we use First-Fit [4] to assign wavelength to every lightpath. The ILP of MLR-*l* is as follows:

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

Variables: (1) W_{ijk}^{l} : number of wavelengths occupied by $L_{ij}^{l,w}$ at the rate r_k; (2) B_{ijk}^{l} : number of wavelengths occupied by $L_{ij}^{l,b}$ at the rate r_k; (3) $f_{ij,l}^{sd}$: traffic from *s* to *d* routed on the l_{th} *p*-lightpath from *i* to *j*.

Objective:

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

Constraints:

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

$\sum_k r_k \beta_{ijk}^l B_{ijk}^l \geq \sum_{sd} f_{ij,l}^{sd} \quad \forall (i,j), l$ (3)

$f_{ij,l}^{sd} \geq 0 \quad \forall (s,d), (i,j), l$ (4)

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

$0 \leq B_{ijk}^l \leq W \in \mathbf{Z} \quad \forall (i,j), l, k$ (6)

$$\sum_{L_{ij}^{l,w} \in P_{mn}} \sum_k \alpha_{ijk}^l W_{ijk}^l + \sum_{L_{ij}^{l,b} \in P_{mn}} \sum_k \beta_{ijk}^l B_{ijk}^l \leq W \quad \forall (m,n) \quad (7)$$

$$\sum_i \sum_l f_{ij,l}^{sd} - \sum_i \sum_l f_{ji,l}^{sd} = \begin{cases} -\Lambda_{sd} & \text{if } s = j \\ \Lambda_{sd} & \text{if } d = j \\ 0 & \text{otherwise} \end{cases} \quad \forall j, (s,d) \quad (8)$$

The formulation for MLR-*p* can be easily obtained by forcing the values of W_{ijk}^l and B_{ijk}^l to be the same. Also, the formulation for PMLR is based on the same Eqns. (1,2,4-8), plus we have to add BL_{ij}^l (set of backup lightpaths that traverse exactly the same physical links as $L_{ij}^{l,b}$) as an input, and Eqn. (3) is changed to be:

$$\sum_k r_k \beta_{ijk}^l B_{ijk}^l + \sum_{L_{ij}^{l',b} \in BL_{ij}^l} \sum_k r_k \beta_{ijk}^{l'} B_{ijk}^{l'} \geq \sum_{sd} f_{ij,l}^{sd} + \sum_{L_{ij}^{l',b} \in BL_{ij}^{l'}} \sum_{sd} f_{ij,l'}^{sd} \quad \forall (i,j), l \quad (9)$$

The details of First-Fit wavelength assignment given a solution of the ILP formulation will not be discussed here.

4. Results and Discussions

The network topology used in our study is Pan-European COST 239 network (Fig. 2), and the traffic matrix is given in Table 2 [5]. It represents a total traffic of 350 Gbps, which is multiplied by different factors to represent a range of loads. The cost of 10 Gbps, 40 Gbps, and 100 Gbps transponders are, respectively, 1×, 2.5×, and 4.5×. The number of wavelengths on a physical link is 60. BER parameters are considered the same as in [3].

Table 2 Traffic matrix for COST239 (in Gbps).

Node	1	2	3	4	5	6	7	8	9	10	11
1	0	1	1	3	1	1	1	1	1	1	1
2	1	0	5	8	4	1	1	10	3	2	3
3	1	5	0	8	4	1	1	5	3	1	2
4	3	8	8	0	6	2	2	11	11	9	9
5	1	4	4	6	0	1	1	6	6	1	2
6	1	1	1	2	1	0	1	1	1	1	1
7	1	1	1	2	1	1	0	1	1	1	1
8	1	10	5	11	6	1	1	0	6	2	5
9	1	3	3	11	6	1	1	6	0	3	6
10	1	2	1	9	1	1	1	2	3	0	3
11	1	3	2	9	2	1	1	5	6	3	0

Table 3 Normalized cost for COST239 (X = 350 Gbps).

Traffic	10*G*	40*G*	100*G*	MLR-p	MLR-ℓ	PMLR
1X	98	99	117	98	98	98
5X	376	285	288	271	271	271
10X	-	505	495	454	454	454
15X	-	725	702	635	630	628
20X	-	940	918	816	806.5	803.5
25X	-	1150	1134	1007	986.5	986
30X	-	1375	1359	1185	1154.5	1154
35X	-	-	1584	1372	1337	1329
40X	-	-	1800	1564	1518	1504.5
45X	-	-	2025	1785	1713.5	1692.5

Table 3 reports the cost, in terms of transponders, for the following six scenarios: three SLR networks, each equipped with either 10G, or 40G, or 100G transponders, and three MLR networks, running MLR-*p*, MLR-*l*, and PMLR. As expected, the MLR approaches can carry more traffic and achieve significant cost reduction compared to the SLR cases. The network, if equipped only by 10Gbps or 40Gbps transponders, cannot carry a traffic larger than 5× and 30×, respectively, because of the limited number of wavelengths. When the traffic is low (e.g., less than 15×), there is no difference between the cost of the three MLR approaches, since most of the *p*-lightpaths carry the same flows along their working and backup lightpaths. As the traffic grows, the cost reduction between SLR and MLR-*p* becomes more significant, i.e., the reduction for 10× traffic is 8.3%, and for 35× traffic, the reduction is 13.4%. When the traffic is relatively high (larger than 30×), the difference in performance among the three protection approaches increases: e.g., cost of MLR-*l* is much less than MLR-*p*, i.e. cost reductions for traffic of 35×, 40×, 45× are 2.55%, 2.94%, and 4% respectively comparing MLR-*l* with MLR-*p*. For high traffic, PMLR also enables the additional opportunity to pack the backup traffic of different connections, and achieved further optimization. From the results, we can see that the additional cost reduction between PMLR and MLR-*l* for traffic of 35×, 40×, 45× are 0.6%, 0.9%, and 1.2%, respectively.

In conclusion, MLR-specific approaches (MLR-*l* and PMLR) to support protection in MLR networks allow to optimize network resources utilization. E.g., in case of MLR-*l* for traffic of 45×, 23 *p*-lightpaths out of 135 have different rates on their working and backup lightpaths, enabling usage of cost-efficient high-bit-rate transponders.

The ILP formulations take several hours to return an optimum solution, so our future work will study effective heuristic approaches. Also, we will investigate shared protection in MLR survivable networks.

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