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

Menglin Liu, Massimo Tornatore, and Biswanath Mukherjee

Abstract—Today’s optical wavelength division multiplexing backbone networks need to support traffic demands with very diverse capacity requirements. Recent studies have shown how to design an optical transport network that supports mixed line rates (MLR), where the wavelength channels of the optical paths (i.e., lightpaths) can have a variety of capacities (10/40/100 Gbps). Some preliminary work on the design of MLR optical networks has already appeared, but survivability, which is a key concern in optical network design, is a nascent topic in MLR networks. This study investigates 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 the lightpath level. We propose three mechanisms: MLR-at-lightpath protection (MLR-\(p\)), MLR-at-lightpath protection (MLR-\(l\)), and MLR-with-backup-flow-grooming protection (MLR-\(g\)). The design problem is solved by two different approaches: (1) a two-step approach that formulates part of the problem as an integer linear program and (2) a heuristic approach. Our results show that, by appropriate assignment of rates to lightpaths, MLR networks can provide protection for diverse traffic demands with much lower transponder cost compared to single-line-rate networks.

Index Terms—Dedicated protection; Lightpath; Mixed line rate; Network design; Optical network; Survivability; Transponder cost; WDM.

I. INTRODUCTION

To handle 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 becoming higher (e.g., 100 Gbps). Technological solutions that allow mapping high rates over WDM channels are being developed: solutions for 40 Gbps are commercialized [1], whereas solutions for 100 Gbps are under research and development [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. For example, in Fig. 1, if we consider a single-line-rate (SLR) network with 10 Gbps transponders, then a lightpath can start from node 2 and end at node 9 with only optical amplification needed along the path; for SLR with 40 Gbps transponders, the lightpath can only reach node 5; and for a 100 Gbps SLR network, the lightpath can only reach node 4 [3]. Thus, increasing the channel capacity from 10 Gbps to 40/100 Gbps represents a trade-off between capacity and reach. On the other hand, since most connections run at sub-10 Gbps rates, the problem of efficiently multiplexing low-bandwidth connections onto high-capacity optical transmission paths or lightpaths (i.e., traffic grooming) is very challenging. When the channel capacity reaches 40/100 Gbps, more complex multiplexing schemes are needed.

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 to satisfy traffic and network asymmetry and (2) support multi-rate transport protocols, achieve efficient traffic grooming, and avoid complex multiplexing schemes. Thus, an optical network with mixed line rates (MLR), e.g., 10/40/100 Gbps, over different wavelength channels is a new networking paradigm. MLR is leveraged to design a cost-effective network by exploiting the volume discount\(^{1}\) of 40 and 100 Gbps transponders in unprotected networks [4–8] and in a survivable network [9].

However, survivability, which is a key concern in optical network design, is a nascent research topic in MLR networks. It is widely agreed that optical protection is essential, since the failure of a network element (e.g., a fiber cut) can cause the outage of several lightpaths, leading to huge data loss. This problem becomes even more compelling if lightpaths are migrated toward very high bit rates, such as 40 Gbps and 100 Gbps. Since connections with various bandwidth granularities have to be accommodated in the network, this opens up the possibility of deploying different mechanisms for multi-layer protection [10–13], where the entity to be protected can be either the lightpath, at the optical layer, or the connection, at the electronic layer.

The opportunities where MLR enables the support of effective protection are largely unexplored. For example, consider a 100 Gbps lightpath with dedicated protection in a SLR network. Even if the primary path is feasible, it may

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\(^{1}\) Volume discount means the cost of a resource increases at a rate that is lower than the linear increase of the rate, e.g., the cost of a 100 Gbps transponder can eventually be 4.5 times that of a 10 Gbps transponder under steady-state conditions, which is less than the rate increase of ten times.
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, all four of which are virtually concatenated through multipath routing. Such a network is called “transparent” if its end-to-end traffic demands flow over all-optical lightpaths with no electronic regeneration. In this study, 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-path protection using three approaches: MLR-at-lightpath protection (MLR-p), MLR-at-lightpath protection (MLR-l), and MLR-with-backup-flow-grooming protection (MLR-g), differentiated by the extent to which (e.g., p-lightpath, lightpath) the rates can be mixed.

The rest of this study is organized as follows. Section II overviews some relevant works on multi-layer protection. In Section III, we formally state the problem and illustrate three proposed schemes for dedicated protection in MLR networks. In Section IV, a two-step approach for MLR network design with dedicated protection is proposed, including a mathematical model, which turns out to be an integer linear program (ILP). Section V presents a more computationally efficient heuristic design algorithm for the problem. Section VI provides illustrative results. Section VII concludes the study.

II. RELATED WORK AND BACKGROUND

The problem of multi-layer protection (i.e., traffic grooming and protection) has received much attention in recent years. The authors in [10,11] proposed protection schemes applied at two different levels. Protection-at-lightpath (PAL) takes care of the flow on each wavelength, which can be groomed by several connections. A connection may go through a concatenation of lightpaths, so PAL is a segment-protected scheme. In a protection-at-connection (PAC) scheme, which is an end-to-end protection scheme, each connection (maybe of sub-wavelength bandwidth) is protected. The protection schemes can also be classified into dedicated [10] and shared protection [11,12,14], depending on whether backup paths can share bandwidth resources or not. The authors in [15] jointly consider grooming and protection in WDM networks: they assume that incoming connections require a working path with minimal-guaranteed availability and a protection path with minimal-guaranteed bandwidth. In [13], multi-layer methods for survivability are compared in terms of resource utilization and configuration cost.

In order to achieve efficient protection in MLR networks, it is crucial to make the protection schemes suitable to the characteristics of MLR. In this study, we consider dedicated protection at the lightpath level, in which a connection is routed through a sequence of protected lightpaths (p-lightpaths). Here, we extend the definition of p-lightpath from that in [10]. In MLR networks, a p-lightpath can be considered as some protected flow. During normal operation, the flow is routed on a working lightpath or several working lightpaths routed on the same physical links. If any failure occurs on the working lightpath, the flow will be rerouted on link-disjoint backup lightpath(s), which also route on the same physical links. Note that one lightpath, no matter working or backup, uses one wavelength on each physical link it is routed on. In an MLR network, a working lightpath may be protected by several backup lightpaths, and a backup lightpath may serve more than one working lightpath. We will elaborate more on this aspect in the next section.

III. PROBLEM STATEMENT AND PROPOSED SCHEMES

A. Problem Statement

We are given the following inputs:

- A physical topology with nodes corresponding to the network nodes and links for the fiber between nodes.
- The number of wavelength channels carried by each fiber.
- The available line rates (i.e., 10/40/100 Gbps).
- The cost of the associated transponders at different rates.
- The traffic demands represented in a traffic matrix.
- k candidate p-lightpaths for each node pair, namely, the routing and rate feasibility of working and backup lightpaths.

Our goal is to route the traffic demands on the candidate p-lightpaths and assign rates and wavelengths to the working and backup lightpaths while minimizing 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 typical case of a fiber network with a fixed number of wavelengths per fiber.) The problem is a routing/wavelength/rate assignment (RWRA).

The constraints are (1) the physical-layer capacity constraint (i.e., the wavelength-clash constraint), where each wavelength on a physical link can be used by only one lightpath; (2) the logical-layer capacity constraint, where the total traffic of all connections routed on a lightpath must be bounded by its capacity; (3) the traffic demand between each source–destination pair must be supported; and (4) BER constraints, i.e., a lightpath can work only at rates where its BER is less than the threshold BER.

The steps to generate the preprocessed candidate p-lightpaths are as follows:
(1) Determine the routing of \(k\) candidate \(p\)-lightpaths between each \(s\)–\(d\) pair of the network. We use a \(k\)-shortest-paths algorithm to generate the \(k\) candidate working lightpaths for every \(s\)–\(d\) pair; then, for each working lightpath, we find the shortest path that shares no common physical link with it as its backup lightpath.

(2) Determine the rate feasibility of \(k\) candidate \(p\)-lightpaths. Calculate the BER for working and backup lightpaths of each candidate \(p\)-lightpath at all bit rates and check whether the calculated BERs are both less than a given threshold \(10^{-3}\) used in this study assuming an advanced modulation technique employing forward error correction (FEC). We say a \(p\)-lightpath is feasible at a rate \((r_w, r_b)\) only when the working lightpath is feasible at rate \(r_w\) and the backup lightpath is feasible at rate \(r_b\).

B. Proposed Schemes

We illustrate three schemes for dedicated protection in MLR networks via simple examples on the network in Fig. 2, where each edge corresponds to a bidirectional fiber.

1) MLR-at-p-Lightpath Protection (MLR-\(p\)): In MLR-\(p\), bit rates of the working and backup lightpaths of a \(p\)-lightpath are the same (we call this rate “the rate of the \(p\)-lightpath”), but the rates of different \(p\)-lightpaths can be different. In other words, rates are different at the \(p\)-lightpath level. We provide an example for the network in Fig. 2. Table I shows three candidate \(p\)-lightpaths from node 1 to 2; e.g., 1 \(\to\) 2 for No. 1 is the physical routing of the working lightpath; its feasible bit rates are 10, 40, and 100 Gbps. Let 80 Gbps traffic be routed on \(p\)-lightpath No. 1 from node 1 to 2; the rate of this \(p\)-lightpath must be 40 Gbps on the working and backup lightpaths, even if its working lightpath is feasible at 100 Gbps, because the rate of the backup lightpath carrying the traffic has to be equal to that of the working lightpath (i.e., the overall rate for a \(p\)-lightpath is fixed). The \(p\)-lightpath will consume two wavelengths for the working and backup lightpaths, as shown in Fig. 3(a).

2) MLR-at-Lightpath Protection (MLR-\(l\)): In the case of MLR-\(l\), the design flexibility is increased by allowing the working and backup rates in a \(p\)-lightpath to be different (i.e., rates are different at the lightpath level). It follows that, in order to carry the same flow, the number of working and backup lightpaths may be different. Let us consider the same previous example. Let 80 Gbps of traffic be routed on \(p\)-lightpath No. 1 from node 1 to 2. The maximum feasible rate of the backup lightpath is 40 Gbps, so we assign it 40 Gbps. While the maximum feasible bit rate of the working lightpath is 100 Gbps, we assign it 100 Gbps to take advantage of the volume discount. Thus, \(p\)-lightpath No. 1 has one working lightpath at 100 Gbps and two backup lightpaths, each at 40 Gbps, as shown in Fig. 3(b).

3) MLR-With-Backup-Flow-Grooming (MLR-\(g\)): Let us consider a third approach. Assume that physical links 1–3, 3–4, 1–5, and 5–4 now have only one free wavelength (this may happen when there is a lot of traffic in the network, leading to wavelength shortage), but still we need to serve 80 Gbps traffic from node 1 to 2. Using MLR-\(l\), the traffic cannot be totally put on any single \(p\)-lightpath in Table I, since it will take two wavelengths on links 1–3, 3–4, 1–5, and 5–4 now have only one free wavelength. Hence, one way to provision the traffic using MLR-\(l\) is to allocate half of the traffic on \(p\)-lightpath No. 2 and the other half on \(p\)-lightpath No. 3, as shown in Fig. 4(a). Now, the backup lightpaths of \(p\)-lightpaths No. 2 and No. 3 are both 1 \(\to\) 2. MLR-\(l\) chooses two backup lightpaths, each at 40 Gbps, although the maximum feasible rate of lightpath 1 \(\to\) 2 is 100 Gbps.

In MLR-\(g\), to minimize the cost of transponders, we explore the volume discount by grooming the backup traffic of different \(p\)-lightpaths. Here, we introduce the concept of a shared-backup-lightpath-group (SBLG). SBLG is a group of \(p\)-lightpaths whose backup lightpaths are exactly the same, so we can consider the backup lightpath as a single entity to protect flows on corresponding working lightpaths of the SBLG. In our example, the \(p\)-lightpaths No. 2 and No. 3 are a SBLG, whose backup lightpath 1 \(\to\) 2 protects flows on both working lightpaths 1 \(\to\) 3 \(\to\) 2 and 1 \(\to\) 5 \(\to\) 4 \(\to\) 2. As shown in Fig. 4(b), during normal operation in MLR-\(g\), traffic is carried over two working lightpaths, each at 40 Gbps, and if either of them fails, traffic will be rerouted on the backup lightpath, at 100 Gbps.
In brief, protection is taken care of per \( p \)-lightpath in MLR-\( p \). The backup lightpath of a \( p \)-lightpath is used to protect the flow on its working lightpath. But in MLR-\( g \), protection is taken care of per SBLG. The backup lightpath of a SBLG protects the flows on all the working lightpaths of that SBLG.

IV. TWO-STEP APPROACH

In our two-step approach, we solve the routing/rate assignment (RRA) and wavelength assignment (WA) problems separately and in sequence. The flow chart is shown in Fig. 5. First, we relax the wavelength-clash constraint to “the number of lightpaths routed on a physical link must be bounded by the number of wavelengths on that physical link.” In other words, the bound granularity changes from per wavelength to per physical link. This relaxation reduces the number of variables and constraints, so we can get results on reasonable study cases. Then, we solve the RRA via an ILP and use well-known WA approaches [16] (e.g., first-fit) to assign a wavelength to each lightpath. We also need to check whether the results of WA satisfy the wavelength-clash constraint, e.g., whether the number of wavelengths needed on each physical link to take the lightpaths generated from RRA exceeds the total number of wavelengths on the physical link. If it does, then we decrease the number of wavelengths on each link in the input by one and solve the RRA and WA again until we find a solution satisfying all the constraints.

A. RRA Mathematical Formulations

Models of RRA for MLR-\( p \), MLR-\( l \), and MLR-\( g \) follow.

Input parameters
- \( G(V,E) \): physical topology of the network with \( V \) nodes and \( E \) links
- \( W \): number of wavelengths on a link
- \( T = [\Lambda_{sd}] \): traffic matrix with aggregated demands \( \Lambda_{sd} \) in Gbps between an \( s \)-\( d \) pair
- \( R = \{r_1,r_2,...,r_\ell\} \): set of available bit rates
- \( D_\ell \): cost of a transponder at rate \( r_\ell \)
- \( L_{i,j,k} \): \( k \)th \( p \)-lightpath from node \( i \) to node \( j \)
- \( L_{i,j,k}^{w(b)} \): working (backup) lightpath of \( L_{i,j,k} \)
- \( l_{mn} \): physical link between nodes \( m \) and \( n \)
- \( P_{mn} \): set of lightpaths passing through link \( l_{mn} \)

Variables
- \( B \): threshold BER
- \( \text{BER}_{i,j,k}^{\text{w}(b)} \): BER of \( L_{i,j,k}^{w(b)} \) at rate \( r_\ell \)
- \( \alpha_{i,j,k}^{\ell} \): Boolean value to denote whether working lightpath \( L_{i,j,k}^{w} \) is feasible at rate \( r_\ell \):
  \[
  \alpha_{i,j,k}^{\ell} = \begin{cases} 
  1 & \text{if } \text{BER}_{i,j,k}^{\text{w}} < B \\
  0 & \text{otherwise} 
  \end{cases} \forall (i,j), k, \ell
  \]
- \( \beta_{i,j,k}^{\ell} \): Boolean value to denote whether backup lightpath \( L_{i,j,k}^{b} \) is feasible at rate \( r_\ell \):
  \[
  \beta_{i,j,k}^{\ell} = \begin{cases} 
  1 & \text{if } \text{BER}_{i,j,k}^{\text{b}} < B \\
  0 & \text{otherwise} 
  \end{cases} \forall (i,j), k, \ell
  \]
- \( SBL_{i,j,k} \): set of backup lightpaths that traverse the same physical links as \( L_{i,j,k}^{b} \)

Fig. 5. Flow chart of the two-step approach.
1) MLR-p

Objective:

\[
\text{Minimize: } \sum_{i,j,k} \sum_{\ell} 2W_{ij,k}^\ell D_{\ell}. \tag{1}
\]

Constraints:

\[
\sum_\ell r_\ell a_{ij,k}^\ell W_{ij,k}^\ell \geq \sum_{sd} f_{ij,k}^sd \quad \forall (i,j),k, \tag{2}
\]
\[
\sum_\ell r_\ell b_{ij,k}^\ell W_{ij,k}^\ell \leq W \quad \forall (m,n), \tag{3}
\]
\[
\sum_i \sum_k f_{ij,k}^sd - \sum_i \sum_k f_{ij,k}^sd = \begin{cases} -\Lambda_{sd} & \text{if } s = j \\ \Lambda_{sd} & \text{if } d = j \\ 0 & \text{otherwise} \end{cases} \quad \forall (i,j,k), \tag{4}
\]

Bounds:

\[
f_{ij,k}^sd \geq 0 \quad \forall (s,d),(i,j),k, \tag{5}
\]
\[
0 \leq W_{ij,k}^\ell \leq W \in \text{integer} \quad \forall (i,j),k, \ell. \tag{6}
\]

We consider a \( p \)-lightpath in MLR-p, where the number of its working lightpaths at rate \( r_\ell \) is the same as the number of its backup lightpaths at rate \( r_\ell \), i.e., \( W_{ij,k}^\ell = B_{ij,k}^\ell \). Thus, there is a factor of 2 in the objective function Eq. (1) when computing the sum of the transponder cost. The \( a_{ij,k}^\ell \)'s (\( b_{ij,k}^\ell \)'s) determine whether the working (backup) lightpath \( W_{ij,k}^\ell (B_{ij,k}^\ell) \) is feasible at rate \( r_\ell \) (i.e., respect the BER threshold). In Eqs. (2) and (3), the multiplication of \( W_{ij,k}^\ell \) with \( a_{ij,k}^\ell \) and \( b_{ij,k}^\ell \) refers to the fact that only those variables are present in the summations for which the combination of \( i,j,k \), and \( \ell \) yields \( a_{ij,k}^\ell = 1 \) and \( b_{ij,k}^\ell = 1 \). Equations (2) and (3) set the capacity constraints at the logical and physical layer. Equation (4) satisfies the flow-conservation constraint. The bounds of the variables are written as Eqs. (5) and (6).

2) MLR-I:

Objective:

\[
\text{Minimize: } \sum_{(i,j)} \sum_k \sum_\ell (W_{ij,k}^\ell + B_{ij,k}^\ell) D_{\ell}. \tag{7}
\]

Constraints:

\[
\sum_\ell r_\ell a_{ij,k}^\ell W_{ij,k}^\ell \geq \sum_{sd} f_{ij,k}^sd \quad \forall (i,j),k, \tag{8}
\]
\[
\sum_\ell r_\ell b_{ij,k}^\ell B_{ij,k}^\ell \geq \sum_{sd} f_{ij,k}^sd \quad \forall (i,j),k, \tag{9}
\]
\[
\sum_{L_{ij,k}^w} \sum_\ell a_{ij,k}^\ell W_{ij,k}^\ell + \sum_{L_{ij,k}^b} \sum_\ell b_{ij,k}^\ell B_{ij,k}^\ell \leq W \quad \forall (m,n), \tag{10}
\]
\[
0 \leq B_{ij,k}^\ell \leq W \in \text{integer} \quad \forall (i,j),k,\ell. \tag{11}
\]

In MLR-I, the rates of working and backup lightpaths in a \( p \)-lightpath can be different, so, to carry the same amount of traffic, the numbers of wavelengths used by working and backup lightpaths can be different, which are denoted by \( W_{ij,k}^\ell \) and \( B_{ij,k}^\ell \). The objective function in Eq. (7) computes the overall cost of transponders, used by both working and backup lightpaths. In Eqs. (8), (9), and (10), multiplication of \( W_{ij,k}^\ell \) with \( a_{ij,k}^\ell \) refers to the fact that only those variables are present in the summations for which the combination of \( i,j,k \), and \( \ell \) yields \( a_{ij,k}^\ell = 1 \), and similarly for \( b_{ij,k}^\ell \). Equations (8) and (9) set the capacity constraints for working and backup lightpaths, respectively. Equation (10) is the physical-layer capacity constraint where the wavelength-clash requirement is relaxed. The flow-conservation constraint is the same as Eq. (4). The bounds of variables are in Eqs. (5), (6), and (11).

3) MLR-g:

In MLR-g, given \( SBL_{ij,k} \), we know which \( p \)-lightpaths form a SBLG. For instance, in the example of Subsubsection III.B.3, \( SBL_{1,2,3} = L_{1,2,2} \), so we know \( p \)-lightpaths No. 2 and No. 3 form a SBLG. The objective function, capacity constraint for working lightpaths, wavelength-clash constraint, flow-conservation constraint, and bounds of variables are the same as in MLR-I. The only difference is the capacity constraint for backup lightpaths: it is taken care of per SBLG as in Eq. (12), instead of per \( p \)-lightpath in Eq. (9):

\[
\sum_\ell r_\ell B_{ij,k}^\ell \beta_{ij,k}^\ell + \sum_{sd} \sum_\ell r_\ell B_{ij,k}^\ell \beta_{ij,k}^\ell' \geq \sum_{sd} f_{ij,k}^sd \quad \forall (i,j),k. \tag{12}
\]

B. WA Heuristic

After solving RRA, we use a typical WA approach (e.g., first-fit) to assign a wavelength to each lightpath. In first-fit [16], all wavelengths are numbered. When searching for available wavelengths, a lower-numbered wavelength is considered before a higher-numbered wavelength. The idea is to pack all of the in-use wavelengths to the lower end of the wavelength space so that continuous longer paths at the higher end of the wavelength space will have a higher probability of being available.

After we assign wavelengths, we check whether the number of wavelengths needed on each link to take the lightpaths generated from RRA exceeds \( W \) (number of wavelengths on a fiber link). If it does, then we decrease \( W \) by 1, which means \( W \) in Eqs. (3) and (10) will be decreased by 1. Then we solve WA and RA again, until we find a solution satisfying all the constraints (as shown in Fig. 5).

C. Comparison Between Three Approaches

The complexity of the ILP formulations is shown in Table II, where \( N \) is the number of nodes, \( L \) is the number of physical links, \( K \) is the number of candidate \( p \)-lightpaths between each node pair, and \( R \) is the number of different data rates. Each scheme has its own pros and cons, addressing the trade-off between performance and complexity. The more the
variables and constraints in the ILP formulations, the longer the time it takes for our ILP solver (CPLEX) to get the result. Thus, as shown in Table II, MLR-p wins in terms of computational complexity. As for cost reduction (which will be revealed in Section VI), MLR-p does not achieve as much savings as the other two schemes, while such comparison offers us the chance to quantify how much more savings we can attain by allowing rate flexibility between working and backup lightpaths. MLR-g allows the backup traffic to be groomed on the same lightpaths and gives the network design more flexibility in a global manner. Thus, it utilizes the capacity resources more efficiently and achieves better results compared to MLR-p and MLR-l. But it takes more time to solve the equations of MLR-g than MLR-l because the capacity constraint for backup lightpaths in MLR-g (Eq. (12)) is more complex than that in MLR-l (Eq. (9)). Thus, MLR-l addresses a good trade-off between performance and complexity, achieving a significant cost reduction and being solved in a reasonable time.

The ILP formulations have very high computation time (approximately 2 to 5 h on ILOG CPLEX 10.0 running on an Intel Core2 Duo CPU, with 2.16 GHz processor speed and 4 Gbytes of random-access memory (RAM)) for the 14-node network in Fig. 1, and it is not solvable for networks with larger size. Thus, for more general networks, we need to employ a heuristic method, which can scale with network size.

V. HEURISTIC APPROACH

We propose a heuristic for MLR-l, which is a good trade-off between the complexity and ability to achieve relevant cost savings. The heuristic is shown in Algorithm 1. First, we give a high-level idea of the algorithm. We sort the demands in a particular order and process them one by one. Initially (i.e., when we process the first traffic demand), we set up new lightpaths. The heuristic is shown in Algorithm 1. First, we give a high-level idea of the algorithm. We sort the demands in descending order, so the selected demand \( \Lambda_{sd} \) is the demand with the maximum feasible rate of the working and backup lightpaths feasible at a certain rate. Essentially, we try to route demands on the lightpaths of which the maximum feasible rates of the working and backup lightpaths are high, so that we have more chances to reduce the network cost by exploring the volume discount of transponders at high bit rates and to avoid wavelength exhaustion when handling a lot of demands. After satisfying some demands, there may be some free capacities on the lightpaths that are already set up. Free capacity of a lightpath is defined as the smaller free capacity on the working and backup lightpaths. We use a logical topology \( G_l \) to keep track of such available free capacities and add a directional edge \((i,j)\) with capacity \(C_{(i,j)}\) into \(G_l\) if there is free capacity \(C_{(i,j)}\) on a lightpath from \(i\) to \(j\). For each following demand, we first try to find a route in \(G_l\). If we can, there is no need to set up new lightpaths for the demand; if we cannot find such a route, then we construct a new auxiliary graph \(G_A\) and find a route in \(G_A\). Note that, throughout the algorithm, we use and update only one logical topology \(G_l\), while a new auxiliary graph \(G_A\) is constructed each time we need to set up a new lightpath for some traffic demand.

<table>
<thead>
<tr>
<th>Approach</th>
<th># of variables</th>
<th># of constraints</th>
</tr>
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<tbody>
<tr>
<td>MLR-p</td>
<td>(\eta \cdot K \cdot R + \eta^2 \cdot K)</td>
<td>(\eta \cdot K \cdot L + \eta \cdot N)</td>
</tr>
<tr>
<td>MLR-l</td>
<td>(2\eta \cdot K \cdot R + \eta^2 \cdot K)</td>
<td>(2\eta \cdot K \cdot L + \eta \cdot N)</td>
</tr>
<tr>
<td>MLR-g</td>
<td>(2\eta \cdot K \cdot R + \eta^2 \cdot K)</td>
<td>(2\eta \cdot K \cdot L + \eta \cdot N)</td>
</tr>
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Algorithm 1: MLR Survivable Network Design.

1: Initialize the logical topology \(G_l = (V, E_l)\) with \(V\) correspondingly to the network nodes and \(E_l = \emptyset\)
2: while there is non-zero demand in \(T\) do
3: sort the demands in \(T\)
4: select first demand \(\Lambda_{sd}\) in traffic-processing sequence
5: run min-hop in \(G_l\) for \(\Lambda_{sd}\)
6: if min-hop path with free capacity \(C_{free}\) exists then
7: groom \(\Lambda_{sd}\) as much as possible onto the path
8: update \(\Lambda_{sd}\) and \(G_l\)
9: else
10: construct an auxiliary graph \(G_A\) for \(\Lambda_{sd}\)
11: while there is no min-hop route \(r\) in \(G_A\) from \(s\) to \(d\) do
12: construct another auxiliary graph \(G_{A}\)
13: if the current \(G_A\) constructed is the same as the previous one then
14: stop the algorithm and return -1
15: end if
16: end while
17: for each hop \((i,j)\) in the \(r\) do
18: pick a \(p\)-lightpath from the candidates
19: assign rate to the \(p\)-lightpath
20: if there is free capacity on the \(p\)-lightpath then
21: add a directional edge from \(i\) to \(j\) with the corresponding free capacity in \(G_l\)
22: end if
23: end for
24: end if
25: end while

Now, we describe the algorithm. Notations of input and objective are the same as in Section IV. Initially, there is no edge but only nodes in \(G_l\). As we process each demand, edges may be added in \(G_l\) when new lightpaths are set up. Line (3) generates a traffic-processing sequence, which may affect optimization. Here, we sort the demand set in descending order, so the selected demand \(\Lambda_{sd}\) is the demand with the largest amount of traffic among those that have not yet been satisfied. For a better result, multiple sequences can be tried, and the best one will be chosen. For each demand, we first try to find it a route in \(G_l\). If we can find a min-hop path with some free capacity \(C_{free}\) from \(s\) to \(d\) in \(G_l\), we groom the traffic demand as much as possible onto the path; i.e., if \(C_{free}\) is no less than \(\Lambda_{sd}\), then the entire demand can be groomed onto the path; if not, \(C_{free}\) traffic will be groomed. After grooming, the traffic demand is updated, as well as \(G_l\): the free capacities of the lightpaths on the min-hop path are decreased and if an updated free capacity is zero, the corresponding edge in \(G_l\) will be removed.

If there is no path from \(s\) to \(d\) in \(G_l\), we will construct auxiliary graph(s) to find a route for \(\Lambda_{sd}\). Now, we discuss
how we construct the auxiliary graph depending on the traffic demand. In an auxiliary graph $G_A$, each edge represents a $p$-lightpath feasible at certain rates. The most important thing is to decide what feasible rates each edge represents. In our algorithm, this relates to $\Lambda_{opt}$. We divide traffic demands into several ranges: $0 \sim B_1, B_1 \sim B_2, \ldots$ (where $B_i$ is the bound of a range). For each range, we associate it with a set of candidate rates $\{CR_1, CR_2, \ldots\}$, and $CR_1 > CR_2 > \ldots$. The basic idea is to try to use $p$-lightpaths with higher feasible rates so that we can benefit from the volume discount of the transponder cost and avoid wavelength exhaustion when dealing with a lot of demands. First, we construct a $G_A$ in which each edge represents a $p$-lightpath feasible at $CR_1$. If we can find a path from $s$ to $d$ in $G_A$, we will use this path to satisfy the demand; otherwise, we construct another auxiliary graph in which each edge represents a $p$-lightpath feasible at $CR_1$ or $CR_2$. If still we cannot find a path, we construct another auxiliary graph where each edge represents a $p$-lightpath feasible at $CR_1$ or $CR_2$ or $CR_3$ and so on, until we find a path for the demand. In our setting, if $B_i > B_j$, then the first candidate rate ($CR_j$) for demand range $B_{j-1} \sim B_j$ is larger than or equal to that of $B_{j-1} \sim B_j$. Thus, for a larger traffic demand, we associate it with higher candidate rates. For example, it is reasonable to assign 80 Gbps traffic with a path feasible at 100 Gbps, but may not be cost effective to assign 5 Gbps traffic with a path at 100 Gbps since the 95 Gbps free capacity may not be used by other demands, resulting in bandwidth wastage. Note that, if the current $G_A$ is the same as the previous one we just constructed, which means we tried all possible auxiliary graphs but still cannot find a route for the traffic demand, then we stop the algorithm and fail to provision this traffic matrix.

Assume that, till we try $CR_2$, we can find a route $r$ in the auxiliary graph. For each hop on $r$, a $p$-lightpath will be assigned to carry the demand. We choose a $p$-lightpath from the $k$ candidates such that it is feasible at any rate from the set $\{CR_1, CR_2, \ldots, CR_k\}$. If more than one candidate satisfies this requirement, then we choose one based on load balancing: we do not pick a $p$-lightpath whose physical links have already taken a lot of wavelengths. If the selected $p$-lightpath is feasible at only one rate from the set, we assign it this rate; if it is feasible at more than one rate from the set, we randomly choose one as its rate. After satisfying the demand, if there is some free capacity on the $p$-lightpath, we add a directional edge with the corresponding free capacity in $G_I$.

To demonstrate the heuristic, we use a simple example on the six-node network in Fig. 2. For each node pair in the network, we consider only one candidate $p$-lightpath, of which the routing and feasible rates are shown in Table III. Assume we have three traffic demands, as shown in Table IV. After sorting the traffic, we first select $\Lambda_1$: 60 Gbps traffic from node 1 to 4. Now, there is no edge in the logical topology $G_I$, and since $\Lambda_1$ is between 40 Gbps and 100 Gbps, we first try to construct an auxiliary graph $G_A$ for $\Lambda_1$ where each edge in $G_A$ corresponds to a $p$-lightpath with working and backup lightpaths both feasible at 100 Gbps (see Fig. 6(a)). The min-hop path in $G_A$ for $\Lambda_1$ is the direct link from node 1 to 4, which is the dotted line. Thus, we set up this $p$-lightpath with working and backup lightpaths, both at 100 Gbps. After satisfying $\Lambda_1$, there is a 40 Gbps free capacity on the $p$-lightpath. Thus, we add an edge with a capacity of 40 Gbps from node 1 to 4 in $G_I$ (see Fig. 6(b)).

Then for $\Lambda_2$, we cannot find a route in $G_I$, so we construct another auxiliary graph for it. $\Lambda_2$ is between 10 Gbps and 40 Gbps, so in the new auxiliary graph, each edge corresponds to a $p$-lightpath with working and backup lightpaths feasible at 40 Gbps (see Fig. 7(a)). The min-hop path for $\Lambda_2$ is the direct link from node 4 to 6, which is the dotted line. Thus, we set up this $p$-lightpath with working and backup lightpaths, both at 40 Gbps. After satisfying $\Lambda_2$, there is 20 Gbps free capacity on the $p$-lightpath. Thus, we add an edge with capacity 20 Gbps from node 4 to 6 in $G_I$ (see Fig. 7(b)).

For $\Lambda_3$, we can find a route in Fig. 7(b) that goes from node 1 to 4 and then to node 6. After we satisfy $\Lambda_3$, $G_I$ is updated: the link from node 1 to 4 now has a free capacity of 30 Gbps, and the link from node 4 to 6 has a free capacity of 10 Gbps.

### VI. Results and Discussions

We first consider the pan-European network topology COST239 (Fig. 8) and a traffic matrix (Table V), which sums...
Cost reduction of MLR approaches compared to 100G-SLR

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7.png}
\caption{(Color online) Graphs used in the algorithm related to $\Lambda_2$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig8.png}
\caption{COST239 network (link lengths in km).}
\end{figure}

\begin{table}[h]
\centering
\caption{Traffic Matrix for COST239 (in Gbps)}
\begin{tabular}{cccccccccccc}
\hline
\textbf{Node} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \\
\hline
1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 0 & 5 & 8 & 4 & 1 & 1 & 10 & 3 & 2 & 3 \\
3 & 1 & 1 & 5 & 0 & 8 & 4 & 1 & 1 & 5 & 3 & 1 \\
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 & 1 & 0 & 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 & 11 & 2 & 3 & 0 & 3 & 0 \\
11 & 1 & 3 & 2 & 9 & 2 & 1 & 1 & 5 & 6 & 3 & 0 \\
\hline
\end{tabular}
\end{table}

We compare the results of our heuristic with the two-step ILP-based approach. Table VI reports the cost, in terms of transponders, and three MLR networks, running MLR-$p$, MLR-$l$, and MLR-$g$. When a table entry is empty, it means the network is unable to carry the load. As expected, the MLR approaches can carry more traffic and achieve significant cost reduction (up to 48%) compared to SLR. The network, if equipped only with 10 Gbps or 40 Gbps transponders, cannot carry traffic larger than 10X and 35X, respectively, because of the limited number of wavelengths. When the traffic is low (e.g., less than 10X), there is no difference between the costs of the MLR approaches, since most $p$-lightpaths carry the same flows along their working and backup lightpaths. Figure 9 shows the cost reduction in percentage of MLR approaches compared to SLR with only 100G transponders. In general, the reduction becomes more significant as traffic grows. MLR-$p$ has rate limitations on working and backup lightpaths, so it saves less compared to MLR-$l$ and MLR-$g$, and the cost reduction also drops a little when the traffic demands are very high (i.e., 45X and 50X). MLR-$g$ achieves better results than MLR-$l$. We find that typically there are only one or two SBLGs in the results while the normalized cost reduction of MLR-$g$ compared with MLR-$l$ can be as high as 15 (for 50X traffic load). Therefore, MLR-$g$ performs better not only by grooming backup traffic when possible but also by giving the network design more flexibility in a global manner.

We compare the results of our heuristic with the two-step ILP. Since there is randomization in rate assignment, we run our algorithm for many (i.e., 200) times and take the best result. Typically, it takes less than 2 min for 200 runs, which is much faster than the running time of the ILP.
running time of the ILP is shown in Table VII). Table VIII shows the comparison of results between the ILP and heuristic approaches for MLR-I and their difference in percentage. All the heuristic results are within 15% of the ILP results, and most of them are within 10%. For medium and large numbers of connection requests (more than 10X), the results are very close.

The heuristic approach is much more scalable than the ILP-based approach even though both are solvable for the COST239 network. Now we also present, using our heuristic, the illustrative results for a larger-scale network, the 24-node US backbone network (Fig. 10) with the same base traffic matrix as used in [4], which adds up to 1 Tbps of aggregate traffic. We generate different aggregate traffic by multiplying the traffic matrix with different multiplying factors. Figure 11 shows the normalized cost for the 24-node US backbone network equipped with 10 Gbps transponders and three MLR transponders, it cannot carry more than 1.3X because few lightpaths are feasible at high bit rates. The cost savings of the MLR approaches from the SLR network increase as the traffic load increases (from 2.2% for 0.2X traffic load to 17.3% for 1.2X).

Table IX reports the cost in terms of transponders for a SLR network equipped with 10 Gbps transponders and three MLR networks using the two-step ILP. Due to the characteristics of the network topology, the differences between the three MLR approaches are trivial. The network with only 10 Gbps transponders cannot carry traffic larger than 1.3X because few lightpaths are feasible at high bit rates. The cost savings of the MLR approaches from the SLR network increase as the traffic load increases (from 2.2% for 0.2X traffic load to 17.3% for 1.2X).

Consider a logical topology where each edge \((i, j)\) represents a \(p\)-lightpath from \(i\) to \(j\) of which the working and backup lightpaths are both feasible at 40 Gbps. If we construct such a topology for Fig. 12 based on BER calculations, we will find that it is not connected, which means that, for some node, there

<table>
<thead>
<tr>
<th>Traffic</th>
<th>Two-step approach</th>
<th>Heuristic approach</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1X</td>
<td>97.5</td>
<td>112.25</td>
<td>12.05%</td>
</tr>
<tr>
<td>5X</td>
<td>240</td>
<td>264.5</td>
<td>10.2%</td>
</tr>
<tr>
<td>10X</td>
<td>397.25</td>
<td>435</td>
<td>9.5%</td>
</tr>
<tr>
<td>15X</td>
<td>545.25</td>
<td>580.75</td>
<td>6.51%</td>
</tr>
<tr>
<td>20X</td>
<td>720</td>
<td>763</td>
<td>6.4%</td>
</tr>
<tr>
<td>25X</td>
<td>866.5</td>
<td>895.25</td>
<td>3.97%</td>
</tr>
<tr>
<td>30X</td>
<td>1024.5</td>
<td>1068.5</td>
<td>4.35%</td>
</tr>
<tr>
<td>35X</td>
<td>1182</td>
<td>1208.75</td>
<td>2.26%</td>
</tr>
<tr>
<td>40X</td>
<td>1341.75</td>
<td>1352.5</td>
<td>0.88%</td>
</tr>
<tr>
<td>45X</td>
<td>1503</td>
<td>1522.25</td>
<td>1.38%</td>
</tr>
<tr>
<td>50X</td>
<td>1659.5</td>
<td>1676.5</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

Fig. 10. 24-node US backbone network (link lengths in km).

Fig. 11. (Color online) Normalized cost for 24-node US network obtained by the heuristic approach.

Fig. 12. (Color online) Modified 14-node NSFNET (link length in km).
is no p-lightpath feasible at 40 Gbps connecting it with any other node, leading to protection infeasibility. This is why we do not have results for SLR 40 Gbps or for SLR 100 Gbps. Also, this confirms that a MLR network enables a survivable, cost-efficient, and flexible network design.

VII. Conclusion

In this study, we have proposed and investigated three novel approaches to design cost-effective MLR networks that provide dedicated protection. We presented two approaches to solve the problem: an ILP-based approach, which addressed the constraints in linear equations, and a heuristic approach, which can give results in a much shorter time and is close to the results given by ILP approaches. We showed how the MLR network cost scales in a more efficient manner for increasing traffic compared to SLR networks. Our study showed that we can design cost-effective MLR survivable networks by intelligent assignment of bit rates to the lightpaths while satisfying all the traffic demands. Future research should address other protection schemes (e.g., shared protection) and a dynamic version of this problem considering protection and restoration.

Acknowledgments

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References


TABLE IX
Normalized Cost for Modified NSFNet Using the Two-Step Approach (X = 1 Tbps)

<table>
<thead>
<tr>
<th>Traffic</th>
<th>10G</th>
<th>MLR-p</th>
<th>MLR-l</th>
<th>MLR-g</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2X</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>88</td>
</tr>
<tr>
<td>0.4X</td>
<td>164</td>
<td>150.5</td>
<td>150.5</td>
<td>150.5</td>
</tr>
<tr>
<td>0.6X</td>
<td>236</td>
<td>211</td>
<td>211</td>
<td>209.25</td>
</tr>
<tr>
<td>0.8X</td>
<td>314</td>
<td>273</td>
<td>269</td>
<td>267</td>
</tr>
<tr>
<td>1X</td>
<td>384</td>
<td>335.5</td>
<td>334.5</td>
<td>332</td>
</tr>
<tr>
<td>1.2X</td>
<td>488</td>
<td>403.5</td>
<td>400</td>
<td>395.25</td>
</tr>
<tr>
<td>1.3X</td>
<td>–</td>
<td>473</td>
<td>456.25</td>
<td>456.25</td>
</tr>
</tbody>
</table>