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A Comparative Study on the Effect of Strategy Selection on Shared Backup in WDM MLR Optical Networks

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ABSTRACT Design of shared backup algorithm in wavelength division multiplexed (WDM) mixed line rate (MLR) optical networks involves numerous attributes together with numerous heuristic alternatives. This study aims at identifying the pros and cons of these alternatives together with examining their performances. For this purpose, performance metrics that characterize sharing are first developed. Joint performance of shared backup metrics and other already existing network metrics is examined extensively throughout simulations. Among the strategies examined, the ones that yield best results are reported. Moreover, the topological dependence of these chosen strategies is discussed by simulations carried out on two popular characteristically different optical networks.

INDEX TERMS MLR, optical WDM networks, routing, rate and wavelength assignment (RRWA), shared backup protection, survivable communication.

ABBREVIATIONS

BBR	Bandwidth Blocking Ratio
BER	Bit Error Rate
BFS	Breath First Search
CGS	Coarse Grain Scalable
DB	Dedicated Backup
DPC	Dedicated Protection Capacity
EON	European Optical Network
FF	First Fit
FGS	Fine Grain Scalable
FSC	Fixed Sharing Capacity
ILP	Integer Linear Program
IMUX	Inverse Multiplexing
LC	Least Cost
LU	Least Used
LUR	Lightpath Utilization Ratio
MHN	Multi-Hop New Lightpath Establishment
MHSB	Multi-Hop Shared Backup
MHTG	Multi-Hop Traffic Grooming
MLR	Mixed Line Rate
MOPT	Multiobjective optimization
OXC	Optical Cross-connect
PAC	Protection at Connection Level
PAL	Protection at Lightpath Level
QoT	Quality of Transmission
RRWA	Routing Rate and Wavelength Assignment
RWA	Routing and Wavelength Assignment
SB	Shared Backup
SGR	Shared Gain Ratio
SHN	Single-Hop New Lightpath Establishment
SHSB	Single-Hop Shared Backup
SHTG	Single-Hop Traffic Grooming
SLR	Single Line Rate
SPC	Shared Protection Capacity
SRG	Shared Risk Group
SRRWA	Survivable Routing Rate and Wavelength Assignment
TCC	Total Communication Cost
TR	Transmission Reach
WDM	Wavelength Division Multiplexing

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I. INTRODUCTION

With increasing number of users and increasing amount of diversifying data sharing patterns, the need for high-speed communication networks has emerged. Communication networks must service diverse variety of traffic requests that have different requirements. As being one of the most popular technologies, optical networks employing wavelength division multiplexing (WDM) on fibers are suitable to support this need by the help of their high transmission capability [1]. This capacity is obtained by means of high capacity of WDM channels (e.g. 100 Gbps and beyond) and large number of wavelengths (e.g. 80 wavelengths with 50 GHz channel spacing in C band).

In wavelength routed networks, a lightpath is an optical data transmission channel which occupies a single wavelength along its predefined path [2]. Connections are established for all traffic requests through lightpaths. The selection of the physical path and wavelength of a lightpath is known as routing and wavelength assignment (RWA) problem [3] and it is proved to be NP-complete [4].

For network design, the selection of transponders to be deployed, thus the selection of line rate, is a vital decision. Higher line rates are favored for their high transmission speeds thus higher capacities. However, the higher the line rate, the higher the effects of physical impairments in long distances. Thus, signal quality degrades dramatically as distance becomes longer. This quality degradation leads to increased bit-error rate (BER) [5]. Thus, for a given modulation format, due to higher impairments, higher rate transmissions have a shorter reach than that of lower rate transmissions [6]. This creates a trade-off between line rate of a signal and its transmission reach (TR). TR is defined as the distance which an optical signal can travel before its quality degrades and its bit error rate increases to an unacceptable level [6]. In single line rate (SLR) network design, this trade-off must be evaluated according to predetermined BER threshold for signal quality. However, mixed line rate (MLR) optical networks are more flexible and enable the usage of various line rates simultaneously. Optical networks with MLR support offer this flexibility by routing traffic requests in cost effective manner [7], [8], [1]. Their ability to choose appropriate line rate dynamically for each traffic request relaxes the network design limitations faced in SLR networks and decreases the overall transmission cost by using the volume discount [1] of high bit rate transponders. MLR networks can support 10/40/100 Gbps capable transponders. Experimentally 400 Gbps and 1 Tbps line rates are also achieved and expected to be industrially used within several years [9]. The well-known RWA problem gains rate allocation feature in MLR optical networks and it is called as routing, rate and wavelength allocation (RRWA) problem.

In MLR networks, crosstalk is another issue that degrades the signal quality. The signals in transmission along neighboring wavelengths using different modulation formats or line rates face crosstalk that decreases the signal quality and thus TR. This property complicates the solution. There are significant works in literature that study the factors affecting signal quality of different line rates and propose solutions to reduce the complexity of impairment aware routing problem [10]–[12].

Even though, there are many factors that affect the signal reach, such as the launched power of the signal, the modulation format, the bit rate, the type of the amplification, the dispersion map, the interference from other signals, and the like [6], for the sake of simplicity, in this work, we will consolidate all of these factors to TR to calculate their feasible line rates.

In case of a failure, the high capacity of an optical link may lead to a loss of huge amount of data. To avoid or minimize such a loss, fast fault recovery mechanisms are needed. Survivability is the ability of a network to continue its functioning even in presence of failures of network components [13], such as the loss of a physical link causing loss of all of its wavelengths. To maintain survivability, the resources assigned to connections must have backups to be used in case of failure. Suitable protection and restoration methods are developed in literature [2], [9]. In protection schemes, to react to failures faster, the backup resources of a connection are preconfigured at the time of connection establishment. On the other hand, reactive restoration schemes are more resource-efficient than proactive backup reservation policies since they dynamically explore backup resources in case of failure and do not reserve capacity in advance. Protection methods may use dedicated backup resources for each connection or may share resources among different connections. Studies of survivable networks show that sharing backup resources offer higher resource utilization efficiency [13] than dedicated schemes, however, their design is more complex and their response is slower. Optimal survivable design turns out to be a more complex problem in MLR optical networks since there are many criteria to be considered [9], [13] especially with shared backup protection. With survivability issue, RRWA problem turns into well-known survivable routing with rate and wavelength assignment (SRRWA) problem.

During resource allocation for a traffic request, as well as establishing a new lightpath, traffic grooming may be used when there is idle capacity on the existing lightpaths that satisfy the requirements of the connection. Traffic grooming is the aggregation of sub-rate traffic onto high bit rate lightpaths for efficient resource utilization [14].

In case where there are no available end-to-end resources, multi hop methods where more than one lightpath (sequence of sub-paths) is established for a traffic request. Clearly, this will increase the number of transponders used hence the overall cost. All these methods are called path establishment methods. It is observed that the priorities of path establishment methods have significant effect over routing performance [15]. In some literature, ''RWA problem with grooming'' is named as ''grooming, routing and wavelength assignment (GRWA) problem'' [16], [17].

In this study, the major factors that affect solution of the SRRWA problem are addressed in MLR WDM optical networks. To be able to study the precedence relations among a number of heuristics, a shared backup path protection algorithm is developed. The focus is on improving the network performance metrics such as communication cost and traffic blocking ratio. By choosing appropriate resource allocation schemes, backup sharing performance is improved.

The performances of the proposed strategies are compared with dedicated backup path protection strategy through simulations. The results show that there is a strict relation between strategy selection and resource utilization performance. Although there are numerous works on SRRWA problem [1], [2], [14], [18]–[22], to the best of our knowledge, there is no work that compares different strategies to improve sharing performance in MLR networks.

The sections of the paper are as follows: In section 2, a brief survey of related work is given together with capabilities and drawbacks of the algorithms developed in the literature. In section 3, the requirements and constraints of SRRWA problem and sharing backup strategy are discussed after which our algorithm is presented. In section 4, we present the resource allocation strategies of our algorithm with their effects on solution. Section 5 presents performance and cost analysis of our algorithm. Finally, section 6 contains concluding remarks.

II. RELATED WORK

The first works in literature are on the problem of SLR RWA problem. Since the proposed solutions of SLR RWA are closely related to the generalized problem of SRRWA with or without grooming, we will first summarize these works. Reference [14] proposes an auxiliary-graph based approach for the problem of survivable traffic grooming and regenerator placement on single line rate (SLR) networks with protection-at-connection (PAC) for dedicated and shared protection. While PAC provides end-to-end protection with respect to connection, protection-at-lightpath (PAL) provides end-to-end protection with respect to lightpath [2]. Simulation results show that PAC outperforms PAL and shared connection-level protection achieves lower cost and longer restoration time than its dedicated counterpart. Reference [20] investigates the tradeoff between cost and capacity of a method cross-connecting predeployed protection subconnections on SLR backbone networks that uses a strategy where a subset of the nodes was selected as protection hubs. The results show that as the number of protection hubs increases together with the number of required transponders, the required capacity to accommodate the traffic decreases.

Reference [23] investigates routing, wavelength assignment and regenerator allocation in translucent optical networks. They present an impairment aware RWA (IA-RWA) algorithm considering several parameters to efficiently choose the optimal utilization of available regenerators of the network to serve online traffic. They propose a framework to evaluate different optimization policies along with selecting the optimal path from a set of paths. The results indicate that, to efficiently serve the online traffic, IA-RWA algorithm has to consider all parameters, i.e., the quality of transmission (QoT) of the lightpaths, the utilization of wavelengths and the availability of regenerators.

Reference [24] proposes to share backup resources against dual link failures. They extend the spare capacity allocation (SCA) algorithm [25] to dual link failures on mesh-like IP or WDM networks, where each connection is associated with three mutually link disjoint paths: a working path, and two pre-determined backup paths. Through simulations, backup paths with shared spare capacity and backup paths with dedicated capacity are compared. Numerical results show that the network redundancy of the dedicated path protection is high while complexity increases in shared backup path protection. Results also show that, hybrid path protection having dedicated primary backup paths and shared secondary backup paths provides intermediate redundancy with the moderate complexity.

Reference [26] introduces multiple working routes and backup routes per traffic request to develop multi-flow shared backup path protection (SBPP) models. They propose a new multi-flow SBPP ILP design model and developed an algorithm to analyze network overall availability for multi-flow SBPP networks.

The first works in MLR investigate the efficiency of the method as compared to SLR. Reference [1] proposes one heuristic and three ILP based approaches to design cost effective transparent MLR networks using dedicated protection. From the results, it is observed that MLR approaches yield lower cost than SLR networks, especially when backup traffic is groomed. Survivability in MLR networks attracted exclusive attention and complexity of the problem forced researchers to either heuristics development or ILP based approaches. Reference [2] investigates survivability of optical WDM networks and proposes various ILP and heuristic-based protection schemes. Reference [7], proposes a cost-effective approach to design an MLR network with transmission-range (TR) constraint. They claim that, by intelligent assignment of channel rates to lightpaths, based on their TR constraint, the need for signal regeneration can be minimized, and a transparent optical network can be designed to support all-optical end-to-end lightpaths.

Reference [18] investigates load intensity fluctuations of daily traffic and proposes a new dynamic line rate assignment heuristic using PAL shared protection SRRWA for dynamic traffic on transparent MLR networks. Comparison results show that the proposed strategy has an average performance while the highest resource utilization and lowest cost values are obtained from the static rate matching [5] line rate assignment method. Reference [19] investigates survivable traffic grooming problem for transparent MLR networks and proposes an ILP-based shared subconnection protection (SSP) approach and compares it with conventional dedicated and shared backup on both SLR and MLR networks. The results emphasize that MLR network with shared protection improves survivable, cost efficient, and flexible network design.

Reference [21] investigates the impairment-aware lightpath provisioning problem in MLR networks using inverse multiplexing technique. It proposes three path finding and two wavelength assignment algorithms and compares the results of six different schemes formed by combining these approaches. While each scheme has an outperforming metric against others, the main observation of the work is that employing inverse multiplexing uses more wavelength links to accommodate the same amount of request, which leads to a decrease in resource utilization. Reference [6] considers RRWA problem and presents cross-rate interference aware algorithms for planning transparent and translucent MLR WDM optical networks. They use an effective length metric to formulate the adaptive reach planning problem. Their algorithms assign wavelengths to lightpaths so as to reduce or avoid cross-rate interference, enabling the establishment of more connections of acceptable quality.

Reference [22] proposes a dynamic resilience approach which minimizes the total amount of bandwidth used for working and protection lightpaths. Their simulation results indicate that their method is more efficient in terms of network resource utilization and blocking probability when compared with conventional protection and restoration schemes. Reference [27] introduces the operation of a simple MLR transponder having two bit-rate options (100/200 Gbps) and proposes a rate-adaptive shared protection scheme for opaque optical networks. They proposed a MLR transponder to be operated at lower rate to handle working capacity and to be temporarily tuned to higher rate to support protection capacity in case of failure. Their results show that their protection scheme is more cost and power efficient compared to the traditional one.

Reference [28] investigates the effect of channel spacing on the quality of signals for MLR WDM optical networks. While decreasing the spacing leads to limitation in band and decrease in gains of the volume discount; increasing it leads to decrease in the number of available wavelengths. They try to identify an optimal value of the channel spacing that leads to the minimum MLR network cost. They claim that increasing the channel spacing up to a certain optimum value decreases the cost in terms of transponders. They also notify that larger topology's network costs are more sensitive to channel spacing. Similarly, [29] investigates the dispersion effect on the signal quality in transparent WDM/DWDM networks. They investigate the estimation and management of physical layer impairment(s) (PLIs) to provide efficient and qualitatively good lightpaths. They consider dispersion and suggest a dispersion penalty (DP) approach to compensate the signal distortion occurring inside the optical fiber. The proposed routing algorithm selects paths having lower DP values to minimize the impact of dispersion guaranteeing PLI-aware RWA.

Reference [30] compares the performance of On-Off Keying (OOK), Differential Phase Shift Keying (DPSK) and Duo-binary (DB) modulation format(S) (MF) based MLR network in the presence of various PLIs. After validating their theoretical model with their simulation results, they claim that the DB MF is suitable for high spectral-efficient MLR systems due to its high resistance to the various PLIs.

Reference [31] proposes a re-provisioning algorithm by taking into account the actual physical layer and traffic conditions. They claim that, by establishing new or adapting existing lightpaths with actual margins and by optimizing placement and transmission parameter decisions for the transponders and regenerators, they observed savings for both elastic and MLR networks.

Even though there are numerous works in literature that study the SRRWA problem, several issues still need to be addressed:

i. There are numerous choices for variety of coupled sub-problems that need to be classified.
ii. There are numerous precedence alternatives among resource allocation strategies.
iii. The validity of the choices on different performance metrics are not comprehensively examined.
iv. The generalization of the choices to different type of networks is not carried out.

In this study, we first introduce single and multi-hop physical path establishment methods with and without grooming onto which we glue the protection strategies. After introducing performance metrics for the network, comprehensive simulations that implement the proposed heuristics of our SRRWA algorithm on two major optical networks are carried out. While some of the obtained simulation results may be considered as expected, others revealed surprising results. For example, it has been observed that shared backup may not always be the best choice for every network.

III. AN EFFICIENT SHARED BACKUP PATH PROTECTION ALGORITHM (SB-SRRWA)

A. SYSTEM MODEL

Physical network topology $G = (V, E)$ consists of a set of vertexes $V = \{1..V\}$ and a set of edges E where $(i, j) \in E$, $i \in V$ *and* $j \in V$. Virtual topology $G' = (V', E')$ consists of a set of vertexes $V' \subseteq V$ and a set of virtual links E' where $(i, j) \in E', i \in V'$ *and* $j \in V'$. These virtual links are called lightpaths. The capacity requirement of a connection established on k^{th} lightpath between nodes (s, d) using physical path (i, j) is symbolized as $f_{ij,k}^{sd} \geq 0$. Since multi hopping may be deployed, (s, d) and (i, j) node pairs may be different from each other. A traffic request is denoted as $R\,(s, d, B, h_t)$, where s and d are the source and destination nodes of the request respectively, B is the bandwidth requirement and h_t is the holding time of the traffic. The traffic requests are assumed to be *subrate traffics* where the traffic generated may have a lower rate than the wavelength line rate [9].

The SRRWA algorithm has two versions; one deals with dynamic traffic requests where holding time is meaningful; and the other version routes static traffic requests for which holding time parameter is not used. In this work, the dynamic traffic provisioning is studied. Traffic requests are generated with uniformly distributed source and destination node pairs. The bandwidth requirements uniformly vary to represent aggregated tasks such as file transfer and/or high-quality video streaming. The arrival process is characterized as a Poisson process and the holding time of each established connection is characterized as an exponential distribution.

Symbol used throughout the paper are as follows.

$W = 80$ number of wavelengths on a link.
$R = \{10, 40, 100\}$ available line rates (in Gbps).
$D = \{1, 2.5, 3.75\}$ normalized costs of transponders D_l operating at rate r_l, where higher-rate transponders provide volume discount [7], [9], [19].
$L_{ij,k}$ k[th] lightpath established between nodes i, j.
BER_threshold threshold BER.
$BER^l_{ij,k}$ the *BER* value of $L_{ij,k}$ at rate r_l.
$\alpha^l_{ij,k}$ the feasibility of $L_{ij,k}$ at rate r_l.

$$\alpha^l_{ij,k} = \begin{cases} 1 & \text{if } BER^l_{i,j,k} \leq BER\_threshold \\ 0 & \text{othewise} \end{cases} \quad (1)[1]$$

Even though, there are many factors affecting the signal reach [6], for the sake of simplicity, with the results of crosstalk and impairment-aware studies [5], [32], we consider only the physical length of the paths and TR of each line rate to calculate the feasibility of a lightpath $L_{ij,k}$ at rate r_l and (1) is transformed into (2).

$$\alpha^l_{ij,k} = \begin{cases} 1 & \text{if } distance_{i,j,k} \leq TR_l \\ 0 & \text{othewise} \end{cases} \quad (2)$$

where TR of each line rate is assumed as follows; $TR_{10} = \infty$, $TR_{40} = 2500\,km$, $TR_{100} = 2000\,km$ [32].

$L^l_{ij,k}$ k[th] lightpath established between nodes i, j at rate r_l.
$W^l_{ij,k} = 1$ Boolean value indicating the existence of a working lightpath established as the k[th] lightpath between nodes i, j at rate r_l.
$B^l_{ij,k} = 1$ Boolean value indicating the existence of a backup lightpath established as the k[th] lightpath between nodes i, j at rate r_l.
$f^{sd}_{ij,k}$ traffic from s to d routed on $L_{ij,k}$.
$P(m, n)$ set of lightpaths passing through a link between nodes m and n.
$r_{ij,max}$ highest line rate r_l that meet $\alpha^l_{ij,k} = 1$.

Solutions to SRRWA problem in transparent WDM MLR optical networks should meet the properties, constraints and objectives that are mentioned in the following subsections [1], [9], [33].

1) PROPERTIES

i. Each lightpath occupies one single wavelength through the physical links it passes.
ii. Two lightpaths passing through same link use different wavelengths.
iii. Total number of established lightpaths, thus resources, must be minimized.
iv. Communication network survives even when a physical link is damaged with all its wavelengths.
v. 100% protection is guaranteed for all serviced traffic requests.
vi. Dedicated and shared backup protection techniques are used to keep communication network survivable.
vii. Backup paths are established using either protection at connection (PAC) or protection at lightpath (PAL) techniques.
viii. Two connections having joint working lightpaths, do not share a backup resource.
ix. Neighboring lightpaths on a fiber may operate at different line rates.
x. Multi hop path provisioning may be used when it is not possible to establish a single end-to-end lightpath between source and destination nodes of a traffic request.
xi. Subrate traffic requests may be aggregated using multi hop and single hop (end-to-end) traffic grooming when there is idle capacity on candidate lightpaths.
xii. Overrate traffic requests may be inverse multiplexed (IMUX) on the same physical path when the capacity of a single lightpath is not adequate for the traffic request.

2) CONSTRAINTS

i. *Wavelength continuity constraint;* Each lightpath uses the same wavelength along its path.
ii. *Line rate continuity constraint;* Each lightpath uses the same line rate along its path.
iii. *BER constraint;* Lightpaths are established using line rates following the TR constraints which are determined by BER constraint of the signals as indicated in (1) and (2).
iv. *Number of wavelengths constraint;* The total number of lightpaths passing through a physical link must be smaller than or equal to the total number of wavelengths W of that link.

$$\sum_{L_{ij,k} \in P(m,n)} \sum_{l} \left(W^l_{ij,k} + B^l_{ij,k}\right) \leq W \quad \forall (m, n), \ \forall (i, j) \quad (3)[1]$$

v. *Grooming capacity constraint;* Total capacity of traffic requests groomed on a lightpath should not exceed the capacity of that lightpath.

$$\sum_{L_{ij,k}} f_{ij,k} \leq r_{ij,max} \quad \forall (i, j) \quad (4)$$

vi. *Total capacity (TC) constraint;* Communication network should have enough capacity for both working and backup flows.

$$TC_{(i,j),k} = \sum_{l} r_l . \left(W^l_{ij,k} + B^l_{ij,k}\right);$$
$$TC_{(i,j),k} \geq 2 \sum_{sd} f^{sd}_{ij,k} \quad \forall (i, j), k \quad (5)$$

where;

$$\sum_{l} r_l . W^l_{ij,k} \geq \sum_{sd} f^{sd}_{ij,k} \quad \forall (i, j), k \quad (5.1)[1]$$
$$\sum_{l} r_l . B^l_{ij,k} \geq \sum_{sd} f^{sd}_{ij,k} \quad \forall (i, j), k \quad (5.2)[1]$$

3) OBJECTIVES

$$\text{i. } Minimize\ TCC = \sum_{ij}\sum_{k}\sum_{l}\left(W^{l}_{ij,k}+B^{l}_{ij,k}\right).D_l \quad (6)$$

$$\text{ii. } Maximize\ LUR = \frac{\sum_{ij}\sum_{k}\sum_{sd}2f^{sd}_{ij,k}}{\sum_{ij}\sum_{k}TC_{(i,j),k}} \quad (7)$$

$$\text{iii. } Minimize\ BBR = \frac{total\ bw\ of\ rejected\ requests}{total\ bw\ of\ serviced\ requests} \quad (8)$$

$$\text{iv. } Maximize\ SGR = \frac{DPC - SPC}{DPC} \quad (9)$$

where SPC is the total capacity reserved for shared protection and DPC is the total protection capacity requirement of the connections sharing their backups with others.

The system model is developed for the purpose of mathematically explaining the constraints and properties of the underlying system and to show what is focused to be optimized. The details of the algorithm are explained in the following subsection.

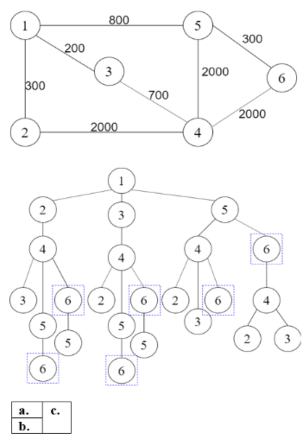
B. SB-SRRWA ALGORITHM

The proposed SB-SRRWA algorithm is an extension of SRRWA algorithm of [15] with shared backup features added. Therefore, we will briefly embed SRRWA features into SB-SRRWA for the integrity of presentation and the reader is referred to [15] for further details. The SB-SRRWA algorithm has two stages. The first stage is performed offline to explore the network resources. The second stage is online to provision dynamic traffic requests.

1) OFFLINE STAGE

In this stage, the physical network is examined, and all simple physical paths are explored between all node pairs. A Breadth First Search (BFS) like algorithm is developed to explore all simple paths of the network. Any given source node s is treated as a root and a tree is generated by traversing all nodes of the network in an adapted BFS manner. The algorithm visits the neighbors of the root and adds them to the tree in the order of their node ids. Then the algorithm repeats first stage for each child of the root and so on. Visited nodes are not marked as *visited* so that they can be processed again. Being different from sink tree, a node can be placed in more than one branch; but it cannot be repeated on a single branch. To satisfy this constraint, when a node is supposed to be added to a leaf position, all ancestors on that branch are examined and new node is added to the tree if and only if it is not placed previously to the same branch. When network is completely explored, the tree becomes complete for source node s. Each branch from the root s to another node, e.g. d, whether an intermediate or a leaf node, forms a simple path between s and d. By ensuring that a node is not placed on a branch twice, a possible loop on the path is avoided. By taking each node as a source, this process is repeated. At the end, all simple physical paths between all node pairs of the network are obtained. Note that, at this stage, the simple physical paths of a node pair are not required to be link disjoint from each other. One could argue that, $k \geq 2$ disjoint shortest paths algorithm could be used for this purpose. However, $k \geq 2$ disjoint shortest paths algorithm eliminates many of the feasible lightpath alternatives since all found alternative paths are link disjoint from each other. Link disjointness property relaxes the backup path searching process but also it limits the discovery of some available paths if they have joint links with an already explored path. The usage of all simple paths instead of $k \geq 2$ disjoint shortest paths increases the number of alternative paths found between each node pair, since it discovers all possible paths even when they are joint with each other. In this case, the link disjointness control of alternative backup paths from assigned working path is performed during provisioning of each traffic request.

In fig. 1.a, a sample network with 6 nodes and 8 links [1] is presented. Fig. 1.b shows a tree generated by all simple paths algorithm for source node 1. Marked nodes indicate that the algorithm is exploring the paths between nodes 1 and 6. Finally fig. 1.c presents a small section of the list of all simple paths produced for the sample network.



(*s-d*)	# Nodes - Path	Length (km)	Feasible Line Rates (Gbps)
1 - 2	5 - 1 5 6 4 2	5100	10
1 - 2	4 - 1 5 4 2	4800	10
1 - 2	4 - 1 3 4 2	2900	10
1 - 2	2 - 1 2	300	100 / 40 / 10
1 - 3	5 - 1 5 6 4 3	3800	10
1 - 3	4 - 1 5 4 3	3500	10
1 - 3	4 - 1 2 4 3	3000	10
1 - 3	2 - 1 3	200	100 / 40 / 10
1 - 4	4 - 1 5 6 4	3100	10
1 - 4	3 - 1 5 4	2800	10
1 - 4	3 - 1 3 4	900	100 / 40 / 10
1 - 4	3 - 1 2 4	2300	40 / 10
1 - 5	5 - 1 3 4 6 5	3200	10
1 - 5	5 - 1 2 4 6 5	4600	10
1 - 5	4 - 1 3 4 5	2900	10
1 - 5	4 - 1 2 4 5	4300	10
1 - 5	2 - 1 5	800	100 / 40 / 10
1 - 6	5 - 1 3 4 5 6	3200	10
1 - 6	5 - 1 2 4 5 6	4600	10
1 - 6	4 - 1 5 4 6	4800	10
1 - 6	4 - 1 3 4 6	2900	10
1 - 6	4 - 1 2 4 6	4300	10
1 - 6	3 - 1 5 6	1100	100 / 40 / 10
2 - 1	5 - 2 4 6 5 1	5100	10
2 - 1	4 - 2 4 5 1	4800	10
2 - 1	4 - 2 4 3 1	2900	10
2 - 1	2 - 2 1	300	100 / 40 / 10
2 - 3	6 - 2 4 6 5 1 3	5300	10
2 - 3	6 - 2 1 5 6 4 3	4100	10
2 - 3	5 - 2 4 5 1 3	5000	10
2 - 3	5 - 2 1 5 4 3	3800	10
2 - 3	3 - 2 4 3	2700	10
2 – 3	3 - 2 1 3	500	100 / 40 / 10
...			

FIGURE 1. A sample network with 6 nodes and 8 links [1] (b) A tree generated by all simple paths algorithm for s = "1" (c) A section of the list of all simple paths produced for the sample network.

In the offline stage of the SB-SRRWA algorithm, in addition to the simple paths found, maximum feasible line rates of these paths are also calculated according to the transmission range constraint. The transmission range of each line rate is taken from the results of a crosstalk and impairment-aware study [5] and is used as 2000 km for 100 Gbps, 2500 km for 40 Gbps and ∞ for 10 Gbps. Since we work on a transparent network, where no regenerator deployed, the maximum line rate whose transmission range is greater than or equal to the physical length of the path is chosen as the maximum feasible line rate of that path. For simplicity, we assume that all nodes have adequate number of transponders for each line rate. Outputs of the first stage simplify the online provisioning stage by eliminating the need to repeatedly search path alternatives

Algorithm 1 SB_SRRWA Algorithm

given. network, dynamic traffic requests $R(s,d,B,h_t)$
output. working and backup lightpaths assigned for each traffic request.
offline stage
foreach (*s-d* pair) **{**
explore all simple physical paths between s-d
calculate feasible line rates for all simple physical paths found.
}
online stage
while (there is new traffic request $R(s,d,B,h_t)$)
{
if (there is no path pair between *s-d*)
reject request; continue.
//construction of working lightpath
SHTG: explore *s-d* lightpaths with idle capacity $\geq B$
MHTG: explore subsequent lightpaths forming a virtual path from *s* to *d* with idle capacity $\geq B$
SHN: explore *s-d* paths with a continuous available empty wavelength, length of the path is constrained by TR of the chosen line rate.
MHN: explore subsequent sub-paths forming a virtual path from *s* to *d* with a continuous available empty wavelength at each sub-path, no wavelength continuity constraint for consequent sub-paths, length of each sub-path is constrained by TR of the chosen line rate for that sub-path.
if (there is no available working resource)
reject request; continue.
Use MOPT to assign the alternative path with optimum performance to the traffic request as working resource.
foreach (working lightpath *i-j* assigned to the request)
{*//construction of backup lightpath*
//explore link-disjoint paths for the assigned working lightpath
SHSB: explore *i-j* lightpaths with sharing capacity $\geq B$
MHSB: explore subsequent lightpaths forming a virtual path from *i* to *j* with sharing capacity $\geq B$
SHTG: explore *i-j* lightpaths with idle capacity $\geq B$
MHTG: explore subsequent lightpaths forming a virtual path from *i* to *j* with idle capacity $\geq B$
SHN: explore *i-j* paths with a continuous available empty wavelength, length of the path is constrained by TR of the chosen line rate.
MHN: explore subsequent sub-paths forming a virtual path from *i* to *j* with a continuous available empty wavelength at each sub-path, no wavelength continuity constraint for consequent sub-paths, length of each sub-path is constrained by TR of the chosen line rate for that sub-path.
if (there is no available backup resource)
reject request; free all assigned resources; continue.
Use MOPT to assign the alternative path with optimum performance to the traffic request as backup resource.
} // end of backup path provisioning.
} // end of path provisioning.

between each source and destination node pairs of traffic requests. Last column of Fig. 1.c indicates feasible line rates.

2) ONLINE STAGE

The online stage of the algorithm is where online provisioning of the dynamic traffic requests ($R(s, d, B, h_t)$) are processed. Traffic requests are processed one at a time according to their arrival time. A request is serviced if and only if suitable working and backup lightpath(s) can be established. Otherwise, the request is blocked. The online stage consists of working lightpath and backup lightpath construction phases that are coupled.

a: WORKING LIGHTPATH CONSTRUCTION

i) PHYSICAL PATH SELECTION

Given the source *s* and destination *d* of the request, among all of the physical paths explored in the offline phase, the ones that are available at the time of the request are examined in terms of total length, total number of hops and number of busy wavelengths. Total length is directly related to TR of lightpaths to be constructed as well as the line rates selected. The goal is the maximization of the line rate to guarantee the volume discount of high bit rate transponders. Total number of hops is related to total number of transponders hence the communication cost which is to be minimized. Number of busy wavelengths is a measure of link utilization that is to be optimized. The evaluation involves a multilevel *multiobjective optimization strategy* that will be called MOPT in which the dominances of attributes are arranged according to operational needs. As an example, if the cost of a path is more important than the emptiness of wavelengths along the physical path, then the alternative physical paths are first ordered in increasing cost and within the available least-cost alternative paths, the path having the largest number of empty wavelengths is chosen. In the sequel, the strategy that considers communication cost as the most important attribute is going to be called Least Cost (LC) and the strategy that considers number of empty wavelengths as the most important attribute is going to be called Least Used (LU). Details of MOPT will further be discussed in section IV.

ii) LIGHTPATH ESTABLISHMENT

Four alternative lightpath establishment strategies are evaluated. These strategies are Single Hop New (SHN), Multi Hop New (MHN), Single Hop with Traffic Grooming (SHTG) and Multi Hop with Traffic Grooming (MHTG).

In SHN, a new lightpath is constructed between source and destination nodes (*s, d*) of the traffic request. The alternative route discovery begins with the shortest simple path between source and destination nodes to allow the usage of higher line rates. Feasible line rates of a path are examined according to the physical length of that path. If an alternative path cannot meet the bandwidth requirement of a traffic request, *inverse multiplexing* (IMUX) over the same physical path may be used. In IMUX, if the request rate is higher than that of supported by the wavelength, it is carried over multiple wavelengths [9]; so, different wavelengths of a physical path are used to construct adequate number of lightpaths to meet the traffic request. However, minimization of the number of IMUX fragments is an optimization goal for all lightpath establishment strategies.

In MHN, a series of consequent new lightpaths are established so that one's end node is the beginning node of the next lightpath. The beginning node of the first lightpath and the end node of the last lightpath are the source and destination nodes (*s, d*) of the traffic request, respectively. The alternative route discovery begins with the longest simple path between source and destination nodes and again feasible line rates are examined according to the physical length of the paths. The motivation of starting the discovery with the longest path is to take away the traffic load from shortest path's links, since those links are the first alternatives for single hop lightpaths and are heavily used. While there is wavelength continuity constraint in single-hop new lightpath establishment, subsequent lightpaths may use different wavelengths in multi-hop lightpath establishment. The IMUX is also available for MHN method. Note that the cost of MHN is higher as compared to SHN since the number of transponders needed is more.

Traffic grooming is a network efficient technique where multiple subrate traffics are carried on a wavelength [9]. In SHTG, existing lightpaths between source and destination nodes (*s-d*) of the traffic request are examined. If their idle capacities are adequate for the new request under consideration ($idle\_capacity \geq B$), then they are qualified as an alternative solution. In MHTG, consequent lightpath's idle capacities are examined in the same manner. Again, there is no wavelength continuity constraint for MHTG, which means that consequent lightpaths may use different wavelengths from each other. Although there is an operational cost associated with grooming, for the sake of simplicity, we omit it and consider only the transponder's costs. The traffic grooming methods are assumed to have no additional cost since they use already established lightpaths. Since numerous connections using same paths may be groomed on lightpaths, for most cases, bandwidth requirement of each lightpath will be greater than the bandwidth requirement of each traffic request using it, which in turn, exploits the need to maximize the lightpaths' line rates in MLR networks.

The proposed MOPT method is an adaptive routing algorithm [3] where, based on the current state of the network, the available path calculation is performed at the time of each request [9]. For wavelength assignment to lightpath, the well-known low complexity heuristic *First Fit* (FF) wavelength assignment strategy [3] is used. In FF strategy, each wavelength is searched from lowest numbered to highest until an end-to-end available wavelength is found along path. While this is a simple heuristic not requiring global knowledge, it is also powerful in terms of blocking probability and fairness [33].

b: BACKUP LIGHTPATH CONSTRUCTION

After assigning the working resource(s), backup resource evaluation begins for the request. For each established working lightpath, a backup resource is assigned to the request as backup path. All working lightpaths of the request are handled one-by-one. Single link failures are assumed in this work.

i) PHYSICAL PATH SELECTION

The physical path attributes used are exactly the ones used in the working lightpath case. The backup path alternatives are evaluated in a similar manner as working path evaluation using MOPT method. However, in the backup case, there is an extra restriction: The backup path must be link disjoint from the working path it will protect [2].

ii) LIGHTPATH ESTABLISHMENT

The protection scheme used is a reverting *protection at lightpath*(PAL) scheme which provides end-to-end protection with respect to a lightpath [2]. In reverting scheme, the protection resources are released by the connection after the failure is repaired [9], i.e., the traffic is switched back from backup lightpath to working lightpath immediately after the recovery of failed link. Using PAL, protection scheme supports both connection and subconnection-based protection, which relaxes the need to find end-to-end protection lightpaths between source and destination nodes of the traffic request. Furthermore, subconnection-based backup paths have more chance to be shared [19]. The implemented protection scheme has m:n property where a working lightpath may be protected by several backup lightpaths and more than one working lightpath may be protected by a single backup lightpath [1].

Using *backup sharing*, the idle capacity reserved for possible backup transmission is expected to be minimized together with improved resource utilization. On the other hand, due to optical cross-connects (OXC) configuration following a failure, the recovery time may be longer than the dedicated protection [2]. Therefore, in addition to SHN, MHN, SHTG and MHTG, two new backup lightpath establishment policies are investigated, namely, Single Hop Shared Backup (SHSB) and Multi Hop Shared Backup (MHSB).

In SHSB, existing lightpaths between source and destination nodes (*s-d*) of the traffic request are considered. Their capacities reserved for sharing are examined to check whether they are sufficient for the new request under consideration. If the sharing capacity is sufficient ($sharing\_capacity \geq B$), these lightpaths are listed as alternative sharing backup resources. In the case of MHSB, consequent lightpath's sharing capacities are examined in the same manner. There is no wavelength continuity constraint for MHSB, which means that subsequent lightpaths may use different wavelengths from each other.

SHSB and MHSB methods are considered to possess no additional communication cost since no extra resource is allocated to a connection using shared backup path protection.

Backup resources can be shared as long as their protected segments (links, sub-paths, paths) are link disjoint [2]. If there is no available alternative sharing resource, *dedicated backup protection* (DB) is used. In dedicated protection, the same amount of capacity of working resources is reserved as the backup of the connection [2]. The reserved capacity is idle until a failure occurs on the related working lightpath.

C. PERFORMANCE METRICS

Performance metrics used to evaluate the algorithm are *bandwidth blocking ratio* (BBR), *total communication cost* (TCC) in terms of transponder cost, *lightpath utilization ratio* (LUR) and *sharing gain ratio* (SGR). BBR, given in (8), is the ratio of blocked traffic bandwidth over serviced bandwidth. TCC is calculated by (6). Note that cost computation always includes backup lightpaths whether they are utilized or not. Therefore, the cost of transponders reserved for possible usage of a backup lightpaths is included in the TCC calculation.

LUR is a metric indicating the resource utilization efficiency. It is the ratio of non-idle capacity of all of the lightpaths over total capacity of them. LUR is periodically measured several times during the communication and the average of these measurements is taken as the LUR value of that communication simulation. The objective is to maximize the utilization ratio given in (7).

SGR serves to observe capacity gain obtained by the usage of shared protection strategy. The difference between the total protection capacity requirement of the connections sharing their backups with others (i.e., total dedicated protection capacity - DPC) and the total capacity reserved to shared protection on all backup lightpaths (i.e., total shared protection capacity - SPC) is the capacity gain observed from backup sharing approach. Note that, the first term excludes the backup requirements of connections already using dedicated protection. Thus, the first term is the sum of protection capacity to be reserved instead of SPC if no sharing was used. Respectively, SGR is the ratio of the capacity gain to DPC. This metric gives the performance of backup sharing approach. The objective is to maximize SGR given in (9).

IV. STRATEGY DEVELOPMENT FOR MULTIOBJECTIVE OPTIMIZATION

In this section, the various factors that affect the performance metrics will be discussed and details of MOPT will be given. Clearly, it is expected that choosing the highest possible data rate for each lightpath constructed would increase the overall network capacity leading to higher throughput and lower BBR. However, higher data rates are only feasible on shorter links which, in turn, increases TCC. Reducing the number of hops for each path would decrease the number of transponders leading to a decrease in TCC. Therefore, there is a tradeoff between BBR and TCC that should be settled in MOPT. On the other hand, maximization of LUR and SGR may also be conflicting since high SGR may not necessarily imply high LUR or vice versa. As a result, it is not straightforward to propose a unique strategy that would serve the purpose of optimizing TCC, BBR, SGR and LUR at the same time.

The path alternatives for the request under consideration are evaluated among available resources. For each provisioning, all alternative resources are evaluated and the one with optimum performance is assigned to the request. The evaluation of a resource is performed by MOPT by considering some of the attributes of the resource, such as the number of its busy wavelengths and the transponder cost to establish it. The dominance of each attribute is arranged according to operational needs. The major factors examined to evaluate an alternative path are the selected path establishment method, the path's usage rate (number of wavelengths used), its communication cost (number of transponders used), and its line rate. These factors may be simplified or increased in number according to the operational needs. MOPT is a multilevel multiobjective optimization scheme where at each sublevel, only the alternatives that satisfy the prior levels best are evaluated, guaranteeing that levels' priorities are met. In this study, first level evaluates path selection strategies (i.e. LU or LC) and second level evaluates path establishment methods (i.e. SHN, SHTG, etc.). Other objectives of lower levels are line rate maximization and number of IMUX fragments minimization. In our studies, several test scenarios with different priorities have been evaluated, while best performance scenarios are presented later in this work.

A. PHYSICAL PATH SELECTION HEURISTICS

Choosing a path among various available alternatives does not only affect the connection under process, but also influences the overall performance of the network. The aim in path selection is to assign appropriate resources to the connection under process and leave as much free resources as possible for future traffic requests. An inappropriate assignment may cause unnecessary increase in cost or may lead to an early resource exhaust as well as possible decrease in backup shareability. Since connections having disjoint working paths can share a backup resource, the working path selection directly influences the sharing efficiency.

To observe the influence of path selection on routing performance, we prepared two heuristics considering different priority sequences. The first heuristic gives the highest priority to path usage (number of wavelengths occupied) and the path having minimum usage is favored. The second heuristic considers communication cost as the highest priority and the path having the minimum cost is favored. The results of these two heuristics are compared via detailed simulations.

Least used path first heuristic (LU) selects the minimum used path among suitable path alternatives. A link's usage value is equal to the number of busy wavelengths at this link. Respectively, a path's usage value is equal to the number of busy wavelengths at the most used link along that path (P), as formulated in (10) [2]. The aim of this formulation is to find the bottleneck of the path under consideration. By choosing the LU alternative, algorithm tries to identify lightly loaded paths and ensures load balancing in the network. The main motivation of this strategy is to increase sharing efficiency. It is expected that by spreading the working communications across various physical paths, their backup communications may share same physical links.

$$path\_usage_P = max\left\{\forall(ij \in P) link\_usage_{ij}\right\} \tag{10}$$

Least cost path first heuristic (LC) selects the path alternative with minimum communication cost. A path's communication cost is calculated according to the cost of transponders used to establish all lightpaths of this path, as formulated in (11) [9]. LC aims to minimize the TCC by minimizing the cost of each established path.

$$communication\_cost_P = \sum\nolimits_{ij \in P} \sum\nolimits_{k} \sum\nolimits_{l} L^{l}_{ij,k}.D_l \tag{11}$$

For both LU and LC heuristics TCC is calculated according to the number of transponders employed to establish both working ($W^{l}_{ij,k}$) and backup ($B^{l}_{ij,k}$) lightpaths regarding their normalized costs as shown in (6) and (12) [3].

$$TCC = \sum\nolimits_{p} communication\_cost_P \tag{12}$$

The other attributes used by both heuristics are path establishment method, line rate, and number of IMUX fragments. While there are variety of heuristics for line rate selection [34], this work selects the maximum available line rate for the path chosen. Within alternative paths using IMUX, the path requiring the minimum number of lightpaths is favored. On the other hand, selection order of path establishment methods requires another strategy.

B. PATH ESTABLISHMENT METHODS SELECTION ORDER HEURISTICS

For new traffic requests, all resource alternatives are listed during provisioning stage considering current network state. Alternatives may use SHN, MHN, SHTG, MHTG, SHSB or MHSB. Moreover, in backup path provisioning, SHSB and MHSB are also used. Since the aim of this work is to enhance the use of sharing, these two methods have the top priority in selection if they are available within path alternatives. On the other hand, the first four methods may be selected with equal priority whenever they are available for both working and backup path provisioning.

During network design, the selection order of the path establishment methods may be arranged according to the operational needs. This selection order directly influences the performance of the routing algorithm. Superficially, since grooming methods use idle capacities on lightpaths with no additional transponder cost, it was expected that giving higher priority to the grooming methods rather than preferring new lightpath establishment methods would be more cost efficient. But through simulations, it has been observed that while this expectation turned out to be true for networks having shorter links, e.g. EON; for networks having relatively longer links, e.g. NSF, single hop methods having higher priorities yielded more effective results in terms of bandwidth blocking, resource utilization, communication cost and shareability metrics.

A detailed work was performed on method selection order and its results were presented in detail in [15] where twenty-four scenarios with all possible selection orderings of path establishment methods are composed. Reference [15] uses SRRWA algorithm having LU and LC heuristics with shared and dedicated PAL in simulations. According to the results of [15], it is concluded that, on networks having longer link lengths in kilometers, (SHTG-SHN-MHTG-MHN) ordering gives the best performance; while, for networks having shorter links (SHTG-MHTG-SHN-MHN) ordering gives the best routing performance. Therefore, we will follow these patterns in path establishment phase.

C. SHARING CAPACITY SCALABILITY HEURISTICS

Backup sharing method protects more than one working resource by reserving common physical capacity. Studies of survivable networks show that sharing backup resources offer higher resource utilization efficiency [13] than dedicated schemes while they are more complex to design and slower to react. Sharing performance is directly affected from routing algorithm's provisioning decisions. As mentioned before, backup resources can be shared as long as their protected segments (links, sub-paths, paths) are mutually diverse [2]. If routing algorithm tends to choose same resources as working paths, finding common backup resources becomes impossible especially in networks having small average nodal degrees, where it is hard to find multiple disjoint paths between node pairs. On the other hand, if the reserved protection capacity on an alternative resource is not enough for a traffic request, again, it cannot share that backup resource. While there are proposed methods trying to minimize these inconveniences [35], some of them may pose additional reconfiguration cost or interrupt on working communication.

One of the reasons to propose LU heuristic is to spread connections on different physical resources in order to be able to share common backup resources for them. With LC heuristic, routing algorithm tries to provision the connections always on lowest cost path until it becomes exhausted. In this case, these connections could not share common protection capacity, since their working resources are not disjoint. With LU heuristic, each time a new traffic request arises, alternative path with lowest busy wavelengths is chosen, which generally leads to different connections between a node pair using different paths. This, in turn, increases sharing possibility.

Sharing capacity is the other issue that we focus on. In some prominent studies, a lightpath's reserved capacity to shared backup is set equal to the first traffic request's data rate establishing that lightpath as its backup path (sharing_capacity = firsttraffic_data_rate) [15]. This method is called as the *fixed sharing capacity* (FSC) strategy. There is no future capacity adaptation option in this strategy. To be able to share a backup lightpath, all successive requests must have a data rate limited by the reserved capacity.

From the results of FSC, we observed that some of the rejected backup sharing alternatives were due to insufficient capacities reserved for sharing on lightpaths. We implemented a scalable strategy which increases the reserved sharing capacity in case of need. This method reserves a sharing capacity on that lightpath adequate for the first traffic request (sharing_capacity = firsttraffic_data_rate). In case of a possible sharing opportunity, this reserved capacity is increased to whole idle capacity of that lightpath (sharing_capacity + =idle_capacity). This strategy is called *coarse grain scalable sharing capacity* (CGS). This method may help increasing sharing capability. On the other hand, by reserving surplus capacity, it may decrease the possible future effective usage of that capacity that could utilize grooming. Simulations results for this alternative show higher blocking.

Our third heuristics is called *fine grain scalable sharing capacity* (FGS) strategy that sets the data rate of the first traffic request as the reserved sharing capacity of the lightpath (sharing_capacity = firsttraffic_data_rate) and increases the reserved sharing capacity in case of need by adding only required amount of capacity (sharing_capacity + = newtraffic_data_rate - SB_capacity). If the required capacity increase (newtraffic_data_rate - SB_capacity) exceeds the idle capacity of the lightpath, the increase request is rejected and underlying resource is removed from the list of alternative backup sharing resources of the traffic request. By this sensitive increase, idle capacities of the lightpaths remain usable by future grooming and sharing candidates. For both scalable methods, since the capacity increase is carried out only for protection resources, active working communications are not interrupted.

Reserving the whole capacity of the lightpath permanently as sharing capacity is another option. From simulations, it is observed that, this heuristic did not perform efficiently in terms of blocking and cost. The main reason is that there exists a small amount of suitable sharing candidates. The sharing constraints are strict and the number of candidate connections meeting these constraints is small. Thus, the possibility of using the idle capacity of a lightpath via grooming is more powerful than sharing possibility. If the whole capacity of a lightpath is reserved for sharing, it will possibly remain idle. This will result in blocking of future traffic requests thereby bad resource utilization. Moreover, total communication cost will increase due to lack of grooming. Table 1 summarizes the anticipated strengths and weaknesses of the proposed sharing capacity heuristics.

TABLE 1. Strengths and weaknesses of sharing capacity heuristics.

Heuristic	Strengths	Weaknesses
FSC	✓ Efficient use of idle capacities on lightpaths by future grooming candidates	✓ Not scalable ✓ No heuristic based first capacity assignment
CGS	✓ Capacity increase in case of need	✓ No future grooming opportunity in case of capacity increase ✓ Inordinate capacity reservation after increase
FGS	✓ Capacity increase in case of need ✓ Ordinate capacity reservation after increase leaving capacity for future grooming candidates	✓ Capacity increase at each capacity insufficiency

V. PERFORMANCE ANALYSIS OF THE PROPOSED ALGORITHMS

We have designed simulations for the proposed SRRWA algorithm using OPT routing strategy and shared and dedicated PAL protection schemes. We have developed our own simulation environment for MLR WDM optical networks on Linux using C programming language. We used two different optical network topologies namely, NSFNET and EON, shown in fig. 2 and fig. 3 respectively with their link lengths in kilometers indicated on each link. Both networks have similar number of nodes (14 vs 16) and links (22 vs 23) and also similar nodal degrees (3,14 vs 2,87) but while NSFNET has 1.936 km average link length, EON has approximately 486 km average link length. This difference affects the line

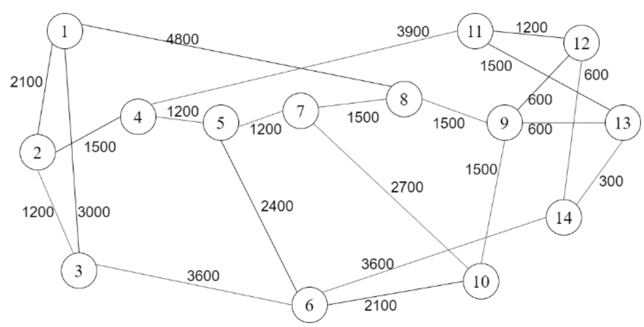


FIGURE 2. The 14-node national science foundation network (NSFNET) topology [7].

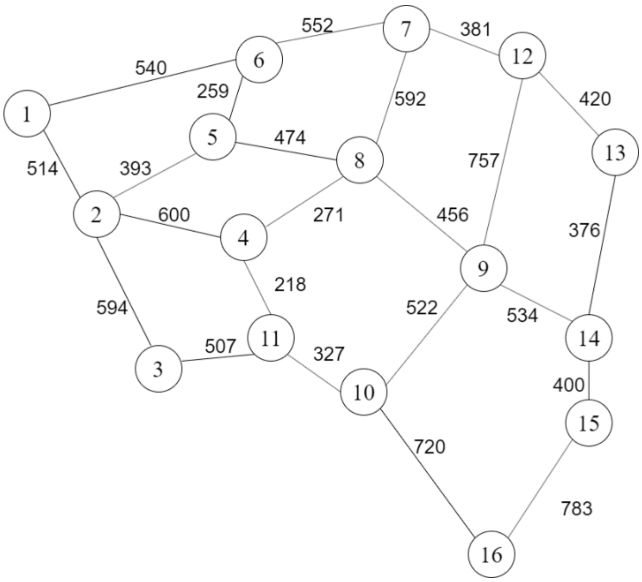


FIGURE 3. The 16-node european optical network (EON) topology [36].

rate assignment process in MLR networks together with the performance of routing algorithm.

In simulations, 500 erl to 1100 erl dynamic traffic requests are generated with uniformly distributed source and destination node pairs. Even though some literature uses fixed bandwidth for requests, we think that varying bandwidth of requests is more realistic. Therefore, we chose the bandwidth requirement of each request to be uniformly varying between 1 Gbps to 10 Gbps to represent aggregated tasks such as file transfer and/or high-quality video streaming. The arrival process is characterized as a Poisson process with average rate $\lambda = 20$ requests/unit time and the holding time of each established connection is characterized as an exponential distribution with average $1/\mu$ time units. Thus, λ/μ gives the total network load in Erlangs (erl) [23]. Each scenario is repeated 50 times and average results are reported.

Three sharing capacity strategies presented are FSC, CGS and FGS. To be able to compare the results of sharing strategies DB is also added to the scenarios. Path selection strategies presented are LU path first and LC path first heuristics. Strategies are summarized in table 2. From the results of [15], path establishment methods selection order chosen

TABLE 2. Strengths and weaknesses of sharing capacity heuristics.

	Heuristics	
Protection	SB	shared backup
	DB	dedicated backup
Path Selection	LC	least cost path first
	LU	least used path first
Sharing Capacity Scalability	FSC	fixed sharing capacity
	CGS	coarse grain scalable sharing capacity
	FGS	fine grain scalable sharing capacity

for NSFNET is (SHTG-SHN-MHTG-MHN); and for EON, it is (SHTG-MHTG-SHN-MHN).

A. SIMULATION RESULTS ON NSFNET

Fig. 4 presents the communication costs (TCC) of proposed strategies at different loads while fig. 5 shows their BBRs. From the results, the dedicated protection presents the worst performance for all performance metrics. DB presents the highest cost with the highest blocking performance, which makes the advantage of resource sharing more visible.

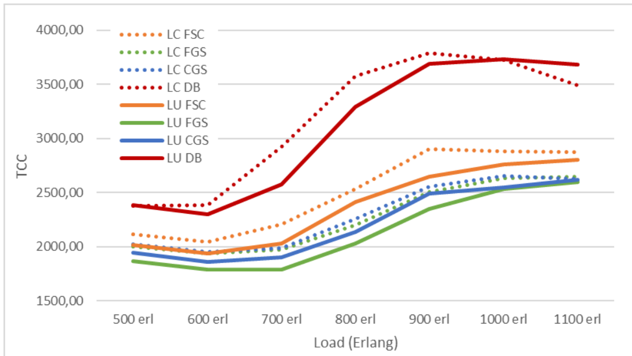


FIGURE 4. Communication costs (TCC) of different heuristics at various loads on NSFNET.

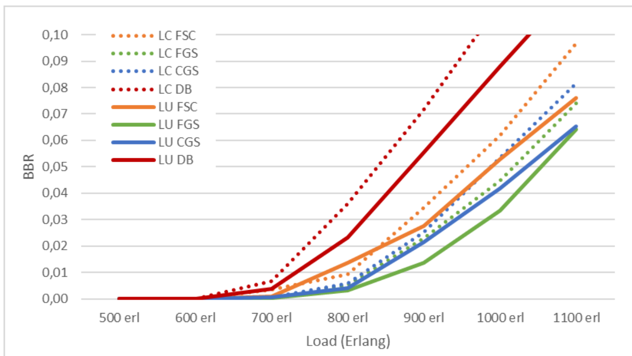


FIGURE 5. Bandwidth blocking ratios (BBR) of different heuristics at various loads on NSFNET.

It is clear that LU strategies present lower costs and blocking than their LC counterparts. While LC chooses the lowest cost alternative for each request, LU heuristic spreads the connections across lightly used paths that leave available capacities for future grooming and sharing opportunities, yielding lower cost and lower blocking for total communication. CGS and FGS strategies present similar performance. FGS presents lower costs and blocking at all loads. This is mainly because of the CGS reserving surplus sharing capacity, which decreases the effective usage of that capacity for possible future grooming. Among shared protection strategies, the worst cost and blocking performance is observed in FSC strategy. Since FSC strategy is not scalable, sharing capacities cannot become an alternative resource with adequate backup capacity for future traffic requests. While FGS increases the possibility of sharing in backup paths, FSC strategy increases the possibility of traffic grooming for non-sharing candidates.

Fig. 6 presents the lightpath utilization ratios (LUR) of proposed strategies at different loads. From the results, it is observed that LC scenarios give better resource utilization ratio than their LU counterparts. LC heuristic always chooses the least cost paths for all connections, which causes aggregation of traffic on paths. On the other hand, LU heuristic spreads the connections over lightly utilized paths in order to increase future grooming and sharing opportunities; but this approach leads to decrease in resource utilization efficiency.

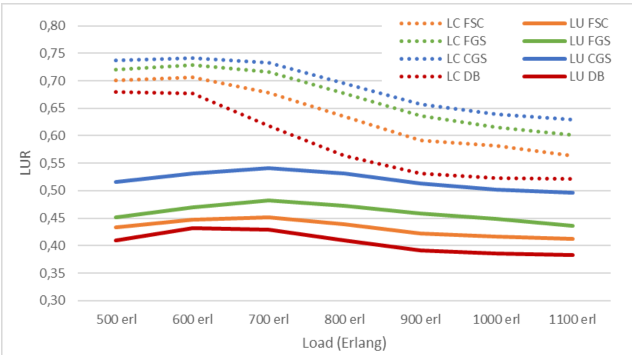


FIGURE 6. Lightpath utilization ratios (LUR) of different heuristics at various loads on NSFNET.

CGS seems to present highest LUR, but this result may be misleading since the sharing capacity reserved may not be fully used by connections. FGS guaranties that the sharing capacity reserved on a lightpath is fully used by at least one of the sharing connections; but in CGS, the maximum required backup capacity of the connections sharing a resource may be less than the sharing capacity reserved on that resource, leaving some unused capacity.

The decrease pattern of LUR values especially presented by LC strategies at heavier loads, is due to the new multi hop lightpath establishments in result of exhaustion in grooming capacities and impossibility of end-to-end lightpath establishment. All strategies favor traffic grooming, thus, they try to consume idle capacities first. While grooming options are present (at 500-700 erl), LUR values show an increase pattern and TCCs show a decrease pattern. When grooming capacity is exhausted (at 700-900 erl), new lightpaths are established. New lightpath establishment poses an increase in communication cost. The unused capacities on these new lightpaths decrease the LUR performance. On the other hand, when single hop new lightpath establishment becomes impossible due to the lack of available end-to-end wavelengths, multi hop path establishment begins which also decreases the resource utilization performance since the established lightpaths traverse longer paths and occupy wavelengths on numerous links. At some point (near 900 erl), TCC and LUR become nearly constant while BBR increases with increasing traffic requests. These results show that the network becomes saturated and only traffic requests suitable to grooming are provisioned, which in turn, do not affect TCC or LUR while BBR is strongly affected.

Fig. 7 presents sharing gain ratios of proposed strategies at different loads which show capacity gain achieved by sharing. SGR values shows that LU scenarios reserve more capacity for sharing than their LC counterparts. This means that they have more connections sharing their backup with others. With both strategies, FGS presents the highest SGR value (63% and 65% with LC and LU resp.). CGS and FGS have nearly the same amount of total protection capacity requirement for connections sharing their backups with others (i.e., total dedicated protection capacity - DPC). However, since CGS reserves surplus sharing capacity, it increases the total capacity reserved for shared protection on all backup lightpaths (i.e., total shared protection capacity - SPC) and decreases its SGR performances to 56% and to 48% with LC and LU strategies respectively. FSC heuristic presents the nearly same 60% SGR for both strategies.

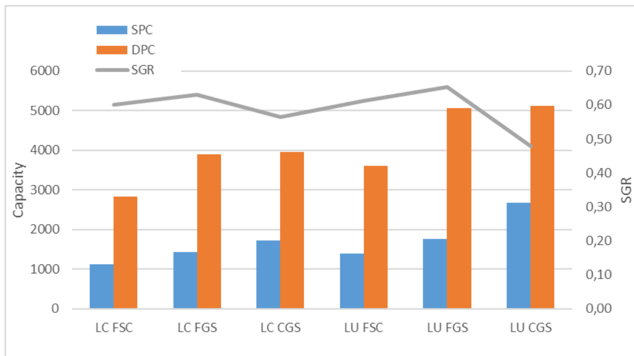


FIGURE 7. Sharing gain ratios (SGR) of different heuristics at various loads on NSFNET.

Table 3 summarizes all the results obtained from both heuristics at NSF network. The second column indicates the strategy that the heuristic shows its best performance. Ticks in cost, BBR, LUR and SGR columns indicate the outperforming scenario where the best performance is obtained.

TABLE 3. Summarized observations for NSFNET.

Backup	Path	TCC	BBR	LUR	SGR	Weaknesses
FSC	LU					Not scalable No heuristic based first capacity assignment
CGS	LC			✓		No future grooming opportunity in case of capacity increase Inordinate capacity reservation after increase
FGS	LU	✓	✓		✓	
DB	LU				-	No backup resource sharing

Weaknesses column present the weak properties of each method, which affect their performances. While for each heuristic, best performance is achieved with LU strategy, for CGS, we saw that its SGR performance decreases dramatically with LU strategy. For other metrics, compared to LC, LU strategy shows slightly higher performance for CGS heuristic. Accordingly, LC is selected as the outperforming strategy for CGS. Evaluating all performance metrics, on NSFNET, FGS heuristic using LU path selection strategy outperforms other scenarios. Another observation is that there is considerable overall improvement in performance when shared backup is implemented in NSFNET.

B. SIMULATION RESULTS ON EON

Fig. 8 presents the communication costs (TCC) of proposed strategies at different loads while fig. 9 shows their BBRs. From the results, LU scenarios present significantly lower TCC values than LC scenarios. At all loads, LU scenarios yield no blocking while LC scenarios yield increasing blocking with increasing load. The difference between two strategies in terms of cost and BBR performance is more obvious on EON than on NSF. Since EON supports high line rate lightpaths, together with load balancing caused by the lightpaths spreading across various physical links, LU heuristic encourages increased grooming opportunities and blocking is minimized. On the other hand, choosing same low-cost physical paths, LC yields decreased the grooming opportunities with increasing load, which leads to increased cost and blocking ratio.

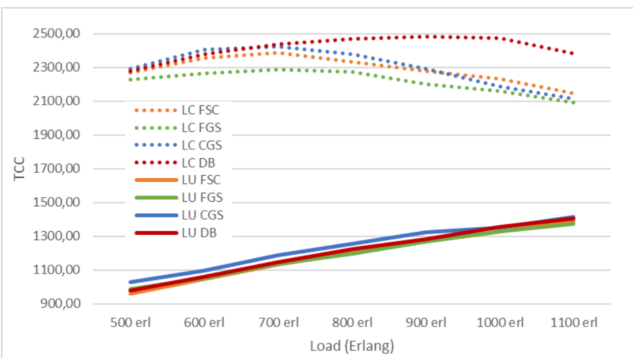


FIGURE 8. Communication costs (TCC) of different heuristics at various loads on EON.

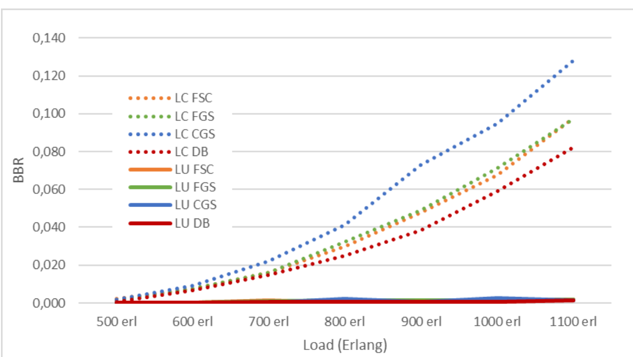


FIGURE 9. Bandwidth blocking ratios (BBR) of different heuristics at various loads on EON.

DB scenarios yield similar performance to that of sharing heuristics. This means that for backup communication, grooming alternatives are adequate to eliminate the negative effects of lack of sharing. CGS has the worst performance on EON. This is mainly due to inordinately increased reserved sharing capacity. Since the lightpath capacities are high on EON, the reserved capacity for backup sharing is also high leading to ineffective resource utilization. This strategy restrains grooming of future requests and forces new lightpath establishment more frequently. On NSFNET, the negative effect of this strategy is lower since the link lengths are longer thereby lowering both the lightpath capacities and possible inordinate capacity reservations. Minimizing this disadvantage, FGS heuristic presents slightly lower cost in increasing traffic load.

Fig. 10 presents LUR of proposed strategies at different loads. On contrary to NSFNET results, EON LU scenarios yield higher resource utilization than LC scenarios as traffic loads increase. Since EON offers higher capacity lightpaths, their idle capacity may efficiently be used by grooming. Load balancing strategy of LU exploits this property. At lower loads (at 500-900 erl), CGS presents highest resource utilization with a small cost penalty. At higher loads (900 erl and more), CGS's effectiveness decreases; other heuristics outperform CGS with similar LUR performances to each other, while FGS present the lowest TCC.

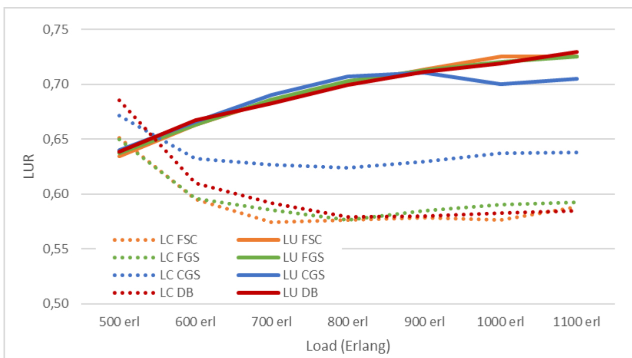


FIGURE 10. Lightpath utilization ratios (LUR) of different heuristics at various loads on EON.

Fig. 11 presents sharing gain ratios of proposed strategies at different loads. SGR values show that LC scenarios reserve more capacity to sharing, which means that LC shares more backup communications compared to LU. With both strategies, FGS presents the highest sharing with 60%. FSC heuristic presents nearly same 57% SGR for both strategies. Similar to NSFNET, CGS present the worst sharing (21% and 16% with LC and LU resp.) which is due to inordinate sharing capacity reservation. Since there exist more idle capacities on high line rated lightpaths on EON, CGS present lowest SGR

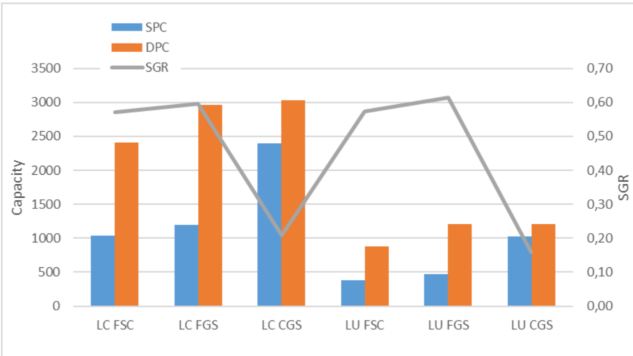


FIGURE 11. Sharing gain ratios (SGR) of different heuristics at various loads on EON.

by reserving complete capacity for possible future backup sharing.

Table 4 summarizes the observations on proposed strategies of EON. The second column indicates the strategy that has best performance. Ticks in cost, BBR, LUR and SGR columns indicate the outperforming scenario. Weaknesses column present the weak properties of each method, which affect their performances. Evaluating all performance metrics, FGS heuristic using LU path selection strategy outperforms other scenarios on EON. Another important observation is that, with LU chosen in EON, the improvement obtained in performance by shared backup seems to be marginal and dedicated backup may as well be preferred to simplify the algorithm. Compared to considerable improvement obtained by shared backup in NSFNET, the marginal improvement of shared backup in EON can be explained by increased overall capacity in EON due to shorter links supporting higher data rates.

TABLE 4. Summarized observations for EON.

Backup	Path	TCC	BBR	LUR	SGR	Weaknesses
FSC	LU		✓	✓		Not scalable No heuristic based first capacity assignment
CGS	LU		✓	✓		No future grooming opportunity in case of capacity increase Inordinate capacity reservation after increase
FGS	LU	✓	✓	✓	✓	
DB	LU		✓	✓	-	No backup resource sharing

VI. CONCLUSION

In this paper, we studied a shared backup path protection strategy for the well-known Survivable Routing, Rate and Wavelength Assignment problem in WDM MLR optical networks. We proposed several heuristics to improve the performance of the proposed resource allocation algorithm. We carried out simulations to compare the performances of the two path selection strategies, i.e., LU and LC, using three shared backup protection heuristics and dedicated backup protection method. The results show that there is a strict relation between strategy selection and resource utilization performance.

We repeated simulations on NSFNET and EON having different average link lengths. This difference affects the line rate assignment process in MLR networks together with the performance of resource allocation algorithm. However, there is no noticeable difference between the performances of the outperforming method (LU FGS) on NSFNET and on EON.

We observed that LU scenarios outperform their LC counterparts in terms of communication cost and BBR. In terms of resource utilization, LC scenarios outperform their LU counterparts on NSFNET, while the opposite is true on EON. This result is due to lightpath capacity difference on networks. EON allows higher line rates on end-to-end lightpaths having higher capacities which, in turn, are effectively used by LU strategy, balancing the load on various physical paths. Evaluating the sharing values, we observed that on NSFNET, LU scenarios have more connections that share their protection resources, which leads to increased SGR. On EON network, the capacity reserved for sharing and capacity required for dedicated backup in absence of sharing is higher for LC, which means that more connections share their backup resources with LC. Eventually, the sharing performances of scenarios are similar on both networks.

We observed also that scalable protection capacity reservation improves the sharing performance of the resource allocation method. Compared to other proposed scenarios, FGS backup resource sharing heuristic using LU path selection strategy outperforms other scenarios in terms of low communication cost and blocking while presenting higher resource utilization and sharing.

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