Optimizing Transceiver Usage in Multiband Elastic Optical Networks via SLA-Differentiated Protection

Soheil Hosseini
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) and Universidad de Valladolid
Castelldefels and Valladolid, Spain
soheil.hosseini@uva.es

Ignacio de Miguel
Universidad de Valladolid
Valladolid, Spain
ignacio.demiguel@uva.es

Ramon Casellas
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Castelldefels, Spain
ramon.casellas@cttc.es

Raul Muñoz
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Castelldefels, Spain
raul.munoz@cttc.es

Evaristo J. Abril
Universidad de Valladolid
Valladolid, Spain
ejabril@tel.uva.es

Ramón J. Durán Barroso
Universidad de Valladolid
Valladolid, Spain
ramon.duran@uva.es

***Abstract*—The recently proposed band division multiplexing (BDM) technology enables network operators to leverage existing optical fibers more effectively. By expanding from the conventional C-band to the L-band, and potentially to the S and E bands, network capacity improves at least two times. This rate of capacity improvement allows the support of significantly more connections compared to the current elastic optical networks (EONs). However, the increased capacity also means that a network failure might cause huge data loss, making the employment of survivability methods a must. On the other hand, since the required level of protection might vary across different users, the implementation of an effective service level agreement (SLA) mechanism is crucial for enhancing network performance and optimizing costs. Since transceivers are among the most expensive components, in this paper, we aim to modify an SLA-differentiated protection for C+L band networks that we previously proposed, focusing on reducing transceiver usage. The modified SLA-differentiated method is evaluated against the original one in terms of network performance and transceiver consumption. We demonstrate that the introduced variation of the SLA mechanism achieves a significant reduction in the number of utilized transceivers.**

Keywords*—*multi-band optical network, survivability, SLA, transceiver, network performance.

I. INTRODUCTION

The rapid growth of traffic demands induces network operators to adapt their optical backbone networks [1]. In this regard, band division multiplexing (BDM) offers a short to medium term solution, enabling network operators to meet the growing bandwidth demands [2-4]. This solution gets around the scarcity of available dark fibers as it exploits the current fiber infrastructure. In other words, BDM is considered as an appealing solution primarily because it enables more efficient use of existing fiber resources, and consequently maximizes the return on investments. The BDM technology is achieved by lighting up the existing spectral bands over the already installed optical fibers. Through extending the transmission window by activating the O-, E-, S-, L-, and U-bands in addition to the conventional C-band, BDM offers approximately 54 THz of bandwidth [5]. Leveraging different spectral bands over a single mode fiber (SMF) is currently on hold, as the required optical components like transceivers, amplifiers and optical cross-connects (OXCs) are not mature enough for all bands. On the other hand, activating the L-band spectrum is a practical approach for the realization of multi-band elastic optical networks (MB-EONs). This is because the required devices for the L-band operation are commercially available, and the optical signal attenuation in the L-band is similar to that of the C-band. Although C+L band systems provide practical benefits, their capacity improvement is lower compared to using two optical fibers with active C-bands (2×C). Nevertheless, it has been demonstrated that in C+L band networks, the penalty to traffic performance remains minimal [6]. The separate amplifiers architecture is usually employed for the implementation of C+L band networks and is depicted in Fig. 1 [7]. In this architecture, each spectral band is equipped with an erbium doped fiber amplifier (EDFA) for the amplification of optical signals. It is important to note that this architecture incurs a capacity penalty due to the required guard band between the C-band and the L-band of the demultiplexer and multiplexer architecture. This capacity penalty results in a bandwidth waste of around 400 GHz [7].

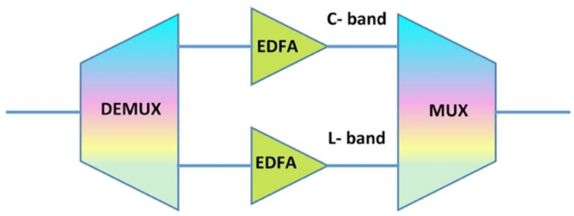

Fig. 1 The implementation of C+L band systems using a demultiplexer/multiplexer structure and separate EDFAs.

This work is part of IoTalentum project that has received funding from the EU H2020 research and innovation programme under the MSCA grant agreement No 953442. It is also supported by Grants PID2020-112675RB-C42 and PID2023-148104OB-C41 funded by MICIU/AEI/10.13039/501100011033 and the later also by ERFD/EU; and HE SEASON (G.A. 101096120).

In MB-EONs, the selection between the potential active spectral bands should be considered in designing the resource allocation algorithms. In fact, the routing, modulation level, and spectrum assignment (RMLSA) problem that should be solved in EONs transforms into the routing, band, modulation level, and spectrum assignment (RBMLSA) algorithm. In this work, the *K*-shortest paths algorithm is executed to solve the routing problem. Then, the appropriate spectral band is selected taking into account that we prioritize the L-band over the C-band. Additionally, the most spectrally efficient modulation format is selected, while ensuring the quality of transmission (QoT) for the established connection requests. In the case of MB-EONs. The selection of modulation format depends not only on the length of a lightpath but also on the spectral band in which the transmission is performed [8]. Table 1 describes the ranges of acceptable optical reach for three different levels of modulation considered in this study. For example, in case that the optical signals between a source-destination pair are transmitted over the C-band and the length of the lightpath is lower than 370 km, the 16QAM modulation format would be used. This value is reduced to 330 km when the L-band spectrum is the case. Similar to the EON, the MB-EON also requires that the spectrum continuity and spectrum contiguity constraints be satisfied during the spectrum allocation phase. In order to meet the aforementioned constraints in C+L band networks, the same spectral band must be used for all links in the selected path.

TABLE I. TRANSMISSION RANGES FOR MODULATION FORMATS IN C+L BAND NETWORKS

Modulation Level	Spectral band	
	C-band	***L-band***
BPSK	>1800 km	>1600 km
QPSK	370 – 1800 km	330 – 1600 km
16QAM	0 – 370 km	0 – 330 km

As it is mentioned, the use of C+L bands doubles the network capacity, making it essential to integrate survivability methods against potential network failures. Therefore, Luo et al. [9] have provided the C+L optical line systems with a protection scheme considering that the network can benefit from parallel transmission enabled by multi-core fibers (MCFs) infrastructure. In [10], we have proposed and analyzed different protection methods in a fully upgraded C+L band networks, employing the separate amplifiers architecture. In that paper, the focus was to ensure protection against at least a single failure in EDFAs. The work by Jana et al. [11] aims to achieve the same level of protection as outlined in our previous work [10] (protection against EDFA failures). However, in their approach, protection is ensured after verifying the lightpath quality considering the fill margin.

Since different users may have different quality of service (QoS) requirements, providing them with the same level of protection is not an effective approach. Therefore, the analysis of service level agreement (SLA) contracted by network users has been widely studied in EONs [12, 13]. In the context of MB-EON, we, for the first time, achieved SLA-aware service provisioning by introducing two SLA categories and exploiting the features of the separate amplifiers architecture (Fig. 1) [14]: one requiring a high level of protection, referred to as "gold", and the other with lower level of protection, termed "silver plus". In that study, we focused on enhancing the performance of survivable C+L band networks with appropriate SLA definitions. However, the impact of protection methods on transceiver utilization was not analyzed. Hence, in this work, we aim to address this gap by developing an SLA-differentiated protection mechanism that optimizes transceiver usage, thereby reducing both CAPEX and OPEX expenditures.

The remainder of the paper is divided into three sections. In Section II, the achievement of efficient transceivers usage within the modified SLA differentiated protection method is explored. Section III presents a simulation study to assess the efficiency of the proposed modification. Finally, in Section IV conclusion remarks are provided.

II. SLA-DIFFERENTIATED PROTECTION WITH OPTIMIZED TRANSCEIVER USAGE

In this paper, our objective is to optimize transceiver usage in the original SLA-differentiated protection scheme for C+L band networks proposed in [14]. To this end, we present a modification of the protection methods that are used to satisfy the level of resiliency required by the high-priority ("gold") and low priority ("silver plus") connections.

In [14], we have proposed a hybrid approach to provide the C+L band systems with protection against at least EDFA failures. With the separate amplifiers architecture, primary and backup lightpaths can be assigned to different spectral bands. Considering that the whole network has been upgraded to the C+L, we use the L-band for the primary and the C-band for the backup connections. This allows transmission to continue even if a single EDFA fails. For those connections that cannot be accommodated due to limited resources in the C-band, the hybrid approach includes a secondary phase to address these cases. In the second phase, attempts are made to establish the primary and backup connections over two link-disjoint paths. In this way, the primary and backup lightpaths can benefit from additional spectral resources, as they are capable of operating over both C and L bands. The second phase of the hybrid approach enhances the level of resiliency of the network by offering additional protection against a fiber failure. In summary, the hybrid approach safeguards all established connections against a single EDFA failure, while connections served in the second phase are protected against both fiber and EDFA failures.

In contrast to the hybrid approach, the classical dedicated path protection (DPP) method provides protection against a single failure in EDFA and optical fibers for all the established connections. The DPP method is employed for the "gold" users, while the "silver plus" users are protected using the hybrid approach.

The original SLA differentiated protection strategy [14] assumes that the hybrid approach and the DPP method are flexible in terms of turning on separate transceivers for the primary and backup connections. This paper is an extension of [14], and the focus is set on a variation of the original SLA differentiated protection method in order to ensure an efficient use of transceivers. To achieve this, a 1:1 protection scenario is considered for the DPP method and the second phase of the hybrid approach. In 1:1 protection approach, signal transmission automatically switches to a backup lightpath when a failure is detected. This approach allows the reuse of the same transceiver, eliminating the need to rely on a different one. Assuming that transceivers are only tunable within a single spectral band, the primary and backup lightpaths must operate within the same band. To further accelerate failure recovery, the proposed strategy requires that the primary and backup lightpaths use the exact same spectral resources. This eliminates the need for any retuning during the switchover. It should be noted that in the first phase of the hybrid approach, different spectral bands are dedicated to the primary and backup lightpaths (L-band for the primary and C-band for the backup). Therefore, in this case, utilizing different transceivers or, alternatively, optical converters (not considered in this study), is required. Through a simulation analysis, we compare the efficiency of the modified SLA differentiated protection mechanism with the original one [14] by evaluating the request blocking ratio and the savings in the number of required transceivers.

As previously mentioned, the DPP method is employed for the "gold" users to achieve survivability against an EDFA failure and a fiber-cut. In the first step, to maximize transceiver efficiency, "gold" users are restricted to using the same range of spectrum for the primary and backup lightpaths. In other words, given that the prioritization between the active spectral bands (C-band and L-band) is given to the L-band, we first attempt to find an exact block of available frequency slots over the L-band for the primary and backup connections. This process ensures the usage of a single (fully tunable) transceiver. In case that finding the same range of spectrum in the L-band for the primary and backup lightpaths is successful, the "gold" connection would be established. Otherwise, we investigate the C-band spectrum to serve the "gold" connections taking into account that the range of assigned frequency slots for the primary and backup lightpaths should be exactly the same. Following the analysis of all possible disjoint paths, if transceiver sharing for the primary and backup lightpaths remains impossible, the original SLA-differentiated protection mechanism will be executed. In this way, the primary and backup connections are assigned to separate transceivers, resulting in the possibility of using different spectral bands for the primary and backup lightpaths. After considering all possible options for the establishment of the "gold" connection, the lack of enough bandwidth might lead the connection to be blocked.

In case that the incoming connection request is classified under the "silver plus" SLA category, the hybrid approach is employed. In the first phase of the hybrid approach, using separate transceivers for the primary and backup connections is unavoidable. This is because in the first phase of the hybrid approach, to protect against an EDFA failure, different spectral bands are assigned to the primary and backup lightpaths. In this phase, in case that limited C-band resources prevent the backup connection from being established, the second phase is executed. The second phase follows a process similar to the DPP method, aiming to optimize the use of transceivers.

The network is represented using a connected graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ in which $\mathcal{N}$ and $\mathcal{E}$ indicate the set of nodes and the set of bidirectional links, respectively. For each *s-d* pair, two sets of K-shortest paths —link-disjoint and non-disjoint— are precomputed. The selection of paths depends on the employed protection method. For the "gold" connections, link-disjoint paths should be used. However, the "silver plus" connections can either use non-disjoint paths (in phase 1 of the hybrid approach) or link-disjoint paths (in phase 2 of the hybrid approach). Each connection is represented as $R(s, d, \gamma, \tau, SLA)$ where s and d show the source and the destination nodes, respectively. The parameter γ indicates the required number of frequency slots if the BPSK modulation format were used, and τ denotes the required service time. Additionally, the priority level (SLA category) that the connection belongs to is specified by the SLA parameter.

Algorithm 1 outlines a heuristic for optimizing transceiver usage while applying the modified SLA-differentiated protection method in C+L band systems. Initially, we restrict the primary and backup connections to the same spectral range, allowing both to share a single transceiver. However, in case that this restriction results in a blocked connection request, two separate transceivers are activated for the accommodation of the primary and backup lightpaths.

In Algorithm 1, five different auxiliary procedures are used. These procedures verify whether the necessary resources for establishing primary and backup connections can be found, considering the scenarios where transceivers for the primary and backup connections may or may not be shared. For instance, for the first phase of hybrid approach, the function primary_spectrum_found(*L-band*) is called in order to serve the primary lightpath. If the primary connection is successful and the function backup_spectrum_found(*C-band*) returns true, the "silver plus" connection is successfully established. The second phase of the hybrid approach, similar to the DPP method, consists of three steps. The first two steps aim to accommodate the connection with a single transceiver over a single spectral band. Therefore, firstly, the function primary_backup_spectrum_found(*L-band*) is called to investigate the possibility of establishing the primary and backup lightpaths with transceiver sharing in the L-band. If the same range of spectrum over the L-band for the primary and backup lightpath is not found, we call primary_backup_spectrum_found(*C-band*) to use the C-band for transceiver sharing. Otherwise, in case that the scenario of using one transceiver leads the connection to be blocked, in the third step, the primary and backup lightpaths can utilize the entire C+L bands with separate transceivers, and we call primary_backup_spectrum_found(*C+L*) procedure.

Algorithm 1: Optimized Transceiver Usage in SLA Differentiated Protection for C+L Bands

Given: Physical network topology, $\mathcal{G} = (\mathcal{N}, \mathcal{E})$
Sets of link-disjoint and non-disjoint *K*-shortest distance paths for each *s*-*d* pair
Input: An incoming connection request $\boldsymbol{R}(\boldsymbol{s}, \boldsymbol{d}, \boldsymbol{\gamma}, \boldsymbol{\tau}, \boldsymbol{SLA})$
Output: Establishment of the connection request

Auxiliary Procedures:
primary_backup_spectrum_found(*L-band*)
primary_backup_spectrum_found(*C-band*)
primary_backup_spectrum_found(*C+L*)
primary_spectrum_found(*L-band*)
backup_spectrum_found(*C-band*)

```
if SLA = "gold":
   # Use the DPP method
   Step 1: Attempt to establish the primary and
   backup connections over the L-band with
   transceiver sharing.
   if primary_backup_spectrum_found(L-band):
      return "Connection established in L-band"
   else:
      Step 2: Attempt to establish the primary and
      backup connections over the C-band with
      transceiver sharing.
      if primary_backup_spectrum_found(C-band):
         return "Connection established in C-band"
      else:
         # transceiver sharing fails
         Step 3: Apply the original DPP [14]
         if primary_backup_spectrum_found(C+L):
            return "Connection established"
         else:
            # All options fail
            return "connection blocked"
if SLA = "silver plus":
   # Use the hybrid approach
   Step 1: # phase 1 of the hybrid approach
   Attempt to establish the primary connection over
   the L-band and the backup over the C-band.
   if primary_spectrum_found(L-band) and
      backup_spectrum_found(C-band):
      return "Connection established"
   else:
      # phase 2 of the hybrid approach
      Step 2: Optimize transceiver usage using the
      DPP method over the L-band
      if primary_backup_spectrum_found(L-band):
         return "Connection established in L-band"
      else:
         Step 3: Optimize transceiver usage using the
         DPP method over the C-band
         if primary_backup_spectrum_found(C-band):
            return "Connection established in C-band"
         else:
            # transceiver sharing for phase 2 of the
            hybrid approach fails
            Step 4: Apply the original version of phase
            2 for the hybrid approach [14]
            if primary_backup_spectrum_found(C+L):
               return "Connection established"
            else:
               # All options fail
               return "connection blocked"
```

III. Simulation Setup and Results

In this section, the proposed variation of the SLA-differentiated protection mechanism in C+L band systems is evaluated. The performance evaluation is performed using a discrete-event Python simulator. For the implementation of C+L optical line system, we consider the separate amplifiers architecture as described in Section I. In the simulation, it is assumed that the required 400 GHz guard band between the C-band and the L-band is deducted from the L-band spectrum. As a result, this architecture provides 320 frequency slot units for the C-band and 516 frequency slots for the L-band. The NSFNet topology, which includes 14 nodes and 21 bidirectional links is considered for the network performance assessment. The simulation operates in an online environment where the connection requests are handled dynamically. This means that an established connection is released (the allocated resources will be available) after the corresponding service time ends. The service time of connections are modeled by an exponential distribution with an average duration of T, and they are generated from a Poisson process with arrival rate λ. The source and the destination for every incoming connection request are assigned based on a uniform distribution. The potential data rates that every connection request may demand are uniformly distributed, ranging from 12.5 Gb/s to 300 Gb/s in steps of 12.5 Gb/s. Data analysis is based the assumption that $10^4 + 10^5$ connections enter the network, with the first 10^4 connections are used to approximate a steady state of the network. The traffic load in this paper is based on the normalized traffic load defined in [15] and is calculated by Equation (1). In addition to the parameters used to calculate the classical traffic intensity or offered load in Erlangs (λT), this equation incorporates three additional parameters: the number of nodes (N) in the network, the average data rate (C_{avg}), and the maximum data rate of connections (C_{max}).

$$Load = \frac{\lambda T}{N(N-1)} \times \frac{C_{avg}}{C_{max}} \quad (1)$$

where $C_{\text{avg}} = (C_{\text{min}} + C_{\text{max}})/2$.

As mentioned in Section I, the RBMLSA algorithm is employed to meet the requirements of the incoming connection requests. For the sets of link-disjoint and non-disjoint paths, the *K*-shortest paths algorithm with *K*=5 is considered. Once the appropriate spectral band and modulation format is selected, the spectrum assignment should be done. The strategy used in this paper for solving the spectrum assignment follows the Best-Fit policy. This policy guarantees that among the available blocks of frequency slots, those closest in size to the requested slots are given priority. This policy combined with an optimized level of modulation ensures efficient spectrum utilization.

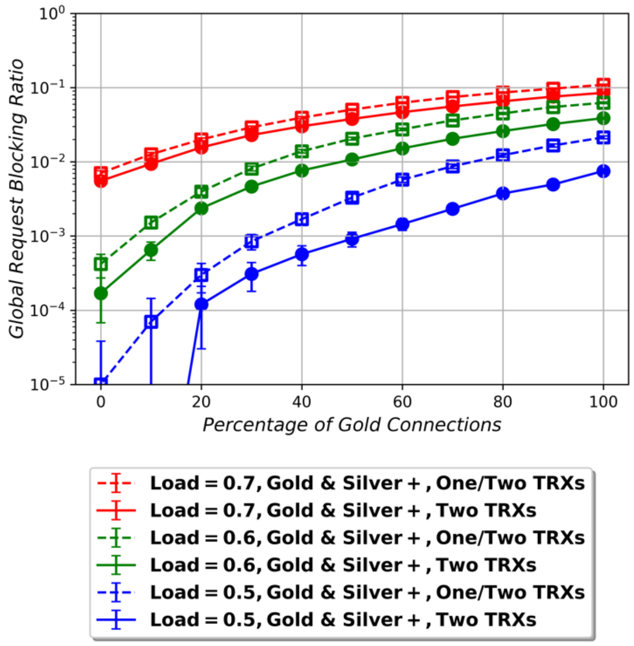

Fig. 2 Global request blocking ratio versus the percentage of "gold" connections at different traffic loads with and without transceiver sharing.

Fig. 2 compares the proposed variation of the SLA differentiated protection method with the original approach [14] in terms of global request blocking ratio. The modified version of the SLA method is represented by dashed lines, while the solid lines correspond to the original SLA strategy. The modification allows the DPP method ("gold" SLA) and the second phase of the hybrid approach ("silver plus" SLA) to attempt using a single transceiver for both primary and backup lightpaths. The increased blocking ratio observed in transceiver-sharing scenario is due to the cases where connections are established by allocating the exact same spectral resources within the same band to the primary and backup lightpaths. As a result, subsequent connections even in the second attempt (with separate transceivers) may struggle to find continuous frequency slots in the C-band or the L-band.

Fig. 3 focuses on the performance of "silver plus" SLA, comparing the transceiver-sharing scenario used in the second phase of the hybrid approach with the original hybrid approach, where separate transceivers are used for the primary and backup connections. In Fig. 4, the impact of transceiver-sharing for the primary and backup connections in the DPP method ("gold" SLA) is shown. It can be observed that similar to the global request blocking ratio and "silver plus" blocking ratio, the modified SLA method leads the blocking ratio of "gold" SLA to be increased.

Although the proposed modification of the SLA mechanism increases the blocking ratio, it leads to significant savings in the number of costly transceivers required. As shown in Fig. 5, enabling the DPP method and the hybrid approach to employ a single transceiver for the primary and backup connections (at least for the first attempt of connection establishment) results in a 25% to 50% reduction in transceiver usage, when at least 50% of the incoming connections belong to the "gold" SLA.

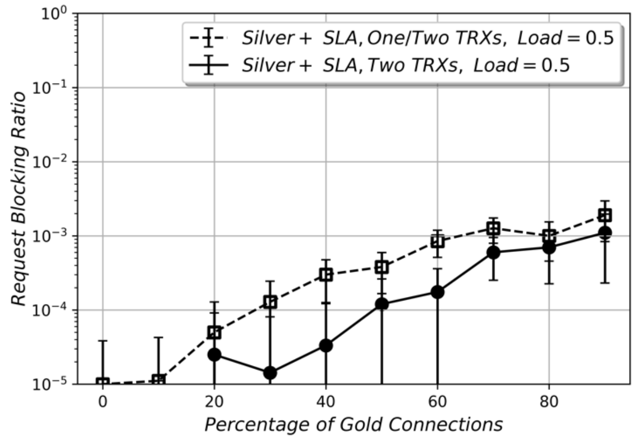

Fig. 3 Request blocking ratio of "silver plus" SLA category versus the percentage of "gold" connections with and without transceiver sharing.

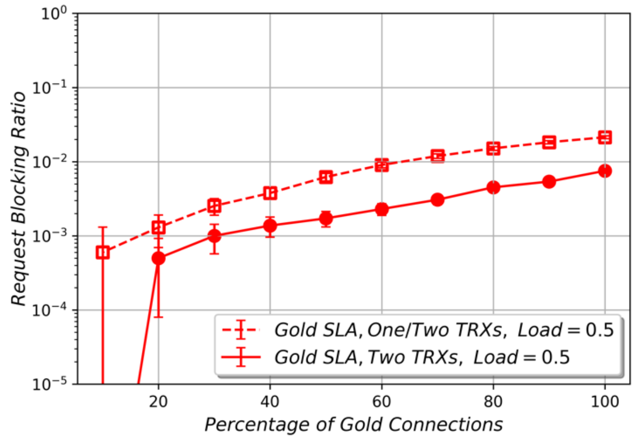

Fig. 4 Request blocking ratio of "gold" SLA category depending on the percentage of "gold" connections with and without transceiver sharing.

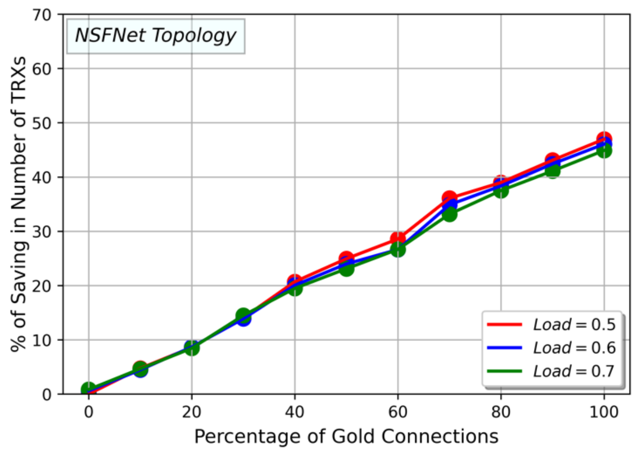

Fig. 5 The percentage of saving in the number of transceivers at different levels of "gold" connections.

IV. CONCLUSIONS

In this paper, we have proposed a variation of the SLA differentiated protection method for C+L band optical networks proposed in [14]. The main objective of this variation is to optimize transceiver usage in 1:1 protection scenarios. Similar to the original strategy, the variation uses the DPP method for the "gold" connections while the "silver plus" connections are protected using the hybrid approach. However, we modify the protection methods so that, in the first attempt, the primary and backup connections try to share a single transceiver. Therefore, during the initial attempt, the primary and backup lightpaths are restricted to using the same spectrum range within the same spectral band. In case of failure in finding the exactly the same range of spectrum within one spectral band, the second attempt is performed, which allows the primary and backup lightpaths to employ separate transceivers. Since in the first phase of the hybrid approach, different spectral bands must be used for the primary and backup connections, this modification is only applied to the DPP method and the second phase of hybrid approach. The simulation results have demonstrated that although the proposed modification may slightly reduce network performance in terms of blocking probability, it leads to significant savings in the number of transceivers required. For instance, up to 50% transceiver savings can be achieved when all incoming connections are assigned to the "gold" SLA.

Future research could explore the impact of the analyzed SLA methods on transceiver utilization efficiency when considering different types of transceivers in C+L band networks, particularly single-band and multi-band transceivers.

REFERENCES

[1] D. Uzunidis, et al., "Strategies for upgrading an operator's backbone network beyond the C-band: Towards multi-band optical networks., IEEE Photonics Journal, 13(2), 2021.

[2] J. K. Fischer, et al., "Maximizing the capacity of installed optical fiber infrastructure via wideband transmission," International Conference on Transparent Optical Networks (ICTON), Bucharest, Romania, 2018.

[3] A. Napoli, et al., "Towards multiband optical systems,", Photonic Networks and Devices (Optica Publishing Group), Jul. 2018, paper NeTu3E.1.

[4] N. Sambo, et al., "Provisioning in multi-band optical networks," Journal of Lightwave Technology, 38, 2598–2605, 2020.

[5] A. Ferrari, et al., "Assessment on the achievable throughput of multi-band ITU-T G. 652. D fiber transmission systems," Journal of Lightwave Technology, 38, 4279-4291, 2020.

[6] E. Virgillito, et al., "Network performance assessment of C + L upgrades vs. fiber doubling SDM solutions," Optical Fiber Communication Conference (OFC), San Diego, CA, USA, March 2020, paper M2G.4.

[7] M. Cantono, et al., "Opportunities and challenges of C+L transmission systems," Journal of Lightwave Technology, 38, 1050–1060, 2020.

[8] M. Nakagawa, et al., "Performance evaluation of multi-band optical networks employing distance-adaptive resource allocation," Opto-Electronics and Communications Conference (OECC), 2020.

[9] Z. Luo, et al., "Survivable routing, spectrum, core and band assignment in multi-band space division multiplexing elastic optical networks," Journal of Lightwave Technology, vol. 40, no. 11, pp. 3442-3455, 2022.

[10] S. Hosseini, et al., "Survivability against Amplifier Failures in Multi-band Elastic Optical Networks," Asia Communications and Photonics Conference (ACP), pp. 1299-1302, IEEE, China, 2022.

[11] R. K. Jana, et al., "Effect of fill margin on network survivability for C+ L band optical networks," Presented at European Conference on Optical Communications (ECOC), Glasgow, UK, Oct. 1-5, 2023.

[12] F. S. Abkenar, et al., "Providing quality of service (QoS) for data traffic in elastic optical networks (EONs)," Arabian Journal for Science and Engineering, vol. 41, pp. 797-806, 2016.

[13] A. Agrawal, et al., "SLA-aware differentiated QoS in elastic optical networks," Optical Fiber Technology, vol. 36, pp. 41-50, 2017.

[14] S. Hosseini, et al., "Enabling Service Level Agreement-Differentiated Protection in C+L Multiband Optical Networks," IEEE Open Journal of the Communications Society, vol. 6, pp. 316-331, 2024.

[15] L. Ruiz, et al., "Routing, modulation and spectrum assignment algorithm using multi-path routing and best-fit," IEEE Access, vol. 9, pp. 111633, 2021.