Minimizing Traffic Disruptions in 6G-Ready Optical Transport Networks

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***Abstract*—As traffic keeps increasing, the impact of connection disruption in case of link failures becomes critical for operators. In order to reduce any connection disruption, there is a need for a spectrum efficient and traffic agnostic recovery scheme. In this paper, we present and evaluate the performance of a link restoration mechanism for flexible optical networks in a multi-period scenario. The proposed method uses spectrum redistribution and an MILP based path restoration method to recover disrupted traffic, along with regeneration capabilities. The paper also investigates spectrum reservation to aid the restoration with increasing traffic. The performance of the restoration mechanism is evaluated with 3 metrics and compared with a dedicated protection scheme over a Nobel-Germany network. The results show the proposed scheme is able to restore upto 80% of the disrupted traffic in the worst case scenario, with spectrum reservation and exhaustive path selection providing further improvement in terms of restoration.**

I. Introduction

With the ever-increasing requirement for high bandwidth by development of data driven Internet services, as well as emerging paradigms such as 6G, optical transport networks (OTN) need to cope with the increasing traffic. OTN planning with efficient spectrum utilization is a major necessity. With the development of flex-grid bandwidth variable transponders (BVTs), network operators can choose different configurations for each lightpath (LP), in terms of datarate, modulation scheme and Forward Error Correction (FEC) [1]. The increasing traffic further emphasizes the importance of network failure management and spectrally efficient network recovery. Network failures need to be managed with minimum network downtime and spectrum-effective recovery of the lost traffic to maintain availability and improve the reliability of the optical network. The recovery mechanisms can be proactive, such as dedicated or shared *protection*; or reactive, such as link or path *restoration* [3]. The cost of redundancy of creating multiple link-disjoint paths in terms of spectrum utilization leads to lower spectrum availability over the years.

In this paper, we consider the restoration approach, which recovers the lost traffic by rerouting the disrupted LPs. We introduce a restoration scheme for link failures, referred as **Spectrum-Aware Path Restoration**, which optimizes the spectrum utilization and provides path restoration based on available k-shortest paths. We also consider an approach to reserve a part of the spectrum for the restoration process, and try to determine the optimal reserved spectrum to maximize the performance of the restoration scheme, while minimizing its impact prior to network failure. We also propose exhaustively selecting new disjoint paths to restore as a solution. We explore the effect of the proposed restoration scheme and a dedicated protection scheme, under increasing traffic demands in a multi-period planning scenario, and aid operators to determine the bottlenecks in efficient network planning for failure management.

The rest of the paper is structured as follows: Section II highlights the related work in different recovery methods, and Section III focuses on the implementation of the proposed restoration mechanism. We introduce the proposed MILP as well as the spectrum reservation. Section IV presents the observed results, including the optimal spectrum reserving ratio, as well as its performance compared to a dedicated path protection mechanism, followed by concluding remarks in Section V.

II. Related Work

The different approaches to network recovery have been widely discussed in the previous literature [3] - [10]. Authors in [3] introduce the concept of survivability and gives an overview of link based and path based dedicated and shared protection schemes. The authors in [4] use numerical models and heuristics for reconfiguration, routing and spectrum allocation for different failure scenarios. [5] considers dual failure scenario, and uses an adaptive restoration scheme to recover from dual link failures under static traffic. [6] uses p-cycles based heuristic for a shared restoration scheme in WDM networks.

The authors in [7] use a meta heuristic, namely Ant colony optimization (ACO), for provisioning LPs based on the frequency slots available on every subsequent hop during routing. Different service types are considered, although with only limited duration of LP of 100 s. [8] uses protection and restoration jointly to recover single failures. The authors in [9] reserves resources for restoration, but does not account

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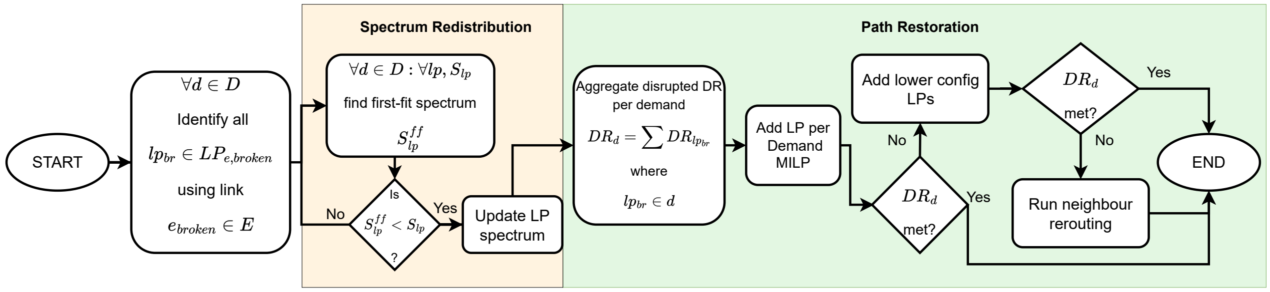


Fig. 1: Flowchart showing the proposed restoration algorithm.

of the variation in the demand traffic increase. [10] uses reinforcement learning to perform autonomous restoration, under different failure scenarios.

In all previous works, the traffic considered does not grow with time, and in cases of traffic variations, the LP provisioning is time limited. Within the scope of this paper, we intend to answer the following:

- The impact of traffic demand increase on the restoration capability, within the spectrum availability and yearly increasing traffic constraints. Furthermore, the paper intends to exploit the spectrum to improve the restoration capability.
- The impact of using regeneration to restore link failures, in order to maximize the spectrum utilization.
- The impact of reserving a portion of the spectrum solely for restoration, and finding the optimal ratio with minimum effect on normal operation and maximum improvement in restoration.

III. Implementation

In this section we present the problem formulation of the path restoration mechanism. The requested traffic generally increases with each planning period, thereby requiring efficient routing, configuration selection and spectrum allocation (RCSA) to reduce underprovisioning and increase spectral efficiency. The traffic model proposed in [1] has been used to allocate the traffic of each demand per planning period. The RCSA and LP provisioning prior to the failure has been discussed in [11]. In this paper, we also consider regeneration [12] and present the results for C-band RCSA and regeneration separately.

A. System Model Input

The network topology is represented as a graph $G(V, E)$ with V nodes and E links. We consider the set of demands $d \in D$, each with the required datarate of $DR_{d,t}$ for a given time $t \in T$. Each demand is met using one or multiple LPs such that the sum of datarates of the LPs is at least equal to $DR_{d,t}$ to prevent underprovisioning (UP). The routing of each LP is achieved using Yen's k-shortest path algorithm, which finds the $k \in K_d$ non disjoint shortest paths. Each LP is characterized by its routed path and configuration. A set of configurations are available for selection for each LP, where each configuration $c \in C$ is defined in terms of its datarate DR_c, modulation format, required bandwidth BW_c, required OSNR, and required launch power. The configuration selection is based on multiple parameters, including $DR_{d,t}$ and available spectrum on the selected shortest path. The set of demands are provisioned sequentially using the RCSA for each planning year and requested datarate [11]. The link failure is simulated once all the requested traffic for the given planning period has been addressed and LPs allocated. In our study, we consider single link failures that cause disruption of all LPs traversing through the failed link.

The proposed restoration algorithm is summarized in Fig. 1. The algorithm is triggered by the link to fail, denoted as $e_{broken} \in E$ and it is executed for all $e \in E$ for the performance evaluation. For each $e_{broken} \in E$, the first step is to identify all the disrupted LPs affected by e_{broken}, which are denoted by $LP_{e_{broken}}$. Since each traffic demand is met using a set of LPs, $LP_{e_{broken}}$ are also grouped in terms of their associated demand.

B. Algorithm Design

1) Spectrum Redistribution: In the underlying RCSA mechanism, we use a first-fit (FF) spectrum allocation method. The spectrum on the working links, previously utilized by the disrupted LPs, can be reallocated to the working LPs using FF, thereby maximizing the contiguous slots. This is done prior to the restoration, which is indicated as **Spectrum redistribution** in the flowchart. Since a large number of LP spectrum reallocation can disrupt the working network, we intend to strike a balance between number of LPs being reallocated to the improvement in the restoration of the disrupted LPs.

2) Add LP per Demand: The first module of the path restoration scheme aggregates the datarate of all interrupted LPs of demand d, which is considered as the new requested traffic for the demand. The LP placement module, referred as **Add LP per Demand**, intends to find a replacement set of LPs per demand d, using an MILP. For this purpose, the module finds new LP(s) on subset of shortest paths, configurations and remaining spectrum to restore the disrupted traffic of each demand. Given the set of disrupted LPs $lp_{br} \in LP_{e_{br}}^{broken}$, mapped for demand d and previously provisioned with configuration c (datarate DR_c, required bandwidth BW_c) on path k, the valid shortest paths $K_d^{valid} \subseteq K - k$ are selected from the k-shortest paths, which do not include e_{broken}. For each k-shortest path $k' \in K_d^{valid}$, a subset of valid

Symbol	Description
$G(V,E)$	Network Graph with V nodes and E links
V	Set of optical add/drop nodes
E	Set of links with single mode fiber pairs
T	Planning time horizon, $t \in T$
D	Set of demands $d \in D$
$LP_{e_{br}}^{broken}$	Set of LPs disrupted due to link failure at link e
C	Set of configurations $c \in C$
BW_c	Bandwidth required for configuration c
K_d	Set of k-shortest paths $k \in K_d$
DR_{lp}	Datarate of LP $lp \in LP_d$
LP_d	Set of placed LPs for demand d
CR_c	Datarate provisioned using configuration c
δ	Permissible overprovisioning
S_{dk}	Maximum number of contiguous slots for d on k path, with each slot 12.5 GHz

TABLE I: Notations

configurations $\widetilde{c} \in \widetilde{C}_{d,k'}^{valid} \subseteq C$ is created for consideration in LP provisioning. The configuration c' is valid on path k' if the bandwidth requirement is lower than the maximum contiguous slots available at k'. The smaller the subset of configurations, the harder the provisioning of configurations with higher bandwidth, which cannot be placed due to spectrum unavailability. The relaxation of the bandwidth requirements allows the placement of LPs on links with densely occupied spectrum at the cost of lower datarate. If $\widetilde{C}_{d,k'}^{valid} = \emptyset$, the path k' is regarded as invalid for provisioning.

The output of the MILP is a set of provisioned LPs, which are then placed using FF spectrum allocation, that conserves the spectrum continuity and contiguity constraints. The MILP is modeled as a multi-objective optimization problem, with the primary objective of minimizing the number of BVTs used to meet the requested traffic (i.e., minimizing the required LPs), and a secondary objective of maximizing the overall datarate of the provisioned LPs in order to cope with the expected increase of traffic of the next time periods. However, a maximum overprovisioning δ is allowed for each demand in a time period. In our study, we keep $\delta = 100\ Gbps$ to ensure all provisioned LPs can cope with the lost datarate when placed. The proposed MILP model uses the following decision variable:

$X_{d,lp,\widetilde{c},k'}$ An integer decision variable to determine number of LPs provisioned for the broken LP lp_{br}, previously mapped for demand d with configuration $\widetilde{c}$ on path $\widetilde{k}$

The MILP model is formulated as:

$$obj1 : \min \sum_{\substack{\widetilde{c} \in \widetilde{C}_{d,k'}^{valid} \\ k' \in K_d^{valid}}} 2X_{d,lp,\widetilde{c},k'} \tag{1}$$

$$obj2 : \max \sum_{\substack{\widetilde{c} \in \widetilde{C}_{d,k'}^{valid} \\ k' \in K_d^{valid}}} CR_c X_{d,lp,\widetilde{c},k'} \tag{2}$$

subjected to following constraints:

$$\sum_{\substack{\widetilde{c} \in \widetilde{C}_{d,k'}^{valid} \\ k' \in K_d^{valid}}} CR_{\widetilde{c}} X_{d,lp,\widetilde{c},k'} \geq DR_{lp_{br}} \tag{3}$$

$$\sum_{\substack{\widetilde{c} \in \widetilde{C}_{d,k'}^{valid} \\ k' \in K_d^{valid}}} CR_{\widetilde{c}} X_{d,lp,\widetilde{c},k'} \leq DR_{lp_{br}} + \delta \tag{4}$$

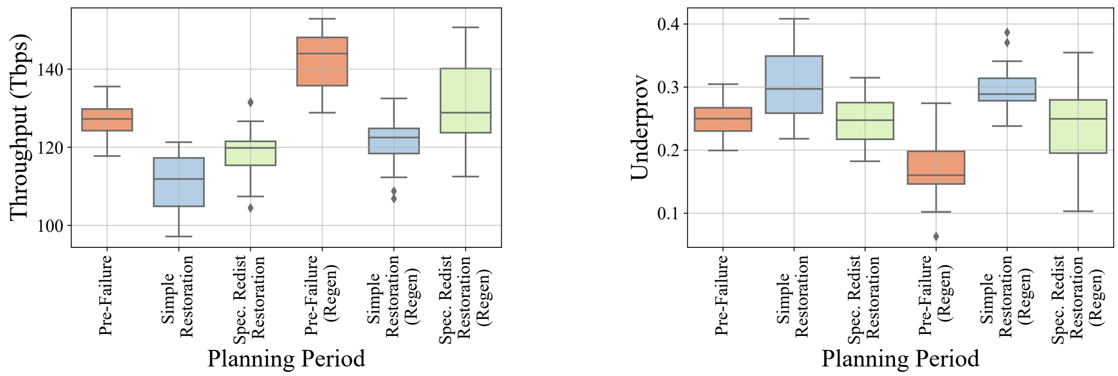
$$BW_{\widetilde{c}} X_{d,lp,\widetilde{c},k'} \leq 12.5 S_{d,k'},\ \forall \widetilde{c} \in C_{d,k'}^{valid}, k' \in K_d^{valid} \tag{5}$$

The first objective (Eq. (1)) minimizes the number of BVTs required for setting up the broken LP. Since each LP only requires 2 BVTs, this objective can also be referred as minimization of the number of provisioned LPs. The second objective (Eq. (2)) maximizes the datarate provisioned for the demand traffic. The constraints in Eq. (3) and Eq. (4) ensure that the provisioned LPs satisfy the required datarate. Eq. (3) ensure that the datarate of the optimal LPs selection can at least satisfy the demand traffic. The Eq. (4) counters the previous constraint by limiting the datarate overprovisioning by a fixed amount δ. Due to stringent bandwidth constraints requirement and lack of spectrum availability, the constraint in Eq. (5) forces the selection of configurations with bandwidth lower than the contiguous bandwidth available at a given shortest path.

The LPs are placed sequentially for all demands and non-linear interference (NLI) η_{NLI} and OSNR are calculated. The NLI coefficient is calculated using an ACF-EGN model [13], which is used to calculate the overall received OSNR, when the signal is transmitted over all links. The provisioned LPs with OSNR lower than required OSNR by the configuration are blocked.

3) Add LPs of Lower Configurations: Due to spectrum unavailability or valid shortest paths, the MILP might not be able to fully restore the requested traffic. The remaining traffic is restored by exhaustively and recursively placing LPs with less bandwidth stringent configurations. Lower bandwidth implies lower datarates, and thus the module is aptly named **Add Lower Config LPs**. The algorithm iterates over each valid path and uses a subset of valid configurations c' are selected for each k'. The LP can only be added if it satisfies the spectrum contiguity constraint over the path and OSNR requirements. If the demand is still not restored, **Run Neighbour Rerouting** module is used, where the working LPs are rerouted to create free slots neighbouring the LP of the considered demand. The LP can be upgraded to configurations with higher datarate, as more BW is available.

4) Spectrum Reservation and Infinite Disjoint Path Restoration: In addition to rerouting and adding LPs with lower datarates, other approaches are considered to increase spectrum availability. Since the FF spectrum allocation method is used, the available spectrum over different shortest paths decreases with increasing traffic, which is further limited when a link failure occurs. In order to maximize the available spectrum during the restoration period, a part of the spectrum



(a) Throughput

(b) Underprovisioning

Fig. 2: Comparison of performance of proposed restoration scheme with and without spectrum redistribution in Nobel-Germany topology for the final planning year.

is reserved only for restoration. A percentage of slots are reserved over all links, when placing LPs during normal operation, and only made available when a link failure occurs, and restoration mechanism is used to place the new LPs. The objective is to reserve the spectrum to maximize the spectrum availability during restoration while meeting the requested traffic demand. This optimal ratio is discussed in the next section. Furthermore, we also consider finding new disjoint paths in case the restoration is not completed by the algorithm in Fig. 1. For a given demand, if the placed LPs do not completely restore the lost datarate, the algorithm finds new paths, disjoint from the the k-shortest paths and places LPs if spectrum is available. The exhaustive nature of the method aids in increasing spectrum utilization, but can also lead to blocking of subsequent placement of newer LPs.

IV. Evaluation and Results

The proposed model is applied to several network topologies, which showed a similar trend in results. Due to lack of space, we have included the results of Nobel-Germany topology ($|V| = 17$, $|E| = 6$ and $|D| = 123$, $diameter = 992.2km$) for $T = 10$ years. The set of demands are defined by each source-destination node pair in the network, $|D| = 123$. The datarates of each demand is defined by a traffic model [1], which increase every planning year. We consider 26 possible configurations C with datarate between 100-600 Gbps with steps of 50 Gbps, QPSK, 8QAM, 16QAM, 32QAM, 64QAM, and 7%, 15%, 27% FEC overhead. The RCSA model performs spectrum allocation on C-band, which is defined as 400 slots with 12.5 GHz granularity. At each planning period, the demands are served with the LPs resulting from the RCSA. Then, all the link failure scenarios are emulated individually and sequentially. The proposed framework has been implemented in Java, and all simulations are run on Intel Core i7-10800H 2.70 GHz, 32 GB of RAM, running Windows 10. Each scenario is ran for 30 iterations to account for the random variation in traffic. The proposed path restoration mechanism is evaluated based on 3 metrics:

- Throughput: It is defined as the aggregated datarates of all placed LPs in a given planning year.
- Underprovisioning: The underprovisioning ratio (UP) quantifies the number of demands which were not fully satisfied. The distribution of the throughput over all demands can be better assessed with the UP ratio, which is defined as

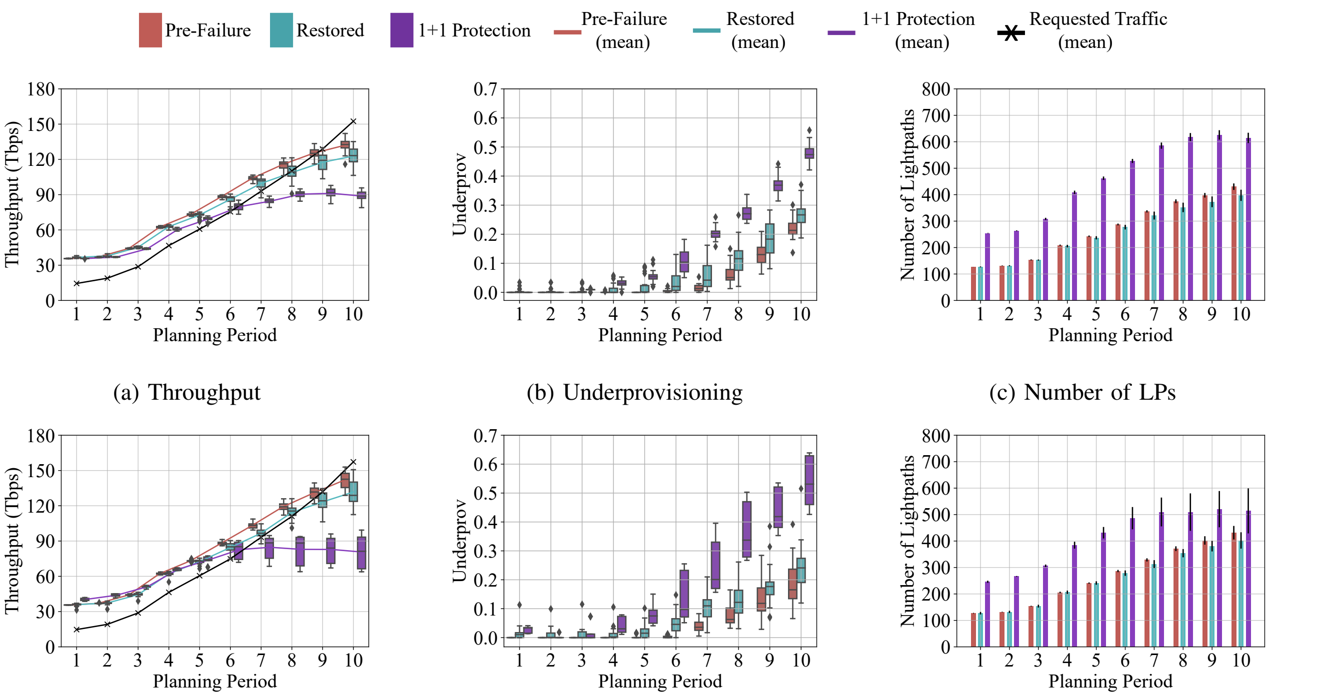
$$UP = \frac{\sum_{\forall d^{‘} \in D^{‘}} (DR_{d^{‘}} - \sum_{\forall lp \in LP_{d^{‘}}} DR_{lp})}{\sum_{\forall d \in D} DR_d} \tag{6}$$

  where $D^{‘} \subseteq D$ are underprovisioned demands, such that $(DR_{d^{‘}} - \sum_{\forall lp \in LP_{d^{‘}}} DR_{lp}) > 0 \forall d^{‘} \in D^{‘}$.
- The number of LPs.

In the presented results, we compare the performance of the proposed restoration algorithm with the normal operation scenario, where no failure is considered (referred as pre-failure), and a dedicated protection scheme (1+1 protection).

A. Impact of Spectrum Redistribution

In order to study the impact of spectrum redistribution, we compare its performance with the restoration algorithm without this redistribution. The spectrum distribution does not reallocate any LPs till year 7 and shows the maximum effect in the final planning year. In Fig. 2, we compare the throughput and UP for three scenarios: pre-failure, simple restoration and restoration with spectrum redistribution. Since the set of broken LPs vary with every link failure, the average over all links is presented. In the final planning year, 15 LPs out of 432 working LPs are reallocated. The Throughput in case of failure is lower than before failures as expected. The metrics indicate that due to spectrum redistribution, the restoration scheme is able to provision and place LPs with higher datarates, thereby increasing the aggregated throughput. With spectrum redistribution, the throughput increases by 8%. The advantage of regeneration can be observed in all cases, with an increase of at least 12% of their counterpart. The higher throughput is also associated to a lower UP (see Fig. 2b). It can be observed that an average of 25% and 18% UP occurs without and with regeneration due to the large demands in the final year. We



(a) Throughput (b) Underprovisioning (c) Number of LPs

(d) Throughput(regen) (e) Underprovisioning (regen) (f) Number of LPs (regen)

Fig. 3: Performance of proposed restoration scheme (with spectrum redistribution) in Nobel-Germany topology with C-band ((a), (b) and (c)) and regeneration enabled ((d), (e) and (f)) LPs.

also see a 3% decrease in UP with spectrum redistribution. The number of LPs are not shown in the plots as there is negligible change.

B. Impact of Regeneration

Fig. 3 shows the three metrics comparison for the pre-failure, protection and the proposed restoration scheme (with spectrum redistribution) for the Nobel-Germany topology. It can be observed, that the proposed restoration scheme is able to restore the throughput with all link failures till year 5 (Figs. 3a and 3d). In terms of spectrum utilization, the maximum utilized link uses 371 out of 400 frequency slots in the final year. Therefore, the limited spectrum on bottleneck links and already placed LPs lead to spectrum unavailability, restricting the placement of new LPs to meet the requested traffic as well as for restoration. The restoration method is able to cope with upto 60% lost traffic in the final planning year. The traffic can be met by increasing the spectrum capacity of the links. Regeneration is able to improve the restored throughput, restoring more than 80% of the lost traffic in the final planning year. The 1+1 protection scheme is able to overprovision during the initial planning periods by rerouting [11], but fails to cope with the traffic due to unavailable protection paths and spectrum unavailability. The spectrum utilization has minimum difference when regeneration is applied.

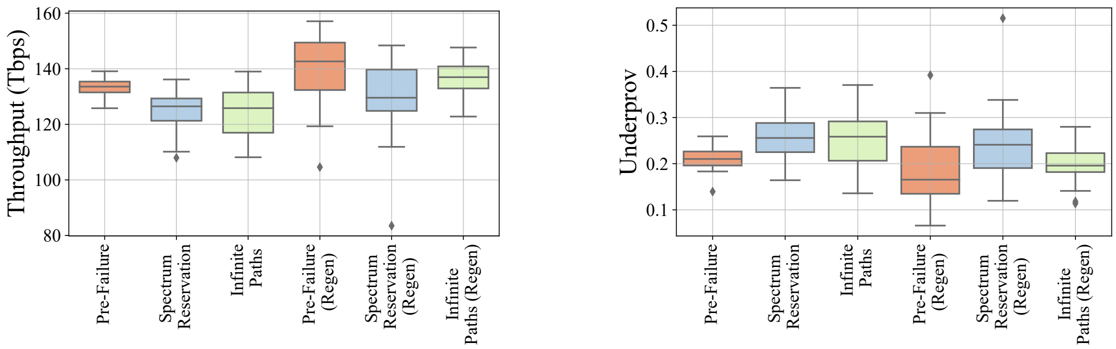
The restoration method provides a very comparable UP to pre-failure operation (Fig. 3b and 3e). In cases of failure of a LP dense link, the UP increases, however the median remains close to the pre-failure scenario. An improvement is observed in the UP with regeneration, which further corroborates that regeneration can help in coping with the increasing traffic. The number of LPs (see Figs. 3c, 3f) are equal for pre-failure and restoration for the initial years, indicating complete restoration. For the subsequent years, the difference in LPs show that some failed LPs are not restored. The number of LPs highlights the spectrum unavailability issue for protection scheme. It is double for 1+1 protection at initial years, but due to lack of spectrum, no protection paths are found and the LPs are blocked, resulting in lower throughput.

C. Impact of Spectrum Reservation

In this study, we also consider reserving different ratios of the resources for increasing the available spectrum during restoration, ranging from 10% to 25% of the total 400 slots on each link. We only reserve from the back end of the spectrum to keep the reserved slots contiguous over all links. This also causes the least interference in the FF spectrum allocation. To find the optimal ratio, we look at the worst case UP difference between pre-failure and restoration in the final planning year. The results are tabulated in Table II.

Percentage of backup resources	C-band	C-band (regen)
10%	0.06	0.02
15%	0.1	0.03
20%	0.12	0.07
25%	0.15	0.12

TABLE II: Worst-case difference in UP with restoration when spectrum is reserved.



(a) Throughput (b) Underprovisioning

Fig. 4: Comparison of performance of spectrum reservation and infinite disjoint paths restoration in Nobel-Germany topology for the final planning year.

The UP difference was the least with 10% spectrum reservation with and without regeneration. Due to lack of space, we compare the performance of **Spectrum Reservation** with **Infinite Paths** restoration, with and without regeneration for the final planning year (Fig. 4). In terms of throughput, spectrum reservation performs better than restoration with spectrum redistribution (see Fig. 2) by almost 7 Tbps. The infinite paths restoration provides further improvement in throughput. In the worst case link failure scenario, the infinite paths restoration fails, as it is not able to find new disjoint paths to restore the lost traffic. The reserved spectrum restores upto 80% throughput in the final year. In case of regeneration, the throughput improvement is higher in case of infinite paths restoration, with upto 90% throughput being restored. Use of regenerators allow for finding new paths and placing regenerators to achieve a higher throughput. The UP ratio for spectrum reservation shows an improvement of by 0.05 from spectrum redistribution scheme and an average improvement by 30%. The infinite paths restoration shows a similar performance, but with lower UP in the best case scenario. Similar to throughput, the infinite paths restoration performs much better than the spectrum reservation in terms of UP, with only 0.03 higher than the average pre-failure. This implies that all demands are equally satisfied with the exhaustive approach. Further improvements would require change in technology to cope with the increasing traffic, such as band division multiplexing.

V. Conclusion

This work present a multi-period planning study of failure management and restoration methods. The results show the proposed method can cope with link failures as long as the traffic demands can be met prior to link failure. The proposed algorithm provides full restoration in the first 5 years with the final year restoration of 60% and 80% throughput without and with regeneration respectively. We find the optimal spectrum reserving ratio to be 10%, with improvements in terms of throughput and UP. With spectrum reservation, the final year restoration throughput increases to 80% and 90% without and with regeneration respectively. Further improvement in restoration can only be accomplished by increasing the spectrum capacity (e.g, multiband). Regenerators can aid in improving the restoration process within the capacity limit.

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