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Dynamic Restoration Assessment in Partially Upgraded Networks from the C to the C+L bands

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***Abstract*—The attraction of new services and applications over the Internet makes it critical for the network operators to increase the capacity of optical networks. To this end, multi-band elastic optical networks (MB-EON) are at the forefront of this capacity improvement for the short and medium term. These networks employ additional spectrum bands from the optical fiber other than the C (conventional) band. Due to the current availability of L-band erbium doped fiber amplifiers (EDFAs), lighting up the L-band of already installed fibers is considered as a pragmatic approach. However, network operators envision a soft migration from current C-band to fully upgraded C+L-bands networks in order to distribute the high cost of equipping all fibers and nodes of a network with multi-band devices over several years. Therefore, it is essential to propose solutions for scenarios where just a subset of network elements has been upgraded, i.e., to consider a hybrid C/C+L optical network rather than a fully upgraded one. As using the L-band besides the C-band doubles the network capacity, the management of the potential fiber failures is an important factor. In this work, the focus is set on the evaluation of the network performance, when considering different levels of partial migration, and comparing the use of dynamic restoration versus dedicated protection. Simulation results demonstrate that the usage of dynamic restoration, mainly in the middle stages of migration towards a fully upgraded network can remarkably boost the supported traffic load compared to the use of dedicated protection.**

***Keywords*—multiband systems, partial migration, dynamic restoration, protection, network performance, bandwidth blocking ratio.**

I. Introduction

The increasing demand for telework platforms, E-meetings, social media, and so on over the past years increases the probability of network traffic congestion [1]. Network operators and the research community are committed to responding this challenge by improving the spectral efficiency and capacity of the already installed optical fibers. To this end, a promising mid-term solution is to efficiently use the spectral bands of the existing fibers through the application of multi-band elastic optical networks (MB-EON) [2, 3]. Band division multiplexing (BDM) is performed through the use of different windows for optical transmission in a single optical fiber. The employment of O-, E-, S- and/or L-bands along with the conventional C-band spectrum provides a capacity of around 54 THz [4].

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Despite the potential of MB systems for capacity improvement, the implementation of these systems is not mature, requiring different types of doped fiber amplifiers (DFAs) for different spectral bands which are not commercialized yet. However, L-band ready erbium DFAs (EDFAs) makes it possible for the network operators to develop C+L band optical line systems. Therefore, lighting up the L-band, which increases the capacity of optical fibers up to almost two times is at the center of attention.

Realizing a fully upgraded network in which all the optical fibers are equipped with C+L band devices is a costly process. This is due to the expensive nature of optical components like transponders, reconfigurable optical add/drop multiplexers (ROADMs), and EDFAs that should be deployed. In order to get around the high cost of a fully upgraded network realization, the spotlight has been put on the partial migration of a network by several literature reports [5, 6]. In the context of partial migration, it is considered that different optical fibers have different degrees of importance, with some being crucial for the migration in terms of performance improvements. Our proposal in [7] aims at achieving a partially upgraded network through prioritizing the optical fibers, which are more at risk of congestion. In [8], we introduced an integer linear programming (ILP) formulation to determine the set of fibers that should be upgraded with the use of the L-band. The selected set maximizes the number of shortest paths that can benefit from the partial upgrade, with the ultimate goal of minimizing the blocking probability of connection establishment requests. Since the number of required L-band EDFAs that should be installed in different optical fibers is different, the costs of upgrading the existing fibers to the L-band vary. Therefore, in [9], we proposed three different methods for the partial migration of a network taking into account the maximum number of EDFAs that the network operator is willing to upgrade.

By lighting up the L-band, the process of selection between the C-band and the L-band should be incorporated into the algorithm of routing, modulation level, and spectrum assignment (RMLSA) [10], which is employed in the EON architectures to establish new optical connections (lightpaths) in the network. Therefore, in C+L band systems, the routing, band, modulation level, and spectrum assignment (RBMLSA) problem must be solved when receiving connection establishment requests [11]. Regarding modulation level, there is a trade-off between robustness (and thus optical reach) and spectral efficiency. In this work, we consider that the most spectrally efficient modulation format is used, as long as the length of the connection to be established does not exceed the optical reach for that modulation format.

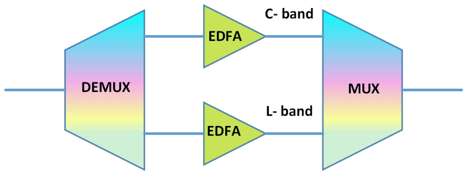

Fig. 1. Separate amplifiers architecture for the implementation of C+L band systems.

Table 1 [12] shows the maximum optical reach for 16QAM and QPSK modulation formats, depending on the selected spectral band. For instance, if the length of a lightpath over the L-band is lower than 330 km, the 16QAM modulation format would be used (enabling the transmission of 4 bits per symbol). Alternatively, if the length of the lightpath is higher than 330 km and lower than 1600 km, the QPSK modulation format (2 bits per symbol) would be selected. Otherwise, the BPSK modulation format should be employed (1 bit per symbol).

The concept of network protection against potential failures has been comprehensively explored in EONs [13]. As C+L band systems increase the capacity of optical networks, survivability against network failures in these systems must get more emphasis. Providing a fully upgraded C+L band network with protection against at least EDFA failures is the focus of our previous work [14]. In contrast, in this study, we evaluate the performance of dedicated protection and dynamic restoration for different levels of partial migration. The process of achieving different levels of partial migration of a network is performed using the algorithm proposed in [8]. The objective of this paper is to analyze the performance of a network in the presence of dynamic restoration during the process of migration from the C-band to the C+L bands.

The remainder of this paper is structured as follows. We first describe the considered scenarios for introducing a link-cut to the network in Section 2. Then, we present the simulation results in Section 3, and finally, Section 4 wraps up the paper.

II. Network Setup and Failure Scenarios

A. Network Setup

To analyze the performance of dynamic restoration and path protection in different scenarios of partial migration, a Python-based MB-EON simulator has been developed. Three geographically different topologies, namely the American NSFNet [15], the Asian JPN12 [16], and the European Deutsche Telekom (DT) network [17] have been considered. The physical characteristics of the analyzed topologies are specified in Table 2, including the number of nodes and the number of bidirectional links. Each fiber consists of the L-band (if upgraded) along with the conventional C-band, including 548 and 320 frequency slots of 12.5 GHz, respectively. For the implementation of the analyzed C+L band network, a demultiplexer and a multiplexer is used to separate and combine the optical signals of both bands. Moreover, signal amplification is performed through the employment of separate EDFAs for each spectral band (see Fig. 1) [18]. While using the above-mentioned architecture for the implementation of C+L band optical line systems, a bandwidth of around 400 GHz is required as the guard-band between the C-band and the L-band. It is worth mentioning that in the simulation, the first 32 frequency slots of the L-

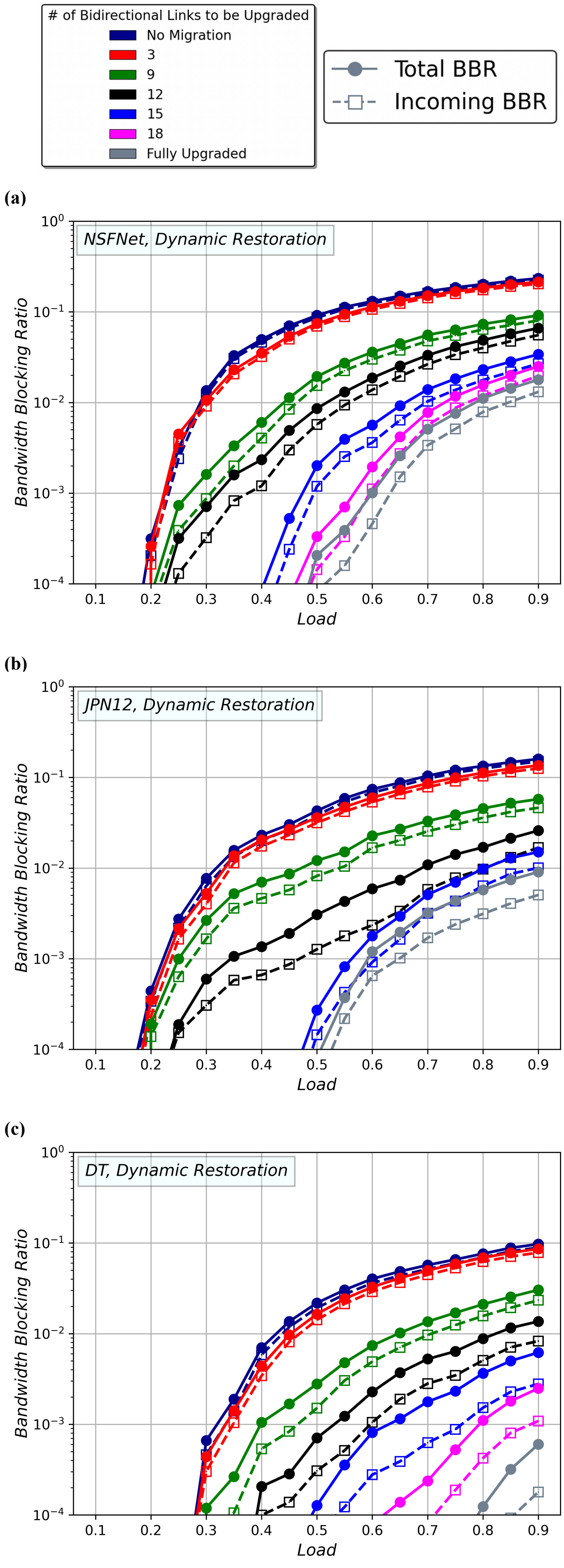

Fig. 2. BBR depending on network load considering partial migration and dynamic restoration in the a) NSFNet, b) JPN12, and c) DT topologies.

band are unusable, as they provide the required bandwidth for the guard-band assignment.

Connection requests arrive randomly according to a Poisson process and, if successfully established, connections are released after an exponentially distributed time. The source and the destination for the incoming connection requests are randomly chosen from a uniform distribution. Potential link disjoint paths between each source-destination pair are precomputed based on the K-shortest paths algorithm with $K = 5$. Assuming the BPSK modulation format, the demanded frequency slot(s) for each connection range from 1 to 24 slots, which is translated to a spectrum request range from 12.5 GHz to 300 GHz. When the BPSK modulation format is used, every slot holds the capacity of 12.5 Gb/s. This value transforms to 25 Gb/s and 50 Gb/s for the QPSK and 16QAM modulation formats, respectively. In addition, resource allocation over the spectral bands follows the Best-Fit policy [19]. In this way, blocks of frequency slots that closely match the requested bandwidth are prioritized over other available sets of slots, resulting in a reduction of the spectrum fragmentation.

TABLE I. EFFICIENT AND QUALITY-AWARE TRANSMISSION BASED ON OPTICAL REACH

Modulation Level	Multi-band Optical Reach (km)	
	C-band	*L-band*
QPSK	1800	1600
16QAM	370	330

In this work, the main objective is to investigate how the partial upgrade of an optical network which relies on restoration can improve the network dynamic performance compared to the use of protection. In this regard, the bandwidth blocking ratio (BBR) of the network is considered as the main metric. The division of the blocked frequency slots to the total requested slots indicates the bandwidth blocking ratio. Furthermore, the traffic load is normalized by the consideration of the average data rate, maximum data rate, and total number of the nodes as specified by parameters C_{avg}, C_{max}, and N, respectively. Equation (1) [19] is employed for the calculation of the normalized traffic load.

It is worth mentioning that before acquiring the simulation data for 10^5 incoming connections, the simulator warms up the employed network using 10^4 connections.

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

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

B. Failure Scenarios and Survivability Strategies

We consider that every 500 connection requests, a single link failure is introduced, and we consider that the failure is repaired after a random repairment time (which is selected randomly to match the interval of receiving from 1 up to 100 connections requests). Nevertheless, we have also decreased the frequency of failures by considering 1000 connections as the successive points of failure occurrence.

It should be noted that a link consists of two fibers, one per direction. Therefore, a link failure implies the failure of both fibers, and thus disrupts all lightpaths traversing any of those fibers. We consider two different survivability strategies. A first option is to rely on dynamic restoration. When a failure takes place, attempts are made to reroute the affected connections. Therefore, for a certain affected connection, the RBMLSA algorithm will be re-executed. In case that among the precomputed link disjoint paths, the required bandwidth can be allocated successfully, the affected connection request will be re-established and thus recovered. Otherwise, it will be marked as an unrecovered connection. The second option is to employ path protection, so that for every connection request two disjoint lightpaths are established, so that the communication will be effectively protected against single link failures.

III. SIMULATION RESULTS

We start the performance evaluation results by analyzing the dynamic restoration method in a partially upgraded network in terms of incoming bandwidth blocking ratio and total bandwidth blocking ratio. The incoming bandwidth blocking ratio metric indicates the proportion of total requests that cannot be established upon reception. This occurs when there are insufficient resources to establish a connection at the specific moment the request is received, accounting for the current state of the network. The total bandwidth blocking ratio is the fraction of requests that either cannot be initially established or, if initially established, cannot be successfully recovered due to an eventual subsequent link failure during their lifetime.

Fig. 2 represents the incoming and the total bandwidth blocking ratio versus traffic load when the (a) NSFNet topology, (b) JPN12 topology, and (c) DT network rely on dynamic restoration for survivability. Different levels of partial migration are displayed in the figure with different color lines. In that figure, the total bandwidth blocking ratio and the incoming bandwidth blocking ratio are specified by the solid lines and the dashed lines, respectively. In Fig. 2, the expected outcome is realized for all the analyzed topologies and the total bandwidth blocking ratio is higher than the incoming bandwidth blocking ratio, since rerouting for the already established connections that may experience the link-cut due to the introduced failure is not always executed successfully due to lack of network resources.

As the focus of this paper revolves around analyzing the impact of partial migration on a network, which is equipped with a survivability method, let us analyze the total bandwidth blocking ratio considering different scenarios of network migration. Assuming that an acceptable value of the total bandwidth blocking ratio is 10-3, Fig. 2(a) demonstrates that upgrading 12 bidirectional links of the NSFNet topology, which is translated to providing L-band optical components for 57% of the network links improves the supported network traffic load by around 1.5 times compared to the C-band only network when the network is protected using the dynamic restoration method.

TABLE II. CHARACTERISTICS OF THE ANALYZED NETWORKS

Topology	# of Nodes	# of Bidirectional Links
NSFNet	14	21
JPN12	12	17
DT	14	23

Besides the NSFNet topology, the results for the JPN12 topology and the DT network verify the suitability of the

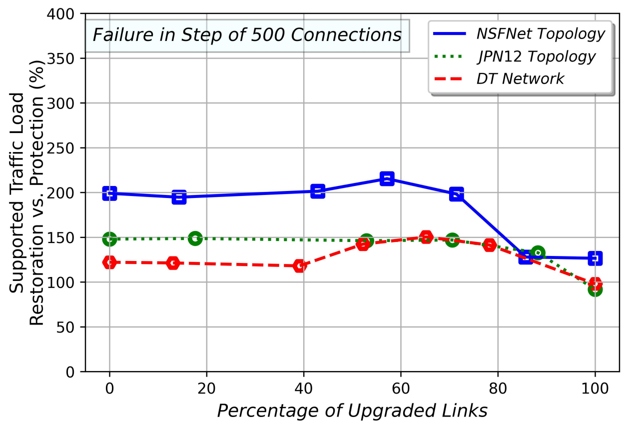

Fig. 3. Supported traffic load with different levels of partial migration using the dynamic restoration with respect to the dedicated protection (failure rate = every 500 connections).

application of partial migration for different network topologies when the dynamic restoration is employed. For better understanding of the advantages of joint application of dynamic restoration and partial migration, in Fig. 3, we compare the traffic load increment when dynamic restoration is used instead of dedicated protection during the migration of network links. The points represented in that figure correspond to cases where the bandwidth blocking ratio is lower than 10^{-3}. The solid line represented in Fig. 3 corresponds to the NSFNet topology, while the dashed line and the dotted line refer to the JPN12 topology and the DT network, respectively. It should be noted that in Fig. 2 and in Fig. 3, it is assumed that the network suffers from quite frequent failures in optical fibers. In other words, a new failure appears in every 500 incoming connections. As shown in Fig. 3, the percentage of bidirectional links to be upgraded to the L-band is specified on the x-axis and the percentage of additional traffic load that can be supported using the dynamic restoration versus dedicated protection is plotted on the y-axis. As can be seen in that figure, due to the better use of resources, the application of dynamic restoration leads the supported traffic load to be significantly improved compared to the use of dedicated protection.

Fig. 3 also shows that for the NSFNet and DT topologies, upgrading of 60% of the total number of bidirectional links contribute to a significant boost in the supported traffic load. For the JPN12 topology, it can be observed that in the middle stages of partial migration, while we increase the percentage of the upgraded links, the excellence of the dynamic restoration over the dedicated protection remains constant. More interesting, it can be concluded from Fig. 3 that the application of the partial migration up to 60% of the bidirectional links within the analyzed topologies brings about more advantages in terms of the supported traffic load than the fully upgraded network compared to the classical protection. Therefore, in case of having limited financial resources, the joint employment of the partial migration and the dynamic restoration method could be an interesting option for the network operators.

We proceed with the simulation results analysis by changing the time between failures. Firstly, we assess the performance of the employed survivability methods, namely classical path protection and dynamic restoration in a partially upgraded network taking into account that no failure is introduced to the network. The additional load that can be supported when using dynamic restoration compared to the protection in no failure scenario is shown in Fig. 4. Once again, in Fig. 4, it can be observed that upgrading 60% of the bidirectional links to the L-band in the NSFNet and DT topologies significantly improves the excellence of the dynamic restoration over the dedicated protection. In fact, this improvement is around 650% and 500% for the NSFNet topology and the DT network, respectively. Based on Fig. 4, when optical fibers within the analyzed topologies do not experience any failure during the simulation, performing the partial migration of around 60% for the NSFNet and DT topologies would provide interesting results. According to Fig. 4, the interesting level of migration for the JPN12 topology changes to 70% of the bidirectional links.

Then, we investigate the network performance considering that the link failure is introduced to the network at each 1000 connections milestone. A similar assumption as before is considered for the time interval that a link failure may remain in the network. Fig. 5 confirms that for the network operators, during the process of network migration, the employment of dynamic restoration is highly recommended as it leads to remarkable increase in the supported traffic load compared to the protection method. The results achieved so far in this paper are based on the assumption that during the resource allocation phase in the RBMLSA algorithm, the priority is given to the L-band. Therefore, firstly, the L-band is analyzed in terms of the availability of resources. Then, in case that the required block of frequency slots is not available in the L-band, attempts are meade to meet the requested bandwidth through seraching over the C-band spectrum.

Another strategy for the resource allocation is also used in which the C-band is prioritized over the L-band while the dynamic restoration method is employed. The comparison between the potential strategies for performing the resource allocation algorithm is out of the scope of this paper, but just to mention, giving the prioritization to the L-band over the C-band significantly improves the total bandwidth blocking ratio. For instance, for the traffic load of 0.45 while 15 bidirectional links are upgraded in the NSFNet topology, providing the L-band with the higher priority results in around two orders of magnitude lower blocking ratio than if the C-band is prioritized.

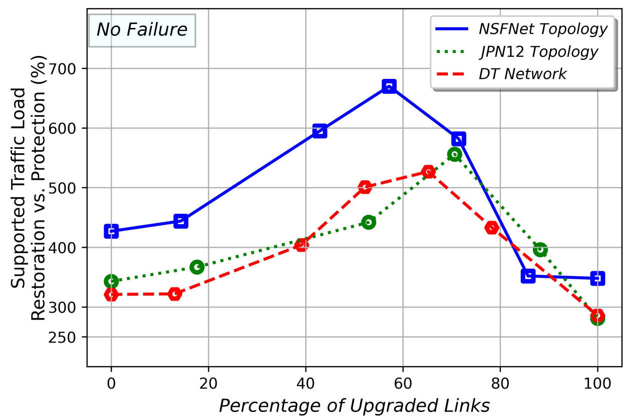

Fig. 4. Supported traffic load with different levels of partial migration using the dynamic restoration with respect to the dedicated protection (fiber-cut failure is not introduced to the network).

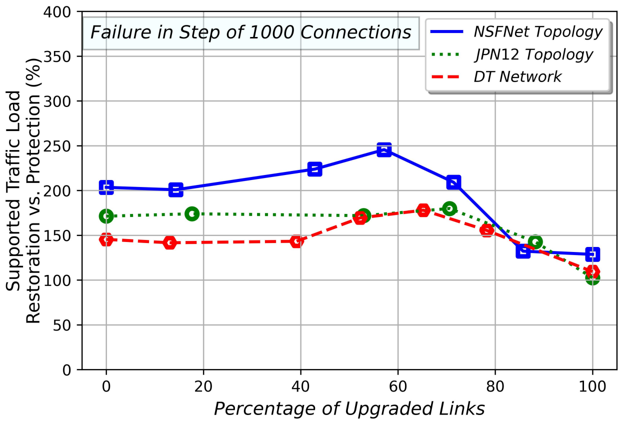

Fig. 5. Supported traffic load with different levels of partial migration using the dynamic restoration with respect to the dedicated protection (failure rate = every 1000 connections).

IV. Conclusions

In this paper, we have analyzed the advantages of using restoration instead of protection during the migration from current C-band to C+L bands optical networks. For that aim, we have evaluated the performance of the NSFNet topology, the JPN12 topology, and the Deutsche Telekom network set up with the classical path protection and the dynamic restoration in different levels of partial migration. The simulation results have demonstrated that in case of having financial challenges, upgrading of around 60% of the links within the NSFNet topology and the DT network in which the dynamic restoration is employed would lead the bandwidth blocking ratio to be improved more than one order of magnitude compared to the C-band network. For the JPN12 topology, this achievement is obtained by upgrading around 70% of the links (assuming no failures or very infrequent ones).

In this work, different scenarios for introducing a link failure to the network when the dynamic restoration is employed have been investigated. Firstly, it has been assumed that the network experiences a link-cut every 500 connection requests. Then, we have evaluated the network performance through an increase in the interval between failures. Furthermore, it has been considered that fixing a link failure may take time and the following 100 incoming connections may suffer from the lack of resources due to the introduced failure. It has been shown that equipping the network with the dynamic restoration method in the middle stages of partial migration could significantly increase the supported traffic load compared to the employment of classical path protection.

Finally, a preliminary analysis suggests that the prioritization of the L-band over the C-band during the resource allocation phase improves the bandwidth blocking ratio in a partially upgraded network. Nevertheless, a more extensive analysis remains as a future research line.

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