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Survivability against Amplifier Failures in Multi-Band Elastic Optical Networks

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Abstract—**We propose and evaluate different techniques to provide protection against, at least, amplifier failures in multi-band (C+L) elastic optical networks using two different amplifier architectures. The strategies are compared in terms of blocking ratio and protection capabilities. We demonstrate that the use of the proposed hybrid protection technique leads to a significant decrease on blocking ratio leveraging on one of the amplifier architectures and exploiting that different connection requests may have different resiliency requirements.**

Keywords-multi-band; elastic optical networks; protection; blocking ratio

I. INTRODUCTION

The efficient use of the C-band spectrum by elastic optical networks (EONs) is not sufficient to cope with growing bandwidth demands [1, 2]. As the nonlinear Shannon limit obstructs the possibility of increasing the capacity of single mode fibers (SMFs), space division multiplexing (SDM) and multi-band (MB) transmission beyond the C-band have been proposed as alternative solutions to satisfy the emerging demands for bandwidth [3]. Replacing the old fibers installed with new multi-core or multimode fibers involves huge investments, and as concluded in [4], the use of SDM for long-haul networks using available dark fibers is more costly than extending the spectrum towards the L-band. Therefore, exploiting the full capacity of fibers using MB transmission becomes the most pragmatic next step in optical network evolution.

To ensure quality of transmission (QoT) for multi-band EONs (MB-EON), the dependence of the optical reach of different modulation formats for different spectral bands should be considered [5]. Enabling the requests to adaptively take a certain advanced (and spectrally efficient) modulation format converts the matter of resource allocation for MB-EONs into a routing, band, modulation level, and spectrum assignment (RBMLSA) problem.

While increasing the capacity of the optical networks, the importance of preserving the transmission of large amounts of data against network failures should be emphasized. The concept of survivability as a critical prerequisite for launching an optical transport network has been extensively studied in the literature in EONs [6-8] and SDM networks [9, 10], but has not yet been completely analyzed taking into account the characteristics of MB-EONs.

In this work, we propose and compare different methods to achieve survivability, at least against single amplifier failures, in MB-EONs using C+L bands, considering dedicated protection, and assessing two different amplifier architectures. We compare different strategies with different trade-offs in terms of protection capabilities and blocking ratio performance, and demonstrate that one of the proposed mechanisms (which leverages on one of the amplifier architectures) provides superior results if the aim is to protect at least against amplifier failures, or if service level agreements (SLA) with differentiated protection capabilities are enabled.

II. RESILIENCY AGAINST SINGLE AMPLIFIER FAILURES

Amplifiers are active components prone to failures, whose repairment requires significant OPEX efforts since their implementation is outside the plant [11]. Moreover, according to [12] the failure rate of amplifiers is approximately 45 times higher than that of fiber failures (assuming amplifiers are located every 100 km); thus, providing resiliency against amplifier failure is of paramount importance. In classical EONs (using only the C-band), the establishment of disjoint end-to-end path connections protects against both amplifier and fiber failures. However, as will be shown later, in MB-EONs it is possible to increase the network performance at the expense of protecting all connections only against the most likely failure (i.e., amplifier failure). For this reason, we focus on protection against single amplifier failures, although we also consider the possibility of protecting some connections against link failures.

As shown in Fig. 1, optical amplification in a MB-EON can be implemented through several architectures [14]. The most popular model (Fig. 1a) employs separate erbium doped fiber amplifiers (EDFAs) for each spectral band. When this architecture is used, there is a bandwidth waste due to the guard-band between the C and L bands required by the demultiplexer and the multiplexer (typically around 400 GHz) [13]. An alternative model (Fig. 1b) employs a wideband amplifier architecture, and thus does not suffer that bandwidth waste.

In terms of survivability, when using the wideband amplifier architecture (Fig. 1b), the use of disjoint paths for primary and backup connections is a must to get protection against amplifier failures, and this also provides protection against fiber failures. When using the separate amplifiers architecture (Fig. 1a), and considering only protection against single EDFA failures, it is possible to route the primary and backup connections over the same fibers but using different spectral bands. Since primary and backup connections use different EDFAs (due to the separate amplifiers architecture), this approach offers resiliency against amplifier failures. Nevertheless, this strategy does not provide protection against fiber failures (in contrast with the use of a disjoint fiber path, which obviously, can also be used if this architecture is employed).

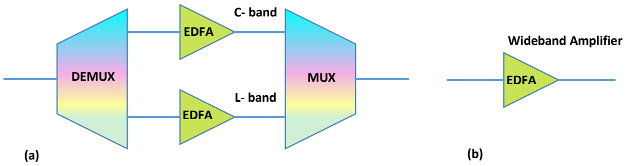

Figure 1. Amplifier architectures for C+L systems,
(a) separate amplifiers, and (b) wideband amplifier.

Therefore, in the case of using the wideband amplifier architecture, two link-disjoint paths for the primary and backup connection must be used when solving the survivable RBMLSA problem. In this scenario, the full spectrum (C+L bands) can be used to establish the primary and backup connections.

When the separate amplifier architecture is employed, different methods are proposed to solve the survivable RBMLSA problem, using dedicated protection.

The first method (from now on, *basic* approach) consists in using the same path for the primary and the backup connection but using different spectral bands for each one. There are two alternatives: using C-band for the primary and L-band for the backup, or vice versa.

The second method (called, from now on, the *hybrid* method) exploits the advantage of using the separate amplifiers architecture, but allowing the primary and the backup connections to follow different end-to-end disjoint paths if needed. The hybrid strategy starts by following the same procedure as the first method: using the same path for both connections but using different spectral bands for each one. If no solution is found due to the unavailability of resources to establish the primary and backup connections, it explores the alternative of routing the primary and the backup connection following two link disjoint end-to-end paths. The primary connection is limited to use one single spectral band (always C or always L), while the backup path can utilize both the C and L spectral bands. It should be noted that connections protected in this way (with an alternate end-to-end path) are resilient not only to amplifier failures but also to fiber failures. Thus, the hybrid method provides amplifier failure resiliency for all connections, and additional fiber failure resiliency for a subset of them.

III. SIMULATION SETUP AND RESULTS

In this section, the performance of the previously mentioned strategies is assessed in terms of blocking probability, and their support for resiliency is also discussed. To this end, a Python simulator has been implemented, and the performance on the NSFNET topology, with 14 nodes and 21 bi-directional links, has been analyzed. All links are composed of SMFs, and spectral slots of 12.5 GHz have been considered. The C-band is thus composed by 320 frequency slots and the L-band by 548 [14]. However, when the separate amplifier architecture is used, due to the 400 GHz guard-band, the L-band has 512 usable slots. Path computation is based on the K-shortest distance path algorithm with $K = 5$. Resource allocation for each spectral band is based on the Best-Fit policy, which means a block of frequency slots with the closest size to the requested slots is prioritized, if it satisfies the contiguity and continuity constraints. Moreover, within the C+L line systems, spectrum occupancy is performed from the C-band to the L-band.

Connection requests are generated according to a Poisson process, and the holding time is obtained by means of an exponential distribution. The source and destination nodes for each connection are randomly selected using a uniform distribution, and a uniform distribution is also assumed to determine the required data rate of a connection request. The requested traffic rate is in the range of 12.5 Gb/s to 300 Gb/s in steps of 12.5 Gb/s, which translates into a demand of 1 to 24 frequency slots if the BPSK modulation format is used for the subcarriers. However, if the connection path does not exceed the optical transmission reach described in Table I (for the used spectral band) [15], a more spectrally efficient modulation format (QPSK or even 16QAM) is used instead. Since different connections demand different data rates, rather than using the classical definition of the traffic load in erlangs, we use the normalized version defined in [16], which takes into account the average and maximum capacity of the connections, as well as the number of nodes in the network. Thus, a normalized traffic load of 1 is equivalent to having, in average, along the whole simulation (and if there were no blocking), one established connection at full data rate between each source-destination pair (i.e., an average of 182 simultaneously established unidirectional connections at 300 Gb/s in the 14-node NSFNet).

TABLE I: MAXIMUM OPTICAL REACH BASED ON THE MODULATION LEVEL FOR EACH SPECTRAL BAND (BASED ON [15]).

Modulation level	**Optical reach (km)**		
	EON	***MB-EON***	
	C-band only	***C-band***	***L-band***
QPSK	2500	1800	1600
16QAM	500	370	330

The simulator is first warmed-up by dynamically generating request and release events (until 10^4 requests are received). Then, results start to be collected until processing 10^5 additional connection requests. Results are represented with 95% confidence intervals.

The request blocking ratio versus traffic load is displayed in Fig. 2 for all studied scenarios, and the bandwidth blocking ratio is shown in Fig. 3. The request blocking ratio is defined as the fraction of requests that are blocked. The bandwidth blocking ratio takes into account that different requests need different bandwidths. Thus, BBR is computed as the quotient between the sum of the requested bandwidths (once considering the selected modulation format) associated with blocked requests and the sum of the requested bandwidths of all requests. Besides the strategies mentioned in the previous section (MB-EON with protection), for comparison purposes, we have also evaluated the use of multiband (C+L) without protection when using the separate amplifier architecture and the wideband amplifier architecture. Obviously, the lowest blocking ratio is obtained for the unprotected transmission, since no resources are used for protection. The results are slightly worse for the separate amplifiers architecture due to the guard-band between C and L bands. These results are only shown to provide a baseline of the blocking ratio that can be achieved without protection, but from now on we focus on resilient solutions.

The blocking ratio for the separate amplifiers architecture with the basic resiliency strategy is the same independently of which band (C or L) is used for primary connections (and the other for backup connections). Since the same number of resources must be reserved for both connections, the lower number of available slots in the C band (320 vs 512) is the limiting factor. Consequently, a significant part of the L band is not utilized.

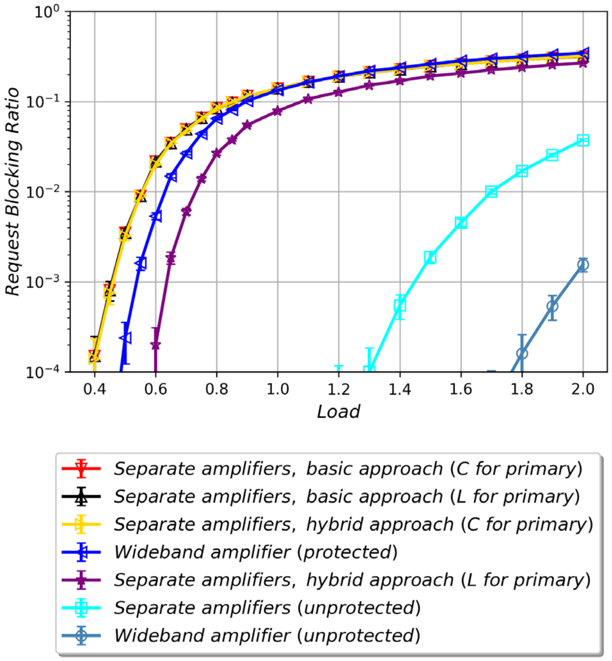

Figure 2. Request blocking ratio depending on the network load.

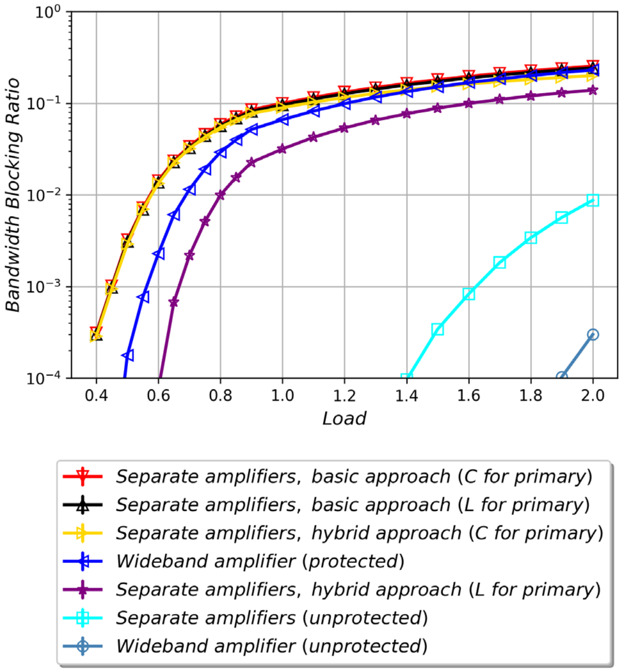

Figure 3. Bandwidth blocking ratio depending on the network load.

In contrast, the use of the wideband architecture with dedicated path protection uses all available spectrum in the C and L bands, and thus provides better results in terms of blocking ratio than the previous alternative, besides providing protection not only for EDFA failures but also for fiber failures.

However, for the separate amplifiers architecture we also proposed a variation to achieve resiliency, the hybrid technique. Fig. 2 shows that when the hybrid technique is used, and the L band is used for the primary connections, a significant decrease on the blocking ratio is obtained compared to all the previous cases with resiliency (using either the separate amplifiers or the wideband amplifiers architectures). It should be noted that when the hybrid technique is used, all connections are resilient to EDFA failures but only a portion of them are also resilient to fiber failures.

Therefore, in terms of resiliency, as expected, the end-to-end disjoint paths approach (which is used with the wideband amplifier architecture) is the most suitable one. However, the use of separate amplifiers and the hybrid protection technique leads to much lower blocking ratio (more than one order of magnitude for traffic loads lower than 0.6). Thus, that technique allows for a more efficient use of resources but requires Service Level Agreement (SLA) differentiation, where some connections are protected by means of an alternate disjoint path (thus being resilient to fiber and EDFA failures), while others are protected by using a different spectral band of the same route (being resilient to EDFA failures).

IV. CONCLUSIONS

We have proposed and compared different strategies to provide survivability against, at least, amplifier failures in multi-band (C+L) elastic optical networks considering two different amplifier architectures: separate amplifiers vs wideband amplifier. We have demonstrated that the use of the separate amplifiers architecture together with the hybrid protection technique has significant performance advantages in terms of blocking probability, thus enabling the network to support higher traffic loads.

This strategy has been combined with SLA differentiation in our new work [17]. In [17], two service levels, “gold” and “silver” are defined, so that “gold” connections are protected against both EDFAs and fibers failures, while “silver” connections are protected only against EDFA failures, and we demonstrate an improvement on network performance when compared with only using the classical path protection strategy for all connections.

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