Long-term Capacity Planning in Flexible Optical Transport Networks

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Abstract: We evaluate four Routing, Configuration and Spectrum Assignment alternatives to increase provisioned capacity in optical networks. Long-term planning shows that regenerators extend the C-Band capacity, whereas multi-band solutions outperform in terms of throughput and under-provisioning.

1. Introduction and Problem Definition

One of the major concerns of optical transport network (OTN) operators is to cope with ever-increasing traffic. The fixed-grid C-Band capacity has been increased with the use of flex-grid bandwidth variable transponders (BVTs) [1]. BVT allows operators to select the best channel configuration for a given lightpath (LP) in terms of data rate, modulation format and forward error correction (FEC). Current configurations differ in terms of modulation formats (QPSK, 8QAM, 16QAM, 32QAM, 64QAM), data rate (100-600 Gbps) and FEC (0%, 15%, 27%). However, as demands keep increasing, triggered by paradigms such as IoT and 6G, alternatives to increase the network capacity furthermore have to be evaluated.

In this work, we study and compare different Routing, Configuration and Spectrum Assignment (RCSA) alternatives to cope with the datarate increase of the demands from an OTN operator's perspective. The network is defined as a graph $G = (V,E)$ being V the optical add/drop nodes and E the links consisting of standard single mode fiber pairs with heterogeneous span lengths. Considering a finite discrete time horizon T and a set of demands D per year. Each demand $d \in D$, identified by the source and destination, has a datarate (DR_d) that increases following the traffic model proposed in [5], which is based on the expected traffic growth between Data Centers, Internet Exchange Points (IXPs) and human population. Each demand $d \in D$ may be fulfilled by one or more lightpaths (LP_d) in the network, which may have different configurations and hence, datarates. The goal is to achieve for all demands that $DR_d \leq \sum_{\forall lp \in LP_d} DR_{lp}$, while reducing the over-provisioning as well as the number of BVTs. Let us compare different alternatives that operators have in order to fulfill the datarate increase of the demands.

2. Routing Configuration and Spectrum Assignment (RCSA) Alternatives

C-Band RCSA

Let us consider as baseline the RCSA proposed in [5], which aims at minimizing the number of LPs added to the network for each planning period t, while trying to meet the requested aggregated datarate generated by the same traffic model which caters for uncertain increase. This RCSA considers two approaches: LP upgrade (i.e., upgrading the configuration of the BVT if possible, to cope with the required datarate), and LP addition (i.e., adding more BVTs so that the requested datarate is met).

This RCSA was further extended in [6] to achieve a higher capacity without undertaking band upgrade. The proposed solution, referred as "C-Band", aims at first minimizing the required BVTs and then maximizing the datarate for each demand $d \in D$ in planning period t, while trying to meet the requested aggregate datarate. For this purpose, three different approaches were considered: LP upgrade, LP addition, and LP rerouting (i.e., a spectrum re-allocation heuristic to reroute spectrally adjacent BVTs such that the released spectrum can be used to upgrade the configuration of the placed BVT).

C-Band RCSA with regeneration

The use of regeneration has been encouraged to cope with long LP as they split the transparent optical distance of the LP into several transparent segments. The compromise of using regenerators with respect the throughput, number of lightpaths and other metrics will be analyzed in this work.

In order to improve the spectrum utilization per link, the C-Band RCSA module is extended to include regeneration capabilities (henceforth referred to as "C-Band (Regen)"). The regeneration locations are pre-calculated for every source-destination demand pair and every configuration on all k-shortest paths, using the minimum receiver OSNR threshold as a configuration selection metric. C-Band (Regen) considers the same approaches as its non-regenerator based counterpart, with the addition of a secondary objective in LP addition, that is, minimizing the number of regenerator locations in the network. Although adding regenerators can lead to higher throughput and reduce under-provisioning as compared to the C-Band approach, there is a need to provision two additional BVTs for every regenerator location for each demand.

BDM enabled RCSA

Band Division Multiplexing (BDM) exploits the use of neighboring bands (C+L Bands and S+C+L Bands in our case), which are a more cost-effective option than space division multiplexing (i.e., lighting fibers) [2]. Existing BVTs can be tuned to any of these bands. However, although commercially available wideband EDFA amplifiers can be used for both C- and L- Bands, S-Band requires TDFA amplifiers [3]. Moreover, Quality of Transmission (QoT) parameters to select configurations for each BVT vary across bands due to higher attenuation on the S- and L- Bands [4]. The previously C-Band solutions consist of frequency slots available in the C-Band range (i.e. 191-196 THz). These 5 THz are split into 400 frequency slots of 12.5 GHz each. Depending on the configuration, each BVT is allocated the required frequency slots, while maintaining the wavelength continuity constraint across the links traversed by its LP. To simulate the availability of additional bands, the C+L-Band range consists of 800 frequency slots (i.e., 186-196 THz), and the S+C+L-Band range consists of 1200 frequency slots (i.e., 186-200 THz). For fairness, we consider a lower QoT on the S-Band and the L-Band, due to the higher amplifier noise figure and attenuation. The basic transmission parameters used are shown in Table 1. For the band filling strategy in case of multiple bands, we always fill the C-Band first, followed by the L-Band and finally the S-Band, if available.

Scenario	Attenuation (dB/km)			Noise Fig. (dB)			Frequency Slots		
	C	**L**	**S**	**C**	**L**	**S**	**C**	**L**	**S**
C-Band	0.22	-	-	5.0	-	-	400	-	-
C+L-Band	0.22	0.24	-	6.0	6.0	-	400	400	-
S+C+L-Band	0.22	0.24	0.25	6.0	6.0	7.0	400	400	400

Table 1: Transmission parameters for multi-band scenario

3. Simulation Results and Discussions

The proposed RCSAs have been compared for different networks: Germany-17 (|*V*|=17, |*E*|=6 and |*D*|=123), Europe (|*V*|=28, |*E*|=41 and |*D*|=378), USA (|*V*|=12, |*E*|=14 and |*D*|=66), and Sweden (|*V*|=25, |*E*|=29 and |*D*|=300)[7]. These networks differ on the average node degree, number of demands *D*, but also on the link lengths, which will have an impact on the configurations that can potentially be used (the longer path, the less suitable configurations). Each link $l \in E$ consists of a single fiber pair and the transponders are equipped to handle 26 different configurations for the C-Band [8]. Due to lack of space, only the results of Europe are presented in this work.

Let us first compare the network throughput for each alternative (referred as Ref. [5], C-Band, C-Band (Regen), C+L Band, S+C+L Band) with respect the requested aggregate datarate, as shown in Fig. 1(a). It can be observed that only multi-band solutions are able to meet the expected throughput throughout the planning period. Also, the use of regenerators postpones the saturation of the C-Band by 3 years. Furthermore, the multi-band solution show similar throughput and datarate distributions, pointing out that an S-Band may not be needed for this planning.

However, in order to have a fair evaluation of the real performance of the network, a detailed analysis of the under-provisioning of each demand has to be performed. For each planning period *t*, the under-provisioning ratio *UP* is defined as $UP = \sum_{\forall \tilde{d} \in \tilde{D}} \left(DR_{\tilde{d}} - \sum_{\forall lp \in LP_{\tilde{d}}} DR_{lp} \right) / \sum_{d \in D} DR_d$ where $\tilde{D} \subset D$ is the set of demands that are under-provisioned, that is, $DR_{\tilde{d}} - \sum_{\forall lp \in LP_{\tilde{d}}} DR_{lp} > 0$ for $\tilde{d} \in \tilde{D}$. Fig. 1(b) depicts the *UP* as percentage for the different solutions. Although all the solutions showed to offer more throughput than the requested one for the first two years, Fig. 1(b) shows that none of the C-Band solutions cope with the 100% of the demands for any year. For example, in year 2, “Ref. [5]” and “C-Band” could not cope with 15% of the datarate, but the use of regenerators reduced the under-provisioning to 5%. In these cases, this under-provisioning was compensated by the overprovisioning of other demands, and hence, increasing the total throughput above the requested one as shown in Fig. 1(a). The C+L and S+C+L Band solutions defer under-provisioning 4 and 7 years respectively, always keeping it lower than 8%.

Another important criteria for operators is the number of required BVTs as it will have a direct impact on the expected capital and operational expenditures (incl. power consumption). This comparison is depicted in Fig. 1(c), which shows that the higher the throughput, the more LPs are set and hence, the more BVTs are deployed. The number of LPs keeps increasing for all the solutions, especially when using regenerators. This fact may seem inconsistent for the C-Band solutions, which are not able to provide the expected throughput (Fig. 1(a)) but they can still set LPs through non-congested links. In year 8, using regenerators in the C-Band needs comparable number of BVTs as the BDM solutions (close to 2500 BVTs), but offering less throughput (200Tbps instead of 300Tbps) and more under-provisioning (33% instead of 6%). Focusing on the C-Band, regeneration increases the throughput and reduces the under-provisioning but requires more BVTs.

Finally, Fig. 1(d) depicts the configuration distribution of the LPs for each RCSA at the last year 10. It can be observed that the most common configuration is 250Gbps. BDM solutions also show higher configurations as they also have more LPs. C-Band solutions have lower LPs and hence, the lower configurations seem more predominant (up to 250Gbps). This is due to the fact that the C-Band capacity is filled within the first years, preventing the possibility to use of higher configurations.

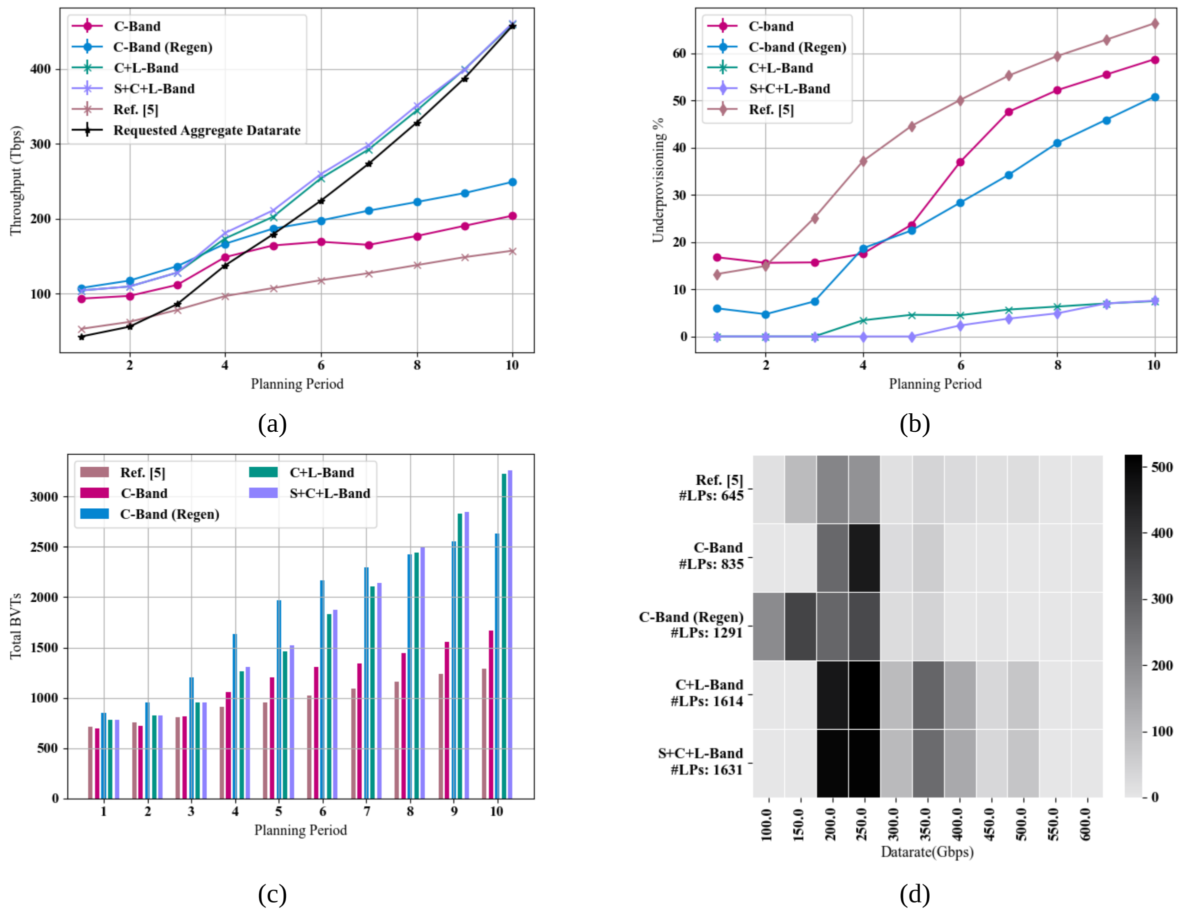

Fig (1) Simulation results and comparison. (a) System throughput, (b) Unprovisioning percentage (c) Number of deployed BVTs, (d) Lightpath datarate distribution in Year 10.

5. Conclusions

This work presented and compared different RCSA solutions in a multi-period planning scenario. The results show the need of using multi-band solutions in order to meet the requested aggregate datarate. Furthermore, it has been shown that most of the BVTs are configured with 200-250 Gbps datarates, which can reduce deployment costs of such solutions (especially C+L-Band, as they use pre-deployed EDFA amplifiers). When operators want to restrict themselves to the C-Band, the use of regenerators can increase the network throughput with lower under-provisioning as compared to its non-regenerator counterpart.

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