Disruption-minimized Re-adaptation of Virtual Links in Elastic Optical Networks

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Abstract: We present a novel re-adaptation approach to accommodate bandwidth increase of virtual links in elastic optical networks. Our approach can incorporate different objectives, as minimizing disruption, by choosing among a comprehensive set of re-adaptation actions.

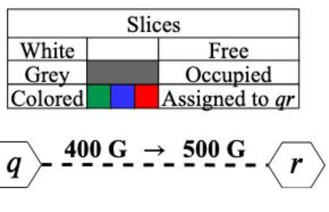
OCIS codes: 060.4256 Networks, network optimization; 060.4251 Networks, assignment and routing algorithms

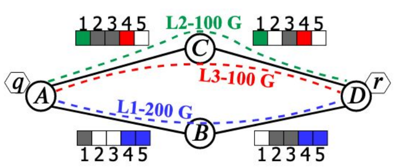
1. Introduction

Elastic Optical Network (EON) virtualization is gaining traction due to its importance in 5G transport network slicing. EONs allow fine-grained spectrum allocation and adaptation of transmission configurations (*e.g.*, modulation, forward error correction (FEC), baudrate) to allocate rightsized spectrum to network slices. A network slice is a virtual network (VN) that connects virtual nodes through virtual links (or lightpaths) embedded on the EON. VNs are typically requested by service providers (SPs) that define a-priori bandwidth requirements for each virtual link. However, applications hosted on a VN evolve over time due to change in number of users and communication patterns. Consequently, an SP may request to increase the bandwidth of a virtual link that is carrying live traffic. To accommodate such bandwidth increase, the infrastructure provider (InP) needs to re-adapt the embedding of the virtual link while minimizing (i) disruption to SP's existing traffic and (ii) additional transponders (Tx) or spectrum (Sp) resources. In addition, the InP has to ensure that re-adaptation causes no disruptions to other SPs' traffic and use existing spectrum as much as possible to reduce network agitation. In this paper, we propose a novel solution to accommodate a virtual link's bandwidth increase in an already provisioned VN with minimal disruption to the existing traffic, while requiring low additional resources. We assume that a virtual link can be provisioned by splitting its demand on one or more lightpaths (up to a maximum of 4) called *splits* [1].

Existing studies on lightpath re-adaptation use a variety of re-configuration actions such as spectrum expansion/contraction, spectrum re-allocation on same or on a new path, and modulation change [2–4]. However, most studies assume the availability of advanced technologies that cause minimal to no disruption to existing traffic. These technologies are still experimental and may require years to qualify as commercial grade. In contrast, we do not assume the existence of any such advanced hardware, and target minimization of disruption caused by different possible re-configuration techniques. The only work that includes disruption as part of its objective considers a worst case re-configuration time as cost [5]. To our knowledge, our work is the first that captures different levels of disruptions caused by different types of re-configuration actions and assigns appropriate costs to the actions. We devise an Integer Linear Program (ILP) for optimally solving the re-adaptation problem. Our ILP models a multi-objective optimization problem and provides an efficient way to tune priorities among different objectives.

2. Proposed solution for Disruption-minimized Re-adaptation





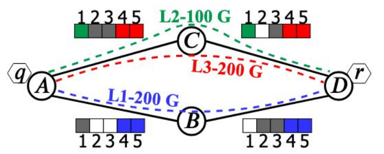


Fig. 1: VN Re-adaptation request Fig. 2: Embedding before re-adaptation Fig. 3: Embedding after re-adaptation

Problem statement. We are given an EON G and a set of VNs $\mathscr{G}$ embedded on G. Each VN $\bar{G} \in \mathscr{G}$ consists of a set of virtual nodes (VNodes) $\bar{V}$ and virtual links (VLinks) $\bar{E}$ where each VLink $\bar{e} \in \bar{E}$ has a bandwidth demand $b_{\bar{e}}$ (See VLink qr with initial demand $400G$ in Fig. 1). Each VNode is assigned to an EON node and each VLink is embedded to a set of paths in the EON where each path p is configured with a transmission configuration or tuple $t = (d, b, m, f) \in \mathbb{T} = (\mathbb{D} \times \mathbb{B} \times \mathbb{M} \times \mathbb{F})$ to provide a data-rate so that sum of data-rates is at least $b_{\bar{e}}$. Here, d, b, m, and f represent *data-rate*, *baud-rate*, *modulation format*, and *FEC* selected from the set of possible values $\mathbb{D}$, $\mathbb{B}$, $\mathbb{M}$, and $\mathbb{F}$, respectively. Each tuple t has a spectrum requirement and a maximum optical reach within which t

Table 1: Different re-configuration actions and corresponding cost

ID	Re-configuration action	Disrup-tion level	Extra Tx?	Extra Sp?	Combination of slot s, tuple t, and path p for the re-embedding of a VLink	c($\bar{e}$pts)
R_1	Reuse spectrum and transmission configuration of an existing split	Zero	No	No	s is used in current splits of $\bar{e}$ with same tuple t on same path p	0
R_2	Modify only transmission configuration of an existing split	Low	No	No	s is used in current splits of $\bar{e}$ with a different tuple $t' \neq t$, but on same path p	$c_1 >> 0$
R_3	Re-allocate a split or create a new split whose spectrum does not overlap with an existing split's spectrum	Moderate	Yes/ No	Yes/ No	s is not used in current splits of $\bar{e}$ and is not occupied by other VLinks	$c_2 >> c_1$
R_4	Expand spectrum allocation of an existing split	High	No	Yes	s is used in a current split of $\bar{e}$ on path p and another slot s' not used in same split of s, and both s and s' are used in a new split of $\bar{e}$'s on path p	$c_3 >> c_2$
R_5	Contract spectrum allocation of an existing split	High	No	No	s is used in a current and new split of $\bar{e}$ on path p and not all the slots of same current split are used in the new split of $\bar{e}$'s	$c_3 >> c_2$
R_6	Re-allocate a split or create a new split whose spectrum overlaps with an existing split's spectrum	Very High	Yes/ No	Yes/ No	s is used in current splits of $\bar{e}$ on path p' where p' and p have a common link	$c_3 >> c_2$

can be used with satisfactory signal quality. Fig. 2 shows the embedding of VLink qr with initial demand of 400G on EON $ABCD$ with three splits of 200G, 100G, and 100G. These three splits are realized by three lightpaths L_1, L_2, and L_3 that are assigned spectrum slots 4-5, 1, and 4 on EON paths ABD, ACD, and ACD, respectively. Fig. 2 shows that slot assignments to lightpaths satisfy spectrum continuity and contiguity constraint [1]. *The re-adaptation request comes as an increase of the demand of a VLink $\bar{e} \in \bar{E}$ belonging to one of the VNs $\bar{G} \in \mathcal{G}$ from $b_{\bar{e}}$ to $b'_{\bar{e}}$.* The objective of our problem is to accommodate a VLink demand increase while minimizing cost in terms of (i) number of transponders, (ii) spectrum occupation, and (iii) disruption to existing traffic. We assume that a set of shortest paths $\mathbb{P}_{\bar{e}}$ is pre-computed for $\bar{e}$ and $|p|$ denotes the number of links present on path $p \in \mathbb{P}_{\bar{e}}$. The spectrum on p is divided into equal-width spectrum slots represented by the set S and enumerated as $1, 2 \ldots |S|$.

Solution Approach and Disruption model. To accommodate a re-adaptation request for $\bar{e}$, we first free up the slots from the paths used in $\bar{e}$'s embedding and mark the slots on the paths taken by the embedding of other VLinks of the same or different VNs as occupied. Then, we re-embed $\bar{e}$ with the new demand $b'_{\bar{e}}$ such that each existing split of $\bar{e}$ adopts one of the re-configuration actions presented in Table 1. These actions cause different levels of disruptions to existing traffic and require different amounts of resources. Each action can be represented by the slot s, tuple t, and path p combinations of an existing split and a split in the re-embedding as specified in Table 1. To prioritize less disruptive actions, we assign a disruption cost $c(\bar{e}pts)$ to each s, t, and p combination of $\bar{e}$'s re-embedding. In Fig. 3, slots assigned to $\bar{e}$'s current lightpaths (L_1, L_2, and L_3) have 0, low, and high cost for R_1, R_2, and R_4-R_6, respectively. Free (white) slots get appropriate cost for R_3-R_6 and remaining slots are occupied. Note that cost of the actions in Table 1 can be arbitrarily set based on the technology and desired objective.

Among the actions, R_1 is preferable as it requires no additional resource and does not disrupt traffic, hence has zero cost. However, R_1 alone may not support the increased demand, necessitating further actions. R_2 needs no extra resources but has non-negligible disruption caused by a transponder re-configuration (*e.g.*, modulation change takes ~ 70 seconds [6]). Although R_3 creates new lightpaths to re-allocate a split's spectrum or to add a new split, they incur moderate disruptions as a new lightpath whose spectrum does not overlap with any existing lightpath can be created with make-before-break (MBB) [7]. MBB cannot be applied to R_4, R_5, or R_6 as they require a change in filters on intermediate nodes of an existing lightpath (or split), hence disrupting the traffic [4]. Note that R_4 and R_5 cannot be represented by one s, t, and p combination and require to examine more than one slots. Fig. 3 shows the re-embedding of VLink qr after its new demand 500G is served by increasing L_3's data-rate to 200G. To do so, L_3's spectrum allocation is expanded to include slot 5 to already allocated slot 4 using R_4, disrupting L_3's traffic. A less-disruptive solution is to create a new lightpath using R_3 on path ACD that provides 100G through slot 5. This less-disruptive solution adds a new split that requires a pair of additional transponders. A least-disruptive and resource efficient solution is to change L_3's modulation using R_2 to provide 200G without changing current spectrum allocation, as long as the reach of new modulation is respected on lightpath L_3.

ILP formulation. To re-embed $\bar{e}$ with the new demand $b'_{\bar{e}}$, we formulate an ILP that leverages disruption cost $c(\bar{e}pts)$ assigned to different s, t, and p combinations. Similar to [1], the ILP has two binary decision variables: i) $w_{\bar{e}pti}$ is 1 if $\bar{e}$ uses i-th instance of tuple t on path p, and is 0 otherwise, ii) $y_{\bar{e}ptis}$ is 1 if $\bar{e}$ uses slot s on path p with the i-th instance of tuple t, and is 0 otherwise. The ILP uses similar slot assignment and spectral contiguity constraints as presented in [1]. It modifies the VLink demand constraint presented in [1] to allow that the sum of data rates of the splits used to re-embed $\bar{e}$ is at least $b'_{\bar{e}}$. It also adds new constraints to exclude the slots occupied by the embedding of other VLinks from the solution space and to compute $c(\bar{e}pts)$ based on the condition specified in Table 1. Finally, the ILP has three cost components: i) transponder usage $Cost^{Tx}_{\bar{e}} =$

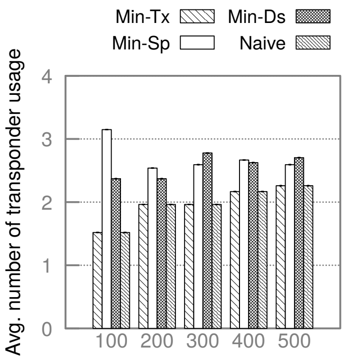


Fig. 4: Transponder usage

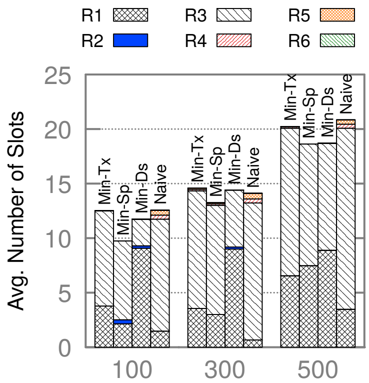


Fig. 5: Slots using actions in Table 1

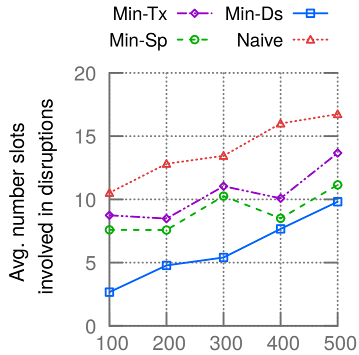


Fig. 6: Disruptions

$\sum_{\forall p \in \mathbb{P}_{\bar{e}}} \sum_{\forall t \in \mathbb{T}} \sum_{i=1}^{4} w_{\bar{e}pti}$, ii) spectrum requirement $Cost_{\bar{e}}^{Sp} = \sum_{\forall p \in \mathbb{P}_{\bar{e}}} \sum_{\forall t \in \mathbb{T}} \sum_{i=1}^{4} \sum_{\forall s \in S} y_{\bar{e}ptis} \times |p|$, and iii) disruption cost $Cost_{\bar{e}}^{Ds} = \sum_{\forall p \in \mathbb{P}_{\bar{e}}} \sum_{\forall t \in \mathbb{T}} \sum_{i=1}^{4} \sum_{\forall s \in S} c(\bar{e}pts) \times y_{\bar{e}ptis} \times |p|$. Combining these three costs, we get the following objective function, where θ, ω, and σ are relative weights to set different priorities to different components.

$$\text{minimize}(\theta \times Cost_{\bar{e}}^{Tx} + \omega \times Cost_{\bar{e}}^{Sp} + \sigma \times Cost_{\bar{e}}^{Ds}) \qquad (1)$$

3. Evaluation

Simulation Setup. We implement the ILP using IBM ILOG CPLEX and use it to solve different re-adaptation instances. We consider a fully-flexible EON using Nobel Germany[1] (17 nodes and 26 links) topology. Each EON link has 4THz spectrum band divided into 160 slots of 25GHz. To emulate a live EON, we develop a discrete event simulator that mimics VN arrivals and departures. In the simulator, VNs are synthetically generated and embedded on the EON using a heuristic algorithm [1]. We capture different snapshots of the EON at different loads and select about 100 VLinks that have initial bandwidth of 500G to increase their demand by 100G to 500G. We solve these problem instances using three variants of the objective presented in (1) and report the mean over all the instances. Among them *Min-Tx* considers $Cost_{\bar{e}}^{Tx}$, $Cost_{\bar{e}}^{Sp}$ and $Cost_{\bar{e}}^{Ds}$ as the primary, secondary, and tertiary objectives; *Min-Ds* swaps the roles of $Cost_{\bar{e}}^{Tx}$ and $Cost_{\bar{e}}^{Ds}$ and *Min-Sp* swaps the roles of $Cost_{\bar{e}}^{Tx}$ and $Cost_{\bar{e}}^{Sp}$. We also compare these variants with a baseline approach, called *Naive*, that uses $Cost_{\bar{e}}^{Tx}$ and $Cost_{\bar{e}}^{Sp}$ as the primary and secondary objectives and sets $\sigma = 0$ to completely ignore disruption minimization.

Discussion. Fig. 4 and Fig. 5 presents transponder and spectrum slot usage for all compared variants. Fig. 5 shows the breakdown of slots used by different actions of Table 1, and Fig. 5 reports number of slots involved in disruption. As expected, *Min-Tx* and *Min-Sp* incur the lowest number of transponders and slots, respectively, due to their prioritization of objective. In contrast, *Min-Ds* tries to reuse existing lightpaths (see R_1's dominance for *Min-Ds* in Fig. 5) with currently allocated data-rates to minimize disruption. Doing so urges *Min-Ds* to create extra lightpaths for satisfying the new demand, forcing *Min-Ds* to use 23% more transponders and 6% more slots than *Min-Tx* and *Min-Sp*, respectively. As adopting R_1 contradicts goal of *Min-Tx* and *Min-Sp*, *Min-Tx* and *Naive* prefer re-allocation with R_3 (see R_3's dominance for *Min-Tx* and *Naive* in Fig. 5 with low transponder usages in Fig. 4). Conversely, *Min-Sp* prefers new split creation with R_3 (see R_3's dominance for *Min-Sp* with its high transponder usage). Note in Fig. 5 that the variants except *Naive* adopt other re-configuration actions with very low probability due to two reasons. First, length of an existing lightpath may not support a transmission configuration with a higher data-rate on the same spectrum allocation inhibiting use of R_2. Second, R_4-R_6 cause higher level of disruption, and are used only when no other options are feasible. Fig. 5 shows that *Min-Ds*, on average, disrupts 44%, 35%, and 58% less slots carrying live traffic compared to *Min-Tx*, *Min-Sp*, and *Naive*, respectively. The key takeaway of our analysis is that minimizing disruption with *Min-Ds* has a trade-off with transponder and spectrum usage, and an InP should choose an objective based on the disruption tolerance of the service being run on the VN.

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