Balancing CapEx reduction and network stability with stable routing–virtual topology capacity adjustment (SR–VTCA)

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Abstract

This paper investigates the merits of the SR–VTCA (stable routing–virtual topology capacity adjustment) approach as a mechanism to find a beneficial trade-off between network stability and reduction in capital expenditures (CapEx). These are two main objectives for the entities that own the optical infrastructure, such as network operators (NOs), and those also acting as Internet service providers (ISPs). The SR–VTCA scheme is a novel approach to adapt transparent optical networks to time-varying traffic by adjusting the number of lightpaths between node pairs, while keeping the IP routing unchanged. Lightpath bundling (LB) and anycast (AS) switching are combined in SR–VTCA operation to advertise lightpath additions/removals to the IP layer as mere adjustments (increments or decrements) in the capacity, allowing to keep the IP routing stable, and thus, simplifying control plane operations. On the contrary, a fully-reconfigurable (FR) network design, where IP routing can be also modified, would increase the burden in the control plane, but at a higher CapEx reduction, since the optical infrastructure is used more efficiently. In this work, we investigate the CapEx overprovision introduced by SR–VTCA with respect to a FR scheme. In order to do this, SR–VTCA planning problem is first modeled as a MILP formulation. A heuristic procedure based on traffic domination is then proposed to solve large instances of the problem. Exhaustive experiments are conducted comparing the SR–VTCA solutions obtained by the aforementioned MILP and heuristic proposal with solutions found by other optimization methods presented in the literature to solve the FR planning problem. Finally, the results show that SR–VTCA can achieve similar results to the FR case in terms of CapEx reduction, while a huge number of IP reroutings are saved by maintaining IP stability. Thus, SR–VTCA provides an advantageous balance between CapEx overprovisioning and the control plane overhead associated with IP rerouting.

1. Introduction

In IP/MPLS over WDM (Wavelength Division Multiplexing) networks, transparent all-optical connections, called lightpaths, are set up over the physical optical infrastructure
in a lower optical layer. The set of established lightpaths is called the virtual topology (VT) since each lightpath represents one virtual link. Packet-switched MPLS frames (carrying IP packets) are then routed over the virtual topology regardless the underlying physical optical network, in the upper electronic layer. Therefore, planning these networks implies solving a multilayer routing problem, referred to as virtual topology design (VTD) [1]. This problem consists of routing packet-switched traffic over lightpaths in the higher layer; and routing and wavelength assignment (RWA) [2] of lightpaths over the optical fibers in the lower layer.

Different VTD planning strategies have been investigated in the literature with respect to multilayer networks in the presence of continuous variations of their traffic volumes. Static planning approaches address the VTD problem by considering long-term traffic estimations, i.e. in the form of one unique traffic matrix, where unexpected short-term fluctuations of traffic can lead to blocking. To overcome this issue, over-provisioning is employed to provide robustness to these sudden traffic changes, but at the expense of higher cost, power consumption and degraded utilization. An alternative strategy to reduce the magnitude of this “over-provisioning” is to incorporate the dynamicity of the traffic into the planning process. According to real traffic traces, such as those collected for the Abilene network and the GEANT network (both available at [3]), traffic follows periodic patterns easy to forecast. These variations (typically weekly or daily) can be modeled as a temporal sequence of traffic matrices, each estimating the demand in a discrete time slot. Then, the estimation of these expected fluctuations, referred to as multi-hour traffic, allows the network planner to reduce the over-provisioning by benefiting from the sharing of network resources (e.g. lightpaths) between time-disjoint traffic demands.

To take advantage of this traffic periodicity, the electronic and/or the optical layer must adapt to the multi-hour traffic (i) by changing the IP/MPLS routing of the electronic traffic over the virtual topology; and/or, (ii) by adjusting the network capacity by dynamically reconfiguring the topology of the lightpaths. In the sequel, we assume that the IP traffic is routed using permanent MPLS virtual circuits (LSPs), one for each different end-to-end route planned in the network. Then, the IP packets are routed to the destination traversing a single LSP. If several LSPs are planned, the IP routing tables are defined such that traffic balancing can be applied in an unconstrained manner: that is, the IP routers can define for each LSP, the specific fraction of traffic to be forwarded. This alternative is not compatible with the OSPF equal-cost multi-path constraint, which mandates an equal balance of traffic among equal-cost LSPs. However, it is compatible with some other signaling systems, including centralized (e.g. routing tables controlled by the management plane) and distributed (e.g. OSPF-OMP [4]). In sum, this approach permits (i) defining several end-to-end routes for the IP traffic for each node pair where each route is implemented by one LSP, and (ii) determining the specific fraction of the traffic to be forwarded in each route in the IP routing tables.

The motivation for our work is that changes in the electronic routing tables or in the virtual topology come at a cost of higher control plane and management plane signaling complexity. Therefore, a good trade-off between efficient resource usage in the context of multi-hour traffic and the aforementioned signaling complexity cost is desirable. Several alternatives have been proposed to provide network adaptability to traffic variations. The option that has the greatest flexibility consists of permitting both (i) the rerouting of (IP/MPLS) traffic flows and (ii) reconfigurations in the virtual topology of lightpaths. We will refer to this scheme as a fully-reconfigurable network (FR). However, rerouting at the electronic layer is something that service providers strongly try to avoid. Namely, traffic flow rerouting complicates not only the control plane but requires reconfiguration of monitoring services and the event correlation database in the management plane, as identified in [5]. Thus, routing stability is a key issue for ISPs. However, the trend in optical networking is towards an agile network with directionless and colorless ROADMs which eases the fast reconfiguration of the topology of lightpaths [6]. Putting together the two previous arguments, there is a technological incentive to explore how optical networks can adapt to traffic variations by reconfiguring only the optical layer, while keeping the IP/MPLS routing unchanged. However, changing the topology of lightpaths in an optical network, while keeping IP/MPLS routing stability, seems to be a contradiction in terms since lightpaths are seen by the upper layer as links which can transmit IP/MPLS packets. Namely, when a new lightpath is added to the network, the electronic layer signaling must advertise it and changes in the routing tables must be conducted to incorporate this new lightpath before packets are transmitted on it. Then, it could be interesting to research new network operation paradigms where tradeoffs between the benefits of routing stability and the advantages of lightpath reconfigurations are present.

An example of such a paradigm was proposed in [7]: the stable routing–virtual topology capacity adjustment (SR–VTCA) scheme. SR–VTCA proposes a way of operating the network where lightpath reconfigurations in the VT are advertised to the electronic layer as adjustments (increments or decrements) in the capacity, but not as new link additions/removals necessary to advertise. Consequently, the electronic routing can be kept stable. The enabling technology that makes the SR–VTCA possible is the adoption of the lightpath bundling (LB) and anycast (AS) switching LB+AS paradigm proposed in [8]. Lightpath bundling (LB) is a control plane artifact, consisting of bundling together in the network those lightpaths which have a common input and output node, so that they appear to the upper electronic layer (MPLS in our case) as a single link of aggregated capacity. Lightpath bundling can be at present implemented in networks based on a GMPLS control plane, by making use of the GMPLS link bundling functionality as described in RFCs 4201 and 4202. Then, lightpath bundling allows the MPLS layer to perceive new lightpaths added/removed between the same pair of nodes as capacity expansions/reductions, i.e. capacity adjustments, of existing virtual links and not new virtual links which require modification of the already planned LSPs in order to be incorporated. The virtual topology is now composed of a set of lightpath bundles, where each
lightpath bundle is a virtual link of variable capacity with lightpath granularity. In its turn, AS consists of instructing the IP/MPLS router to implement a per-packet-granularity balancing of the traffic among the lightpaths in the bundle. This happens transparently to the IP layer which, because of the LB configuration, sees the bundled lightpaths as a single entity. Therefore, lightpath bundling (LB) and any-cast (AS) switching enforce an operation of the network where the electronic (IP/MPLS) layer can maintain stability (e.g. unmodified IP routing tables and unmodified LSPs), and adapt to traffic variations by dynamically adjusting the capability by adding/removing lightpaths in the lightpath bundles, implementing the SR–VTCA vision.

The SR–VTCA scheme was presented for the first time in [7], where its benefits and trade-offs were studied from the perspective of an Internet service provider (ISP) operating the IP/MPLS layer, who hires bandwidth (lightpaths) from a different network operator (NO) or owner of the optical infrastructure. The NO offers a lightpath-on-demand service to the ISP, with a per-lightpath tariff proportional to the amount of time each lightpath is active (a business model envisioned e.g. in [9]). This leased capacity along time supposes for the ISP an important (a business model envisioned e.g. in [9]). This leased capacity along time supposes for the ISP an important operational expenditure (OpEx) cost to minimize. Then, the study in [7] is focused on the potential benefits of SR–VTCA to reduce the OpEx. Results show that SR–VTCA could achieve practically the same OpEx as a fully-reconfigurable network (FR) where both the electronic routing and the VT can change to adapt to traffic variations.

Conversely, in the current paper, we study the SR–VTCA paradigm in a different scenario: the case when the NO is both the owner of the physical infrastructure and also acts as the ISP. In this business model, a per-lightpath-per-time leasing OpEx cost is not useful, since both the ISP and the NO are the same institution. Now, the cost figure to observe is the capital expenditure (CapEx) costs of the equipment required to establish the lightpaths. The network planning target is minimizing the CapEx of the optical infrastructure that is able to support the traffic in a network operated according to the SR–VTCA paradigm.

The CapEx cost figure considered in our studies as a valid representative is the number of transceivers the nodes have to be equipped with [10]. Namely, each lightpath requires a transmitter and a receiver (commonly called transceivers) at its source and destination nodes, respectively. According to this, we estimate the network cost as the total number of E/O and O/E transceivers required at the network nodes. The difference in the planning target with respect to [6] is highly relevant to the solution approach, since it enables network carriers to achieve savings by sharing transceivers at nodes between lightpaths set up at different instants, exploiting estimations in traffic variations. Fig. 1 depicts the scheme of an IP/MPLS over WDM node which enables such transceiver sharing. This node is derived from attaching an IP/MPLS router to the colorless and directionless ROADM of degree 3 (i.e. it serves three bidirectional fiber links) shown in Fig. 1 in [11]. The IP/MPLS router forwards the traffic to the appropriate output line cards according to its forwarding table. Line cards are not directly hard-wired to long-reach transceivers. Instead of that, as proposed in [11], a client-side cross-connect stands between the line cards and the tunable transceivers. Then, the architecture of power splitters (PS), wavelength-selective switches (WSS) and colorless multiplexers/demultiplexers (mux/demux) allows these transceivers to be assigned to any fiber link and wavelength. This is the enabling technology to permit transceiver sharing among all the client-side connections and lightpaths. Essentially, the E/O transceiver at node \( n \) and \( n' \) can be reused by lightpaths with the same origin node \( n \) but a different destination node at time periods when offered traffic between nodes \( n \) and \( n' \) decreases and some transmitters become idle. The same situation happens at the destination node \( n' \) if we consider O/E receivers. Thus, the total number of transceivers installed at the nodes is not necessarily proportional to the total number of lightpaths active over time.

In this paper, we address the stable routing with virtual topology capacity adjustment (SR–VTCA) planning of a network aimed at minimizing the CapEx. We consider as input parameters the physical network topology and the multi-hour traffic estimation, and obtain the stable flow routing and a set of time-varying lightpaths between each pair of nodes. The frequency of VT reconfigurations (e.g. every 4 h) is also an input parameter to the problem. This is a desirable flexibility for two reasons. First, emerging bandwidth markets will allow bandwidth users to hire on-demand bandwidth to the network operators at granularities even as small as five-minute blocks [12]. Secondly, results in [13] suggest that trade-offs between savings in CapEx, such as transponder cost, and increments in control plane overhead can depend strongly on the frequency of VT reconfiguration.

We model the problem as a MILP (mixed integer linear program) formulation which minimizes the total number of transponders installed at the nodes, the CapEx estimation. Note that the proposed scheme does not calculate the routing and wavelength assignment (RWA) of each lightpath. We assume that the remaining optical resources, such as optical line amplifier (OLAs), Dispersion compensating fibers (DCF), or dynamic gain equalizers (DGEs) [10], are allocated in such a way that any lightpath can find a valid RWA. This scenario corresponds to a metro or long-haul network with an overprovisioned fiber plant. Such a case constitutes a realistic assumption since network operators usually over-dimension the optical layer resources, as shown in [14]. Also note that introducing RWA constraints in most cases would not affect the problem with respect to the obtained CapEx (transponder) costs for the SR–VTCA and fully-reconfigurable networks which is the main topic of this work. The reason is that the number of transponders is completely defined by the temporal evolution of lightpaths, independent of the RWA scheme. Recall that each lightpath requires transponders only at its end nodes, and not at the intermediate nodes of their physical routing. Consequently alternative RWA schemes for the same virtual topology yield equal transponder costs. The RWA constraints only affect the solutions when they are hard enough to reduce the feasible lightpath sets (i.e. solution space) which is not the case if we assume an overprovisioned fiber plant. Thus, removal of the RWA constraints does not significantly impact
our problem while providing an important complexity reduction.

Since the SR–VTCA problem is clearly NP-hard, as is the standard VTD problem (integer capacity planning) [15], we also propose an efficient heuristic approach to handle large-sized problem instances. The heuristic proposal computes the electronic stable routing and time-varying virtual topology making use of the traffic domination concept introduced in [16] and previously applied in the multi-hour context in [17,18]. Informally speaking, if a sequence of traffic matrices $H^1$ dominates a sequence of traffic matrices $H^2$, then we can solve the multi-hour network planning problem by using $H^1$, so that the solution obtained is valid for the original traffic $H^2$.

The rest of this paper is organized as follows. Section 2 surveys the state of the art on multi-hour planning in optical networks. Section 3 provides the MILP model of the planning problem investigated. In Section 4, the heuristic approach is presented. Section 5 describes the experimental methodology and the obtained results; and, finally, Section 6 concludes the paper.

2. Related work

The introduction of traffic fluctuations into the network planning process has been researched for various network technologies [7,9,13,17–33]. In ATM networks, the concept of adjusting the capacity of the virtual paths while keeping routing stability was investigated in [20,21]. In its turn, in WDM networks, the planning problem under time-varying traffic models has been more recently researched in [7,9,13,17,18,22–33]. Initial works in this area [22–26] considered one-step virtual topology reconfigurations for better adaptation to traffic changes in a cost-effective
manner. In these works, an existing virtual topology migrates to a target one as a reaction to a variation in the traffic. In such cases, the most common design objective is to minimize the associated reconfigurations to avoid traffic disruptions. In subsequent works [7,9,13,17,18,27–33], different traffic variation patterns are considered. For example, in [27], periodic short term-fluctuations and expected long-term changes in both the traffic demand and the physical topology are jointly considered.

A set of monitoring campaigns exposing daily and weekly periodic variations in the traffic in core networks (i.e. [3]) have triggered the interest in multi-hour traffic models ([7,13,17,18,28–33]). In optical networks, the initial research efforts under multi-hour traffic were centered on the planning problem in the optical layer, i.e., given a sequence of VTs, one for each time interval in a multi-hour traffic pattern, the problem consists of finding a valid RWA for each time interval. This is the idea of scheduled temporary lightpaths, proposed in [28], under the name of Scheduled Lightpaths Demands (SLDs). Several heuristic algorithms have been proposed under the SLD scheme: branch and bound and tabu search approaches were presented in [28], while more scalable tabu-search based heuristic and greedy algorithms were introduced in [29].

A more general sliding scheduled traffic model is studied in [30,31]. In this model, the known starting and holding times of lightpath demands are allowed to slide within a predefined window.

Recently, other works ([7,13,17,32,33]) have studied the problem of finding a sequence of VTs (number of lightpaths to establish between each node pair), for a given multi-hour traffic demand. In [17,32], the authors study the problem of finding a static (non-reconfigurable) virtual topology, that is able to support the multi-hour traffic demand at any time instant. In the works [7,13,33], a reconfigurable optical layer is assumed, which permits setting up and tearing down lightpaths dynamically to adapt to traffic variations. The works in [13,33] assume that both the flow routing and the virtual topology can be reconfigured at every time interval. In [33], a naïve approach is used to plan the optical layer reconfiguration, where the VTs are independently planned in each time interval. In [13], the tradeoff between minimizing the transceivers needed over time and minimizing the number of lightpath reconfigurations is investigated by means of an efficient heuristic, called GARF (greedy approach with reconfiguration flattening).

A different and original approach with respect to [13,33] is followed in [7]. While in [13,33] the upper layer (i.e. IP) routing is assumed to be reconfigurable, together with the optical layer, in [7] the SR–VTCA approach is introduced and studied. Then, the problem addressed consists of finding a stable (not time-variant) higher layer routing that optimizes a network in which the optical layer can be reconfigurable. In this paper, we study a similar problem from a different approach. In [7], the SR–VTCA paradigm is investigated from the perspective of an ISP who hires bandwidth from an NO. Then, the network planner is interested in minimizing OpEx costs, such as the bandwidth leased (number of lightpaths) along the time. Conversely, in the present work, we study the case in which the ISP is also the owner of the physical infrastructure and, thus, is interested in reducing CapEx costs comprised largely by the number of transponders.

Finally, we sketch the main contributions and applications of traffic domination in the network planning since traffic domination is the basic concept applied to devise the heuristic proposal presented in the paper. The domination between two traffic matrices was introduced, first in [16], and later extended to multi-hour traffic sequences of matrices in [34,35]. It provides a useful tool to build more or less sophisticated reduction methods on the number of matrices required to model the planning problem by trivially applying its main property: if one matrix (or one sequence) dominates another matrix (or sequence), then we can use solely the former one to solve the planning problem. The traffic domination concept has been successfully applied in [17,18] in the framework of network planning for periodic multi-hour traffic. In both works, in contrast to the present one, traffic domination was employed in planning problems where the network capacity was constant. Here, we apply traffic domination to a problem where the capacity changes along time.

3. MILP formulation

In this section, we present a MILP (mixed integer linear programming) formulation model to solve the SR–VTCA problem from the point of view of the optical infrastructure owner, minimizing the dominant CapEx cost, i.e., the total number of transceivers required at all nodes considered over all time intervals. Let $N$ be the number of nodes in the network, and $T$ the number of time intervals in the multi-hour traffic demand. Let $i, j, s, d, n = (1...N)$ be the indices for the nodes, and $t = (1...T)$ be the index for the time slots. Due to the periodic time nature, in this model we assume that the last time slot $t = T$ is followed by the first time interval $t = 1$. Let $h^s$ denote the traffic matrix at time slot $t$, and $h_{sd}^t$ denote the IP traffic demand (measured in Gbps) from node $s$ to node $d$, during time interval $t$. Note that in our target network, the traffic between each $(s,d)$ node pair can take different routes, each of them implemented by an LSP. Let $C$ denote the lightpath capacity also measured in Gbps and let $c$ represent the cost of a transceiver (transmitter or receiver).

In our model, time intervals are grouped into a certain number of non-reconfigurable epochs denoted as $R$. Flow routing $f$ is kept constant, without any changes along the time, while virtual topology $p$ can be adjusted between two consecutive non-reconfigurable epochs indexed as $r = 1,...,R$. In this work, we assume that all of the present epochs $r$ are of the same duration which can be calculated as a multiple of the duration of the time slots $T/R$ traffic matrices. In order to make our notation clearer, we use $t(r)$ to denote the non-reconfigurable epoch containing time interval $t$, while $t(r)$ represents the set of consecutive time intervals associated to epoch $r$. For instance, in Section 5 containing the numerical results, we test a traffic demand composed of 168 matrices ($T = 168$) corresponding to one hour intervals spanning over a whole week ($24 \times 7$ days = 168), and run simulations for several values of non-reconfigurable epochs per week, such as $R = 28$. 


In this case, $T/R=6$ matrices are associated to each epoch, supposing that the virtual topology could be adjusted four times each day.

The decision variables of the SR–VTCA problem are

- $p_{ij}^r \in \{0, 1, 2, \ldots\}$. Number of lightpaths in the lightpath bundle from node $i$ to node $j$, during non-reconfigurable epoch $r$.
- $f_{ij}^d \in [0, 1]$. Fraction of the total electronic (e.g. IP) traffic demand from node $s$ to node $d$ which is routed over the existing lightpaths in the lightpath bundle from node $i$ to node $j$.
- $\tau_n = \{0, 1, 2, \ldots\}$. Number of transmitters installed at node $n$.
- $\rho_n = \{0, 1, 2, \ldots\}$. Number of receivers installed at node $n$.

The problem formulation is given by (1a) and (1b).

$$\min c \sum_{n} (\tau_n + \rho_n) \quad (1a)$$

subject to

$$\sum_{j} f_{nj}^cd - \sum_{i} f_{im}^d = \begin{cases} 1, & \text{if } n = s \\ -1, & \text{if } n = d, s, d \in \{1, \ldots, N\} \\ 0, & \text{otherwise} \end{cases} \quad (1b)$$

$$\sum_{i,j} (f_{ij}^d x_{ij}) \leq C \times p_{ij}^{(s)}, \quad i,j \in \{1, \ldots, N\}, \quad t = \{1, \ldots, T\} \quad (1c)$$

$$\tau_n \geq \sum_{t} p_{nj}^r, \quad n \in \{1, \ldots, N\}, \quad r = \{1, \ldots, R\} \quad (1d)$$

$$\rho_n \geq \sum_{t} p_{in}^r, \quad n \in \{1, \ldots, N\}, \quad r = \{1, \ldots, R\} \quad (1e)$$

The objective function (1a), where $c$ denotes the cost per transceiver, minimizes the total cost of the transmitters and receivers which need to be installed at the nodes to support the traffic demand. Constraints (1b) are the link-flow routing conservation constraints for the stable routing $f$ fixed along all the time intervals. Note that the bundle of lightpaths between a node pair $(i, j)$ is considered as only one virtual link between $i$ and $j$ nodes. Constraints (1c) are the link-capacity constraints in the lightpath bundles, i.e., the capacity of each lightpath bundle between a pair of nodes $(i, j)$ must be enough to carry all the traffic traversing it at any time interval $t$. The set of constraints (1d) guarantee the number of transmitters installed at each node is sufficient to set up the bundle of lightpaths starting at node $n$ at any non-reconfigurable epoch $r$. Constraints (1e) are analogous to (1d) but consider receivers instead of transmitters.

### 4. The proposed heuristic approach: Dominant stable routing algorithm (DSRA)

In this section, we propose an effective algorithm to solve the SR–VTCA problem for large problem instances, referred to as DSRA (dominant stable routing algorithm). The algorithm presented here is based on the total domination relation between traffic matrices from [16]. Appendix A sums up the main traffic domination notions applied in the present work, but we encourage the interested reader to consult [16,34,35] for more details regarding the total domination concept.

The algorithm receives as an input parameter the sequence of $T$ traffic matrices $h^1, \ldots, h^T$ each of them of size $N \times N$, and obtains a stable flow routing valid for all the time intervals and the virtual topology for each non-reconfigurable epoch following a scheme composed of three basic steps:

- **Step 1 (replace with one dominant matrix).** We replace the initial sequence of $T$ traffic matrices $h^1, \ldots, h^T$ by one unique dominant matrix $h^\ast$ which totally dominates each of the matrices in the initial series. The total domination property guarantees that any VT $p$ and traffic routing $f$ that is able to support $h^\ast$, will also support any of the traffic matrices $h^1, \ldots, h^T$. According to [17], the traffic matrix with the smallest volume that satisfies this condition is: $h^\ast = \max(h^1, \ldots, h^T)$.

- **Step 2 (stable flow routing).** The heuristic algorithm [36] is used to obtain a VT $p^\ast$ that is able to carry the traffic of the dominant matrix $h^\ast$ obtained. The heuristic intends to (suboptimally) minimize the number of lightpaths of the VT. Then, we run a multicommodity flow LP formulation [37] to calculate a traffic routing $f$ of the traffic matrix $h^\ast$ onto the obtained virtual topology $p^\ast$, with the objective of minimizing the average number of hops. Finally, we deliver this routing $f$ to the next step and we disregard the virtual topology $p^\ast$.

- **Step 3 (virtual topology capacity adjustments).** For each non-reconfigurable epoch $r$, given the routing $f$ previously calculated and the known traffic evolution given by the traffic matrices in this epoch, we trivially obtain the number of lightpaths between each pair of nodes required to support the traffic between those nodes at any time slot within the epoch. This is represented by the capacity assignment $p^r$ for non-reconfigurable epoch $r$:

$$p_{ij}^r = \left\lceil \frac{\sum_{t \in \{r\}} (\tau_n + \rho_n)}{C} \right\rceil, \quad i,j \in \{1, \ldots, N\}, \quad r = \{1, \ldots, R\} \quad (2)$$

Finally, the number of transceivers required at each node using the capacity assignment $p^r$ along the non-reconfigurable epochs can be also easily calculated. The number of transmitters (receivers) at a node $n$ is the maximal number of lightpaths originating (terminating) at node $n$ over all non-reconfigurable epochs (see Eq. (3)). That is, the number of transmitters (receivers) a node needs is the number of transmitters (receivers) it uses in the epoch when it is using the most.

$$\tau_n = \max_{r \in \{1, \ldots, R\}} \left\{ \sum_{i=1}^{N} p_{ij}^r \right\}, \quad n \in \{1 \ldots N\} \quad (3a)$$

$$\rho_n = \max_{r \in \{1, \ldots, R\}} \left\{ \sum_{i=1}^{N} p_{in}^r \right\}, \quad n \in \{1 \ldots N\} \quad (3b)$$
5. Results

This section presents results targeted to evaluate (i) the benefits of the SR–VTCA paradigm in terms of the tradeoff between transceiver costs and complexity of the control plane; and, (ii) the quality of the DSRA algorithm as a heuristic approach to solve the SR–VTCA problem. For the first evaluation target, the benefits of SR–VTCA are compared with respect to a free fully-reconfigurable (FR) paradigm, where an unbounded number of changes is independent of the physical network topology. Under these considerations, the SR–VTCA scenario is evaluated to demonstrate the tradeoff. For the second evaluation target, the optimal solutions found by the MILP formulation (1) will be used to assess the quality of the DSRA as an optimization technique.

All the proposals were implemented in the MatPlanWDM tool [38] which links to the TOMLAB/CPLEX library [39] used to solve the MILP (mixed-integer linear programming) formulations.

5.1. Testing scenarios

Since we consider that any VTD has a feasible RWA solution, following the assumption stated in Section 1, the optimization problem is independent of the physical network topology, save for the number of nodes N of the topology. Therefore, the multi-hour demand is the only input data to the planning problem, and the number of rows and columns of the matrices gives the number of nodes in the topology. Under these considerations, the SR–VTCA and FR approaches are evaluated for two different scenarios: (a) small artificial networks with a reduced number of nodes and synthetically generated traffic matrices; and (b) larger reference networks from the literature and using data from real traffic traces. The testing scenarios are detailed below.

5.1.1. Small networks with synthetic traffic

In this scenario, three topologies are considered with the number of nodes set to N={4, 5, 6}. For each topology, five sample sequences of T=12 traffic matrices are synthetically generated, representing the daily variations of the traffic in 2-h time intervals. The matrices are generated following the multi-hour traffic generation method presented in [17] and summarized in Eq. (4).

\[ h_{ij}^t = b_{ij} \times \text{activity}(t) \times rf(a), \quad \forall i, j, t. \]  

For each sample, the traffic \( h_{ij}^t \) between two nodes (i, j) at a given time t is calculated as the product of three factors. First, a base traffic matrix \( b_{ij} \) is generated, where 80% of the values (randomly chosen) are set to one, while the remaining 20% are set to two. Second, the activity factor \( \text{activity}(t) \) in (4) introduces the effect of daily traffic variations by using the daily intensity variation pattern presented in [40]. Lastly, factor \( rf(a) \) is a random value uniformly distributed in interval [1–a, 1+a]. In our tests, parameter \( a \) was set to 0.2. Finally, the generated sequence of traffic matrices is multiplied by a normalization factor so that the average traffic between two nodes in the most loaded time slot is equal to \( \rho C \), where C is the lightpath capacity, and \( \rho \) is the traffic load parameter. The values tested in our study are \( \rho = \{0.1, 1, 5, 10\} \). A value of \( \rho = 0.1 \) corresponds to the case where the average traffic between two nodes in the most loaded time slot is only 10% of a single lightpath capacity. On the contrary, a value of \( \rho = 10 \) captures cases in which the average traffic between two nodes in the most loaded time slot is the capacity of 10 lightpaths.

Moreover, we also test the evolution of the network cost considering different numbers of non-reconfigurable epochs. Here, the duration of the epochs is denoted as \( \beta \), and three cases are studied with \( \beta = \{4 \text{ h}, 8 \text{ h}, 12 \text{ h}\} \). When \( \beta = 4 \text{ h} \), the network is reconfigured every 4 h where the number of non-reconfigurable epochs is 6 per day. When the maximum duration value (\( \beta = 12 \text{ h} \)) is considered, the network is reconfigured twice a day yielding only two non-reconfigurable epochs per day.

5.1.2. Larger networks with real traffic

We also investigate two larger network topologies with real traffic data: the 11-node Abilene network and the 23-node GEANT network, for which real traffic traces are publicly available at [3]. The traffic sequences in [3] span several weeks extracted from monitoring studies. From this data, we average the values taken at the same time and day in the week to obtain a sequence representing the average week in 1-h time intervals (168 traffic matrices per week) for each network topology (Abilene and GEANT). To test different traffic loads in the network, the average week sequence obtained previously is normalized for four traffic load factors \( \rho = \{0.1, 1, 5, 10\} \), in the same way as we described above.

Again, we study how the network cost changes for different non-reconfigurable epoch values. As in the previous subsection, we focus on three values of \( \beta = \{4 \text{ h}, 8 \text{ h}, 12 \text{ h}\} \). To illustrate, when \( \beta = 4 \text{ h} \), the network is reconfigured every four hours so the number of non-reconfigurable epochs is 42 (6 per day). Conversely, if we set \( \beta = 12 \text{ h} \), the network is reconfigured twice a day, i.e., 14 non-reconfigurable epochs in a week.

5.2. Benefits of the SR–VTCA paradigm

This subsection evaluates the advantageous tradeoff between CapEx cost and network stability introduced by the SR–VTCA paradigm. To this end, the SR–VTCA and FR approaches are compared for the two scenarios described above mentioned. For the smaller networks, the comparison is performed using MILP formulations; whereas, for the larger ones, heuristic algorithms are applied.

First, the two paradigms are compared for the three small topologies for which optimal solutions can be found. We compare the optimal results obtained using the MILP formulations proposed in this paper for the SR–VTCA approach, and those presented in (2) from [41] for the FR
paradigm. Then, to further validate the results and conclusions derived from the smaller scenarios based on synthetic traffic, we extend the investigation to the larger networks based on realistic traffic. These scenarios are solved using the DSRA heuristic proposed in this paper for the SR–VTCA approach, and an efficient heuristic algorithm called GARF (greedy approach with reconfiguration flattening) proposed in [13] for the fully-reconfigurable variant.

To study the tradeoff between CapEx cost and network stability, the CapEx cost is represented by the total number of transponders; whereas, network stability is characterized by the changes in both the VT and the flow routing which impacts the control plane. By maintaining the flow routing stable in the SR–VTCA designs, we expect to significantly reduce the number of VT/flow routing changes while only slightly increasing the transceiver cost with respect to FR designs. The subsequent paragraphs are devoted to assessing this tradeoff.

The overall transponder costs (represented by the total number of transponders) obtained for the (4, 5, 6)-node topology cases are shown in Fig. 2-(a)–(c), respectively; whereas, a number of transponders obtained for the Abilene and GEANT networks are shown in Fig. 3-(a) and (b), respectively. The top of the black bars shows the SR–VTCA cost, while the top of the white bars marks the cost associated to a fully-reconfigurable (FR) network plan. These bar plots help us to compare the SR–VTCA and FR paradigms in a very visual way, since the size of the black bar represents the maximum extra savings that could be reached if we employ an FR network design instead of an SR-VTCA one. From Fig. 2, we can see that the magnitude of these savings is not very significant, yielding 6% to 8% when the traffic demands are several times larger than a single lightpath capacity ($\rho = 5$ and $\rho = 10$); and practically negligible (between 0% and 3%) for cases where the traffic demands between node pairs are several times smaller than a single lightpath capacity ($\rho = 0.1$) or in the same order ($\rho = 1$). The same trends emerge in Fig. 3 but with figures slightly larger (the maximal FR savings in Abilene and GEANT cases are 13% and 14%, respectively).

Considering the impact of the reconfiguration frequency in the SR–VTCA approach, we find a natural result: longer non-reconfigurable epochs imply less frequent reconfigurations producing higher figures of transceivers. Note that in the FR scenarios, the number of transceivers at a given traffic load $\rho$ and a given topology is constant, since the FR scheme does not depend on the duration of the non-reconfigurable epochs. The FR paradigm may perform as many changes as required at any time to minimize the transceiver cost, in both optical and electronic layers. Therefore, this figure constitutes a lower bound on the SR–VTCA optimal cost. Interestingly, the data indicates that the SR–VTCA does not need to incur very frequent VT reconfigurations to approach this lower bound. Even for two VT reconfigurations daily ($\beta = 12$ h), the cost savings due to FR do not exceed 14%. Consequently, these results suggest that a moderate number of changes in the VT while maintaining the IP routing stable (SR–VTCA paradigm) can provide transponder costs close to those

![Fig. 2. Transceiver cost comparison between SR–VTCA (MILP) and FR (MILP) for (a) 4-node, (b) 5-node, and (c) 6-node topologies. The x-axis ranges for different load factors $\rho = (0.1, 1, 5, 10)$ and reconfiguration epoch durations $\beta = \{4 \text{ h}, 8 \text{ h}, 12 \text{ h}\}$.](image-url)
obtained if we are free to perform any modification in the multilayer network.

To evaluate the control plane complexity of the FR and SR–VTCA paradigms, we identify the types of changes in the VT and electronic flow routing that affect the number of control operations which must be performed. Different criteria depending on the considered paradigm are applied to identify these changes:

The FR criterion: Two kinds of changes in the FR planning may impact on the electronic layer: (i) any set-up or tear-down of a lightpath; and (ii) any modification in the electronic routing table in terms of a change in the fraction of a given electronic flow routed over a given lightpath.

The SR–VTCA criterion: In contrast to the FR case, the only changes which impact the electronic layer are the additions (or removals) of bundles of lightpaths, i.e., adjustments in the bundle capacities implying transitions from (or to) zero lightpaths, since all the lightpaths in the bundle are seen as a single entity due to the LB functionality. Note that the stability in the electronic routing trivially implies the absence of changes in the fraction of electronic flows routed over the bundles so this does not affect control plane operation.

Table 1 reports the average number of the network changes per time slot for all the scenarios described in Section 5.1 under the FR paradigm. Since the FR scheme does not depend on parameter $\beta$, this parameter is not considered. In the FR criterion, we consider that a modification in the electronic routing table takes place when the fraction of a given electronic flow routed over a given lightpath changes at least 1%. From Table 1, we can see that the amount of such changes tends to grow with the size of the network topology and the traffic load. This is expected since the number of individual lightpaths (and, thus, the number of changes in the FR scheme) increases with both parameters. Note that in FR planning, the electronic routing matrix is defined over individual lightpaths, in contrast to SR–VTCA where the matrix is defined over bundles of lightpaths. With respect to the SR–VTCA paradigm, no changes (in the sense defined by the corresponding criterion) were found in any of the tested scenarios, except in one case ($N=4$, $\rho=1$ and $\beta=4$ h) where an average value of 0.13 changes per reconfigurable epoch was reported. The comparison between FR and SR–VTCA clearly shows the huge alleviation in control plane complexity achieved by the SR–VTCA approach. This reduction evidently achieves an advantageous trade-off with the moderate increase in transponder costs in comparison with the FR approach, highlighting the benefits of the proposal.

5.3. Assessing the quality of the heuristic algorithm: DSRA

In this subsection, we attempt to provide an insight in the merits of the DSRA algorithm proposed in this paper, as a valid optimization technique for solving the SR–VTCA problem. For this purpose, both the heuristic proposal and the MILP formulation in (1) are run for the small network scenarios detailed in Section 5.1.1, since MILP formulations cannot reach optimal solutions for larger problems. The gaps between the cost of the solutions provided by DSRA and the optimal costs obtained by the formulations, i.e., the so-called optimality gaps, are used to assess the quality of the heuristic approach. Table 2 shows the optimality gaps as a percentage of the obtained DSRA transceiver cost.

Results show that the optimality gap decreases for increasing values of the load factor $\rho=(0.5, 1, 5, 10)$, with values approximately 20%, 5%, 2% and 1%, respectively. These results support the efficiency of the DSRA approach for solving the SR–VTCA optimization problem, particularly, at medium and high loads where very narrow optimality gaps were found.

6. Conclusions

This paper studies the merits of the stable routing with virtual topology capacity adjustment (SR–VTCA) scheme in
lightpath-based optical networks when the Internet service providers (ISPs) also own and handle the optical infrastructure as network operators (NOs). The network cost is then dominated by the operator’s capital expenditures (CapEx), estimated as the cost of the E/O and O/E transceivers installed at the network nodes. SR-VTCA combines stable electronic traffic (e.g. IP) routing (an important concern for any ISP) with the flexibility to dynamically follow traffic variations by reconfiguring the virtual topology. These VT reconfigurations are advertised to the IP routing tables as mere capacity adjustments (increments or decrements) instead of new links, by applying lightpath bundling to group parallel lightpaths into single virtual links of variable capacity. This reduces the associated signaling in the control plane and avoids harmful disruptions of existing connections.

We present an exact MILP formulation for modeling such an SR–VTCA scheme in optical networks under multi-hour traffic. Due to its NP-hard nature, we also devise a heuristic approach based on the application of the traffic domination concept to handle larger instances of the problem. Exhaustive experiments are conducted to evaluate SR–VTCA versus a fully reconfigurable (FR) network plan, where electronic flows can be rerouted according to the traffic variations in addition to the virtual topology. The numerical results indicate that the SR–VTCA approach removes almost all the network reconfigurations while incurring only moderate extra CapEx costs with respect to the FR scenario. Moreover, the SR–VTCA achieves this performance with a very low frequency of VT adjustments (e.g. two or three times per day), by applying path bundling to group parallel lightpaths into single virtual links of variable capacity. This reduces the associated signaling in the control plane and avoids harmful disruptions of existing connections.

property 1. Let h and h’ be two traffic matrices. We say that traffic vector h totally dominates h’ if UX(h) ⊆ UX(h’). In other words, h totally dominates h’ if any capacity and routing pair (u, x) supporting h, also supports h’.

Herein we present a property extracted from [16] enabling us to detect if there exists a total domination relation between two matrices (see [16] for the proof).

property 1. For a fully connected graph, h totally dominates h’ if and only if and only if h_{sd} ≥ h’_{sd}, for any coordinate of the matrices s, d = {1, ..., N}.

We apply this property to find dominant traffic matrices in the proposed heuristic.

Finally, we note that, in the paper, we refer to capacity allocations u and flow allocation x as virtual topologies p and flow routings f, respectively, using the notation from Section 3. The notation (p, f) is more compact for describing VTD problems, such as the SR–VTCA and it is trivially related to the notation (u, x) by the following equations: u_{ij} = C \cdot p_{ij}^{(t)}, i,j = 1, ..., n, t = 1, ..., T; and, with f_{ij}^{sd} = h_{sd} \cdot f_{ij}^{sd}, i,j,s, d = 1, ..., n, t = 1, ..., T.

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