

Multi-layer Virtual Topology Design in Optical Networks Under Physical Layer Impairments and Multi-hour Traffic Demand

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Abstract—In this paper, we consider the virtual topology design (VTD) problem in multi-protocol label switching (MPLS)/wavelength division multiplexing (WDM) networks with an hourly changing traffic pattern, in the presence of physical layer impairments. We propose a multi-layer VTD scheme that satisfies the constraints in both layers with guaranteed bit error rates assuming no wavelength conversion. The proposed scheme involves interaction of the control planes of MPLS and WDM layers and can be applied without the necessity of a unified control plane. When the virtual topology is designed by considering only MPLS layer constraints, some lightpaths in the designed topology cannot be established, and this may result in a large amount of blocked traffic. We show that, by applying interaction between MPLS and WDM layers during topology design, the blocking ratio is reduced by an amount between 53% and 89% in the investigated cases. We also propose different information sharing strategies between the layers and show that, if physical layer information is available to the MPLS layer, a better blocking performance can be achieved and physical layer resource usage can be reduced by an amount up to 21%.

Index Terms—Optical network; Physical layer impairments; Routing and wavelength assignment (RWA); Static lightpath establishment; Virtual topology design; Wavelength division multiplexing (WDM).

I. INTRODUCTION

We investigate the virtual topology design (VTD) problem in optical networks in the presence of physical layer impairments. The VTD problem has a multi-layer nature, as it includes the problems of allocating the resources and routing the traffic in both electronic and optical layers. Solution approaches to the VTD problem differ depending on whether they tackle the joint multi-layer problem or solve the subproblems arising in specific layers separately.

In a joint VTD solution, the constraints and objectives of both layers are considered, and this results in a very high computational complexity. In most of the joint solutions

proposed in the literature, the computational complexity is reduced by making simplifying assumptions in one or both of the layers. Another important drawback of such solutions is that they necessitate a single operator having full information and control over both layers, resulting in potential inter-operability problems [1].

An alternative approach to avoid the high computational complexity of the joint VTD problem, which is applied also in this study, is to decompose the overall problem into multiple subproblems, each of which is confined to a single layer [2]. We assume in this paper that multi-protocol label switching (MPLS) is employed in the electronic layer, and the multiplexing technology used in the optical layer is wavelength division multiplexing (WDM). In a virtual topology design approach that considers only the MPLS layer subproblems, the common assumption is that the WDM layer can provide any amount of lightpath connections between any two nodes in the network [3–6]. However, the number of available lightpaths along the fibers can be a limiting factor, especially when the same physical infrastructure supports multiple virtual topologies in the upper layer. Moreover, as a lightpath traverses multiple fiber-optic links, the accumulative effect of physical layer impairments can increase the bit error rate (BER) along a lightpath to values above the acceptable threshold, making it infeasible to reliably communicate through the lightpath.

Conversely, in a solution that considers only the WDM layer issues, it is assumed that the lightpaths to be established are determined completely by a process running in the upper layer. Design of the requested lightpath set, or the question of whether it is possible to route the same traffic on a different virtual topology that utilizes fewer physical layer resources, are outside the scope of this single-layer problem. In order to produce an efficient and feasible solution to the complete virtual topology design problem, it is essential to consider the constraints and performance metrics stemming from both layers.

In this study, we focus on the multi-hour version of the VTD problem. An hourly changing traffic pattern and static lightpaths are assumed. We propose a multi-layer VTD scheme, in which the two subproblems arising in the MPLS and WDM layers are solved iteratively and interactively. The traffic is rerouted in the MPLS layer in order to accommodate hourly variations of the traffic, whereas the WDM layer provides the fixed set of lightpaths that connect routers. The problem in

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each layer is solved by applying fast and efficient heuristic algorithms, which are integrated within a collaboration scheme. Hence, the resulting multi-layer multi-hour VTD scheme can produce solutions in reasonable amounts of time, even for large problems. With the interaction of layers, a more efficient use of the network resources is achieved, and the feasibility of the designed virtual topology in the physical layer is verified.

We also develop a mixed integer linear programming (MILP) formulation for the joint problem. The formulation cannot be solved to optimality for the investigated cases, even for a small number of wavelengths, within a reasonable amount of time; however, the MILP formulation generates valid solutions that constitute bounds on the optimum solution. The proposed VTD scheme produces solutions with at least 66% lower bandwidth blocking ratios than the suboptimum solutions generated by the MILP solvers, in all of the investigated cases. To demonstrate the importance of layer interaction, we also implement a non-interactive version of the proposed scheme and show that the amount of blocked traffic is reduced by a value between 23% and 89%, when interaction between MPLS and WDM layers is employed, compared with the scenario with no interaction.

We then investigate different information sharing mechanisms between the control planes of MPLS and WDM layers and show that if the MPLS layer uses physical layer connectivity information during topology design, solutions with lower blocking ratios can be obtained, and optical layer resource utilization can be reduced by an amount up to 21%. However, in these solutions, the number of lightpaths and consequently the total cost of optical to electrical interfaces required to construct the resulting topology are higher.

The rest of the paper is organized as follows. In the next section, a review of the VTD approaches in the literature is provided. In Section III, the developed multi-layer topology design scheme is explained. In Section IV, the proposed interaction scheme and information sharing strategies between the MPLS and WDM layer control planes are introduced. Numerical evaluations and comparisons of the developed schemes are presented in Section V, and Section VI concludes the paper.

II. MULTI-LAYER VIRTUAL TOPOLOGY DESIGN

In this study, we investigate the multi-layer multi-hour VTD problem in the presence of physical layer impairments. The complete multi-layer VTD can be decomposed into four subproblems: deciding the lightpaths of the virtual topology (logical topology design), routing the electronic layer traffic on the resulting virtual topology (traffic routing), routing the lightpaths on the physical topology (lightpath routing), and assigning the wavelengths to lightpaths (wavelength assignment) [2]. The first two problems correspond to the MPLS layer and can be referred as the single-layer VTD problem, while the remaining two make up the routing and wavelength assignment (RWA) problem in the WDM layer. For successful communication through the established lightpaths, physical layer impairments should also be considered in the RWA problem, together with wavelength continuity and fiber capacity constraints.

Due to the large number of variables and constraints in both layers, a complete joint solution to these four problems is not tractable for moderate and large size networks. On the other hand, when they are solved separately, care must be taken to provide a strong integration between the solutions; otherwise, the complete solution may result in having a worse performance.

Because of the computational complexity of the joint problem, most of the studies in the literature focus on the subproblems corresponding to one layer and omit those arising in the other layer [3–6], or make simplifying assumptions to relax some of the subproblems [7–9]. There are also studies proposing formulations and solution methods for the joint problem [2,10]. A detailed description of the problem and a survey for the proposed solution approaches are described in [2]. A complete MILP formulation covering all the subproblems is introduced with the objective of minimizing the maximum link load. However, physical layers are not considered and no alternative solution approaches are proposed for this NP-hard problem. A similar joint formulation is proposed in [10], with a bound on the maximum number of hops of the lightpaths on the physical topology. A heuristic approach is proposed for the solution of the formulation, but the actual number of wavelengths necessary in the solution can be larger than the number of wavelengths used in the formulation.

An hourly changing traffic pattern is assumed in our study, and the aim is to design and construct a static virtual topology that satisfies as much of the offered traffic during the whole day as possible, using network resources efficiently. This problem is referred to as a multi-hour virtual topology design (MH-VTD) problem in the literature [11]. Another approach in case of an hourly changing traffic is to design a separate virtual topology for each time period. Each topology is optimized according to the traffic requirements of the corresponding period, and topology reconfigurations are performed between the consecutive time periods. However, in such an approach the traffic will be disrupted in the reconfiguration instances. Moreover, numerous studies show that the cost savings of such an approach are minimal and, by using the knowledge of the traffic matrices with careful planning, it is possible to design a static topology achieving a performance that is close to a reconfigurable one [3,9,11,12].

Few works investigate the MH-VTD problem in a multi-layer fashion and consider the subproblems arising in both layers. Most of the studies focus on the subproblems corresponding to the MPLS layer. In [9], the authors study the problem, assuming fixed lightpaths and label switched path (LSP) routes, and propose an MILP formulation. Assuming full wavelength conversion, the wavelength assignment problem is not considered. To produce suboptimal solutions for large problems, a resolution strategy integrating space-reduction and decomposition heuristics is also introduced.

In [3–6], the MH-VTD problem is studied as a single-layer problem without the consideration of RWA. The aim is to minimize the number of transceivers/lightpaths in [3,4]. An MILP formulation and a tabu search based heuristic are proposed in [3]. Splittable flows and varying LSP routes are assumed. The reconfigurable and fixed virtual topology scenarios are compared, and it is shown that lightpath reconfiguration is not cost effective in most of the cases. Formulations for

two versions of the problem with splittable and nonsplittable LSPs are developed in [4]. Heuristics applying the concept of traffic domination are proposed for complexity reduction of the problem. The authors of [5] propose a multi-objective MILP formulation minimizing the average packet hop distance, the maximum link utilization, and the number of lightpaths for the solution of the MH-VTD problem. They investigate both fixed and re-routable LSPs versions of the problem. A tabu search based heuristic algorithm with the aim of maximizing the routed traffic is developed in [6]. An MILP model with splittable flows is also presented, and the heuristic solution is compared with the upper bounds generated by solving the MILP. This tabu search based heuristic algorithm is the basis of the multi-layer VTD algorithm we develop in this study.

The subproblem corresponding to the WDM layer, the RWA problem, under physical layer impairments has recently been subject to increasing attention in the literature. Among the proposed solutions, there are linear programming formulations [13–15], applications of meta-heuristics such as tabu search [16], genetic algorithms [17,18], and heuristic algorithms [19–22]. A comprehensive literature survey on physical layer impairment aware (PLIA) RWA solutions is presented in [23]. In this study, solution of the RWA problem is carried out by employing the heuristic algorithm we proposed in [22]. Subsection III.B provides a more detailed explanation of this algorithm.

To the best of our knowledge, this is the first study proposing a solution to the multi-hour multi-layer VTD problem with the consideration of wavelength assignment and physical layer impairments. Our objective is to design a static WDM layer virtual topology that is feasible in the physical layer, which maximizes the routed traffic during the day, as the traffic changes on an hourly basis, with the assumption of nonsplittable but re-routable LSPs. Verification of the transmission quality along lightpaths is ensured by BER calculations carried out according to the physical model. Details of the utilized physical layer model and the calculations are presented in the next section.

III. MULTI-LAYER VIRTUAL TOPOLOGY DESIGN SCHEME

In this section, the multi-layer VTD scheme is explained. In this scheme, the selection of node pairs between which the lightpaths are established, and routing of the MPLS LSPs on the resulting virtual topology, are carried out by the MPLS layer control plane. Routing of the lightpaths on the physical topology and wavelength assignment functions are performed by the WDM layer control plane. In the rest of this section, we first give an overview of the physical layer model utilized and the tools required for the implementation of the proposed VTD scheme. Then, the developed VTD algorithms are explained and a complete MILP formulation for the joint problem is introduced.

A. Physical Layer Model

The optical wavelength routing node (WRN) architecture introduced in [24] is assumed in the utilized physical layer

model. The WRN consists of an array of demultiplexers, optical wavelength routing switches (WRSs), an array of multiplexers, and a pair of erbium-doped fiber amplifiers (EDFAs) and optical power taps, on the input and output sides at each port. For the lightpath architecture, the model presented in [25] is used. Along the fiber, backward-pumped distributed Raman amplifiers (DRAs) are used as in-line amplifiers. In each amplification span, a standard single mode fiber (SSMF) is followed by a dispersion compensating fiber (DCF). The attenuation along the DCF and the SSMF and the chromatic mode dispersion along the SSMF are completely compensated by the DRA and the DCF, respectively. The attenuation between the last DRA and the WRN is compensated by the EDFAs at the input and output ports of the cross-connect switch (XCS) along with the internal losses of the WRN resulting from the taps, multiplexers, demultiplexers, and the switching fabric of the XCS.

B. Implementation of Multi-layer VTD

For the implementation of the proposed VTD scheme, the decisions and calculations specific to the WDM and MPLS layers should be carried out by tools that are run in an integrated manner with the control planes. A WDM layer network planning and operation tool (WNT) should be integrated to the WDM layer control plane. The WNT has related information on the situation of the WDM layer such as the current wavelength usage on each link and physical impairment characteristics. Using this information, the WNT determines the feasibility of an input lightpath set. In this study, the WNT performs this function by running the reordered lightpath establishment (ROLE) algorithm, proposed in [22]. ROLE is a heuristic algorithm proposed for solving the lightpath establishment problem, with the objective of maximizing the number of established lightpaths from the offered lightpath demand set. It can produce solutions with an objective value close to the optimum solution and can solve large problem instances in a reasonable amount of time. ROLE estimates the BER of the established lightpaths by using the Q -factor approach [26] and allows only lightpaths with acceptable BER values to be established. The details of ROLE and a comparison of its performance with that of other algorithms proposed for the lightpath establishment problem are presented in [22].

The topology design algorithm is run by a VTD tool (VTDT) that is employed by the MPLS layer control plane. The VTDT has the related MPLS layer information needed to design the virtual topology, such as traffic demands for each hour, number of available optical to electrical interfaces, and the routing policies. Communication and interaction occur between the VTDT and the WNT during the topology design. When a VTD process is initiated, the WNT first sends the related optical layer information (e.g., connectivity, impairment characteristics) to the VTDT, according to the information sharing strategy employed. Then, during the process, the VTDT asks the feasibility of the resulting lightpath sets to the WNT and the WNT replies if the requested set is feasible or not. When the VTD process is finished, the WNT will have produced the lightpath set that will be established and the route and wavelength of each lightpath as the output. These lightpaths are established by the WDM layer control plane using this

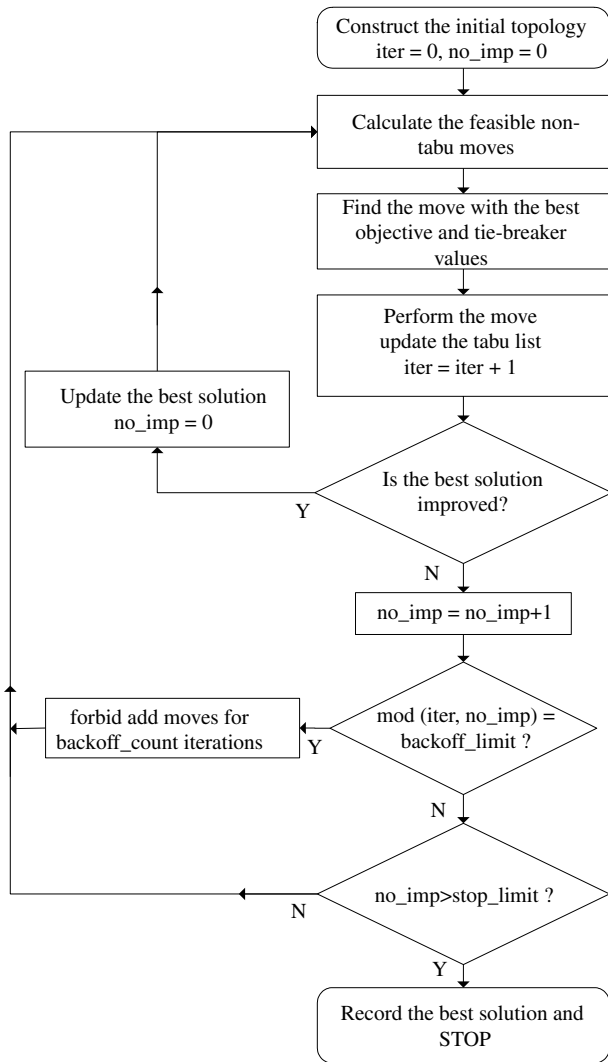


Fig. 1. Flowchart of the Tabu Search Virtual Topology Design (TS-VTD) algorithm.

information. The VTDT provides the routing tables for each time period to the MPLS layer control plane.

There are three inter-operation models for the MPLS over WDM networks: overlay, augmented, and peer models [27]. In the overlay or augmented inter-operation model, the WNT and the VTDT should be run in the WDM layer and the MPLS layer, respectively. In the peer model, both tools can be run by the single unified control plane.

C. Virtual Topology Design Algorithms

1) *Tabu Search Virtual Topology Design (TS-VTD)*: For VTD, we propose a tabu search based heuristic algorithm: tabu search virtual topology design (TS-VTD). This algorithm searches the solution space, which consists of the topologies that satisfy the optical to electrical interface constraints, i.e., the topologies in which the maximum number of lightpaths emanating from a node does not exceed the chosen threshold. The algorithm starts from a randomly generated topology that

is connected and satisfies the optical to electrical interface constraints and improves it iteratively by a series of moves. There are two types of topology update move: deleting an existing lightpath from the topology and adding a new one. The objective criterion to maximize is the total amount of traffic that can be routed on the established topology over all considered time periods. The objective value is calculated by sorting the demands in a decreasing order for each time period and routing them on the shortest paths calculated with link weights inversely proportional to the residual capacities.

The flowchart of the algorithm is presented in Fig. 1. At the start of each iteration, all the moves that are feasible, i.e., that lead to a topology in the solution space and that are not in the tabu list, are calculated along with the objective function value for the resulting topologies. Then, the move with the highest objective value is executed. To differentiate between moves resulting with the same objective value, the number of lightpaths in the resulting topology is used as a tie-breaker function, and the move with the lowest tie-breaker value is chosen. A performed move is declared tabu, stored in a tabu list, and forbidden for a number of iterations in order to prevent entrapment of the algorithm in cycles. When adding an entry to the tabu list, both the performed move and the topology configuration before the move are stored. Each entry in the tabu list is assigned a “tenure” which is decremented at each iteration. When the “tenure” of an entry expires, that entry is removed from the tabu list.

To achieve a more efficient search of the solution space, a backoff mode is introduced to the algorithm. If the objective function has not improved for a certain number of (backoff_limit) iterations, the algorithm performs only delete moves for a number of (backoff_count) iterations. Hence, it can reach a different region in the solution space by the following moves. The stopping criterion for the algorithm is that no improvement is achieved for a specific number of (stop_limit) iterations. When this criterion is met, the solution with the highest objective function value is recorded as the final solution. If there are multiple topologies giving the same objective value, then the final solution with the maximum value of the tie-breaker function is chosen.

2) Greedy Search Virtual Topology Design (GS-VTD):

The GS-VTD algorithm is used as a benchmark to evaluate the performance of the TS-VTD algorithm. The solution space, move types, and the initial solution are the same as in the TS-VTD algorithm. The difference of the GS-VTD algorithm is that it does not accept non-improving moves. When there is no move with a higher objective function value or with the same objective function and a lower tie-breaker function value, GS-VTD records the topology generated with the last move as the final result. Comparison of the results generated by the TS-VTD and GS-VTD provides a quantification of the improvement provided by the tabu search based procedure in TS-VTD.

D. MILP Formulation

We developed an MILP formulation for the multi-layer VTD problem, considering the physical layer impairments. The formulation contains a large number of variables and constraints in order to address limitations of both layers. The solution of

the problem to optimality may not be possible for most problem cases due to the resulting memory and time requirements. Nevertheless, it can be used to provide an upper bound and the best solution that can be obtained within a limited amount of time for providing a benchmark to evaluate the performances of other solutions to the multi-layer VTD problem.

A path based approach is used to model the RWA functions in the WDM layer, and a flow based approach is used for routing the MPLS LSPs on the virtual topology. In the developed formulation, the undirected graph $G = (N, L)$ represents the physical topology, where N is the set of nodes and L is the set of optical links. We assume that each optical node is attached to a label switching router (LSR), which does not violate the generality of the formulation. The lightpaths are assumed to be bidirectional. D denotes the set of MPLS layer bidirectional LSP demands, H is the set of considered time intervals for which the traffic measurements are done, W is the set of wavelengths, and P_{ij} denotes the set of precalculated shortest paths from node i to node j over the physical topology. The rest of the formulation is as follows.

Constants:

V^{dh} : volume of demand d at time h .

$s(d)$: source node for demand d .

$d(d)$: destination node for demand d .

C : bandwidth capacity of a single MPLS link (capacity of a wavelength).

O_{\max} : maximum nodal degree in the logical topology, corresponds to the maximum number of optical interfaces installed to LSRs.

F_l : number of fibers along link l .

$$T_{lp} = \begin{cases} 1 & \text{if link } l \text{ lies on path } p \\ 0 & \text{otherwise.} \end{cases}$$

Decision Variables:

x_{ij}^{dh} : MPLS layer flow variable from node i to node j belonging to demand d at time h (continuous).

u_{ij}^{dh} : 1 if demand d is routed along link (i, j) at time h , 0 otherwise (binary).

r^{dh} : total amount of MPLS layer flow belonging to demand d , routed at time h (continuous).

y_{ij} : number of established lightpaths between nodes i and j (integer).

z_{ij}^{wp} : number of established lightpaths between nodes i and j using wavelength w on path p (integer).

Objective Function:

$$\text{Maximize } \sum_{h \in H} \sum_{d \in D} r^{dh} \quad (1)$$

Subject to:

$$\sum_{j \in N} x_{ij}^{dh} - \sum_{j \in N} x_{ji}^{dh} = \begin{cases} r^{dh} & \text{if } i = s(d) \\ -r^{dh} & \text{if } i = d(d) \\ 0 & \text{otherwise,} \end{cases} \quad (2)$$

$$\forall i \in N, h \in H, d \in D,$$

$$\sum_j u_{ij}^{dh} \leq 1, \quad \forall i \in N, h \in H, d \in D, \quad (3)$$

$$x_{ij}^{dh} \leq V^{dh} \cdot u_{ij}^{dh}, \quad \forall i, j \in N, d \in D, h \in H, \quad (4)$$

$$\sum_{d \in D} x_{ij}^{dh} + \sum_{d \in D} x_{ji}^{dh} \leq C \cdot y_{ij}, \quad \forall i, j \in N, h \in H, \quad (5)$$

$$\sum_j y_{ij} \leq O_{\max}, \quad \forall i \in N, \quad (6)$$

$$\sum_{w \in W} \sum_{p \in P_{ij}} z_{ij}^{wp} = y_{ij}, \quad \forall i, j \in N, \quad (7)$$

$$\sum_{i, j \in N} \sum_{p \in P_{ij}} z_{ij}^{wp} \cdot T_{lp} \leq F_l, \quad \forall l \in L, w \in W, \quad (8)$$

$$K \cdot (\sigma_0^2 + \sigma_1^2) \leq M \cdot (1 - z_{ij}^{wp}) + \sigma_{\text{lim}}^2, \quad \forall i, j \in N, p \in P_{ij}, \quad (9)$$

$$w \in W.$$

The objective in this formulation is to maximize the amount of total traffic routed summed over all time intervals. Routing of the whole demand matrix is not introduced as a constraint. Therefore, the decision variables $\{r^{dh}\}$ are used in the objective function and in the flow constraint, Eq. (2). Since the decision variables $\{x_{ij}^{dh}\}$ should be continuous, a binary decision variable is needed to guarantee that the flows are routed without being split. For this purpose, the decision variables $\{u_{ij}^{dh}\}$ are introduced. Constraint (3) ensures that each flow is routed along at most one path, without being split. Equation (4) states that, if x_{ij}^{dh} is greater than 0, u_{ij}^{dh} is set to 1, and the routed traffic cannot exceed the offered traffic for each flow. Equation (5) is the lightpath capacity constraint and Eq. (6) is the nodal interface constraint. Constraint (7) ensures that each established lightpath is routed along a path and assigned a wavelength in the optical layer, and constraint (8) is the optical link capacity constraint.

The last constraint (9) imposes an upper bound on the BER along the established lightpaths. The expressions σ_0 and σ_1 denote the noise standard deviations for bits 0 and 1, in the optical signals carried along the lightpath established between i and j , if it is routed on path p and wavelength w . σ_{lim}^2 is the upper limit on the noise variance along a lightpath satisfying the BER constraint. K is an upper bound on the ratio of $(\sigma_0 + \sigma_1)^2$ to $(\sigma_0^2 + \sigma_1^2)$, and M is a large constant used for implementing the classical big- M linearization [28]. $(\sigma_0^2 + \sigma_1^2)$ depends on the signal, asynchronous spontaneous emission (ASE) noise, and crosstalk power levels corresponding to lightpath (i, j) , and the expression for the crosstalk power level contains decision variables with wavelength w and a path which has a common node with p . The detailed explanation of Eq. (9) can be found in [22]; it is omitted here because of space considerations.

IV. INTERACTION BETWEEN CONTROL PLANES

Design of the virtual topology can be carried out with or without interaction of the MPLS and WDM layer control planes. In the non-interactive case, the design process is carried out solely by the MPLS layer control plane. Establishment of the resulting virtual topology is then requested from the WDM layer control plane. The WDM layer control plane

tries to establish the maximum number of lightpaths in the requested topology. The lightpaths that are calculated to be feasible are established and the remaining lightpath requests are blocked. The MPLS layer control plane routes the MPLS LSPs on the resulting lightpath topology. In this approach, since there is no interaction between the MPLS and WDM layer control planes during the design phase, some lightpaths in the designed logical topology may not be established over the physical topology due to optical layer constraints, and the resulting topology may cause inefficient use of optical layer resources.

An alternative approach is to implement the topology design scheme in an interactive way. This can be done by introducing the interaction of the control planes into the VTD algorithm, as explained in Subsection III.B. The VTD process is managed by the VTDT tool that is run in the MPLS layer control plane. During the process, the WNT tool integrated to the WDM layer control plane checks the feasibility of the requested virtual topologies in the physical layer. At each iteration of the VTD algorithm, the VTDT sorts all possible moves (i.e., lightpath reconfigurations) according to the objective and tie-breaker values used by the algorithm, as described in Subsection III.C. Then, the feasibility of the resulting virtual topology is checked with the WNT for each move, until a positive answer is received. If the resulting topology is feasible, that move is performed and the algorithm continues with the next iteration, calculating the set of possible moves and the resulting objective and tie-breaker values for the new topology.

In the original TS-VTD algorithm, the MPLS layer does not possess any information about the physical layer, and the only interaction with the WDM layer is based on querying the feasibility of the resulting virtual topologies during the topology design process. We now investigate if the performance of the virtual topology design scheme can be further improved by using information from the WDM layer. We present below three different information sharing strategies. The utilized VTD algorithm is assumed to be TS-VTD through the rest of this section, although the proposed information sharing strategies can also be incorporated with other algorithms.

A. No Information Sharing (NoS) Strategy

This strategy refers to the case when no information is passed from the WDM layer to the MPLS layer. In this strategy, the topology design algorithm uses a randomly generated virtual topology as the initial topology. As the tie-breaker function, the total number of lightpaths is used. At each iteration, when the candidate set of moves is being sorted, among two moves resulting with topologies giving the same objective function value, the one with the smaller tie-breaker function value is placed before the other, as explained in Subsection III.C.

B. Topology Information Sharing (TIS) Strategy

In this information sharing strategy, the WDM layer control plane shares the physical connectivity information with the MPLS layer, and this information is used in the topology design

process. Physical topology connectivity information is used in two ways during topology design in the TIS strategy. First, the initial topology is chosen to have the same connectivity with the physical layer topology, and lightpaths are opened between each node pair which is connected through a fiber-optic link. Second, the tie-breaker function utilized is the sum of physical hop distances between the nodes of the lightpaths in the resulting topology, which can be expressed as

$$\sum_{\{i,j\} \in R} l_{\min}(i,j), \quad (10)$$

where R is the set of lightpaths in the resulting topology of the move and $l_{\min}(i,j)$ denotes the hop distance between nodes i and j on the physical layer topology.

The aim of this strategy is to prefer opening lightpaths between the nodes which are closer in the physical topology, in terms of hop counts. This approach disfavors opening lightpaths that traverse a large number of fiber links and helps to provide a more efficient usage of the physical layer resources.

C. Physical Impairment Information Sharing Strategies

Under realistic conditions, the physical characteristics of optical components in a network may not always be uniform. Some of the fiber-optic links or optical switches may be installed at different times, and they may be manufactured using a newer or older technology, or may be produced by different vendors. In this section, we investigate whether the performance of the virtual topology design algorithm can be further improved, if the MPLS layer were to make use of information about physical impairment characteristics in its decisions during VTD.

We focus on three physical layer parameters, each having an important impact on the BER and therefore on the feasibility of the lightpaths: the polarization mode dispersion (PMD) coefficients (D_{PMD}) of fiber-optic links, the switch crosstalk ratio (X_{SW}) of optical switches, and the ASE factor (n_{sp}) of the optical amplifiers in the network [22]. We investigated three scenarios: in each scenario one of these parameters is distributed non-uniformly among the network components. For each scenario, we developed an information sharing strategy, in which the distribution information of the non-uniform impairment parameter is made available to the MPLS layer, along with the physical layer connectivity information. In each of these strategies, the main objective in topology design is the amount of routed traffic, but the utilized tie-breaker function is different in each case, and it depends on the considered physical impairment. For the scenario in which the PMD coefficients of the links are non-uniform, we developed the PMD information sharing (PIS) strategy. For the non-uniform switch crosstalk ratio scenario a crosstalk information sharing (XIS) strategy and for the non-uniform ASE factor scenario an ASE information sharing (AIS) strategy are developed.

1) *PMD Information Sharing (PIS) Strategy*: The PIS strategy makes use of the D_{PMD} information during topology design. In this version, the MPLS layer control plane receives

the connectivity information, and the length and PMD coefficient for each fiber-optic link in the physical topology, from the WDM layer control plane. Using this information, it calculates the accumulated PMD effect along the shortest path for each lightpath in the resulting virtual topology. The tie-breaker function can be expressed as

$$\sum_{\{i,j\} \in R} \sum_{l \in p_{i,j}} D_{\text{PMD}}(l) \cdot l_{\text{phy}}(l), \quad (11)$$

where $p_{i,j}$ denotes the shortest path between nodes i and j , $D_{\text{PMD}}(l)$ is the PMD coefficient along fiber-optic link l , and $l_{\text{phy}}(l)$ is the physical length of l . Of the moves that have the same objective function, the one with the lower tie-breaker value is chosen. The aim is to prefer opening lightpaths along which the signals will receive a smaller PMD penalty.

2) Crosstalk Information Sharing (XIS) Strategy: In the XIS strategy, the MPLS layer control plane uses X_{SW} information in the tie-breaker function. The tie-breaker function is given by the summation of the switch crosstalk values of the nodes along the shortest paths between the source and destination nodes of each lightpath in the resulting virtual topology, which is expressed as

$$\sum_{\{i,j\} \in R} \sum_{n \in p_{i,j}} X_{\text{SW}}(n), \quad (12)$$

where $X_{\text{SW}}(n)$ is the switch crosstalk ratio for node n , which lies on the shortest path $p_{i,j}$, between nodes i and j . Of the moves that have the same objective function, the one with the lowest tie-breaker value is chosen. This strategy favors opening lightpaths whose paths traverse optical switches with smaller X_{SW} values.

3) ASE Information Sharing (AIS) Strategy: The AIS strategy is based on sharing of the ASE factor information between layers. The tie-breaker function used in the topology design algorithm run by the MPLS layer is the sum of the n_{sp} values of the amplifiers along the shortest paths between the source and destination nodes of each lightpath. This function can be expressed as

$$\sum_{a_k \in p_{i,j}} n_{\text{sp}}(a_k), \quad (13)$$

where $n_{\text{sp}}(a_k)$ is the ASE factor of the k th amplifier a_k along $p_{i,j}$, the shortest path between nodes i and j . The move resulting with the lowest tie-breaker function is chosen when the objective values are the same.

The initial topology generation mechanisms and the tie-breaker functions for all the information sharing strategies are summarized in Table I.

V. NUMERICAL RESULTS

In this section, we evaluate the performances of the VTD algorithms and the information sharing strategies employed by generating and solving problem instances with various traffic rates.

TABLE I
INITIAL TOPOLOGY GENERATION AND TIE-BREAKER
FUNCTIONS USED BY THE INFORMATION SHARING
STRATEGIES

Str.	Initial topology	Tie-breaker function
NoS	Randomly generated	Number of lightpaths
TIS	Physical connectivity	Sum of shortest path lengths
PIS	Physical connectivity	Sum of shortest path PMDs
XIS	Physical connectivity	Sum of shortest path X_{SW} s
AIS	Physical connectivity	Sum of shortest path n_{sp} s

A. Traffic and Network Topology

We assume a traffic pattern changing with the time of the day, and the topology design algorithms implemented utilize the available capacity in the network, in the most efficient way, by assigning different paths to the traffic flows for different time periods. Therefore, they are best suited to wide area networks (WANs) whose nodes are spread over a large geographical area, and the busiest hour is not the same for all the traffic flows in the network. The NSFNET topology [29], with 21 links and 14 nodes spread over four different time zones, satisfies this criterion and is commonly used in the literature. We evaluated the proposed algorithms on this topology assuming single-fiber links. The physical layer parameters for the nodes and links of the topology can be found in [22].

The traffic pattern changes with the time of the day in order to reflect the characteristic daily behavior of the Internet traffic that depends on the provider and consumer activities [30]. For each node i , a traffic activity function $\text{act}(i, t)$, which depends on the time zone of the node, and a daily traffic generation rate tgen_i , representing the population, are defined. The expected instantaneous traffic of a traffic flow between nodes i and j at time t is calculated as

$$T_{\text{expected}}(i, j, t) = \text{tgen}_i \times \text{act}(i, t) \times \text{tgen}_j \times \text{act}(j, t). \quad (14)$$

In a real-life scenario, the traffic generated from and destined to a node may depend on other factors such as the industrial and commercial activities and the frequency of Internet usage among the population. To represent this effect, we define a unit traffic generation rate tgen_u , and the actual traffic generation rate of each node is chosen by adding a random variable to tgen_u between $\pm 10\%$ of tgen_u for each generated problem instance. The ratio of the square of unit traffic generation rate to the capacity of a single wavelength (tgen_u^2/W_C) is referred to as the “Traffic Magnitude” and it is used as a traffic metric when evaluating the performances of the topology design solutions.

When generating the traffic demand matrix, the day is divided into six time periods, each consisting of 4 h. For each node pair, the maximum expected traffic between the nodes in a time period is taken as the traffic demand belonging to that node pair in the considered time period.

TABLE II
BANDWIDTH BLOCKING PERCENTAGES FOR THE MILP SOLUTIONS, GS-VTD ALGORITHM, AND TS-VTD ALGORITHM WITH AND WITHOUT LAYER INTERACTION, FOR $|W| = 4$

Traffic Mag.	MILP Solution	GS-VTD	TS-VTD w/o Int.	TS-VTD w. Int.
0.1	26.2	10.81	14.9	0
0.11	33.59	16.65	20.11	0
0.12	21.07	18.04	22	0
0.13	22.85	22.83	26.49	0.05
0.14	34.1	25.13	31.24	0.25
0.15	31.9	27.82	36.7	0.03
0.16	38.56	33.67	30.51	1.09
0.17	34.72	31.49	27.9	3.75
0.18	36.05	40.14	31.48	11.04
0.19	30.66	39.6	34.97	9.93
0.20	32.97	41.34	38.73	10.96

B. Evaluation of Topology Design Algorithms

In this section, the TS-VTD and Greedy Search virtual topology design (GS-VTD) algorithms, and the solutions generated by the proposed MILP formulation introduced in Subsection III.D, are comparatively evaluated. The TS-VTD algorithm is run with both interactive and non-interactive control planes, as explained in Section IV, in order to evaluate the effect of providing interaction between the MPLS and WDM layer control planes. The GS-VTD algorithm is run only with interactive control planes and is used to investigate the effectiveness of the tabu search based search procedure implemented in the TS-VTD algorithm.

The MILP formulation is solved using the CPLEX 12.1 optimization problem solver, applying the branch and cut method. The solver is run with an upper limit on the spent CPU time of 100,000 s. Due to the large number of decision variables and constraints, an optimal solution could not be generated for any of the problem instances investigated, and the best integer solution generated within the given time limit is recorded as the MILP solution.

Problem instances are generated with the *Traffic Magnitude* value changing between 0.1 and 0.2, and for four wavelengths per fiber ($|W| = 4$), to be able to generate solutions by solving the MILP formulation. Five demand sets are generated for each *Traffic Magnitude* value. The average bandwidth blocking percentages are presented in Table II. As is seen from the results, valid solutions can be obtained by solving the MILP formulation, but in these solutions the blocking ratio is above 25% for all values of *Traffic Magnitude*, while TS-VTD with interactive layers achieves the lowest blocking ratio among the four methods considered. We observe that good solutions cannot be obtained by using the MILP formulation, even for a small number of wavelengths. To make a comparison of the running times of the solution methods, the average running times of the GS-VTD algorithm and non-interactive and interactive TS-VTD algorithms are recorded as 6.36, 39.27, and 636.83 s, respectively.

The GS-VTD and TS-VTD algorithms are also tested on the same network for $|W| = 16$. Ten problem instances with different demand sets are generated for each *Traffic Magnitude* value. To keep the traffic/capacity ratio the same, four traffic flows are generated per node pair for each demand set. The results are presented in Fig. 2. Applying the tabu search

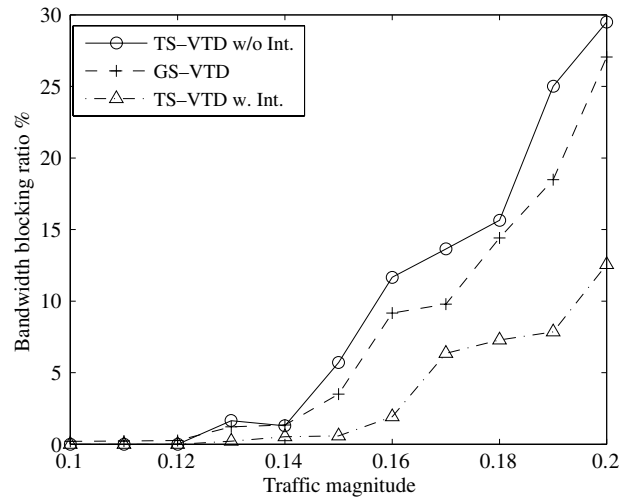


Fig. 2. Bandwidth blocking ratios for the GS-VTD algorithm and TS-VTD algorithm with and without layer interaction, for $|W| = 16$.

meta-heuristic, TS-VTD can reduce the traffic blocked by the GS-VTD algorithm by an amount between 35% and 100%, when interaction exists between the WDM and MPLS layers. This result justifies the effectiveness of the search algorithm used in TS-VTD. However, when TS-VTD is run without interaction between the layers, some of the requested lightpaths cannot be established, and the MPLS layer tries to route the traffic on the established virtual topology instead of requesting other lightpaths, even if there are sufficient physical layer resources to establish new lightpaths. As a result, the blocking ratio is worse than that for the simple GS-VTD algorithm implemented with layer interaction, whereas, by employing interaction between the WDM and MPLS layers in the TS-VTD algorithm, the blocked traffic is reduced by an amount between 53% and 89%. For $|W| = 16$, the average running times of the GS-VTD algorithm and non-interactive and interactive TS-VTD algorithms are recorded as 528, 507, and 16,695 s, respectively.

C. Single-Hour Versus Multi-hour Topology Design

As stated in the previous section, the TS-VTD algorithm employs a multi-hour approach: LSP routes are determined

TABLE III
BANDWIDTH BLOCKING RATIOS (BBR) IN EACH TIME PERIOD FOR THE TS-VTD ALGORITHM WITH MULTI-HOUR AND SINGLE-HOUR APPROACHES AND THE TRAFFIC INTENSITY

Time Period	Blocking ratios (%)		Traffic Intensity (%)
	Single-hour	Multi-hour	
1	0.00	0.00	3.04
2	2.57	0.56	17.94
3	3.92	3.31	23.20
4	3.92	3.28	23.20
5	3.84	3.37	23.04
6	0.29	0.00	9.58
Whole Day	3.19	2.40	100

separately for each time period according to the traffic demands in that time period. Another approach which has lower complexity is to consider the peak values of the traffic demands during the whole day. In this single-hour approach, for each source–demand pair the highest traffic demand during the day is used as the bandwidth requirement of that pair. The routes of the LSPs are fixed and calculated based on this bandwidth requirement information.

We evaluate the benefits of multi-hour topology design by comparing these two approaches. To this aim, the TS-VTD algorithm (with interaction) is modified to run with the single-hour approach. We generated problem instances with different values of *Traffic Magnitude*, between 0.1 and 0.2. Ten different traffic sets are generated for each value and the number of wavelengths per fiber is taken as 8, i.e., $|W| = 8$. The blocking ratios for both approaches in each time period are presented in Table III. The values in the table represent the averaged blocking ratios over all values of the *Traffic Magnitude* parameter. The ratio of the offered traffic in each time period to the total traffic generated during the whole day is also given under the name *Traffic Intensity*.

As can be seen from the results, for both approaches most of the blocking occurs between time periods 3 and 5, in which the network is most highly loaded. In the less active time periods such as 2 and 6, the multi-hour approach can make better use of the free capacity in the network and result in much lower blocking ratios than the single-hour approach. When the whole day period is considered, multi-hour design reduces the overall blocking probability from 3.19% to 2.40%, compared with the single-hour approach. It should be noted that, in the NSFNET topology used in this study, the largest time zone difference for a node pair is equal to 3 h. For networks covering a larger number of time zones, the distribution of the traffic in the network will change more significantly according to the time period, and the performance difference between the two approaches is expected to be wider.

D. Effect of Topology Information Sharing

In this section, we investigate the effect of information sharing between the WDM and MPLS layer control planes. First, we assume a scenario with uniform physical layer impairment parameters throughout the network. In this scenario, TS-VTD is run with layer interaction and the

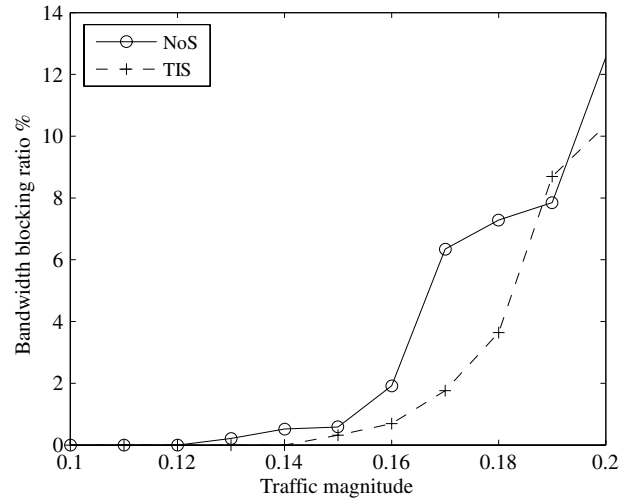


Fig. 3. Bandwidth blocking ratios for the NoS and TIS strategies.

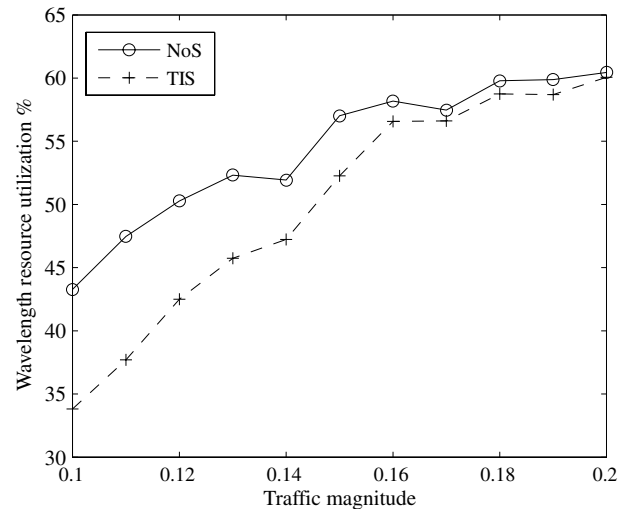


Fig. 4. Wavelength resource utilization for the NoS and TIS strategies.

NoS and TIS strategies. The aim is to investigate if it is possible to generate better solutions by using the physical topology connectivity information in the MPLS layer, during topology design. Problem instances are generated with *Traffic Magnitude* value changing between 0.1 and 0.2, for $|W| = 16$. Ten problem instances with different demand sets are generated for each value of *Traffic Magnitude*, and the averages of blocking ratio and wavelength usage are calculated for the two strategies.

The blocking ratios are presented in Fig. 3 as a function of the *Traffic Magnitude*. As is seen from the results, TIS has a lower blocking ratio than NoS, in all the cases except one and on the average. TIS also uses a smaller ratio of the physical layer resources, i.e., wavelength resources, as shown in Fig. 4. Wavelength resource utilization is the total number of wavelengths occupied by the established lightpaths, in all the optical fibers in the physical topology. The percentage value for this metric is calculated by taking its ratio to the total

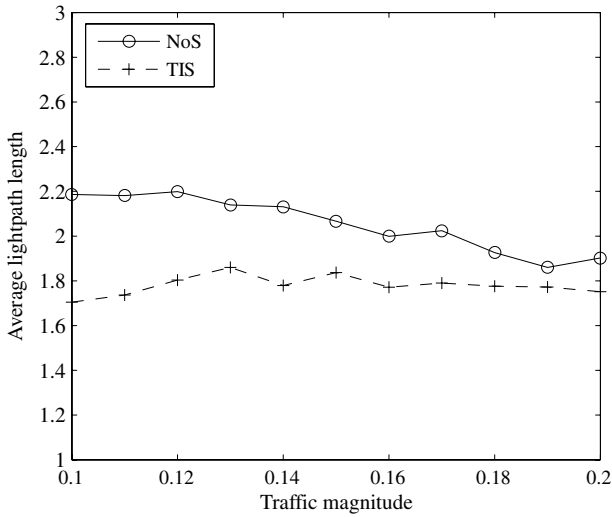


Fig. 5. Average hop lengths of the established lightpaths for the NoS and TIS strategies.

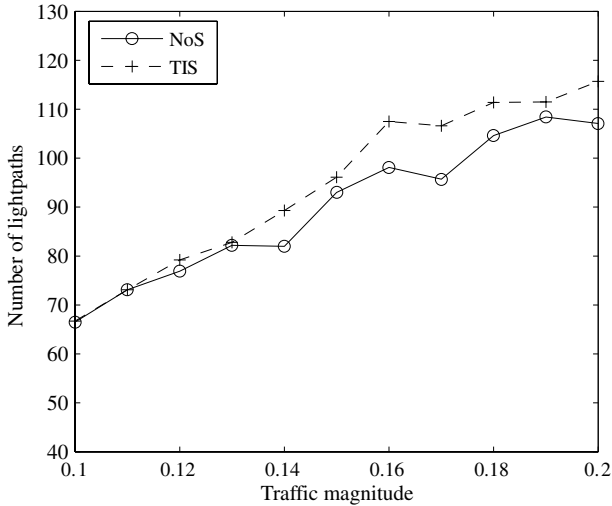


Fig. 6. Average number of established lightpaths for the NoS and TIS strategies.

available wavelength resources in the physical topology, which is the product of the number of wavelengths and the number of fiber-optic links in the physical topology. The wavelength resource utilization of TIS is up to 21% lower than that of NoS.

When the average hop lengths of the lightpath in the topologies generated by both strategies are examined, it can be observed that the TIS strategy establishes shorter lightpaths than the NoS strategy in terms of number of hops, as depicted in Fig. 5. This is an expected result, since TIS favors opening lightpaths between nodes that are closer in the physical topology. By preferring opening lightpaths between closer nodes, TIS manages to make a more efficient use of the optical layer resources, as can be observed from Fig. 4.

The average number of lightpaths in the established virtual topologies is presented in Fig. 6. Since optical to electrical interfaces need to be deployed on the MPLS routers at the start

and end of each lightpath, the number of lightpaths reflects the cost of the established virtual topology, to the MPLS layer operator. This value is higher for the TIS strategy than it is for the NoS strategy, since the secondary objective of the NoS strategy is to minimize the number of lightpaths.

As a result, the TIS strategy has a better blocking performance and lower optical resource usage than NoS, thanks to the use of physical connectivity information. But NoS has a lower MPLS layer cost, since it focuses on minimizing the MPLS layer cost while maximizing the routed traffic.

E. Non-uniform Physical Impairment Scenarios

In this section, we investigate three scenarios in which the physical layer impairment characteristics in the network are not uniform. In the first one, the fiber-optic links in the network have different PMD characteristics. The PMD coefficient D_{PMD} of each link is chosen among the values 0.1, 0.2, and 0.4 ps/ $\sqrt{\text{km}}$, randomly. The TIS strategy and the PIS strategy, which uses the total accumulated PMD along the lightpaths as the tie-breaker function, are compared in this scenario.

In the second scenario, the switch crosstalk ratio value X_{SW} of the optical switches is chosen randomly. In the physical layer model utilized, switch crosstalk is the most significant contributor to the noise related penalty. Its effect on the lightpath establishment performance of the WDM layer was investigated in [22], and it was shown that the ratio of successfully established lightpaths changes with X_{SW} for X_{SW} values between -25 dB and -35 dB, for the assumed parameters. In this scenario, the X_{SW} value of each node is chosen randomly within this range, and the performances of the TIS and XIS strategies are evaluated.

The third scenario addresses the case of amplifiers with non-uniform ASE factors (n_{sp}). The n_{sp} values are determined randomly, within the range (1, 2). TIS is compared in this scenario with the AIS strategy, which is based on sharing the ASE information.

The blocking and wavelength resource utilization ratios and average lightpath lengths for the TIS and PIS strategies in the first scenario are depicted in Figs. 7, 8, and 9, respectively. The same metrics for the TIS and XIS strategies in the second scenario are shown in Figs. 10, 11, and 12, and for the TIS and AIS strategies in the third scenario in Figs. 13, 14, and 15, respectively.

The results show that the bandwidth blocking ratio increases significantly when the switch crosstalk ratio X_{SW} is non-uniformly distributed in the network. This is an expected result, because, as stated above, switch crosstalk is the most dominant physical layer impairment for the chosen parameters. Due to the non-uniform distribution, some nodes in the network have a high X_{sw} value; this decreases the number of lightpaths that can be established, and as a result the number of bandwidth blockings increases.

When we compare the blocking ratios of the information sharing strategies, we see that TIS and PIS have a very close performance in the first scenario (Fig. 7). The XIS strategy in the second scenario performs better than TIS for some cases and worse for others, but their overall performances are also

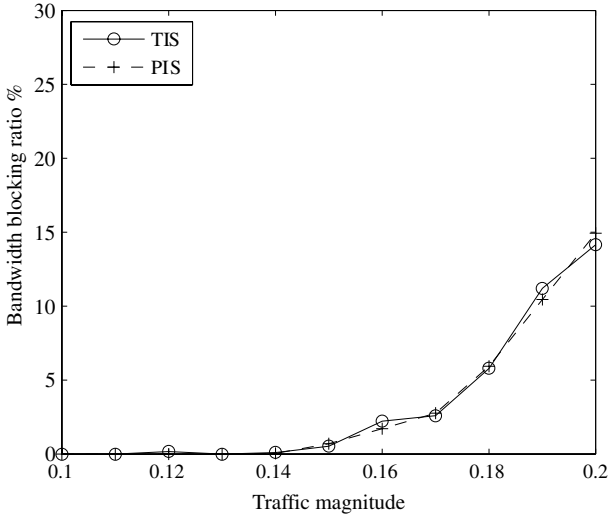


Fig. 7. Bandwidth blocking ratios for the TIS and PIS strategies.

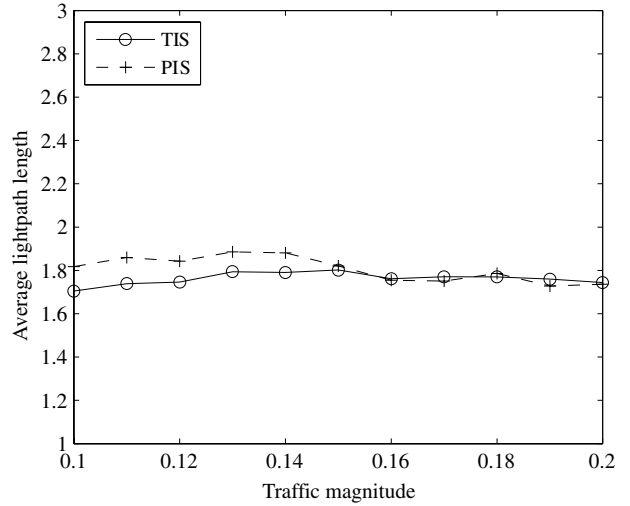


Fig. 9. Average hop lengths of the established lightpaths for the TIS and PIS strategies.

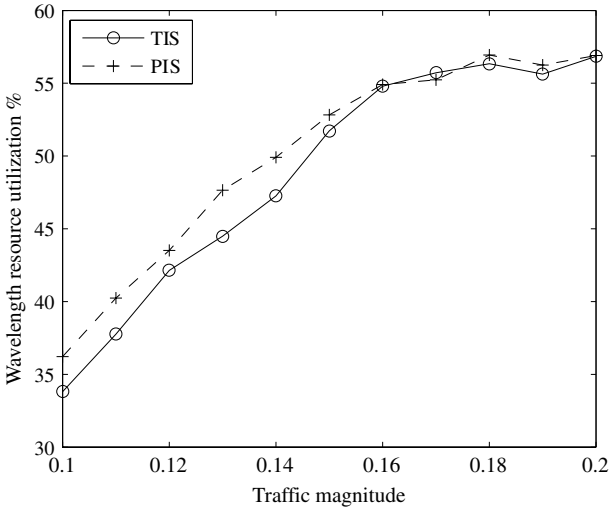


Fig. 8. Wavelength resource utilization for the TIS and PIS strategies.

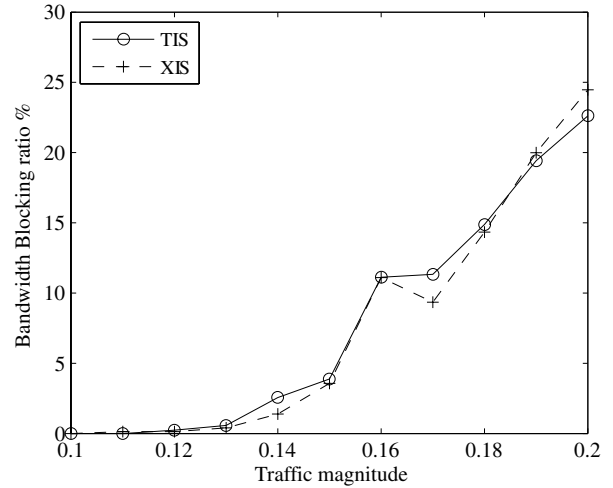


Fig. 10. Bandwidth blocking ratios for the TIS and XIS strategies.

close (Fig. 10). In the third scenario, the AIS strategy performs slightly worse than TIS in the low load region and slightly better for higher loads, but their overall performance is not significantly different (Fig. 13). Examining the wavelength resource utilizations of the information sharing strategies in Figs. 8, 11, and 14, it can be seen that the TIS strategy has a slightly lower resource utilization due to slightly shorter average lightpath hop length (Figs. 9, 12, and 15).

Using the node crosstalk and ASE factor characteristics as tie-breakers in the TS-VTD algorithm, a slightly lower blocking ratio can be achieved for some traffic loads, but the overall performance averaged over different traffic loads does not change significantly. The topology information using the TIS algorithm does not use any physical impairment information directly, but it prefers lightpaths with smaller numbers of hops, and since the physical impairments are cumulative, in most cases, a lightpath with shorter hop length will accumulate

fewer physical impairments than a longer one. As a result, it considers the physical layer impairments in an indirect way.

Another important fact is that signal quality degradation is not the result of a single physical impairment, but a combination of them. The physical impairment information sharing strategies investigated in this study are based on sharing one type of impairment information between the layers, which is shown to be inefficient. It may be possible to further improve the network performance by topology design methods using information on a combination of the dominant physical layer impairment factors. Development of such methods is left as a future study.

VI. CONCLUSIONS

In this study, we have proposed a multi-layer scheme for the VTD problem with an hourly changing traffic pattern.

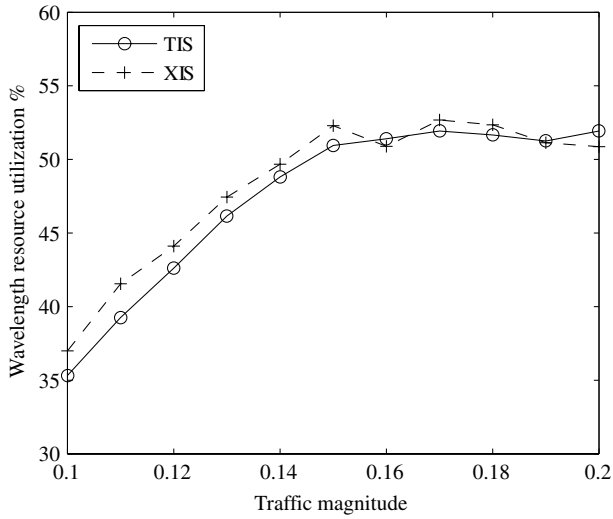


Fig. 11. Wavelength resource utilization for the TIS and XIS strategies.

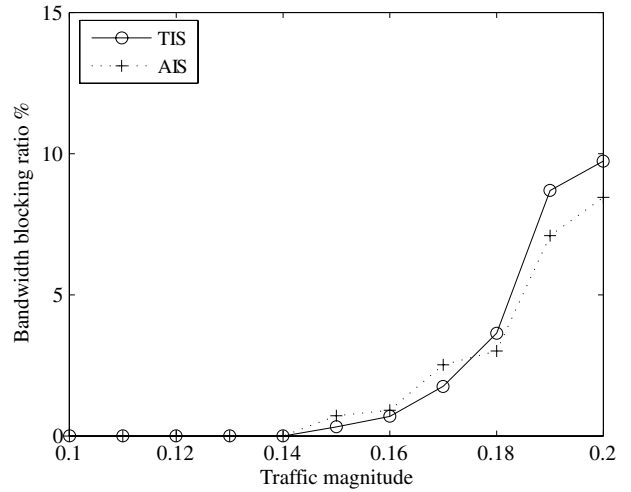


Fig. 13. Bandwidth blocking ratios for the TIS and AIS strategies.

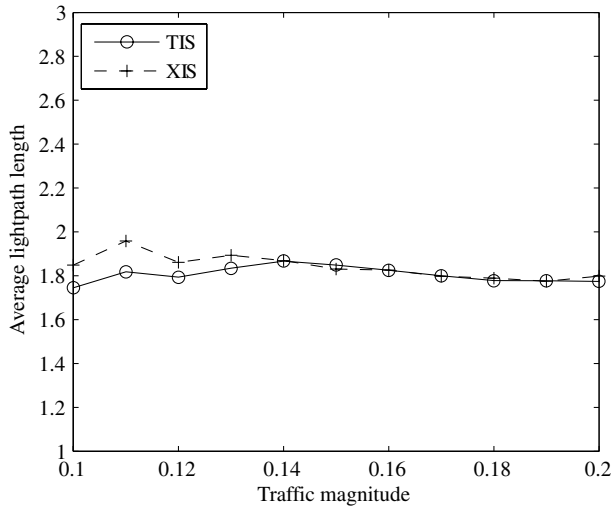


Fig. 12. Average hop lengths of the established lightpaths for the TIS and XIS strategies.

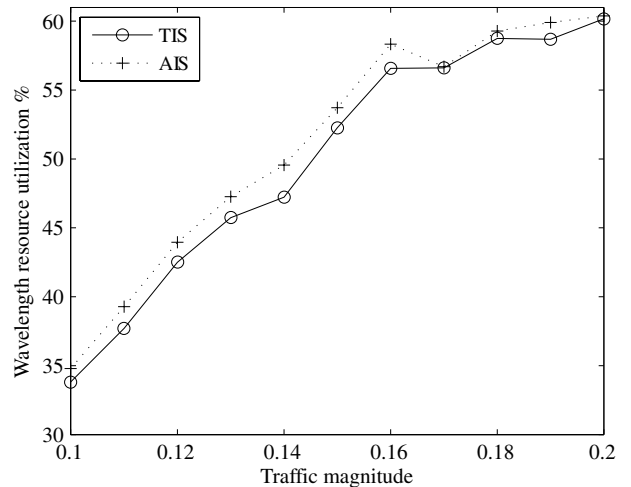


Fig. 14. Wavelength resource utilization for the TIS and AIS strategies.

The objective in this problem is to design a fixed virtual topology with varying LSP routes, in order to maximize the amount of routed traffic. The WDM layer constraints and physical layer impairments are also considered. The proposed method solves the multi-hour logical topology design and LSP routing problems arising in the MPLS layer, and routing and wavelength assignment problems in the WDM layer, in an integrated approach that does not necessitate a single common control plane for both layers. An MILP formulation is also developed for the joint problem, but good solutions cannot be obtained by solving this formulation, even a for small number of wavelengths.

The proposed scheme involves a simple interaction mechanism for the MPLS and WDM layer control planes to verify the feasibility of the designed virtual topology. By comparing with the non-interactive version of the proposed method, it is shown

that an important amount of traffic is blocked if the WDM layer constraints are not considered during VTD, whereas, on considering interaction between the MPLS and WDM layers, the blocked traffic is reduced by an amount between 53% and 89%.

A tabu search meta-heuristic is employed in the virtual topology design algorithm of the proposed scheme. The effectiveness of the topology design algorithm is demonstrated by comparing its solutions with those of a simple greedy search algorithm, and it is shown that the tabu search based algorithm can reduce the blocking ratio of the GS-VTD algorithm by 35%–100%.

Different information sharing approaches between the MPLS and WDM layer control planes are also investigated. The results show that, if physical layer connectivity information is available to the MPLS layer control plane, it is possible to design a virtual topology with a lower blocking ratio and smaller usage of physical layer resources. However, this

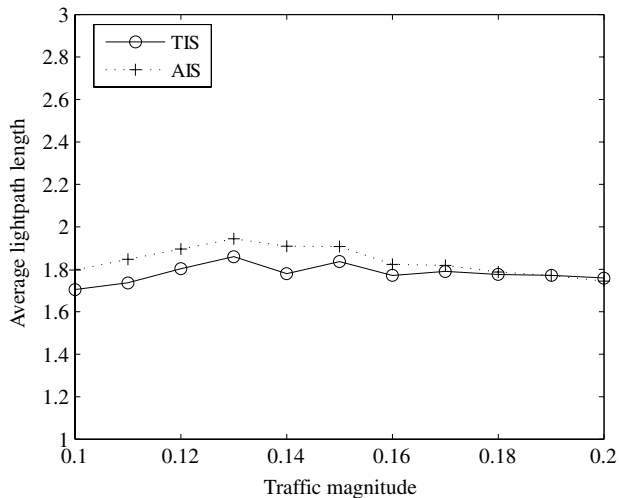


Fig. 15. Average hop lengths of the established lightpaths for the TIS and AIS strategies.

improvement comes with an increased cost in the MPLS layer with a larger number of lightpaths. Using the physical layer connectivity information in the MPLS layer may also provide advantages in developing more effective protection schemes, which is left as a future study. We also investigated the use of physical layer impairment information in the MPLS layer, but no significant improvement is achieved by considering only a single impairment factor. Development of new topology design schemes that may produce better solutions using information on a combination of the physical layer impairment characteristics is the subject of another future study.

ACKNOWLEDGMENTS

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REFERENCES

- [1] J. E. Gabeiras, V. Lopez, J. Aracil, J. Palacios, C. Argos, O. Dios, F. Chico, and J. Hernandez, “Is multilayer networking feasible?” *Opt. Switching Networking*, vol. 6, no. 2, pp. 129–140, 2009.
- [2] R. Dutta and G. Rouskas, “A survey of virtual topology design algorithms for wavelength routed optical networks,” *Opt. Networks Mag.*, vol. 1, no. 1, pp. 73–89, 2000.
- [3] N. Skorin-Kapov, P. Pavon-Marino, B. Garcia-Manrubia, and R. Aparicio-Pardo, “Scheduled virtual topology design under periodic traffic in transparent optical networks,” in *Proc. BROAD-NETS*, 2009, pp. 1–8.
- [4] P. Pavon-Marino, R. Aparicio-Pardo, B. Garcia-Manrubia, and N. Skorin-Kapov, “Virtual topology design and flow routing in optical networks under multihour traffic demand,” *Photonic Network Commun.*, vol. 19, no. 1, pp. 42–54, 2010.
- [5] G. Agrawal and D. Medhi, “Lightpath topology configuration for wavelength-routed IP/MPLS networks for time-dependent traffic,” in *Proc. IEEE Globecom*, 2006, pp. 1–5.
- [6] N. Sengezer and E. Karasan, “An efficient virtual topology design and traffic engineering scheme for IP/WDM networks,” in *Proc. ONDM*, 2007, pp. 319–328.
- [7] L. Gouveia, P. Patrício, A. de Sousa, and R. Valadas, “MPLS over WDM network design with packet level QoS constraints based on ILP models,” in *Proc. IEEE INFOCOM*, 2003, vol. 1, pp. 576–586.
- [8] D. Banerjee and B. Mukherjee, “Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study,” *IEEE/ACM Trans. Netw.*, vol. 8, no. 5, pp. 598–607, 2000.
- [9] F. Ricciato, S. Salsano, A. Belmonte, and M. Listanti, “Off-line configuration of a MPLS over WDM network under time-varying offered traffic,” in *Proc. IEEE INFOCOM*, 2002, vol. 1, pp. 57–65.
- [10] R. Krishnaswamy and K. Sivarajan, “Design of logical topologies: A linear formulation for wavelength-routed optical networks with no wavelength changers,” *IEEE/ACM Trans. Netw.*, vol. 9, no. 2, pp. 186–198, 2001.
- [11] D. Medhi, “Multi-hour, multi-traffic class network design for virtual path-based dynamically reconfigurable wide-area ATM networks,” *IEEE/ACM Trans. Netw.*, vol. 3, no. 6, pp. 809–818, 1995.
- [12] N. Sengezer, B. Puype, E. Karasan, and M. Pickavet, “A comparative study of single-layer and multi-layer traffic engineering approaches on transparent optical networks,” in *Proc. ICTON*, 2007, vol. 4.
- [13] K. Manousakis, K. Christodoulopoulos, and E. Varvarigos, “Impairment-aware offline RWA for transparent optical networks,” in *Proc. IEEE INFOCOM*, 2009, pp. 1557–1565.
- [14] I. Tomkos, D. Vogiatzis, C. Mas, I. Zacharopoulos, A. Tzanakaki, and E. Varvarigos, “Performance engineering of metropolitan area optical networks through impairment constraint routing,” *IEEE Commun. Mag.*, vol. 42, no. 8, pp. S40–S47, 2004.
- [15] K. Christodoulopoulos, K. Manousakis, and E. Varvarigos, “Considering physical layer impairments in offline RWA,” *IEEE Network*, vol. 23, no. 3, pp. 26–33, 2009.
- [16] X. Yang, L. Shen, and B. Ramamurthy, “Survivable lightpath provisioning in WDM mesh networks under shared path protection and signal quality constraints,” *J. Lightwave Technol.*, vol. 23, no. 4, pp. 1556–1567, 2005.
- [17] M. Lima, A. Cesar, and A. Araujo, “Optical network optimization with transmission impairments based on genetic algorithm,” in *Proc. SBMO/IEEE MTT-S Int. Microwave and Optoelectronics Conf.*, 2003, vol. 1, pp. 361–365.
- [18] D. Monoyios, K. Vlachos, M. Aggelou, and I. Tomkos, “On the use of multi-objective optimization algorithms for solving the impairment aware-RWA problem,” in *Proc. IEEE Int. Conf. Communications*, 2009, pp. 1–6.
- [19] S. Azodolmolky, Y. Pointurier, M. Klinkowski, E. Marin, D. Careglio, J. Solé-Pareta, M. Angelou, and I. Tomkos, “On the offline physical layer impairment aware RWA algorithms in transparent optical networks: State of the art and beyond,” in *Proc. ONDM*, 2009, pp. 13–18.
- [20] M. Ezzahdi, S. Al Zahr, M. Koubàa, N. Puech, and M. Gagnaire, “LERP: a quality of transmission dependent heuristic for routing and wavelength assignment in hybrid WDM networks,” in *Proc. ICCCN*, 2006, pp. 125–136.
- [21] Y. Huang, J. Heritage, and B. Mukherjee, “Connection provisioning with transmission impairment consideration in optical WDM

networks with high-speed channels," *J. Lightwave Technol.*, vol. 23, no. 3, pp. 982–993, 2005.

- [22] N. Sengezer and E. Karasan, "Static lightpath establishment in multilayer traffic engineering under physical layer impairments," *J. Opt. Commun. Netw.*, vol. 2, no. 9, pp. 662–677, 2010.
- [23] S. Azodolmolky, M. Klinkowski, E. Marin, D. Careglio, J. Pareta, and I. Tomkos, "A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks," *Comput. Netw.*, vol. 53, no. 7, pp. 926–944, 2009.
- [24] B. Ramamurthy, D. Datta, H. Feng, J. Heritage, and B. Mukherjee, "Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks," *J. Lightwave Technol.*, vol. 17, no. 10, pp. 1713–1723, 1999.
- [25] Y. Huang, W. Wen, J. Heritage, and B. Mukherjee, "Signal-quality consideration for dynamic connection provisioning in all-optical wavelength-routed networks," *Proc. SPIE*, vol. 5285, pp. 163–173, 2003.
- [26] G. Agrawal, *Fiber-Optic Communication Systems*. Wiley, New York, ch. 4, pp. 162–164.
- [27] B. Rajagopalan, J. Luciani, and D. Awduche, "IP over optical networks: A framework," *IETF RFC 3717*, Mar. 2004.
- [28] W. Winston, *Operations Research: Applications and Algorithms*. 4th ed., 2004.
- [29] K. Frazer, *NSFNET: A partnership for high-speed networking, Final Report. 1987–1995*, Merit Network, 1995.
- [30] J. Milbrandt, M. Menth, and S. Kopf, "Adaptive bandwidth allocation: Impact of traffic demand models for wide area networks," in *19th Int. Teletraffic Congress (ITC19)*, Beijing, China, 2005.



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