

Crosstalk-aware Routing Spectrum Assignment and WSS Placement in Flexible Grid Optical Networks

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Abstract— Due to crosstalk-induced interactions among different connections, malicious high-power jamming signals can potentially spread widely in a transparent optical network. Moreover, due to imperfect port isolation in wavelength selective switches (WSSs), present within optical switching nodes, crosstalk also affects the quality of the transmitted signal. Therefore, it is necessary to design an optical network in a way that the effect of crosstalk is minimized, while at the same time keeping the cost and the power consumption of the network low. This is achieved in this work by the design of appropriate WSS placement and crosstalk-aware Routing and Spectrum Assignment (RSA) algorithms in flexible grid optical networks, in the form of an Integer Linear Program (ILP) formulation and a heuristic algorithm analogous to vertex coloring. The objective of the optimization algorithms is to minimize the impact of the crosstalk effect, thus minimizing the impact to the normal operation of the network. The optimization objective is enhanced with proper functions in order to minimize the capital expenditure (CAPEX) and the operational expenditure (OPEX) of the networks investigated in terms of cost and power consumption respectively. Performance results indicate that the proposed algorithms minimize the number of WSSs required to compensate for the crosstalk effect, while only slightly increasing the spectrum utilization.

Index Terms—Crosstalk effect, network optimization, physical layer security, routing and spectrum allocation, wavelength selective switch.

I. INTRODUCTION

IN order to meet the increasing traffic demand of core networks, their available bandwidth has to be continuously upgraded, leading to higher data rate signals [1]. While the industry wants to move quickly to higher capacity optical transport networks and enhance the 10-Gbps systems currently employed, there are a number of technology issues that need to be addressed. Transmission performance, cost, footprint (space), and power dissipation per bit have to be improved to justify the use of solutions with bit rates higher than 10Gbps. It is anticipated that, as the optical technology for higher data

rates matures and becomes more efficient, 40, and 100Gbps rate connections will be incorporated in existing 10Gbps networks systems [2]. Thus, a transport network will end up managing a variety of line rates, i.e., what is usually referred to as a Mixed Line Rate (MLR) system.

The next step in optical transmission is 400 Gb/s systems and then even higher rates. However, such transmissions would not fit in the 50 GHz wavelength grid of current single line rate (SLR) and MLR Wavelength Division Multiplexed (WDM) systems. Flexible grid optical networks [3] is a promising technology for next generation optical networks that can support several data rates without the constraint of the 50 GHz wavelength grid, while more efficiently utilizing resources compared to WDM and MLR networks (through a “flexible” assignment of spectrum resources for each connection) [4], [5]. The Routing and Spectrum Allocation (RSA) problem is one of the most important problems in flexible grid optical networks. The main constraints of this problem are the spectrum continuity constraint, analogous to the wavelength continuity constraint of the WDM networks, the contiguous spectrum constraint, where the spectrum assigned to a connection must be consecutive in the frequency domain, and the non-overlapping spectrum constraint [3].

In transparent optical networks, connections are vulnerable to physical layer attacks, since data signals remain in the optical domain for the entire path. An attack is defined as an intentional action against the ideal and secure functioning of the network [6]. Physical layer threats and attacks in optical networks have been studied in the literature by several researchers [6]-[13]; operators also consider of paramount importance the security and availability of their systems, and these features have always been a top priority in their solution designs. Further, several vendors are developing tools that protect optical networks, offering intrusion detection and prevention at the physical layer, as well as alerting capabilities for the operators.

One type of physical layer attack in optical networks is service disruption that can result from high-power jamming through the crosstalk effect. It is worth noting that this kind of attack can be performed from remote locations without physical access to the node under attack. Due to the high bit rates of flexible grid optical networks and the large number of lightpath interactions, a jamming attack can cause a huge amount of information loss, as this attack may propagate in the

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network, affecting other lightpaths as well [11]-[13]. Therefore, the limitation of crosstalk interactions in order to prevent service disruption is a crucial consideration in the planning of flexible grid optical networks.

Another important aspect in optical network design is the port isolation in optical switching nodes (e.g., reconfigurable optical add/drop multiplexers (ROADMs)). Due to the fact that traffic in core optical networks is increasing rapidly [1], there is a need for higher number of ports in ROADMs to satisfy this traffic. The high number of ports in WSSs, that are used to implement ROADMs, makes the crosstalk effect within the nodes even more severe. A possible solution to this problem would be to have higher port isolation [19]; however, this would lead to WSSs with higher cost. A more cost-effective way to minimize the impact of the crosstalk effect is via the minimization of crosstalk interactions, through appropriate RSA algorithms. This approach would lead to lower signal degradation and the need for WSSs with lower port isolation (and subsequently lower cost).

Finally, another key design issue in optical networks is the minimization of the power consumption and of the cost of the network. Numerous works dealt with these issues in flexible optical networks as detailed in [21]-[25].

The novelty of this work compared to other techniques lies in the design of a network architecture where multiple bit rates can be transmitted through the network, and every node can be employed with a different architecture, which differs in its flexibility, cost, and power consumption, while at the same time providing security against malicious attacks and also minimizing cost and power consumption. The ultimate goal of this work is to provide significant advances to the development and operation of future secure core optical networks.

The rest of the paper is organized as follows. Sections II and III discuss the state-of-the-art and the network architecture utilized, respectively. Section IV describes the problem addressed by the paper. Section V details the proposed ILP formulation for the routing and spectrum allocation that accounts for the minimization of in-band crosstalk interactions, while Section VI presents the proposed heuristic algorithm. Performance results are discussed in Section VII, while Section VIII presents some concluding remarks.

II. PREVIOUS WORK

A survey of flexible grid optical networks where authors classify a range of spectrum management techniques, including offline and online RSA, distance-adaptive RSA, fragmentation-aware RSA, traffic grooming, and survivability and related technologies, can be found in [26]. Several techniques have been developed to solve the RSA problem [5] while also considering the physical layer constraints [27].

The energy efficiency of WDM networks has also been studied in the past few years. Efforts focused mainly on the design of energy-aware algorithms whose goals were to grant the same quality of service (QoS) with the lowest possible energy consumption and the lowest CAPEX [28]-[30]. Moreover, several works evaluated and compared the network

power consumption for different fixed and flexible optical network architectures [20]-[25]. Even though there is significant research effort in trying to minimize power consumption and cost in flexible optical networks, there is still a need to examine power consumption in attack-aware networks. This is mainly due to the fact that by trying to minimize the power consumption during the logical design problem, the lightpaths tend to reuse modules already powered-up, which subsequently leads to more interactions (rather than using components that are set to sleep or power-off mode which will lead to significantly less interactions).

The concept of attack-aware Routing and Wavelength Assignment (RWA) problem presented in [9]-[13] dealt with WDM optical networks. However, jamming attacks in flexible grid optical networks have not been considered yet. Only recently, in [14] authors considered how to improve the physical-layer security-level of multi-domain flexible grid optical networks. Specifically, they proposed to differentiate the RSA schemes of intra- and inter-domain requests with security considerations.

The use of space division multiplexing (SDM) over multi-core fiber (MCF) and multi-mode fiber (MMF) would allow the transport network to keep pace with traffic growth beyond the Petabit per second level. The concept of MCF and MMF systems in flexible optical networks has been investigated in [15]. Signals transmitted in MMF interfere with each other and are degraded due to crosstalk. Authors in [16], [17] solve the routing, spectrum, and core assignment problem considering the crosstalk effect in order to improve the performance of the SDM flexible optical networks with MCFs. Further, authors in [10] proposed a core prioritization policy based on the MCF's architecture to reduce the crosstalk by avoid filling adjacent cores. However, the crosstalk effect within network nodes has not investigated while solving the routing and spectrum allocation in flexible optical networks.

This work extends the authors' previous work in [12], where the focus was on the minimization of crosstalk interactions in WDM networks, and their work in [31], where a novel ILP formulation and a heuristic algorithm were developed to solve the RSA problem in flexible grid networks taking into account the in-band crosstalk effect. This work significantly extends the previous works by taking into account the WSS placement in order to compensate for the crosstalk interactions (the assumption in this work is that a crosstalk interaction occurs when lightpaths using the same wavelength cross the same switching node) and also to minimize the network cost and power consumption. Specific Architectures on Demand (AoD) that are placed in the nodes of the network are now also considered during the network design phase. Finally, the heuristic algorithm proposed extends a well-known graph coloring algorithm [43] in order to support several colors per vertex (equivalent to frequency slots) while at the same time taking into account the in-band jamming interactions.

III. NETWORK ARCHITECTURE

A. Flexible Grid Optical Networks

Flexible grid optical networks appear to be a promising technology for next-generation optical networks. In flexible grid optical networks, the C-band spectrum resource is divided into a number of narrow spectrum grids that are called slots. A frequency slot is defined by its nominal central frequency and its slot width. The slot width is the full width of a frequency slot in a flexible grid. A flexible grid network migrates from the fixed 50 GHz grid that traditional WDM networks utilize [32], and has granularity of 12.5 GHz, as standardized by the International Telecommunication Union (ITU-T) [33].

One of the motivations for the usage of the flexible grid is to allow a mixed bit rate or mixed modulation format transmission system to allocate frequency slots with different widths so that they can be optimized for the bandwidth requirements of the particular bit rate and modulation scheme of the individual channels [33]. Moreover, flexible grid can also combine spectrum slots, to create wider channels, i.e., an optical channel's spectrum can span several frequency slots. Another advantage of the flexible grid pattern is the improvement in spectral efficiency enabled by more closely matching the channel size with the signals being transported and by improved filtering that allows the subcarriers to be more closely squeezed together.

B. ROADM Architecture

ROADMs [40]–[42] are the key elements for building the next-generation optical transport networks. They have the advantage of allowing express optical channels that do not require local processing to pass through the nodes without optoelectronic conversions and at the same time permitting dynamic node reconfiguration at the optical layer via control plane software. Specifically, a ROADM takes as input signals at multiple wavelengths and selectively drops some of these wavelengths locally, while letting others pass through, switching them to the appropriate output ports. The choice of ROADM architecture and underlying technology depends on how effectively current and future traffic can be addressed. The choice of ROADM architecture and technology influences cost, power consumption, optical performance, and configuration flexibility.

The components that are used to build the ROADMs are WSSs, amplifiers, and splitters. Clients interface with the ROADMs via add/drop ports (called terminals); furthermore, at the add/drop terminals, Bandwidth Variable Transponders (BVTs) and WSSs are utilized, ensuring the tunability and the re-configurability of the architecture and thus realizing the vision of spectrum-and-rate flexible networking. Thus, a ROADM architecture offers full flexibility of add/drop ports, meaning that traffic can be added/dropped to/from an arbitrary transmission fiber originating from or terminating at the node and at any wavelength. ROADM architectures have the capability to support dynamic traffic evolution in a flexible and economic manner and are a very cost-efficient architecture from the operator's perspective, since these

architectures are modular and components can be added on a node that needs to be upgraded, without affecting existing transit traffic. Such nodes that are remotely configurable and utilize colorless and directionless add/drop ports are also called optical cross connects (OXC).

ROADMs based on broadcast-and-select (BS) or route-and-select (RS) architectures are the current choices in deployed optical networks and can remotely configure all transit traffic. BS-based nodes (Fig.1a) include a splitter first-stage that implicitly provides broadcast towards the outputs. In a BS-based architecture, the WSSs' functionality resembles a multiplexer (they switch the spectrum slices that contain the signals that require to be passed to a certain output). Although this is a simple and popular architecture, the loss introduced by the power splitters limits its scalability and can only be utilized in network nodes with small degrees. On the other hand, RS-based nodes (Fig.1b) have a WSS first-stage that provides on-demand multicast. Both implementations have a WSS second-stage that provides the selection of the wavelengths at the output fibers, allowing full flexibility (any wavelength from any incoming fiber can pass through or any wavelength from the add/drop terminals can be added/dropped). The basic advantage of the RS-based architecture with respect to the BS-based architecture is that the through loss is not dependent on the degree of the node. However, it requires additional WSSs at the input stage, which makes it more costly to realize.

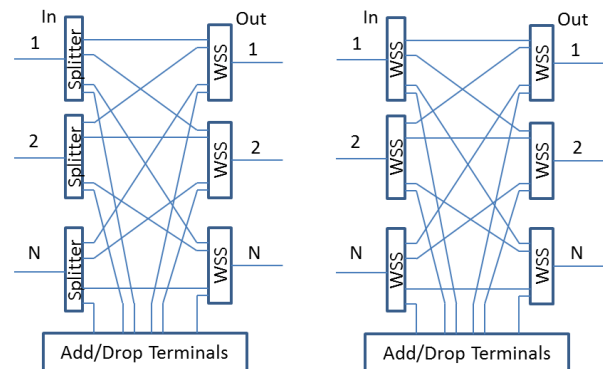


Fig. 1. a) Broadcast and Select (BS) (left) and b) Route and Select (RS) (right) node architecture

C. WSS Architecture

WSS technology [42] is currently being used for the implementation of ROADMs and for the deployment of cost-effective dynamic wavelength switched networks. The WSSs are complex multiplexers/demultiplexers that select the corresponding outputs to forward the data carried by each wavelength.

The WSS architecture is depicted in Fig. 2. The WSS can steer each optical channel present on its common input port toward one of its output ports according to the wavelength of the channel. At the same time, it can attenuate the optical power of this channel to a level required by the user. The commercially available WSSs feature up to 10 ports with 100 GHz or 50 GHz channel spacing. Due to the current requirement in terms of spectral efficiency, the 50 GHz channel spacing version suits more the core network

application with up to 96 channels per fiber.

Currently, flexible grid WSSs with finer granularity are under development [35]. These WSSs are key for the development of flexible nodes, as they feature a fine spectrum granularity that enables the implementation of highly customizable filters with variable bandwidth [18]. Thus, having flexible grid-capable ROADMs can improve spectral efficiency. Further, since the subcarriers are fully tunable to any wavelength, they can simply be tuned to the existing 50-GHz grid pattern, allowing full backward compatibility with existing ROADM networks.

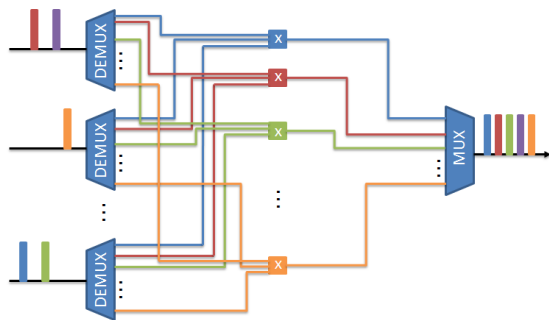


Fig.2. Nx1 WSS architecture

D. Crosstalk Effect

In-band crosstalk and out-of-band crosstalk at the ROADM output ports is usually caused by imperfect port isolation of optical switches and wavelength filters [20]. The impact of crosstalk is quantified by the power penalty parameter, which is commonly defined as the additional optical power required at the receiver in order to maintain a given bit error rate (BER). In-band crosstalk is considered much more detrimental to network performance than out-of-band crosstalk, because contrary to out-of-band crosstalk case, it cannot be removed by filtering, as in the case of in-band crosstalk the primary signal and the leakage signal have the same nominal wavelength.

Studies have addressed the impact of concatenated ROADM passband narrowing on the performance of 100 Gb/s modulation formats [36] and the effects of spectrally shaped crosstalk arising from non-ideal WSS isolation [37]. Further, authors in [38] considered the effects of cascaded ROADM passband narrowing and finite isolation jointly in the two main WSS-based ROADM architectures, namely BS-based and RS-based, indicating that for high port counts, RS-based architectures are preferred.

In the optical networks architecture considered, utilizing WSS-based ROADMs, as the traffic increases, the number of WSS ports also needs to increase, thus subsequently increasing the lightpath interactions (through the crosstalk effect) at the WSSs. A cost-effective way to limit the crosstalk effect is the proper spectrum assignment of the resources, which is precisely the focus of this work.

E. Architecture on Demand (AoD)

In current deployed networks, where optical nodes are already installed, the upgrade of all the nodes to ROADMs will have a significant impact on the network cost. For this

reason, it is envisioned that a fraction of the network nodes will be upgraded in order to provide cost-efficient solutions without compromising optical performance and flexibility [18]. These Architectures on Demand (AoD) will contain either splitters or WSSs at the input ports as can be seen in Fig. 3. Depending on the network traffic, it will most likely be preferable to keep the legacy network nodes as well, due mainly to the high cost of the node upgrades (high cost of the required WSSs). Thus, it is envisioned that a fraction of the network nodes will be BS-based, other nodes will be RS-based, and the rest will be hybrid nodes (AoD nodes). For these AoD nodes, with the placement of a few WSSs at the input stage, WSS isolation requirements are now not as stringent, since two points of suppression exist for paths where interference was present. By significantly easing the port-isolation requirement for each WSS, it is now feasible to achieve the necessary cumulative isolation, a high port count, and fast switching [19].

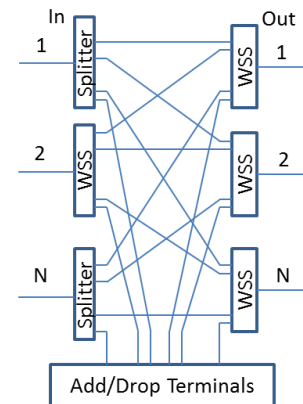


Fig.3. Architecture on Demand (AoD)

IV. PROBLEM DESCRIPTION

In this paper, the joint problem of in-band crosstalk-aware routing, spectrum assignment (RSA), and WSS placement in flexible grid optical networks is solved for a given set of connection requests.

The objectives of the problem are the following:

- i. Minimize the required spectrum in order to establish the set of the connection requests (total used spectrum or the maximum id of the used spectrum).
- ii. Minimize the number of required WSSs in order to have zero crosstalk interactions among lightpaths. The minimization of the number of WSSs also minimizes the total cost and the power consumption of the network.

The algorithms assume initially that the network nodes are BS-based as illustrated in Fig. 1a. Subsequently, the algorithms decide which splitters will be replaced by WSSs as shown in Fig 3. The intuition behind the algorithms is to initially minimize the crosstalk interactions among lightpaths as much as possible, trying to achieve zero interactions. If this is not possible, then splitters are replaced by WSSs in the input stage of the ROADMs (utilizing the minimum required number) in order to further compensate for the crosstalk effect. To address this problem, an ILP model is formulated in

Section V, while in Section VI an efficient heuristic algorithm based on vertex coloring is proposed.

V. OPTIMIZATION ALGORITHM

In this section, an ILP formulation is presented for the efficient establishment of connections in flexible grid optical networks in order to minimize the impact of in-band crosstalk. In particular, the problem of Routing and Spectrum Assignment (RSA) is solved with the objective to minimize the interactions among connections through in-band crosstalk. In addition, the algorithm finds which input ports should have their splitters replaced with WSSs (minimum possible number of replacements) in order to compensate for the in-band crosstalk effect and at the same time minimize the network cost and power consumption. The RSA algorithm consists of two phases; in the first phase, k candidate paths are identified for serving each requested connection, while in the second phase the ILP problem is formulated taking as input the output of the first phase.

A. First Phase: Path Computation

To serve a connection request Λ_{sd} , the requested data rate from source s to destination d is initially transformed to the corresponding number of required spectrum slots. The number of the required spectrum slots aparta from the requested data rate depends on the modulation format to be used. The number of such required slots is equal to $\lceil Bd/W \rceil$ where Bd is the baud rate (symbol rate), and W is the slot width. The baud rate is equal to the requested bit rate divided by the bits per symbol of the modulation format.

In turn, in this phase, k candidate paths for each source-destination pair of the network are calculated. Dijkstra's algorithm is utilized to find the shortest path and subsequently $k - 1$ deviations of the shortest path are found. Specifically, the cost of the links belonging to the shortest path is increased and Dijkstra's algorithm is executed again; this procedure is repeated until k paths are found. The reader should note that any k shortest path algorithm can be employed in this phase.

B. Second Phase: ILP formulation

In this work an Integer Linear Programming (ILP) formulation is proposed that addresses the problem of Routing and Spectrum Assignment with the objective to minimize the crosstalk interactions while also minimizing the required numbers of WSSs to be placed in the nodes and as a consequence minimizing the network cost as well as the consumed power.

The following parameters and variables are used for the ILP formulation:

Parameters:

- $s, d \in V$: network source and destination nodes
- $f \in F$: a frequency slot over the available frequency spectrum F
- $p \in P$: a candidate path
- $l \in E$: a network link
- F_{sd} : the required number of slots
- P_{sd} : set of candidate paths to serve the connection

(s, d)

- P : set of all candidate paths
- B : a big constant that is used to activate/deactivate a constraint
- M : a big constant that is used to activate/deactivate a constraint, where $M \gg B$

Variables:

- x_{pf} : Boolean variable, equal to 1 if path p and frequency slot f are used to serve demand (s, d) and equal to 0 otherwise.
- y_{pf} : Boolean variable, equal to 1 if frequency slot f is the starting spectrum slot of a contiguous spectrum to serve the demand or part of the demand (s, d) over path p and equal to 0 otherwise.
- g_{lf} : Boolean variable, equal to 1 if link l and frequency slot f are used by a connection as a guard-band and equal to 0 otherwise. A guard-band is an empty slot which separates two contiguous signals so that the two signals do not interfere.
- z_l : Boolean variable, equal to 1 if there is a WSS at the end of the link l and equal to 0 otherwise.

Objective:

Minimize: $\sum_p \sum_f c_1 x_{pf} + c_2 \sum_p \sum_f y_{pf} + c_3 \sum_l z_l$

Constraints:

- Demand Constraint

$$\sum_{p \in P_{sd}} \sum_f x_{pf} = F_{sd}, \forall (s, d) \text{ pairs} \quad (1)$$

- Contiguous frequency slot assignment (spectrum contiguity constraint - each demand is assigned contiguous spectrum on all the fibers of each path).

$$x_{pf} - x_{p(f-1)} \leq y_{pf}, \forall p \in P, f \in F \quad (2)$$

Case: $f = 1$, then $x_{p(f-1)} = 0$

- Non-overlapping spectrum

$$g_{lf} + \sum_{p|l \in p} x_{pf} \leq 1, \forall l \in E, f \in F \quad (3)$$

- Enable guard-band link-slot

$$\sum_{p|l \in p} y_{pf} \leq B \cdot g_{l(f-1)}, \forall l \in E, f \in F \quad (4)$$

Case: $f = 1$, then $g_{l(f-1)} = 0$

- WSS placement

$$\sum_{\{p'|n \in p, p'\}} x_{p'f} + B \cdot x_{pf} - M \cdot z_l \leq B, \forall l \in p, \forall p \in P, \forall f \in F \quad (5)$$

Note that the spectrum continuity constraint (each demand is assigned the same spectrum along all the edges of the path) in this formulation is taken into account via the definition of the x_{pf} variable.

The objective function of this formulation accounts for the number of required slots, the number of required transponders, and also the number of required WSSs. Each coefficient c_i declares the relative impact of each term of the objective.

Coefficient c_{1p} is relative to the number of links that constitute path p . In this way, the greater the number of links on a path, the greater the cost of the objective function in terms of occupied frequency slots. Coefficient c_2 declares the importance of the number of BVTs, while coefficient c_3 the importance of the number of WSSs.

Constraint (1) ensures that all the lightpaths have total capacity equal to the requested demand and thus all the incoming traffic is satisfied. Constraint (2) ensures that each demand is assigned contiguous spectrum on all the fibers of each path. Constraint (3) is the non-overlapping spectrum constraint and ensures that each spectrum slot is used at most once on each fiber or it is used as a guard-band slot. Constraint (4) is used in order to ensure that the guard-bands have their own slots in the spectrum of the link. The spectrum continuity constraint is implicitly taken into account by the definition of the x_{pf} variable. Finally, constraint (5) is included in order to account for the in-band crosstalk interactions and minimize the required number of WSSs. In constraint (5), B and M are constants (taking large values), where $M \gg B$. The reason for introducing constant B is to take into account only the constraints for the lightpaths that will be used from all the candidate lightpaths (activate/deactivate the constraint). Additionally, the reason for introducing constant M is to replace the splitters with WSSs and again activate/deactivate the constraint. $\sum_{\{n|n \in p, p'\}} x_{p'f}$ is the total number of in-band crosstalk interfering sources that affect the signal of lightpath (p, f) in node n . Finally, the z_l variable specifies where to place the required WSSs. Note that node n in constraint (5) is the end of link l .

C. Objective Functions

In order to consider several factors of the objective function as described above, the following cost functions are studied:

- Minimize: $\sum_p \sum_f c_{1p} x_{pf} + c_2 \sum_p \sum_f y_{pf} + c_3 \sum_l z_l$ (6)
- Minimize: $FS + c_2 \sum_p \sum_f y_{pf} + c_3 \sum_l z_l$ (7)

By controlling coefficients c_1 - c_3 , the objective function can minimize the required cost depending on its relative importance. These coefficients signify the resources of interest (slots, BVTs, WSSs), the cost of the equipment (BVTs, WSSs), or the power consumption of the equipment (BVTs, WSSs).

The difference between the two cost functions (6) and (7) is the fact that (6) minimizes the number of the total slots used in the network, while (7) minimizes the maximum id of the slot used in the network. In order to use cost function (7), the following constraint (8) must also be added, where FS is the maximum occupied slot.

$$\begin{aligned} &\text{Maximum occupied slot} \\ &f \cdot x_{pf} \leq FS, \forall f \in F, p \in P \end{aligned} \quad (8)$$

VI. HEURISTIC ALGORITHM

In some cases, where the ILP formulations cannot be solved efficiently for large networks, it is desirable to obtain efficient

heuristic algorithms. The RSA problem has been proven that it is NP-complete [4]; for this reason, a heuristic algorithm is proposed to solve the same problem as the one described in Section V above (heuristic HXT-VC-RSA). The heuristic algorithm presented in this section breaks the problem into three separate sub-problems, namely (i) routing, (ii) spectrum allocation, and (iii) WSS placement sub-problems, and addresses each sub-problem separately and sequentially. It is worth noting that by decomposing the problem into its constituent sub-problems, the optimal solution of the joint problem may not be found. Nevertheless, as shown in the performance results section below the proposed heuristic techniques achieve very good results that are comparable to the optimal solutions.

Specifically, the proposed heuristic approach solves the problem by sequentially serving one-by-one the connections and consists of three phases. In the first phase, k candidate paths are calculated for each requested connection and a path is chosen based on an ILP formulation. In the second phase, the spectrum allocation subproblem is solved by employing a Vertex Coloring (VC) algorithm with the objective to minimize the number of in-band lightpath interactions. The frequency slots are defined as colors in the VC algorithm. Then, in the third phase, the WSS placement is performed with the objective to minimize the cost and power consumption in the network.

A. Path Selection

The algorithm selects k -shortest paths by utilizing the k -shortest path algorithm described in Section V.A. Subsequently, the following ILP formulation is employed in order to select a path for each source–destination pair.

ILP Formulation

Parameters:

- As defined in Section V.B
- MF : Maximum frequency slot of the network

Variables:

- x_p : Integer variable, equal to the number of frequency slots that are necessary to serve demand (s, d) through path p .
- u_l : Integer variable equal to the number of paths that use the same link l .
- v_n : Integer variable equal to the number of paths that use the same node n .

Objective:

$$\text{Minimize: } \sum_p c_{1p} x_p + c_2 \sum_l u_l + c_3 \sum_n v_n \quad (9)$$

Constraints:

- Demand Constraint
- $\sum_{p \in P_{sd}} x_p = F_{sd}, \forall (s, d) \text{ pairs} \quad (10)$
- Maximum spectrum slots per link

$$\sum_{p|l \in p} x_p \leq MF, \forall l \in E, f \in F \quad (11)$$

- Link interactions

$$\sum_{p|l \in p} x_p \leq u_n, \forall l \in E, f \in F \quad (12)$$

- Node interactions

$$\sum_{p|n \in p} x_p \leq v_n, \forall l \in E, f \in F \quad (13)$$

Objective function (9) accounts for the number of required slots, and also the number of link and node interactions among paths. Each coefficient c_i declares the relative impact of each term of the objective. Coefficient c_{1p} is relative to the number of links that constitute path p . In this way, the greater the number of links in a path, the greater the cost of the objective function in terms of occupied frequency slots. Coefficient c_2 declares the importance of the number of link interactions and coefficient c_3 the importance of the node interactions.

Constraint (10) ensures that all requested demands are satisfied. Constraint (11) ensures that the maximum capacity of each link is not violated. Constraint (12) calculates the number of link interactions, while constraint (13) calculates the number of node interactions.

The reader should note that this phase of the algorithm, even though it is formulated as an ILP, it is computationally tractable for the size of backbone networks.

B. Vertex Coloring

Phase 2 incorporates a VC algorithm to perform the spectrum allocation. For a given undirected graph $G=(V, E)$ the vertex coloring problem requires to assign a color (frequency slot in our case) to every vertex so that adjacent vertices are all colored differently and the total number of colors employed is minimized. The VC algorithm utilized in this work is based on the DSATUR [43] algorithm. However, this algorithm is modified in order to (i) assign more than one colors to each vertex, (ii) incorporate constraints related to the spectrum allocation, and (iii) take into account in-band crosstalk interactions.

The VC phase is constituted by two sub-phases: a) auxiliary graphs creation and b) color assignment.

1) Auxiliary Graph Creation

In this phase of the algorithm, two different auxiliary graphs are constructed. The first auxiliary graph G' (*auxg-1*) takes into account the paths with common edges and the second auxiliary graph G'' (*auxg-2*) takes into account both the paths with common edges and the paths with common nodes. The creation of auxiliary graphs *auxg-1* and *auxg-2* takes place as follows: (i) each vertex of the auxiliary graphs corresponds to a path between a source-destination pair of the optical network (these paths are the output of the first phase of the algorithm – Section VI.A), (ii) each vertex is associated with a number f_i that signifies the number of required slots between the source-destination pair, and (iii) graph *auxg-1* is created by adding an edge between two vertices of the graph if the corresponding paths have common links, while graph *auxg-2* is created by adding an edge between two vertices of the *auxg-1* if the

corresponding paths have common nodes.

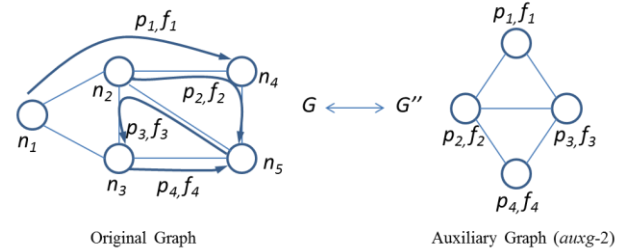


Fig. 4. Auxiliary graph *auxg-2* creation example.

Fig. 4 gives an illustrative example of the graph transformation between the original network and auxiliary graph *auxg-2*. Specifically, in this example it is assumed that there are four paths (p_1 - p_4) between source-destination pairs as shown in the original graph. Each path p_i ($i=1:4$) is represented by a vertex in the auxiliary graph. In the original graph, paths p_1 and p_2 have a common edge, thus in the auxiliary graph there is an edge between vertices p_1 and p_2 . Moreover, paths with common nodes in the original graph also have edges in the *auxg-2* as can be seen in Fig 4.

2) Vertex Color Assignment

The VC algorithm then assigns colors to the vertices of the auxiliary graphs. In the general vertex coloring problem, two adjacent vertices (connected by an edge) must not have the same color assigned. In our case however, there is an exemption to this rule; the same color can be assigned between two adjacent vertices if this color is used to represent a guard-band slot. Initially, the algorithm starts with auxiliary graph *auxg-2*. For this graph, the algorithm picks the vertex with the maximum degree and colors it with the lowest available f_i consecutive colors (representing contiguous slots (including the guard-band slots at either side) in the corresponding spectrum assignment problem). Subsequently, the algorithm selects the next node by selecting the node with the maximum degree of saturation. The degree of saturation of a node is defined as the number of unique colors assigned to its neighboring nodes. Thus, the algorithm will select the node that has the higher number of unique neighboring colors. In case of a tie, the degree of the node is used as a tie-breaker (the algorithm selects the node with the largest degree). The aforementioned procedure is repeated until all vertices have been colored (with the required number of colors, i.e., the required number of slots between the source-destination pair) or the available colors have been exhausted without fully coloring all the vertices in the graph. The total number of colors available in each vertex is equal to the available number of slots in a network fiber. In case where all vertices are colored, then the established lightpaths will have zero in-band crosstalk interactions.

If the procedure finishes and the vertex coloring is incomplete, then the algorithm continues by coloring auxiliary graph *auxg-1*. The vertex coloring of *auxg-2* is copied to *auxg-1* and the remaining uncolored vertices of *auxg-1* are colored following the same procedure as described above. The reader should note that in this case (i.e., using this coloring) the

lightpaths will now have some in-band crosstalk interactions.

Finally, in case there are no available colors in order to color a vertex, then the corresponding request is blocked.

The pseudocode of the VC algorithm is shown in Fig. 5. The VC algorithm is executed for each one of the m nodes of the auxiliary graph. Assuming that the number of the network nodes of the optical network is equal to n , then the maximum number of nodes in the auxiliary graph m is equal to $m=n^2-n$, since m is the maximum possible number of paths in the original graph. One vertex v is colored at each iteration, thus in total m iterations of the algorithm are required. For each coloring instance, the algorithm chooses an uncolored vertex v with the largest degree of saturation. In the worst-case, the algorithm will perform checks in all vertices to find suitable colors. This gives an overall worst-case complexity of the VC algorithm equal to $O(m^2 \cdot F)$, which is equal to $O(n^4 \cdot F)$, where F is the number of available colors in each vertex.

Input 1: $G''(V'', E'')$ //auxg-2 graph
 f_n // Set of requested colors for connection n
 $C_n = \{c_1, \dots, c_F\}$ // List of available colors per vertex
 $V_n \leftarrow \{\}$ // Set of colored vertices
 $V_{un} \leftarrow V''$ // Set of uncolored vertices
 $V_{ex} \leftarrow \{\}$ // Set of examined vertices

Output1 = Vertex Color Assignment (Input 1)
1: $n \leftarrow n_{\max_degree}$ // Start with the vertex that has the maximum degree (n : current node)
2: **while** $V_{ex} = V''$ // Examine all vertices
3: $V_{ex} = V_{ex} + \{n\}$ // Add the vertex to the set of examined vertices
4: **if** $f_n \leq \max_contiguous[C_n]$ // There are enough contiguous colors
5: $n_c = f_n$ // Color the current vertex with the lowest available colors
6: $V_{un} \leftarrow V_{un} - \{n\}$ // Remove vertex from the set of uncolored vertices
7: $V_n \leftarrow V_n + \{n\}$ // Add the vertex to the set of colored vertices
8: $C_n \leftarrow C_n - F_n$ // Remove assigned colors from the list of available colors of vertex n
9: $C_{nadj} \leftarrow C_{nadj} - F_n$ // Remove assigned colors from the list of available colors of adjacent vertices of n apart from the guard-band colors
10: **end if**
11: $n \leftarrow \max_saturation_degree$ // Select the next node by selecting the node with the maximum degree of saturation. In case of a tie, select the node with the largest degree.
12: **end while**

Input 2
 $G'(V', E')$ //auxg-1 graph
 F_n // Set of requested colors per connection
 $C_n = C_n$ (Output 1)
 $V_n = V_n$ (Output 1)
 $V_{un} = V_{un}$ (Output 1)
 $V_{ex} = V_{ex}$ (Output 1)
13: **Vertex Color Assignment (Input 2)**

Fig.5. Pseudocode of the VC heuristic algorithm.

C. WSS Placement

In the third phase of the algorithm, WSS placement is addressed (splitters are replaced by WSSs in selected locations) in order to compensate for any residual interference due to in-band channel interactions among the established lightpaths that still exist after the execution of the second phase of the algorithm. For this phase of the heuristic, after the spectrum assignment, the in-band interactions in each node are calculated; the WSSs then replace the splitters in order to have zero interactions (i.e., BS-based node architectures become AoD-based node architectures as illustrated in Fig. 3).

In order to calculate the number of in-band lightpath

interactions in every node, the following procedure is followed: (i) every path p is characterized by its constituted nodes and its slots ids, (ii) in every input port the algorithm calculates the number of input ports where lightpaths crossing this port have common slot ids with other lightpaths from other input ports (for every input port a number specifies how many other ports interact with this port), and (iii) splitters are replaced by WSSs in the input ports where there are interactions. Thus, by replacing splitters with WSSs, there are now zero interactions among the input ports.

The pseudocode of the WSS algorithm is shown in Fig. 6. The overall complexity of this phase is equal to $O(n \cdot D^2 \cdot P \cdot F)$, where n is the number of nodes in the original graph, D is the maximum degree of the network nodes, P is the maximum number of paths crossing an input port, and F is the number of available spectrum slots in each fiber. In essence, the WSS placement algorithm is executed for each node n of the original graph. Then, for each input port of the node, the algorithm checks which paths crossing this port have at least one common slot with the paths crossing all other ports of the node. Thus, in the worst-case (complete graph with $D=n-1$), the overall complexity will be of the order $O(n^3 \cdot P \cdot F)$.

Input 3: $G(V, E)$ //network graph
 p // path constituted by n nodes and f slots

WSS Placement (Input 3)
1: **for** every n // n : network node
2: $in_band(m, n) = 0$
3: **for** every m // (m, n) : input port of network node n
4: **for** every j // (j, n) : input port of network node n
5: $crosstalk = 0$
6: **for** every p' crossing port (j, n)
7: **if** $f_p = f_{p'}$ // At least one slot f of p (crossing (m, n)) and p' (crossing (j, n)) are the same
8: $crosstalk = 1$ // There is in-band crosstalk between ports (m, n) and (j, n) ports
9: **end if**
10: **end for**
11: **if** $crosstalk = 1$
12: $in_band(m, n) = in_band(m, n) + 1$ // Calculate the number of different input ports of node n that interact through in-band crosstalk with port (m, n)
13: **end if**
14: **if** $in_band(m, n) > 0$
15: $place_wss(m, n)$ // place a WSS in the input port (m, n) of node n
16: **end if**
17: **end for**
18: **end for**

Fig.6. Pseudocode of the WSS placement algorithm.

VII. PERFORMANCE EVALUATION

To evaluate the performance of the proposed algorithms, a number of simulation experiments were performed. In the simulations, a small network with 6 nodes and 9 links, the generic Deutsche Telekom (DT) network with 14 nodes and 23 links, and the Geant-2 network topology that comprises of 34 nodes and 54 links were considered (Fig. 7).

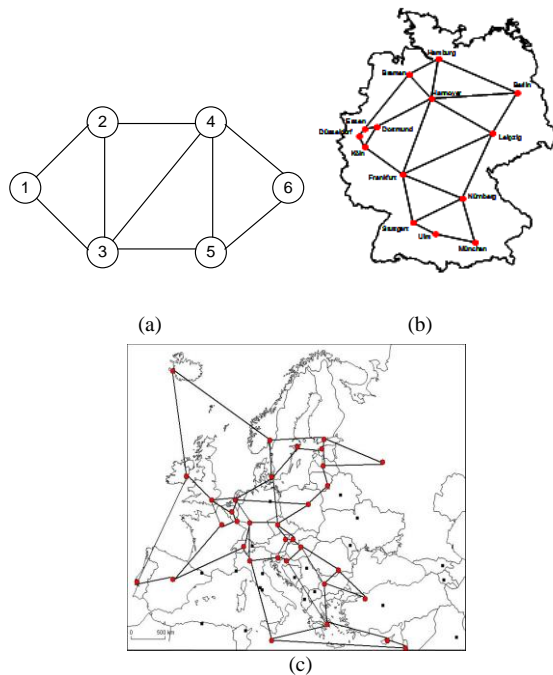


Fig. 7. (a) 6-node network, (b) DT network and (c) Geant-2 network topology.

Each spectrum slot was assumed to occupy 12.5 GHz. The 6-node network supports 40 slots, while the DT and the Geant-2 networks support 320 slots. The traffic matrices of the 6-node and the DT and Geant-2 networks used in our simulations were generated according to a uniform distribution. For the 6-node network the total traffic lies between 0.77 and 5.32 Tb/s, while for the DT network between 3.78 and 36.94 Tb/s, and for the Geant-2 network between 4.33 and 70.25 Tb/s. For each traffic load, 10 different instances were used and averaged over. For solving the ILP related formulations, the Gurobi library was used [44] and a PC with Core i5-2400@3.1GHz and 4GB memory was used for the simulation environment.

The algorithms investigated are as follows (the ‘I’ and ‘H’ in front of the name of the algorithms stand for ILP and Heuristic, respectively):

- Proposed crosstalk-aware algorithms IXT-RSA-sum and IXT-RSA-max based on objective functions (6) and (7) respectively, as presented in Section V.
- The I-RSA-pure algorithm derived by the formulation of Section V with the difference that the variables and the constraints related to crosstalk are not applied. The objective of the I-RSA-pure algorithm is to minimize the total number of used slots.
- Heuristic HXT-VC-RSA as presented in Section VI. For comparison purposes, two other heuristics are also presented in the results, namely the HXT-RSA (crosstalk aware RSA) and HFF-RSA (first-fit RSA) heuristic algorithms [31]. These heuristics are modified (by also now using the third phase of heuristic algorithm HXT-VC-RSA regarding WSS placement (Section VI.C), in order to be comparable to the proposed techniques.

A. Crosstalk Interactions

Fig. 8 depicts the number of lightpaths that interact through

in-band crosstalk with other lightpaths vs. network load for the 6-node network. It is obvious that the performance of the proposed algorithms (IXT-RSA-sum, IXT-RSA-max, HXT-VC-RSA and HXT-RSA) is significantly better than the crosstalk-unaware algorithms (I-RSA-pure and HFF-RSA), with IXT-RSA-sum having the best performance. While it is shown that the performance of the crosstalk-unaware algorithms is almost independent of the network load, exhibiting high number of lightpath interactions, for the crosstalk-aware techniques, with increasing traffic load the number of interactions remain low (even though as the traffic increases more lightpaths are established in the network and therefore more lightpath interactions are potentially possible).

In Fig. 9 the total number of used slots over all links vs. network load is presented for all the algorithms. From Fig. 9 it is clear that the proposed methods can utilize network resources effectively, since only a very small increase is observed in the total number of utilized slots compared to the crosstalk-unaware cases. In this figure, the I-RSA-pure algorithm provides the lower bound on the total wavelength utilization, while clearly the proposed algorithms have a spectrum utilization that is very close to this lower bound (with the proposed ILP and heuristics having almost identical results).

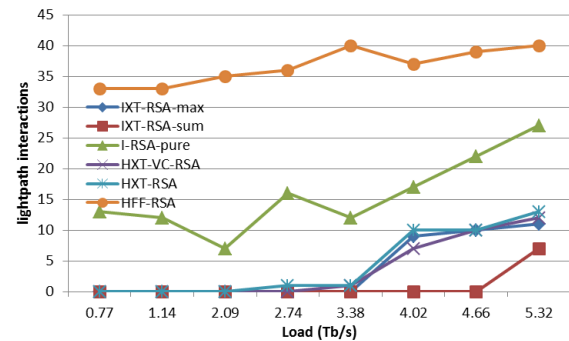


Fig. 8. Lightpath interactions vs. traffic load for 6-node network.

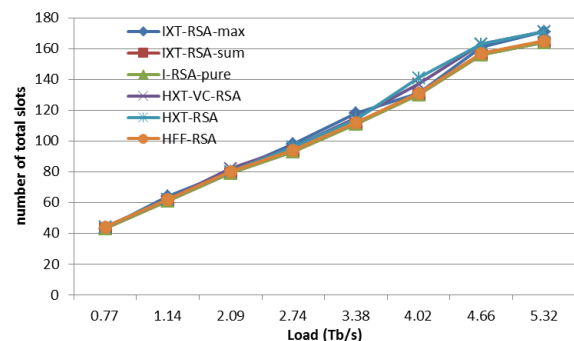


Fig. 9. Number of total used slots vs. traffic load for 6-node network.

The difference in the spectrum usage is depicted in Fig. 10, where the maximum used slot throughout the network is illustrated. From Fig. 10, it is clear that only the HFF-RSA algorithm minimizes the maximum used slot id, since this is the objective of this algorithm, while for all other metrics this heuristic had the worst performance. The other algorithm that tries to minimize the max slot id is the XT-RSA-max algorithm. However, this algorithm's objective function includes, except from the max used slot id, additional

parameters (i.e., cost, power consumption) and for this reason the max used slot id found is always higher than that of the HFF-RSA algorithm. Nevertheless, it is always lower than that of the rest of the algorithms examined. The IXT-RSA-sum algorithm has the worst performance in terms of max used slot id, since there is no consideration of this parameter in its objective function. Comparing Figs. 8 and 10, it is clear that there is a tradeoff between the lightpath interactions and the max used slot id. As the max used slot id is minimized, the lightpath interactions are increased.

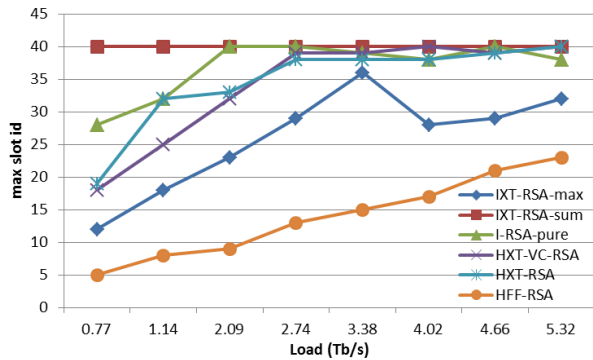


Fig. 10. Maximum used slot vs. traffic load for 6-node network.

Regarding the DT network, the performance of the ILP crosstalk-aware algorithms is not provided due to their complexity. As can be seen from Figs. 11 and 12, the heuristic algorithms follow the same trend as in the 6-node network. The figure that depicted the number of total used slots for the DT network was almost the same as in Fig. 9 and for this reason was not included in the results. In Fig. 12, it is important to note that the proposed HXT-VC-RSA heuristic algorithm performs better than the HXT-RSA heuristic in terms of max slot id, since HXT-VC-RSA utilizes a vertex coloring algorithm with the objective to minimize the number of used colors (max slot id), while HXT-RSA minimizes the total number of slots. Moreover, the two algorithms have almost the same number of lightpath interactions (Fig. 11).

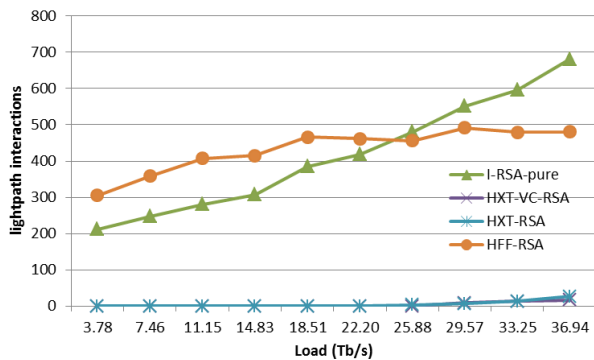


Fig. 11. Lightpath interactions vs. traffic load for DT network.

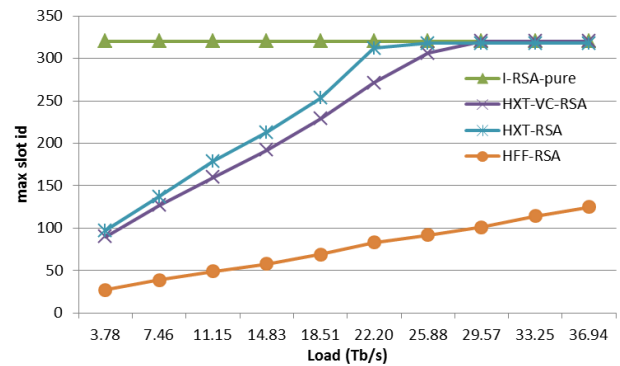


Fig. 12. Maximum used slot vs. traffic load for DT network.

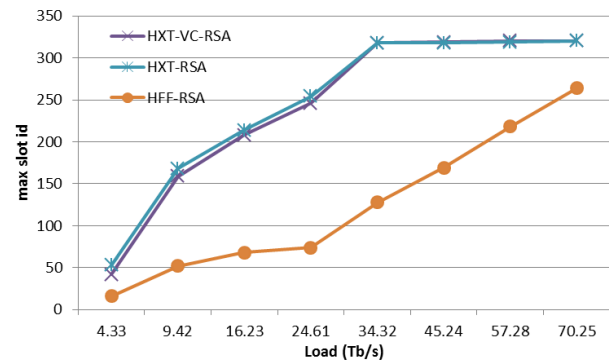


Fig. 13. Maximum used slot vs. traffic load for Geant-2 network.

Finally, regarding the Geant-2 network, the performance of the ILP algorithms is not provided due to their complexity. The heuristic algorithms follow the same trend as in the 6-node and the DT network. For this reason only the max slot id is depicted for the heuristic algorithms in Fig. 13.

After establishing all requested connections, the highest max slot id can be obtained as depicted in Figs. 9, 12 and 13 for the three networks examined. For the same set of connections a higher index in max slot id means that the spectrum resources are more fragmented, while a lower index means the resources are less fragmented. As can be seen from these figures the crosstalk-aware algorithms lead to more spectrum fragmentation. However, as the IXT-RSA-max and HXT-VC-RSA algorithms minimize also the max slot id, they give solutions with less spectrum fragmentation.

Table I depicts the required running time in seconds for all the algorithms in order to find the routes and the slots for all requested connections. The running time is computed as the mean value of all the different instances and all the network loads as depicted in the figures. As expected, the crosstalk-unaware algorithms need considerably less time, while between the two crosstalk-aware heuristics, HXT-VC-RSA runs faster than HXT-RSA. It is worth noting that most of the running time of the HXT-VC-RSA heuristic is utilized for the vertex coloring phase and only a very small amount of time is utilized for the other two phases. For the ILP formulations, IXT-RSA-max requires more running time than IXT-RSA-sum, since it is more difficult to obtain the optimum of IXT-RSA-max. This can be explained by the additional constraints

required by IXT-RSA-max in order to be implemented (i.e., Constraint (8) of Section V.C). As can be seen from Table I, IXT-RSA-max does not converge within the time limit (*) that was set to 3 hours for each instance. This explains the fluctuations in the results of IXT-RSA-max shown in Fig. 10.

Table I: Running time (sec).

Algorithm	6-node	DT	Geant-2
IXT-RSA-max	10800*	-	-
IXT-RSA-sum	49.62	-	-
I-RSA-pure	1.62	3.3	-
HXT-VC-RSA	0.14	8.41	46.5
HXT-RSA	0.15	25.9	126.1
HFF-RSA	0.01	0.03	0.05

B. Cost and Power Consideration

The consideration of this work on network cost and power consumption minimization is based on the WSS placement. The proposed algorithms aim to optimize the basic network objectives with respect to power consumption and monetary cost, without degrading the quality of the provided services and the network security.

The number of required WSSs to compensate for the crosstalk-related interaction among lightpaths for each algorithm is presented in Figs. 14, 15 and 16 for the 6-node, DT, and Geant-2 network respectively, in relation to the network load. As can be seen, the performance of the crosstalk-unaware algorithms requires a high number of WSSs, and especially with the use of the HFF-RSA algorithm there is a need to place WSSs at all network nodes. On the contrary, the crosstalk-aware algorithms require significantly less number of WSSs (as can be seen in the 6-node and especially in the DT network). Specifically, IXT-RSA-max, HXT-RSA, and HXT-VC-RSA require a much smaller number of WSSs, while IXT-RSA-sum requires even less. As previously mentioned, this number of WSSs and their specific placement is the minimum number required so that we will have zero crosstalk effects.

It is also important to note that this improvement in terms of the number of required WSSs is achieved by the proposed algorithms while also not increasing the required network resources in terms of spectrum utilization.

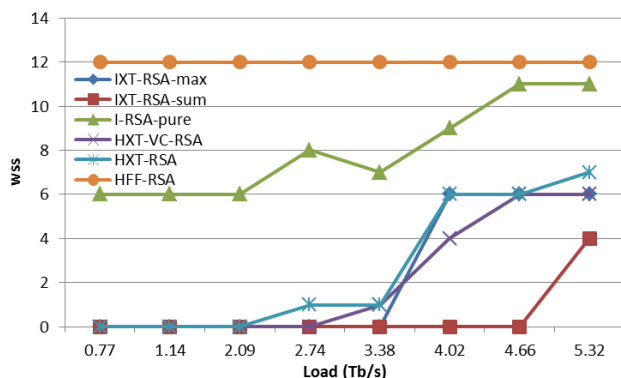


Fig. 14. Number of required WSSs vs. traffic load for the 6-node network.

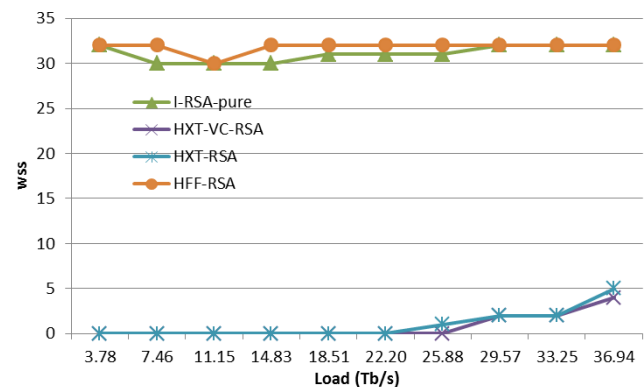


Fig. 15. Number of required WSSs vs. traffic load for the DT network.

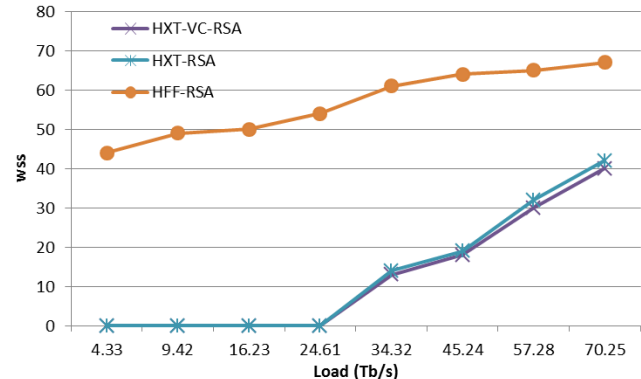


Fig. 16. Number of required WSSs vs. traffic load for the Geant-2 network.

VIII. CONCLUSION

This work proposed crosstalk-aware RSA algorithms (ILP and heuristic techniques) for the efficient utilization of resources in flexible grid optical networks. The objective of the algorithms was the minimization of in-band crosstalk interactions among lightpaths that utilize the same network nodes, thus ultimately reducing the need for higher port isolation at the WSSs and also preventing the spread of high-power jamming attacks within the network. The proposed algorithms reduce the number of lightpath interactions and the required number of WSSs in order to provide network security and quality of service, while at the same time keeping the cost and power consumption within the network low (through strategic WSS placements). The performance results indicate that the proposed solutions achieve all their stated objectives, while at the same time exhibiting a performance that is very close to the crosstalk-unaware RSA algorithms in terms of total resource utilization in the network.

REFERENCES

- [1] "Cisco Visual Networking Index: Forecast and Methodology, 2014-2019," *Cisco White Paper*, May 2015.
- [2] T. Wuth, M. W. Chbat, and V.F. Kamalov, "Multi-rate (100G/40G/10G) Transport Over Deployed Optical Networks", *Proc. IEEE/OSA Optical Fiber Communications Conference (OFC)*, San Diego, CA, Feb. 2008.
- [3] O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic Optical Networking: A New Dawn for the Optical Layer?" *IEEE Commun. Mag.*, 50(2):12-20, 2012.
- [4] K. Christodouloulopoulos, et al., "Elastic Bandwidth Allocation in Flexible OFDM-based Optical Networks", *IEEE/OSA Journal of Lightwave Technology*, 29(9):1354-1366, 2011.

- [5] M. Klinkowski and K. Walkowiak, "Routing and Spectrum Assignment in Spectrum Sliced Elastic Optical Path Network", *IEEE Commun. Lett.*, 15(8):884-886, 2011.
- [6] C. Mas, I. Tomkos, and O. K. Tonguz, "Failure Location Algorithm for Transparent Optical Networks", *IEEE Journal on Selected Areas in Communication*, 23(8):1508-1519, 2005.
- [7] M. Fok, Z. Wang, Y. Deng, and P. Prucnal, "Optical Layer Security in Fiber-Optic Networks", *IEEE Transactions on Information Forensics and Security*, 6(3):725-736, 2011.
- [8] K. Kitayama, M. Sasaki, S. Araki, M. Tsubokawa, A. Tomita, K. Inoue, K. Harasawa, Y. Nagasako, and A. Takada, "Security in Photonic Networks: Threats and Security Enhancements," *IEEE/OSA Journal of Lightwave Technology*, 29(21):3210-3222, 2011.
- [9] N. Skorin-Kapov, et al., "A New Approach to Optical Networks Security: Attack-aware Routing and Wavelength Assignment," *IEEE/ACM Transactions on Networking*, 18(3):750-760, 2010.
- [10] N. Skorin-Kapov, M. Furdek, R. Pardo, and P. Mariño, "Wavelength Assignment for Reducing In-band Crosstalk Attack Propagation in Optical Networks: ILP Formulations and Heuristic Algorithms", *European Journal of Operational Research*, 222(3):418-429, 2012.
- [11] K. Manousakis and G. Ellinas, "Equalizer Placement and Wavelength Selective Switch Architecture for Optical Network Security," *Proc. IEEE Symposium on Computers and Communication*, Cyprus, 2015.
- [12] K. Manousakis and G. Ellinas, "Attack-aware Planning of Transparent Optical Networks", *Optical Switching and Netw.*, 19(2):97-109, 2016.
- [13] M. Furdek, N. Skorin-Kapov and L. Wosinska, "Attack-Aware Dedicated Path Protection in Optical Networks," *IEEE/OSA Journal of Lightwave Technology*, 34(4):1050-1061, 2016.
- [14] J. Zhu, B. Zhao, W. Lu, and Z. Zhu, "Attack-Aware Service Provisioning to Enhance Physical-Layer Security in Multi-Domain EONs," *IEEE/OSA J. Lightwave Technology*, 34(11):2645-2655, 2016.
- [15] B. Shariati et al., "Investigation of Mid-term Network Migration Scenarios Comparing Multi-Band and Multi-Fiber Deployments," *Proc. Optical Fiber Communication Conference (OFC)*, 2016, paper Th1E.1.
- [16] S. Fujii, Y. Hirota, H. Tode, and K. Murakami, "On-Demand Spectrum and Core Allocation for Reducing Crosstalk in Multicore Fibers in Elastic Optical Networks," *IEEE/OSA J. Opt. Commun. Netw.*, 6(12): 1059-1071, 2014.
- [17] A. Muhammad, G. Zervas, D. Simeonidou, and R. Forchheimer, "Routing, Spectrum and Core Allocation in Flexgrid SDM Networks with Multi-core Fibers," *Proc. IEEE Int. Conf. on Optical Network Design and Modeling*, Stockholm, Sweden, pp. 192-197, 2014.
- [18] N. Amaya, G. Zervas, and D. Simeonidou, "Introducing Node Architecture Flexibility for Elastic Optical Networks". *IEEE/OSA J. Opt. Commun. Netw.*, 5(6):593-608, 2013.
- [19] P. Roorda "Critical Issues for the Flexible Spectrum Network", *LUMENTUM White Paper*, 2015.
- [20] R. Shankar, M. Florjańczyk, T. Hall, A. Vukovic, and H. Hua, "Multi-degree ROADMs based on Wavelength Selective Switches: Architectures and Scalability", *Optics Communications*, 279(1):94-100, 2007.
- [21] P. Papanikolaou, P. Soumplis, K. Manousakis, G. Papadimitriou, G. Ellinas, K. Christodoulou, and E. Varvarigos, "Minimizing Energy and Cost in Fixed-grid and Flex-grid Networks", *IEEE/OSA Journal of Optical Communications and Networking*, 7(4):337-351, 2015.
- [22] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy Efficiency of Optical OFDM-based Networks," *Proc. IEEE Int. Conf. on Communications*, June 2013, pp. 4131-4136.
- [23] J. Lopez, Y. Ye, and I. T. Monroy, "Energy Efficiency in Flexible Bandwidth Optical Networks," *Proc. Int. Conf. on the Network of the Future (NOF)*, Nov. 2011, pp. 107-111.
- [24] J. Lopez, Y. Ye, V. Lopez, F. Jimenez, R. Duque, and P. M. Krummrich, "On the Energy Efficiency of Survivable Optical Transport Networks with Flexible-grid," *Proc. ECOC*, Sept. 2012, paper P5.05.
- [25] H. Khodakarami, B. Gopalakrishna Pillai, B. Sedighi, and W. Shieh, "Flexible Optical Networks: An Energy Efficiency Perspective," *IEEE/OSA J. Lightwave Technol.*, 32(21):3356-3367, 2014.
- [26] S. Talebi, et al., "Spectrum Management Techniques for Elastic Optical Networks: A Survey" *Optical Switching and Netw.*, 13:34-48, 2014.
- [27] K. Christodoulou, P. Soumplis, and E. Varvarigos, "Planning Flexible Optical Networks under Physical Layer Constraints," *IEEE/OSA J. Opt. Commun. Netw.*, 5(11): 1296-1312, 2013.
- [28] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-aware Fixed Network Infrastructures," *IEEE Commun. Surv. Tutorials*, 13(2):223-244, 2011.
- [29] R. S. Tucker, R. Parthiban, J. Baliga, K. Hinton, R. W. A. Ayre, and W. V. Sorin, "Evolution of WDM Optical IP Networks: A Cost and Energy Perspective," *IEEE/OSA J. Lightwave Technol.*, 27(3):243-252, 2009.
- [30] Manousakis, A. Angeletou, and E. Varvarigos, "Energy Efficient RWA Strategies for WDM Optical Networks", *IEEE/OSA Journal of Optical Communications and Networking*, 5(4):338-348, 2013.
- [31] K. Manousakis and G. Ellinas, "Crosstalk-aware Routing and Spectrum Assignment in Flexible Grid Networks", *Proc. IEEE Symposium on Computers and Communication (ISCC)*, Messina, Italy, 2016.
- [32] T. Stern, G. Ellinas, and K. Bala, *Multiwavelength Optical Networks: Architectures, Design and Control*, 2nd ed. Cambridge University, 2008.
- [33] ITU-T G.694.1: Spectral Grids for WDM Applications: DWDM Frequency Grid, *ITU-T Recommendation*, 2012.
- [34] V. Kaman, R. Helkey, and J. Bowers, "Multi-degree ROADM's with Agile Add-drop Access", *Proc. Photonics in Switching Conference*, San Francisco, CA, Aug. 2007.
- [35] K. Falta and C. Cameron, "Balancing Performance, Flexibility, and Scalability in Optical Networks", *Finisar White Paper*, March 2012.
- [36] S. Bhandare, Z. Wang, K. Kim, M. Colyar, and H. N. Ereifej, "Narrow Optical Filtering Tolerance of 127-Gb/s DP-QPSK utilizing Real-Time DSP with 20 Cascaded 50-GHz Filters in the Presence of 40,200-ps/nm Chromatic Dispersion," *Proc. IEEE/OSA Optical Fiber Communication Conference (OFC)*, 2013, paper NM2E.5.
- [37] Mark Filer and Sorin Tibuleac, "Generalized Weighted Crosstalk for DWDM Systems with Cascaded Wavelength-selective Switches," *Opt. Express*, 20:17620-17631, 2012.
- [38] M. Filer and S. Tibuleac, "N-degree ROADM Architecture Comparison: Broadcast-and-select versus Route-and-select in 120 Gb/s DP-QPSK Transmission Systems," *Proc. IEEE/OSA Optical Fiber Communications Conference (OFC)*, San Francisco, CA, 2014.
- [39] R. Younce, J. Larikova, Y. Wang, "Engineering 400G for Colorless Directionless-Contentionless Architecture in Metro/Regional Networks", *IEEE/OSA J. Opt. Commun. Netw.*, 5(10): 267-273, 2013.
- [40] W. Way, P. Ji, and A. Patel, "Wavelength Contention-free via Optical Bypass within a Colorless and Directionless ROADM", *IEEE/OSA J. Opt. Commun. Netw.*, 5(10):220-229, 2013.
- [41] Y. Li, L. Gao, G. Shen, and L. Peng, "Impact of ROADM Colorless, Directionless, and Contentionless (CDC) Features on Optical Network Performance", *IEEE/OSA J. Opt. Commun. Netw.*, 4(11):58-67, 2011.
- [42] S. Gringeri, B. Basch, V. Shukla, R. Egorov, and T. J. Xia, "Flexible Architectures for Optical Transport Nodes and Networks," *IEEE Commun. Mag.*, 48(7):40-50, 2010.
- [43] D. Brelaz, "New Methods to Color the Vertices of a Graph", *Communications of the ACM*, 22(4):251-256, 1979.
- [44] Gurobi Optimization, Inc. "Gurobi Optimizer Reference Manual", 2016, <http://www.gurobi.com>

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