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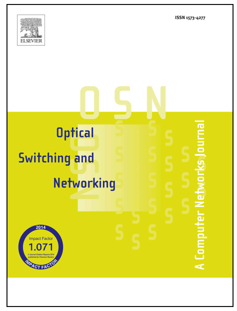

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Attack-aware Resource Planning and Sparse Monitor Placement in Optical Networks

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Abstract

This work presents joint optimization algorithms for lightpath establishment as well as sparse placement of optical performance monitoring (OPM) equipment in optical networks. OPMs are necessary to efficiently monitor the impact of physical layer attacks and are usually placed at locations that are more probable to be impacted by jamming attacks. A jamming attack is defined as a harmful signal interference with other signals, leading to service degradation, that is possible through intra-channel or inter-channel crosstalk effects. An Integer Linear Program (ILP) formulation is proposed to solve the problem of attack-aware routing and wavelength assignment (Aa-RWA), jointly with the placement of OPM equipment, in order to minimize the impact of physical layer jamming attacks in optical networks. Moreover, a Genetic Algorithm (GA) is proposed to solve the same optimization problem. The proposed GA algorithm is compared to the ILP formulation as well as to an attack-unaware RWA algorithm that has as an objective the minimization of the number of wavelengths required to accommodate all traffic demands, not accounting for the crosstalk interactions. Simulation results indicate that the proposed GA algorithm provides a solution that is close to the optimal in terms of crosstalk interactions, while also providing a very good solution in resource usage, measured in terms of the required number of wavelengths.

Keywords- *routing and wavelength assignment; monitor placement; physical layer attacks; optical networks.*

1 Introduction

With the exponential network traffic growth, optical network operators are required to provide upgraded architectures for their large-scale data transport networks in order to accommodate the increasing traffic, while also avoiding service disruption due to either malicious attacks or faults. Optical performance monitors in wavelength division multiplexed (WDM) optical networks are currently being utilized by the network operators for effective fault/attack detection as well as signal monitoring, thus ensuring better quality-of-transmission (QoT) for these networks. In all-optical WDM networks, data are transmitted through lightpaths, realized by determining a path between the source and the destination of a connection and allocating an available wavelength on all the links of that path. The selection of the path and the wavelength to be used by a lightpath is an important optimization problem, known as the routing and wavelength assignment (RWA) problem [1], [2]. The RWA problem belongs to the category of NP-complete problems, that is, the computational time for these problems would increase exponentially with the problem size. Thus, a wide range of optimization methods and heuristics have been proposed to solve various optical network optimization problems related to RWA [3], [4]. Genetic algorithms (GAs) are stochastic search optimization methods that are widely used in combinatorial optimization and parameter tuning applications and have also been used for solving the RWA problem [5], [6].

All-optical networks are vulnerable to physical layer attacks, such as high-power jamming attacks, as long as the data signals remain in the optical domain throughout the path, and are not regenerated at intermediate nodes. An *attack* is defined as an intentional action against the ideal and secure functioning of the network [7]. Significant research work has been carried over the last few years on the topic of physical layer threats and attacks in optical networks [7]-[17].

In general, there are two main categories of physical layer attacks in transparent optical networks, namely (i) eavesdropping and (ii) service disruption. In the case of an eavesdropping attack, the attacker passively analyzes the traffic in the optical network after gaining access to the transport network. Usually, in order to gain mid-span access, the eavesdropper has to physically access an individual fiber [8]. The service disruption attack on the other hand is a result of high-power jamming through the crosstalk effect. This kind of attack is classified in three categories: (i) *in-band jamming* due to intra-channel crosstalk, which is the result of power leakage between lightpaths on the same wavelength crossing an optical node (with non-ideal isolation of its input/output ports). Note that intra-channel crosstalk cannot be filtered out, since the interfering signal is on the same wavelength as the affected one. (ii) *out-of-band jamming* due to inter-channel crosstalk that appears due to power leakage between neighboring channels and nonlinearities for channels co-propagating on the same fiber (under high-power input). (iii) *gain competition in optical amplifiers*, which appears due to the increased power of a high-power jamming signal, resulting in reduction in the gain of the rest of the co-propagating channels on the same fiber. These attacks can potentially propagate through the network and affect several connections, resulting in the loss of a large amount of data. Thus, techniques must be designed that can eliminate or at least minimize the impact of such types of attacks.

Today's transparent optical networks are not only highly vulnerable to external threats but also to attacks from internal threats, which are usually difficult to defend against. Thus, the infrastructure of these networks should be planned/designed in such a way that mitigates or minimizes the effect of external as well as internal attacks.

Management of attacks and security mechanisms in WDM transparent optical networks have become critically important for the network operators due to the high data rates employed and the several security vulnerabilities that their transparency imposes on the network. In order to protect optical networks against service disruption, and reduce the impact of high-power jamming attacks by limiting their propagation within the network, different methods have been explored. For example, in [9], authors proposed heuristic algorithms for attack-aware wavelength assignment that minimizes the propagation of in-band crosstalk jamming attacks, in order to achieve better protection against such types of attacks. An ILP formulation for the routing sub-problem has been proposed in [10], that aims to minimize the effect of out-of-band jamming and the gain competition caused in optical fibers and optical amplifiers, respectively. Also, a tabu search heuristic algorithm for larger networks has been proposed. In [11], authors also proposed ILP formulations and heuristic algorithms in order to minimize the attack propagation, while in [12], ILP formulations were proposed in combination with relaxation techniques to solve the RWA problem with the objective to minimize the effect of in-band jamming attacks. In [13] authors propose ILP and heuristic algorithms based on simulated annealing techniques in order to minimize the in-band and out-of-band jamming attacks, while in [14], authors propose a GA in order to solve the RWA problem with the objective to minimize the in-band and out-of-band crosstalk interactions and therefore to minimize the impact of jamming attacks. An overview of security challenges in communication networks can also be found in [15].

Additionally, research work has also been undertaken that focuses on the placement of optical devices in WDM transparent optical networks in order to limit the propagation of high-power jamming attacks [16], [17]. Specifically, in [16], the authors proposed a heuristic algorithm and in [17] an ILP formulation for the placement of optical attenuators as power equalizers for a given routing scheme, having as an objective the minimization of the number of required attenuators. Moreover, optical performance monitors (OPMs) can be used to monitor the optical signal at specified nodes in order to detect signal anomalies, thus ensuring better QoT in the network. Authors in [18] proposed a novel monitor placement algorithm to minimize the number of monitors required for facilitating performance monitoring at the network operation time. Further, in [19], authors extended their previous work by presenting an optimization algorithm focused on the placement and the minimization of the number of required monitoring equipment. Finally, in [20], a review of various OPM techniques is presented for direct-detection systems and digital coherent systems and future technologies and challenges are analyzed for power monitoring in optical networks.

This current work extends on previous methods presented in the literature, proposing a novel ILP formulation, as well as a novel GA technique in order to solve the attack-aware RWA problem with the objective to minimize the in-band (intra-channel) and out-of-band (inter-channel) crosstalk interactions, thus minimizing the impact of high-power jamming attacks in the network. The algorithms are enhanced with a monitor placement feature so as to decide the minimum number of required OPMs to monitor the crosstalk interactions as well as the placement of these monitors in the network (sparse placement is assumed only at specific output ports of the nodes). Attack awareness is taken into consideration during the network planning phase so that the number of the affected connections from an intentional attack will be minimized during the network operation phase. The novelty of the ILP formulation derives from the fact that the RWA problem is now solved having as objectives (jointly) the minimization of the crosstalk interactions as well as the number of required monitors. Further, this work considers also the use of a GA technique in order to solve the RWA problem with the objective to minimize the impact of in-band and out-of-band crosstalk effects and also to minimize the required monitors. Crosstalk awareness is taken into consideration during the crossover and mutation process of the GA in order to handle the lightpath interactions more effectively. The novelty of the GA technique derives from the fact that the GA is enhanced in order to consider the placement of the monitors at specific locations of the networks and at the same time to minimize the crosstalk interactions and the number of required wavelengths. Finally, the proposed approaches now consider the problem of monitor placement at specific output ports of the network nodes and not to the entire nodes that is the common practice in other works. This approach clearly is better than other proposed techniques, as it results in considerable opex and capex savings.

The performance results presented in this work, show that, by considering crosstalk-aware RWA algorithms, a significant decrease on the impact of in-band and out-of-band channel interactions and on the number of required monitors is achieved, as compared to the case where the RWA is implemented without any consideration for possible attacks. Thus, this work is essential for the network planning phase, ensuring that when the network is in operation, the effect of any physical layer attack will be effectively addressed.

The rest of the paper is organized as follows. Section 2 describes the network architecture and the possible crosstalk interactions considered. Moreover, this section describes the use of OPMs at network locations where the crosstalk interactions are present. In Section 3, the attack–aware RWA (Aa-RWA) and monitor placement (MP) problems are described. This is followed in Section 4 by the proposed ILP formulation that accounts for the minimization of the in-band and out-of-band crosstalk interactions and the number/placement of the necessary OPMs, having as a goal the minimization of the effect of high-power jamming attacks. In Section 5, the proposed genetic algorithm (GA) technique is presented to solve the same problem, followed by the performance results in Section 6. Finally, Section 7 presents some concluding remarks.

2 Network Architecture and Crosstalk Interactions

A network topology is represented by a connected graph $G=(V,E)$, where V denotes the set of optical cross-connects (vertices), and E denotes the set of (point-to-point) single-fiber links (edges). Each fiber link is able to support a common set $C=\{1,2,\dots,W\}$ of W distinct wavelengths, while nodes are assumed to be all-optical and do not have any wavelength conversion capabilities. The building components of a WDM optical backbone network consist of optical nodes interconnected by pairs of bidirectional fiber links. Further, in a WDM optical system, transmitter-receiver pairs, known as transceivers, are required in order to receive/transmit data via optical channels.

Reconfigurable optical add/drop multiplexers (ROADMs) [21]-[23] are the key elements currently utilized in order to build an optical node. 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 the underlying technology depends on how effectively current and future traffic can be addressed. ROADM architecture and technology influences their cost, power consumption, optical performance, and configuration flexibility.

Figure 1 illustrates a typical WDM network, where three lightpaths are established in order to satisfy a set of connection requests. The first lightpath (p_0,w_i) from n_0 to n_6 is established using wavelength w_i. The second lightpath (p_1,w_{i+1}) from n_0 to n_6 is established using wavelength w_{i+1} and the third lightpath (p_2,w_i) from n_1 to n_5 is established using wavelength w_i. In general, there are several ways to establish these lightpaths. According to the current lightpath establishment, lightpaths (p_2,w_i) and (p_1,w_{i+1}) interact through inter-channel crosstalk in link (n_1, n_2) because these lightpaths occupy adjacent wavelengths. In addition, lightpaths (p_0,w_i) and (p_2,w_i) interact through intra-channel crosstalk when crossing node n_4, because these lightpaths utilize the same wavelength.

In Fig. 1, examples of both high-power in-band and out-of-band jamming attacks are presented; let (p_2,w_i) be a malicious lightpath (high-power signal) that uses wavelength w_i. This lightpath affects lightpath (p_1,w_{i+1}) by degrading its QoT when crossing link (n_1, n_2) through inter-channel crosstalk. In addition, lightpath (p_0,w_i) is also affected when crossing node n_4, through intra-channel crosstalk.

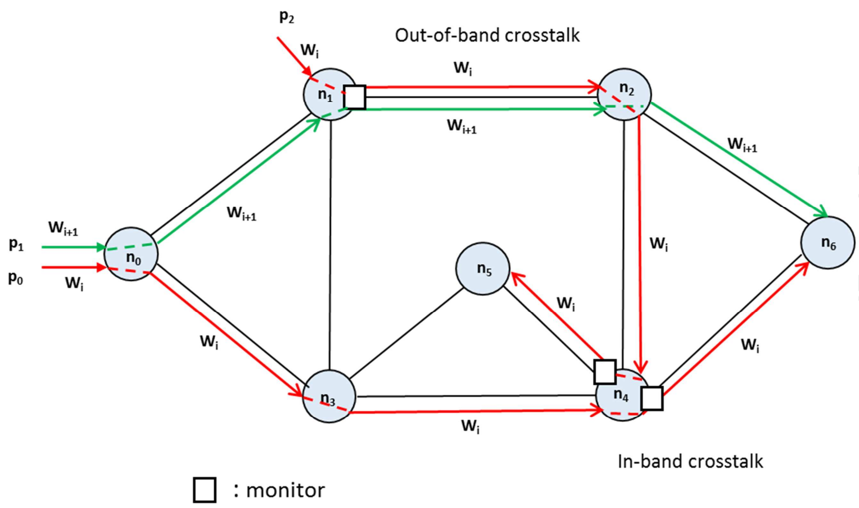


Fig. 1. Network architecture and crosstalk interactions.

Due to the fact that an attack can be spread through the network (an attacked lightpath becomes now a secondary attacker, affecting other lightpaths that it interacts with and so on), it is important to consider both the in-band and out-of-band jamming attack propagation during the planning/design phase of a transparent optical network. For this reason, OPMs are required in places where the crosstalk effect is present. As an example, in Fig. 1, OPMs (that can provide continuous and real-time information about the optical signals) are placed at the output ports of network nodes (denoted by squares in the figure) in order to detect/monitor high-power jamming attacks at the locations where the signal is degraded (due to an attack). Specifically, at node n_1, an OPM is placed at output port (n_1, n_2) to monitor the inter-channel crosstalk interaction of lightpaths (p_1,w_{i+1}) and (p_2,w_i). Moreover, at node n_4, two OPMs are placed at output ports (n_4, n_2) and (n_4, n_6) in order to monitor the intra-channel crosstalk interaction of lightpaths (p_0,w_i) and (p_2,w_i). By utilizing OPMs, as soon as the signal degradation (due to an attack) is detected, specific action can be taken to enhance the signal quality, thus mitigating the effect of the attack; this is achieved by adjusting the power of the transmitted signal as soon as an attack is detected, in order to provide an acceptable optical signal-to-noise-radio (OSNR) at the receiver.

3 Attack–aware RWA and Monitor Placement - Problem Definition

In this section, the problem of attack-aware routing and wavelength assignment, as well as monitor placement in WDM optical networks, is described for a given set of connection requests. The algorithms are given a specific RWA instance; that is, a network topology, the set of wavelengths that can be used, and a static traffic scenario. OPMs can be used in the WDM optical network in order to monitor physical layer attacks, which affect the network performance. Due to cost considerations, it is not possible to have an OPM at every port of the network. Thus, the problem addresses the sparse placement of OPMs in the network. The objectives of the problem are the following:

1. Minimize the number of wavelengths required to establish the given set of lightpaths.
2. Minimize the number of required OPMs at the output ports of optical nodes and specify the locations where these monitors should be placed. This objective minimizes also the in-band and out-of-band crosstalk interactions among different lightpaths that interact in the optical nodes and fibers.

The objective of the algorithms is to minimize the crosstalk interactions among lightpaths as much as possible, trying to achieve zero interactions. If this is not possible, then OPMs at the output ports of optical nodes are required in order to monitor possible attacks at the interaction points. To address this problem, an ILP model is formulated in Section 4, while in Section 5 an efficient GA approach is proposed that tries to minimize the crosstalk interactions, while at the same time keeping the required number of wavelengths and OPMs as small as possible.

4 Optimization Algorithm

In this section an ILP formulation is presented in order to jointly solve the problem of attack-aware RWA and monitor placement (*ILP-MP*). The proposed *ILP-MP* algorithm consists of two phases. In the first phase, k candidate paths are identified for serving each requested connection. These paths are selected by employing a k-shortest path algorithm (any k shortest path algorithm can be used). In this work the following k shortest path algorithm is used. First, the shortest path is calculated using Dijkstra's algorithm, assuming that all the links have cost equal to one. Then the cost of the links which belong to the shortest path is increased (doubled in this work) and Dijkstra's algorithm is executed again. This procedure is repeated until k paths are found. After a subset P_{sd} of candidate paths for each source-destination pair (s,d) is computed, the total set of computed paths, $P = \bigcup_{s\text{-}d} P_{sd}$, is inserted to the next phase. The advantage of using k shortest paths as a preprocessing phase is that the formulation can now be more computationally tractable, because the search space is reduced. With this approach, there is a high probability that the optimal solution will be inside this search space (this probability increases with the value of k - when k is large enough in order to include a large number of paths between the source and the destination there is a much higher probability the optimal solution will be inside this search space) or the solution is close to the optimal (clearly, it is not expected that a particular lightpath will pass through all the links of the network but it is more likely to pass through the links of the shortest paths (note that the k paths are not edge disjoint)). Obviously, global optimality requires enumerating all the possible paths between each source-destination pair (if all the possible paths are in the search space, then the optimal solution is in this space) [2]. However, this makes the problem intractable even for networks of smaller size. For this reason, we have opted on utilizing the preprocessing phase in the formulation. While our approach, with the preprocessing phase included, may not always provide the global optimal solution, however such a technique is necessary to be included in the ILP formulation for more effectively defining constraints related to crosstalk.

In the second phase, the problem is formulated as an ILP with two objectives: 1) Minimize the maximum number of required wavelengths and 2) Minimize the required number of monitors and place them at specific locations that exhibit crosstalk interactions.

4.1 ILP-MP Formulation

The following parameters, constants, and variables are used for the *ILP-MP* formulation:

Parameters:

- $s, d \in V$: network source and destination nodes, $|V| = N$.
- $w \in C$: an available wavelength, $|C| = W$.
- $l \in E$: a network link, $|E| = L$.
- $p \in P_{ij} \subset P$: a candidate path from i to j, $|P_{ij}| = k$.
- $\{p' | (m,n) \in p, p'\}$, p' is a path that has the link (m,n) common with path p.

Constants:

- Λ_{sd}: the number of requested connections from node s to node d.
- B: a constant (taking large values). Constant B is used to take into account only the constraints for the lightpaths that will be utilized from the set of all candidate lightpaths.
- M: large constant, with $M >> B$. Constant M is used to specify the location where a monitor will be placed.

Variables:

- $x_{p,w}$: a Boolean variable, equal to 1 if path p occupies wavelength w, and 0 otherwise.

- y_{mn}: a Boolean variable, equal to 1 if there is a monitor at the output port of node *m* at the beginning of link (*m*,*n*), 0 otherwise.
- $W_{\max}$: the maximum assigned wavelength in the network.

The formulation of the *ILP-MP* problem is presented below:

Objective

Minimize: $c_1 \cdot W_{\max} + c_2 \cdot \sum_m \sum_n y_{mn}$

The first term of the objective accounts for the maximum used wavelength and the second term accounts for the required number of monitors. The coefficients c_1 and c_2 declare the relative importance of the maximum used wavelength and the number of required monitors, respectively.

Subject to the following general constraints:

(1) Incoming traffic constraint:

$$\sum_{p \in P_{sd}} \sum_{w} x_{p,w} = \Lambda_{sd} \text{ , } \forall (s,d) \text{ pairs}$$

(2) Distinct wavelength assignment constraint:

$$\sum_{p:l \in p} x_{p,w} \leq 1 \text{, } \forall\, l \in E, \forall\, w \in C$$

(3) Maximum assigned wavelength:

$$w \cdot x_{p,w} \leq W_{\max}\ \forall\, w \in C, \forall\, p \in P$$

(4) Constraining the out-of-band crosstalk interactions and placing the required monitors:

$$\sum_{\{p' | (m,n) \in p, p'\}} \left(x_{p',w-1} + x_{p',w+1} \right) + B \cdot x_{p,w} - M \cdot y_{mn} \leq B,\ \forall\, (m,n) \in p, \forall\, p \in P, \forall\, w \in C$$

(5) Constraining the in-band crosstalk interactions and placing the required monitors:

$$\sum_{\{p' | m \in p, p'\}} x_{p',w} + B \cdot x_{p,w} - M \cdot y_{mn} \leq B \text{ , } \forall\, m \in p, \forall\, p \in P, \forall\, w \in C$$

4.2 Analysis of the Constraints

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) is the distinct wavelength assignment constraint and ensures that each wavelength is used at most once on each fiber. Constraint (3) is used in order to compute the maximum used wavelength. The available wavelengths are in sequential order so as to account for the maximum wavelength that will be utilized. In this way, by minimizing the maximum utilized wavelength, we try to restrict the usage of the spectrum. This is done as the second objective tries to spread the spectrum in order to achieve the desired minimization in terms of crosstalk interactions. Thus, by having these two objectives, a balance is achieved between the spectrum utilization and the crosstalk interactions. The wavelength continuity constraint requires that the same wavelength must be used on all the links that a lightpath traverses. This constraint is implicitly taken into account by the definition of the $x_{p,w}$ variable, since this variable uses the same wavelength *w* across all links that constitute a path *p*. Therefore, there is no need to include the wavelength continuity constraint as an additional constraint in the formulation.

To avoid the *out-of-band jamming* attacks, Constraint (4) is used for every path *p* and wavelength *w* in order to count the out-of-band channel interactions of adjacent wavelengths through the term $\sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right)$. That is, the total number of out-of-band crosstalk interactions that affect the signal of lightpath (*p*,*w*) on link (*m*,*n*).

The effect of out-of-band crosstalk for each path *p* and wavelength *w* is formulated as follows:

1) Case where $y_{mn} = 0$, that is the case where there is no monitor attached to link (*m*,*n*). Then, Constraint (4) becomes

$$\sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right) + B \cdot x_{p,w} \le B. \qquad (4a)$$

a) In case lightpath (*p*,*w*) is selected in the solution ($x_{p,w}$=1), then $B \cdot x_{p,w}=B$, and the above constraint becomes

$$\sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right) \le 0, \qquad (4a\text{-}i)$$

b) In case lightpath (*p*,*w*) is not selected ($x_{p,w}$=0), then $B \cdot x_{p,w}=0$, and the above constraint becomes

$$\sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right) \le B, \qquad (4a\text{-}ii)$$

which always holds, when constant *B* is large enough. Thus, constant *B* is used to make the constraint active when lightpath (*p*,*w*) is utilized, and inactive (always true), otherwise.

2) Case where $y_{mn} = 1$, that is the case where there is monitor attached to link (*m*,*n*). Then Constraint (4) becomes:

$$\sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right) + B \cdot x_{p,w} - M \le B. \qquad (4b)$$

In this case, the above inequality is always true since $M >> B$ and thus irrespective of the value of the variable $x_{p,w}$ the above inequality becomes

$$\sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right) - M \le 0. \qquad (4b\text{-}i)$$

Thus, Constraint (4) is used to minimize the out-of-band interactions among the lightpaths and also to place the minimum number of monitors in the proper locations (through variable y_{mn}), in order to eliminate the out-of-band jamming attacks.

Constraint (5) follows the same principle as Constraint (4) for accounting for the in-band crosstalk interactions, where in this case $\sum_{\{p'|m\in p,p'\}} x_{p',w}$ is the total number of in-band crosstalk interfering sources that affect the signal of lightpath (*p*,*w*) on link (*m*,*n*).

It is worth noting that a monitor at the output port of a node can monitor both the in-band and the out-of-band crosstalk interactions. For this reason, the y_{mn} variable is again used for monitor placement and is common in both Constraints (4) and (5).

5 Genetic Algorithm

Genetic algorithms (GAs) are heuristic search methods used for finding optimized solutions based on the theory of natural selection and evolutionary biology. GA techniques try to emulate a phenomenon observed in nature: survival of the fittest by using evolutionary biology techniques such as natural selection, crossover, and mutation. Usually, each solution is represented using a *gene*, and all solutions, i.e., all genes, form an individual *chromosome*. The latter mate with each other to create outcrossings, until a good *individual* (solution) of the problem is found. Genetic algorithms do not guarantee that an optimal solution can be found, since these are stochastic processes. The main steps for executing a GA are as follows:

Initialization: In the initialization phase, a random set of individual chromosomes (also called initial population) is initialized with random values. A unique cost metric is assigned to all, to identify their *fitness* function. This fitness function depends on the problem to be solved and also determines the fitness of each individual. The fitness function is the function which takes a candidate solution to the problem as input and produces its cost value as output, which denotes how "fit" or how "good" a solution is with respect to the problem under consideration.

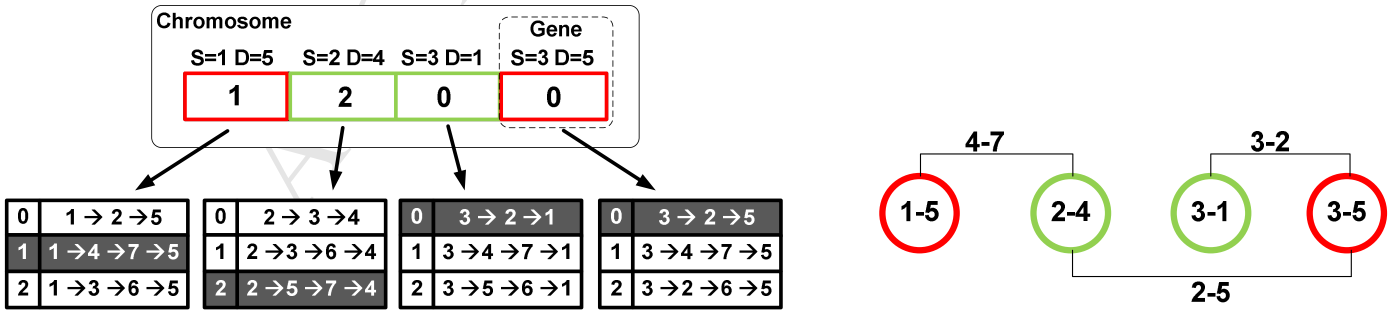
Crossover: In the crossover phase, individual chromosomes are crossovered (mate) with a specified probability, to produce the next generation of individuals that are added to the total population. The cost of each additional individual chromosome created is calculated again, based on the fitness function, and the worst performing ones are discarded. Usually, an upper bound on the number of individuals is maintained (population), and when this is reached, all the rest are not considered for next generation crossovers.

Mutation: During this step a single gene is modified. This is done to avoid loops around a local, but not global (optimal) solution. This is necessary since GAs, as stochastic search engines, may be trapped around sub-optimal solutions during random crossovers between the best performing individuals.

5.1 Genetic Algorithm for RWA

As defined in Section 2, $G(V,E)$ denotes a simple graph that models the network, where V is the vertex set and E is the edge set. The demand set D is a set of source-destination pairs $\{(s_1, d_1), (s_2, d_2) \ldots, (s_n, d_n)\}$, where $s_i, d_i \in V$, $i = 1, \ldots, n$, with n being the total number of requests for connections, and (s_i, d_i) are the source and destination nodes of that request, respectively. For each request i, a specific lightpath L_i is assigned with a specific path and wavelength (w_i). The constraints that must be satisfied by the GA (*GA-Simple*) in order to solve the RWA problem are the incoming traffic constraint, the wavelength continuity constraint, and the distinct wavelength assignment constraint, as defined in the previous section.

In the case of *GA-Simple*, each gene in an individual chromosome represents one of the k-shortest paths for a specific source-destination pair. Each chromosome consists of n genes, where n is the number of all source-destination pairs and constitutes a solution for the routing problem. Fig. 2a shows an example for k=3, for the network topology of Fig. 4b. The genes that constitute an individual correspond to the following source-destination *(s,d)* pairs: {*(1,5), (2,4), (3,1), (3,5)*}. Each gene denotes a certain routing path. If the best chromosome is the one shown below (Fig. 2a), an auxiliary graph is created (Fig. 2b) in order to calculate the minimum number of wavelengths, by assigning a different color to the nodes of the graph that are connected (vertex coloring of the created auxiliary graph). The nodes in Fig. 2b correspond to the genes of the solution, while the edges correspond to the common links between the paths that the genes represent. Note that a heuristic is utilized for vertex coloring as this problem is NP-complete [24].



(a) (b)

Fig. 2. (a) Example of the individual (chromosome) structure with four genes, each pointing to a candidate routing path. (b) Illustrative solution displaying the common edges of the genes (s-d pairs). For example, gene (1-5) and gene (2-4) have edge (4-7) in common.

The main features of the proposed genetic algorithm (*GA-Simple*) are the following:

Fitness function: The objective of *GA-Simple* is to minimize max{w_i}, that is the maximum number of wavelengths that are required in order to establish the connection requests. This is equivalent to coloring the auxiliary graph with the minimum possible number of wavelengths utilizing the vertex coloring heuristic.

Let F_l be the cost of a link *l*, that is equal to the number of paths that cross link *l*. In the GA proposed in [5], the *fitness* of a chromosome *Ch* is given by $F(Ch) = \sum_{l \in E} N^{F_l}$, where *N*=|*V*| is the number of nodes in the network. However, summing the exponential costs of the links does not reveal the true fitness of the chromosome *Ch*, since a link that is utilized by many paths in the chromosome can significantly increase the cost of a path. Thus, the GA may discard a good candidate solution and not reach the global optimum. To avoid this, a cost for each gene of the chromosome is defined and three different fitness functions *F*(.) for the chromosomes are examined [6]. These fitness functions are based on the average μ(.) and the variance σ(.) of the cost values of the genes that comprise the chromosome.

To obtain a graph that can be colored with a small number of wavelengths it is important to avoid the repeatability of the links in the paths (genes) that comprise the chromosome. Thus, in the proposed formulation, we assign to each gene (*s*,*d*) of the chromosome *Ch* the following cost $c_{sd} = \sum_{l \in p} F_l,\ p \in P_{sd}$ and $p \in Ch$. The following three fitness functions of the chromosome *Ch* are defined:

i) $F(Ch) = \sigma(c_{sd})$, ii) $F(Ch) = \mu(c_{sd})$, iii) $F(Ch) = N^{\mu(c_{sd})}$, where μ(.) and σ(.) are the average and the variance of the cost values that comprise *Ch*. Based on the analysis and results of [6], out of the three fitness functions examined, the fitness function that results in the minimum number of required wavelengths is $F(Ch) = N^{\mu(c_{sd})}$ and this is precisely the fitness function utilized in this work.

Thus, for example, to find the cost $F(Ch) = N^{\mu(c_{sd})}$ of the chromosome *Ch* depicted in Fig. 2a, we need to examine each gene and calculate its cost c_{sd}. The first gene that corresponds to source-destination pair (1,5) has one common edge with the second gene (namely, edge (1-4)), and thus $c_{1,5}$ = 1; the second gene (2,4) has one common edge with the first gene (edge (1-4)) and one common edge with the fourth gene (edge (2-5)), and thus $c_{2,4}$ = 2; the third gene (3,1) has one common edge with the fourth gene (edge (3-2)), and thus $c_{3,1}$=1; finally, the fourth gene (3,5) has one common edge with the second gene (edge(2-5)) and one common edge with the third gene (edge (3-2)), and thus $c_{3,5}$=2. Since in the given topology *N*=7, the cost of this solution is:

$$F(Ch) = N^{\mu(c_{sd})} = 7^{\frac{1+2+1+2}{4}} = 18{,}52\ .$$

Crossover: A single-point crossover method is used to generate new individuals from two existing chromosomes (parents). The two parents for crossover are chosen based on the conventional Roulette Wheel selection scheme as in [5]. During the crossover operation, the crossover point *c* is selected randomly between {1, *n*}, where *n* is the number of genes in an individual (number of source-destination pairs). The genes {1, *c*-1} of the first parent and the genes {*c*, *n*} of the second one are used to create the new individual which is included in the population. After crossover, if the population is of size *v*, then the first *v* individuals are maintained based on their fitness, while the rest are discarded.

Mutation: A random uniform mutation is used in this approach with a probability of $1/\sum_{(s,d)\,pairs} \Lambda_{sd}$. During the mutation phase, the created chromosome replaces itself regardless of the (new) fitness function. The individual with the worst fitness function is selected for mutation. This is done in order to produce a fitter individual out of a “non-fit” individual in the population.

5.2 Attack-aware RWA and Monitor Placement Genetic Algorithm

The objective of the attack-aware and monitor placement GA (*GA-MP*) is to establish for each source-destination (*s*,*d*) pair a lightpath with the smallest number of in-band and out-of-band channel interactions, minimum number of monitors, and minimum number of required wavelengths. Fig. 3 presents the pseudocode of the proposed *GA-MP* algorithm. The proposed algorithm works as follows. At the beginning, the initial population is created by using a set of shortest paths. This set of shortest paths is computed by employing a *k*-shortest path algorithm, where *k* denotes the number of shortest paths per lightpath (*line* 1, in Fig. 3). Each iteration of the algorithm solves the RWA problem based on the *GA-Simple* algorithm (*line* 9, in Fig. 3) as described in Section 5.1. The wavelength assignment process is necessary to count the crosstalk interactions for each lightpath (*line* 10, in Fig. 3 calculates the crosstalk interactions by counting the in-band and out-of-band lightpath interactions). If there exist crosstalk interactions in any of the lightpaths, the algorithm tries to apply “fixes” (*line* 12, in Fig. 3), for eliminating the crosstalk among the established lightpaths. These “fixes” are performed with the objective to retain the maximum id of the utilized wavelengths. In particular, when a given lightpath interacts with other lightpaths (in-band or out-of-band crosstalk), the algorithm tries to assign a different wavelength from the already assigned ones in the existing solution. The optimum solution is to find a wavelength that produces zero crosstalk interactions, without violating the constraints of the RWA solution. When this fails, the algorithm tries to find the solution that produces the minimum number of crosstalk interactions by minimizing the crosstalk cost (number of in-band and out-of-band lightpath interactions).

For reducing the required monitors in the network, the algorithm minimizes the spread of the in-band and out-of-band interactions across the affected nodes and links. In particular, the algorithm tries to maintain the in-band and out-of-band interactions in the same nodes and links, resulting in using fewer monitors in the network. During the calculation of the spread of the interactions (*line* 13, in Fig. 3) the algorithm iterates through all the in-band and out-of-band interactions of the various lightpaths to find out common nodes and links. The smaller the number of common nodes and links, the greater the spread of the interactions. The total cost of the chromosome is then just the sum of the crosstalk cost plus the interactions spread cost (*line* 14, in Fig. 3). Finally, the algorithm terminates by selecting the fittest solution in the population (i.e., the chromosome with the smallest cost), utilizing the fitness function of the *GA-MP* algorithm as shown below:

$$F(Ch) = \frac{C_1}{\max C_1} + \frac{C_2}{\max C_2} + \frac{C_3}{\max C_3}$$

where:

- $C_1 = N^{\mu(c_{sd})}$ is the fitness cost of the *GA-Simple* approach as defined in Section 5.1.
- $C_2 = C_{21} + C_{22}$ with:

  $C_{21} = \sum_{\{p'|(m,n)\in p,p'\}} \left(x_{p',w-1} + x_{p',w+1}\right)$ is the number of out-of-band crosstalk interactions and $C_{22} = \sum_{\{p'|m\in p,p'\}} x_{p',w}$ is the number of in-band crosstalk interactions as defined in Section 4.2.
- $C_3 = \frac{1}{\sum_{mn} L^{CI_{mn}}}$ accounts for the spread of the interactions across the output ports of the affected network nodes. By minimizing this term the interactions are constrained to a few output ports and thus, the number of required monitors is also minimized. In this term, CI_{mn} denotes the number of lightpath interactions at output port *mn, L* is the number of links in the network, and $L^{CI_{mn}}$ is the exponential cost of the lightpath interactions at output port *mn*. Thus, term $\sum_{mn} L^{CI_{mn}}$ denotes the sum of this cost across all output ports. This term has to be maximized in order to minimize the number of required monitors. Therefore, in order to achieve this maximization term $\frac{1}{\sum_{mn} L^{CI_{mn}}}$ has to be used as a minimization term in the fitness function.

To give each of the optimization components a normalized value, each term is divided with the maximum (*maxC*) value of the term found in the population. The monitors are placed at locations (output ports of the nodes) where there exist in-band and/or out-of-band interactions based on the established lightpaths.

```
Population = GenerateInitialPopulation(k)

Epoch = 0

While True {

  Epoch = Epoch + 1

  If OptimizationCriteria(Population)= True
     Exit While;
  Else{

     For each chromosome in Population{
       Solve_RWA(chromosome)

        Crosstalk = CountCrosstalk(chromosome)
       If Crosstalk > 0
          FixCrosstalk(chromosome)

       InteractionsSpread = InteractionsSpread(chromosome)

        chromosome.Cost = Crosstalk + InteractionsSpread
   }
  }
}
```

Fig. 3. The pseudocode of the proposed attack-aware and monitor placement genetic algorithm (*GA-MP*).

6 Performance Evaluation

To evaluate the performance of the proposed algorithms, a number of simulation experiments were performed. For these simulations, a small network with 6 nodes and 9 links, as well as the generic Deutsche Telekom (DT) network topology that comprises of 14 nodes and 23 links were considered (Fig. 4). The results were obtained using a series of traffic matrices produced by a random traffic generator. The network load ρ is denoted as the ratio of the total number of requested connections over the number of single requested connections between all possible source-destination pairs, that is $\rho = \frac{\sum \Lambda_{sd}}{N^2 - N}$, where Λ_{sd} is the number of requested connections for the source destination pair *s*-*d*, $\sum \Lambda_{sd}$ is the total requested connections of the network, N is the number of network nodes, and $N^2 - N$ is the number of single requested connections between all possible source-destination pairs. Ten (10) RWA executions were performed corresponding to different random static traffic instances for each traffic load. For the DT network, we have also used synthetic data based on the data provided for the DICONET project [25], that were randomly modified in order to include several traffic conditions, from small to medium and higher traffic loads. For solving the ILP related formulations, the Gurobi library was used [26], utilizing a PC with Core i5-2400@3.1GHz and 4GB memory for the simulation environment.

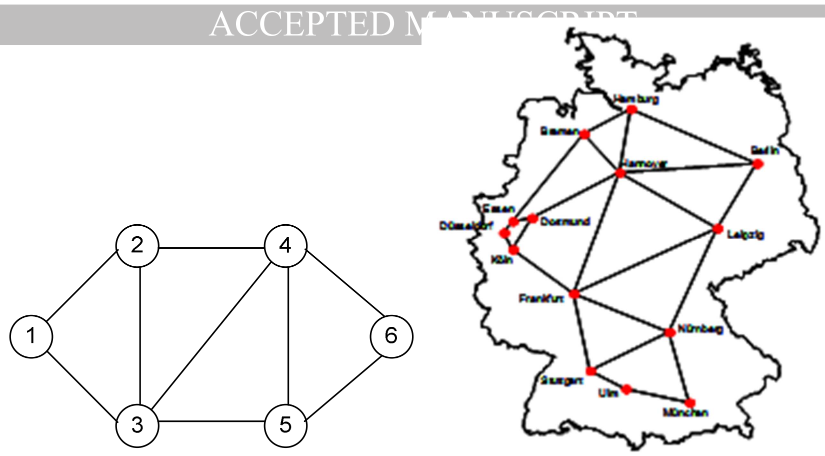


Fig. 4. Network topologies used in the simulation: (a) 6-node network and (b) DT network topology.

Table 1 shows the simulation parameters for the genetic algorithm. The same parameters are used for both the *GA-Simple* and *GA-MP*. The number of shortest paths was chosen equal to 2 (i.e., k=2). The initial and maximum population chosen was 50 and 75 respectively, while the number of iterations (epochs) was set to 300. It must be noted that the *GA-Simple* algorithm is a crosstalk-unaware algorithm and is used only as a benchmark for the worst case, since it does not consider the placement of the OPMs and the lightpath interactions.

TABLE 1. Genetic algorithm simulation parameters.

Shortest paths k	2
Initial population	50
Max population	75
Epochs	300

One of the metrics used for comparison of the algorithms is the number of in-band and out-of-band lightpath interactions. In order to compute the value of this metric, for each lightpath L_i, the number of the established lightpaths that interact with it through in-band and out-of-band crosstalk is computed. The sum of the interactions across all lightpaths is then the value for this metric (the total number of in-band and out-of-band lightpath interactions).

6.1 Crosstalk Interactions and Traffic Load

6.1.1 *6-node network*

Figures 5 and 6 depict the performance analysis of the proposed algorithms (ILP and GA) in the 6-node network. In Fig. 5, the number of lightpaths that interact through in-band and out-of-band crosstalk vs. network load is presented. For the 6 node network, the number of available wavelengths per fiber was chosen to be equal to 12. The rationale behind the choice of the number of wavelengths for the experiments was the fact that under the given requested connections, in order to point out the benefits of the proposed algorithms, a relative small number of available wavelengths would give no room for improvement to any algorithm. The resources would be limited, and therefore no algorithmic technique would be effective in minimizing the crosstalk effect. Similarly, a relative large number of available wavelengths would produce zero lightpath interactions and zero required number of WSSs (with any algorithm, after a certain number of wavelengths, no benefit would be obtained). Thus, the number of wavelengths was chosen so as to demonstrate that for small loads, there is no need for WSSs and the need for WSSs is required after a certain point of traffic in order to compensate for the crosstalk effect.
The estimated mean values for the ten runs are represented together with 95% confidence intervals as error bars based on the Student-t distribution. The confidence interval is visible only for the case of the GA-Simple algorithm, because for the other two algorithms this interval is small and lies inside the symbols that represent the estimated mean value.

Moreover, 95% confidence intervals are represented only for Figs. 5 and 7, since in all other cases the size of the confidence intervals was smaller than the size of the symbols.

It is obvious that the performance of the proposed GA algorithm (*GA-MP*) is significantly better than that of the *GA-Simple* algorithm and also its performance is very close to the solution given by *ILP-MP*. The performance of the *GA-Simple* algorithm exhibits a high number of lightpath interactions, while the crosstalk-aware techniques demonstrate that even with increasing traffic load, the number of interactions remains low (even though as the traffic increases more lightpaths are established in the network and therefore more lightpath interactions are potentially possible). The reader should note that the confidence interval is visible only for the GA-Simple algorithm, since this algorithm is a crosstalk-unaware algorithm, and the number of in-band and out-of-band lightpath interactions differ for every run, as this performance metric is not in the optimization objective of the algorithm. On the other hand, the confidence intervals of the two crosstalk-aware algorithms are not shown in the figure because these are too small (lie within the symbols), since their performance metric is now part of the optimization function and as a result different runs return very similar results.

In Fig. 6, the number of required wavelengths vs. network load is presented. Fig. 6 shows that the proposed *GA-MP* algorithm can utilize network resources effectively, since only a very small increase is observed in the number of required wavelengths. Note that the results of the *GA-Simple* algorithm as presented in Fig. 6 signify the lower bound of the required number of wavelengths, since the objective of *GA-Simple* is to minimize the number of required wavelengths of the network without taking into account crosstalk interactions. It is worth noting that *ILP-MP* requires a slightly larger number of wavelengths in some instances compared to *GA-MP*, since the prime objective of the *ILP-MP* formulation is the minimization of the crosstalk interactions rather than the minimization of the number of required wavelengths. This is the case, because in the proposed formulation, the relative cost of the OPMs and as a consequence the cost of the lightpath interactions is taken to be larger than the cost associated with the number of utilized wavelengths. This is usually the case, since the cost of adding extra OPMs requires extra monetary cost which is much higher compared to the cost of using extra wavelengths that are already available in the WDM system (the assumption here is that the additional spectrum utilization cost is much lower than the additional capex cost associated with extra OPMs being introduced in the network).

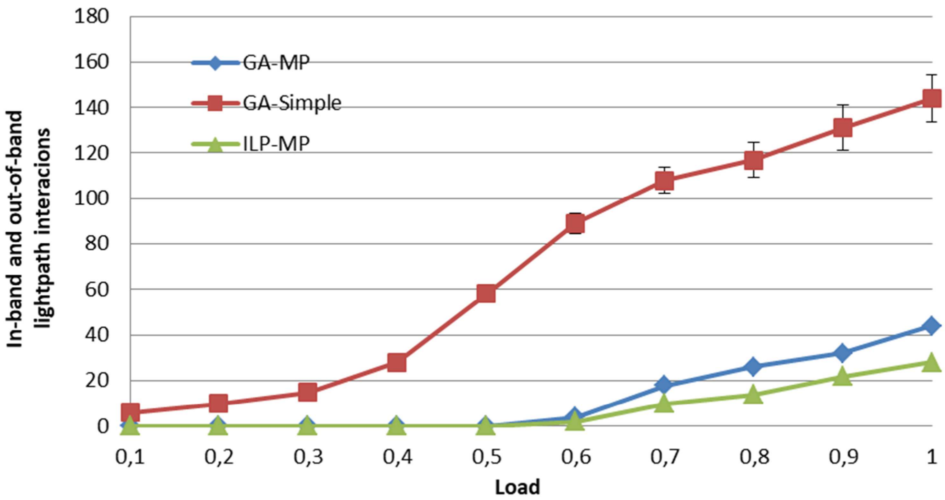


Fig. 5. Number of lightpaths that interact through in-band and out-of-band crosstalk vs. network load (6-node network).

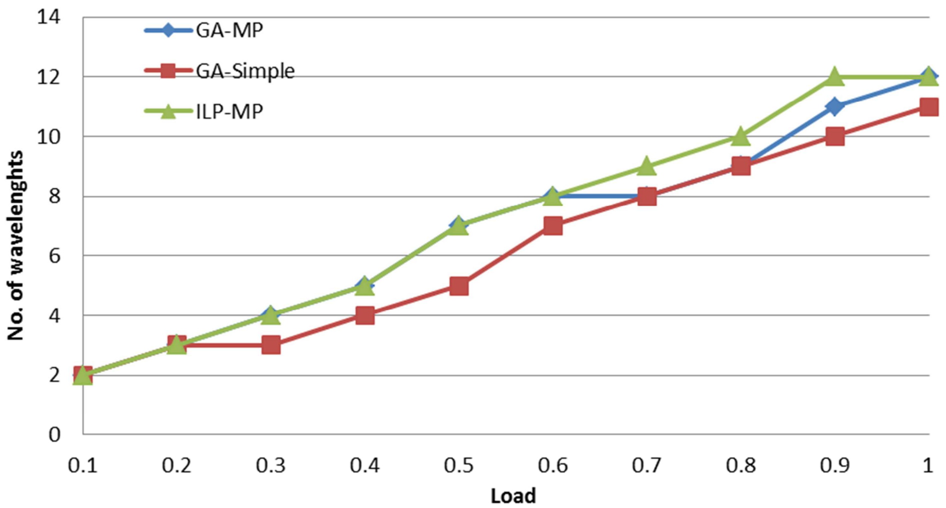


Fig. 6. Total number of wavelengths used over all links vs. network load (6-node network).

6.1.2 *DT Network*

Regarding the DT network, as can be seen from Figs. 7 and 8, the performance of the proposed crosstalk-aware algorithms follow the same trend as in the 6-node network. The number of available wavelengths per fiber was assumed to be equal to 20 for the DT network (chosen in the same manner as for the 6-node network). Again, the average number of lightpaths that interact through in-band and out-of-band crosstalk vs. network load is presented in Fig. 7, while Fig. 8 presents the results on the number of required wavelengths vs. network load.

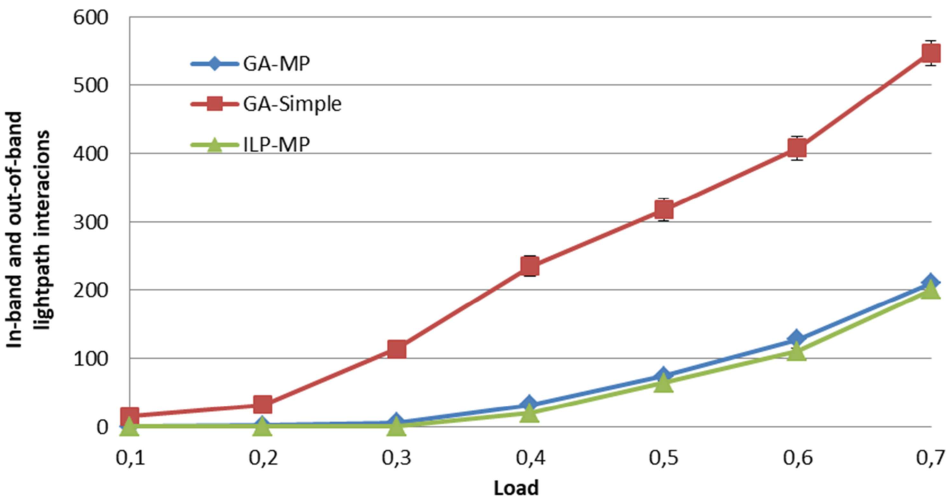


Fig. 7. Number of lightpaths that interact through in-band and out-of-band crosstalk vs. network load (DT network).

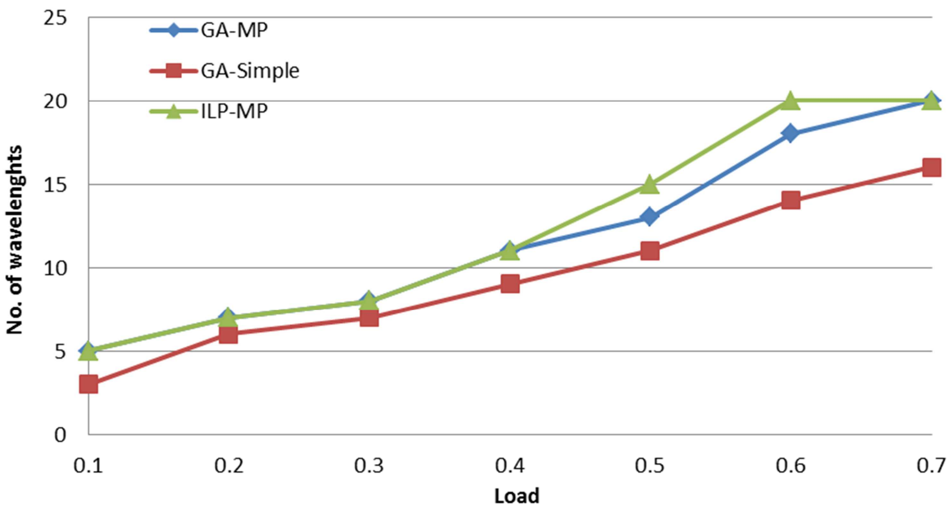


Fig. 8. Total number of wavelengths used over all links vs. network load (DT network).

6.1.3 Time Complexity

Figures 9 and 10 depict the execution times of the algorithms when computing the required number of wavelengths and the required number of monitors. Each execution time is computed as the mean value of all the different instances for each traffic load. As expected, *GA-Simple* requires considerably less time compared to the other two algorithms (*GA-MP* and *ILP-MP*). Moreover, *GA-MP* requires significantly less time than *ILP-MP*, while having comparable results. The maximum running time for *GA-Simple* is 22 minutes for the 6-node network and 37 minutes for the DT network, while the maximum running time for *GA-MP* increases to 40 minutes and 3.3 hours for the 6-node and DT networks respectively. In the case of *ILP-MP*, it requires 1 hour for a load equal to 1 for the 6-node network, while for the *DT* network it does not converge within the time limit (set to 10 hours for each instance) for the cases with load equal to 0.5 and above. Therefore, in cases where the running time is a crucial parameter the *GA-MP* algorithm should be preferred.

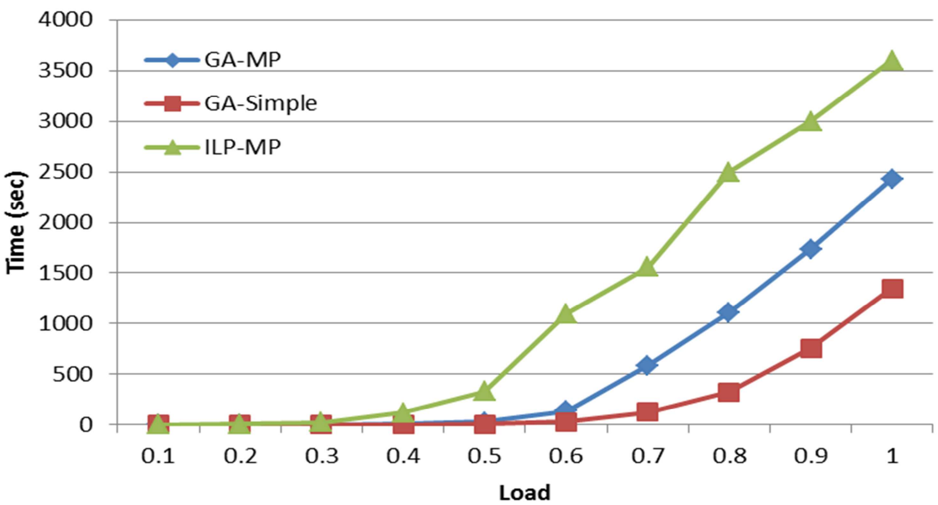


Fig. 9. Execution time vs. network load (6-node network).

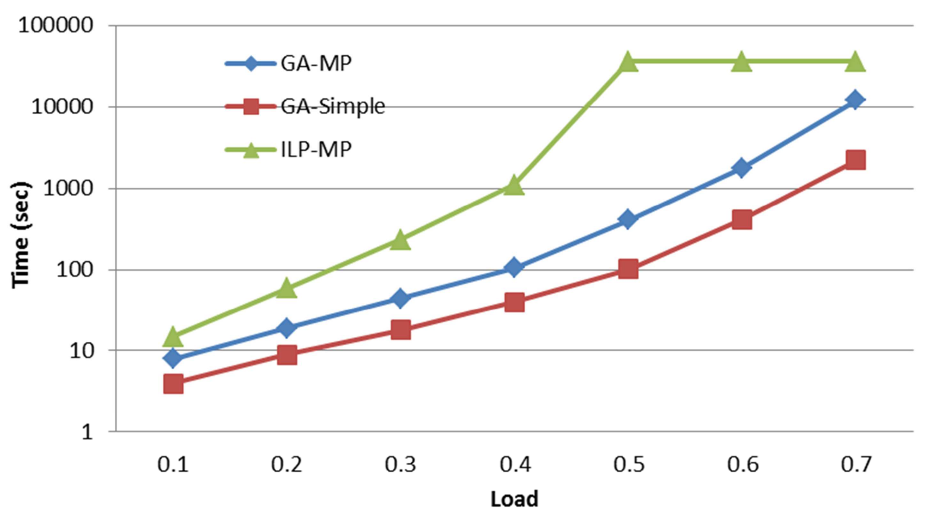


Fig.10. Execution time vs. network load (DT network).

6.2 Crosstalk Interactions and Number of Wavelengths

6.2.1 6-node network

In Fig. 11, a comparison between the proposed attack-aware RWA algorithms (*GA-MP* and *ILP-MP*) and the *GA-Simple* algorithm for the 6-node network is depicted. The network load was assumed to be equal to 0.8. Fig. 11 presents the number of lightpaths that interact through in-band and out-of-band crosstalk in relation to the number of available wavelengths. As it can be seen from the figure, the performance of *GA-Simple* is independent of the number of available wavelengths, since the objective of the algorithm is to minimize the number of required wavelengths. For the *GA-MP* and *ILP-MP* algorithms, the number of interactions decreases significantly with increasing number of available wavelengths. Furthermore, *GA-MP* and *ILP-MP* exhibit similar performance that is significantly better than that demonstrated by *GA-Simple*. Further, as the number of wavelengths increases beyond a certain point, no more crosstalk interactions occur. This is expected, as the attack-aware RWA algorithms (*GA-MP* and *ILP-MP*) are designed to exploit the wavelength domain in order to avoid crosstalk interference among the established lightpaths.

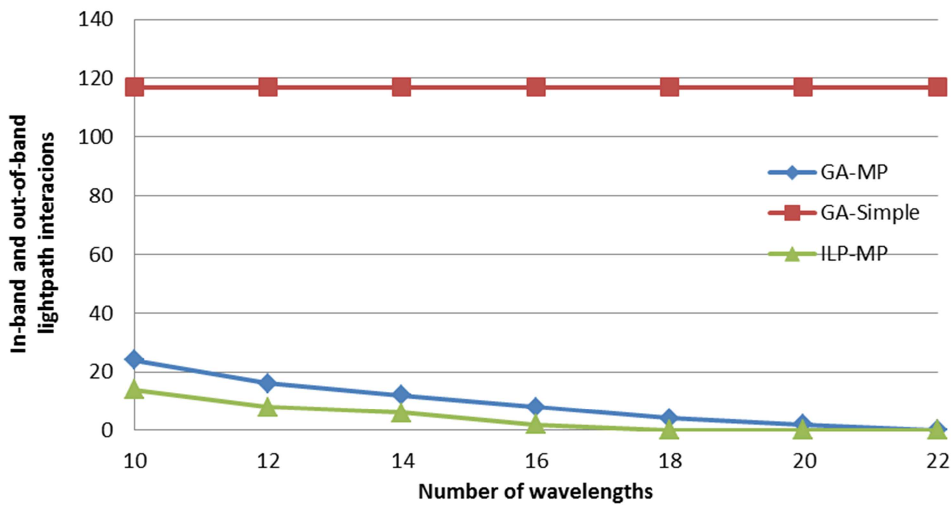


Fig. 11. Number of lightpaths that interact through in-band and out-of-band crosstalk vs. number of wavelengths for the 6-node network (load=0.8).

6.2.2 DT Network

A second simulation for the DT network was also performed in order to validate the results obtained for the (smaller) 6-node network topology. Fig. 12 depicts the results for the DT network topology in the same manner as the results presented for the 6-node network in Fig. 11. For the results of the DT network in Fig. 12 the load was assumed equal to 0.6 and the number of available wavelengths was increased from 20 to 38. The performance results for the DT network follow the same trend as in the 6-node network in terms of the lightpath interactions. Note that in Fig. 12, the *GA-MP* and the *ILP-MP* exhibit almost the same performance. Note also that, in some cases, for larger networks, the *ILP-MP* algorithm could not find the optimal solution within the set time limit. Thus, in general, as the network size and the traffic load increases, the *GA-MP* algorithm is preferable in order to achieve results close to *ILP-MP* in faster running times.

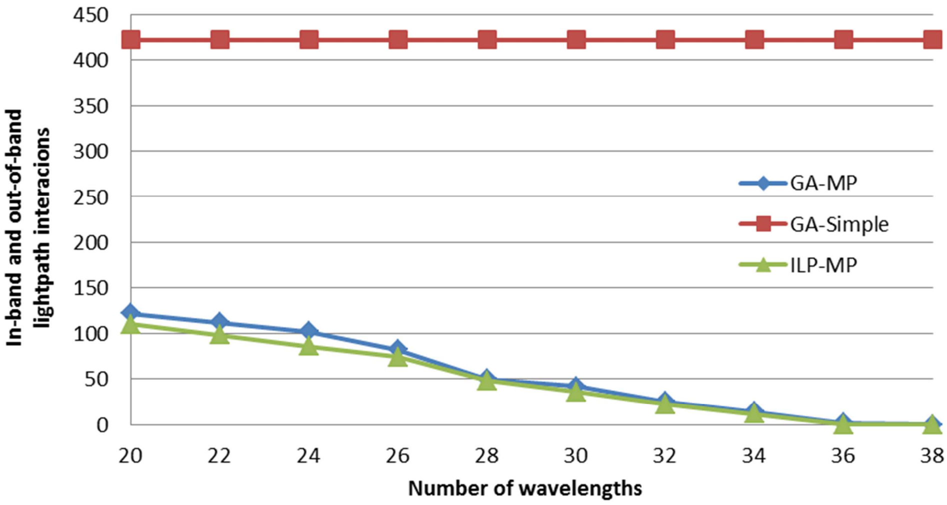


Fig. 12. Number of lightpaths that interact through in-band and out-of-band crosstalk vs. number of wavelengths for the DT network (load=0.6).

6.3 Monitor placement

Figures 13 and 14 present the number of required OPMs in order to monitor the crosstalk-related interactions among lightpaths vs. network load for the 6-node topology and DT network, respectively. The Full-Placement approach provides the upper bound when all the network nodes are equipped with OPMs. The number of wavelengths was assumed equal to 12 and 20, for the 6-node topology and DT network, respectively. As it can be seen from the figures, the performance of the *GA-Simple* algorithm requires a higher number of monitors, approaching the case where monitors are placed at all ports of all network nodes (for higher traffic loads). On the contrary, the crosstalk-aware algorithms require significantly less number of monitors. Specifically, *ILP-MP* requires the smallest number of OPMs in both networks, while *GA-MP* requires a slightly higher number of OPMs.

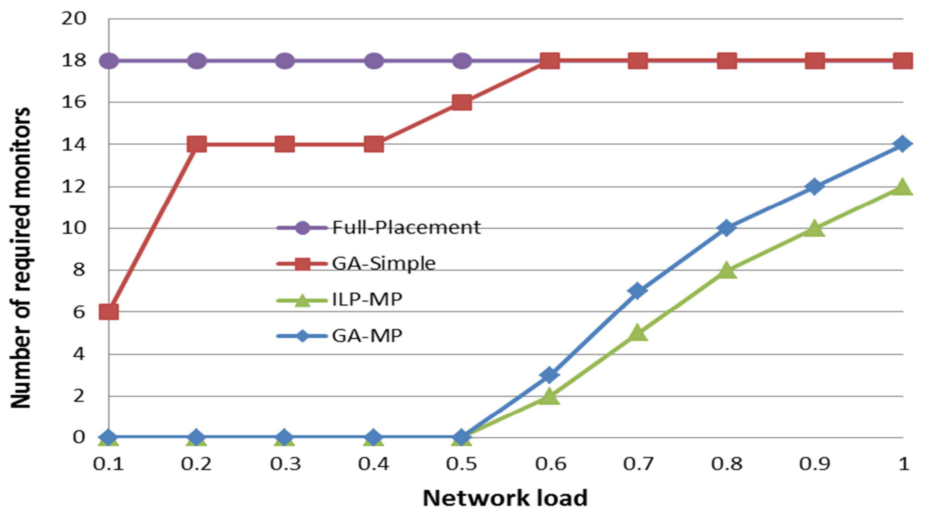


Fig. 13. Monitor Placement vs. network load (6-node network).

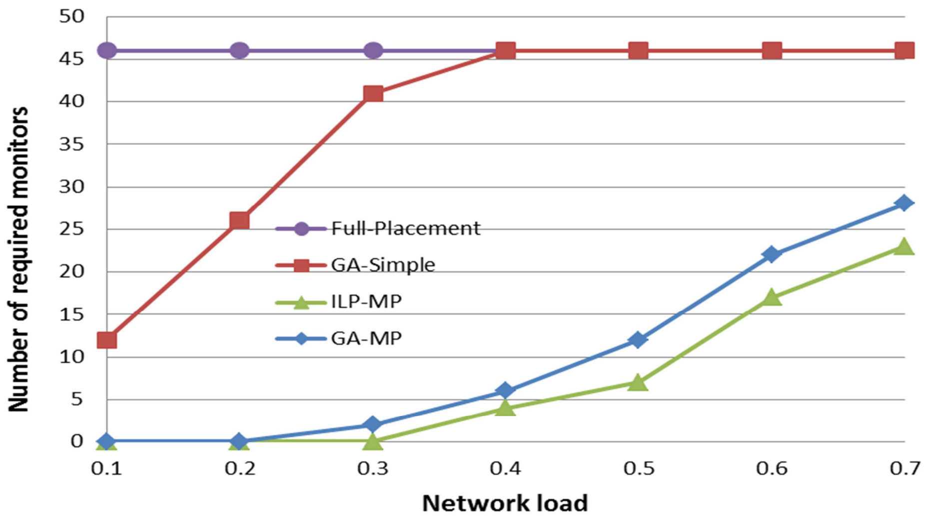


Fig. 14. Monitor Placement vs. network load (DT network).

It is important to note that this improvement in terms of the number of required monitors is achieved by the proposed algorithms while also not increasing the required network resources in terms of required wavelengths (as previously demonstrated in Figs. 6 and 8).

It is also worth noting that the number of required OPMs in both networks can be significantly reduced by using more wavelengths in the network. Based on Fig. 11 for the 6-node network, the *GA-MP* algorithm requires 22 wavelengths in order to avoid using OPMs while the *ILP-MP* algorithm requires 18 wavelengths. On the other hand, by using the *GA-Simple* algorithm, this cannot be achieved, since as it was previously demonstrated, the number of interactions in that case does not decrease with an increasing number of wavelengths. In addition, for the DT network, the required number of wavelengths to achieve the same goal, based on Fig. 12, is 38 for *GA-MP* and 36 for *LP-MP*. In the DT network these values are now closer, since the *ILP-MP* algorithm is now unable to find its best solution within the specified time constraint due to the larger size of the network.

7 Conclusion

This work proposed an ILP formulation (*ILP-MP*) and a GA (*GA-MP*) technique for solving the RWA problem during the design phase of a transparent WDM optical network having as objectives to minimize the required number of wavelengths, the in-band and out-of-band crosstalk interactions, and also the required number of monitors that are placed at the output ports of optical nodes. Minimizing crosstalk interactions protects the network against the spread of potential high-power jamming attacks in the network, while the monitoring of lightpath interactions with the smallest possible number of OPMs will enable to more cost-efficient network design that allows for effective monitoring of the optical signal, thus ensuring better QoT within the network. The proposed attack-aware genetic algorithm technique (*GA-MP*) reduces the number of lightpath interactions, with a performance close to the one obtained by *ILP-MP*, while at the same time having a performance that is close to the *GA-Simple* approach in terms of the required number of wavelengths in order to establish all requested connections. Thus, the proposed *GA-MP* solution that can be utilized for large network topologies (in contrast to the ILP formulation) can obtain excellent results in terms of minimizing the effect of physical layer attacks (minimizing lightpath interactions) while at the same time utilizing a small number of resources (in terms of the required number of wavelengths) and keeping the network cost low (in terms of the number and placement of optical performance monitors).

Future work under consideration includes the expansion of this work in flexgrid networks, as well as networks where there is uncertainty in the traffic forecast.

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