Chapter 3

Multi-Period Attack-Aware Optical Network Planning under Demand Uncertainty

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.68491

Abstract

In this chapter, novel attack-aware routing and wavelength assignment (Aa-RWA) algorithms for multiperiod network planning are proposed. The considered physical layer attacks addressed in this chapter are high-power jamming attacks. These attacks are modeled as interactions among lightpaths as a result of intra-channel and/or inter-channel crosstalk. The proposed Aa-RWA algorithm first solves the problem for given traffic demands, and subsequently, the algorithm is enhanced in order to deal with demands under uncertainties. The demand uncertainty is considered in order to provide a solution for several periods, where the knowledge of demands for future periods can only be estimated. The objective of the Aa-RWA algorithm is to minimize the impact of possible physical layer attacks and at the same time minimize the investment cost (in terms of switching equipment deployed) during the network planning phase.

Keywords: physical layer attacks, routing and wavelength assignment, optical networks, multi-period planning, demand uncertainty

1. Introduction

In wavelength division multiplexed (WDM) optical networks, wavelength routing is used for establishing communication between source-destination pairs. In these networks, data are transmitted over all-optical WDM channels called lightpaths. A connection is established by utilizing a lightpath, which is determined by choosing a path between the source and the destination and allocating a wavelength on all the links of the path. The selection of the path and wavelength is an important optimization problem and is known as the routing and wavelength assignment (RWA) problem [1].

In WDM optical networks, transparent optical cross-connects (OXCs) are used in order to provide efficient space and wavelength switching functions [2]. An OXC takes as input signals at multiple wavelengths and some of these wavelengths can be dropped locally, while others pass through by switching them to the appropriate output ports. For the implementation of OXCs, wavelength selective switch (WSS) technology is used for the deployment of cost-effective and dynamic wavelength-switched networks [3].

In transparent optical networks, where data signals remain in the optical domain until they reach their destinations, connections are vulnerable to physical layer attacks. An attack is defined as an intentional action against the ideal and secure functioning of the network. One type of attack in optical networks is high-power jamming which can affect the signal through in-band jamming that is the result of intra-channel crosstalk or out-of-band jamming that is the result of inter-channel crosstalk and nonlinearities [4]. This type of attack propagates through the transparent network affecting several connections, and as a consequence, the localization of this kind of attack is a difficult problem. Due to the high bit rates of optical networks and the interaction of the connections, a jamming attack can potentially cause a huge amount of information loss. Therefore, the limitation of attack propagation is a crucial consideration in optical network planning. An overview of security challenges in communication networks can be found in Ref. [5].

Physical layer attacks in optical networks have been studied by several researchers [6–10]. In these works, the concept of attack-aware routing and wavelength assignment (Aa-RWA) is analyzed. Specifically, in Ref. [6], authors proposed an integer linear program (ILP) formulation and a tabu search heuristic algorithm for the routing sub-problem in optical networks in order to minimize the effect of out-of-band jamming and the gain competition caused in optical fibers and optical amplifiers, respectively. In Ref. [7], authors proposed ILP formulation and heuristic algorithms for the wavelength assignment sub-problem in optical networks in order to minimize the in-band jamming attack caused in optical nodes. In Ref. [8], authors proposed ILP and heuristic algorithms based on simulated annealing techniques in order to minimize the in-band and out-of-band jamming attacks. Moreover, in Ref. [9, 10], authors proposed a greedy randomized adaptive search procedure (GRASP) heuristic and an ILP formulation, respectively, for the placement of power equalizers in order to limit the jamming attack propagation in transparent optical networks.

Another important aspect in network planning that usually is not taken into account is the uncertainty of the connection requests. In most cases, the demands are considered to be known before network planning; however, in some cases, network planning must be performed for a period of time where the demand requests can only be forecasted with uncertainty. One approach to deal with demand uncertainty is by overprovisioning, essentially allocating many resources that can satisfy any traffic demand. However, this approach requires a high cost investment (capital expenditure—capex) from the network operators [11]. More sophisticated approaches to deal with demand uncertainty are necessary in order to achieve a cost-effective network investment strategy [12].

Stochastic programming (SP) [13] and robust optimization (RO) [14] are the main alternative techniques to deal with uncertain data both in a single period and in a multi-period decision making process. In SP, the probability distribution functions of the underlying stochastic parameters must be known. On the other hand, RO addresses the uncertain nature of the problem without making specific assumptions on probability distributions. The uncertain parameters are assumed to belong to a deterministic uncertainty set. RO adopts an approach that addresses uncertainty by guaranteeing the feasibility and optimality of the solution against all instances of the parameters within the uncertainty set.

In Ref. [15], authors apply robust optimization in order to incorporate the uncertainty of demands into the network upgrade problem. Under the robust network upgrade model, the network planning can be performed by tuning the trade-off between network cost and robustness level. Further, in Ref. [16], authors propose multi-period network planning approaches based on SP, where the demands are forecasted over periods of time and the network investments are performed based on these forecasts.

In this chapter, novel Aa-RWA algorithms are proposed to address the problem of multi-period network planning under demand uncertainty with the objective to minimize the impact of possible physical layer attacks and at the same time to minimize the network infrastructure investment cost. Physical layer attacks are modeled as interactions among connections through in-band and out-of-band channel crosstalk. Moreover, the investment cost is taken into account in this formulation via the number of WSSs required in order to minimize the impact of a possible physical layer attack.

The simulation results show that when the distribution of demands for all the time periods is taken into account in advance, better results can be obtained in terms of the number of WSSs required to be placed in the network nodes so as to minimize the impact of a jamming attack, compared to the case where the distribution is known only for the period under consideration.

The chapter is organized as follows. Section 2 describes the network architecture, while Section 3 describes the planning approaches for demand uncertainty. In Section 4, the physical layer attacks in optical networks are presented, and in Section 5, the problem of attack-aware RWA with given traffic demands is solved. This is followed in Section 6 by the attack-aware RWA under demand uncertainties. Performance results are presented in Section 7, while Section 8 presents some concluding remarks.

2. Network and node architecture

An optical network topology is represented by a connected graph $G = (V, E)$, where V denotes the set of optical cross-connects (nodes) and E denotes the set of (point-to-point) single-fiber links (edges). Each fiber link is able to support a common set $C = \{1,2,\ldots,W\}$ of, W, distinct wavelengths. Source-destination pairs are equipped with transmitter-receiver pairs, also known as transponders (TSP), in order to transmit/receive data. Optical nodes currently deployed in optical networks are based on two architectures. The first architecture utilizes a broadcast-and-select (BS) configuration and the second a route-and-select (RS) configuration. Both of these optical node architectures consist of two stages and can remotely configure all transit traffic and only differ in the implementation of their first stage. The building components of these node architectures are the WSSs. A WSS can steer each optical channel present on its input port toward one of its output ports according to the desired routing choice.

BS-based nodes (**Figure 1**) include a splitter first stage (1 × N) that implicitly provides a broadcast capability toward all outputs. In a BS-based architecture, the WSS functionality (second stage) resembles a multiplexer (it switches each individual wavelength 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.

RS architecture nodes (**Figure 2**) on the other hand have a WSS first stage (1 × N) that provides on-demand routing to the required output. 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 be implemented.

Both implementations have a WSS second stage (N × 1) that provides the selection of the wavelengths at the output fibers, allowing full switching flexibility (any wavelength from any incoming fiber can pass through or any wavelength from the add/drop terminals can be added/dropped).

In order to deal with the losses introduced by the power splitters of the BS-based architecture and the high cost of the RS-based architecture, a hybrid architecture can also be used (**Figure 3**). This architecture contains either splitters (1 × N) or WSSs (1 × N) at the input ports as can be seen in **Figure 3**. In essence, hybrid nodes are constructed by replacing splitters with WSSs at the input stage of the BS-based nodes.

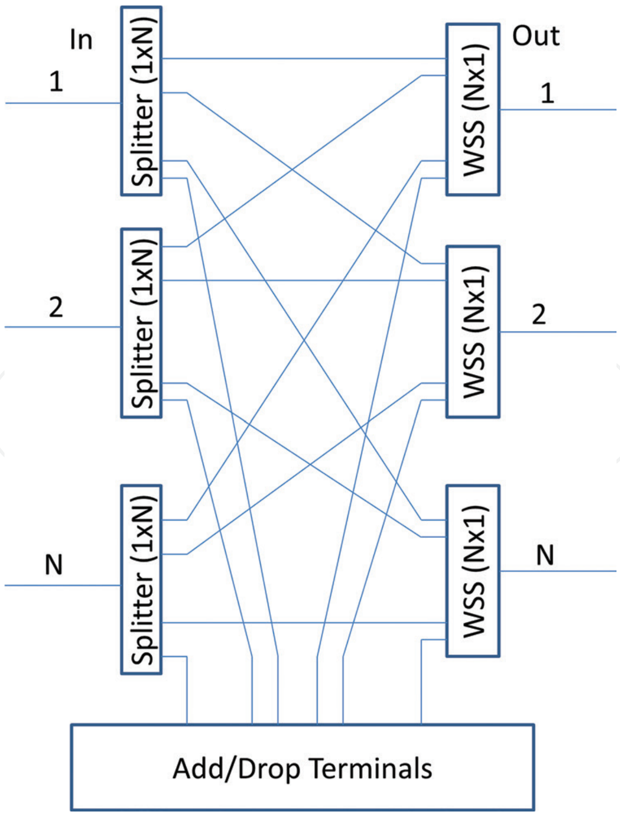

Figure 1. Broadcast-and-select-based node architecture.

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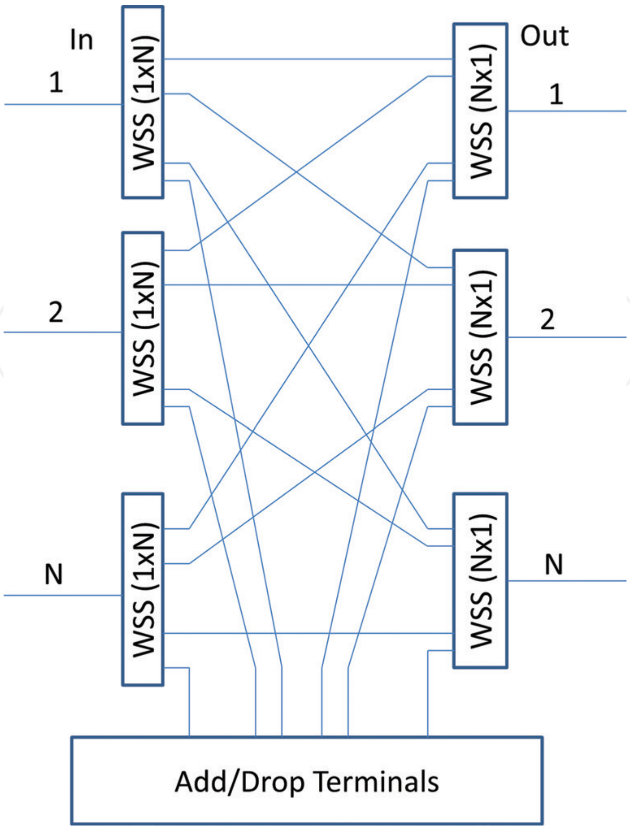

Figure 2. Route-and-select-based node architecture.

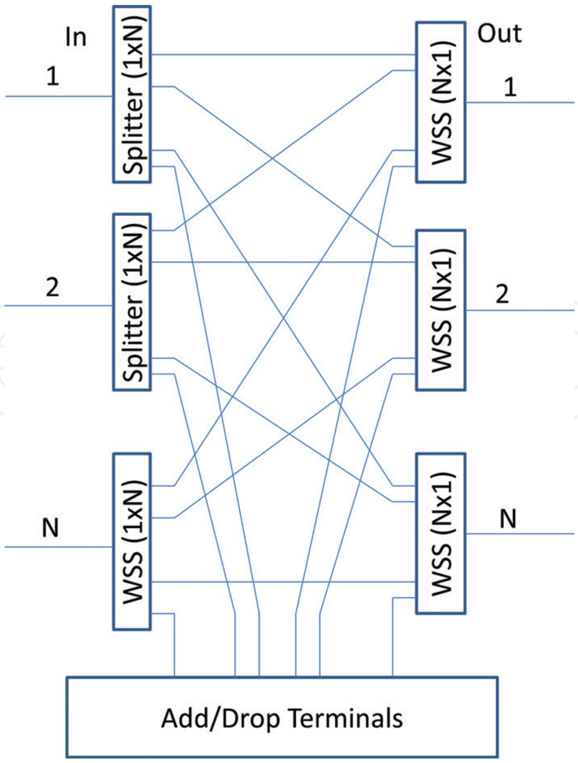

Figure 3. Hybrid node architecture.

Depending on the network traffic, 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. The objective of the proposed algorithms of this chapter is to use hybrid nodes in order to minimize the lightpath interactions and at the same time to minimize the network cost. This means that WSSs are placed only in some of the input ports and specifically only at the locations that are necessary in order to allow only the necessary wavelengths to pass through the WSS and avoid all crosstalk interactions. Thus, by using hybrid nodes and not RS-based nodes, we can minimize the network cost while at the same time eliminating crosstalk interactions and consequently protecting the network against jamming attacks.

3. Planning approaches for demand uncertainty

In order to provide cost-efficient network solutions, it is necessary to plan optical networks over a long-time horizon. When dealing with optical networks, where the cost to build the network is high and the investment that takes place should last for a long time, sophisticated planning decisions must take place to ensure that the network infrastructure will not require any major upgrades over a predetermined amount of time. The problem becomes more involved in the case of future traffic demand forecasts that include uncertainty, as network planning decisions must be taken without the exact knowledge of future traffic demands. In this case, these decisions will be based on estimations. In the remaining of this chapter, the proposed multi-period network planning approaches with uncertain traffic demands are discussed. The planning approaches assume that for the first period, the demands follow a known distribution and for the periods that follow the demands are increased based on a multiplicative factor.

The multi-period network planning problem in this chapter will be investigated for two different period-planning types as detailed below.

3.1. Incremental network planning

This approach considers the demands of the next period and optimizes the investment cost in each period. Therefore, the solution is calculated sequentially for each period. The solution can be optimal for each period but not jointly for all the periods under consideration. Once the solution is provided for one period, then this solution affects the solution of the periods that follow. This is due to the fact that the solution of one period is assumed to be fixed and the solutions of the periods that follow are now based upon the previously found solutions.

3.2. Multi-period network planning

This approach considers the demands of all periods and optimizes the investment cost from the beginning of the planning period, that is the multi-period approach minimizes the network cost over all periods at once. Therefore, the demand distribution for every time period is necessary. This approach can calculate an optimal overall solution and provide decisions for the investment strategy of network operators.

4. Physical layer attacks

In general, the physical layer attacks in transparent optical networks can be grouped in two main categories: eavesdropping and service disruption.

In eavesdropping, the purpose of an attacker is to passively analyze the traffic in the network after gaining access to the information through an unauthorized observation method. To gain mid-span access to the fiber, the eavesdropper has to cut through and strip away the cable's outer jacket to access the individual fibers in its center.

Service disruption can be performed through high-power jamming attacks and can be classified into three sub-categories based on the effects it inflicts on the signal:

i. in-band jamming which is the result of intra-channel crosstalk,

ii. out-of-band jamming that is the result of inter-channel crosstalk and nonlinearities, and

iii. gain competition in optical amplifiers, where a high-power jamming signal can increase its own power, thus resulting in reduction in the gain of the rest of the co-propagating channels on the same fiber.

These types of attacks propagate through the transparent network affecting several connections, and as a consequence, the localization of an attack is a difficult problem. Due to the high bit rates of optical networks and the interaction of the connections, a jamming attack can cause a huge amount of information loss. Therefore, the limitation of attack propagation is a crucial consideration in designing transparent WDM optical networks.

The focus of this study is to deal with service disruption and especially with in-band and out-of-band jamming attacks.

4.1. In-band jamming attack

High-power in-band jamming attack is an attack that can be performed through the intra-channel crosstalk effect. Intra-channel crosstalk is the effect of power leakage between lightpaths crossing the same switch and using the same wavelength due to non-ideal isolation of the inputs/output ports of the switching fabric. Intra-channel crosstalk cannot be filtered out, since the interfering signal is on the same wavelength as the one affected. Thus, a high-power jamming signal can cause significant leakage inside the switches between lightpaths that are on the same wavelength as the attacking signal.

Figure 4 illustrates an example of a high-power jamming attack in node n_1 of the network through lightpath (p_1, w_i). In this figure, the attacker uses the lightpath (p_1, w_i) in order to attack the network. The attacking signal initially affects lightpath (p_0, w_i), through intra-channel

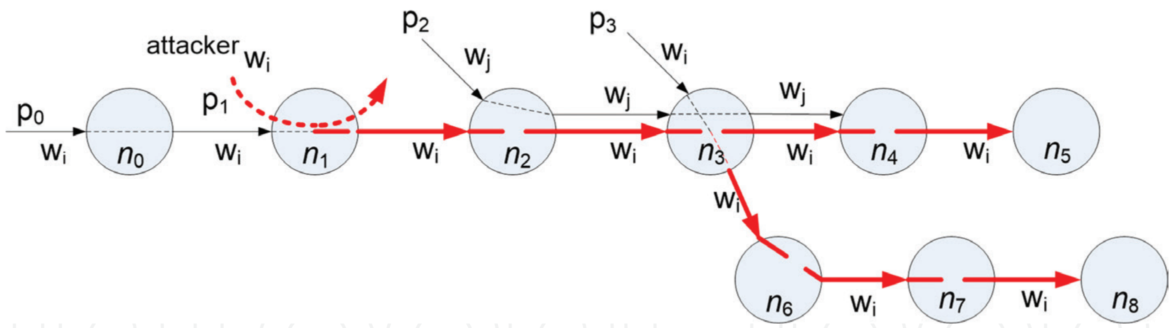

Figure 4. High-power in-band jamming attack propagation.

crosstalk because this lightpath uses the same wavelength and is crossing the same node as the attacking lightpath. In turn, lightpath (p_0, w_i) becomes an attacker too called "secondary attacker". Thus, lightpath (p_0, w_i) spreads the attack further to lightpath (p_3, w_i).

4.2. Out-of-band jamming attack

High power out-of-band jamming attack is an attack that can be performed through the inter-channel crosstalk effect. Inter-channel crosstalk results due to the power leakage between adjacent channels.

Figure 5 illustrates the high-power out-of-band signal propagation through the inter-channel crosstalk effect. In this case, lightpath (p_1, w_{i+1}) is used by an attacker in order to attack the network. Lightpath (p_1, w_{i+1}) then affects lightpath (p_0, w_i) as the two lightpaths co-propagate along the same fiber utilizing adjacent wavelengths. Then, the affected lightpath (p_0, w_i) becomes a "secondary attacker" and affects lightpath (p_3, w_{i-1}).

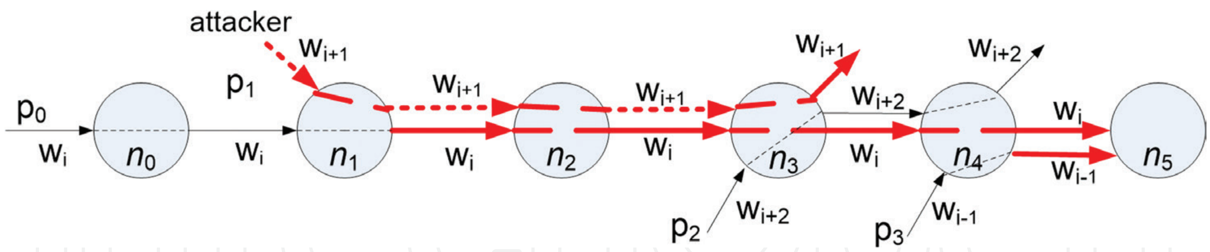

Figure 5. High-power out-of-band jamming attack propagation.

5. Attack-aware routing wavelength assignment

In this section, a heuristic algorithm is presented for the Aa-RWA with given demands in order to minimize the propagation of physical layer attacks. The algorithm aims at minimizing the interactions among lightpaths in order to avoid the propagation of high-power jamming attacks, in terms of affected lightpaths through intra- and inter-channel crosstalk. As discussed above, with these types of attacks, an affected lightpath can also affect other lightpaths, thus spreading the attack to other parts of the network. The goal of the Aa-RWA techniques is then to minimize as much as possible the spread of any attack that can occur in the network.

The proposed heuristic approach solves the problem by sequentially serving one-by-one the connections and consists of two phases. In the first phase, k candidate paths are calculated for each requested connection. In the second phase, the algorithm establishes the connections sequentially with the objective to minimize the number of in-band and out-of-band lightpath interactions.

5.1. Finding candidate paths

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. The k-shortest path algorithm pre-calculates for each source-destination pair (s, d) a set of k candidate paths P_{sd} as follows: first, the shortest path is calculated using Dijkstra's algorithm, and then, the cost of the links which belong to the shortest path is doubled 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 is given as input to the next phase of the algorithm.

5.2. Attack-aware RWA

This section describes the heuristic algorithm for establishing the connections, one-by-one, in some particular order with the objective to minimize the lightpath interactions through the crosstalk effect.

5.2.1. Definitions

Each link l of the network is characterized by a Boolean wavelength availability vector $BWAV_l(i)$, $1 \le i \le W$, whose i^{th} element is equal to 0 if the i^{th} wavelength of link l is utilized by a connection and is equal to 1, otherwise. W is the number of wavelengths that each fiber is able to support.

Each path p is characterized by a Boolean wavelength availability vector $BWAV_p(i)$, $1 \le i \le W$. The $BWAV_p$ consisting of links $l \in p$ is defined as the Boolean AND operation to the $BWAV_l$ of these links in each of the wavelengths of the $BWAV_l$ vectors.

$$BWA\,V_p = AND_{l \in p}\left(BWA\,V_l\right) \tag{1}$$

Thus, the element $BWAV_p(w)$ is equal to 1 if wavelength w is available over path p. The above equation enforces the wavelength continuity constraint among the links comprising a path. Each element $BWAV_p(i)$ represents a lightpath (p, w) between source-destination pairs (s, d).

5.2.2. Algorithm description

The aim of the heuristic algorithm is to establish Λ_{sd} lightpaths for (s, d) under the current utilization state of the network, given in the form of the wavelength availability vectors $BWAV_l$, for all l and the established lightpaths up to that point. The objective of the Aa-RWA heuristic algorithm is to minimize the number of lightpaths that interact with other lightpaths through intra- and inter- channel crosstalk and thus to minimize the propagation of high-power jamming signal attacks.

The wavelength utilization $BWAV_p$ of the candidate pre-calculated paths for the source-destination pair (s, d) is computed based on the $BWAV_l$ of the links. For each demand, the lightpath (p, w), from the set of candidate lightpaths with the smallest number of in-band and out-of-band channel interactions with the already established lightpaths, is chosen. To evaluate this, the wavelength availability vectors $BWAV_l$ are used to identify the interactions of established lightpaths. Then, the lightpath with the minimum sum of in-band and out-of-band channel interactions is established.

After establishing the lightpath (p, w), the corresponding $BWAV_l$ is updated. The algorithm at each step establishes a requested connection Λ_{sd}. If there are no available wavelengths, then the connection is blocked. Subsequently, the algorithm establishes lightpaths for all the connection requests in sequential order. The output of the algorithm is a set of established lightpaths in terms of paths and wavelengths. For each lightpath, the algorithm also returns two scalars that represent the number of inter-channel and the intra-channel interactions of this lightpath with the other established lightpaths.

6. Attack-aware routing and wavelength assignment under demand uncertainty for multi-period planning

As emphasized above, multi-period network planning is crucial in avoiding overprovisioning WSSs within hybrid nodes. As such, the aforementioned Aa-RWA algorithm is extended in this section to consider the demand forecasts of future time periods and in doing so to ensure that the WSS placement considers the changing network characteristics. In line with the most popular period-planning types available in the literature, the Aa-RWA algorithm is applied for both the incremental network planning case as well as the multi-period planning approach. In the former case, the Aa-RWA algorithm is applied in each step, the WSS placement for that step is decided, and the subsequent period considers the presence of those WSSs in the network when running the Aa-RWA algorithm for the next time period. In the multi-period approach on the other hand, the in-band and out-of-band interactions in each node are calculated for all time periods by the Aa-RWA algorithm and then statistical measures are used to assess the level of interaction and the extent to which a WSS is needed at a specific node.

In either case, the level of in-band and out-of-band interactions (and the subsequent decision on WSS placement) is strongly governed by the demand uncertainties and the assumptions made on growth year after year. The growth factor is assumed to be the mean value around a normally distributed random variable of the actual traffic growth between source destination pairs and thus Monte Carlo simulations are conducted to investigate the overall performance under independent trials. Details of the network setup and the exact values considered are detailed in Section 7.

6.1. Incremental Aa-RWA network planning

In incremental Aa-RWA network planning, there is knowledge for the demand distribution for only one period at a time (the period under consideration). For this reason, decisions

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are taken only for the current period. The flowchart of the proposed algorithm is given in **Figure 6**. The algorithm takes as input N independent sets of demands. For each one of the N sets, the algorithm solves the problem according to the deterministic Aa-RWA algorithm as presented in Section 5 and produces N outputs with metrics related to in-band and out-of-band interactions. These metrics associate two values for each input port of every network node. Specifically, these values count the number of lightpaths that interact though in-band and out-of-band crosstalk in the specific input port. Based on these values, the algorithm specifies the ports where WSSs should be placed. The assumption in this work is that in every period a maximum number of m WSSs can be placed due to budget constraints. The input ports where the WSSs are placed are chosen according to the maximum mean values of the in-band and out-of-band interactions. Subsequently, the output of each period contains the established lightpaths, and the next period takes as input the already established lightpaths and the placement of the WSSs from the previous period. The same procedure is followed for every period during the entire time horizon under consideration.

6.2. Multi-period Aa-RWA network planning

In multi-period Aa-RWA network planning, there is a priori knowledge for the demand distribution for all the time periods under consideration. Therefore, decisions are taken based on the traffic estimate for all time periods. The flowchart of the proposed algorithm is given in **Figure 7**. The algorithm takes as input N independent sets of demands for every one of the T periods (increasing over time based on a multiplicative factor as previously mentioned).

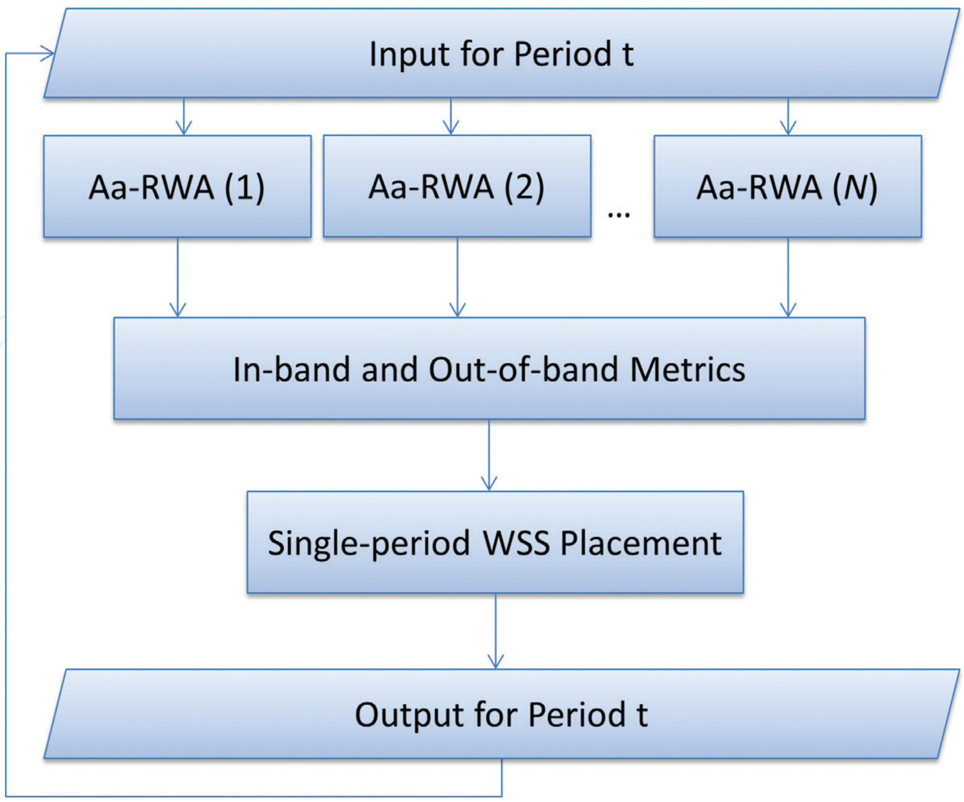

Figure 6. A flowchart of the incremental Aa-RWA algorithm.

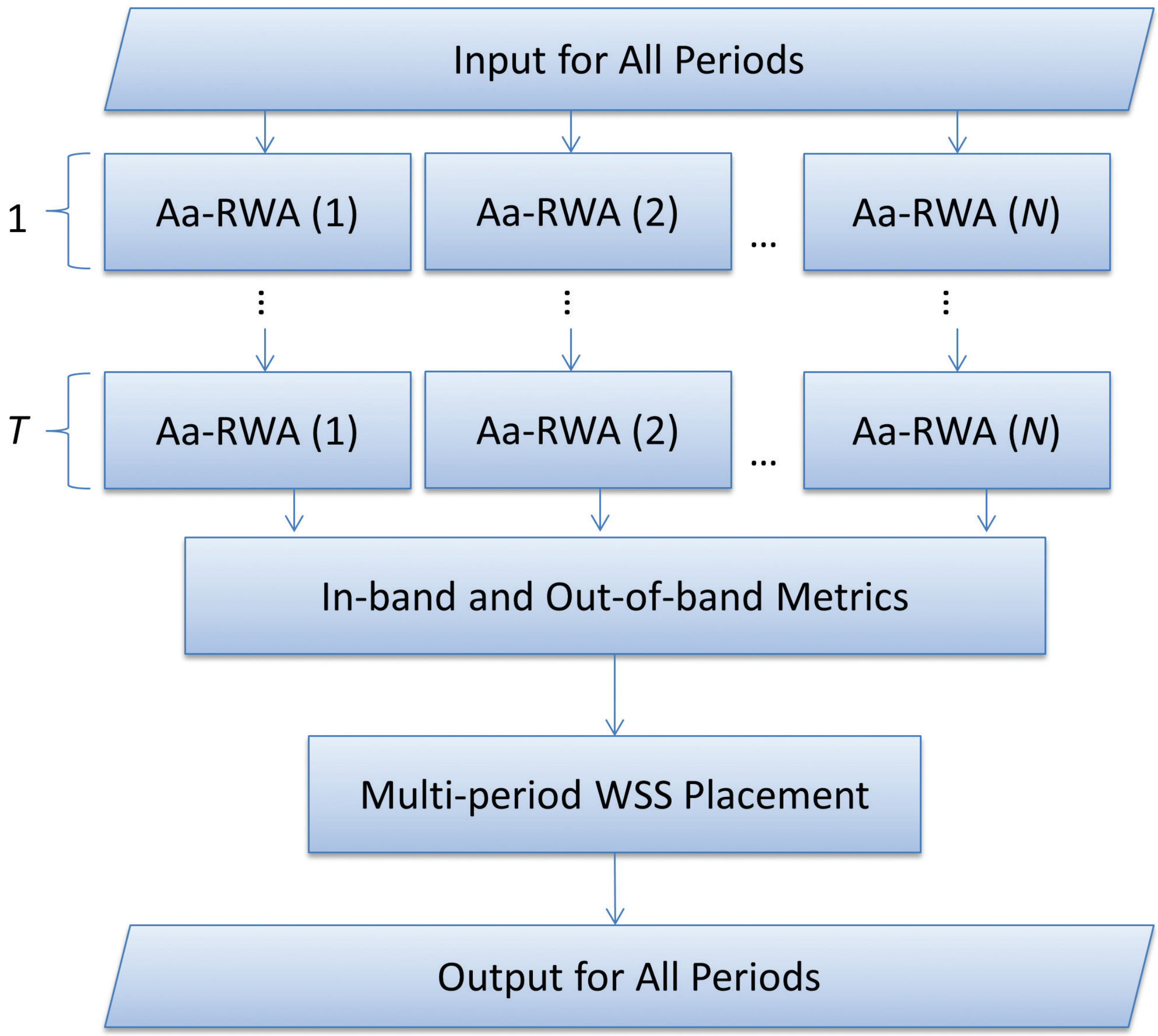

Figure 7. A flowchart of the multi-period Aa-RWA algorithm.

For each one of the N sets and for each time period, the algorithm solves the problem according to the deterministic Aa-RWA algorithm and produces $N*T$ outputs with metrics related to the in-band and out-of-band interactions. Based on these values, the "multi-period WSSs placement" module specifies the input ports and the time periods for the placement of the WSS. Again, the assumption is that in every period, a maximum number of m WSSs can be placed due to budget constraints. In this case, the placement of the WSSs is performed based on the maximum mean values of the in-band and out-of-band interactions over all instances and all periods.

7. Performance results

The network topology used in our simulations was the Geant-2 network topology [17] that has 34 nodes and 54 bidirectional links (108 fibers; shown in **Figure 8**). Each fiber is able to

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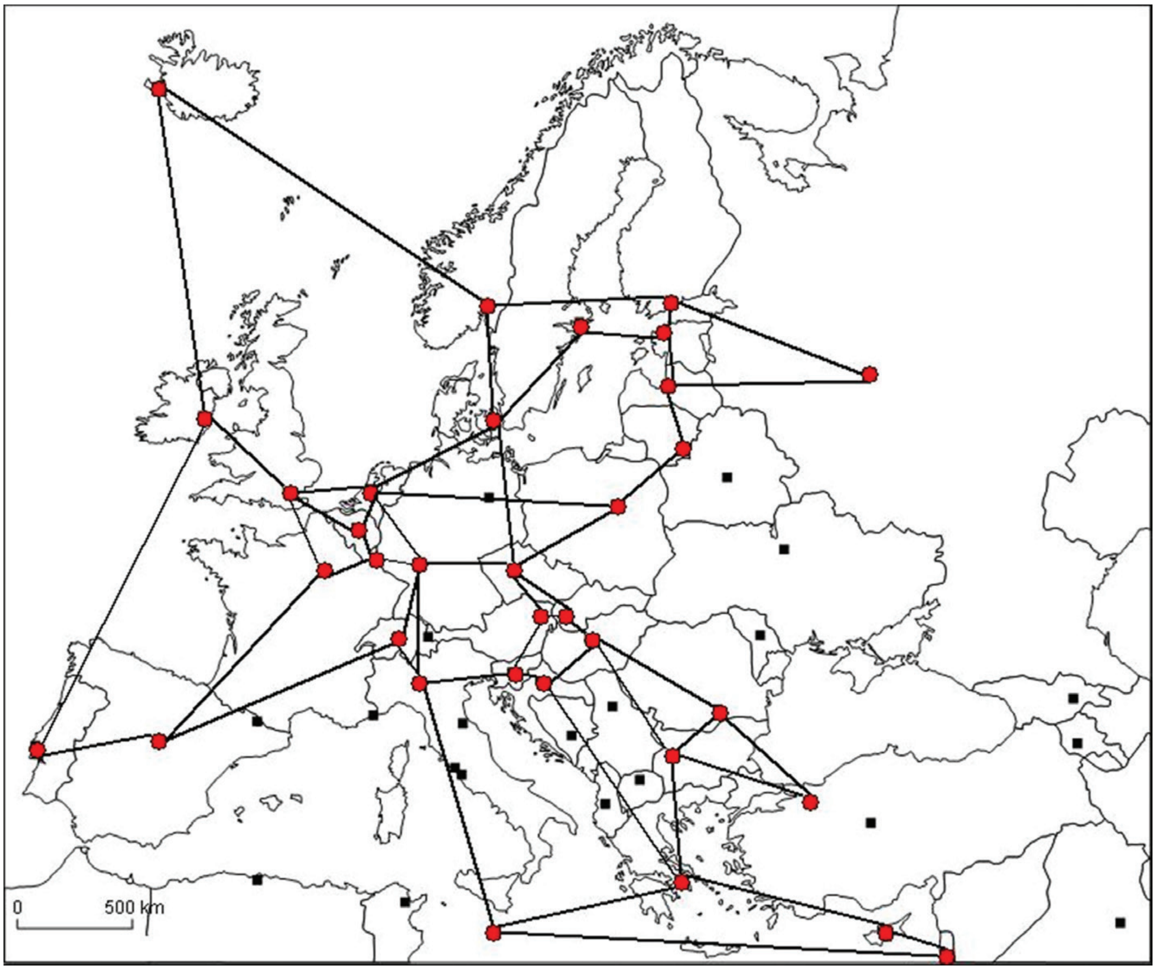

Figure 8. Geant-2 network topology: 34 nodes, 54 links.

support 80 wavelengths. The capacity of each wavelength was assumed equal to 10 Gbps. Initially, 50 different traffic matrices were produced with uniform distribution between source destination pairs and mean value equal to 1.35 Tbs of total requested capacity. Both algorithms (multi-period Aa-RWA and incremental Aa-RWA) were studied for five periods. The growth factor for each period was assumed to be equal to 1.5. The demand increase for each period applies for the source destination pairs that have a non-zero value at the initial traffic matrix. The algorithms for each source destination pair computed $k = 3$ alternative candidate paths.

In **Figure 9**, results for the multi-period Aa-RWA algorithm are depicted. Specifically, in **Figures 9(a)**, **(b)**, the mean values for inter-channel and intra-channel crosstalk for a horizon of five periods are presented, respectively. The mean values are the result of the 50 different traffic matrices. The inter-channel and intra-channel crosstalk per link (input port of a node) are the number of the interactions at this port. In **Figure 9**, the central mark of each box is the median, and the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points that are not considered outliers, and outliers are plotted individually.

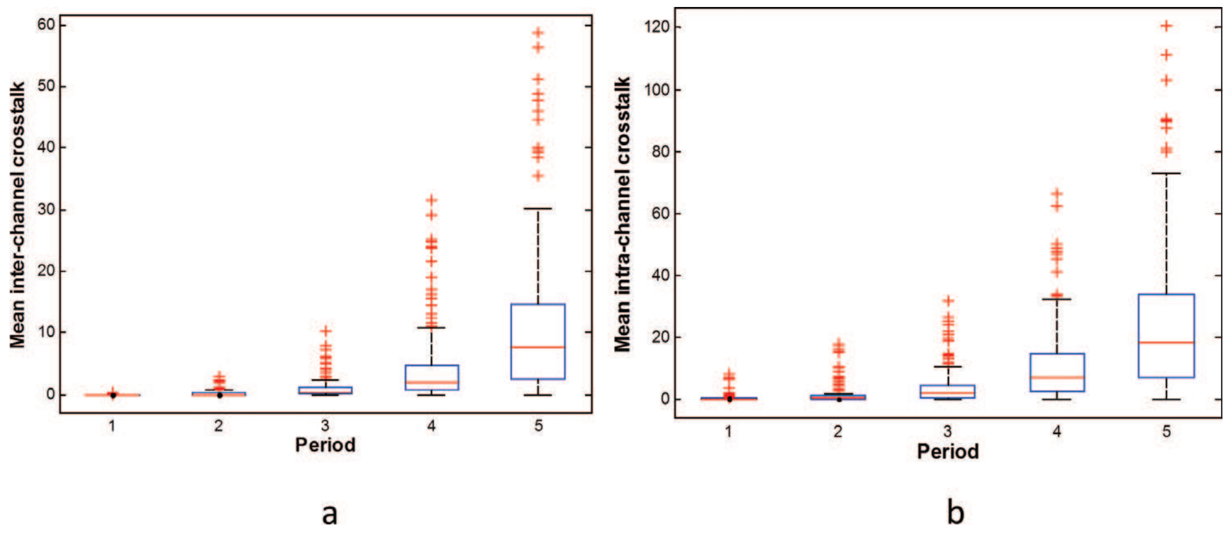

Figure 9. Mean values of multi-period Aa-RWA algorithm for (a) inter-channel crosstalk and (b) intra-channel crosstalk for a horizon of five periods.

Both inter- and intra-channel crosstalk increase exponentially with increasing traffic demands. However, as shown in **Figures 9(a)**, **(b)**, specific links experience significantly higher crosstalk than others. Therefore, the required WSSs can be placed only at the input ports of the nodes that experience high crosstalk.

Incremental Aa-RWA algorithm follows the same trend as the multi-period Aa-RWA algorithm (as illustrated in **Figure 10**). Note that the trend would be completely different in the case where an attack-unaware RWA algorithm was used. In that case, all the periods would experience high values of crosstalk as can be found from the results of [8]. These results are not presented here, since the scope of this chapter is to plan an optical network in order to deal with physical layer attacks and therefore an attack-unaware RWA algorithm is out of the scope of this study.

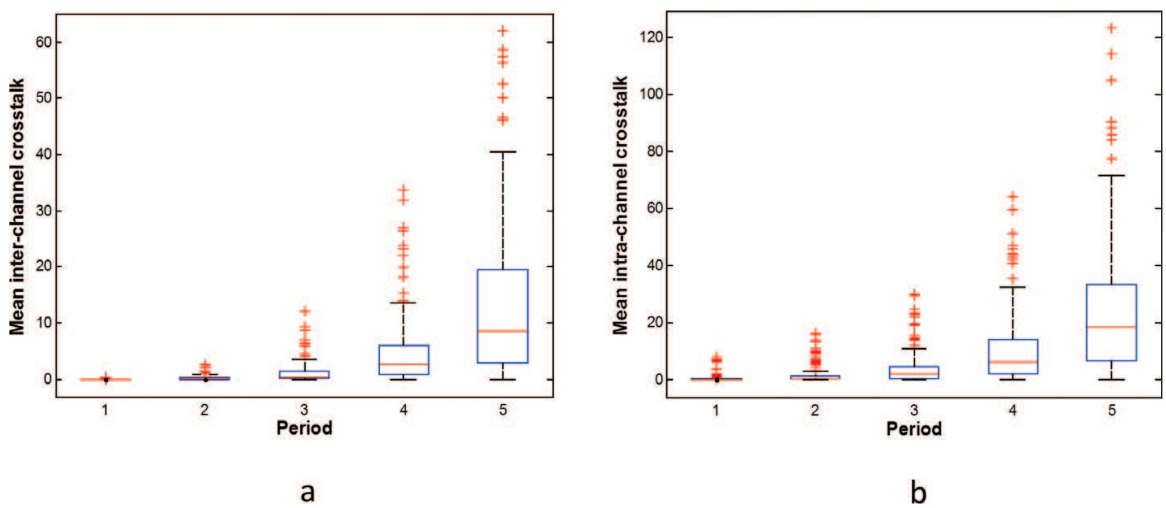

Figure 10. Mean values of incremental Aa-RWA algorithm for (a) inter-channel crosstalk and (b) intra-channel crosstalk for a horizon of five periods.

In **Figure 11**, the mean value of inter- and intra-channel crosstalk that the links experience during time period 5 is presented for the multi-period Aa-RWA algorithm. The results are presented in the form of histograms, where each column represents the number of links that have crosstalk between the ranges that are depicted in the x-axis of the histograms. From **Figure 11**, it is clear that a very small number of links have very high crosstalk, while the majority of links experience only a small crosstalk effect. This result offers a good indication that an addition of a small number of WSSs at the specific nodes where high crosstalk is experienced will significantly improve the performance of the network, thus minimizing the effect of a jamming attack. Note that the larger the number of links that appear in the leftmost bar, the smaller the crosstalk effect at the input ports of these nodes. Therefore, the best algorithms will be those where their histograms are more left shifted.

In **Figure 12**, the same histograms are presented for the case of the incremental Aa-RWA algorithm. Compared to the previous results of the multi-period case, the crosstalk effect of the incremental updating results to slightly increased inter-channel crosstalk and comparable intra-channel crosstalk. Nevertheless, the same crosstalk trends are observed here as well, where a small number of links experience significant crosstalk, while the rest of the links experience significantly lower crosstalk.

In **Figure 13**, the total number of required WSSs in order to minimize the impact of crosstalk effect per period is presented for the two proposed algorithms. For each period, the algorithms decide to place a WSS at the input port of a link when the mean values of the inter- and intra-channel crosstalk are above a certain threshold. Based on these decisions, the multi-period Aa-RWA algorithm requires less number of WSSs per period as compared to the incremental Aa-RWA algorithm. This is due to the fact the routing and wavelength assignment of the multi-period algorithm takes into account the future traffic demands, and the decisions are more appropriate. On the other hand, the incremental algorithm may decide to place a WSS in one period, and in future periods, there will be demands that would not be able to be established over already placed WSSs due to insufficient number of wavelengths. Thus, there would be not enough choices for efficient routing and wavelength assignment.

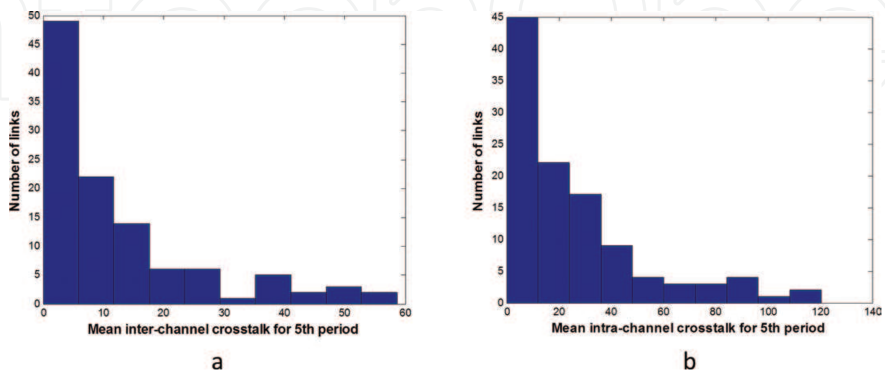

Figure 11. Histogram for link (input ports of nodes) distribution related to (a) inter-channel and (b) intra-channel crosstalk interactions for multi-period Aa-RWA algorithm for the fifth period.

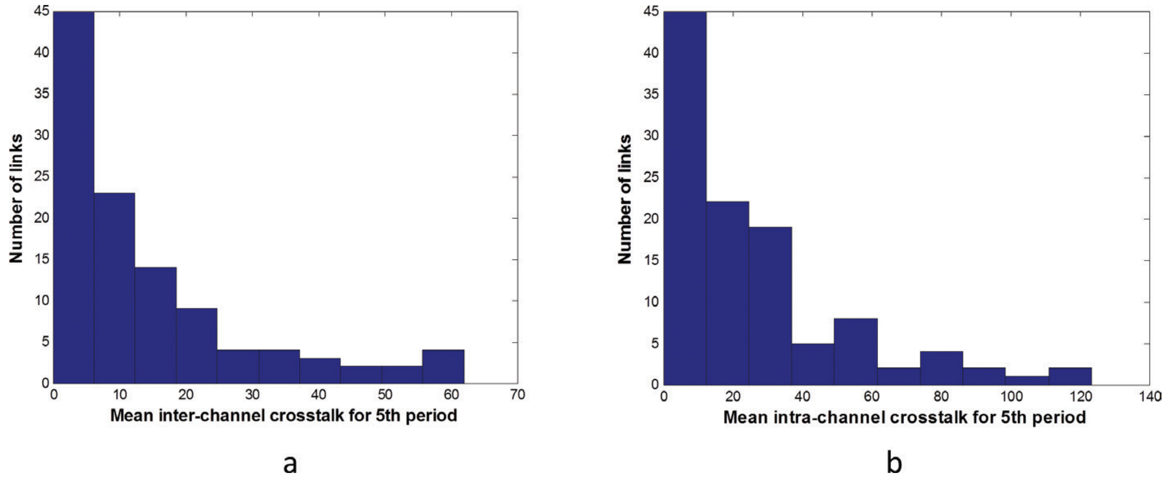

Figure 12. Histogram for link (input ports of nodes) distribution related to (a) inter-channel and (b) intra-channel crosstalk interactions for incremental Aa-RWA algorithm for the fifth period.

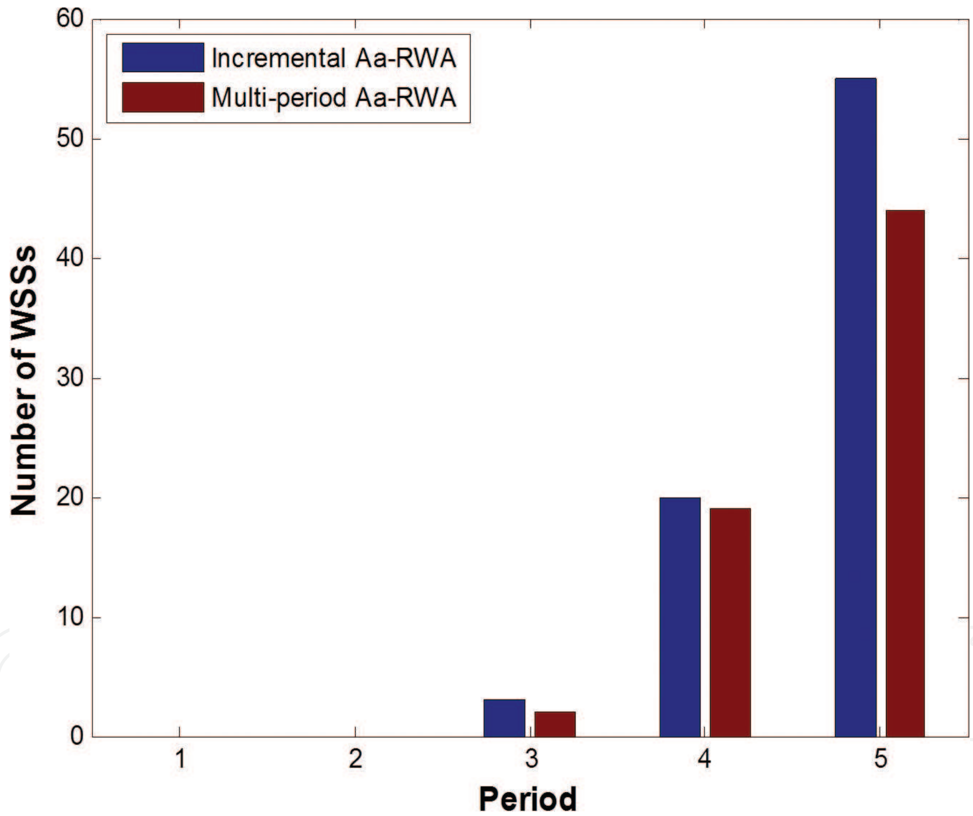

Figure 13. Number of required WSSs per period for the incremental Aa-RWA and the multi-period Aa-RWA algorithms.

8. Conclusions

This chapter proposed new attack-aware RWA algorithms for the multi-period planning of optical networks under demand uncertainty. These algorithms decide on the placement of wavelength selective switches at the input ports of network nodes and the period that the placement

http://dx.doi.org/10.5772/intechopen.68491

should be performed. The decisions are taken based on the distribution of the demands with the objective to minimize the impact of physical layer attacks over all periods. The algorithm that takes into account jointly all the time periods has a better performance than the algorithm that takes into account the periods in a sequential manner, resulting in a smaller number of required WSSs to be placed in the network so as to minimize the effect of a jamming attack.

Acknowledgements

This chapter is based upon work from COST Action CA15127 ("Resilient communication services protecting end user applications from disaster-based failures: RECODIS") supported by COST (European Cooperation in Science and Technology). This work has received funding from the People Program (Marie Curie Actions) of the European Union's Seventh Framework Program (FP7/2007–2013) under REA Grant Agreement n° 630853.

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