A framework for analyzing in-band crosstalk accumulation in ROADM-based optical networks

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Highlights

- A framework to analyze the in-band crosstalk accumulation in a network is proposed.
- An empirical formula is also derived for computing the number of crosstalk terms.
- Excellent agreement between the results of the framework and the empirical formula.

Abstract

Reconfigurable optical add-drop multiplexers (ROADMs) are central pieces in building transparent optical transport networks. However, due to physical limitations, these devices can be a source of in-band crosstalk, which affects the quality of the lightpaths routed and the network performance. Hence, to efficiently design optical networks it is important to study how this impairment is generated and to understand its dependency on relevant network parameters, such as the number of wavelengths used and the node degree. In this paper, we propose a framework to analyze the in-band crosstalk accumulation inside of ROADM-based networks. The framework computes the number of accumulated crosstalk terms in each link of a lightpath considering different physical topologies, as well as different routing and wavelength assignment strategies. An empirical formula is also derived for computing the maximum number of accumulated crosstalk terms as a function of the network parameters. We observe that in the majority of the studied cases, there is a complete agreement between the results of the proposed framework and the empirical formula.

Keywords

optical networks; in-band crosstalk; routing and wavelength assignment; reconfigurable optical add-drop multiplexer; contentionless degree.

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1. Introduction

In order to face with the constant increase in traffic demands and the widening variety of applications network operators must be able to increase the capacity of their transport infrastructure in a cost-effective way and at the same time enhance their flexibility in bandwidth usage to facilitate reconfigurability and automation [1].

Optical transparent networks can be seen as an appropriate platform to address these issues. In these networks, end-to-end optical connections (called lightpaths or optical channels) can be established over the network to avoid the expensive optical-electrical-optical conversions at the intermediate nodes. Each optical channel has its own wavelength, which is multiplexed in optical domain to form DWDM (dense wavelength division multiplexing) signals. Routing and wavelength assignment (RWA) is a fundamental problem in the context of designing optical transparent networks and involves two operations: (i) routing, which is responsible for finding the best path to be used by an optical channel, and (ii) wavelength assignment, which is responsible for choosing an appropriate wavelength to be used by the routed optical channel taking into account the wavelength continuity and the distinct wavelength constraints.

The reconfigurable optical add-drop multiplexer (ROADM) is a central piece of today's optical transport networks. This network element has the advantage of permitting the express optical channels, that are not directed to a node, to pass through it in the optical domain and at the same time enables the reconfiguration of the node remotely by software, adding flexibility to the optical layer. There are three important ROADM features that can be explored to design a flexible optical layer: colorless, directionless and contentionless (CDC) [2]. A ROADM is colorless if any wavelength can be assigned to any port in the add/drop module. A ROADM is directionless if any wavelength can be routed to any of the fibers (directions) served by the node. A ROADM is contentionless if the same wavelength can be used for different add/drop operations.

A key optical device to implement these features is the wavelength selective switch (WSS). This device is responsible for the ROADM dynamism, since it provides wavelength switching between its input/output fibers (or ports), with the interconnection pattern being changed by the control/management plane. The WSS is an analogue device, so its physical properties are important for characterizing the signal quality of the optical channels. One of these properties is the isolation level, which is defined as the ratio between the optical power of a selected optical channel and the leakage power of unselected channels [3]. In the presence of imperfect isolation, the originated leakage signals, usually known as crosstalk signals, will interfere with the primary signal at the receiver end, contributing to degrade the signal quality. This interference is particularly harmful when both the signal and interference have the same nominal wavelength leading to the in-band crosstalk [4], which accumulates as the optical signal propagates along the lightpath in a network. The impact of this impairment on system performance for ROADM-based networks has been widely analyzed in the literature at the physical layer level for different modulations formats, considering the dependence of crosstalk accumulation on the number of cascaded

ROADM nodes [3–6].

Another important aspect is to understand how in-band crosstalk accumulation influences network design. Numerous publications dealt with this issue, both in the context of dynamic networks [7–10] and in the context of static networks [11, 12]. Reference [11] is a seminal work in the area, but the node structure considered is a quite simple one and the analysis is only applied to ring networks. In [7] it was evaluated the blocking probability in the presence of physical impairments, like crosstalk, while [8] and [9] proposed crosstalk aware RWA algorithms to mitigate the crosstalk impact. The work in [12] also tried to reduce its impact by assigning spectrum in such a way that the number of optical channels that interfere in each node is minimum. In [10] a channel provisioning policy that takes into account the in-band crosstalk levels in order to decide the best transmission channel format and spectrum assignment to be used is developed. However, most of the referred works failed to present a detailed analysis of the origin of the in-band crosstalk inside of multi-degree ROADMs, preventing an adequate understanding of the dependency of the number of crosstalk terms on node parameters and CDC properties. The only exception is [10], but the analysis presented is only focused on CD ROADM architectures and the study is based on a particular RWA algorithm.

It is worth to note that the disposal of simple physical layer models is also important in the context of optical networks based on software defined networks (SDN) and optical networks with a Generalized Multi-Protocol Label Switching (GMPLS) control plane, in order to permit to network controllers to compute quickly the transmission quality of each lightpath and configure accordingly the network elements. An example of such networks is proposed in [13], in the context of cloud radio over fiber networks (C-RoFN), where the wireless network, the processing unit domain that provides the processing resources and cloud computing for users to accommodate the services, and the optical network are controlled by SDN controllers. In particular, in this work a physical layer model of the optical network, based on a reconfigurable radio-wavelength selective switch (RWSS) architecture, is considered with the respective RWA algorithm. Other works, in the area of spatial division multiplexing (SDM) networks, e.g. [14], are also considering physical layer models in the respective RWA algorithms, including for example the crosstalk between the fiber cores, to achieve a more efficient use of the network resources (e.g. spectrum, wavelength, fiber core).

The contribution of this work resides on a detailed modeling of the in-band crosstalk generation inside of multi-degree ROADMs in order to understand how its accumulation depends on the physical and logical topologies, on the node parameters, as well as on the routing and wavelength strategies used in the analysis. The proposed framework assumes that each node keeps a lightpath routing table (LRT) with information about all the added/dropped/expressed wavelengths at the node and the corresponding crosstalk terms generated. With this information the number of crosstalk terms, at the receiver end, in a given lightpath can be computed. In addition, an empirical formula, which permits to quantify this number of accumulated crosstalk terms as a function of the network topology parameters is also derived, and the results are compared with the ones obtained with the proposed framework. Note that by knowing this number the performance degradation in terms of the bit error rate can be easily evaluated by relying on an appropriate model that takes into account the impact of crosstalk on system performance evaluation (see for example [4], [15]).

The rest of the paper is organized in the following way: Section 2 describes the ROADM architecture that will be used in this study and Section 3 explains how the in-band crosstalk is generated inside a ROADM and studies its dependency on network topological parameters and RWA strategies. The framework proposed to compute the accumulation of the crosstalk terms along the lightpaths is presented and discussed in Section 4. In Section 5 the crosstalk accumulation is analyzed for various physical topologies, as well as different RWA algorithms, and the accuracy of the empirical formula is assessed. Finally, Section 6 concludes the paper.

2. ROADM architecture

The ROADM is the basic network element of optical transparent networks. This element adds/drops some of the wavelengths of a DWDM signal that require local processing, while the remaining wavelengths pass through it directly from input to output ports. The main devices used to build a ROADM are the WSSs, optical amplifiers, splitters and combiners. Fig.1 shows a basic architecture of a colorless and directionless (CD) ROADM, which is based on a broadcast-and-select architecture (B&S). Note that in this figure the optical amplifiers are not represented since they do not impact the crosstalk characteristics of the node. As can be seen this architecture can be divided into the input/output (I/O) and add/drop (A/D) sections. The I/O section includes a splitting stage that interconnects each input fiber port to all the other output fiber ports and to the drop section and a WSS second-stage that assembles the signals coming from every direction and from the add section and multiplexes them into the output fiber ports. The number of input ports are assumed to be identical to the number of output ports and this number defines the node degree (N_d).

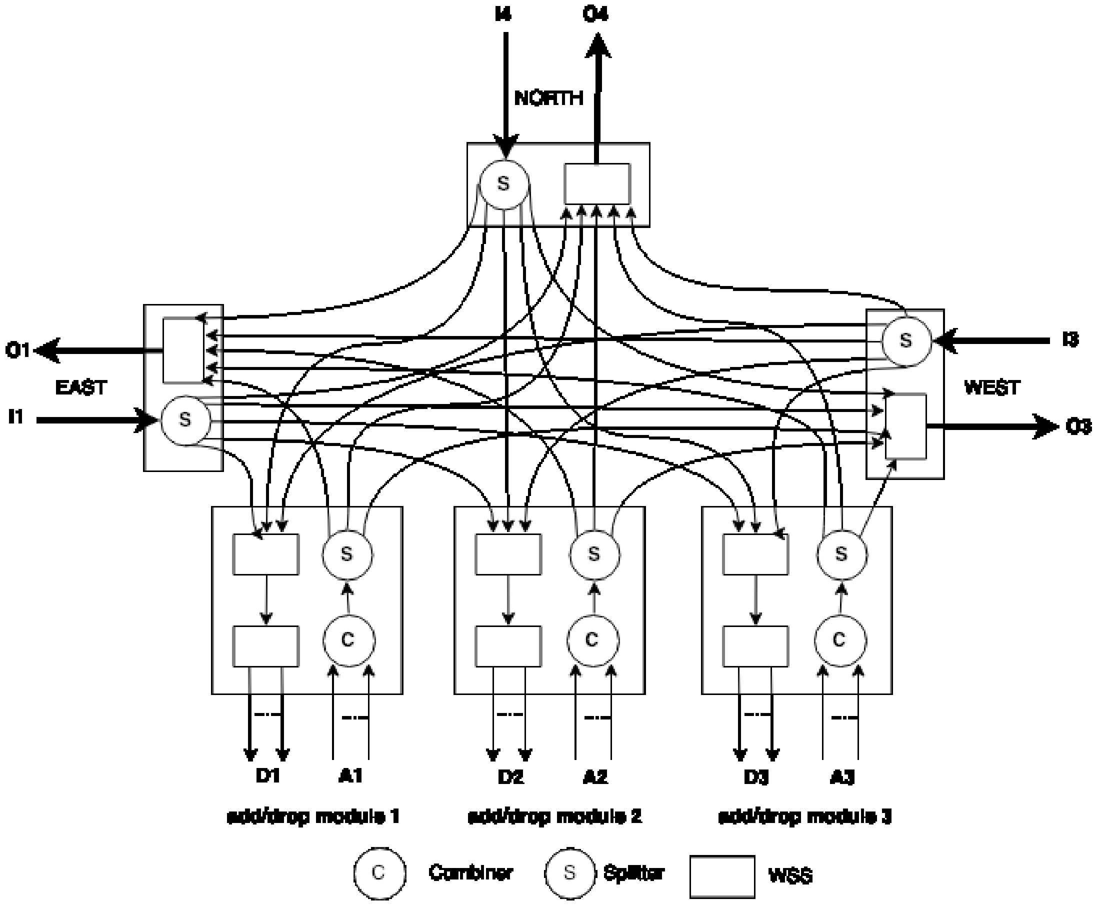


Fig. 1: B&S ROADM architecture with $N_d = 3$ and $C_d = 3$.

Furthermore, the add/drop section can comprise many add/drop modules, where each module includes a cascade of WSSs in the drop part and a set of splitter/combiners in the add part. The number of these modules defines the contentionless degree (C_d) [2]. As can be seen from Fig. 1 there are 3 add/drop modules, so the contentionless degree is equal to 3, *i.e.* $C_d = 3$. When C_d is equal to the number of directions, the ROADM turns out to be a CDC ROADM [16].

The route-and-select architecture (R&S), where the input splitter stages are replaced by WSS devices, is an alternative configuration that can be used to build ROADMs. This solution induces low crosstalk, but has the disadvantage of having higher complexity, cost and power consumption besides introducing a larger passband narrowing effect [17]. For these reasons, it will not be considered in this work.

3. Crosstalk modelling

To quantify the in-band crosstalk terms accumulated along a lightpath, it is important to understand how crosstalk terms are generated inside each ROADM node and then how these crosstalk terms are propagated along the lightpath, as it passes through a series of cascaded ROADMs. These aspects will be studied in this section, and an empirical formula, which quantifies the maximum number of accumulated crosstalk terms, will be also derived at the end of this section.

The crosstalk originated inside of ROADMs is due to the fact that WSS devices have an imperfect isolation, which gives rise to leakage signals known as crosstalk. The crosstalk can be classified as in-band, if the signal and the crosstalk have the same nominal wavelength, and out-of-band if the respective wavelengths are different. The latter type of crosstalk can be neglected because it can be filtered out by the transponders present at the drop port.

Figure 2 illustrates how these two types of crosstalk are generated inside a ROADM with N_d = 2. At the ROADM input in the West side, there are four optical channel signals with wavelengths λ_1, λ_2, λ_3 and λ_4 passing through a splitter. The signals with wavelengths λ_3 and λ_4 are dropped at the drop section while the optical signals with wavelength λ_1 and λ_2 are blocked by the WSS present in the drop section (see Fig. 1) originating out-of-band crosstalk terms. On the other hand, λ_1 and λ_2 pass-through the ROADM to the East output and the optical channels with wavelengths λ_3 and λ_4 are blocked by the output WSS. The leakage signals corresponding to these blocked wavelengths act as in-band crosstalk if in the Add Section signals with the same wavelengths are added, as happens in Fig. 2. Note that in Fig. 2 scenario only the wavelength λ_3 is added in the Add Section, so at the ROADM East output one in-band crosstalk term will accumulate along this signal.

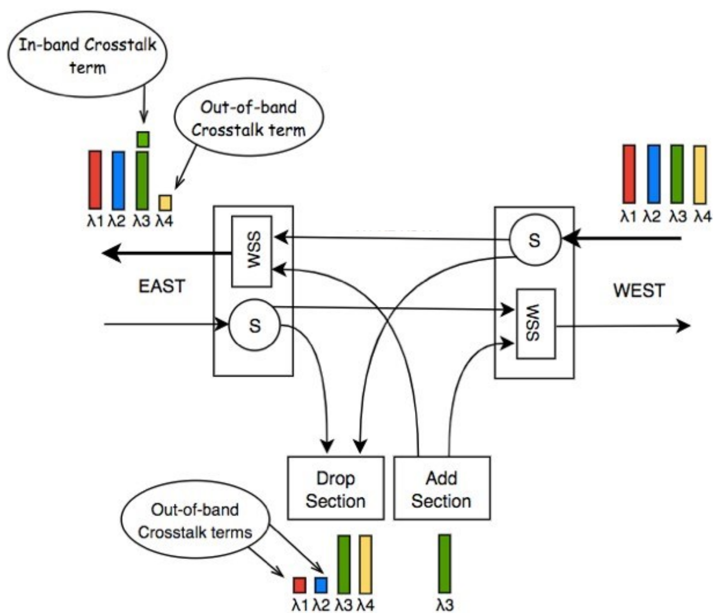


Fig. 2: Generation of in-band and out-of-band crosstalk terms inside a B&S ROADM architecture with N_d = 2.

Besides having a clear understanding of crosstalk origin, it is also important to study the dependency of the number of in-band crosstalk terms on network parameters like the contentionless degree C_d and the node degree N_d, as well as on the wavelength assignment strategy used. In order to do so, we consider a four-node network with a star physical topology that support a uniform traffic demand (*i.e.* a full mesh logical topology) with one unit of traffic between all the nodes, and we also consider that all the routes are obtained using a shortest-path algorithm. Furthermore, we consider two wavelength assignment (WA) strategies [18]: (i) first-fit WA (FFWA) with a shortest-first sorting strategy, whose results are depicted in Fig. 3; (ii) graph coloring WA (GCWA) using a greedy strategy (e.g. the coloring starts with the nodes with the highest degree), whose results are depicted in Fig. 4.

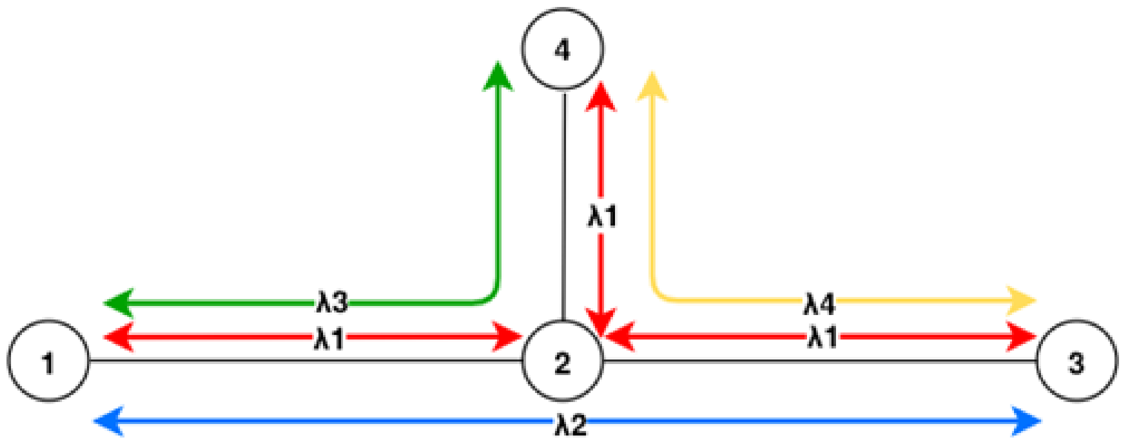


Fig. 3: FFWA strategy for a 4-node star physical topology with a full-mesh logical topology.

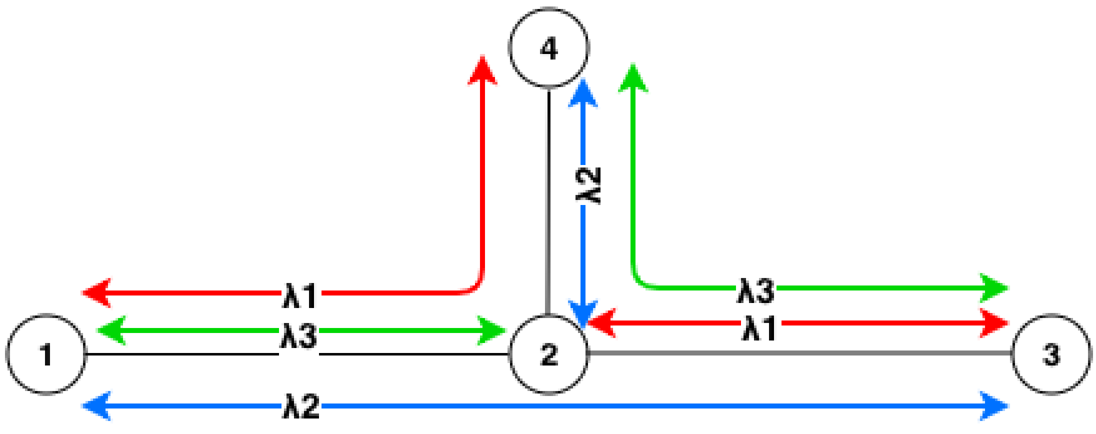


Fig. 4: GCWA strategy for a 4-node star physical topology with a full-mesh logical topology.

To understand how the crosstalk is generated in the 4-node star topology represented in Fig. 3, we will focus on Node 2, which is a 3-degree node, whose architecture is shown in Fig. 1. Fig. 5 shows the in-band crosstalk terms generated in this node for the FFWA strategy considering a worst-case scenario, which, in general, corresponds to wavelength patterns with the same wavelength presented in all the input modules or add/drop modules. To facilitate the analysis, we have represented the ROADM architecture in a different way from the one of Fig. 1: input/output sections are designated as Ik/Ok, where k is the node number that is physically connected from/to the node being considered, and Ai/Di are the add/drop modules, where i denotes the sequential order of the add/drop modules.

The worst-case scenario is considered since one of our goals, in this work, is to derive simple equations to describe the dependence of the number of accumulated in-band crosstalk terms on the network parameters. For example, in Node 2 of Fig. 3, represented in Fig. 5, wavelength λ_1 is present in all the input ports $I1$, $I3$, and $I4$, whereas the other wavelengths are only present in two of the input ports, making the wavelength λ_1 the worst-case scenario for express and drop operations. The same wavelength λ_1 is present in all three add modules (note that Node 2 has a contentionless degree, C_d, equal to 3), which also makes it a worst-case for the add operation. So, from Fig. 5, we can see that the dropped signals are affected by two in-band crosstalk terms that come from the other two directions, while the added signals, at the output ports, are affected by four in-band crosstalk terms, two terms come from the other two directions and the other two come from the add ports. The other output wavelengths different from λ_1 are express wavelengths and are not affected by in-band crosstalk.

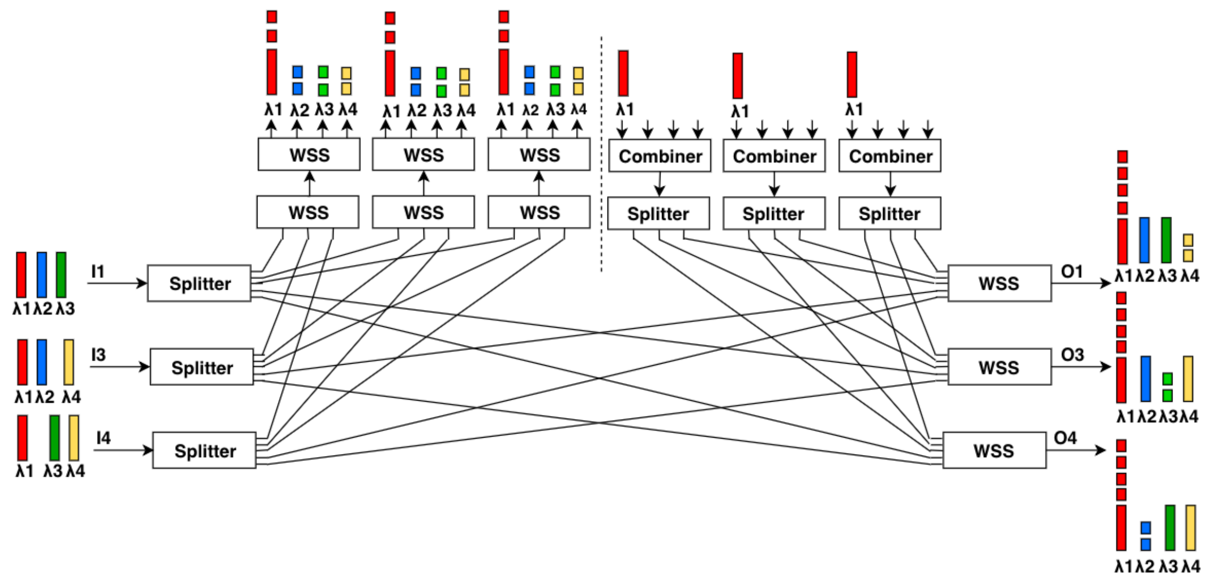


Fig. 5: Crosstalk generation inside Node 2 of the 4-node star network shown in Fig. 3.

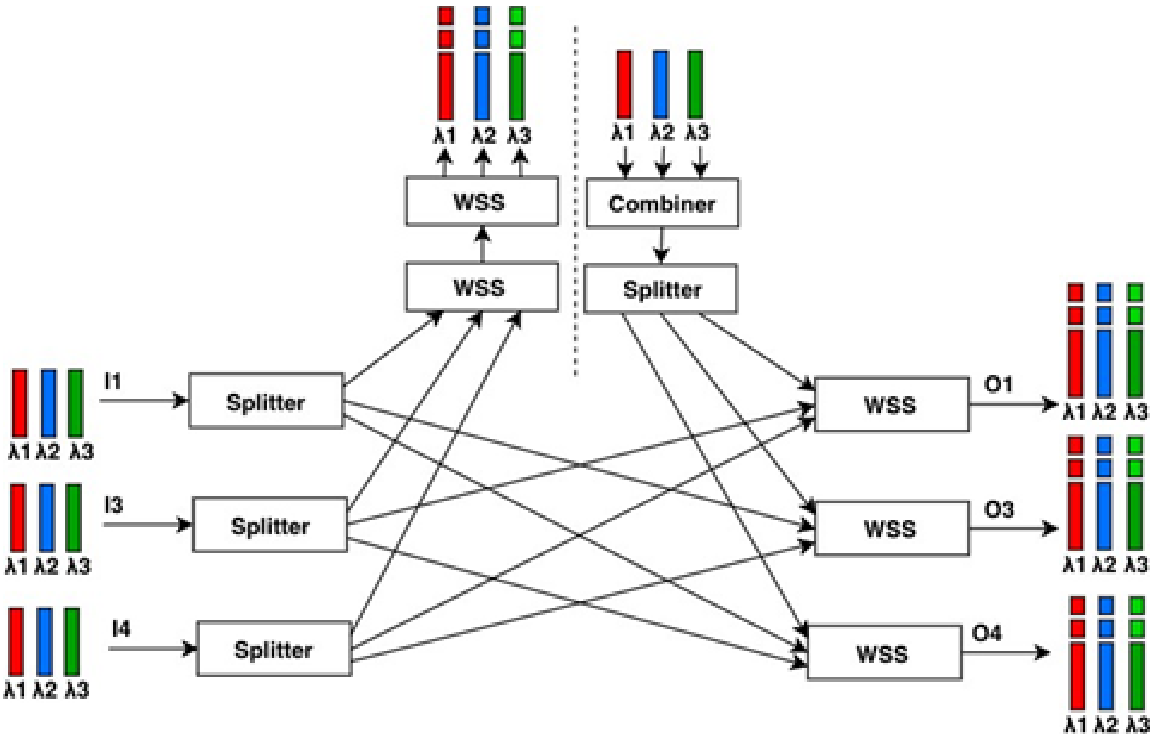


Fig. 6: Crosstalk generation inside Node 2 of the 4-node star network shown in Fig. 4.

Fig. 6 depicts again the ROADM architecture for Node 2 of the same 4-node star network given in Fig. 4, but showing the crosstalk terms generated when the GCWA strategy is used instead. The resulting WA for the GCWA strategy is illustrated in Fig. 4. In this case, it is not possible to identify a worst-case wavelength scenario, because all the used wavelengths are affected by crosstalk in the same way. Moreover, the GCWA strategy requires one less wavelength that the FFWA one and a contentionless degree equal to 1 instead of 3. As a consequence, as can be seen in Fig. 6, the added channels are impaired at the output ports by two crosstalk terms originated from the other two directions, at the drop side the dropped channels are impaired by two in-band crosstalk terms that also come from the other two directions, whereas the express signals at the ROADM outputs are affected by two crosstalk terms, one term coming from ROADM inputs and the other coming from the add operation.

Generalizing all the above results for a CDC ROADM with degree N_d and contentionless degree C_d, for the worst-case scenario, the following conclusions can be drawn: 1) the number of crosstalk terms on an add signal at the ROADM output is given by $(N_d - 1) + (C_d - 1)$; 2) the number of crosstalk terms on a drop signal is given by $(N_d - 1)$; and 3) the number of crosstalk terms on an express signal at the ROADM output is given by $(N_d - 2) + 1$.

Now, we are in conditions of computing the crosstalk accumulation in a generic lightpath, by just summing the crosstalk generated in each node of the lightpath. The worst-lightpath is the one with the highest number of accumulated crosstalk terms. It can be shown that the total number of accumulated crosstalk terms for the worst-lightpath is given by the following equation:

$$N_x = [(N_d(max) - 1) + (C_d(max) - 1)] + (D - 2) \times \left[\left(N_d(avg)\text{-}2\right) + 1\right] + \; [(N_d(max) - 1)], \quad (1)$$

where $N_d(avg)$ is the average node degree (round-up) in the network, $N_d(max)$ is the maximum node degree in the network, D is the number of nodes traversed by the worst-lightpath (*i.e.* the lightpath corresponding to the maximum in-band crosstalk terms accumulated), and $C_d(max)$ is the maximum value of C_d. The first term of Eq. (1) is the contribution of the add ROADM node, the second term is due to the express ROADMs and the last one results from the drop ROADM node. The express ROADMs contribution uses $N_d(avg)$ instead of $N_d(max)$ to account for the fact that not all the traversed nodes are worst-nodes, so it makes more sense to use average values. Furthermore, the term $(D - 2)$ arises to include all the nodes traversed by the worst-lightpath in the calculation, excluding the add and drop ROADM nodes, whereas (+1) term accounts for the possible presence of crosstalk terms originated in the add section. The accuracy of Eq. (1) will be evaluated in Section 5, for different network topologies and WA strategies.

A final note regarding Eq. (1) is that this equation remains valid if a R&S architecture is considered instead of the B&S architecture considered in this work [19]. Despite the number of interfering terms N_x remaining the same, the order of the interferers would change, in particular for the R&S architecture some of the interfering terms are of second order instead of first order, as happens for the B&S architecture, which makes the R&S architecture more robust to crosstalk [19].

4. Proposed framework to compute the number of crosstalk terms

In this section, we describe the framework proposed by the authors to compute the number of crosstalk terms accumulated along all the lightpaths established in a given network for a given RWA strategy.

The complete flowchart of the framework is shown in Fig. 7. As seen, it includes eight steps, whose functionalities will be detailed in the following text.

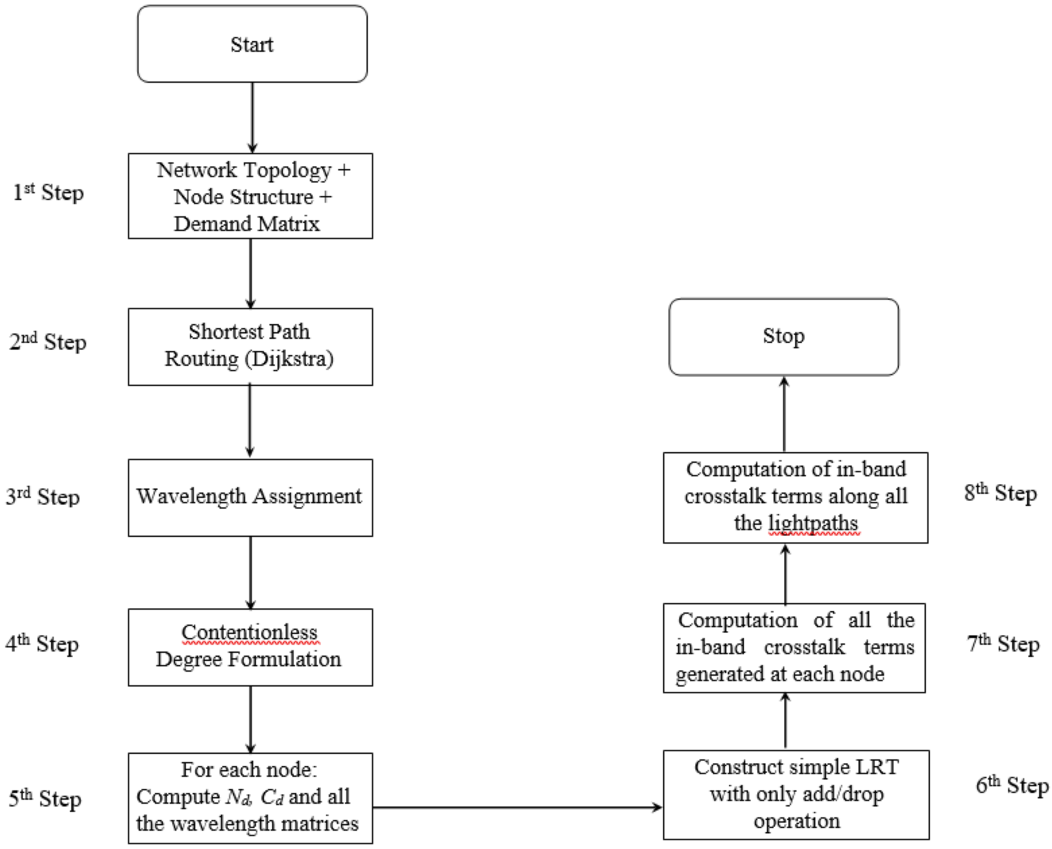


Fig. 7: Flowchart of the proposed framework to compute the accumulation of the in-band crosstalk terms.

In *Step 1* the input data and assumptions are provided as follows:

i. A description of the network topology through an undirected graph, where V denotes a set of N nodes (ROADMs) and E denotes a set of L optical links. Each link is assumed to be bidirectional meaning that it uses one optical fiber for transmission in one direction and another fiber for transmitting in the opposite direction. The ROADMs considered are based on a B&S architecture and use the number of add/drop modules adequate for CDC operation.

ii. A set of traffic demands which is described by a traffic matrix T. Each element of the matrix T_{ij} represents the number of traffic demands to be allocated between nodes i and j. In this work, we assume that there is only one traffic demand between each pair of nodes, *i.e.* $T_{ij} = 1, \forall i, j$ and $T_{ij} = 0$, for $i = j$. This scenario corresponds to a uniform traffic pattern also denoted as a full-mesh logical topology. The demands are expressed in terms of OTU4 units. OTU stands for Optical Transport Unit and is a standardized container to transport data payloads with data rates of about 100 Gb/s. As a consequence, each lightpath is accommodated by an optical channel with capacity equal to one OTU4 and supported in one wavelength.

In *Step 2* the appropriate lightpaths to route the traffic corresponding to the different demands are found. We have used the Dijkstra shortest-path algorithm considering two-cost metrics: the number of hops and the geographical distance (in km). The number of hops refers to the number of fiber links traversed by the path.

After computing the set of lightpaths corresponding to all traffic demands it is necessary to assign a single wavelength to each lightpath. This operation corresponds to *Step 3* and was carried out using FFWA and GCWA algorithms referred in Section 3. In the FFWA scheme, the order in which the wavelengths are assigned can impact the result, so it is important to define an adequate sorting strategy. In this work, we have assumed a shortest-first ordering strategy, *i.e.* the lightpaths with the lowest cost are assigned first. The application of the GCWA scheme involves the construction of an auxiliary graph *G(P,W)*, where P denotes the set of nodes, with each node corresponding to one of the computed lightpaths, and W is a set of edges between the nodes, having in mind that an edge between two nodes is only added if the corresponding lightpaths have common fiber links [18]. Then, the algorithm, using a greedy strategy, assigns a color (wavelength) to every node, so that adjacent nodes have different colors. In the greedy strategy considered the nodes with the highest degree appear first in the ordering list. This strategy was chosen because it offers a quite good compromise between accuracy and computation time [20].

The next step of the algorithm, *Step 4*, involves the implementation of the contentionless degree C_d of each node in order to guarantee a CDC operation in all the nodes.

In *Step 5* the contentionless degree C_d and the node degree N_d of each ROADM are computed. From the previous steps of the framework, all the lightpaths/wavelengths that are added/dropped/expressed at each node are known, so it is easy to compute the number of add/drop modules required to guarantee a contentionless operation, as well as the node degree. *Step 5* is also used to compute a set of matrices in order to compute the crosstalk accumulation along the network. With this goal in mind it is important to maintain lookup tables, named here lightpath routing tables (LRT), in each node with a detailed information about the crosstalk behavior of the node. As an intermediate stage to create these tables a number of wavelengths matrices has to be defined: the first matrix indicates what are the wavelengths used from each source node to all the corresponding destination nodes; the second matrix contains information about the wavelength usage in all the fiber links of the network; the third matrix details the set of wavelengths that are locally processed in each add/drop module of each node, bearing in mind that the number of these modules is equal to the contentionless degree; the fourth matrix specifies for each node which are the wavelengths added/dropped to/from the other nodes; the last matrix lists for each node the set of wavelengths that are express wavelengths, *i.e.* that pass-through the node without local processing.

By using all the information collected from the contentionless degree formulation and from all the wavelength matrices just defined it is possible to build a LRT for each network node, which is done in *Step 6*. The LRT provides information about the input/output ports, add/drop modules, wavelengths added/dropped/expressed with the corresponding crosstalk terms generated inside the node.

In order to give some insight in these tables Fig. 8 shows the LRT for Node 2 of the network represented in Fig. 3 (FFWA strategy). The first table corresponds to the drop section and has a number of columns equal to the number of drop modules and a number of lines equal to the number of inputs ports. Furthermore, each column is subdivided into three sub-columns. The first one indicates the wavelengths dropped (WL) at the drop module *Di*, the second one shows the crosstalk terms (XT) received at the same module and the third sub-column is for the number of in-band crosstalk terms (Inband) that impair the dropped signal. The second table of Fig. 8 corresponds to the output section where the number of columns of the second table of Fig. 8 is equal to the number of output ports and the number of lines is equal to the number of add modules plus the number of input ports. In this table WL indicates the wavelengths added or expressed. To understand how the tables are filled it is convenient to take into consideration Fig. 5. From this figure it can be seen that the input section has the ports *I*1, *I*3 and *I*4, the output section the ports *O*1, *O*3 and *O*4, while the add/drop section has the add module *A*1, *A*2 and *A*3 and the drop modules *D*1, *D*2, *D*3. It can also be observed that the wavelength λ_1 coming from *I*1 is dropped at *D*1, simultaneously with crosstalk terms λ_2 and λ_3. In the same way *I*3 contributes to *D*1 with the crosstalk terms λ_1, λ_2 and λ_4 while *I*4 contributes with the crosstalk terms λ_1, λ_3 and λ_4. Now, it is evident that the wavelength λ_1 at D1 is impaired by two in-band crosstalk terms because we have two interferers with the same wavelength as the dropped signal. This data permits to fill in the column *D*1 of the first table of Fig. 8. A similar reasoning helps us to understand how the LRT is built using the data from Fig. 4 (GCWA strategy).

Input Ports	D1			D2			D3		
	WL	XT	Inband	WL	XT	Inband	WL	XT	Inband
I1	λ1	λ2,λ3	2		λ1,λ2,λ3			λ1,λ2,λ3	
I3		λ1,λ2,λ4		λ1	λ2,λ4	2		λ1,λ2,λ4	
I4		λ1,λ3,λ4			λ1,λ3,λ4		λ1	λ3,λ4	2

Add Modules/ Input Ports	O1			O3			O4		
	WL	XT	Inband	WL	XT	Inband	WL	XT	Inband
A1	λ1		4		λ1			λ1	
A2		λ1		λ1		4		λ1	
A3		λ1			λ1		λ1		4
I1				λ2	λ1,λ3	0	λ3	λ1,λ2	0
I3	λ2	λ1,λ4	0				λ4	λ1,λ2	0
I4	λ3	λ1,λ4	0	λ4	λ1,λ3	0			

Fig. 8: LRT for Node 2 referenced to Figure 3 (FFWA strategy), where the first table corresponds to the drop section and the second one to the output section.

In *Step 7*, after computing the LRTs for all the nodes in the network, the proposed framework computes the number of crosstalk terms that are added by each ROADM as the lightpath propagates through a series of cascaded ROADMs.

Finally, in *Step 8*, the in-band crosstalk terms generated at each node in a lightpath are summed to compute the total in-band crosstalk terms generated along that lightpath.

5. Results and discussions

In this section, the results obtained with the framework described previously are analyzed considering two sets of physical network topologies. One set includes a number of real or planned topologies, and another set includes a number of regular topologies. The first set comprises the COST239 network (11 nodes, 26 links) [21], the Finland network (12 nodes, 19 links) [22], the NSFNET network (14 nodes, 21 links) [23], the EON network (19 nodes, 36 links) [21] and the UBN network (24 nodes, 42 links) [21]. The second set comprises star topologies (see Table 1) and other well-known regular topologies, described in Table 2. All the network nodes, with exception of the nodes with node degree equal to 1, are CDC ROADMs, which are designed with a number of add/drop modules equal to the contentionless degree. The nodes with a node degree equal to 1 are based on a simple WSS and work as a WDM multiplexer/demultiplexer device.

The pattern of connections is described by a uniform traffic demand model, with one unit of traffic (OTU4) per node pair. The demands are routed using the Dijkstra algorithm and, as referred two metrics have been considered: the number of hops and the geographical distance. Furthermore, we have used both the FFWA and GCWA strategies to assign wavelengths to the different lightpaths.

Figures 9 and 10 show histograms of the number of in-band crosstalk terms accumulated along the lightpaths for the COST239 network using the geographical distance in km (Fig. 9) and the number of hops (Fig. 10), for both FFWA and GCWA strategies. Figures 11 and 12 give the same type of information for the UBN network.

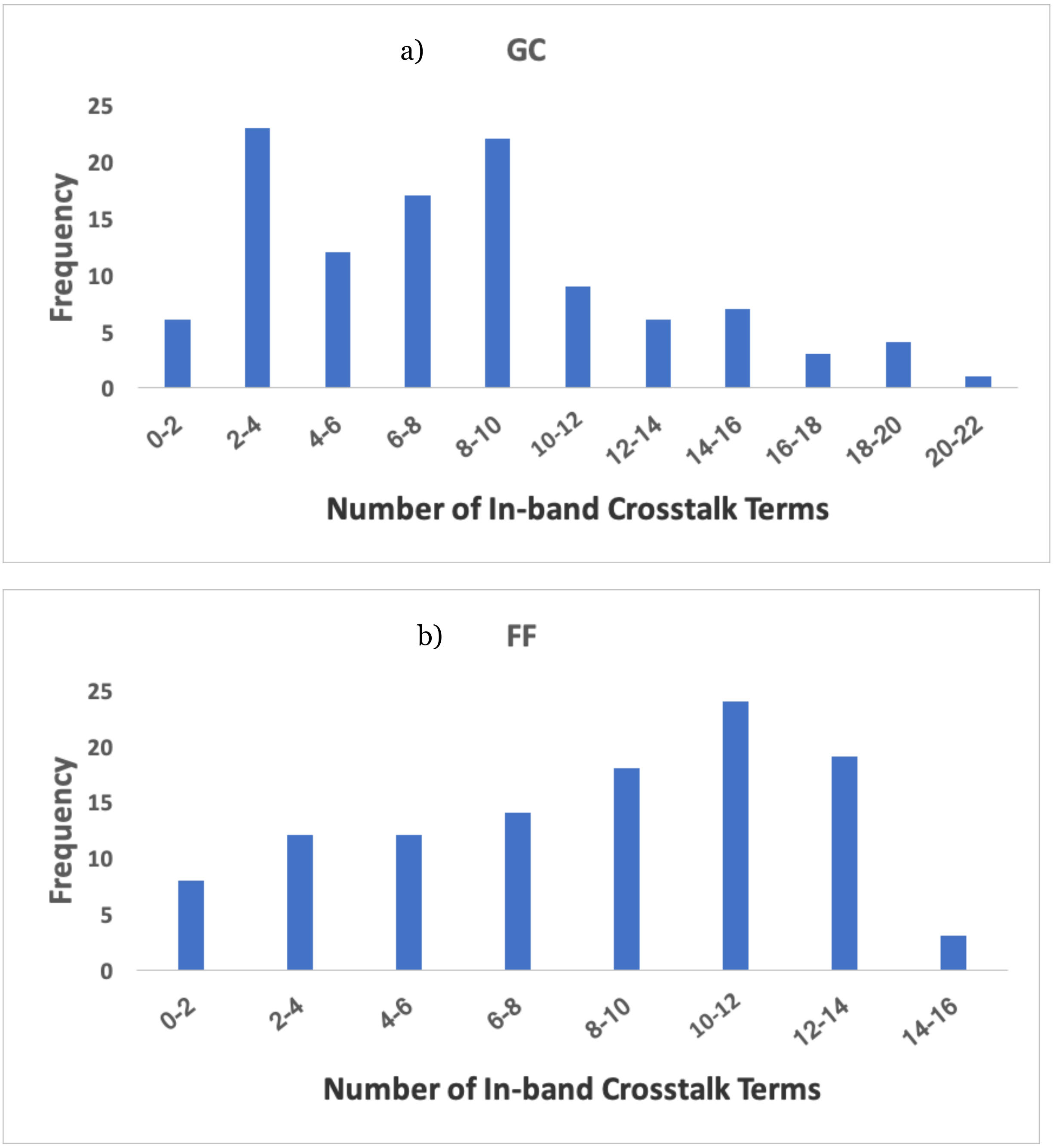
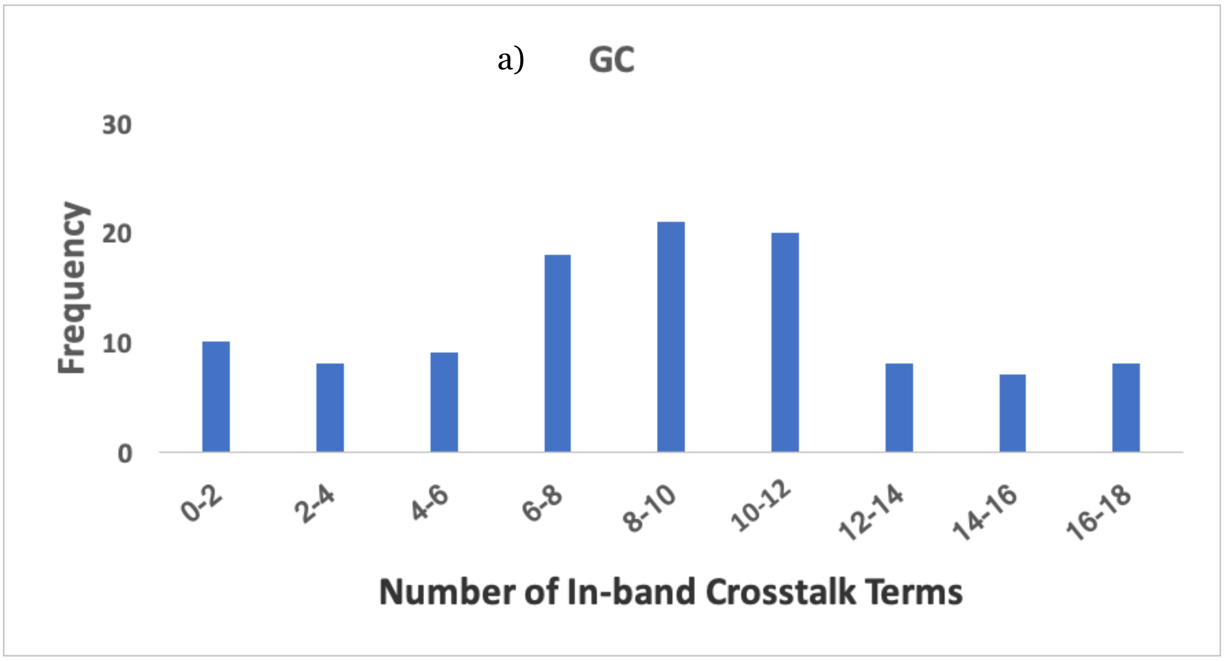


Fig. 9: Histograms for the number of in-band crosstalk terms accumulated per lightpath considering the COST239 network with the a) GCWA strategy; b) FFWA strategy. The metric used is the geographical distance.



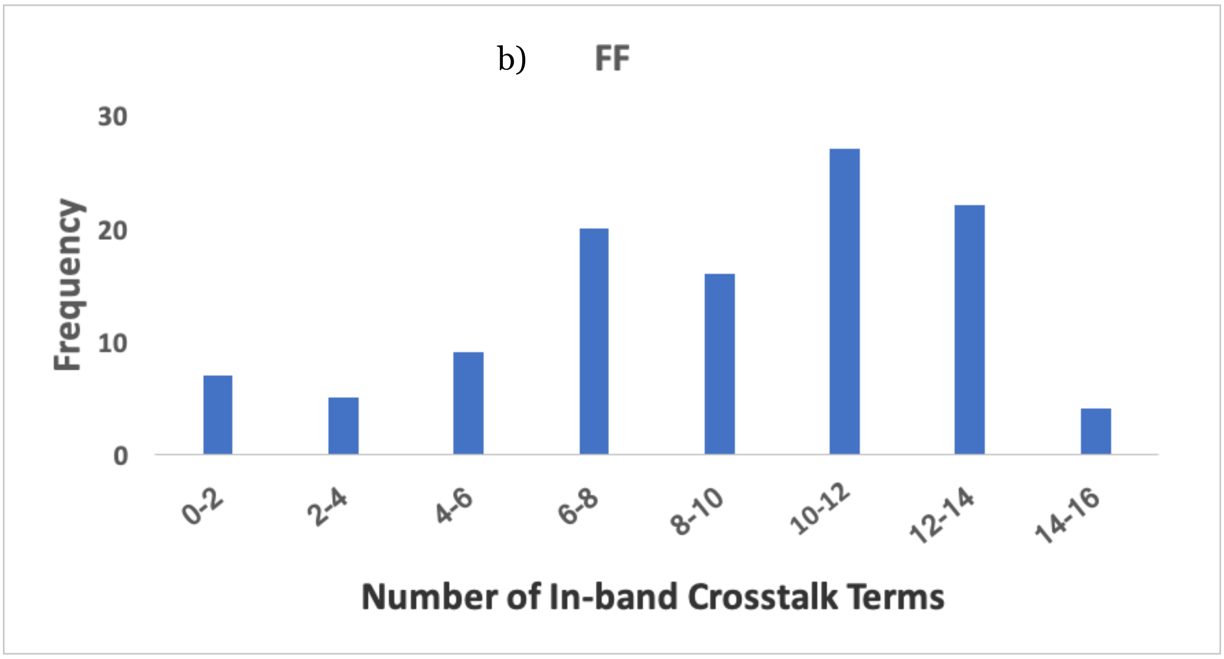


Fig. 10: Same as Fig. 9, but the metric used is the number of hops, instead of the geographical distance.

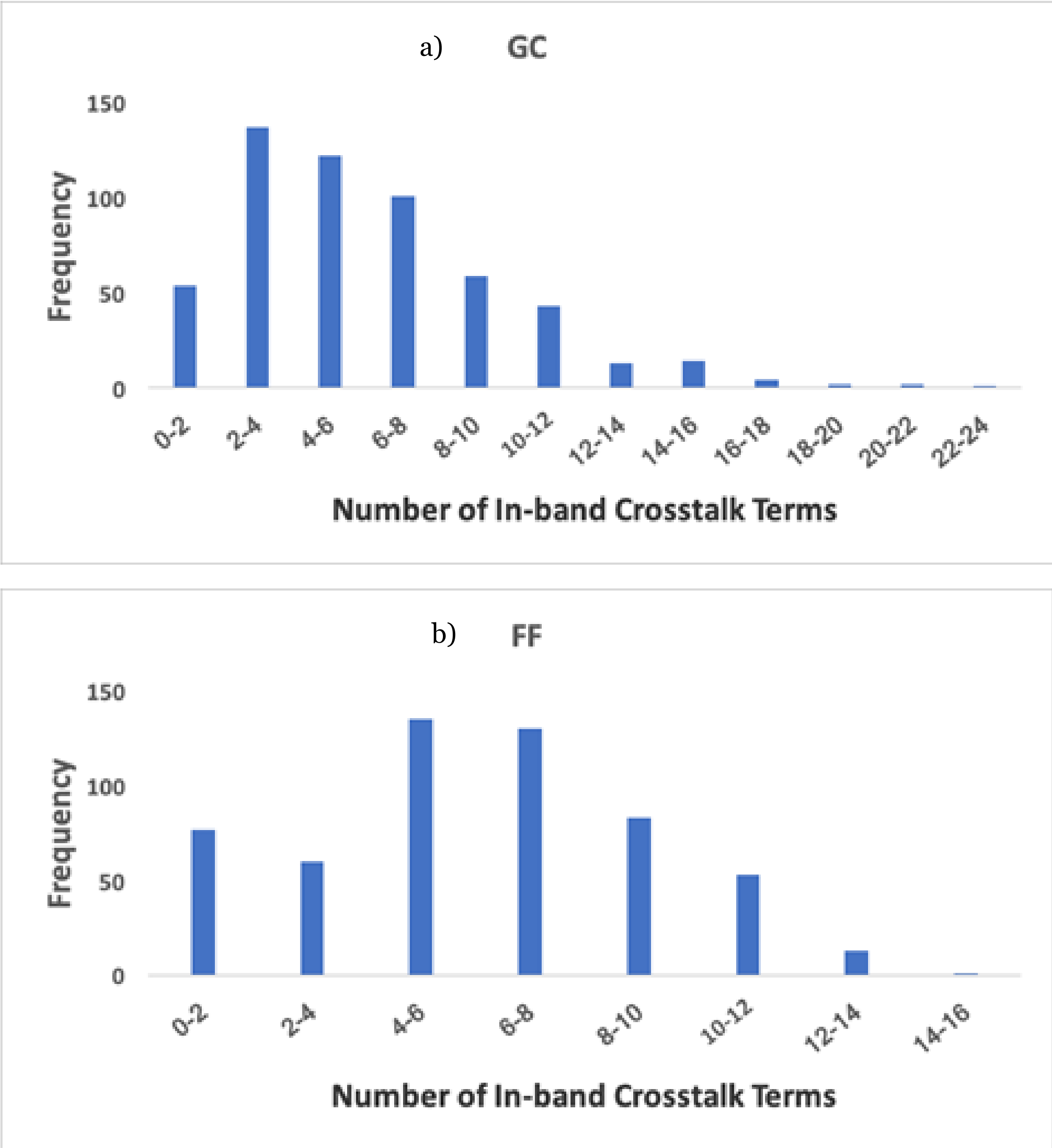


Fig. 11: Histograms for the number of in-band crosstalk terms accumulated per lightpath considering the UBN network with the a) GCWA strategy; b) FFWA strategy. The metric used is the geographical distance.

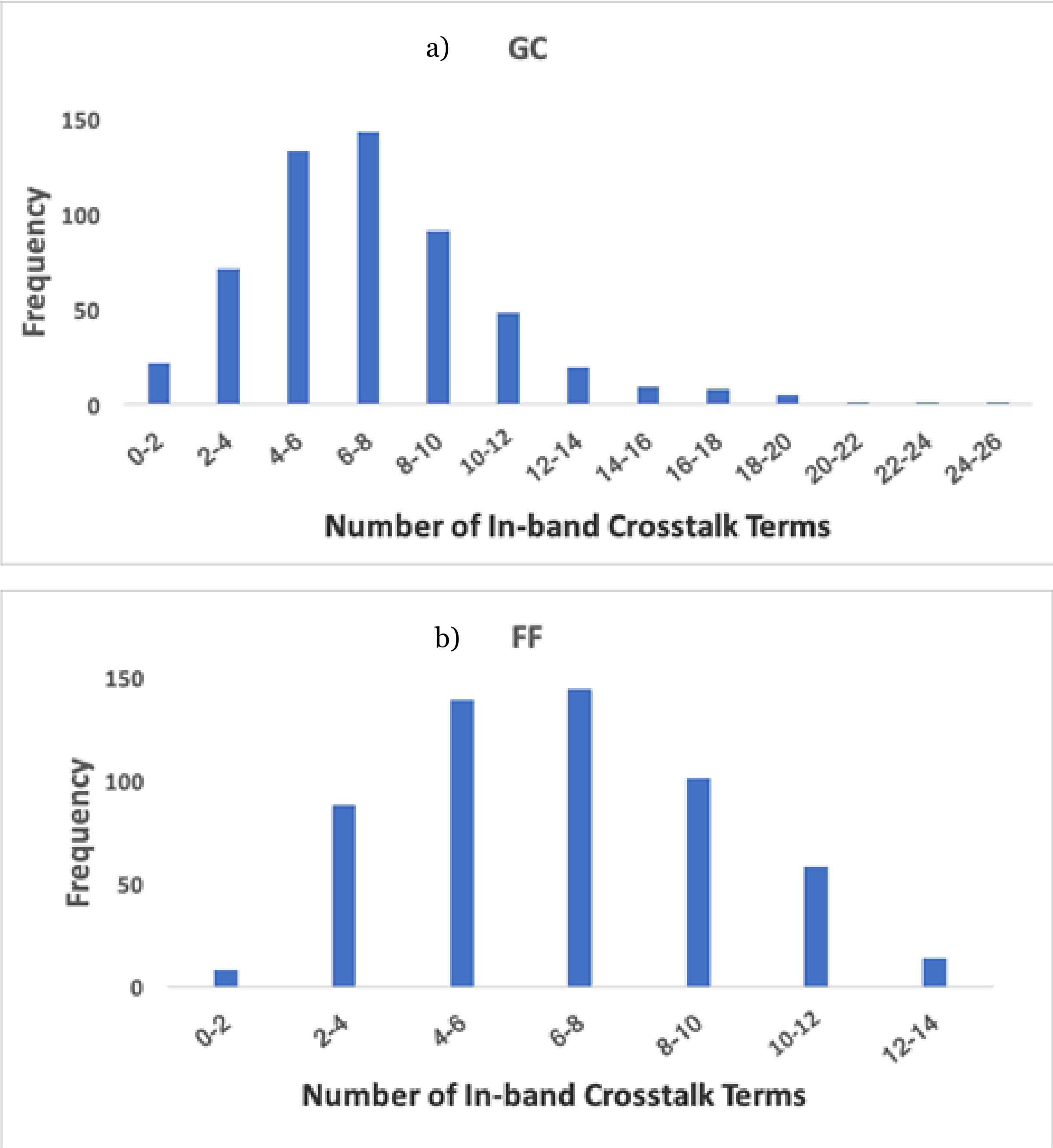


Fig. 12: Same as Fig. 11, but the metric used is the number of hops, instead of the geographical distance.

By comparing these figures, we can conclude that, despite the UBN network having a higher number of nodes than the COST239 network (24 nodes versus 11 nodes), the number of lightpaths with a higher number of accumulated crosstalk terms is larger for COST239 network than for the UBN network. This can be explained by noting that the COST239 network has an average node degree of 5, whereas in the UBN network this value is 4 (see Table 3), and a higher node degree indicates a higher number of crosstalk terms. Another conclusion we can get by comparing these figures is that the number of accumulated crosstalk terms per lightpath is quite dependable on the wavelength assignment strategy used. It can be observed that the use of the FFWA strategy leads to a lower number of crosstalk terms per lightpath than the GCWA one. This behavior is in part explained by the circumstance of the FFWA requiring in general more wavelengths than GCWA and when the number of wavelengths increases, the impact of crosstalk is less detrimental. In the limit we can always find a WA strategy that, by increasing the number of wavelengths, eliminates the crosstalk effect [12]. A final conclusion regarding the results of Figures 9 to 12 is related with the metric used in the routing process. We can see that its impact on the number of crosstalk terms per lightpath is not too significant. However, it influences the shape of the histograms, and in particular for the UBN network and the FFWA strategy, the metric based on the number of hops leads to a bell-shaped distribution, *i.e.* it reduces the number of terms at the borders and enhances the number of terms in the central part of the curve.

Another aspect that deserves to be investigated is the accuracy of the empirical formula – Eq. (1), presented in Section 3, to estimate the maximum number of in-band crosstalk terms per lightpath This can be done by comparing the results obtained with the proposed framework, presented in Section 4, with the results obtained with Eq. (1). The analysis was undertaken considering the metric based on the number-of-hops for the routing process and the physical network topologies referred at the beginning of this section, which can be categorized in the following scenarios:

1. Star networks, with increasing N_d *(max)* and constant N_d *(avg)*;
2. Regular networks, with all the nodes having the same N_d;
3. Real networks with variable N_d *(max)* and variable N_d *(avg)*.

The results corresponding to these scenarios are given in Tables 1, 2 and 3, respectively. These tables detail many parameters, like: total number of wavelengths (WL) used, node degree (N_d), maximum contentionless degree (C_d (*max*)), parameter D and the maximum number of in-band crosstalk terms per lightpath (Max In-band XT) computed using Eq. (1) and the proposed framework.

Table 1: Results from star networks with increasing N_d *(max)* and constant N_d *(avg)*.

Networks	WA	Total WL Used	Node Degree		C_d *(max)*	D	Max In-band XT along the Lightpath	
			N_d *(avg)*	N_d *(max)*			Framework	Eq. (1)
3-degree (N=4)	FF	4	2	3	3	2	6	6
	GC	3	2	3	1	3	6	6
4-degree (N=5)	FF	4	2	4	4	2	9	9
	GC	4	2	4	4	2	9	9
5-Degree (N=6)	FF	8	2	5	5	2	12	12
	GC	7	2	5	3	3	14	14
6-Degree (N=7)	FF	8	2	6	6	2	15	15
	GC	7	2	6	2	3	16	16

Table 2: Results from regular networks, with all the nodes having the same N_d.

Networks	WA	Total WL Used	N_d	C_d *(max)*	*D*	Max In-band XT along the Lightpath	
						Framework	Eq. (1)
Tetrahedral (N=4)	FF	1	3	3	2	6	6
	GC	1	3	3	2	6	6
Cubical-Graph (N=8)	FF	9	3	3	2	6	6
	GC	9	3	3	2	8	8
Truncated (N=12)	FF	13	3	3	3	8	8
	GC	11	3	3	4	10	10
Dodecahedral (N=20)	FF	31	3	3	4	10	10
	GC	27	3	3	5	12	12
Ring Network (N=24)	FF	91	2	2	2	3	3
	GC	78	2	2	2	3	3
Truncated-Octahedral (N=24)	FF	48	3	3	4	10	10
	GC	45	3	3	6	14	14
Small-Rhombicuboctahedral (N=24)	FF	37	4	4	4	14	15
	GC	37	4	4	6	21	21
Snub Graph (N=24)	FF	29	5	5	4	17	20
	GC	29	5	5	5	26	24

Table 3: Results from real networks with variable N_d *(max)* and variable N_d *(avg)*.

Networks	WA	Total WL Used	Node Degree		C_d *(max)*	*D*	Max In-band XT along the Lightpath	
			N_d *(avg)*	N_d *(max)*			Framework	Eq. (1)
COST239 (N=11)	FF	7	5	6	6	2	14	15
	GC	7	5	6	6	3	18	19
Finland (N=12)	FF	13	3	4	4	2	9	9
	GC	12	3	4	3	4	12	12
NSFNET (N=14)	FF	17	3	4	4	2	9	9
	GC	17	3	4	3	4	12	12
UBN (N=24)	FF	44	4	5	5	3	13	15
	GC	42	4	5	3	7	24	25
EON (N=24)	FF	30	4	7	7	2	18	18
	GC	29	4	7	4	6	23	27

Table 1 includes some aspects already referred in Section 3, for the networks shown in Figs. 3 and 4 (star network with 4 nodes), and evidences a complete agreement between the results from the empirical equation and the results from the proposed framework.

Table 2 is targeted for regular networks, which by definition are networks whose nodes have all the same node degree. Two sets of scenarios can be identified: (i) the number of nodes increases, and N_d is kept constant (equal to 3); (ii) the number of nodes is kept constant (equal to 24) and N_d increases. From the results of the first scenario, we can see that the number of accumulated crosstalk terms per lightpath increases with the number of nodes, since as the signal pass-through a greater number of nodes it is expected that the number of interferers increases. From the second set we can observe that for networks with the same size, the number of wavelengths required to accommodate the traffic demands decreases as the network node degree increases, a trend already referred in the literature [24], while the number of crosstalk terms per lightpath grows with the node degree. These results also confirm a feature referred before that the number of accumulated crosstalk terms are much more dependable on the node degree than on the network size. In this case, we can also see that there is an almost perfect agreement between the results from the empirical formula and the proposed framework. Small discrepancies are observed for the two networks with the highest node degrees, for which the worst-case empirical equation accuracy is about 82.3%.

The empirical equation also led to reasonable accurate results for the real networks, as reported in Table 3, although more discrepancies are observed for these networks. This is explained by noting that, as the network size increases the uncertainty of the empirical equation also increases, as it uses the N_d *(avg)* instead of considering the exact N_d of each node the lightpath traverses, which hampers the accuracy of the calculation. Nevertheless, even for the real networks with random N_d, the accuracy of the empirical equation is about 82.6%, and in the cases where the equation did not predict accurately, the error deviations are not very high as shown in Table 3.

The results from Tables 1 to 3 also show that, for some networks there is a significant difference in the number of crosstalk terms accumulated along the lightpath for the FFWA and GCWA strategies. This is because the FFWA strategy uses the shortest-path-first ordering strategy favoring the lightpaths with lower value of *D,* while the GCWA strategy favors the lighpaths with higher value of *D*. As an example, consider the UBN network, for which the maximum number of crosstalk terms per lightpath given by the proposed framework is, respectively, 13 and 24 for FFWA and GCWA strategies. This huge discrepancy is due to the fact that parameter *D* is, respectively, 3 and 7, for FFWA and GCWA strategies. The reason why FFWA strategy has a very low parameter *D*, even for a large network, like UBN, is because the parameter *D* is determined by the most used wavelengths in the network and FFWA strategy has a higher probability of assigning the most used wavelength to the shortest-path with fewer nodes, as FFWA strategy is sorted using shortest-first scheme.

As a final note, regarding the proposed framework complexity, we have assessed the computation time of some of the network scenarios discussed in Tables 2 and 3 and concluded that this time increases a little bit for networks with more nodes, e.g. UBN (around 40 seconds), and also increases for networks with more used wavelengths, e.g. Ring (around 50 seconds). The computation time was assessed in a PC with an Intel i7 @ 2.7 GHz processor and with an 8GB RAM. It is also worth to stress that our empirical analytical formula has an enormous advantage in terms of computation time in comparison with our proposed framework, and since it was shown that the results obtained with this formula are quite accurate for the majority of the studied cases we can use this equation results and save a lot of computation time.

6. Conclusion

In this paper we have dealt with the impact of in-band crosstalk terms in the design of ROADM-based networks. We have analyzed in a detailed way how this impairment is generated inside of the networks nodes and developed a framework to compute its accumulation along the established lightpaths, in order to understand its dependency on relevant network parameters, as well as on the routing and wavelength assignment strategies used. The obtained results showed that the routing process mainly influences the shape of the histograms of the number on in-band crosstalk terms per lightpath, while the wavelength assignment process has a deep impact on the number of accumulated crosstalk terms, with the GCWA strategy giving a higher number of terms than the FFWA one. Furthermore, we have obtained an empirical formula to compute the maximum number of accumulated crosstalk terms in the worst lightpath in terms of crosstalk accumulation and we have showed that this empirical formula is quite accurate in the majority of the studied cases.

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