Pluggable Optical Layer Optimization Algorithm for Mesh Networks

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***Abstract*—The access and edge metro networks traffic growth combined with the limitations of CapEx and OpEx, have led to the search for more cost-effective solutions, with smaller footprint and lower power consumption. This problem has led to the recent concept of disaggregation of optical layer elements and consequent interest in fixed and passive pluggable components instead of traditional reconfigurable structures (ROADM). Therefore, this paper proposes a routing and wavelength assignment method, adapted to the limitations imposed by these fixed components, and a filter selection method, responsible for choosing the best combination of pluggable filters, which minimizes the cost of the planned metro networks.**

These two methods are applied to a set of networks with different characteristics. For chain and ring networks was done a statistical analysis based on Monte Carlo method, while for the mesh networks two real metro networks using a set of typical metro region demands were designed. By comparing the results obtained using the proposed heuristic methods and using a reconfigurable solution to both analyzed scenarios, cost reductions superior to 45% are guaranteed.

***Index Terms*—Disaggregation, pluggable optical components, metro networks, RWA method, graph coloring, node architecture.**

I. Introduction

TODAY'S metro networks are experiencing tremendous traffic growth, caused by new application and service requirements, from cloud computing and video streaming, to significant increase in mobile data access. In the coming years, the expected increase in bandwidth of these services, combined with the imminent evolution of LTE to 5G, are not being matched by revenue growth. These factors have force network operators to support this traffic growth in a restricted CapEx and OpEx environment [1].

To solve this problem a recently introduced concept aims at disaggregating the full suite of optical layer components and functionalities into compact pluggable modules, that operators can mix and match according to their requirements. In this way, it is possible to customize each implementation without having to pay for unnecessary or undesirable functionalities. Switching or adding new components allow to extend network features while preserving the investment made in unchanged components. The objective is to provide a highly cost-effective solution, with small footprint, low power consumption and capable of scaling bandwidth in metro networks. Therefore, it is proposed the utilization of pluggable fixed filters, passive and low-cost components, instead of reconfigurable modules such as WSS. However, the strong interdependence between the demands' choice of paths and wavelengths and the consequent choice of suitable filters make the network planning a complicated task, poorly optimized and with a high error propensity, in particular for networks with mesh topologies [2].

This paper analyses the benefits and limitations introduced by the pluggable components, with special focus on the fixed filters and, based on identified constraints, proposes a Routing and Wavelength Assignment (RWA) method that, combined with a filter selection method, can be used to design complex metro networks with a high optimization level.

To evaluate the quality of the provided solution, the proposed methods were applied to a set of networks with different physical and logical topologies. For chain and ring networks there were performed a high number of random simulations and a statistical analysis of the results obtained was made based on Monte Carlo method. For mesh Networks were designed two real networks, with a set of typical metro region demands. At the end, the results were compared with the ones expected, obtained from the application of traditional RWA methods and from using a reconfigurable solution.

II. Benefits and Limitations of Pluggable Components

ROADM offers a flexible and future-proof solution with simplified planning and lower operational costs but introduces a higher upfront CapEx, a potentially larger footprint and higher power consumption. Using a set of active and passive components, like the pluggable amplifiers and DWDM fixed filters, it is possible to provide the best fit for metro access applications where low cost, small footprint and low power consumption are high priorities.

Fixed filter-based networks limit the channel availability since these components are designed to drop and pass through a group of specific channels. For simple network cases, these constrains are easily overcome but, for meshed applications, it turns the network planning more complex increasing the risk of choosing suboptimum and expensive solutions over the required one.

The fixed filter structures considered in this paper are composed by a band splitter that splits the input signal through the express port and the Add/drop filter ports, as shown Fig.1.

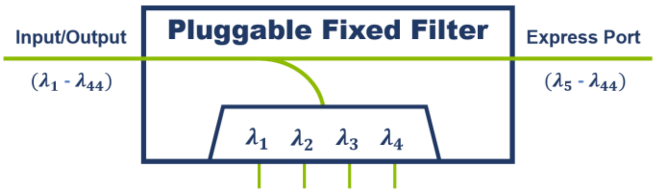

Fig. 1. Four channels DWDM pluggable fixed filter

The express port guarantees an optical express capability, creating an express path with lower losses, and allowing cascade solutions, connecting the first filter express port to the input/output port of the next filter. Thus, only the necessary channels are added or removed. However, it is necessary to take into account that the filters cascade introduce extra attenuation. Since channels will be inserted or removed in different degrees of the cascade, the attenuations of these channels will be different. This problem can lead to optical channel power imbalance and for this reason, in this paper, the cascading was limited up to 3 filters.

Since the filters have a single express port, each node direction can establish one and only one express link with another direction of the node. For that reason, the number of express connections that can be established is limited and if a node direction needs to perform more than one express connection, it is said that exist, at least, one invalid express connection. This problem will influence the routing method.

Since the number of filters that can be combined in cascade is limited, the assignment of wavelengths must be such that there is a combination of filters, capable of adding / removing all desired channels in a given direction of the node without, thereby, blocking channels that should be passed by the express links.

The channels that cannot be passed by the filter express port, should be removed, regenerated and re added. This process is called Drop & Re-add with regeneration and its application for invalid express links and for unduly removed channels is illustrated in Fig. 2. Alternatively, the node direction where express connection has been blocked can be changed to a ROADM direction.

Since it is not intended to use WSS directions, the problem of channel power equalization may be overcome by using electronic variable optical attenuators (EVOAs) however, this and other topics related with optical propagation are not covered in this research work.

III. RWA For Pluggable Optical Networks

In this paper, the possibility of use wavelength converters is not considered. In this case, the network planning requires dealing with the distinct wavelength constraint, which defines that all lightpaths using the same links must have different wavelengths assigned, and with the wavelength-continuity constrain, which defines that a lightpath would occupy the same wavelength on all fiber links through which it passes [3]. For each demand, it is necessary to determine the lightpath between the source and destination nodes and assign a valid wavelength. Since the planning is done using fixed filters, the traffic must be known until the network end of life. A complex RWA

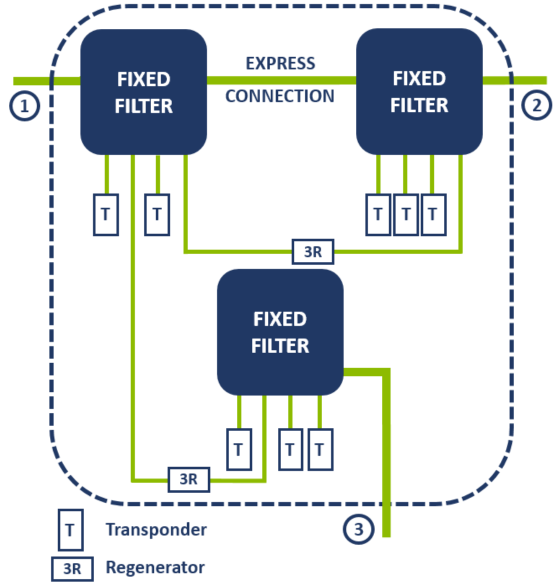

Fig. 2. Scenario with an invalid express connection needed between direction 1 and 3, and with one unduly removed channel between direction 1 and 2. Both of the cases were solved using Drop & Re-add with regeneration

problem can be divided into two smaller sub problems, (1) routing and (2) wavelength assignment, and each sub problem can be solved separately, in an efficient way [4].

A. *Heuristic Routing Method*

The routing problem for networks with simpler topologies, such as chain or ring, is easy to solve. For chain networks, regardless of the demands that need to be routed, there is one and only one path that can be assigned. For ring networks, since all nodes in the network have degree 2, regardless of the routing method chosen, an invalid express connection will never be defined. In this type of networks, demands must be routed by the shortest path. If both existent paths have the same length, the one with the least loaded path must be chosen to ensure the traffic balancing. The order in which the demands are routed is defined by the shortest-first metric.

However, for mesh networks these methods do not lead to efficient results. Due to the unequaled nature of the solution, fixed filter based networks limit the number of express directions that can be establish in a node. Therefore, it is preferable to choose a longer path that goes through an existing express connection, instead of choosing a shorter path that requires a new express direction. Therefore, the concept consists in limiting the creation of new express directions and reusing the existing ones.

An example of the suggested routing methodology is shown in Fig. 3. In this example, a new path needs to be created between nodes 1 and 3, knowing that the green paths are already routed. It is preferable to choose the longest path (red) that reuses an express direction, instead of using the shortest path (red dash) which creates a new express direction.

Based on the presented methodology, the following heuristic routing method is proposed for mesh networks:

1. Calculate the shortest-path for each demand.
2. Route by the shortest-path, demands with one hop paths.

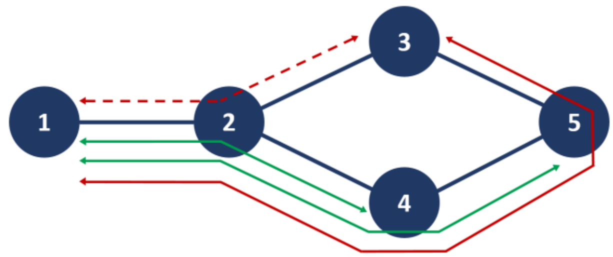

Fig. 3. Routing Method application

3. For the remaining demands determine the 3-shortest-path and calculate the number of hops of each path;
4. The paths that are composed only by intermediate nodes with two directions must be assigned to their demands;

For the demands to be routed:

5. Order the demands, taking into account the number of hops of each path, prioritizing demands where there is a greater difference.
6. While there are demands for routing:
    a. Count for each path of the highest priority demand, the number of express connections that need to be made, identifying if there are new express connections (not yet defined) and/or invalid express directions.
    b. If there is any path that does not need to create new express connections:
        i. Route the demand along this path;
    c. Else, if there are paths that do not create invalid express directions:
        i. Route the demand by the shortest path with fewer express connections;
    d. Else:
        i. Determine the 6-shortest-path and repeat the points a. and b. for the new paths;
    e. If the demand has not yet been routed:
        i. Choose the shortest path where a smaller number of invalid Express connections are defined;
    f. Update the list of already defined express connections;
    g. Advance to next demand.

Another challenge in fixed filter based network is to guarantee network protection. Different degrees of protection against failures need to be considered. Link protection can be provided by reserving a backup path that doesn't share any common links with the primary lightpath, also referred as link-disjoint. To further protection against node failures, the primary and the backup lightpaths may also be node disjoint. Regardless of the type of protection, the backup lightpath must be routed using the methodology presented here, with the condition that the protection paths are routed only after all primary paths have been defined.

B. *Heuristic Wavelength Assignment Method*

For the wavelength assignment problem, a heuristic algorithm based on dynamic *graph-coloring* is proposed. Like in the traditional graph-coloring approach, described in [3] [4], an auxiliary graph G'(V, E) is used to identify the interdependence between the demands. Each network lightpath is represented by a node of the graph G' and an undirected edge between two nodes is created if the corresponding lightpaths share a common physical fiber link. After the graph construction, the multiple nodes must be colored, always ensuring that two adjacent nodes do not have the same color.

In order to create a computationally efficient heuristic model, an adaptive sequential coloring approach is proposed, in which the choice of the next node to be colored is performed in a dynamic way, applying the *Largest number of colored neighbor-first* (LNCN) metric, with highest priority given to nodes with a larger number of already colored neighbors. In each iteration, a new node is colored and the priority demands list must be reordered. This is called the Dsatur Algorithm and was described for the first time in [6], in a graph theory environment.

In order to adopt this algorithm to the optical networks context, some modifications are required. In case of equal priority in the demands list, the metrics *Largest number of neighbor-first* (LNN), *Longest-first* (Lon) and *Largest-first* (Lar) must be adopted, in this order. If a demand is composed by more than one channel, the wavelengths must be assigned simultaneously. For single or multichannel demands, wavelengths should be assigned using an adaptation of the *First-fit* selection rule, where first wavelength to be assigned to each demand must also correspond to the first wavelength of one of the available filters. Thus, regardless of the available filters it is possible to avoid that wavelengths that need to be passed by express are unduly removed at the intermediate node of the path. An example with the proposed selection rule application is shown in Fig. 4, considering that 1-channel filters are not available. Another selection rules are presented in [4] and [5].

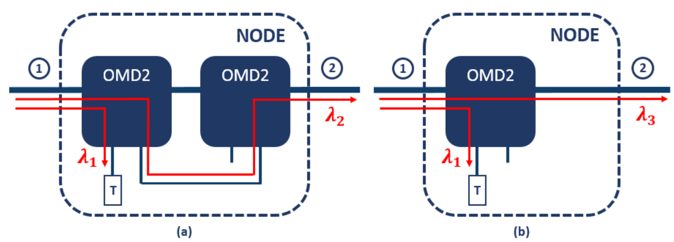

Fig. 4. (a) First-fit, assigning consecutive wavelengths; (b) Allocation of wavelengths taking into account the minimum number of channels that can be filtered in each direction of the node (proposed selection rule)

In the context of wavelength assignment two types of protection can be provided. The most cost-effective protection is performed by using a pluggable optical switch in the interface line output. In this case, the demand with the primary path and the demand with backup path will use the same wavelength, and their assignment must be simultaneous, occurring when either demand is the highest priority in the list of demands. The assigned wavelength must be valid for both demands. On the other hand, if an additional line interface is used for the protection path, the primary and backup paths may use different wavelengths, and the assignment may be performed separately, being the backup path handled as a normal demand.

An example of the proposed wavelength assignment method is shown in Fig. 5. In this example, seven demands are routed in a mesh network with five nodes. Note that the demand 1 uses three channels and the demand 2 uses two. All other demands use only one channel. Additionally, the demand 7 is a backup path of demand 5, and these two demands use the same wavelength. However, although the demand 6 is a backup of demand 4, they can have different wavelengths. No limitation was considered in terms of the filters that could be used. This example has already been explained in [ICT].

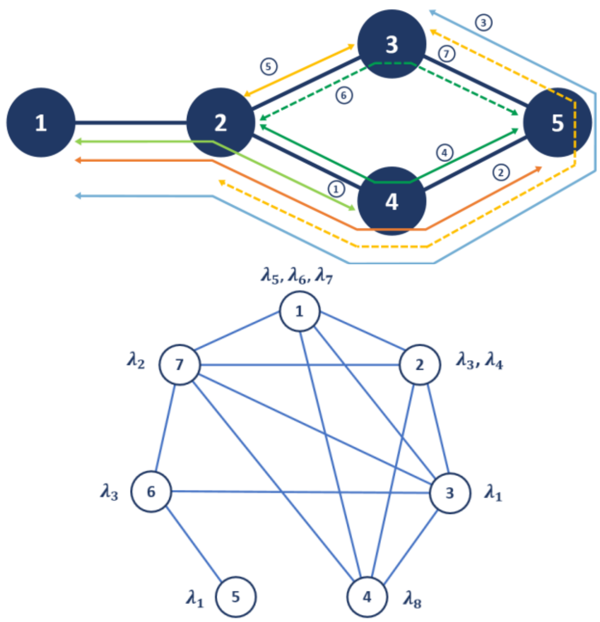

Fig. 5. Wavelength Assignment Method application

IV. Filter Selection Algorithm

Once the routing and assignment of the wavelengths have been performed, each demand is characterized by a path and one or more wavelengths.

With this data it is possible to identify the wavelengths that are added / removed in each node direction and determine the wavelengths that must be passed through optical express connections. If there is an invalid express connection, it must be identified whether these channels should be passed by Drop & Re-add with regeneration or which fixed filters should be changed by ROADM directions.

After this step it is necessary to identify the combination of pluggable fixed filters that must be chosen in order to optimize the network to be planned.

In order to perform the selection of fixed filters, the following heuristic method is proposed:

1. Identify for each node direction, the single filters that ensure the addition/removal of all required wavelengths;
2. Identify for each node direction, the filter cascades (with degree 2 or 3) that ensure the addition/removal of all required wavelengths;
3. These filters should be saved in a List of Interim Solutions (LIS);
4. Check which LIS filters allow the required express connections to be established without removing any undue wavelength. These filters should be saved in the Solutions List (SL).
5. If there are node directions with no solution in SL:
    a. Identify, for these node directions, how many wavelengths are unduly removed by each previously identified SIL configuration.
    b. Save for each node direction only the solution where it removes a smaller number of wavelengths;
    c. If it is chosen that these wavelengths should be passed by Drop & Re-add with regeneration:
        i. Re-determine the valid filter configurations, taking into account the new wavelengths that have to be added/dropped, in the node direction that is connected by the express port.
        ii. Update the number of regenerators needed;
    d. Else:
        i. Replace in this direction the fixed filters by a ROADM direction.

A network is considered fully configured when all node directions have been properly characterized, that is, when valid equipment (fixed filters or ROADM directions) is assigned to all node directions.

V. Results and Analysis

In order to evaluate the quality of the results obtained using the RWA method and the proposed filter selection method, a set of different networks are analyzed in this chapter according to different types of approach.

For chain and ring networks was performed an intensive statistical analysis. The first step in this analysis is to choose, for each network, the number of nodes and the logical topology considered. In order to identify the evolution trend of the networks based on the increase in the number of demands, seven different scenarios were considered. In each scenario, a different number of demands was planned. The scenarios considered have 10, 15, 20, 25, 30, 35, 40 demands. Within each scenario, 1000 different simulations were performed, being the demands for each randomly generated.

Since a large number of random simulations was performed, it was possible to calculate heuristically, according to the Monte Carlo statistical method, the probabilities of the events. For each scenario, histograms like the one in Fig. 6, were constructed for the following parameters:

- Number of filters;
- Number of channels passed by Drop & Re-add;
- Total cost of the final solution.

Based on the distribution of the results obtained for each parameter, the worst result within a 90% confidence interval was chosen. In this way, it is guaranteed at least that 90% of the simulations performed have better or equal results to those considered for analysis.

Since networks with mesh topology may differ greatly from one another, unlike a generic analysis such as the one performed for chain and ring networks, two real networks (CalREN and

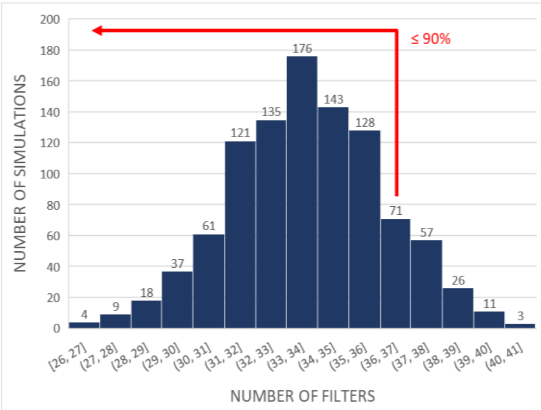

Fig. 6. Example of one of the histograms used

RedIRIS) [7] were designed, considering a set of metro region demands, with and without protection. The obtained results were compared with a fully reconfigurable solution and a fixed filter-based configuration, planned with traditional RWA method based on shortest path and traffic balancing metrics.

In all the cases analyzed, the cost of the network was used as a minimization parameter. The final cost presented for each scenario was calculated based on the cost factor of each equipment, presented in Table I. The filters used are part of the Coriant's portfolio and are called OMDx, where x is the number of wavelengths that are added / removed [8].

TABLE I – EQUIPMENT COST FACTOR

Equipment	Cost Factor
OMD2	1
OMD4	3
OMD8	6
OMD44	8
10G Transponder	12
100G Transponder	60
ROADM Direction	80

A. *Chain and Ring Networks Analysis*

The analyzed chain network consists in 8 nodes and uses a Horseshoe logical topology, shown in Fig. 7. Typically, this type of network is used to perform extensions of already existing networks. The demands are established between one of the chain end nodes, which works as hubs, and an intermediate node of the chain. These demands have a single channel with a bandwidth of 10G. Thus, to regenerate a channel passed through Drop & Re-add it is necessary to use two additional 10G transponders.

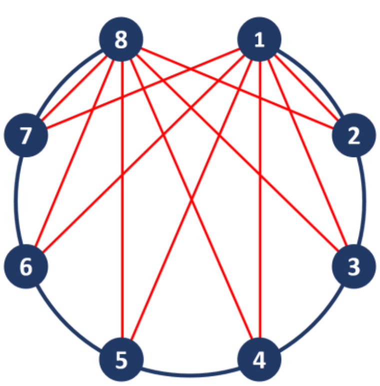

Fig. 7. Horseshoe Logical Topology

The graph with the evolution of the number of filters used, based on the number of demands supported, is shown in Fig. 8. In this case, 14 filters are required to support 10 demands and 26 filters to support 40 demands, being added, in average, 2 filters for each 5 new demands planned. OMD2 is the most commonly used filter type because, from the economic point of view, it is preferable to use a cascade of two OMD2 than a single OMD4.

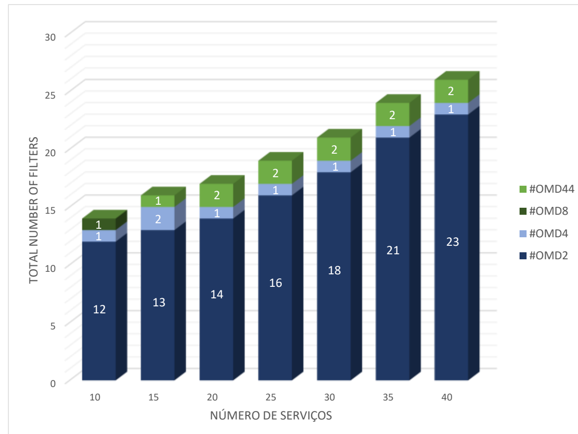

Fig. 8. Number of Filter, based on the number of demands

The evolution of the number of channels passed by Drop & Re-add and the cost of the final solution, taking into account the increase in the number of supported demands, is presented in Fig. 9. The cost of the final solution is calculated by the number of filters and the number of additional transponders used for the channels passed by Drop & Re-add. As in the scenario with 40 demands there are 5 channels that need to be regenerated, 30% of the cost factor of the final solution is related to the filters chosen, while the remaining 70% is related to the additional transponders that needed to be used.

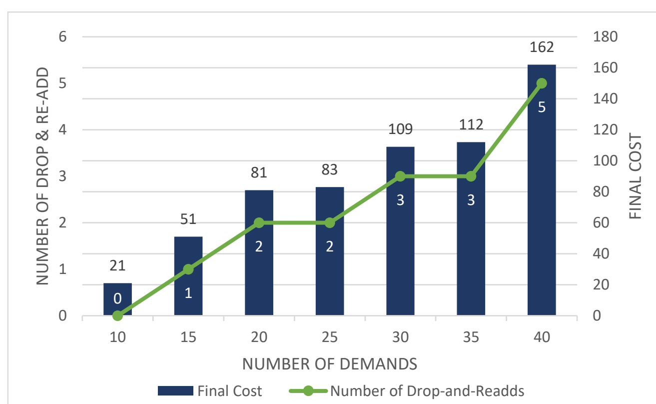

Fig. 9. Final Cost and number of Drop & Re-add according to the number of demands

In the case of the reconfigurable solution all the directions of the nodes would be equipped with ROADMs. In total, 14 ROADM directions would be required. Taking into account the values presented in Table II, regardless of the number of demands considered, the reconfigurable solution would have a cost factor of 1120. Thus, comparing this result with the one obtained for 40 demands using the proposed methods, a reduction in the cost factor of 85% is guaranteed.

The ring network considered is composed by 8 nodes and was analyzed according to two different logical topologies. In the first analyzed logical topology (topology 1), one of the nodes acts as a hub, establishing connections with all other nodes in the network. This topology is typically used to interconnect mobile communication antennas. The hub node is the Base Transceiver Station that aggregates the traffic of this subnet, which is then passed to an existing core network. In the second logical topology (topology 2) no type of limitation was defined in the establishment of demands. These two logical topologies are shown in Fig. 10.

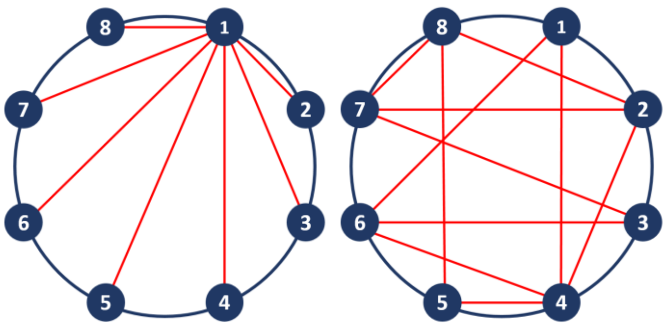

Fig. 10. Logical Topologies considered for the ring network: (a) Topology 1; (b) Topology 2

The graph with the evolution of the filters' numbers used, considering the number of demands supported, using a logical topology 1 and 2, is presented in Fig. 11.

In the first case, Fig. 11 (a), 13 filters are required to support 10 demands and 21 filters to support 40 demands. For scenarios with more than 25 demands two OMD44 filters are required, one per direction on the hub node. In this type of logical topology, it was possible to quadruple the number of demands by increasing the number of filters by only 61.5%.

In the second case, Fig. 11 (b), 20 filters are required to support 10 demands and 44 filters to support 40 demands. Comparing the results obtained for topology 2 with those of topology 1, in most scenarios, the number of filters used doubled. This increase is justified by the greater complexity of the demands generated according to a logical topology in mesh. In this case, OMD44 filters are used because there are no longer any filter cascades compatible with the wavelengths that have to be added / removed in a given node direction. Since these filters do not have any express port, it is expected that the use of OMD44 will lead to an increase in the number of channels passed by Drop & Re-add.

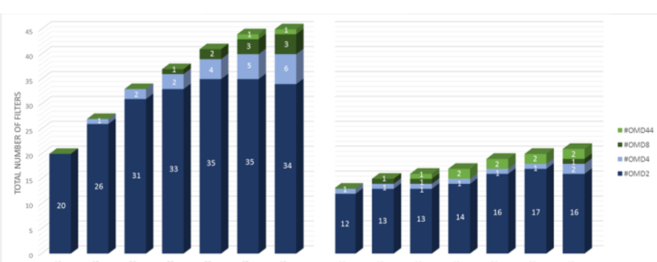

Fig. 11. Number of filters according to the number of demands for: (a) Topology 1; (b) Topology 2

The graph with the evolution of the number of channels passed by Drop & Re-add, considering the number of demands supported is shown in Fig. 12.

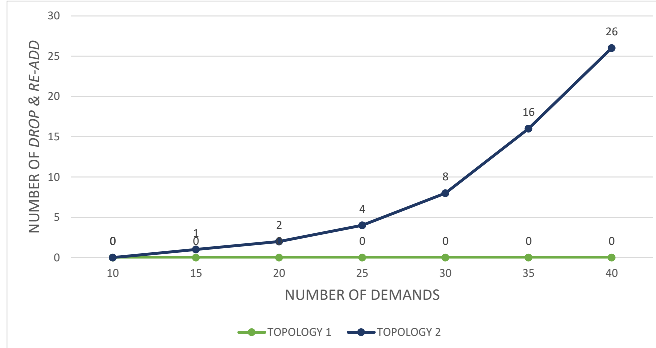

Fig. 12. Number of Drop & Re-add according to the number of demands

In the case of topology with a hub node, regardless of the number of demands supported, no channel needs to be passed by Drop & Re-add. In the case of mesh topology, for scenarios with more than 10 demands, it is necessary to pass channels through Drop & Re-add. From this point on, the addition of 5 new demands corresponds, approximately, to doubling the number of channels passed by Drop & Re-add.

The graph of the cost factor evolution of the final solution, considering the increase in the number of demands supported, using topology 1, represented in green, and topology 2, represented in blue, is presented in Fig. 13.

For topology 1, the cost factor does not change significantly with the increase in the number of demands however, for topology 2, the increase in the number of demands leads to an increase in the number of channels passed by Drop & Re-add. This situation will, eventually, lead to an increase in the cost factor of the final solution caused by the introduction of additional transponders. For that reason, for the 40 demands scenario, the topology 2 solution costs approximately 16 times more than the topology 1 solution.

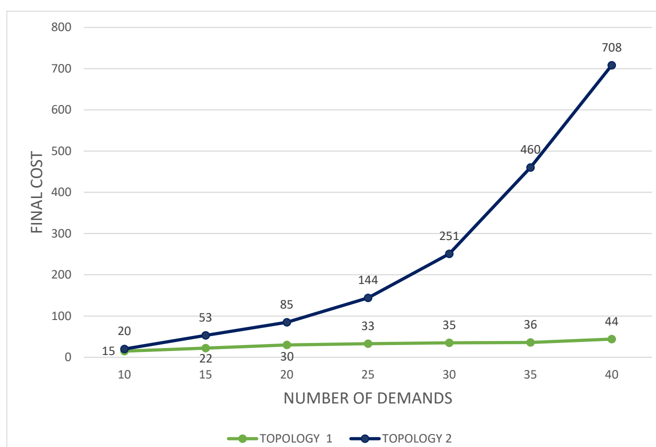

Fig. 13. Final Cost for the ring networks analyzed according to the number of demands

Regarding the reconfigurable solution, 16 ROADM directions are required, which corresponds to a cost factor of 1280. Thus, comparing this result with the one obtained for the proposed solution in the 40 demands scenario, one can conclude, independently of the topology used, that the proposed solution based on fixed pluggable filters, guarantees a reduction of 45 % in the final solution cost.

B. Mesh Networks Analysis

The RWA model presented in this paper was applied to real networks (CalREN and RedIRIS) [7], considering a set of typical metro region demands. The obtained results were compared with a fully reconfigurable solution and a fixed filter-based configuration, planned with traditional RWA method based on shortest path and traffic balancing metrics. For both networks were considered demands of a single channel using 100G line interfaces.

Each network was analyzed according to two different approaches. For the first approach, it was defined that channels passed by invalid express connections and channels improperly removed, would be passed through Drop & Re-add connections with regeneration, while in the second approach it was defined that these problems would be solved by the introduction of ROADM directions. The obtained results are resumed in Table II.

The CalREN network is shown in Fig. 14. The physical (blue) and logical (red) topologies are provided.

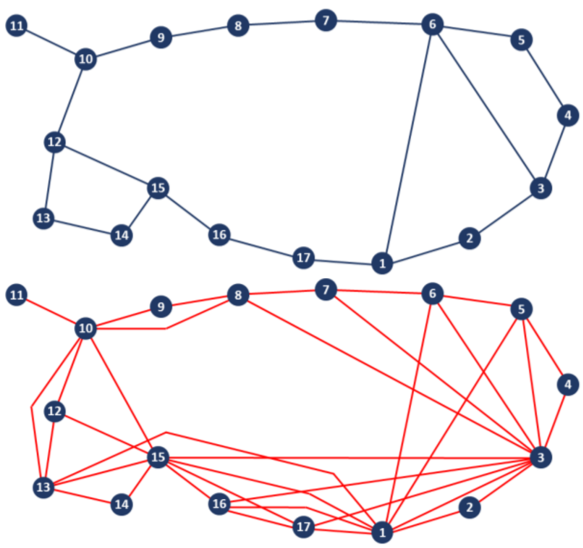

Fig. 14. CalREN network

This network is composed by 37 single-channel demands and 17 nodes, three of them aggregate high amounts of traffic. For the reconfigurable approach, 40 ROADM directions are needed, while for the pluggable components approach, using the traditional RWA method, 71 fixed filters and 8 additional transponders are needed to regenerate 4 channels passed by Drop & Re-add or, alternatively, 57 fixed filters combined with 6 ROADM directions. This already represents a solid reduction however, by applying the proposed RWA method, it was possible to route the various demands without establishing more than one express direction for each node direction and also assign the minimum of different wavelengths possible, equal to the number of channels that pass on the most charged link. This lead to a final solution that only uses 67 fixed filters.

The solutions cost factors of the different methods and approaches analyzed are shown in Fig. 15. Comparing the solution obtained by the proposed RWA method with the reconfigurable solution, a reduction in the final solution cost factor of 97.5% was achieved. By making the same comparison with the solution obtained by the traditional economically

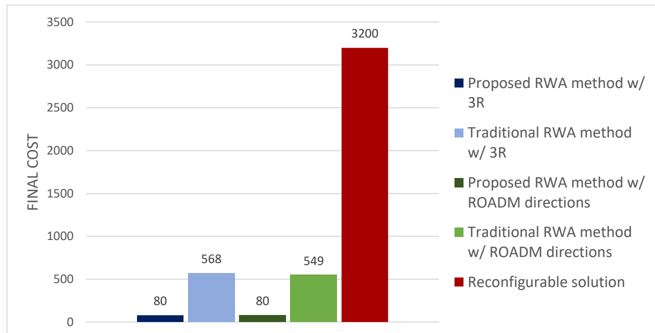

Fig. 15. Final cost of each method used for the CalREN network

viable RWA method, a reduction of 85.4% was obtained.
The second simulated network was the RedIRIS network, shown in Fig. 16. This network is composed by 17 nodes, one of them works as hub with express directions, in a mesh topology. This network consists in 38 services, 18 of which are protected services, making a total of 56 paths. The protected services must be routed through two disjoint paths, using the same wavelength.

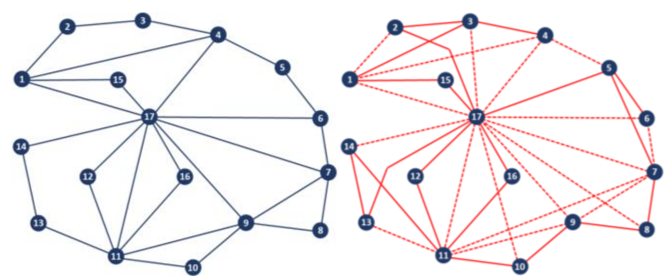

Fig. 16. RedIRIS network

Using the proposed RWA method, were identified two invalid express connections and a channel improperly added/dropped when it should be passed through the filter express port. Applying the Drop & Re-add approach with regeneration, a solution with 106 filters and 3 channels needing to be regenerated (forcing additional use of 6 transponders) was generated. Applying the ROADM approach, these problems were avoided by using 103 filters in conjunction with one ROADM direction. The new routing algorithm for mesh networks generated better results than those presented in [9].

TABLE II – RESULTS FOR CALREN AND REDIRIS NETWORKS

	CalREN				RedIRIS			
	1st Approach		2nd Approach		1st Approach		2nd Approach	
	Fixed Filters	Nº of Drop & Re-add	Fixed Filters	ROADM Directions	Fixed Filters	Nº of Drop & Re-add	Fixed Filters	ROADM Directions
Reconfigurable Solution	-	-	0	40	-	-	0	56
Traditional RWA method	71	4	57	6	115	8	89	9
Proposed RWA method	66	0	66	0	106	3	103	1

Using the traditional RWA method, according to the Drop & Re-add approach, a solution using 11 filters and 8 regenerated channels was generated, while according to the ROADM approach, 89 filters and 9 ROADM directions were used.

Regarding the reconfigurable solution, it would be necessary to use 56 ROADM directions, which would lead to a total network cost of 4480.

Fig. 17 shows the costs obtained applying the methods and approaches analyzed. For both proposed RWA methods and the traditional RWA method, the most economically viable solution is used in ROADM directions. However, the proposed RWA method guarantees a cost reduction of 25% when compared to the traditional RWA method.

When compared to the reconfigurable solution, the solution obtained according to the proposed RWA method presents a reduction in the final cost of 95.5%.

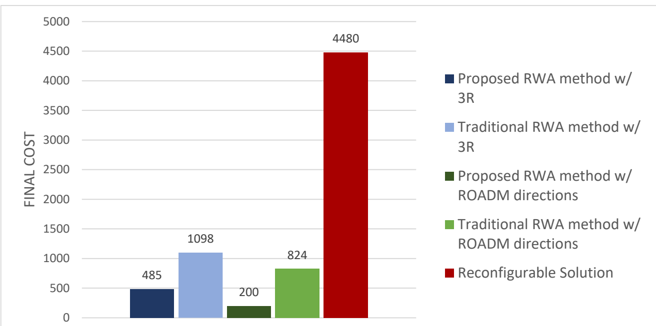

Fig. 17. Final cost of each method used for the RedIRIS network

VI. Conclusion

This paper describes a filter selection and a RWA method adapted to deal with the constraints imposed by fixed pluggable components. These methods were applied to a chain and a ring network and a statistical analysis based on Monte Carlo method was performed.

The results obtained were, posteriorly, compared with the ones from the reconfigurable solution. For the chain network, a reduction of 85% in cost was guaranteed. The ring network was analyzed according to two distinct topologies. For logical topology with a hub node, it was possible to plan up to 40 demands without having to pass a single channel by Drop & Re-add.

For this reason, a reduction of more than 96% in the network's cost was guaranteed. For mesh topology, in the scenario in which 40 demands were planned, it was necessary to resort 26 times to regeneration. In this case, a 45% reduction in the network's cost was ensured.

Two mesh networks with mesh topology were also planned, using a set of typical metro region demands. For both cases a significant number of ROADM directions were avoided. The number of different express directions established, and the number of different wavelengths used, was also minimized. For this reason, reductions over 95% in the network's cost were guaranteed for both networks.

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