Path Computation Solutions for Multi-Domain OTN Networks and Federated Controllers

Pedro Robalo

Abstract—**Network traffic demands keep growing both in number and in size at an incredible rate together with network's dimensions. Consequently, the importance of network resource's efficient usage together with a higher simplicity of all the controlling processes of optical networks became a main concern for nowadays. A possible solution to this problem can be to implement and exploit the benefits brought by multi-layered networks. The Optical Transport Network (OTN) over flexible-grid Dense Wavelength Division Multiplexing (DWDM) network managed by an intelligent Generalized Multi-Protocol Label Switching (GMPLS) control plane is an example of such multi-layered networks where the control plane is responsible for path computation and network resources provisioning. With the evolution of computing sciences and the growing complexity of the DWDM network topologies has been created the concept of Software Defined Networks (SDN) to act as a centralized optical control plane. With this brand-new concept have appeared the challenge of how to implement path computation abilities in a SDN control plane to manage single-vendor OTN network's routing processes with very big dimensions as the ones used nowadays. Hence, this document proposes different algorithmic approaches to solve the routing process and frequency slot's reservation challenge in SDN networks and several protection algorithms to act on top of path computation algorithms to ensure network's survivability. This study's results are measured by the number of demands successfully routed, the algorithm processes latency and the number of regenerators needed for each traffic demand.**

Index Terms — **OTN, DWDM, multi-layer, GMPLS, path computation, SDN, protection, demands, latency, regenerators**

I. Introduction

As communication networks have grown in size and complexity, streamlining the architecture to reduce costs, simplify management, improve service provisioning time and improve resource utilization has become increasingly important. In these networks, displacing control logics from forwarding operations would help to address all the idealizations enumerated. A network control plane is often used to find and configure the required resources in the network, as well as map the application traffic to these resources [1]. In order to decouple control plane from data plane, it is important to ensure that parameters affecting application's performance, such as bit rate or packet loss, are fulfilled through the awareness of the application requirement by the underlying Optical Transport Networks (OTN).

The OTN standard defines a hierarchy for the OTN signals, where the signals can be split into electrical and optical domains. The electrical domain is responsible for inserting the client signal into the OTN transport signals.

The optical domain resorts to multiplexing techniques where multiple signals are combined into a single stream for transmission over a shared medium. The most commonly employed multiplexing technique for optical signals is Dense Wavelength-Division Multiplexing (DWDM). International Telecommunication Union (ITU) standardization sector ITU-T specified a fixed-grid of frequencies to be used with DWDM, with channel spacings which are generally of 50 GHz [2].

For optical domain's multiplexing the most common element to use in DWDM networks are Reconfigurable Optical Add/Drop Multiplexers (ROADMs).

To make all the decisions to be executed on optical network elements used in DWDM systems there is a control plane that can be deployed embedded with network's forwarding plane, which is commonly deployed on today's networks through the use of Generalized Multi-Protocol Label Switching (GMPLS) networks, or can be separate from.

Software Defined Networking (SDN) appears as a paradigm that provides separation between control and forwarding planes. The foundation of SDN is about making the decision on how a flow (or a connection) needs to be set up across the network and configuring the network accordingly, where the decision can be optimized based on network resource state, policies and application demand. All decisions are executed on the switching plane through a SDN's network control protocol, such as ForCES or OpenFlow [1]. This concept of SDN is represented in Figure 1, where it shows an abstraction layer acting as control plane over the switching plane controlled by an orchestrator that communicates through Application Programming Interfaces (APIs) with other applications or services.

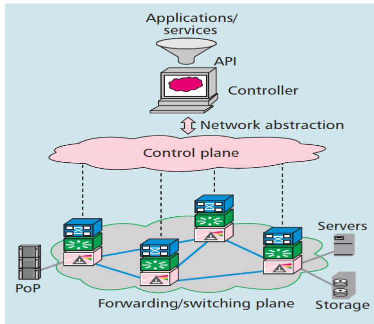

Figure 1 - Illustration of SDN concept [1]

The intention of decoupling path computation tasks was already observed on GMPLS networks through the development of Path Computation Element (PCE) protocols which are hosted on separated elements of the GMPLS networks. For the deployment of these PCEs it is usually adopted a hierarchical architecture with the use of PCE parent and PCE child elements commonly used in multi-domain networks.

Initially, SDN was planned with a centralized architecture depending only one single element called orchestrator where all the decision-making process is done. Although, this means it is required an incredible amount of computing resources, like storage and CPU, to handle path computation process for nowadays OTN networks which have very large dimensions, in some cases covering areas with thousands of kilometers. To address this issue, it is proposed a SDN architecture, for single-vendor OTN networks, based on federated controllers where the optical network is divided into several clusters or sections, each managed by a SDN controller called Sub-Network Controller (SNC) and all federated SNCs are managed by a single Network Controller (NC), as illustrated in Figure 2.

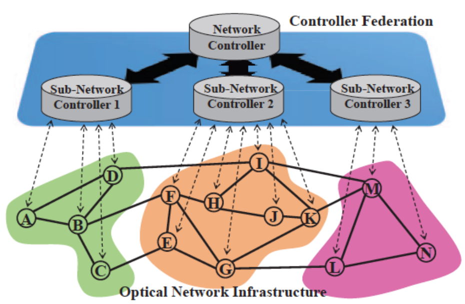

Figure 2 - Illustration of federated SDN controller architecture [2]

With the optical network divided into clusters there will be optical links inside a cluster, known as intra-domain links, and optical links connecting all clusters together, called inter-domain links.

So, NC is responsible for receiving the traffic demand's request and analyze network topology in order to understand if the traffic demand is going to be routed between nodes on the same cluster or if it is between nodes of different clusters. For intra-domain traffic demands, NC will forward a path computation request to the respective cluster's SNC in order to the path computation, the frequency slot reservation and regeneration cards provisioning if needed to route the demand. For inter-domain traffic demands, NC will do the inter-domain path computation and will forward a path computation request to each cluster's SNC of the computed inter-domain path, in order to get a full valid path between source and destination nodes.

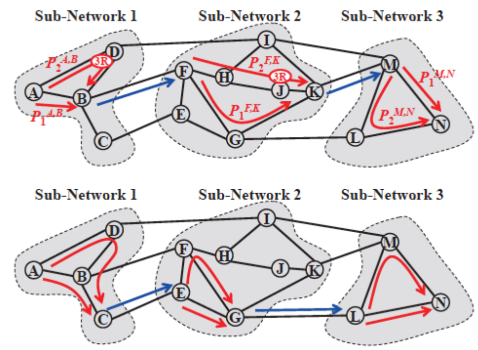

Figure 3 - Route computation over multiple sub-networks [2]

NC and SNCs synchronization and coordination allows to distribute the system's load of a possible centralized architecture to several federated SDN SNCs that do computation and provisioning processes in parallel related to the respective cluster.

In this work, is used the federated SDN controller architecture together with several OTN networks where it is considered network's clustering from a logical point of which can turn an advantage in order to spare computation resources, such as CPU or storage, if NC and SNCs have the right path computation algorithm implemented.

This paper presents four path computation algorithms where two of them are based on *a priori* path computation with NC and SNCs controllers that have a built-in path's database when deployed on the network. The other two do the path computation when processing each traffic demand.

With these path computation algorithms, the objective is to find a balance between successfully routed demands and the time that takes the algorithm to finish routing all demands generated, also called latency. This latency is the sum of inter-domain path computation process time, the intra-domain path computation process time and the path validation process time, being represented by the following formula:

$$t_{intra}\,(\text{ms}) + t_{inter}\,(\text{ms}) + t_{validation}\,(\text{ms}) = t_{total}\,(\text{ms}).$$

Another important goal, is the need of keep operational costs as low as possible through the measurement of the number of regeneration cards, known as 3Rs, needed to route all the demands or through the average of 3Rs per active demand.

Besides path computation on federated SDN controller architecture, these path's survivability is an important issue to address in this study in order to prevent service interruption caused by optical fiber's cuts, for example.

Since SDN analyzes traffic by flow represented by a traffic demand, it is proposed the application of 1+1 Dedicated Path protection technique, which consists on doing a backup path reservation being the demand's computed path known as working path. This path protection is applied at Optical Channel (OCh) layer meaning that there will be the same physical backup path computed to different working paths but each demand will have its own wavelength reserved.

This paper is structured as follows: Section II provides a description of the problem to be solved by the path computation algorithms and path protection algorithms proposed. Section III describes in general all the implemented algorithms enumerating the main differences between them and how path protection algorithms run on top of the implemented path computation algorithms. Section IV presents the results obtained with the execution of path computation algorithms and path protection algorithms for different networks. It is also analyzed the differences obtained in the results for different values of algorithm parameters. Section V presents final remarks about results presented in this study.

II. Problem Definition

In order to fully understand the problem being defined, it is first necessary to analyze the problem input variables.

Firstly, it must be provided the optical network topology over which the problem will be solved. This network topology is represented by a graph $G = (V, E)$, where V represents the set of nodes and E the set of links connecting the nodes. Each link consists in a pair of nodes $\{i,j\} \in E$ and the distance in km between those nodes $d\{i,j\}$. Additionally, since each link represents a fiber optic in the physical network, each link has a limit in terms of available spectrum, $sp\{i,j\}$. Whenever this link is used, the amount of available spectrum is reduced. Each link starts with $s\{i,j\}$ = 4.8 THz of spectrum, divided into slots with 12,5 GHz of width, to be utilized on frequency slots reservation after path computation phase.

Secondly, a traffic matrix D is generated during scenario's simulation. This matrix contains several traffic demands $d \in D$, where each demand is represented by a pair of source node s_d and target node t_d, and a bit rate r_d. The bit rate represents the data being transmitted with that demand. Here it is considered demands corresponding to 100 Gb/s OTN signals. The demands are generated before doing any path computation process with a uniform distribution, where each type of demand is equally probable to be found in the network.

For demand's generation is set the total bandwidth B_t that will traverse the optical network during simulations.

Lastly, path computation algorithms use K-shortest paths algorithm, or Yen's algorithm, in order to NC and SNCs compute K_{inter} and K_{intra} domain possible paths, respectively.

Each computed path has an associated cost as metric of the shortest path selection, where the inter-domain path's cost is the number of hops between clusters and intra-domain path's is the total distance between border nodes of the respective cluster.

To transport a given demand d over the network, it is established one or more lightpaths L_p between s_d and t_d. A lightpath is defined as a transparent connection between two end nodes. A lightpath can cross over a set of intermediate nodes, but whenever regeneration is performed, it is terminated and a new one is created. A new lightpath is created every 2500 km traversed by a demand and if lightpath's maximum distance is located on an inter-domain link, SDN's NC will provision a 3R in the beginning of that inter-domain link.

There is also the need of setting the total number of clusters C_{total} and the Similarity S_{ij} between nodes i and j, explained in [2].

So, to transport a demand over the network it may be necessary to use one or more lightpaths. The number of lightpaths employed will depend on the network topology and the path's computed conditioned by the frequency slots available on each optical link. Whenever a lightpath is created, it spends a part of the spectrum of each link in its path. This way, if there is a high number of lightpaths using the same network link, it may not be possible for a new lightpath to pass through that link. To transmit a demand, it must be chosen how to serve that demand. In particular, decide which lightpath or set of lightpaths must be chosen to carry that demand and then allocate the necessary spectrum for their path.

The problem definition is now resumed. Given:

1. An optical network topology represented by a graph $G = (V, E)$;
2. A set of traffic demand D is generated;
3. A pre-planned number of clusters
4. K_{intra} and K_{inter} values of possible paths;

the objective is find the best path computation algorithm together with the most appropriate path protection algorithm which:

1. Maximizes the number of active demands
2. Minimizes simulation's latency
3. Minimizes the number of 3Rs provisioned

While imposing the constraint:

1. Maximum network link spectrum equal to 4.8 THz;
2. Maximum lightpath's distance of 2500 km

After solving the problem, it should be obtained the number of demands successfully routed together with simulation's latency and the number of 3Rs provisioned. This will help to analyze the path computation algorithm and the path protection algorithm with best performance when acting in federated SDN controller architecture with

III. Optical Network Simulator Algorithm's Description

A. *Global Optical Network Simulator Description*

For this study, it is used an optical network simulator, provided by João Santos from Coriant, which already have built-in a path computation algorithm. This simulator consists on 4 sections, already implemented, which are:

1. Clustering section,
2. Demand's generation section;
3. Path computation algorithm's section;
4. Path validation and provisioning section.

In the beginning of a simulation it is inserted, as an input, optical network's topology together with values of K_{inter} and K_{intra} possible paths and the number of trials or iterations to each scenario's simulation.

Clustering section includes the implementation of a clustering algorithm responsible for dividing network's topology $G (V, E)$ into C_{total} clusters, according to the Similarity Code S_{ij} which defines the affinity between network nodes in order to group them into clusters. After finishing network's clustering section, it begins to generate a set of 1000 demands

D, each with r_d of 100 Gb/s, in order to route a B_t of 100 Tb/s throughout the optical network. Demand's generation has a uniform distribution, which guarantees equal demand's generation, for each possible source/destination pair of nodes.

Path computation algorithm's section consists in calculating the K_{intra} shortest paths between demand's source and target nodes of that belong to the same cluster, employing Yen's algorithm. For the case of source and destination nodes in different clusters, firstly it is compute K_{inter} shortest paths between source node's and destination node's clusters and secondly are computed K_{intra} shortest paths for every cluster that belongs to each inter-domain path of K_{inter} paths. Both inter and intra-domain path's lists have the shortest path first sorting metric applied. Shortest path first means that the demands with lowest number of nodes in its path come first in the list. This section does path computation for scenarios with or without path protection applied on the optical network used for simulation.

Finally, there's the path validation and provisioning section which consists on selecting the best available inter-domain path together with respective cluster's intra-domain paths comparing distances related to the combinations between K_{inter} and K_{intra} path's lists, the number of required 3Rs and the available frequency slots for each lightpath in the selected path. Also in this section, all lightpaths are provisioned with the required frequency slots reserved. The federated SDN controller architecture allows storing intra-domain path's state into the respective SNC's database and inter-domain path's state into NC's one.

After all simulations done, it is expected as output the number of demands routed, the simulator's latency, the total number of required 3Rs as functions of a set for C_{total} value with a defined S_{ij} value. This data will help to analyze the impact of the amount of clustering used for deploying a federated SDN architecture while comparing each of the implemented path computation algorithms. Additionally, will address the issue of analyzing which path protection algorithm maximizes both NC's and SNC's system resources and the number of protected active demands in the network while keeping the number of 3Rs as low as possible. If it isn't found the perfect combination between clustering and path protection running on top of path computation algorithms, the objective is to find a solution with well-balanced results.

B. Path Computation Algorithms Description

Path computation algorithm's section comes always after all clustering algorithms are complete. In this section, there are four path computation algorithms implemented. These algorithms can be differentiated into two criteria which are the timing of path computation process and the computed path selection method, which is related to the process of path validation and provisioning section.

For the path computation process timing case, they can use the offline method which consists in doing the path computation for all possible source/destination pair of nodes before processing any demands having a static path's database on federated controllers. On the other hand, there is the online method where path computation is done when processing each incoming traffic demand being this computation done only for the source/destination pair of the respective demand.

In terms of computed paths selection method, there is the best-fit method which analyzes every K_{inter} and K_{intra} paths available and selects the best path to route the traffic demand. And there is the first-fit method that selects the first valid path to route the demand which is expected to be the one that will exhaust lightpath's frequency slots faster but it will take less time to do the path selection than the best-fit method.

In the optical network's simulator provided there was already a path computation algorithm implemented which was the Offline Computation and Best-fit Algorithm (OffCBA). This algorithm applies the offline method together with the best-fit path selection as previously explained. This algorithm helped to implement an alternative version of this applying the first-fit path selection method called Offline Computation with First-fit Algorithm (OffCFA).

In order to test if the online method can come through when faced with the offline ones, was created the Flexible Online Computation with Best-fit Algorithm (FOnCBA) which follows the principle of an online algorithm applying the best-fit path selection method, but with a particular routine, running on the NC and SNCs, allowing to analyze the network's state in terms of frequency slots available in each optical network's link. If one of the best candidate computed paths become unavailable due to the lack of frequency slots, this routine will look to every controller's databases in order to find a new available path to put on the candidate path's list providing some dynamic to the path computation process avoiding a whole new path computation process or a higher number of blocked demands. For the case where none of the candidate paths becomes unavailable, path's database stays as it is without adding or removing any of the paths selected as candidate to route the incoming demands between those source and destination nodes.

To have one good alternative to the FOnCBA algorithm, it was created the Memoryless Online Computation with Best-fit Algorithm (MOnCBA) that instead of having a routine that searches unavailable paths, it will do the path computation process every time that processes an incoming traffic demand deleting all path's database residing on the federated controllers. This algorithm will ensure that every computed path for a demand is the shortest available path at the moment of processing that demand although it will take more time in order to provision all database structures and computed paths, comparing to FOnCBA algorithm, resulting in higher latency values especially to large dimension network's topologies.

These algorithms described ensure that a traffic demand will get a path to be routed from its source to its destination node, but this will happen without any backup path provisioned in order to prevent some link's or node's failures and here is where path protection algorithms turn out to be as relevant as the path computation algorithms.

C. Path Protection Algorithm's Description

In order to ensure OCh protection to the proposed federated SDN controllers architecture, proposed in [2], were implemented four path protection algorithms to run together with path computation algorithms, described in the previous section. These protection algorithms are based on a 1+1 protection scheme where each computed working path has a disjoint backup path provisioned for the same demand. The backup path computation will lead to a higher occupation of optical link's frequency slots because now, for each demand, it is provisioned a working/backup pair of paths.

Path protection algorithms computes a disjoint backup path by removing from the network's topology graph *G = (V, E)* all the links that form the path that will be protected and repeating the path computation process with the resulting graph. If it is intended to protect the path at links and nodes level, so it will remove all the links that come from or go to the nodes that are traversed by demand's working path.

A demand's working path can have only its inter-domain path protected, can have inter-domain and intra-domain paths protected or these two combined with protection at working path's nodes level. Thus, the four implemented path protection algorithms are: Inter-Domain Path Protection algorithm (IPP), Inter-Domain and Intra-Domain Path Protection algorithm (IIPP), Inter-Domain Path and Nodes Protection algorithm (IPNP) and finally, Inter-Domain and Intra-Domain and Nodes Protection algorithm (IIPNP).

All path protection algorithms were implemented within the OffCBA and MOnCBA algorithms. And these were the chosen path computation algorithms, because both do a fresh path computation process without having some dynamic routines interfering and the only difference between them is the persistency of controller path's databases. So, this choice of path computation algorithms will help to analyze the impact of the four protection algorithms in terms of active demands, simulator's latency and the total number of 3Rs provisioned. Done the description of all the implemented algorithms to act in a federated SDN controller architecture, the next step is the analysis of the data extracted from all the simulations performed and the explanation why is important to consider clustering in a SDN architecture where the actual concept is to adopt a totally centralized architecture based on single NC responsible for whole underlying Optical Transport Network. Other goal of this study, is how the combination of all algorithms can improve network's performance in a clustered SDN architecture.

IV. RESULTS AND DISCUSSION

In this section, the results obtained using the optical network simulator to test all algorithms previously described are analyzed.

As previously referred, different parameters can be given as arguments to the algorithm, such as the path computation algorithm's and path protection algorithm's selection. Most of these parameters lead to different choices being made while executing the algorithm, such as choosing the approach when executing the iterative section of the algorithm. On other perspective, the algorithm can also be executed for different input variables, i.e. different network scenarios, different K_{inter} and K_{intra} values. So, if for the same input variables, the parameters given are different, the solutions obtained will vary. If the algorithm parameters are kept constant but the input variables change then the solutions obtained will also change.

In order to reduce the scale of the solutions that are studied, this section is divided into two subsections. In the first, it is explained what is the impact of using a path computation algorithm in different network topologies for different amounts of clusters.

In the second onde, it is explored the differences in the results obtained when changing the path computation algorithm parameter and the C_{total} clusters for the same optical network topology. Also, it is comprised changing the optical network topology and C_{total} clusters for the same path computation algorithm.

In the second section, it is comprised the changing of path protection algorithms and C_{total} clusters running with the same path computation algorithm and the same network topology. Also, it is analyzed the impact of changing the path computation algorithm together with C_{total} clusters for the same path protection algorithm and network topology. Two different networks are studied, one of medium dimension and a large dimension one. The medium network corresponds to the EON network and the large network corresponds to the GEANT network, both illustrated in Figure 4.

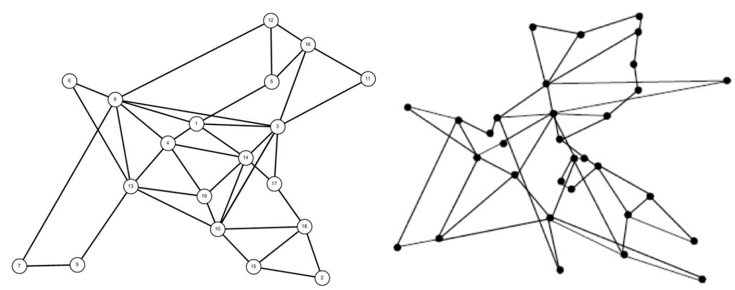

Figure 4 - Optical network's topologies studied

In result analysis, it is not comprehended the change of K_{inter} and K_{intra} and of the Similarity code S_{ij} because there is one in [2] already where it is reflected the same behavior than the one obtained during this study. For result's analysis purpose, it is considered $K_{inter}=5$ and $K_{intra}=5$ together with the node's affinity criteria, known as Similarity Code, being the inter-domain distance from the shortest to the longest.

As previously mentioned, it is considered that traffic demands have a constant bit rate of 100 Gb/s and for every simulation the B_t parameter is always 100 Tb/s, so for simulation purposes there will be always a total of 100 incoming traffic demands when all are processed and set as blocked or active, the results are printed out and the simulation ends.

Four result metrics are discussed in this chapter, which are the number of active demands, the total latency of each simulation, the total of 3Rs provisioned and the average of 3Rs per active demand. These metrics are analyzed through the comparison of their absolute values comparing directly all the obtained results.

A. *Network topologies impact analysis*

In this section, it is analyzed the impact of using different network topologies with path computation algorithms implemented. For this, it was made a comparison between the use of MOnCBA algorithm on both EON and GEANT networks, as it is presented in Figure 5.

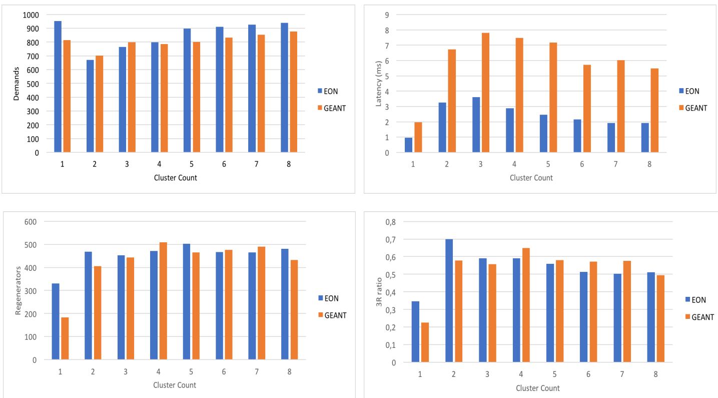

Figure 5 - Comparison of result's metrics between EON and GEANT networks running MOnCBA algorithm

This figure shows that there is an increase of more than 100 active demands in average, for EON network's case, which can be an indicator of having a higher node's connectivity degree meaning that have nodes with a large number of links as coming from or going to it, leading to a higher number of node's pairs combinations while doing the path computation process. Also, for low number of clusters there is about 30% of blocked demands which is a very high value considering that these optical networks deal with large amount of crucial data to be transmitted. The reason for this is that for cases with low number of clusters even with possibility of having more inter-domain links between two clusters than in cases with 7 clusters, for example, the number of clusters that a demand can traverse is lower, decreasing the possible combinations of clusters that the traffic demand can traverse due to the constraint that the demand can't be routed through a cluster twice.

In terms of latency, GEANT network reaches to almost 3 times the value obtained in EON network which is explained by its large dimension. Also, it is illustrated that for cases with less clusters the latency reaches the maximum value registered being this caused by the lack of ability to find a valid path to route most of demands, spending time searching for a path's solution that will not find due to the inexistence of valid available paths to route some traffic demands.

Regenerator's metric is directly proportional to the active demand's metric, so if for it is obtained a high number of demands the number it is possible that the number of 3Rs provisioned will be high too. However, in some cases EON network can have a higher number of 3Rs provisioned than in GEANT network even with less active demands which is caused by the fact of the GEANT having its nodes closer to each other.

On the other side, 3R ratio's metric is inversely proportional to the active demand's metric and it represents an average of 3Rs provisioned for each demand. This metric shows that the minimum value is obtained in GEANT network without clustering reflecting again the fact of having its nodes closer to each other than in EON network because the number of active demands in GEANT network without clustering is much lower than in EON's, which should reflect higher values for GEANT network and this does not happen. Although, 3R ratio are results are very low in general demonstrating that most of demands does not need any regenerator provisioned to be routed, meaning that the majority of computed paths are formed by one lightpath only.

In conclusion, there are two best-case scenarios in terms of the number of federated SDN controllers reflected by the number of clusters are: a centralized architecture which is the 1 cluster's case or an architecture with a high number of federated controllers where the optical network is extremely logically divided. Being the first case the most favorable when looking into the obtained results.

B. *Path computation algorithm's analysis*

The purpose of this section is to analyze the effects of the path computation algorithm selection for a given optical network's topology being divided or not into a predefined number of clusters.

For this result's analysis, it was selected two path computation algorithms, OffCBA and MOnCBA, in order to do a comparison between them in terms of all the metrics mentioned in the beginning of section IV.

Based on some arguments presented in the previous section, it is expected to have less active demands when adopting an architecture with a low number of clusters and consequently less 3R ratio since now the analysis is made always on the same optical network.

Since OffCBA algorithm do the path computation process once for the whole network and MOnCBA algorithm does this same process every time it processes a demand even if already received a traffic demand more than once for the same source/destination nodes, the latency for OffCBA algorithm is expected to be lower than for MOnCBA algorhtm. The number of active demands between these two algorithms can be very similar although it is expected to have slightly more active demands for MOnCBA algorithms due to the fact of OffCBA doing controller path's database being static along the whole traffic demand routing's process. With this, OffCBA does not have the ability of computing paths based on the actual network's state in terms of searching for the best available paths.

In order to prove if these theoretical expectations are reflected by the results obtained with each scenario's simulations, it is presented Figure 6, with the data resulting of the execution of the two chosen algorithms in EON network.

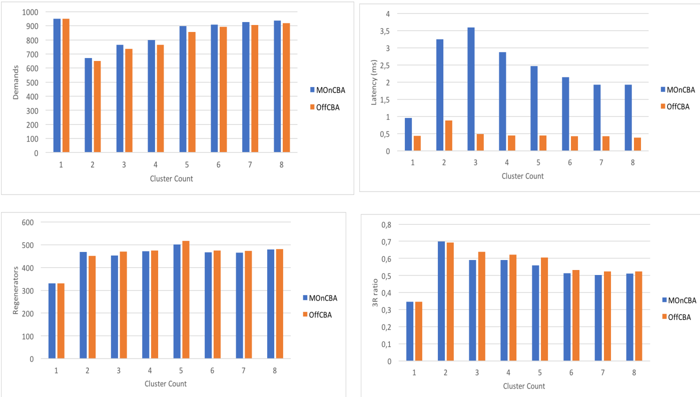

Figure 7 - Comparison of result's metrics between MOnCBA and OffCBA path computation algorithms in EON network

As it was expected, MOnCBA algorithm can route around more 50 (~5%) traffic demands than OffCBA algorithms due to the fact of doing the path computation process for each processed demand deleting all path's databases which allows to refresh the list of candidate paths according to the current network's state.

This continuous MOnCBA's path computation process increases a lot the required NC's and SNC's controller resources which is reflected by latency results presented in the figure above. Its latency is between four and six times higher than in OffCBA algorithm. With this is important to understand if the latency obtained for MOnCBA equals the scale when faced to the 5% of more traffic demands, since this increase of active demands is verified only in scenarios with clustering.

In terms of total regenerators provisioned, OffCBA has higher results because once the shortest paths are unavailable it won't update the computed path's database to analyze if the ones still available on the candidate path's list are the best K_{inter} and K_{intra} domain choice of paths. One thing to be considered, in path computation process is that if there are several computed paths with the same cost, their selection will be randomly done. So, when MOnCBA does the path computation process it will select always the best set of available paths at the demand's processing moment. Additionally, even with MOnCBA algorithm as the one with higher demands what could cause to have more regenerators provisioned, OffCBA's static database

have a bigger impact on the number of 3Rs because it is the one with the highest number of 3Rs for all simulation's scenarios.

Being OffCBA algorithm, the one with less active demands and more regenerators it is expected that will have the highest number of 3Rs per demand, as presented in Figure 6.

C. Path protection algorithm's analysis

After measuring path computation algorithm's performance, it follows the path protection analysis, by testing all path protection algorithms described running together with a pre-selected path computation algorithm.

For testing purposes, it is considered that now K_{inter} and K_{intra} represent working/backup possible pair of paths instead of only possible working paths. The values considered to this analysis remain as $K_{inter}=5$ and $K_{intra}=5$, like in path computation algorithm's analysis.

In order to state the differences between implemented path protection algorithms, are presented results comparing IPP algorithm and IIPNP algorithm running within MOnCBA algorithm on EON network, since besides latency it is the algorithm with best performance and EON network is smaller than GEANT which will not impact the latency, so much. The importance of the latency's values in this analysis is because when running path protection algorithms there is more computation processes involved than in simulation's scenarios without path protection applied.

The reason of using IPP and IIPNP path protection algorithms is to be able to evaluate the impact of the backup path computation constraints about the protected entities because the first algorithm just apply protection for inter-domain paths and the second one applies protection for the whole working path including inter-domain, intra-domain paths and all the nodes that the traffic demand traverse while using the working path computed.

The results obtained using the optical network simulator with path computation and path protection algorithms are presented in Figure 7.

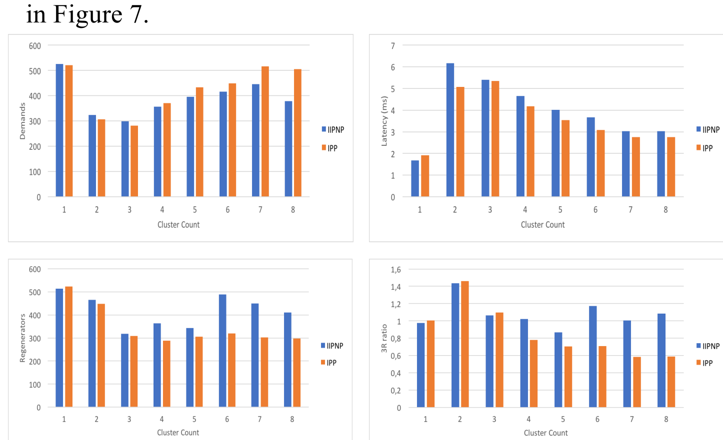

Figure 6 - Comparison of result's metrics between IPP and IIPNP algorithms running with MOnCBA in EON network

It is possible to observe through previous figure, that IPP algorithm has more demands successfully routed and the gap between both protection algorithm's active demands is higher as the number of clusters increases, which makes sense since IPP has only one constraint that is finding inter-domain disjoint paths to serve as working/backup pair of paths. For scenarios without clustering results of both algorithms are higher because there are not any inter-domain paths to apply protection and so there is no need to compute an inter-domain disjoint path. Additionally, the maximum value of active demands is around 530 demands from a total of 1000 demands generated because in order to provision both working and backup paths there is a higher number frequency slots reserved for each demand comparing to a scenario without path protection, so it will have a faster exhaustion of available frequency slots in network's optical links.

The latency results register higher values for the IIPNP algorithm because it has more constraints about finding a backup path which makes more this task more difficult leading to more time spent in the backup path's computation process. Since there isn't inter-domain path protection for scenarios without clustering, the latency value is the lowest obtained, for both protection algorithms.

In the number of 3Rs provisioning results, there is a huge increase in IIPNP algorithm when applied to EON network with a large amount of SNCs deployed, because the difficulty in finding working/backup disjoint paths makes this algorithm compute longer paths than in IPP algorithm needing more than one regenerator per demand, as illustrated in 3R ratio's results. This leads to the conclusion than these paths computed with IIPNP algorithm can have a length of more than 2500 km in order to route a traffic demand ensuring its survivability through path protection.

V. Conclusion

In this paper, it was presented four path computation algorithms and four path protection algorithms which are capable of doing the routing process while ensuring survivability of successfully routed traffic demands, in a federated SDN controller architecture. The problem solved by all of these implemented algorithms had the objective of minimizing controller system's load for path computation and provisioning tasks by distributing NC system's load, typical of a centralized SDN architecture, to several federated controllers where each one is responsible for managing one section of the optical transport network and to maximize the number of the generated demands that are set as active. The simulator used to implement these algorithms has its global architecture, divided in four main sections, explained. Then, it was presented a description of all path computation and path protection algorithms in order to clarify what are the differences between them and their roles on the path computation and provisioning processes. Results were obtained and it was done a comparison about the impact of applying some algorithms to certain network topologies and two comparisons between two path computation algorithms and two path protection algorithms running together with a predefined path computation algorithm, respectively. Finally, it was shown that scenarios without clustering or with a big number of clusters have very favorable results in terms of active demands and latency, being the variation about the number of 3Rs provisioned more dependent on the path computation and path protection algorithm used. Also, it was observed in network topology's comparison that node's connectivity degree can have a significant influence on the path computation process, therefore have an impact on the results obtained. From path protection algorithm's analysis, there is the conclusion that the higher is the number of constraints in the backup path computation process the worse is the path computation algorithm's performance, in terms of both active demands or latency.

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