Technology Dimensioning Model for an IP/MPLS NGN (Next Generation Networking)

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Abstract—Dimensioning models are essential for network providers with the objective of minimizing the CAPEX, increasing the network robustness in terms of resources and resilience to failures. The purpose of this work is to implement survivability to an existent dimensioning model. With this objective, the study of routing algorithms and mechanisms of survivability are in focus. It is approached the concept of Constraint-Routing that intends to introduce some limitations to the routing. The constraint in focus is the residual capacity of a network link. The algorithm for computing disjoint paths is important for survivability analysis. The survivability is implemented to guarantee end-to-end maximum bandwidth, obtaining a service path and a protection path that are able to carrier a certain traffic flux. The costs increase since it is dependent of the allocated load. The linear 1+1 path protection requires a huge investment by the service network provider. The 1:1 protection outputs the blocking ratio if it is intended to setup a path under capacity planning conditions.

Keywords—Network planning, Backbone, Service network, Multi-Protocol Label Switching, Survivability, Routing algorithms

I. INTRODUCTION

The telecommunication networks sector is a business that provides millions to operators and stakeholders involving directly or indirectly the customer experience. The planning of a service network is important to perform a business plan to overcome the equipment and capacity that will be purchased to the transport network provider. For the network dimensioning and planning, it is important to use tools based in algorithms for routing, survivability, traffic engineering or another applications. Be connected to a network is just a minimal requirement because it is necessary resources for packet transmission, service availability and network security [1].

MPLS over IP is considered an added value technology from operator’s point of view and it was developed to improve the performance of IP packet transmission [1]. The IP/MPLS has the possibility to merge in a single packet infrastructure the triple-play services as voice, video and data provided by the operators and other types of services as for corporative or governmental institutions. Concerns about SLA are considered in MPLS technology with Traffic Engineering (TE) and Quality of Service (QoS) in order to guarantee its compliance.

With the traffic growth in each year [2], the service providers face the need to develop and implement efficient and cost-effective solutions. The increase of traffic demand requirements, as example in radio access networks, leads to significant transformation in the backbone requirements [3] and the emerged new complement technologies as Ethernet and Carrier Ethernet 2.0.

The routing algorithms allow to simulate the end-to-end packet transmission with the objective of obtaining paths that minimize the costs. These algorithms are also efficient to minimize the network costs and its different usage can traduce in different routing models. The Dijkstra algorithm is used for obtaining the shortest-path between a node pair, which is a typical approach for dimensioning the links capacities in the MPLS network. The K-Shortest Path algorithm obtains multiple K shortest paths, which is used for balance the link load.

Survivability intends to guarantee the resistance to network failures, accomplishing the service availability. The algorithm for survivability is based in the routing algorithm for shortest path computation. The difference is that the physical link topology is changed before the computation of the shortest path. The algorithm intends to compute, based in a shortest path provided by the routing, an alternative path without the links and nodes used in the shortest path.

The constraint-routing introduces limitations which are settled by each traffic class. These limitation are defined to avoid establish connections that not accomplish the SLA committed. The implementation of traffic engineering aspects are important for the Next Generation Networks and it is deeply studied in this work. These constraints are implemented in algorithms with routing and survivability purpose, obtaining paths that accomplish the limitations imposed by a certain traffic demand.

The main goal is to explore different algorithms for point-to-point connections and upgrade the planning tool with a feature for survivability in IP/MPLS networks. It is important to identify the elements that are part of an IP/MPLS network with the planning components referred to the node and links capacities. It is also an objective to recap the basic of optimization algorithms to compute shortest paths in order to minimize the network costs.

II. BASIC CONCEPTS AND STATE OF THE ART

A. Network Concepts

A network is defined by a group of elements interconnected, describing a topology. The network physical topology is represented by a graph $G(V, E)$ where $V$ is the set of $N$ network nodes (vertices) and $E$ is the set of $M$ network links (edges):
\(V = \{v_1, v_2, \ldots, v_N\} \); \(E = \{e_1, e_2, \ldots, e_M\}\). Each link \(e_i\) is defined by an initial node \(v_x\) and an end node \(v_y\) which corresponds to a pair \(e_i = (v_x, v_y)\). The group of links \(E\) is characterized by the physical capacity described by \(C = \{c_1, c_2, \ldots, c_M\}\) where \(c_j\) is the physical capacity for the link \(e_j\) and measured in Gigabit per second (Gbps).

A path in a network is a sequence of links that can be represented as \(p_{xy} = \{e_x, \ldots, e_y\}\) from a source node \(v_x\) to a destination node \(v_y\). The links \(e_x\) and \(e_y\) must contain source node and destination node respectively, in a way that a path can also be represented by a sequence of nodes \(p_{xy} = \{v_x, \ldots, v_y\}\). Both representations are derivative if each node pair represents only a link. A group of paths can be defined by \(P\) and a group of paths between two nodes as \(P_{xy}\).

In logical topologies, the links correspond to logical connections that characterize traffic flows. The traffic flows are analysed in different periods \(t\) belonging to a group of periods \(T\). The traffic flows or demands are described by the traffic demands matrix \(D^t\) where \(d_{xy}^t\) is the traffic demand between the nodes \(v_x\) and \(v_y\) for the planning period \(t\). Here it is assumed that the traffic flow units are the same as the link capacity units and therefore are express in Gbps.

\[
d^t = \begin{bmatrix}
0 & \cdots & d_{1N}^t \\
\vdots & \ddots & \vdots \\
d_{N1}^t & \cdots & 0
\end{bmatrix}_{N \times N} \text{ [Gbps]} \quad (1)
\]

Different traffic demand matrices can be attributed to the traffic model. In this work, there are considered full-mesh logical topologies. The full-mesh logical topologies are characterized by connections in between every node pair with equal demands. The number of bidirectional connections can be calculated by \(N(N - 1)/2\).

Each demand \(d_{xy}^t\) is transmitted by a path determined by the routing. The routing is the mapping of the logical topology over the physical topology and intends to minimize the cost considering different cost metrics as the hops, distance, latency, load or residual capacity. It is possible to consider that a demand can be divided in \(n\) multiple paths in a period \(t\), \(P_{xy}^n\), or through a \(K\) resilience level, \(P_{xy,K}^n\), used for network survivability. The allocated demand in each \(n\)-path is set as \((d_{xy}^t)n\).

As mentioned before, there are different cost metrics. The hop is a transition between a node to an adjacent one referring a unitary cost. The distance is the length of the physical connection between two adjacent nodes. The latency (or delay) corresponds to the time that a given data packet takes to go from the source node to the destination node.

As result of the routing process, in each link is allocated load described by \(L = \{l_1, l_2, \ldots, l_M\}\) where \(l_x\) is the allocated load in link \(e_x\). This load is the result of traffic demand routing where the load is allocated into the links from the path that supports the traffic flow. The units for both concepts are measured in Gbps.

A concept regarding the link capacity and the load is the residual capacity. The residual capacity is defined by \(R = \{r_1, r_2, \ldots, r_M\}\) and represents the available capacity of a link, i.e., the physical link capacity less the load transmitted through a determined link where \(r_y\) is the residual capacity in link \(e_y\).

The maximum bandwidth \(B\) is the group of available path capacities where \(b_{xy}\) is the available capacity of the path \(p_{xy}\). The maximum bandwidth is obtained by the minimum residual capacity of the links that forms it, \(b_{xy} = \min[r_x, \ldots, r_y]\).

In the telecommunications, there are circuit and packet switching networks. The packet switching is the basis for the IP [4] and offers a connectionless or a connection-oriented services. Connection-oriented packet-switched networks imitate circuit-switched network with a connection associated to a specific Class of Service (CoS), providing the requested QoS. The connection-oriented networks guarantee sufficient resources to carry a new flow and end-to-end path may satisfy delay, jitter and packet loss constraints within a priority basis for transmission [5].

Telecommunication networks can be divided in service and transport layers in a multilayer representation that is presented in Figure 1. The service layer is a conceptual architecture for carrying network services as voice, video, data, M2M and is where MPLS over IP operates. The transport network considered is the Optical Transport Network (OTN) where the network elements are optical devices named as Reconfigurable Optical Add-Drop Multiplexer (ROADM). The IP/MPLS network elements are MPLS routers, which are detailed in Section II.B. The service network interacts with the transport networks to establish point-to-point connections. Most of service networks elements operate in the electrical domain while the transport layer elements operate in the optical domain. The service and transport layers are typically connected by 10 GbE or 100 GbE line cards that contains transceivers converting electrical to optical signals.

The logical connections between ROADM are defined as Light Paths (LP). The routing and wavelength assignment (RWA) algorithms have the purpose to maximize the number of LPs. The LP establishment problem is out of scope in this study. It is considered that a transport network provider will afford capacity services and the service network operator will purchase capacity \(C\) in the transport network to establish the network links \(E\) and to define \(G(V, E)\).
B. Multi-Protocol Label Switching

The Multi-Protocol Label Switching is a connection-oriented network whose elements are Label Switch Routers (LSR) for routers inside the network or Label Edge Routers (LER) for routers in the network border. MPLS uses a Label Switching technique to define virtual circuits to switch packets by consulting a label. The label defines the next hop direction based in the information stored in routers proceeding with a fast re-routing without consulting an IP address.

The Label Switched Path (LSP) is a unidirectional point-to-point connection in which are up to steer traffic along the network. The routers are advertised about network resources via the routing protocols like OSPF. The MPLS technology specifies the explicit path resources that should be used for a specific tunnel defined by the ingress node with a determined hop sequence. The LSP is the label assignment result determined by the Label Distribution Protocols.

MPLS provides constraint-based path computation at network layer in order to divert the traffic away from the congested links and optimizing the network load [6]. Congested links could be considered the links without enough residual capacity $R$ to support traffic demands $D$ or the residual capacity of the link that reaches a certain ratio for link utilization $R/C$.

The following example establishes four connections with different throughputs and services, starting from LSR1 and LSR2, respectively, with LSR8 router as destination. The traffic demands established are divided by two 750 Mbps VoIP flows ($d_{18VoIP}$, $d_{28VoIP}$) and two standard traffic flows of 250 Mbps ($d_{18}$, $d_{28}$).

![Example of LSP establishment](image)

A constrain for half link utilization is defined to balance the traffic to avoid the acceptance of new connections in links that exceeded 50% of its utilization. In impossibility of ensuring a traffic demand, i.e., all possible paths do not accomplish the service constrains, the demands have to be transmitted in best effort.

The demands $d_{18VoIP}$ and $d_{18}$ are allocated through the shortest path because the sum of both demands is 1 Gbps which does not reach the half link utilization of 1.25 Gbps. After these demands allocation, the network links has $R = \{r_{13}, r_{23}, r_{34}, r_{35}, r_{47}, r_{56}, r_{57}, r_{78}\} = \{1.5, 2.5, 1.5, 2.5, 2.5, 2.5, 1.5\}$ where $r_{xy}$ is the residual capacity from the link composed by the routers LSR$x$ and LSR$y$ measured in Gbps.

Consequently, the demand $d_{28VoIP}$ is the next in the queue with 750 Mbps. All links in the network has residual capacity above the half utilization and the shortest path will carry this demand. The link residual capacity is $R = \{r_{13}, r_{23}, r_{34}, r_{35}, r_{47}, r_{56}, r_{57}, r_{78}\} = \{1.5, 1.75, 0.75, 2.5, 0.75, 2.5, 2.5, 0.75\}$ after the $d_{28VoIP}$ allocation.

The links $e_{34}$, $e_{47}$ and $e_{78}$ are now above the half utilization and it is presented to carry a new demand $d_{28}$, with a standard traffic of 250 Mbps. The VoIP service used the shortest path between LSR2 and LSR8, which is now constrained for the standard services. The decision will be made in LSR3 and, as the link $e_{34}$ reached the half utilization, the traffic demand will follow through the link $e_{35}$, which is unloaded.

The specific case is in the LSR7 where the options are limited for reaching the LSR8. Before $d_{28}$ allocation, the link $e_{78}$ has a residual capacity of 750 Mbps, which is enough to carry this demand although it does not comply the constraint imposed to accomplish the SLAs.

C. Survivability

The survivability has a huge importance, since it indicates the capability of keeping the services after a failure occurrence or a resource degradation. Survivability can be classified as protection and restoration. Protection is a mechanism to anticipate a failure while restoration guarantees survivability after-the-fact with dynamic signaling recovery [7] [8] [9].

Protection is provided by the linear point-to-point connections. The linear protection is done at path or at section level that can be defined as dedicated or shared. The path linear protection establishes a connection between source and destination while section linear protection ensures link and/or node redundancy. The restoration is normally applied in networks with a physical topology and it is intended to find alternative paths to the paths with failures. This process is coordinated by the network control plane [10].

The path connection from a source to a destination node assuming no failures is denominated as working path, WP. The alternative path, which is used under the failure presence, is referred as protection path or backup path, BP [8]. The working and backup paths must be disjoint between each other, i.e., the backup path does not contain the links and/or nodes used in the working path.

Contrasting with the path protection, the section protection will locally recovery the working path. The section node protection provides an alternative path that surrounds the node with failure while the section link protection is an alternative path connecting the nodes that compose the failed link.

Dedicated protection ensures that will be available resources to entirely recover from the failure in working path, assuming that the resources of a protection path have not also failed [8]. The dedicated protection is divided in 1+1 and 1:1 protection schemes. In 1+1 dedicated protection is considered an active backup path where exploits the live redundancy, i.e, the working
and protection paths are transmitting the same traffic flow and the destination select the better of two paths. The 1:1 dedicated protection set the backup on hold without transmitting the traffic flow until a failure occurs on the working path.

The failures are detected in the end node, so the 1+1 dedicated protection immediately recovers from a failure while the 1:1 is slower because the end node needs to advise source to transmit through the backup path. However, the great disadvantage of 1+1 is the need of more equipment and transport resources to support two active paths [8].

III. ROUTING ALGORITHMS

The routing algorithms perform operations in a network graph \( G(V,E) \) to obtain the shortest path. The routing algorithm solutions can be heuristic or deterministic. The heuristics lead to achieve workable and efficient results as close as possible to the optimal solution given by deterministic solutions. The deterministic solutions as Integer Linear Programming (ILP) are unfeasible due to computation times.

The proposed algorithms studies the way to find the shortest path, multiple order of shortest paths (also considering path disjunction) and introducing constraints to the previous algorithms under analysis.

A. Shortest path

For the shortest path computation, the used algorithm is the Dijkstra. The Dijkstra implementation requires the network representation given by the physical topology \( G(V,E) \) and aims to obtain the shortest path for a cost metric. The Dijkstra algorithm is the solution that provides lower complexity for finding the shortest path if the edges have positive costs.

B. Multiple order of shortest paths

The objective in finding more than a single path with the lowest cost is frequently documented for solving the problem in determining more than a single shortest loop less paths. The Yen’s algorithm known as K-Shortest Paths obtains the K shortest loopless paths between a nodes pair.

The Yen’s algorithm appeals to Dijkstra algorithm to obtain the shortest path between a node pair on network. The difference in K-Shortest paths algorithm usage is based on possibility to compute the alternative paths starting from different deviation node. However, it does not guarantee path disjunction, being a disadvantage for dealing with path survivability applications. Therefore, if the intention is to guarantee a backup path with any nodes and/or links in common, the heuristic algorithm described below will be helpful and is the simple way to generate multiple K-Shortest disjoint paths [11].

The strategy for obtaining a disjoint path in \( G(V,E) \) is do not consider the links and/or nodes used in the previous computed path(s) while is running the Dijkstra algorithm. If the maximum source and end nodes degree is lower than the K value, it will be unachievable due to physical limitations.

C. Constraint-Routing

The idea behind Constraint-Routing algorithms is to compute a shortest-path between a node pair under some constraint conditions. These constraints can be the residual capacity, the delay or availability of links. For example, if a given traffic demand requiring A units of traffic is routed over a link, whose residual capacity is less than A, then this is a critical link that must be disregarded for routing this demand.

Constraint-Routing can be applied inside the routing algorithms, validating the steps with constrains or simply modifying the input physical network topology \( G(V,E) \), by discarding the critical links that does not verify the imposed constraints. The physical network topology that considers that links are discarded is represented by \( G'(V,E) \).

Algorithm I intends to compute the K-Shortest Path restricting the links that not have enough capacity to support a certain input demand. The inputs to perform a path computation are the demand traffic matrix \( D' \), the K path level and the physical network topology \( G(V,E) \). The algorithm outputs are the paths and the blocked paths \( BIP \) for each path level \( K \). The purpose of this algorithm is to check, in between the \( K \)-Path levels, what is the path level \( K \) that converges in lower number of blocked paths.

<table>
<thead>
<tr>
<th>Algorithm I: ConstraintRouting for a K-Shortest Path</th>
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<tbody>
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<td><strong>Input:</strong></td>
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<td><strong>end</strong></td>
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The algorithm called in step 4 is the K-Shortest Path algorithm and obtains a number of K paths. However, only one path will be considered for demand allocation and the blocked paths. The K-Shortest Path algorithm might not output a path because the path was not able to be computed and the blocked paths counter must be incremented.

Algorithm II has the objective of computing the K Disjoint Shortest Path restricting the links that not have enough capacity to support a certain input demand. The inputs to perform a path computation are the physical network topology \( G(V,E) \), the demand traffic matrix \( D' \) and the maximum \( K \) path level for an alternative path. The algorithm outputs the blocked shortest paths and the blocked alternative disjoint paths \( (K > 1) \) that characterizes the working path and the backup paths in survivability. The purpose of this algorithm is to verify if it is possible to ensure a working and backup path.
Algorithm II: Constraint Routing with Survivability

Input: 
- \( G(V, E) \) – network physical topology;
- \( K \) – Maximum level of paths to compute;
- \( D^i \) – Traffic demands;

Output: 
- \( \text{Obtained Paths} \) – structure with the obtained paths;
- \( \text{BIP} \) – number of blocked paths;

Data: 
- \( p_{xy} \) – group of \( K \) paths;

1. begin
   2. for \( k = 1 : K \)
      3. for each \( D^i \) entry defined by \( d_{xy}^i \):
         4. Disable links with \( R < d_{xy}^i \) and the links in previous paths, \( p_{xy} = \{ p_{xy}^{k-1}, ..., p_{xy}^{1-1} \} \);
         5. Compute \( p_{xy}^k \) with Dijkstra;
         6. if \( p_{xy}^k = \text{NULL} \) then
            7. \( \text{BIP} = \text{BIP} + 1; \)
         8. else
            9. \( p_{xy}^k \to \text{Obtained Paths}; \)
         10. end
         11. if \( k < K \) then
             12. Remove the demand \( d_{xy}^i \) from the R from links belonging to path \( p_{xy}^k \);
             13. Enable all links;
         14. end
     15. end
   16. end
   17. end

The algorithm is able to compute the number of paths that are not possible to establish under constraint limitations and, in this way, to calculate the number of blocked traffic demands, i.e., the traffic demands that do not assure the committed SLAs. The blocking ratio defined as the ratio between the blocked demands and the total demands can be used as a performance metric.

The alternative for blocking paths is the traffic demand transmission in best effort, violating the constraints. This algorithm can be useful for checking the network reliability in offering services with certain constraint levels and survivability if applied the \( K \) path level.

D. Analysis with Constraint-Routing

The simulations consider the blocking path ratio and the congested link ratio concepts. The blocked paths determine the blocking path ratio over the connections represented by each traffic demand. The congested link ratio are the number of links without residual capacity in all network links.

The analysis is done by varying the initial link’s residual capacity and using the constraints to routing algorithms previously described, considering a unitary full-mesh logical topology and a hop count metric for the Dijkstra and K-Shortest Path algorithms. The initial link residual capacity is the available capacity of a link before the capacity planning process. The networks used are the COST239, NSFNET and UBN.

The first simulation considers an initial residual capacity for each links with the objective of testing the capacity to draw all the demands through limited resources. Figure 3 considers the blocking path ratio as function of initial link capacity while Figure 4 is the congested link ratio for the same scenario.

With the initial residual capacity increasing, becomes easier to compute a path inside the network and the link congestion decreases. The COST239 network have 62% of congested links when all demands were successful assigned. For the same scenario, in NSFNET and UBN networks, the congested links percentages are 12% and 21%. The COST239, NSFNET and UBN network requires 4, 14 and 35 Gbps in each link to complete the allocation without blocked paths.

The K-Shortest path with residual capacity restriction also outputs the paths blocked. The thresholds for the initial residual capacity value ensures that any path is blocked or any link is congested. These values are presented in Table I and II.

| TABLE I. INITIAL RESIDUAL CAPACITY THRESHOLD FOR PATH BLOCKING |
|-----------------|----------------|----------------|
| COST239         | K=2            | K=3            |
| COST239         | 4              | 7              | 8              |
| NSFNET          | 14             | 24             | 24             |
| UBN             | 35             | 39             | 45             |

| TABLE II. INITIAL RESIDUAL CAPACITY THRESHOLD FOR LINK CONGESTION |
|-----------------|----------------|----------------|
| COST239         | K=1            | K=2            | K=3            |
| COST239         | 8              | 19             | 18             |
| NSFNET          | 18             | 45             | 36             |
| UBN             | 43             | 92             | 75             |

In COST239 network, the blocking ratio is 0% for an initial capacity of 4, 7 and 8 Gbps using the shortest path, the second and the third order paths, respectively. It means that for \( K = 2 \) and \( K = 3 \) are needed more network resources in relation to the shortest path to perform the traffic demand matrix allocation. The remaining networks also need higher resources in \( K > 1 \) to guarantee any blocked path.

The link congestion also follows the blocking ratio behavior. With \( K = 1 \), it is possible to have any congested link with initial residual capacity of 8, 18 and 43 Gbps for the networks under
analysis. Considering $K = 2$, the initial residual capacity values are 19, 45 or 92 Gbps and, for $K = 3$, these values are 18, 36 and 75 Gbps.

The following simulations will analyze the backup path availability after performing the allocation of the working path defined by the shortest path. The Figure 5 presents the blockage ratio for the disjoint backup path. The simulation considers that backup path resources are not allocated, performing a 1:1 linear path protection scheme. Note that only the traffic demands with working paths will obtain backup paths.

![Figure 5. Blocking path ratio for the shortest disjoint path](image)

The disjoint backup path can be planned for all demands if the initial residual capacity is 5, 15 and 38 Gbps for COST239, NSFNET and UBN, respectively. These values are interesting to service network provider because in the results that have 0% of blocking ratio, the SLAs commitments are accomplished and also ensures the service continuity in case of occurrence of any failure in working path.

According to threshold values of Table I, in order to guarantee network resilience, i.e, the establishment of a working and a backup path, is necessary to upgrade the COST239 and NSFNET network in 1 Gbps. In UBN are need 3 Gbps resources plus in relation to shortest path allocation.

### IV. PLANNING TOOL

The planning tool has the objective of computing paths inside a MPLS network described by a graph $G(V, E)$ that will carry the traffic demands $D^t$. The software is divided in two modules, one for path computation and other for capacity planning. The software was developed in Perl language and is linked with a SQL database.

Path Creator algorithm computes a group of path $P$ for all network. The group of paths $P$ is an aggregation of the results from Path Finder algorithm that obtains the group of paths between the nodes $v_x$ and $v_y$, designed as $P_{xy}$.

After the path computation, the traffic demand matrix $D^t$ serve as input for the Capacity Planning procedure for demand simulations. A single or a group of n-LSP carrier a traffic demand $d_{xy}$, and the variation along the time. The allocation process follows Begin of Life with forecast planning [12] which contains the first period load and the growing factors for the $T$ periods.

Figure 6 presents a flowchart diagram for the Routing Model of the Capacity Planning process, considering the paths obtained in Path Creator algorithm and the network physical topology $G(V, E)$ as input. The traffic demand $(d_{xy})_n$ is defined with an index $n$ that corresponds to the algorithm instance, differentiating the demand division through $n$ alternative paths. The output are the link load $L$ and the group of paths $P_{xy}$.

![Figure 6. Capacity planning in Planning Tool](image)

The capacity planning process will ascending sort the paths obtained by the cost and descending by the maximum bandwidth $B$, considering a higher priority for the cost metric. The algorithm updates the residual capacity $R$ in links where were set a traffic demand and the maximum bandwidth $B$ for the paths that suffer changes in residual capacity.

The capacity planning process tries to allocate the demand $(d_{xy})_n$ in the first path on the list $P_{xy}$. If the $P_{xy}$ has insufficient bandwidth for the traffic demand, the algorithm will fill the $P_{xy}$ with $(d_{xy})_0$ and the remaining traffic $(d_{xy})_1$ will be distributed on the following paths. In the case of not having enough maximum bandwidth in the path to satisfy the traffic demand, it will be purchased the required capacity in $P_{xy}$.

Path resilience is an implemented feature introduced to the planning tool provided. This feature is related with survivability and, as mentioned before, the survivability mechanism applied is the linear path protection described by the 1:1 and 1+1 protection techniques. The linear 1:1 path protection sets a protection paths $P_{xy}$, this feature is related with survivability and, as mentioned before, the survivability mechanism applied is the linear path protection described by the 1:1 and 1+1 protection techniques. The linear 1:1 path protection sets a protection paths $P_{xy}$, which covers the traffic demand and is calculated in the following way:

$$
(d_{xy})_n = (d_{xy})_0 - \sum_{i=1}^{n-1} (d_{xy})_i
$$

Figure 6 presents a flowchart diagram for the Routing Model of the Capacity Planning process, considering the paths obtained in Path Creator algorithm and the network physical topology $G(V, E)$ as input. The traffic demand $(d_{xy})_n$ is defined with an index $n$ that corresponds to the algorithm instance, differentiating the demand division through $n$ alternative paths. The output are the link load $L$ and the group of paths $P_{xy}$.
Figure 7 is the representation of the implemented 1:1 linear path protection. The inputs regard the network physical topology $G(V, E)$ after the demand assignment in a group of working paths $P^1$ with its correspondent loads $L$ and residual capacity $R$ for period $t$. The path resilience algorithm for linear 1:1 protection computes the backup paths $P^2$ for all periods and outputs the number of blocked paths.

The implementation of this feature will allow knowing the capability of the network in answering to failures, considering the existing capacity planning. The path resilience process for 1:1 do not allocates resources, since all disjoint paths will take in consideration the same residual capacities. A link or node failure might cause drops in a group of paths. Under this statement, it is complicated to assure that link have capability to support all the backup paths that it might carrier.

The linear 1:1 path protection is commonly used for network auditing when it is intended to observe the resilience of the network. It is used only the first level of resilience for the tentative of assuring a single backup path. However, Algorithm II may test the network for higher levels of resilience.

The linear 1+1 path protection is implemented in the planning tool. Though this protection technique over duplicate the network load, it should be analyzed if is a model to consider. The flowchart in Figure 8 represents the functioning of the 1+1 implementation. The inputs regard the network physical topology $G(V, E)$ after the demand assignment in a group of working paths $P^1$ with its correspondent link’s load $L$ and residual capacity $R$ for period $t$. The path resilience algorithm for linear 1+1 path protection computes the backup paths $P^2$ for all periods and outputs link load $L$ after backup path allocation.

The concept introduces the need of allocating the backup demand and assures the obtainment of it. The 1:1 is observing the network in a passive way, i.e., the technique will not change anything in the network while the 1+1 significantly congests the network resources.

V. ANALYSIS OF RESULTS

The capacity planning simulations consider a traffic demand matrix $D^t$ for a group of periods $T = \{t_0, \ldots, t_{10}\}$ with an initial demand of 1 Gbps and a growing percentage of 50% from the previous period. The links of the networks start with a residual capacity of 100 Gbps. A new network named AFR is based in a real network and has its own $D^t$ and $R^t$.

The AFR demands variate from 0.25 to 31.25 Gbps with growing percentages of 0.6% to 6%. The initial residual capacities of the links take values from 15.52 to 10476 Gbps. The capacity planning procedure obtains the working path (WP) used to carry a traffic demand. The next simulation considers linear 1+1 path protection. The backup path (BP) for a period $t$ is computed considering the residual capacities of links after the capacity planning in the same period. The working paths considered are the obtained for demand allocation in the period $t$.

The results of Figure 9 consider the network load for a scenario without protection and other with an active WP and BP.

The network load curve is higher considering path protection. Since the protection curve contains the curve without protection, considering positive load quantities, the curve slope with protection is obligatorily equal or higher than the slope assuming only the working path. For AFR scenario observation, the protection load is growing more than the one obtained in capacity planning process. For the period $t_0$, the difference between both cases are 17.6 Tbps while, in period $t_{10}$, it is observed a difference of 24.3 Tbps.

Figure 10 presents the percentage of load considering protection over the case that is not considered.
The network load increases to above the double. The load variation of 150% is represented by the load duplication and the remaining 50% is associated to the growing percentage defined for COST239, NSFNET and UBN networks. The growing percentages are around 4% in AFR network.

Figures 11 and 12 represent, respectively, the maximum link load and the capacity need to be purchased to the transport network provider. The capacity costs are presented in consumer units (c.u.) and reflect a calculation component of transport layer CAPEX based in [13]. These components are divided in capacity packets which costs considers OTN line ports, long-term transceivers, transponders and fixed costs. The capacity packet used were the 10, 40 and 100 GbE with, respectively, 14.45, 24.43 and 44.60 c.u..

The maximum link load follows the same proportions of network load. The purchased capacity cost graphs aims to give an idea about the costs necessary to spend in order to guarantee link capacity for the protection paths. Along the time, the interface capacities have been increasing and, in this work, is not reflected any devaluation on equipment and costs.

Nevertheless, the purchasing periods are anticipated for a network with protection in relation to the network without protection. In COST239, the purchasing moment happens in the period $t_7$ with protection while without protection is only acquired capacity in period $t_8$. The purchasing moments in NSFNET are in periods $t_3$ and $t_4$. For UBN network, both purchasing moments are in $t_3$ but, with the protection scenario, the resources required are a little more than the double in relation to without protection.

Figure 13 presents the relation for the purchased capacity cost with and without protection along the project periods. Only it is represented the relation for AFR network due to the constant purchasing moments that not happen in the remaining networks as shown in Figure 12.

The cost difference between the case with 1+1 protection and without protection is the decreasing along the periods. The decrease of the cost variation does not mean that the capacity needs will decrease. The resources purchased for the supporting working path can be also used for the backup path. This fact might be correlated with the capacity expansion implemented to compute the optimal capacity for the capacity to be allocated. The optimal capacity is always higher than the capacity to be allocated.

The next result considers the 1:1 linear path protection with time variation. For each period $t$ is presented the blocking ratio.
for the backup paths considering the number of working paths determined by the traffic demands. The corresponding blocking ratio is graphically represented in Figure 14 for each period belonging to T.

The obtained values are concordant with the ones obtained in previous sections for capacity planning allocation. As much the link load is exponential for COST239, NSFNET and UBN, the blocking ratio is the inverse. In fact, with the network load increase, the resources start to be short to fulfill the exigencies of getting a disjoint path with maximum bandwidth for a traffic demand. The blocking ratio starts to be above zero at the previous moment that it is necessary purchasing capacity to transport network provider as demonstrated in Figure 12.

AFR network results are an exception since the demands and the initial residual capacities starts from a different basis. As mentioned, the AFR demands variate from 0.25 to 31.25 Gbps with growing percentages of 0.6% to 6%. The initial residual capacities of the links take values from 15.52 to 10476 Gbps. However, as seen in Figure 9, the load is described with a close straight-line representation with positive slope. The load variation from period t₀ and t₁₀ is below than 10 Tbps. For this network, the blocking ratio starts in 83% and, as seen in Figure 14, there are purchased capacity in t₀. The decrease on variation is justified by the capacity expansion over the needs.

The numeric values for the working and backup paths fleets due to the propriety, in used routing model, of dividing a demand through multiple n-paths as detailed in Figure 6.

VI. CONCLUSIONS

With the constant increase of traffic and constant necessity to improve efficiency and network robustness, it is important to provide a correct dimensioning of a network to ensure the service availability, accessibility and retainability. This work intended to introduce the survivability problem in a planning tool for MPLS networks. To accomplish this goal, a new feature that computes alternative disjoint paths was implemented.

Section II describes the basic concepts and the terminology used in the work. The service and transport layer were introduced to understand the multilayer approach with its associated costs. Label Switching for connection-oriented streams introduced the routing in MPLS. Survivability was also detailed, presenting the concepts of working and backup paths. Section III approached some routing algorithms which were adapted to introduce constraints that limit the routing through the paths that not accomplish the imposed requirements. Simulations were done for different routing metrics, networks and algorithms to conclude aspects about network resources usage. Section IV applies the studied algorithms in the planning tool, simulating different routing algorithms and introducing survivability. Section V presented the results of the network planning tool simulations.

The results of Chapter III demonstrated that restricting the obtaining paths with residual capacity constraints, it has changed the network load configuration. The constraints perform a distribution of demand through links with residual capacity and this idea might be applicable to an optimization based in balancing. For multiple paths, the second and third shortest paths need more resources to fulfill the demands than the used in the shortest path. For establishing the first disjoint path, it is also necessary to spend more resources than the shortest path.

Related to simulation in the Chapter V, it is assumed that capacity planning process obtains the working paths. The backup paths are obtained with 1+1 and 1:1 protection techniques. The network load has an exponential behavior in capacity planning process, the backup blocking ratio is inversely proportional to the network load. The 1+1 protection simulations have an effect of network load over duplication.

As a final conclusion, the analysis of the routing algorithm allows the implementation of a survivability feature. With this feature, the service network provider can evaluate its network doing a resilience study about the network connection regarding 1:1 path protection. The service network provider can also dimension its network for 1+1 path protection based on load of the allocation of backup paths.

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