Performance Analysis of a Traffic Engineering Solution for Multi-Layer Networks based on the GMPLS Paradigm

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Abstract— **This paper presents the performance analysis of a Traffic Engineering (TE) system for new generation multi-layer networks based on the GMPLS paradigm. Such a TE system aims at dynamically reacting to traffic changes and, at the same time, fulfilling QoS requirements for different classes of service. The proposed solution consists of a hybrid routing approach and a bandwidth management strategy. The former makes use of both off-line and on-line methods to accommodate traffic requests, while the latter, based on an "elastic" use of the bandwidth, allows to handle different priorities among data flows. Pre-emption mechanisms and traffic re-routing permit the accommodation of the largest amount of traffic, while guaranteeing good performance to mission critical services. The main building blocks and the operations of the system are reported and the major advantages are discussed.**

I. Introduction

It is generally accepted that traffic will be increasingly dominated by Internet-based services, with respect to traditional voice traffic, owing to the increased adoption of high-speed access technology and the migration of more and more services towards the Internet Protocol (IP). As a result, Next Generation Networks (NGNs) will have to be IP-centric and provide multi-service capabilities, that means being able to support several types of traffic with different requirements in terms of Quality of Service (QoS) [1]. However, IP is a connectionless, best-effort technology that was not designed for voice or any other real-time service. Thus, a new generation IP-based infrastructure has to be developed.

Since Internet services will be the dominant portion of traffic, its characteristics must be taken into account in the design of the NGN [2]. In particular, the unpredictability and instability of Internet traffic, demand for new requirements for NGN: flexibility and ability to promptly react to traffic requests changing with time. Over-provisioning, that is the common solution to the problem of unpredictable bottlenecks in nowadays telecom networks, it is not a cost effective solution for new generation networks.

Moreover the migration of all services over IP, including the real time ones, requires guaranteeing QoS for a sub-set of services that should be comparable to that one provided by the telecom based networks nowadays.

In order to overcome such challenging requirements a key role is played by advanced Traffic Engineering (TE) strategies, able to dynamically route the traffic over the network in order to minimize congestions and to optimize the use of the network resources, while at the same time guaranteeing a certain grade of service, handling traffic fluctuations and offering multi-service capabilities [3].

A promising solution to actualize TE in NGN is given by Generalized Multi-Protocol Label Switching (GMPLS) paradigm. GMPLS extends the features of the well-known MPLS technique [6][5] to both packet and circuit switching network, providing a common set of IP based protocols to control heterogeneous network such as ATM, SONET/SDH, and WDM [21]. In principle, GMPLS can improve network performance through multi-layer TE, allowing the integration of the control plane of different layers, which were previously considered and managed as completely separate domains. However, in practice, the definition and analysis of a TE strategy exploiting the capabilities of GMPLS is a very challenging task. Many papers deal with specific TE functions such as routing, wavelength assignment, pre-emption algorithms [8][9][10][11]; in [12] a solution combining specific TE functions in an integrated strategy has been proposed, describing its building blocks and mode of operations, and discussing its characteristics. The goal of the present paper is addressing the technical details and the performance analysis of the solutions proposed in [12].

This paper describes in section 2 the reference network scenario, and in section 3 the realization of the network solution previously reported in [12], addressing the above-mentioned issues, by exploiting the GMPLS network model, in a multi-layer scenario. Section 4 reports the results of the performance analysis accomplished by means of a simulation tool. Conclusions and perspectives for future works are discussed in section 5.

II. REFERENCE NETWORK SCENARIO

It is widely recognized that MPLS technology together with proper constraint-based routing solutions enables advanced TE capabilities and support of QoS, in an IP-based network [13]. In fact, MPLS allows explicitly routing a traffic request through the network by forcing it on a specific path according to user and network constraints and reserving the resources for that path. Basically, MPLS re-proposes the concept of virtual connection, previously introduced with ATM, but adopting IP-based signaling and reservation protocols [14][15][16]. The virtual connection established by MPLS is called Label Switched Path. The MPLS routers achieving label switching are named Label Switched Routers (LSRs). An LSP can be set up, torn down, re-routed if needed, and modified by means of the variation of some of its attributes, including the bandwidth [16]. Furthermore, pre-emption mechanisms on LSPs can also be used in order to favor higher priority data flows at the expenses of lower priority ones, to avoid congestion in the network [17]. Another important feature of MPLS relates to the possibility of stacking labels that provides the means of nesting an LSP into another one of higher hierarchical level [18].

GMPLS extends the features of the MPLS technology [21][22][23]. In particular, it can manage heterogeneous network elements, such as IP/MPLS routers, ATM switches, SDH/SONET elements, or even optical elements, using a suitably extended version of well-known IP protocol suite and exploiting the concept of nested LSPs, already available in MPLS context, that facilitates building a forwarding hierarchy [24]. This hierarchy is based on the switching capabilities of the devices' interfaces. At the bottom of this hierarchy, there are nodes that have fiber switch capable interface, then wavelength switch capable interface, and so on up to packet switch capable interface. Each LSP belonging to this hierarchy should start and terminate on similar devices.

As a result, heterogeneous LSPs are considered in the framework of GMPLS scenario, such as MPLS LSPs, ATM LSPs, and optical LSPs. The latter ones are usually named "lightpaths", and represent the optical channels spanning several OXCs and connecting an ingress OXC to an egress one at the WDM layer. As a result, in GMPLS context, a single instance of the control plane can span multiple technologies and a LSP of low order can be tunneled into an already existing LSP of higher order that acts as a link.

In principle, GMPLS can support different architectural models, according to different level of inter-working between the layers. The overlay and peer models represent two main cases [21]. The overlay model is based on a client-server approach, that means that the layers of the network have separated control planes and communicate, one to each other, by means of a standard User Network Interface (UNI) [25]. For example in case of IP/MPLS over WDM network, the optical layer provides connections to IP/MPLS in order to satisfy its traffic requests. On the contrary, in the peer model a single control plane can manage the two layers in an integrated and homogeneous way. This means that all the network elements act as peer devices, sharing the same complete topological view. The overlay model is suitable for an environment of multiple administrative domains, but leads to a less efficient use of the network resources because of the separation of the two control planes. On the other hand, the peer model allows a coordinate routing between the two layers, leading to a more efficient resources utilization taking advantage of multi-layer traffic engineering. The price for that is a huge amount of information that has to be handled by any network element.

The traffic engineering solution proposed in this paper can be in principle favorably applied in both the architectural models, but finds its natural application in a network based on the peer model.

For sake of simplicity, but without loosing generality, in this paper a two-layer network is considered as reference scenario. It consists of an IP/MPLS layer, whose network elements are LSRs, and a WDM transport layer, whose nodes are OXCs as depicted in figure 1.

From a routing perspective, GMPLS is adopted to provide flexibility and efficiency in the use of network resource. In fact, GMPLS can exploit Constraint-Based Routing (CBR) concept, already developed in MPLS based networks, and multi-layer routing. CBR allows the calculation of the LSP routes taking into account of network status and user constraints, (e.g. the actual link occupancy and the bandwidth requirement), by means of an extended routing protocol, (e.g. OSPF-TE). Hence, CBR may find longer but less congested paths instead of heavily loaded shortest paths, leading to a more uniform traffic distribution through the network and preventing congestions. Multi-layer routing allows considering the MPLS layer and the optical layer jointly, so that in a single routing instance an LSP can be routed on a concatenation of optical paths, leading to a more effective use of network resources.

Moreover in order to efficiently deal with QoS requirements, GMPLS can take advantage of suitable extension of signaling protocol, (e.g. RSVP-TE), to allow the reservation of network resource, and priority mechanisms to assign resources to higher priority LSPs at expense of lower priority LSPs, if necessary.

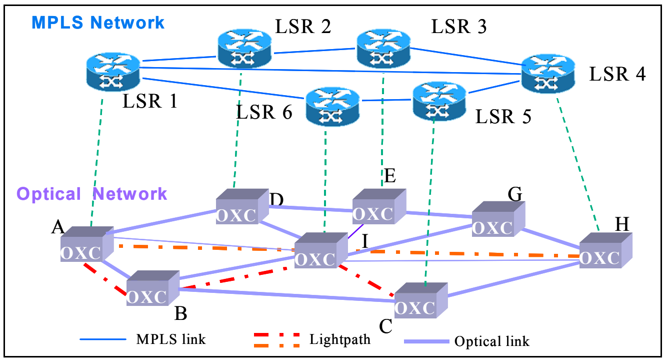

Figure 1. Multi-layer reference network scenario

III. TRAFFIC ENGINEERING SYSTEM FOR NEW GENERATION MULTI-LAYER NETWORKS

The main goals for a TE system in new generation networks are the optimization of the use of network resources, the actualization of the "bandwidth-on-demand" concept, and

Identify applicable sponsor/s here. *(sponsors)* the support of different classes of service by guaranteeing the required QoS. The proposed TE system aims at solving those issues, by means of a hybrid routing approach, based on off-line and on-line methods, and of a bandwidth engineering system that, by adopting an "elastic" use of the bandwidth resource and priority mechanisms, allows QoS requirements to be fulfilled.

The key idea of the hybrid routing derives from the consideration that the traffic entering a new generation network can vary with time, both in a predictable way (e.g. flexible VPN whose connections are expected to vary in a planned way) and in an unpredictable way (e.g. typical Internet traffic). In general, the traffic that varies in predictable way, as in the case of traditional voice traffic, can be efficiently accommodated through an off-line routing. An off-line approach is adequate for achieving a global optimization of route calculation based on a foreseen traffic matrix. The global optimization typically requires some computing time that increases with the network and traffic size, but it allows exploiting the network resources in an optimal way, particularly when a multi-layer approach that finds a route considering concurrently the MPLS and optical layers is adopted.

Unfortunately, a pure off-line approach can result unsatisfactory in the case of Internet traffic, that is quite unpredictable and unstable, or more generally, when the foreseen traffic matrix strongly mismatches with the actual traffic entering the network. Over-provisioning is a common solution to the problem of unpredicted bottlenecks, but it does not seem a viable and cost-effective solution for the new generation IP-based network scenario.

On the other hand, a pure on-line routing approach, consisting in evaluating the route "on-demand", is more adequate to promptly react to traffic changes, but it does not lead to the same efficient use of the network resources as in the case of off-line approach, since it does not provide a global optimization.

In the proposed hybrid routing solution, the off-line and the on-line methods are combined to efficiently manage with both predictable and unpredictable components of traffic.

In the presence of more than one class of service, the flexibility provided by the hybrid routing can be enhanced by means of a Bandwidth Engineering (BE) module. The BE allows better exploiting network resources by taking advantage of an "elastic" use of the bandwidth and suitable priority and re-routing mechanisms, while at the same time fulfilling QoS requirements. In practice, the BE functions operate so that the temporarily unused reserved bandwidth of a higher priority LSP can be released and put at disposal of lower priority requesting LSPs, provided that the bandwidth is given back to higher priority LSP, when needed. In other words, the bandwidth attribute of any existing LSP can be varied on-demand according to specific traffic requests, leading to an elastic bandwidth attribute. As soon as higher priority traffic needs the released bandwidth, a procedure that handles pre-emption of lower priority LSPs is activated; moreover re-routing procedure can be used to move lower priority traffic on less-congested available routes, in order to serve as much traffic as possible. Essentially, the BE module accomplishes its functionalities by means of bandwidth modify mechanisms, pre-emption algorithms and re-routing operations according to a defined priority policy.

For practical purposes, in the rest of the paper two main groups of LSPs are identified. The LSPs belonging to the first group relate to the traffic with very tight QoS requirements, and they can be referred as HP (Higher Priority) LSPs. HP LSPs are guaranteed at any time and in any traffic conditions, whatever is their bandwidth attribute, up to the maximum value previously agreed by the SLA. Since the HP traffic behavior is regulated by the SLA, it can be considered as the predictable component of the traffic entering the network, and HP LSP routes can be calculated by means of the off-line procedure. On the other hand, the LSPs belonging to the second group of LSPs relate to all the other types of lower priority LSPs, and they can be referred as LP (Lower Priority) LSPs. These connections represent the unpredictable component of the traffic that can be estimated by means of statistical evaluations and measurements. The LP LSPs are not guaranteed and can be pre-empted if they are using the bandwidth required by the HP traffic.

In the considered TE solution, the off-line procedure is employed to configure the optical and the MPLS connections, based on the predictable traffic component and of an average estimation of the unpredictable one. Both HP and LP traffic are served on demand, but HP traffic routes are off-line calculated and fixed, while LP traffic routes can be dynamically changed according to the actual network status. In order to efficiently use the bandwidth capacity, the TE strategy allows that HP traffic consumes only the amount of bandwidth that it really needs and for the time it is necessary, and temporarily releases the unused bandwidth to LP traffic. Thus, bandwidth modify operations are dynamically performed for HP traffic, by means of the BE function that pre-empts those LP-LSPs to make available the required bandwidth for HP-LSP and tries to re-route the removed LP-LSPs on less congested routes. Bandwidth modify operations referring to a bandwidth decreasing request are achieved by known modify MPLS mechanisms and the released bandwidth is put at disposal for accommodating other requests.

To make clearer how the TE system operates, it is useful to give more details about the specific building blocks that constitute the TE system: hybrid routing and bandwidth engineering. The other elements needed to actualize such TE solution, which are the databases where the required information are recorded, are described in [12].

A. Hybrid Routing Solution

1) Off-line routing: the global path provisioning

The off-line routing is actualized by the global path-PRovisioning (PR) module, whose input and output are schematically sketched in figure 2. Essentially, the PR module designs the optical logical topology and calculates the LSP routes, according to foreseen LSP traffic requests and to the physical topology of the network. The foreseen traffic requests are originated either by agreements stipulated between client and network operator (HP LSPs) or by an estimation made through statistical evaluations (LP LSPs).

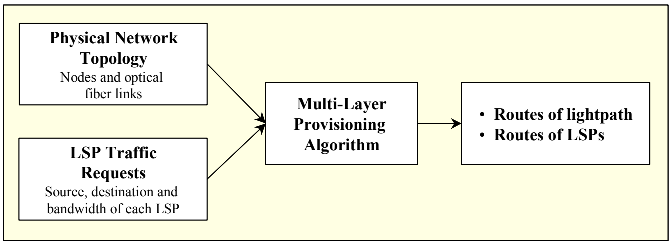

Figure 2. Sketch of the provisioning module

The physical topology of the optical network, assumed to be set during the network planning phase, is composed of a set of nodes connected by a set of links in a given mesh topology. Each link is a bundle of fibers between two adjacent nodes and a single fiber can support a fixed number of wavelengths. Each node can consist of either an LSR integrated with an OXC or a stand-alone OXC. The OXCs are assumed to have full wavelength conversion capability. Two types of ports can be recognized in each OXC: 1) inter-office ports, supporting fibers coming from or going to adjacent OXCs; 2) intra-office ports, connecting the OXC to the upper-standing LSR.

The output of the PR module consists of the set of lightpaths (i.e. λ LSPs according to GMPLS LSP hierarchy) that represent the logical topology of the optical layer, and the routes for all the LSPs groomed into the lightpaths of the logical topology.

Different objective functions can be defined for the path provisioning problem according to the network operator policy. For instance, the objective function could be the maximization of the efficiency of network resources consumption (optical resources, electrical resources or both), the minimization of the traffic lost, or the average packet hop distance [9] [10]. The specific objective function considered here is the minimization of the congestion on the network resources. Formally, it is defined as the maximum ratio between used and available resources over all the optical resources, that is, wavelengths on each optical link, ports incoming to each LSR node, and ports outgoing from each LSR node.

The PR algorithm operates in a multi-layer fashion. This means that the selection of the lightpaths and the calculation of their routes on the physical topology, are performed *concurrently* with the calculation of the LSP routes on the logical topology [26]. Clearly, solving the provisioning problem with a multi-layer approach increases the complexity of the algorithm, but it leads to a more efficient use of network resources.

A heuristic procedure has been used to implement the algorithm in the simulations. However, the "goodness" of the adopted method (i.e. the estimation of the distance between the obtained solution and the optimal one) has been tested by means of a comparison with an algebraic algorithm, achieved by solving the ILP formulation of the problem through the optimization solver CPLEX under different conditions. The results are reported in [26].

2) On-line routing: the dynamic path selection

The DR module evaluates "on-line" the route for the entering LP LSP request, expressed in terms of source and destination nodes, and bandwidth requirements, taking into account the updated link state status of MPLS and WDM layers.

For sake of simplicity, it has been assumed that the DR module cannot set up new lightpaths, but it can only operate on the logical topology derived during the off-line provisioning phase. As a result, the establishment of one or more lightpaths can only follow the decision of off-line providing a greater logical capacity to the network (e.g. when a new Internet Service Providers enters the network).

The logical topology provided by the PR module is enriched with the information of bandwidth availability on each logical link and on each lightpath constituting the logic link, learnt by a suitable extension of signaling protocol (e.g. OSPF-TE). In fact, as shown in figure 3, each logic link between two LSRs is constituted by a set of lightpaths connecting the two OXCs integrated with those MPLS nodes.

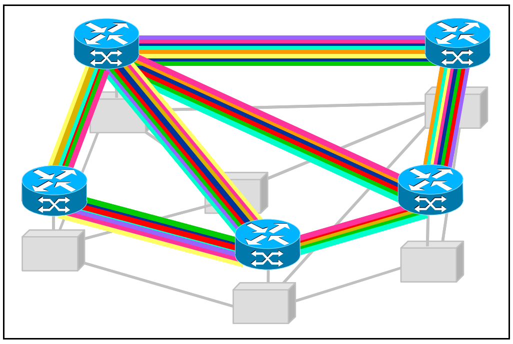

Figure 3. Logical Topology

The DR module aims at better utilizing network resources, by using less congested paths instead of shortest, but heavily loaded paths. In order to accomplish this, the DR algorithm has to concurrently satisfy two criteria:

- finding the shortest route that minimizes congestion, evenly distributing the traffic at MPLS layer.
- selecting the lightpath in the logic link, privileging the choice of more filled wavelengths in order to facilitate the accommodation of subsequent requests with more severe bandwidth requirements.

The two criteria can be fulfilled by using a shortest path algorithm with a weight function that takes into account of number of hops between the source and destination nodes in the MPLS layer, the capacity availability in logical links and the capacity availability on each lightpath in the logical link.

The weight function adopted in this paper has been derived by extending the least resistance routing weight method [8] to our GMPLS reference scenario, leading to the following formula:

$$w(i) = \frac{C^T}{C_i^A} + \begin{cases} 0 & if \quad C_{ij}^{A} \leq R \\ & \max\ j \\ \infty & otherwise \end{cases} \qquad (1)$$

where C_i^A is the available bandwidth in the MPLS link i (as the sum of individual spare capacities inside the wavelengths), C^T is the maximum link capacity in the MPLS network, R is the bandwidth required by the LSP, and C_{ij}^A is the available bandwidth in the *j-th* wavelength of the *i-th* MPLS link. According to the formula, the weight of a link increases as the available aggregated capacity of that link decreases, while it is set to ∞ when there is no wavelength, whose unused capacity is greater than or equal to the required one. If it can be found a route with a finite cost, the lightpath selection is performed by privileging the choice of more filled wavelengths [27].

It is worth noting that the DR module can be regarded as a CBR algorithm in which the constraint is the bandwidth requirement associated to that request. Since the DR operates in a multi-layer scenario, it has to consider that bandwidth constraint ranges in a continuous domain in the IP/MPLS layer, while the resource at the optical layer range in a discrete domain (number of wavelengths).

3) Hybrid Routing

It has to be highlighted that both the above described on-line and off-line routing modules aim at improving network performance (i.e. minimizing the utilization of network resources and the blocking probability), but while the former operates on the basis of a statistical estimation of traffic pattern, the latter operates on actual traffic requests. Clearly, the dynamic routing is able to handle the temporary congestion due to the increment of actual traffic volume and/or to the different traffic distribution among the nodes with respect to the estimated traffic considered in the provisioning phase.

To facilitate the integration of the PR and DR an opportune flexibility factor, α, is introduced during the provisioning phase. The basic idea is to suitably scale the physical topology during the off-line procedure by reducing the bandwidth of each wavelength, so that the PR module must select more lightpaths in order to accommodate the same amount of foreseen traffic. As a result, the task of the DR module is facilitated since it operates on an enforced topology, at the expense of an increment of physical network resources utilization. In other words, if the factor $\alpha \in [0,1]$ is introduced and if the wavelength capacity is b_w, the wavelength bandwidth used during the PR procedure, is limited to αb_w, while during the DR operation those lightpaths, constituting the logical topology, are considered with their actual bandwidth, i.e. b_w.

The value of the factor α, which leads to an improvement of the dynamic network performance with a minimum number of network resources, depends both on the network load and on the relationship between the expected and the actual traffic [28]. The impact of the factor α will be discussed in section 4, where the performance of TE are reported in different conditions, to test the robustness of the solution itself to promptly react to traffic fluctuations and unpredictability.

B. Bandwidth engineering

The TE system is based on an elastic use of the bandwidth [29]. This means that bandwidth assigned to higher priority LSPs during the provisioning phase, can be temporarily released for the amount of time in which it is not needed and put at disposal of all the other lower priority LSPs. This means that as soon as the HP LSPs require back their bandwidth, the TE system immediately has to satisfy that need in some way. In order to do that, a function that handle pre-emption of lower priority LSPs or, even better, that can move lower priority traffic on less-congested routes is needed. In [29] it was proposed a BE system for that scope, that in this paper has been integrated as a module invoked in a global TE solution. Specifically, BE makes use of two key elements: i) a bandwidth handling algorithm (BHA), which select those LP LSPs that need to be moved to make available the bandwidth required by the HP LSPs, and ii) the previously mentioned DR algorithm, which aims at re-routing those selected LP LSPs on alternatives paths. In this way BE allows bandwidth resource to be managed in an effective way, with the aim of both accommodating more traffic with respect to classic (non TE) networks, and guaranteeing the required QoS for different CoS.

In particular, the BHA is invoked when an HP LSP requires more bandwidth on its route and at least one link on that route is congested because of the presence of other LP LSPs. Its operation consists in selecting the LP LSPs that have to be moved and re-routed by means of the DR. It is applied on all the congested links of the HP path requiring more bandwidth. On each congested link, it works iteratively until there is enough free bandwidth to let pass the HP traffic. Parameters used to calculate weights are re-calculated in each step of the iteration. Several solutions have been investigated in [29]. The simplest one, herein considered, is an implementation of the MinConn algorithm reported in [30] for an IP/MPLS network. The BHA works as follows:

i) Search for congested links: it proceeds sequentially along the HP LSP, starting from the first link of the HP LSP path.

ii) Weight calculation of LP LSP, $w_{i,j}$, related to the *i-th* LP LSP on the *j-th* congested link:

$$w_{i,j} = \frac{B_{LP-LSP(i),j} - \delta_j}{\delta_j} \qquad (2)$$

where δ_j is the bandwidth to be released on the *j-th* link to accommodate HP LSP request, $B_{LP-LSP(i),j}$ is the bandwidth used by the *i-th* LP LSP, crossing the link *j-th.*

iii) Weight Sorting, by increasing order (taking into account the weight sign).

iii) Selection of LP LSP: if there exists at least one positive weight, the LP LSP with the lowest positive weight is selected to be torn down from the link under evaluation and the correspondent bandwidth is released on all the links crossed by that LP LSP. The selected LP LSP is submitted to a DR procedure so as trying to re-route it. If re-routing fails, the LP LSP is torn down from the network by the BE control. If there are only negative weights (when LP LSPs bandwidths are singularly smaller than the bandwidth to be free), iteratively, the algorithm selects more LP LSPs until the constraint of the bandwidth to be free is satisfied. Again, each selected LP LSP is passed to a DR procedure, which re-routes it. If re-routing fails that LP LSP is torn down by the BE control.

IV. PERFORMANCE ANALYSIS

In section 4.1, the details of the analysis environment are described. In particular, the network topology and the simulated traffic behavior for both HP and LP classes are presented.

Section 4.2 shows the achieved results for the multi-service network scenario, in which the proposed TE solution is applied.

A. Analysis environment

The physical network topology is depicted in figure 4. It is composed by N=8 nodes and L=12 bi-directional optical links. Each optical link supports 16 wavelengths, with a wavelength capacity equal to b_w=2,5Gb/s.

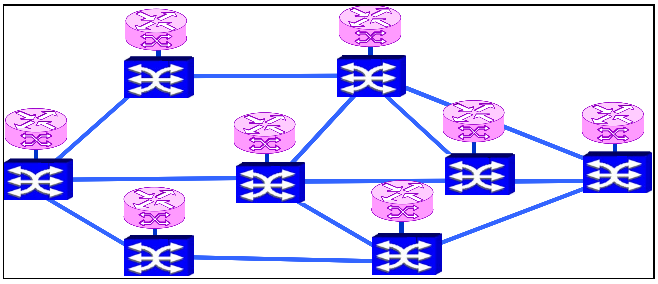

Figure 4. Network Topology

Both for HP and LP traffic, the offered traffic can be described by a traffic matrix, whose generic element B_{ij} is the aggregated bandwidth considering the set of LSP requests between node *i* and node *j*:

$$[B]^k = \begin{bmatrix} \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & B_{ij}^k & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix} \qquad k = HP, LP \qquad (3)$$

The sum of the bandwidth requested by all the LSPs for each pair of nodes is the Traffic Volume, *TV*:

$$TV = TV^{HP} + TV^{LP} = \sum_{i,j\in V} B_{ij}^{HP} + \sum_{i,j\in V} B_{ij}^{LP} \qquad (4)$$

In order to characterize the traffic entering the network, a network load parameter, ρ, defined as the ratio between the total offered bandwidth and the network available bandwidth has been introduced and given by:

$$\rho = \frac{\bar{h}\,TV}{C_{net}} \qquad (5)$$

where $\bar{h}$ is the average minimum distance between each pair of source-destination nodes, and C_{net} is the total available bandwidth on the physical optical network. It is worth to highlight that, in this paper, ρ refers to the occupancy of physical resources. As consequence the corresponding ρ for the logical resources is higher according to the formula described in[28].

In the simulations, the aggregated bandwidths are chosen randomly. In particular, for each pair of nodes, *i* and *j*, a random number uniformly distributed between 0 and 1, $C_{ij}\in[0,1]$, is picked so that the aggregated bandwidth of all the LSPs from node *i* to node *j*, B_{ij}^k, is $r^{(k)}C_{ij}$, where $r^{(k)}$ is a scaling parameter. The scaling parameter is chosen so that:

$$\sum_{ij} r^{(k)} C_{ij} = TV^k \qquad k = HP, LP \qquad (6)$$

According to the proposed TE strategy, the off-line procedure operates using as input the estimated traffic matrix, while the on-line procedures (LP set-up and HP bandwidth modify) operate using as input the actual traffic matrix.

In case of estimated traffic, B_{ij}^k represents the average expected aggregated bandwidth from node *i* to node *j*, determined by statistical evaluations, for the LP traffic; while it represents the maximum allowed amount of traffic from node *i* to node *j*, agreed by SLAs, for HP traffic. In the simulations, the estimated traffic matrix has been derived by generating a set of N_{ij} LSP requests with $b_{ij}^{(n)}$, representing the bandwidth associated to each LSP from node *i* to node *j*, so that:

$$\sum_{n=1}^{N_{ij}} b_{ij}^{(n)} = B_{ij}^k \, , \; b_{\min}^k \le b_{ij}^{(n)} \le b_{\max}^k \, , \quad k = HP, LP \qquad (7)$$

where b^k_{min} and b^k_{max} represent the minimum and the maximum estimated bandwidth requested by an LSP in case of LP traffic, while they represent the range values defined for the SLAs, for HP traffic.

In case of actual traffic matrix, it has been assumed for LP traffic requests that the connection arrival process between node *i* and node *j* follows a Poisson distribution, with rate λ_{ij} and the connection holding time follows a negative exponential distribution with mean $1/\mu$. The bandwidth of each LP LSP is uniformly distributed between b_{min} and b_{max}, with mean $b=(b_{max}-b_{min})/2$. Thus, the average aggregated bandwidth, B_{ij}, between *i* and *j*, can be expressed as follows:

$$B_{ij} = \frac{\lambda_{ij}}{\mu} b \quad (8)$$

In the simulations, by fixing μ, b_{min}, and b_{max}, from formula (6), it is possible to get λ_{ij} for each source-destination pair (i,j), and, hence, to generate the process.

For HP traffic, bandwidth modify events are generated for each HP LSP. The arrival time of bandwidth modify event is assumed to be uniformly distributed between t_{min} and t_{max}, with mean $t=(t_{max}-t_{min})/2$. The amount of bandwidth modify is uniformly distributed between b_{min} and $b_{ij}^{(n)}$, with mean $b=(b_{ij}^{(n)}-b_{min})/2$, where $b_{ij}^{(n)}$ is specified in the HP traffic matrix, and represents the SLA for each LSP.

Essentially, the traffic generation bases on the assumption that a traffic matrix, derived by SLAs, is at disposal of the provider for the HP traffic, hence the maximum actual traffic is assumed consistent with the estimated traffic used in the provisioning phase. In the case of LP traffic, instead, the actual traffic can exceed and/or mismatch in spatial distribution the estimated one. Thus, in order to test the robustness of the proposed TE solution, three relevant case studies corresponding to different relationships between estimated and actual traffic have been considered. In practice, the three cases differ from the level of accuracy of information available on both the traffic volume and the aggregated bandwidths:

- **Case 1**: it corresponds to have an accurate a-priori knowledge of the traffic behavior. That means that the information on both the traffic volume and the aggregated bandwidths between each pair of source-destination nodes are correct and, hence that $(\rho)_a=(\rho)_e$, $(B_{ij})_a=(B_{ij})_e$ where the subscripts, a and e, refer to actual and estimated traffic and the relation on the aggregated bandwidths is valid for each (i,j).
- **Case 2**: it corresponds to a case in which the information on the total traffic volume entering the network is correct, but it is not known how the traffic is distributed among the source-destination network nodes. That means that only parameter ρ is equal for the actual and estimated traffic: $(\rho)_a=(\rho)_e$.
- **Case 3**: it corresponds to the worst case where the estimation of traffic volume and of the traffic distribution among network nodes is incorrect. Specifically, it has been assumed that the estimated ρ is 25% less than actual ρ.

In all the simulations the value of the holding time, $1/\lambda$, is assumed constant for all the LP LSP connections and it is 200 *s*. The LP LSP bandwidths are assumed to be uniformly distributed from 1 to 500Mb/s. For the HP traffic, the average *modify* holding time for each LSP is 2% of the simulation duration. The HP LSP SLAs range between 1 and 500Mb/s and the modified bandwidth are assumed to be uniformly distributed from zero to the maximum bandwidth allowed by each LSP SLA.

In order to relate the HP and LP traffic load to the total network load a factor β has been defined, representing the percentage of HP traffic load with respect to the total network load such that:

$$\rho = \rho_{HP} + \rho_{LP} = \beta \cdot \rho + (1-\beta) \cdot \rho \quad (9)$$

In the next section results refers to the cases β=0.1 and β=0.5, that mean an HP traffic load corresponding to 10% and to 50% of the total network load, respectively.

B. Simulation results

The network performances have been analyzed for the three aforementioned cases and for two different values of β, in terms of the following performance parameters: the connection blocking probability and the optical network resources utilization.

The connection blocking probability is defined as the number of rejected connection requests with respect to the total number of connection requests. The optical network resources utilization is defined as the average ratio between the number of the used wavelengths and of the available wavelengths for each optical link.

By means of a simulative analysis, it has resulted that in order to make negligible the dependence of the simulation results on traffic matrix patterns, the simulative curves have been averaged on 20 different matrices.

Figure 5 shows the connection blocking probability and the network resources utilization versus α, for the three different case studies, when the TE strategy is applied. Two different network load conditions (ρ=0.5 and and ρ=0.8) are considered, assuming the HP traffic is a half of the total offered traffic (β=0.5).

When α=1, that means that no enhanced flexibility is introduced during the provisioning phase, the blocking probability has the highest value, while the network resources utilization shows the lowest value, for both values of ρ.

As the flexibility factor α decreases, the blocking probability improves at the expense of a corresponding increase of the resources utilization. In particular, an α value in the range [0.5-0.7] leads to an improvement of the network blocking probability of about 90% for ρ=0.5 and 30% for ρ=0.8 in the worst case (case 3). These results correspond to a reasonable increase of network resources utilization, i.e. 15 % for ρ=0.5 and 4% for ρ=0.8. It has to be noted that Case 2 and Case 1 show the same behavior in terms of resources utilization since during the network configuration phase the same traffic matrices have been used.

Altough Case 2 corresponds to a worse estimation of traffic distribution among the network nodes respect to Case 1, the difference in terms of blocking probability is small. Specifically, for values of ρ=0.5the distance between the blocking probability curves is of the order of 10^{-5}, while for ρ=0.8, it is in the range between 10^{-4} and 10^{-3}. Such a behavior is almost independent of α showing the effective cooperation between the off-line and on-line procedures without the need of using additional flexibility factor.

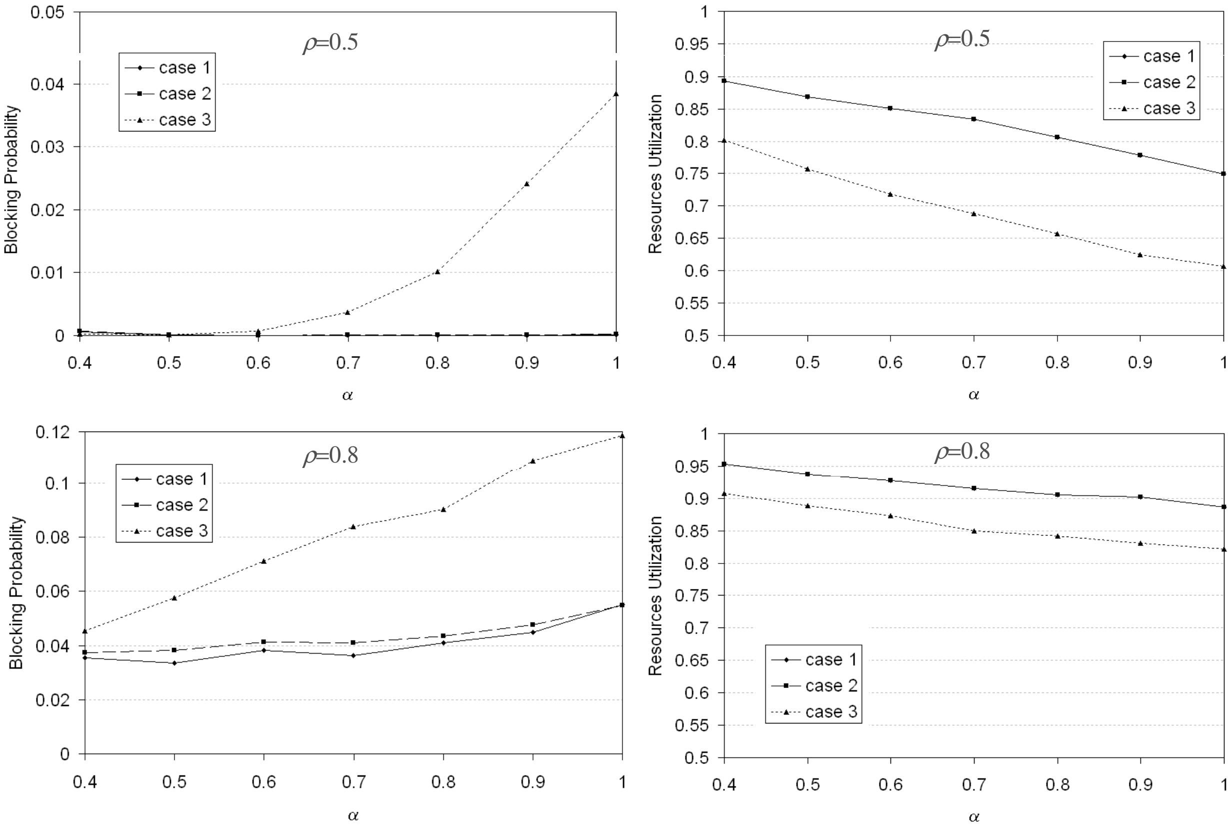

Figure 5. Connection Blocking Probability and Network Resources Utilization versus α, for the three different traffic relationship cases, with ρ=0.5 (up) and ρ=0.8 (bottom) and β=0.5.

It has to be noted that in Case 3 the blocking probability increases more rapidly as α increases than in the other two cases, especially for ρ=0.5. This means that when the traffic is badly estimated (Case 3 corresponds to a traffic under-estimation of 25% respect to the actual traffic volume) the role of α is more evident. In fact, as α decreases, the provisioning algorithm provides a logical topology that is "more meshed" respect to the case of α=1, thus it facilitates the task of the dynamic routing.

In each of the considered *case studies* the advantage provided by a flexible use of the bandwidth has been evaluated. In practice, the results obtained by making use of the proposed BE system have been compared with the results with a dedicated bandwidth (DB) approach. In the DB approach, the bandwidth reserved for the HP traffic cannot be accessed by the LP traffic requests, but it is completely dedicated to HP, even when the HP LSPs are not requiring the maximum bandwidth allowed by their SLAs.

In Figure 6 network performance improvement due to the adoption of the BE strategy with respect to a DB approach is shown with reference to Case 3, in which the need for a resource management strategy is more stringent due to a worse traffic estimation respect to the other two cases.

Figure 6 shows the performances of the BE solution with respect to the DB approach in terms of connection blocking probability versus ρ, for two values of β (β=0.1 and β=0.5) and with α=0.6.

For each value of ρ, it is evident the improvement obtained with the application of the BE approach, with respect to the DB approach, in both the cases β=0.1 and β=0.5.

In particular, the advantage of using the BE strategy respect to the DB approach is more evident when the parameter β is higher: in fact for a higher percentage of HP traffic respect to the total offered traffic (i.e. β=0.5) the amount of bandwidth that is at disposal of the LP LSPs is greater thanks to the BE approach. Specifically, for ρ=0.6 the adoption of the BE approach reduces the blocking probability of about 90% with respect to the DB approach in case of β=0.5 and about 24% in case of β=0.1. It has to be noted that, the improvement in terms of blocking probability due to BE leads to an increase of signaling messages in order to handle LP LSP pre-emption. In order to evaluate the amount of pre-emption that the strategy requires, in the figure 7 the percentage of pre-empted LP LSPs with respect to the total LP LSPs accommodated in the network, has been reported for β= 0.1 and β=0.5.

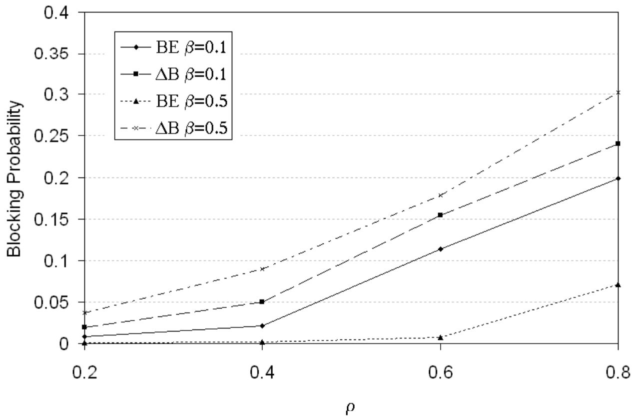

Figure 6. Comparison between the BE and the DB strategies in terms of Connection Blocking Probability versus ρ for different values of β in Case 3 with α=0.6.

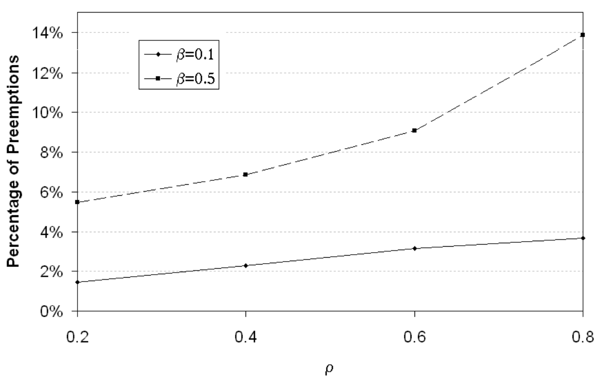

Figure 7. Number of Preemption Operations required in the case □=0.1 and in the case □=0.5, normalized to the average number of LP LSP requests.

Specifically, at ρ=0.6 the percentage of LP LSP that are pre-empted is about 9% for β=0.5, while it is 3% for β=0.1.

V. CONCLUSIONS

This paper reports the performance of a multi-layer TE strategy, which applies to a multi-service scenario in a GMPLS-based network. The features of the considered TE solution are based on two key aspects: a hybrid routing approach and a bandwidth engineering strategy. The former allows an optimization of the use of the network resources and, at the same time, an improvement of the dynamic performance of the network and the robustness against traffic unpredictability. The latter further improves the performance of the network by actualizing an elastic use of the bandwidth, so that the temporarily unused bandwidth by HP traffic is not wasted, but put at disposal of LP traffic. As a result, the TE solution guarantees QoS requirements to be fulfilled, while at the same time optimizes the use of the network resources, increases the flexibility of the network, and allows a large amount of traffic to be accommodated.

In order to test the efficiency of the considered TE solution the performances have been evaluated for different estimations of traffic volume and distribution respect to the actual traffic entering the network.

The simulation results show that, even in the worst traffic estimation case (Case 3), there is a range of values for the flexibility factor α, which lead to a blocking probability values very close to the cases in which a better traffic estimation is supposed (Case 1 and Case 2), with limited resource utilization. As an example, in case of ρ=0.5 the distance between blocking probability curves for the two extreme case studies is of the order of 10^{-4}, provided that α<0.7. This means that the TE strategy is quite robust against incorrect estimation of traffic volume and traffic distribution among the nodes.

Moreover, the proposed TE strategy allows accommodating a larger amount of LP traffic, while at the same time fulfilling QoS requirements on HP traffic, thanks to an elastic use of the bandwidth. Specifically, when the HP traffic is 50% of the total offered traffic, the blocking probability of the LP LSPs that are accommodated in the network is reduced of about 90% with respect to a dedicated bandwidth approach. It is worth to highlight that, although major advantages of TE strategy are achieved at high percentages of HP traffic, also when HP traffic is 10% of total traffic (β=0.1), the TE strategy still provides a reduction of blocking probability of 24%.

Furthermore, it has been calculated the number of LP LSP pre-emption operations required by the considered TE strategy as a function of traffic load, for different percentages of HP traffic. The results show that the number of pre-emption operations is low, thanks to a combined use of an effective hybrid routing that distributed the routes in suitable manner among HP and LP traffic, and a suitable selection criterion for pre-empting LP LSP by BE.

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