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ANALYSIS OF ELASTIC TRAFFIC
EFFECTS ON WDM DYNAMIC GROOMING
ALGORITHMS (extended version).

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Analysis of Elastic Traffic Effects on WDM Dynamic Grooming Algorithms

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Abstract—Traffic grooming in IP over WDM networks introduces a coupling between the optical layer and the IP layer. Grooming algorithms are normally studied with a very simple traffic model that completely ignores this interaction. This paper compares the performance of two simple grooming algorithms with a traditional, Poisson based traffic model and a more complex one that takes into account the IP traffic elasticity and the inherent interaction between the IP routing and the optical layer. Simulation results, supported by heuristic considerations and a very simple analytical model highlighting the interaction effects, show that ignoring the two layer interaction is not correct and may lead to wrong conclusions. Besides, it is shown that grooming algorithms that ignore the interaction between the IP and the optical routing, can lead to great resource waste, because the IP routing over the virtual, lightpath based topology, has no knowledge of the actual resource use, while the optical layer, when required to open a new lightpath ignores the overall traffic pattern, taking a decision that is based on a local optimum that may negatively affect later decisions.

I. INTRODUCTION

IP over WDM is one of the racehorses that pulls the train of large bandwidth networking. New services are continuously deployed over IP, and WDM evolution [1], [2] provides the transmission speed needed to pump the information through the network. One of the main issues in IP over WDM architectures, is the traffic aggregation or *grooming*. The traffic is generated as tiny trickles over IP, while the transmission pipe over a single λ within an optical fiber is enormous (devices driving an OC192 channel over a single λ are commercial), hence the IP and optical routing layers must interact, possibly dynamically, in order to exploit resources.

Many grooming algorithms were proposed in recent years (see [3], [4], [5], [6] to cite just a few), and compared one another, or simply against standard wavelength routed networks where no grooming is performed. Some works assume static grooming [6], [7], and generally tackle the problem with some optimization technique, while others assume that grooming is dynamic [5], [8], [9], [10]. All these works, however, simply disregard the elastic nature of TCP/IP traffic: IP over WDM is indeed modeled like a traditional circuit switched traffic!

As shown in [11], considering the adaptivity of traffic has a deep impact on the network performance and on routing algorithms in particular. The reason lies in the feedback

nature of the interaction of elastic traffic with the network: the network status (e.g., congestion) induces a reaction in the source behavior that, depending on the control signal¹ can be a positive or a negative feedback. It is obvious that a positive feedback has, to say the least, a noxious impact on performance, since congestion, or any other performance detrimental status, is exasperated by the positive feedback.

As usual in closed loop systems with delay, the nature of feedback (positive or negative) can change with changing conditions, so that, for instance, a negative feedback at low loads can change to a positive feedback at high loads, leading to instability phenomena.

The aim of this paper is to investigate how traffic elasticity impacts on some basic grooming algorithms and assess their performance in dynamic networking scenarios where the optical and IP level of the network interact one another. The problem in itself is rather complex, since it requires to take into account how competing groomed flows interact one another, e.g., sharing resources following a max-min criterion, as well as how the optical management plan behaves and assigns resources to traffic relations.

Elasticity in groomed traffic can arise due to a number of reasons and in very different scenarios. In emerging metro-area optical network, the foreseen trend is a very dynamic and aggressive use of optical paths, thus leading to traffic relations that are very close to a simple host-to-host IP flow².

In more traditional wide-area optical networks, where it is generally assumed that traffic relations are peering contracts between operators with highly aggregated flows, the elasticity still arise from the fact that all the flows within a traffic relation are elastic: if congestion arises, then all the flows will react reducing their offered load and the result is the overall elasticity of the aggregation.

In closing this introduction, we note that emerging applications such as GRID computing on metro-area networks, can indeed lead to scenarios where bandwidth-hungry flows are opened and closed with dynamics similar to normal TCP-IP flows, and WDM based optical backbones with dynamic routing capabilities will definitely need to take into account

¹We use the term “control signal” though it is not necessary to have a notification protocol to have feedback. Implicit signals, network measures, or simply source-destination interaction can carry the feedback information.

²We are not interested here in discussing whether such flows are based on UDP, TCP or whatever other transport protocol, we just notice that any recent discussion and proposal on transport protocols includes elasticity and end-to-end congestion control

the performance of elastic traffic when routing and grooming is designed.

The remaining part of the paper is organized as follows. Sect. II introduces the grooming algorithm we consider and shortly explain their heuristics; Sect. III describes the simulation tool we use for performance evaluation and how traffic elasticity is modeled without the need of actually transmitting packets, hence keeping simulations very fast. Sect. IV presents sample results and Sect. V ends the paper with some comments and possible extensions of the study.

II. GROOMING ALGORITHMS

The network architecture considered in this work is IP over WDM with dynamic optical routing, i.e., optical paths are opened on demand.

The optical level is based on Optical Crossconnects (OXC) interconnected by fiber links. Routing is shortest path with First-Fit wavelength assignment for the establishment of lightpaths. OXCs do not have wavelength conversion capabilities. The search for a lightpath is greedy, but it is terminated when a predefined maximum number of crossed links N_l is reached. This threshold is very important both to limit the complexity of routing and wavelength assignment and the waste of optical resources on very long lightpaths.

The IP level assumes traditional routers with shortest path routing based on the number of hops at the IP level, so that an optical path is seen as a single hop regardless of the number of OXCs it crosses.

There are two node architectures: a node can be a pure OXC, which allows to switch entire lightpaths from an ingress port to an egress port, or it can be a Grooming OXC (G-OXC), which supports sub-wavelength traffic flows and groom them onto wavelength channels through a grooming fabric. A G-OXC is also an IP router. We are not concerned here on the *technology* (optical or electronic) used for grooming, but transit traffic, which does not terminate in the IP router, can be groomed with incoming traffic. Low-speed traffic can then be transmitted or received only in G-OXCs.

In this architecture, a path connecting two routers in the IP layer is called a *virtual* or logical path, because is created over some established lightpath in the optical layer. IP traffic dynamically follows the virtual topology build by the optical level underneath. A G-MPLS [12] like control protocol is assumed, so that each node is always informed of the network status in term of wavelength usage and lightpath occupation. Using this information and the grooming strategy defined below G-OXCs decide whether a new traffic relation must be routed at the IP level or a new lightpath should be opened.

The decision to route the incoming requests over the existing virtual topology or to establish new lightpaths to create more room for them can lead to different network performances. A general analysis of different “grooming policies” is carried out in [5] under the hypothesis of bandwidth-guaranteed (circuit-based) traffic. When elastic traffic is considered, there is no obvious upper limit to the possible number of flows which is routed onto the existing logical layer. In this case, the need for the establishment of new lightpaths must be introduced based

on some suitable parameter. We introduce this parameter, called *optical opening threshold* th_o , as a threshold on the instantaneous throughput obtained by connections, defined as a fraction of the peak rate B_{M_i} required by each flows.

In this work we consider the following two grooming policies.

- *Virtual-topology First (VirtFirst)*. Each time a new IP request arrives in some router, the current virtual topology is considered first to route the request. If, once routed, the amount of bandwidth for some flow (not necessarily the one being routed) is less than th_o , a new lightpath is set-up between source and destination (if possible). If the setup is successful the IP request is routed over it (it is a one hop route at the IP level) and a new virtual topology is computed at the IP level. The new topology does not affect already routed requests (i.e., no re-routing is considered), but will be used for routing all new requests. If the new lightpath cannot be set up, then the request is routed based on the current virtual topology. Whenever a closing flow leaves a lightpath empty, the lightpath is closed too (after a suitable timeout) and the virtual topology is re-computed.
- *Optical-level First (OptFirst)*. Each time a new IP request arrives in some router, the G-OXC always attempts first to set up a new lightpath in the optical layer, in order to route the request over it. If no free wavelengths are available here, the IP router routes the incoming request over the current virtual topology. Indeed, a virtual topology is defined only when optical resources for the considered source-destination pair are exhausted.

As in *VirtFirst* if a closing flow leaves a lightpath empty, the lightpath is closed. The closing timeout is normally set to zero.

These two opposite policies have been often considered by different authors to perform comparisons with new grooming algorithms proposals or to study the impact of some specific network constraints, such as OXC node’s architecture. In this paper we considered them to study the impact of elastic traffic and analyze whether it affects them differently.

III. THE SIMULATION TOOL

The simulator we developed for this study, named GANCLES is described extensively in [13] and a web page [14] is maintained where the software will be made available starting July 2004, when the documentation is completed and more grooming algorithms are added and tested.

GANCLES is an extension of the connection level simulator ANCLES [15], developed at the Politecnico of Torino. The original version was meant for simulating ATM and IP traffic, providing several routing and CAC algorithms.

Several improvements were made to ANCLES over the years, some regarding the introduction of best-effort, elastic traffic as described in [11] and some related to the introduction of optical routing capabilities [16].

The detailed description of GANCLES is beyond the scope of this paper, thus we only give here some basic information about the key features enabling the study of grooming algorithms.

The key point required to jointly study the IP and the optical level is the capability of handling both a physical topology (a directed graph of links and OXCs) and a virtual topology (a directed graph of virtual links and the routers embedded in G-OXCs). The links of the virtual topology match lightpaths provided dynamically by the lower level. Dynamic grooming solutions presented in Sect. II (and others being added) correlate the optical and IP level during simulations.

Several optical routing and wavelength assignment algorithms are available on the optical level, even with protection capabilities. The IP level can be managed through standard IP routing algorithms, but also through MPLS based routing. In this work we use only very simple routing algorithms both at the optical and at the IP level. This is done to highlight clearly the interaction of grooming algorithms and elastic traffic.

When elastic traffic is considered, no admission control is enforced, and no backpressure on traffic sources is available, the network can become instable, as the number of flows within the networks grows to infinity and their individual throughput goes to zero. To avoid this risk, and to build a more realistic scenario, we introduced a starvation threshold th_s expressed as a fraction of the peak bandwidth B_M required by the flow³. If at some time instant one or more flows receive a throughput smaller than th_s (due to the arrival of a new flow), the elastic flow with the highest backlog is immediately closed. An important performance meter is the rate of flows interrupted this way. We call this meter *starvation* probability. Notice that if admission control is enforced, this simply means refusing the arriving flow instead of closing a flow as just described. The two actions are however not equivalent, because: i) the arriving flow may not be a starved one (e.g., has a smaller required B_M); ii) blocking is not influenced by the flow dimension, while the starvation is higher for larger flows; iii) starved flows waste network resources and may influence overall throughput, which is computed only on completed flows.

A. Traffic Models

We introduce two different models of elastic traffic. Both share the characteristic that a flow i arrives to the network with a backlog of data D_i to transmit and both include some form of elasticity, though very different one another.

The first model, that we name *time-based* (TB), assumes that the elasticity is taken into account only reducing the transfer rate when congestion arises. The flow duration is determined when the flow arrives to the network, based on its backlog D_i and its “requested bandwidth” B_{M_i} (e.g., the peak negotiated rate, or the access link speed) $\tau_i = \frac{D_i}{B_{M_i}}$. The effect of congestion is just that the throughput of flows is reduced, but their closing time is not affected. A consequence of this behavior is that the data actually transferred by a flow i is generally less than the “requested” amount D_i . This model is very simple and does not grab all the complexity of the closed-loop interaction between the sources and the network. It simply

³Notice that th_s is structurally identical to th_o introduced in Sect. II, but its meaning is very different and its numerical value can be different too.

models the fact that the more congested is the network, the smaller is the throughput the flows get.

The second model, that we name *data-based* (DB), assumes instead an ideal max-min sharing of the resources within the network at any given instant. Flows still arrive to the network with a backlog D_i , but the acceptance of a new flow will affect not only all the other flows on the same path, but indeed all the flows in the network, since the max-min fair share is completely recomputed updating the estimated closing time of all the flows in the network. The same applies when flows close, freeing network resources. This model includes the most important feature of elastic traffic, which is the positive feedback on the flows duration. The more congested is the network, the longer the accepted flows remain in the network. Congestion spreads over time enhancing the possibility that still further flows arrive in the network worsening congestion.

The DB model is clearly much more accurate, closely mimicking the behavior of an ideal congestion control scheme; however its complexity and computational burden are much larger, specially for high loads. Investigating whether (or under which conditions) the simpler TB model is accurate enough in the context of IP over WDM with dynamic grooming, or if it leads to gross approximations can be very important both for theoretic research and for practitioners.

IV. NUMERICAL EXAMPLES

As we shall discuss in Sect. IV-B, the phenomena involved in routing/grooming elastic traffic are rather complex, and often far from intuitive. As performance parameter we consider the following five: three at the IP level and two at the optical level.

T : The average throughput per flow

$$T = \frac{1}{N_c} \sum_{i=1}^{N_c} T_i$$

where N_c is the number of observed flows (e.g., during a simulation). Notice that in a resource sharing environment this is not the average resource occupation divided by the number of flows, since flows have all the same weight, regardless of their dimension.

p_s : The starvation probability. It is the probability that a flow is closed during its life because it is not receiving service with acceptable quality. A flow i will close and drop the network if its instantaneous throughput T_i falls below a threshold th_s expressed as a fraction of the peak bandwidth request of the flow.

N_h : Average number of IP hops per flow.

R_o : The ratio between the opening rate of optical paths and the arrival rate of flows at the IP level. It is a measure of the optical level routing effort. For an optical routed network without grooming $R_o = 1$, while for a purely IP routed network $R_o = 0$.

N_{l_o} : Average number of links per optical path.

Clearly, the goal of a grooming algorithm is maximizing T while minimizing p_s , R_o and N_{l_o} .

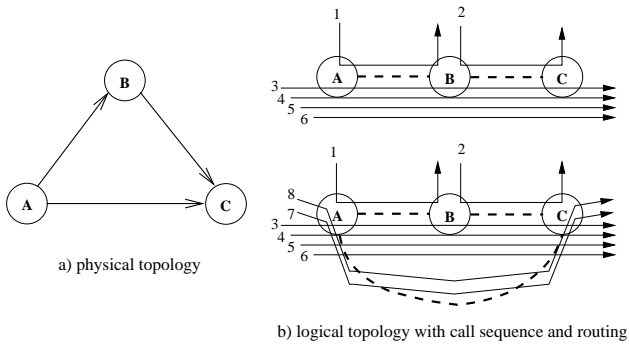


Fig. 1. Simple 3-node topology used for the theoretic verification of results

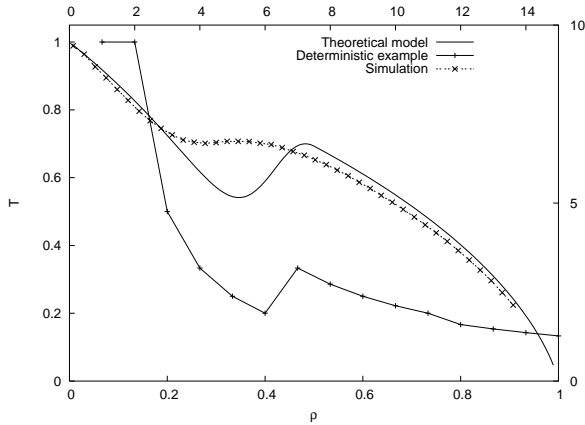


Fig. 2. Average throughput computed deterministically, via simulation and with a simple stochastic model for the scenario depicted in Fig. 1 a)

Before discussing results on a mesh topology, we highlight some peculiar behavior of the *VirtFirst* grooming in a very simple scenario, that will help in interpreting results in more complex scenarios.

A. A Trivial Example

Consider the simple 3-node topology of Fig. 1 a), where only a single wavelength per link is present and the active traffic relations are only A–B, B–C, and A–C. Assume that *VirtFirst* grooming is used and, starting with the network empty, the following sequence of flows arrives: AB, BC, AC, AC, AC, AC, ... (AB identifies a flow originating in A with destination B and so on). We set $th_o = 0.2$ and $th_s = 0$ and all flows are able to fully exploit the optical path capacity. The average throughput obtained by flows is represented by the solid line with cross marks in Fig. 2 (this curve refers to the top x-axis and left y-axis), as can be easily seen following the logical topology evolution reported in Fig. 1 b).

This example show that with *VirtFirst* grooming, it is possible that T increases while the load increases due to the interaction between the IP and optical layer. However, a deterministic example is not enough to draw conclusions. In order to investigate further in the behavior, we have set up a simple (and approximate) queuing model of the same scenario based on processor sharing queues that mimic the max-min resource division. In order to simplify the analysis, we assume that a lightpath is always open on the links A–B

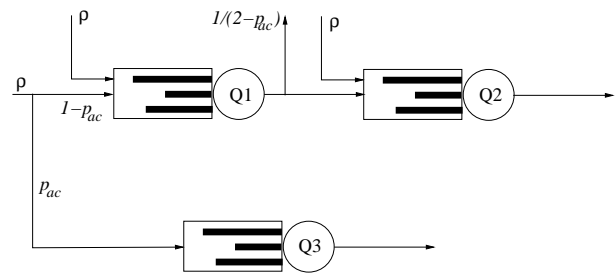


Fig. 3. Queuing model corresponding to the simple scenario of Fig. 1

and B–C. With this assumption the queuing network depicted in Fig. 3 represents fairly well the behavior of the network we consider. Assume the three traffic relations offer the same load ρ (normalized to the optical path capacity) to the network⁴. Queue Q1 represent the lambda on link A–B, queue Q2 represent the link B–C and queue Q3 represents the link A–C. All queues are M/M/1-PS. The routing probability p_{ac} describes the fact that with *VirtFirst* grooming and lambdas always open on A–B and B–C links, the AC traffic is routed over A–C links only when the th_o threshold is hit, then it is routed on A–C until this link empties and the relative optical path is closed. $th_o = 0.2$ means trying to open a new lightpath when a new flow would lead some existing lightpath to have more than $N_o = 5$ flows on it.

The exact computation of p_{ac} is complex, because it is in fact due to the superposition of transients and it is not a steady state probability, as the simple model assumes. We approximate it starting from the clients distribution in queues Q1 and Q2 when all traffic is routed through A–B, B–C, and assuming that flows are routed over A–C only when there are more than N_o flows either on A–B or B–C links. The simple model assumes that Q1 and Q2 are independent (which is not true in reality, since flows cross both links, and hence occupies both queues, at the same time), which implies $p_{ac} = 2p_t - p_t^2$ where $p_t = (2\rho)^{N_o}$; $\rho < 0.5$ or $p_t = 1$; $\rho \geq 0.5$.

The M/M/1-PS average throughput is computed following the approximate formula derived in [17].

Fig. 2 reports, beside the simple deterministic example, results obtained with the simple stochastic model and with simulations (DB traffic model) for $th_o = 0.2$. The simulation curve does not show the same increase in throughput around the load $\rho = 0.5$ displayed by the model (however, we have observed it for much smaller thresholds). The reason is that the dynamic routing of flows makes the transition from routing the AC traffic mainly through A–B and B–C to routing it mainly over A–C smoother than in the approximate model. In this case we set $th_s = 0$, so that $p_s = 0$. Given the simple scenario $N_{lo} = 1$, while R_o and N_h are not of much interest.

This simple example give some insight on the complex behavior of grooming associated with elastic traffic, which, to the best of our knowledge was never observed in other works, that, using constant-bit-rate like traffic models, cannot

⁴The model can cope with different loads on traffic relations; however, the focus here is not on the model capabilities but on the explanation of grooming algorithms behaviors in IP over WDM networks hence we keep the model as simple as possible.

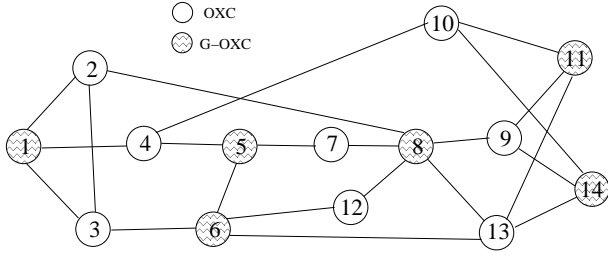


Fig. 4. NSFNET network

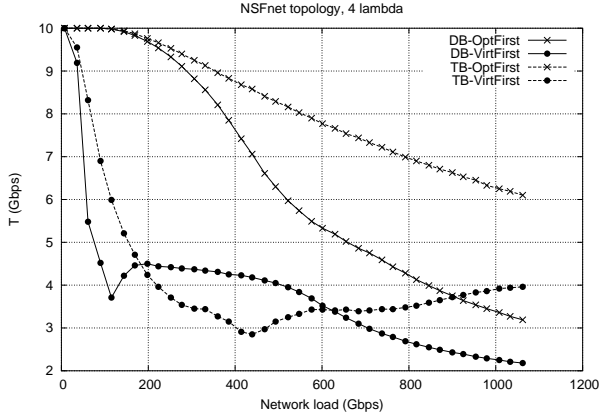


Fig. 5. Average throughput T for the DB and TB traffic models for the two grooming policies

observe throughput performance. In the following we study a more realistic scenario (by simulation only), to gain more insight on grooming and elastic traffic interaction.

B. Results for Mesh Topologies

We present results obtained on the NSFNET network [18] shown in Fig.4, which has 14 nodes and 21 fiber links. Each fiber carry up to 4 wavelengths, and only 6 nodes out of 14 have grooming capability, i.e., they are G-OXCs. Each wavelength has a capacity of 20 Gbps. A best-effort traffic source is connected to each G-OXC, opening flows with $B_M = 10$ Gbps; each flow transfer data whose size is randomly chosen from an exponential distribution with average 12.5 GBytes. A uniform traffic pattern is simulated, i.e., when a new traffic relation is generated, the source and destination are randomly chosen with the same probability; $th_s = 0.1$ in all simulations and $th_o = th_s$ for the sake of simplicity. All simulations are run until performance indices reach a 95% confidence level over a $\pm 5\%$ confidence interval around the point estimate. Estimations are carried out with the *batch means* technique.

Fig.5 presents a comparison of the average throughput T obtained modeling best-effort traffic relations using the TB approach (dotted lines) and the DB approach (solid lines) when the two grooming algorithms *VirtFirst* (round marks) and *OptFirst* (cross marks) are used. With the same graphic rules, Fig.6 reports the starvation probability.

The difference in performance results of the two approaches is striking. Let's consider first the *OptFirst* grooming policy. Both approaches show T starting from 10 Gbps when the

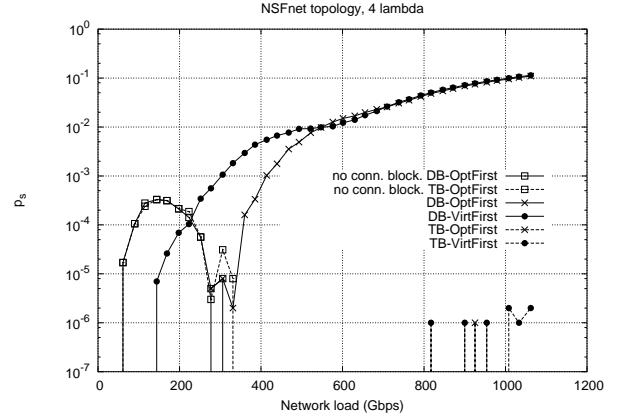


Fig. 6. Starvation probability p_s for the DB and TB traffic models for the two grooming algorithms

offered load is low; however, they immediately diverge as the offered load increases. Indeed, the DB traffic model shows much faster decrease in T as soon as the offered load increases and this is due to the spreading of congestion over time with a sort of snow-ball effect. On the contrary, the TB traffic model shows a smoother decrease of the average bandwidth.

Analysing the starvation probability in Fig.6 adds more insight. When the traffic is very low (below 350 Gbit/s) both traffic models show the same, very strange behavior: the starvation increases and then decreases sharply. This form of blocking is independent of the traffic model and it is due to a very aggressive and dynamic use of optical resources that sometimes leads to have no connectivity at the IP level, i.e., a flow request arrive and there is no possible path, neither optical, nor through multiple IP hop, between the source and the destination. When the load increases, however, lightpaths become more stable (because there is always traffic keeping lightpaths open) and the probability that the virtual topology is not completely connected becomes negligible. To highlight the difference of this phenomenon from the real starvation, in Fig.6 the curves relative to it are plotted with square marks. When the load increases further, the two traffic models behavior diverges: the TB model show no starvation at all, apart from points at very high loads, which show a blocking probability around 10^{-6} , while the DB model show a starvation probability increasing steadily. This difference in the starvation behavior enhance the differences in T , since aborting flows cause a waste of bandwidth.

When considering the *VirtFirst* grooming policy instead, the behaviour of both traffic model is different from the previous one. Both DB and TB T decrease sharply even when the offered load is low, due to the conservative policy of *VirtFirst*. In fact, *VirtFirst* sets up the minimum number of lightpaths in order to guarantee the minimum network connectivity, and keeps this configuration unchanged until some flow crosses the starvation threshold th_s . Only in this case *VirtFirst* increases the resources at IP level by setting up new lightpaths. In particular, the T for DB traffic relations decreases very rapidly, causing an earlier set-up of new lightpaths compared to TB traffic. This lead the DB traffic throughput T to “bounce”

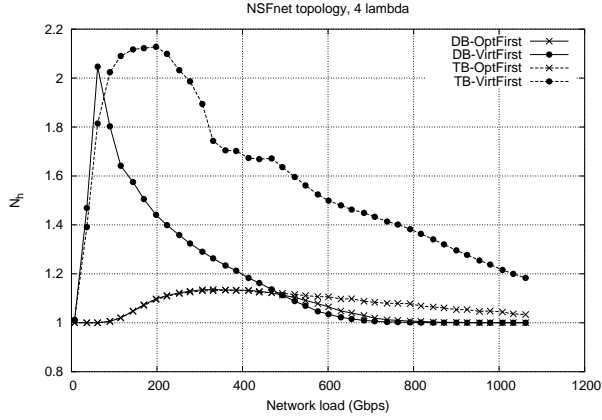


Fig. 7. Average number of hops N_h at the IP level.

taking advantage of the higher number of lightpaths in the network, at a load much smaller than for the TB model, that starts increasing again at higher loads. Obviously, both models would show another (and definitive) decrease in T for higher loads, not simulated here. It is interesting to notice that the starvation rate (see Fig. 6) for the TB model is in this case always zero (apart from a single point around load 900 Gbit/s), while the starvation rate of the DB model increases steadily and shows a behavior similar to the DB model in the *OptFirst* case.

Fig. 7 reports the average number of IP hops per flow N_h . As expected the *OptFirst* policy keeps this parameter very close to one. The *VirtFirst* instead show a sharp increase for low loads due to the fact that at very low loads the probability that a flow arrives and find the virtual, IP topology already connecting the source and destination is very low, thus a new lightpath is always opened also with *VirtFirst* policy. As the load increase, this parameter converges to one also in the *VirtFirst* case, since the number of wavelength per link considered allows a complete optical mesh connecting every G-OXC. Clearly this would be different in different topologies or if a smaller number of wavelengths per link were considered.

Fig. 8 shows the ratio R_o . As expected, when *VirtFirst* grooming policy is used, R_o decreases quickly with the load, indicating a burden for the optical level that does not increase with the traffic (indeed, it might also decrease when the load is high). It is interesting to notice the very different behavior also of this parameter between the two traffic models. When the *OptFirst* grooming policy is adopted, R_o decreases slowly and smoothly, indicating a much higher burden for the optical level.

Fig. 9, finally, plots N_{l_o} . Once again the behavior of the *OptFirst* policy is more predictable, with the number of links that decreases steadily with the load, and roughly converges to the weighted average distance in number of links between G-OXCs. The *VirtFirst* policy shows instead very long optical paths. This effect is due to the intrinsic behaviour of this grooming policy: most of the lightpaths set up by *VirtFirst* are in fact never torn-down since they are carrying traffic almost all the time. Then, when new lightpaths must be established, it

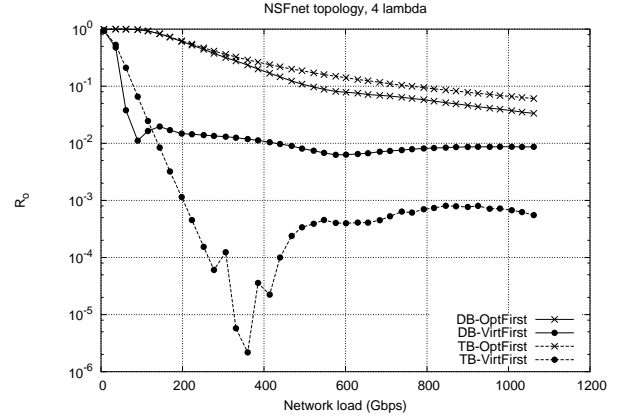


Fig. 8. Ratio R_o between the opening rate of optical paths and the arrival rate of flows at the IP level.

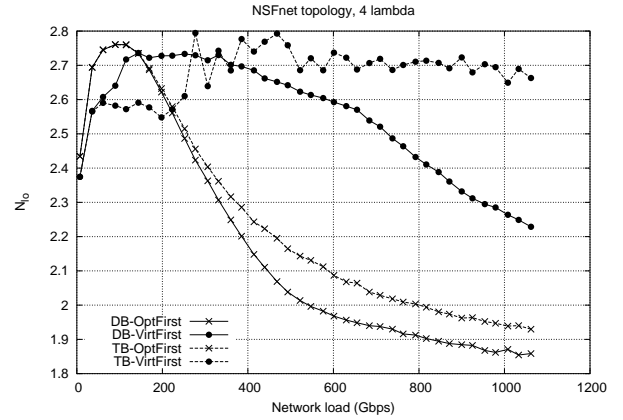


Fig. 9. Average number of links N_{l_o} per optical path.

is more likely that they would be set up in the optical network through longer routes.

To avoid the risk that the highlighted behavior are rooted in the chosen topology and not in the grooming-algorithm/elastic-traffic interactions, we have run several simulations with different topologies and number of wavelength per link. One example is the simple topology shown in Fig. 10 where only two wavelengths per link are available.

Figs. 11 and 12 reports the T and p_s obtained in this case. The qualitative behaviors are clearly the same, even if curves are generally smoother and easier to explain due to the simpler scenario.

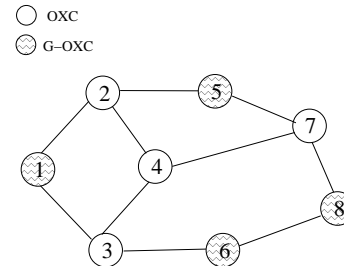


Fig. 10. Simple mesh topology used for additional results, two wavelengths per link.

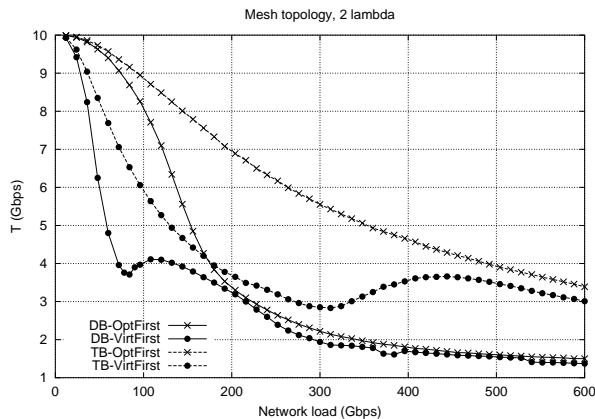


Fig. 11. Average throughput T for the DB and TB traffic models for the two grooming policies in the second topology.

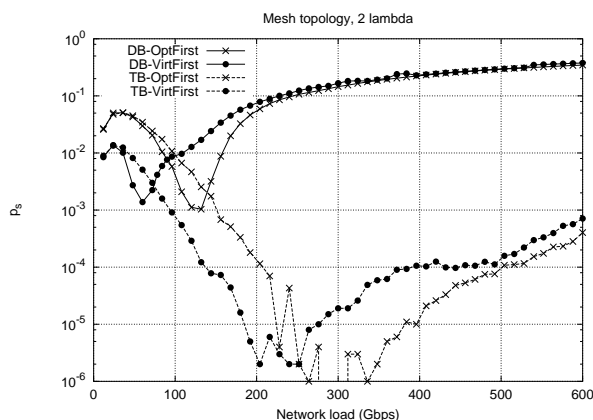


Fig. 12. Starvation probability p_s for the DB and TB traffic models for the two grooming algorithms in the second topology.

V. DISCUSSION & CONCLUSION

This paper has introduced the analysis of dynamic grooming algorithms in IP over WDM with elastic traffic. The elasticity of traffic interacts with the grooming algorithms as well as with the routing both at the IP and optical level, leading to unexpected results.

Two very simple grooming algorithms have been considered, one privileging the opening of new optical paths, named *OptFirst*, the other privileging the use of the already available IP logical topology, named *VirtFirst*.

In both grooming algorithms the impact of elastic traffic, included with a sophisticated model in the simulations tool, is dramatic, showing clearly that approximating IP traffic with CBR-like traffic can lead to wrong conclusions when routing and grooming are considered. The different performance induced in the network by the elastic traffic is such that conclusions drawn with traditional traffic models can be completely misleading.

The focus of the paper was on the impact of the traffic elasticity, thus little attention was placed on the “suitability” of the grooming algorithms analysed. Both the *OptFirst* and *VirtFirst* algorithms, however, have clearly shown that they are not suited for the management of an IP over WDM network,

since the lack of coordination between the IP and the optical level leads to waste resources. As shown on the NSFNET topology the *OptFirst* policy may even lead to block requests with very low network loads because a very aggressive use of optical resources may lead to IP-level virtual topologies that are not completely connected.

This observation open new and interesting questions on the heuristics that dynamic grooming algorithms in IP over WDM networks should pursue in order to optimize the use of resources and, at the same time, maximize the satisfaction of the end users.

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