MAXIMUM TRAFFIC SCALING IN WDM NETWORKS OPTIMIZED FOR AN INITIAL STATIC LOAD

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Abstract Dynamic traffic is becoming important in WDM networks. In the transition towards full dynamic traffic, WDM networks optimized for a specific set of static connections will most likely also be used to support on-demand lightpath provisioning. Our paper investigates the behavior of a WDM network optimized for a given static traffic, in case of an unpredictable increase of the number of connection requests. New lightpaths are setup as dynamic traffic exploiting idle capacity left in the network after static optimization. Traffic is grown until a given blocking probability value is reached. The maximum allowable traffic scaling factor is evaluated by simulation in some case-study networks. Results obtained with different routing and wavelength assignment criteria are compared.

Keywords: Wavelength Division Multiplexing, scaling traffic, routing algorithms

Introduction

In recent years the importance of WDM networks has rapidly grown, leading them to become the core of the telecommunication infrastructure, able to face the increase of data and video traffic. If WDM technology can offer a solution to the large bandwidth demand, WDM protocols (management and control systems) have been developed in order to guarantee that the WDM layer will act in the future as a common transport platform able to operate in an integrated multi-protocol environment, providing a high quality of service.

Up to the present time WDM networks have mainly been regarded as static systems, both in planning and management. One of the main issues of research on optical networks, developed under the drive of the operators' needs, has been network optimization: a vast number of procedures and algorithms have been proposed in literature to evaluate the lowest-cost capacity dimensioning given a certain static set of connection requests. The "static paradigm" was justified by the fact that optical connections has been mostly used as long-distance backbones to carry large aggregates of telephone traffic between distant locations, mainly involving end-customers of a single operator, thus with highly predictable traffic volume.

We are witnessing a new evolution of WDM networks today, as a consequence of a big change in the application scenario. Data traffic is going to overcome traditional telephone traffic in volume: statistical modeling of network load has to be modified to describe a new reality with less regular flows, more and more independent from geographical distances. Moreover, WDM has been successfully adopted in regional- and metro-area networks, in which flows are less aggregated and more sensitive to traffic relations due to single, large bandwidth applications. Finally, many operators are beginning to offer the "lambda service" (i.e. optical connections for lease) and the carrier-of-carries service to support the so-called "bandwidth-trading" business.

The static conception of the network is showing its limitations since it is no longer able to cope with these new applications. The focus of research is thus moving from static planning to lightpath on-demand provisioning. The change is also reflected by the evolution of WDM protocol standardization. The simple static Optical Transport Network (OTN) is already well-defined by the main standard bodies [1–2], while the new model known as Automatic Switched Optical Network (ASON) is currently under development. Its main feature is the ability to accommodate on-line connection requests issued to the network operating system, which has to activate new lightpaths in real time. Despite current economy difficulties may impose a slower evolution pace, this change of paradigm from static to dynamic system does not seem to be reversible.

It is however likely that the evolution from OTN to ASON is going to happen as a gradual process in order to preserve the investments of the network operators. While upgrading network control and management systems to ASON will be a relatively easy and quick task, the installed transmission systems and the existing capacity of an operator will probably remain unchanged for a certain period. In this transition phase static and dynamic traffic will co-exist and share the same WDM network infrastructure. Mostly likely, this infrastructure has been designed and optimized in order to support a given original static traffic, according to the OTN design approach. So an interesting issue is to evaluate how many on-demand lightpaths can be provided in an optimized WDM network without disrupting or reconfiguring the original static connections.

In this work we have more precisely identified the particular situation in which the new on-line connection requests are generated as an expansion of the original static traffic. In practical terms, this happens when each original customer of the network operator wants to add more optical connections to his already established set in order to increase the bandwidth of his traffic relations. The operator has to satisfy the new requests exploiting the current network idle capacity, without adding additional physical resources to his existing infrastructure. It should be noted that we chose this particular scenario to perform a sort of worst-case analysis: obviously, a wise operator would probably have over-dimensioned the network during the design phase adding some extra capacity to the amount prescribed by an optimization procedure. However our purpose here is to ascertain whether the set of resources left idle after an optimization procedure is suitable to be used to accommodate a traffic expansion, so no over-dimensioning is considered.

Section 1.1 describes in details the network model we adopted. In section 1.2, some routing, fiber and wavelength assignment algorithms are presented. In section 1.3 we will show and compare the results obtained by simulating the traffic growth in some case-study networks.

1. Network model

Let us describe into details the network model we are referring to in this paper. The physical topology (either ring or mesh) is composed of WDM transmission links and WDM switching nodes connected according to a given graph. In the ring case the nodes of the physical topology correspond to Optical Add Drop Multiplexers (OADMs), while in the mesh network they represent Optical Cross Connects (OXCs). A WDM link represents a multifiber bidirectional cable: some fibers are used in one propagation direction, and some others (not necessarily the same number) in the opposite direction. All the fibers of the network carry the same number W of WDM channels, each transmitted on a different wavelength.

In WDM networks traffic is carried by means of circuit-switched transport entities, optically routed on the basis of their wavelength. These entities are the lightpaths, each composed of a sequence of WDM channels connecting a source node to a destination node. In the present work we will consider two types of WDM networks, according to their wavelength conversion capability [3]:

- Virtual Wavelength Path (VWP) network: all the OXC are able to perform full wavelength conversion, i.e. an incoming optical signal having any wavelength can be converted to an outgoing optical signal having any possible transmission wavelength;
- Wavelength Path (WP) network: no wavelength conversion is allowed in the whole network.

In the WP case, all the WDM channels composing a lightpath must be at the same wavelengths (wavelength continuity constraint).

Our study comprises two different steps. First, a WDM network optimized for a given static traffic, setting up all the static optical connections initially requested and minimizing the total number of fibers of the network (section 1.1.1. Secondly, traffic growth is simulated by setting up new lightpaths until the idle capacity is exhausted, as we are going to describe later on in section 1.1.2.

1.1 Static optimization

The optimization is carried out by exploiting a tool that we developed and which is reported in details in a previously published work (Ref. [4]). Let us briefly describe the tool operation.

The set of requests for static connections (virtual topology) is fed to the design tool, together with a description of the physical characteristics of the network (topology, wavelength conversion, etc.). The tool gives the possibility to select a WDM protection strategy for the optical connections. Since in our scenario we implicitly assume that static traffic has high priority (static connections can not be disrupted or reconfigured), it seems reasonable to expect that these connections should also be highly reliable. Therefore we decided that all the static connections are protected by a protection mechanism (for simplicity, we have chosen the same mechanism for all the connections).

There are different implementations of protection in the WDM-layer [5]: link protection, dedicated path-protection, shared path-protection, etc. In this work we have chosen the Dedicated Path-Protection (DPP). According to this strategy resources must be pre-allocated so that for each optical connection between a source and a destination node a working and a protection lightpath can be set up. In order to guarantee the recovery of the connection in case of a single link failure, the two lightpaths must be setup in physical route diversity, i.e. they can not share any common link[1]. For brevity, we will say that a request for a static protected optical connection is satisfied by allocating resources in order to set-up a working/protection pair (w/p pair). Differently from shared path protection, in DPP a spare WDM channel is rigidly allocated to a specific protection lightpath, so that two different w/p pairs never intersect.

The dedicated path protection comprise two implementations: (a) 1+1 path-protection, in which the signal always propagates on both the working and spare lightpaths also in absence of failures; (b) 1:1 path-protection, in which the signal normally travels on the working path and in absence of failures the spare path is used to carry "low priority" traffic that is lost when a failure occurred. In the following paper we will consider the dedicated 1+1 path-protection: this implies that resources allocated to static protection lightpaths can not be used to provision lightpaths in the traffic-growth phase. A different scenario assuming 1:1 DPP for static connections will be considered in future works.

Once the protection technique is selected the design tool proceeds in evaluating Routing, Fiber and Wavelength Assignment (RFWA) for all the w/p pairs or for all the lightpaths, in order to satisfy all the static connections of the virtual topology. In doing this, it also determines the number of fibers that must be installed in each WDM link of the network, thus solving the dimensioning problem of the physical topology. This is done by exploiting a heuristic optimization cycle which assumes the total number of fibers installed in the network as cost function. The heuristic technique we have defined leads to very good suboptimal results, i.e. returning a network design (lightpath configuration and link capacity) very close to the one necessary and sufficient to support the given set of connection requests (the heuristic results are compared to integer linear programming results in Ref. [4]).

1.2 Traffic scaling

In the second phase the optimized network with all the static w/p pairs set up is fed to a discrete-event simulator, whose basic event is the provisioning of a connection in the network keeping the current resources occupancy state into account at the arrival of a new request.

It should be noted that for the purpose of this work the time instant of arrival of a new requests does not matter, since all the connections are

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[1] A stronger condition of node-sharing prevention can be imposed if protection to node failures has to be enforce. This can be easily implemented with the same tool, but any further investigation of this aspect is left for future the papers.

supposed to be permanent (there are no death events). The only relevant aspect is the sequence of the requests. To simulate an homogeneous growth of static traffic we have adopted the following request-generation procedure. A couple of source and destination nodes is randomly and uniformly chosen among all the couple of nodes having a static traffic relation. One new connection is requested for that couple. If available resources are not sufficient to satisfy the request, then it is blocked and lost forever [6–7]. If instead resources are sufficient, the connection is setup by allocating the suitable sequence of WDM channels for an indefinite time. Then, independently of the result of the previous allocation, a new couple is chosen and another request is issued, and so on.

We considered two different and alternative cases in which the connections requested in the traffic-growth phase are either all unprotected or all protected by 1+1 DPP. In the first case a single lightpath is sufficient to satisfy the request, while in the second a w/p pair has to be setup.

All the requests for new optical connections are managed as dynamic traffic. At each arrival system applies a heuristic RFWA algorithm (that will be presented in Sec. 1.2) trying to setup the corresponding lightpath using the available WDM channels. The network resources available to support a new connection are the WDM channels still unassigned at the request arrival. At the beginning of the traffic-growth phase, available resources comprise WDM channels of the optimized network that are not occupied by static lightpaths, since no disruption of high-priority static lightpaths is admitted. Such channels are present in the optimized WDM network due to the fact that during the optimization phase capacity can be added to or subtracted from links with a finite granularity given by the fixed number of wavelengths per fiber W. Though the optimization process tends to fill-up all the network fibers, in most cases it can never achieve this task completely.

As more and more extra lightpaths are setup in the simulation, resources for new connections continue to decrease, as no reconfiguration of already active extra lightpaths is admitted.

The chance of being able to accept a new connection is measured by the blocking probability parameter P. At a given simulation event, P is defined as the ratio between the number of unsuccessful events (requests which could not have been satisfied) and the total number of events occurred so far. At the beginning of the traffic-growth phase a threshold value of P is given to the simulator. The simulation is stopped when P reaches the pre-fixed threshold value of blocking probability. For example, a threshold value $P = 0$ implies that the simulation is stopped at the first connection refusal.

At the end of the simulation the scaling factor parameter is measured and returned as output. The traffic scaling factor is defined as the ratio between the number of extra connection requests accepted during the traffic-growth phase and the total number of static connections in the network.

2. Heuristic Routing algorithms

One particular aim of this work is to compare the effectiveness of different RFWA algorithms in terms of maximum scaling factor obtainable in the traffic-growth phase, given a threshold on the average blocking probability.

At the arrival of a new connection request, the control system of the network must solve a RFWA problem. This consists in the identification of the route (sequence of links) from the source to the destination and in the selection of a WDM channel in a particular fiber for each link to be allocated to the new connection. Since the way in which RFWA is solved contributes to determine the blocking probability of the network, RFWA must be performed under some optimality criterion.

Several techniques have been proposed to perform RFWA. In principle, techniques based on mathematical programming could be applied, but these methods require very high computational efforts. Moreover, the formal definition of an objective function to be minimized which is directly related to blocking probability is not an easy task. Therefore most of the works in literature regarding dynamic WDM networks propose heuristic methods to solve RFWA. Some of these methods are based on disjoint solution first of routing and then of fiber and wavelength assignment. In our work we adopted a heuristic method which jointly solves routing, fiber and wavelength assignment without imposing constraints on the viable routes (unconstrained routing [8]). This method is basically the same employed in our static-network design tool [4]and adapted to the dynamic network environment. It is based on the *multifiber layered graph* (MLG) representation of the network. Each WDM channel of the network is represented by an arc of the MLG, as well as each traffic-generating node has an image node in the MLG. In order to jointly solve RFWA, all the arcs of the MLG are assigned proper weights prior to setup the new connection.

The weighted MLG is employed into two different ways according to the type of connection that must be setup. If the connection is unprotected, then the Dijkstra algorithm is run on the MLG, finding the least-total-weight route between the image node corresponding to the source OXC and the image node corresponding to the destination OXC.

If the connection is protected by DPP, the Bhandari (or one-step) algorithm is run [4]. In this case, the least-total-weight link-disjoint cycle between the node couple is found on the graph. In both cases, the MLG arcs belonging to the identified route correspond to the WDM channels that must be allocated to the new lightpath or to the new w/p pair.

The key point of our heuristic approach is weight assignment to the MLG arcs. First of all an infinite (actually, very large) weight is given to arcs corresponding to unavailable WDM channels. We recall that WDM channels available for dynamic traffic at a given instant are those left idle by currently active working and protection lightpaths (either static and extra lightpaths). Secondly the MLG weight system is used to support all the optimality heuristic criteria adopted to solve RFWA. In our approach specific criteria for routing, for fiber assignment and for wavelength assignment can be combined together with a given priority order. To do this each MLG arc is actually assigned an array of weights instead of a single scalar weight. Each weight of the array is determined by a specific criterion. We have modified the Dijkstra and Bhandari algorithms so that the criteria can be applied in a prioritized sequence. Each time several alternative MLG routes have an equal total weight according to the primary criterion, they are compared according to the secondary criterion, and so on.

In all the simulations we have performed we have always assigned the highest RFWA priority to routing; fiber and wavelength assignment follow in order of decreasing priority. To find a wavelengths assignment, the set of wavelengths or fibers could be searched in a fixed order or an adaptive order [6]. We used the following criteria both for fiber and wavelength assignment:

- MOST USED (MU): This algorithm (also known as "pack")attempts to route the connection requests on the most utilized wavelength first i.e., wavelength are searched in descending order of utilization, in order to maximize the utilization of available wavelengths.
- FIRST FIT (FF): The search order is fixed *a priori* e.g., λ_0,λ_1,$\cdots$,λ_{W-1}.

The first algorithm requires information about global wavelength utilization. In this paper, we will consider both fixed and adaptive wavelength assignment in conjunction with unconstrained routing.

The two best-known and simplest routing algorithms for dynamic traffic in a WDM network are the Shortest Path Routing (SPR) and the Least Loaded Routing (LLR).

The first one routes the lightpath on the minimum distance available path between source and destination: distance is evaluated as the number of hops (i.e. WDM links) crossed by the lightpath. It is very easily implemented by setting to 1 the weights of all the available WDM channels. This routing algorithm is *static* since the corresponding weights do not depend on the state of the network.

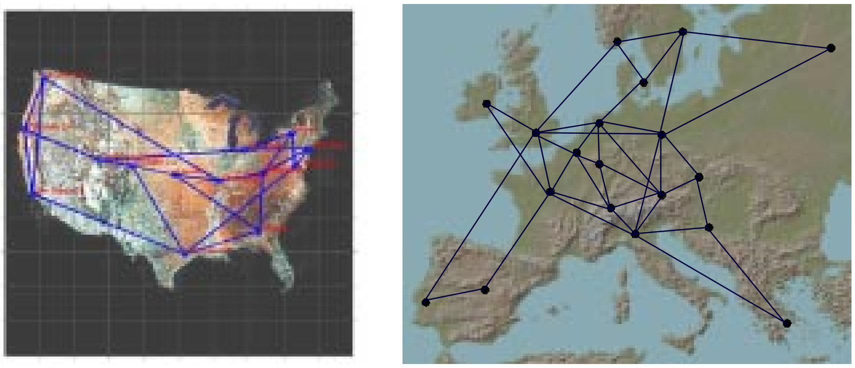
LLR tries instead to route the new lightpath on a path which carries the lowest possible amount of traffic generated by already active connections at the time of connection set up. It obviously requires a knowledge of the network state: it can therefore be classified as an *adaptive* routing algorithm. To perform LLR WDM channels are weighted by the so-called *link congestion parameter*: if a given channel belongs to link j, then it is assigned a weight b_j equal to the number of busy WDM channels on that link. The algorithm allocates the new lightpath on the route having the least possible *route congestion parameter*. This latter variable is equal to the maximum link congestion parameter among all the links crossed by the route itself.

It should be noted that each the above algorithms is effective in reducing blocking probability of dynamic connections on a single different front. SPR tends to minimize the amount of resources that a new connection is going to subtract from the pool of available WDM channels of the network. LLR tends to uniformly distribute the load over the links of network. A very interesting option offered by our network model is that more criteria concerning the same aspect of RFWA can be applied in sequence, taking advantage of the best heuristic quality of each one. We applied this to routing, creating a new algorithm from the combination of LLR and SPR in a prioritized sequence, named LLR/SPR. The highest priority is given to LLR; when two routes are equal according to the least-loaded criterion, the shortest one is selected according to SPR. We can expect that cascading LLR and SPR can improve blocking probability compared to both the single algorithms.

3. Case-study result analysis

The results we are going to present in this paper were obtained by applying the C++ design tool and network simulator as described in the previous sections. The final goal of these experiment has been the evaluation of the maximum traffic scaling in different conditions.

A first set of simulations was carried out considering two realistic case-study networks, namely the USA National-Science-Foundation Network (NSFNET) and the European Optical Network (EON). Their physical topologies, shown in Fig. 1, have been derived from data reported in Ref. [9]and Ref. [10]for NSFNET and EON, respectively. A number $W = 32$ of wavelengths per fiber has been chosen to carry out all the experiments of this first set. Moreover, both the two alternative cases with (VWP) and without (WP) wavelength converters have been considered for each network.



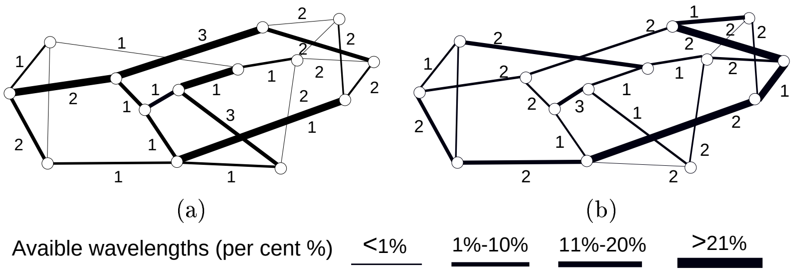
NSFNET EON

Figure 1. Physical topology of the National-Science-Foundation Network (NSFNET) and the European Optical Network (EON).

The optimization phase of each of the two networks has been solved with two different (symmetric) static traffic matrices. A first matrix per each network has been defined starting from data based on real traffic measurements and reported in the two papers cited above (Refs. [9–10]). We name this virtual topology *non-uniform static traffic*, since each node couple has a different number of connection requests. The two non-uniform matrices comprise 360 and 1380 unidirectional connection requests for NSFNET and EON, respectively.

The second static traffic matrix has been obtained for each of the two networks be evenly distributed the same number of connection requests of the non-uniform virtual topology among all the node-couples. In this way a *uniform static traffic* has been obtained in which all the node couples ask for roughly the same amount of optical connections.

Figures 2 and 3 represent the result of the static optimization phase carried out on the NSFNET and the EON. The labels associated to the links correspond to the number of unidirectional fibers averaged on the two propagation directions, while the link thickness represents the percentage of WDM channels of the link that are left idle after to setup of all the static connections. In the case of non-uniform traffic (see figures 2 (a) and 3 (a)) there are parts of the network which are almost disconnected since many links are completely saturated. On the opposite, uniform traffic originates a more uniform distribution of the load on the links. As a consequence, the amount of links that are either extremely underutilized and overloaded decreases (see figures 2 (b) and 3 (b)).



(a) (b)

Figure 2. NSFNET at the end of the static optimization phase, loaded with (a) non-uniform and (b) uniform static traffic.

A quantitative assessment of the difference between the idle capacity distribution in the two cases of uniform and non-uniform traffic is obtained by evaluating the effective connectivity factor. Given a network with n nodes, $L_f = [n \cdot (n-1)]/2$ is the number of (unidirectional) links of a theoretical fully-connected network having the same number of nodes. Let L be the number of the actual links of the physical topology of the given network. We define the connectivity factor as the ratio $\alpha = L/L_f$. At the end of the optimization process, only a subset of the L physical links of the network is not completely saturated by static traffic. Let L_e be the number of links belonging to this subset. We then define the effective connectivity factor as the ratio $\alpha_e = L_e/L_f$.

In the NSFNET case ($\alpha = 0.242$) the effective connectivity factor with uniform traffic is $\alpha_e = 0.219$, while it decreases to $\alpha_e = 0.154$ in the non-uniform case. For EON ($\alpha = 0.215$), α_e in the uniform case is 0.197, while it fall down to 0.133 under non-uniform traffic.

As we are going to show next, the exhaustion of available resources on some particular cut-sets and the saturation of all input and/or output links of a node have a great impact on the possibility to scale the traffic over the optimized network.

The following set of graphs represent the detailed report of all the experiments performed on NSFNET and EON. The maximum scaling factor at the end of the growth phase is always plotted as a function of the preset blocking-probability threshold P. The curves obviously tend to saturate as P approaches 1 ($P = 1$ means that any new connection request is blocked).

A first and a second group of graphs concern the situation in which the traffic scales by setting up new path-protected connections, in the NSFNET (figure 4) and in the EON (figure 5), respectively. For each

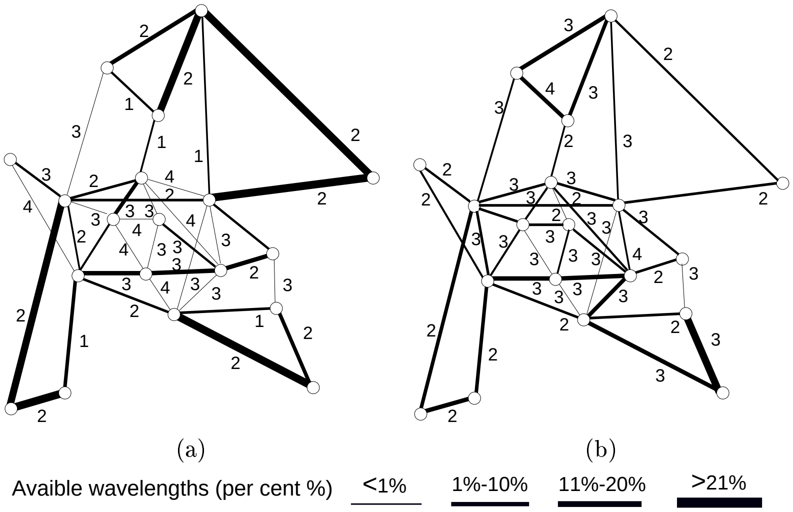


Figure 3. EON at the end of the static optimization phase, loaded with (a) non-uniform (b) and uniform static traffic.

network four graphs are reported corresponding to the combination of VWP and WP and uniform and non-uniform traffic. As expected, wavelength conversion and traffic uniformity improve the possibility of scaling. It is however noticeable that traffic distribution is more important than wavelength conversion.

One of the objectives of this study is the evaluation of the impact of the particular RFWA criteria used in the growth phase on the final maximum scaling factor. We can comment on this point by observing the curves of figures 4 and 5.

As far as routing is concerned, the combined use of LLR and SPR, giving to LLR the highest priority (LLR/SPR), is always the best choice, much better than when the two algorithms applied separately. Then LLR has always better performance than SPR. This latter comparison is typical of a dynamic traffic environment, as actually is our growth phase: it is another prove of the importance of avoiding cut-set saturations to lower blocking probability, even at the cost of routing lightpaths on longer routes. The differences between the three routing algorithms are more evident in the uniform traffic case in which the number of alternatives to route the connection requests is higher. In the non-uniform case there are almost no routing choices for many lightpaths since many links are unavailable (see figures 4 and 5).

Let us concentrate now on the impact of the wavelength and fiber assignment criteria on the scaling factor. The two algorithms to compare

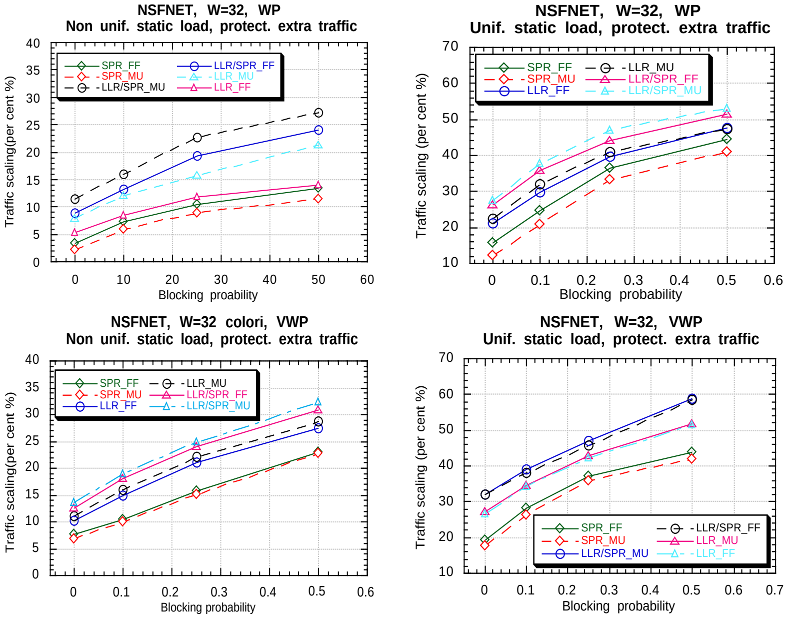


Figure 4. Traffic scaling on NSFNET (WP and VWP case) loaded with non-uniform and uniform static load for different values of the blocking probability threshold P. Dedicated path-protection is adopted for the new connections.

are the First Fit (FF) and the Most Used (MU), both presented in section 1.2.

We first consider the WP network. When the routing algorithm is SPR, FF behaves better than MU. This is due to the fact that FF tends to pack-up short lightpaths on the same wavelengths, leaving wavelengths with high index free to accommodate long monochromatic lightpaths. The MU algorithm behaves “locally” as the FF at each new request, but the priority order of the wavelengths can change from one event to the other, so we can not have the same beneficial effect for long connections. The difference between FF and MU appears more evident when the network is loaded with uniform static traffic compared to the non-uniform case.

When the routing algorithm is LLR or LLR/SPR, then MU is the best performing fiber and wavelength assignment algorithm. This behavior is probably due to the load-balancing effect of LLR. It conveys the idea that an adaptive routing algorithm is better matched by an adaptive wavelength assignment algorithm than by a fixed-order algorithm as LL.

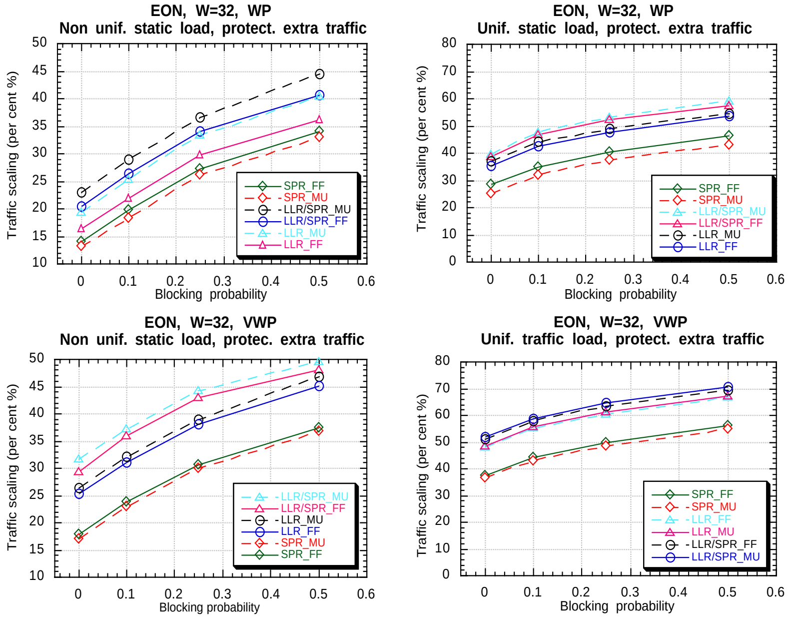


Figure 5. Traffic scaling on EON (WP and VWP case) loaded with non-uniform and uniform static load for different values of the blocking probability threshold P. Dedicated path-protection is adopted for the new connections.

Wavelength conversion does not change the behaviors described above. In the VWP network the differences between FF and MU are less evident than the WP network (see figures 4 and 5).

The graphs reported next in figures 6 and 7 have been obtained by scaling traffic with unprotected connections (only data regarding the WP case have been plotted). The scaling factor is obviously larger than in the protected case and tends to double for low values of P. This gain is partially due to the additional capacity that is required by protection and partially by the link-disjoint constrain. All the other observation on the protected case apply also to the unprotected. The advantages of LLR-SPR (and LLR) compared to SPR are more evident.

Figure 8) has been added in order to summarize the effects of RFWA algorithm, traffic uniformity, wavelength conversion and protection mechanism of extra connections on the scaling factor of NSFNET and EON. The scaling factors refer to the case $P = 0$, which is the most likely real condition. Only the two best and worst performing RFWA algorithms have been considered.

A second set of traffic-growth simulations has been carried out to understand how the traffic scaling capability of an optimized network is

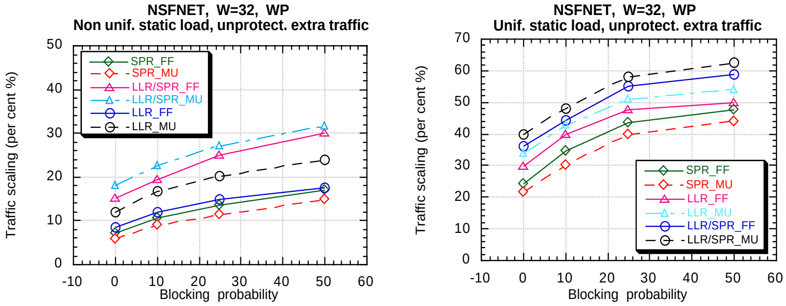


Figure 6. Traffic scaling on NSFNET (WP case) loaded with non-uniform and uniform static load for different values of the blocking probability threshold P. No protection is adopted for the new connections.

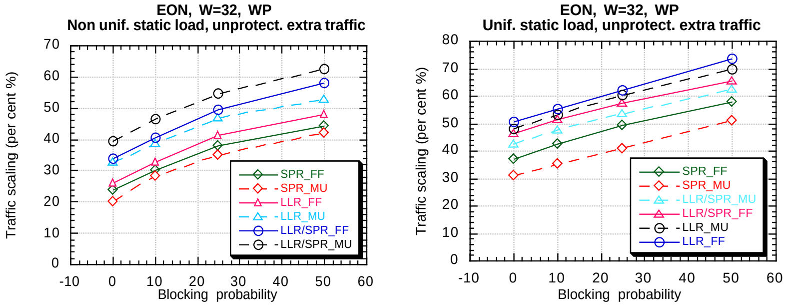
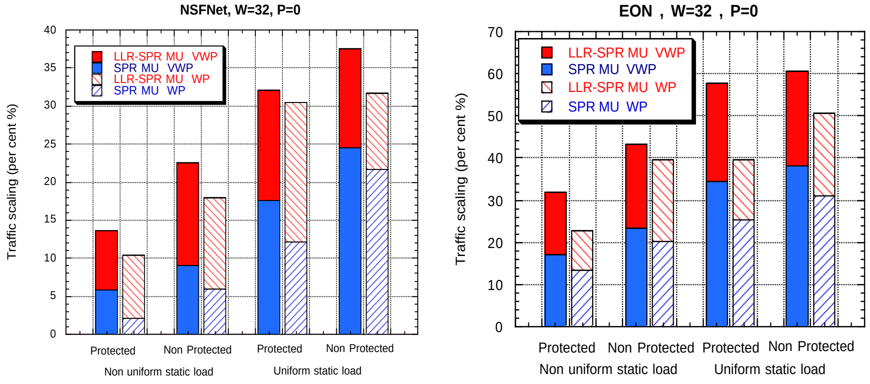


Figure 7. Traffic scaling on EON (WP case) loaded with non-uniform and uniform static load for different values of the blocking probability threshold P. No protection is adopted for the new connections.

influenced by its physical topology. As case-study networks this time we considered a sequence of regular and quasi-regular topologies, with 8 nodes and with an increasing number of links $L \in \{8, 9, 10, 11, 12, 28\}$ (see figure 9). The corresponding increase of the topological complexity is measured by the already defined connectivity factor $\alpha \in \{0.29, 0.32, 0.35, 0.4, 0.43, 1\}$.

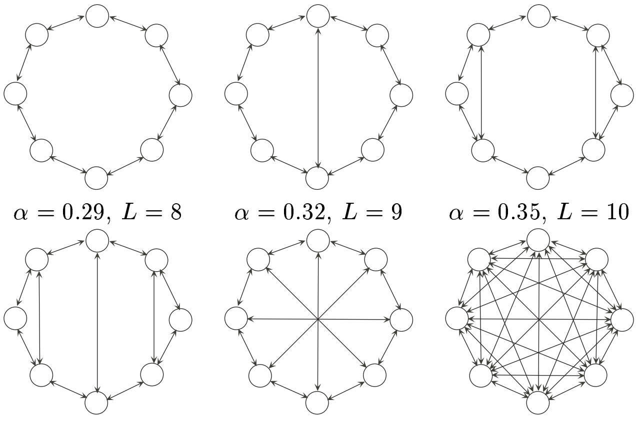
In particular, the first topology with $L = 8$ is a ring network. The next ($L = 8$) is obtained by adding one link so to build an interconnected ring pair. The next two topologies ($L = 10$ and $L = 11$) are still interconnected-ring planar networks of 3 and 4 rings. The final two networks (the "12-L wheel" and the full-mesh) are non-planar.

The two graphs of figure 10 are referred to the VWP and WP cases, respectively. The traffic scaling has been plotted as a function of the network connectivity factor α. The networks have been loaded with uniform static traffic with the same number of connection requests for all the networks. These have also been dimensioned in order to have



(a) (b)

Figure 8. Traffic scaling on NSFNET and EON with blocking probability threshold $P = 0$.



$\alpha = 0.29,\ L = 8$ $\alpha = 0.32,\ L = 9$ $\alpha = 0.35,\ L = 10$

$\alpha = 0.4,\ L = 11$ $\alpha = 0.43,\ L = 12$ $\alpha = 1,\ L = 28$

Figure 9. “Wheel networks”, used to study the influence of connectivity factor α on the expansion of traffic.

roughly the same number of idle WDM channels initially available for traffic growth.

The figure clearly shows that the maximum scaling factor increases with the increase of the connectivity factor. However there is a step discontinuity corresponding to the shift from planar to non-planar networks (from $\alpha = 0.4$ to $\alpha = 0.43$). From a practical point of view this means that single ring and multi-ring WDM networks have almost the same traffic scalability. It is possible to greatly improve this feature with a little cost increment by resorting to a WDM mesh network. This is due to the fact that a non-planar mesh topology provides a much larger number of alternative paths than a similar-size multi-ring network.

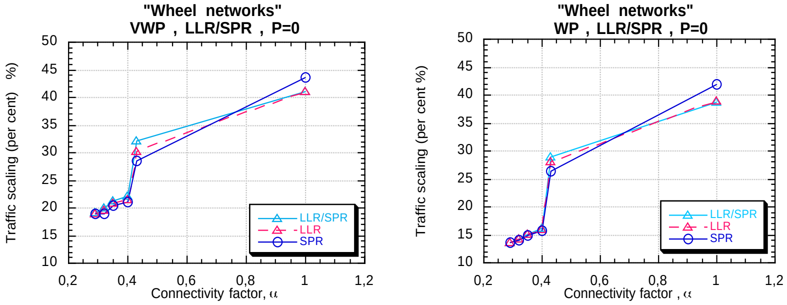


Figure 10. Scaling factor as a function of the network connectivity, under different routing algorithms in the VWP and WP cases.

Figure 10 also shows the influence of the routing algorithm (FF is always adopted for fiber and wavelength assignment) in the case of the "wheel networks". In the single ring configuration there are no differences between SPR, LLR and LLR/SPR since there are only two alternatives to route the connection requests. If the number of alternatives increases the LLR and LLR/SPR become more efficient than SPR, as explained in the previous sections. In the full-mesh networks the SPR is more efficacious than the other two algorithms, due to the particular fact that the SPR routes the connections on the directed-link with high probability, while LLR tends to unnecessarily spread the connections all over the network.

4. Conclusions

We have considered the future scenario of WDM networks designed and optimized for static traffic (with dedicated path protection) and then employed to provide lambda-connection service on demand, without disrupting the static lightpaths. The issue we intended to investigate was whether the set of resources left idle after an optimization procedure of the network for a particular static traffic can be used to accommodate a traffic expansion. Simulation carried out on some case-study networks in various conditions proved that a substantial number of extra-connections can be setup exploiting the idle capacity of the optimized network, even without adding new capacity to the optimized physical topology. We have shown that the maximum scaling factor is very sensitive to the distribution of the initial static traffic. In particular, traffic scalability improves when the static traffic is uniformly distributed. Another relevant element is the routing, fiber and wavelength assignment criteria chosen to setup the extra lightpaths. The results also depend on the wavelength conversion capability of the network and the WDM protection mechanism that may be adopted for the extra connections. We have also investigated the impact of the network connectivity. The simulations confirmed that a non-planar network allows a higher traffic expansion compared to the classical ring and overlaid multi-ring topologies.

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