Routing Algorithms in WDM Networks under Mixed Static and Dynamic Lambda-Traffic

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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 issue of routing of dynamic connections in WDM networks which are also loaded with high-priority protected static connections. By discrete-event simulation we compare various routing strategies in terms of blocking probability and we propose a new heuristic algorithm based on an occupancy cost function which takes several possible causes of blocking into account. The behavior of this algorithm is tested in well-known case-study mesh networks, with and without wavelength conversion. Moreover, Poissonian and non-Poissonian dynamic traffics are considered.

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Keywords

Wavelength Division Multiplexing, dynamic traffic, routing algorithms

I. Introduction

THE past few years (up to 2001) witnessed the flourishing of telecommunication industry as one of the fastest-growing and most wide-spread phenomena in economy ever recorded. The core of that technological revolution has been Wavelength Division Multiplexing (WDM) optical networks, with their unique capability to offer the best solution to the large bandwidth demand on one side and to guarantee high quality of service and high reliability on the other side. Thanks to these features the area of applications of WDM networks drastically expanded from the original voice traffic transport to become a common high speed transport platform carrying data, video and voice. WDM protocol has been developed in order to operate in an integrated multi-protocol environment, serving Sonet, SDH, GMPLS, IP, etc.

When the general crisis hit the telecommunication market it found WDM networks at the dawn of a new evolution. Optical transport networks in the past have mainly been designed and operated as static systems: optical connections were used as long-distance trunks mostly to carry large aggregates of telephone traffic, usually serving only customers of the network operator itself. Traffic was thus highly predictable.

The scenario is much different today. Data traffic is going to overcome traditional telephone traffic in volume. The former is characterized by less regular flows than the latter, which are more and more independent of geographical distances. This change in traffic statistics is further amplified in the regional and metro area, where flows are less aggregated and more sensitive to traffic relations due to single, large bandwidth applications. Finally, many WDM network operators are beginning to offer the “lambda service” (i.e. optical connections for lease) and the carrier-of-carriers service to support the so-called “bandwidth-trading” business. This implies that their network infrastructure is no longer used solely from their own final customers, making a quota of connection demands no longer deterministically predictable. Lambda-service customers such as Internet Service Providers (ISP) may requests limited duration connections with a wide range of possible time-scales. Duration can be for example: several months to provide temporary connectivity to an ISP waiting for the installation of his new network; few days to cover some special event (e.g. the Soccer World Cup or the Olympic Games); few hours to respond to daily traffic variations; tens of minutes to perform the backup of a large data-storage facility. The recent development of the Generalized Multi-Protocol Label Switching (GMPLS) technique seems to convey the idea that lightpaths in the future will have to be set up and torn down on a very short time-scale, even few seconds, perhaps paving the way to a possible optical packet-switching (or optical burst-switching) era.

All the facts mentioned above are pushing research in security, management and network design to re-focus its attention from the simple static Optical Transport Network (OTN) to Automatic Switched Optical Network (ASON). While OTN is already well-defined by the main standard bodies [1], [2], the new ASON model, able to set-up and release lightpaths on-demand based on on-line requests, is still undergoing an intense research and standardization activity. Despite economy may impose a slower evolution pace today, this change of paradigm from static to dynamic systems does not seem to be reversible for WDM networks. This justifies the birth of dynamic traffic as a new subject of research in optical networks. This area accounts today probably for less works than those published on static planning and it offers several open issues, such as efficient routing and traffic modelling.

In this paper we are going to address both the above issues, but in a new very particular context. Given the evolution from OTN to ASON as an actual process, this will surely occur gradually, in any case always preserving the investments of the network operators. In the transition the two paradigms of static and dynamic traffic have to co-exist and to be supported by the same WDM network infrastructure. Mostly likely, these infrastructure has been designed and configured in order to support a given original static traffic and it is then employed also to provide lightpaths on-demand. We have more precisely imagined the situation of a WDM network operator who has optimized his network according to a given set of protected static connections, adopting WDM path protection (in the two alternative versions, dedicated and shared) as survivability technique. He still wants to keep its original customers of the static connections, regarding these as high-priority traffic which should not be disrupted. In addition, the operator wants to do the best to accommodate as many lightpaths as possible to satisfy dynamic traffic requests by exploiting the same WDM network.

In this paper we propose and discuss a heuristic strategy for routing lightpaths for dynamic traffic that allows to increase the acceptance rate of dynamic connection requests (or, equivalently, to decrease the blocking probability) compared to other previously known routing algorithms. Such a new algorithm is based on a global network function which provides an estimation of the available network resources according to different criteria. This allows to assign resources to the new lightpath so that chances of having congestion in the most critical spots of the network are kept as low as possible. We are going also to study the performance of the heuristic algorithm proposed under different types of dynamic traffic. The paper can be summarized in the following way. In Sec. II we present our network model and introduce our simulation method. In Sec. III we describe the models employed to simulate different types of traffic conditions of dynamic lightpath requests. Then, in Sec. IV, the new heuristic routing algorithm is proposed, showing its differences from other classical algorithms. In Sec. V we will show the results obtained by simulating case-study networks under dynamic traffic.

II. Network model

Let us describe in detail 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.

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. All the WDM channels composing a lightpath must be at the same wavelength (wavelength continuity constraint).

According to the scenario described in Sec. I, our network model must be able to represent both static and dynamic optical connections. In this paper we will concentrate on the dynamic aspects of the problem (low-priority traffic), while all the static aspects have been solved by applying a tool that we developed and which is described in a previously published work [4]. We need only to briefly summarize the main features of this tool.

The set of requests for static connections (virtual topology) is known “a priori” and is fed to the design tool, together with a description of the physical characteristics of the network (topology, wavelength conversion, etc). Then a protection strategy is selected for the static optical connections. For simplicity all the static connections are protected with the same WDM-layer path-protection strategy. For each optical connection between a source and a destination node a working and a protection lightpath are set up. In order to guarantee the recovery of the connection in case of a single link failure, the two lightpaths must be in physical route diversity, i.e. they can not share any common link [1]. For brevity, we will say that a static request is satisfied by allocating resources in order to set-up a working/protection pair (w/p pair).

In the following of the paper we will consider two different implementations of path protection: 1:1 dedicated path-protection and mesh shared path-protection. In the dedicated case a spare WDM channel is rigidly allocated to a specific protection lightpath, so that two different w/p pairs never intersect. In shared path-protection two or more protection lightpaths belonging to different w/p pairs can share one or more WDM channels, provided that their respective working lightpaths are link-disjoint. It is well known that shared protection has the advantage of reducing the amount of resources used for protection and thus the global cost of the network.

Once the protection technique is selected the design tool proceeds to evaluate Routing, Fiber and Wavelength Assignment (RFWA) for all the requested w/p pairs, jointly 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 cost optimization 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 static connection requests (further details on the tool are given in [4]).

We recall that our aim is to model a realistic situation in which an operator wishes to employ

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

its WDM network initially designed for static traffic to offer lightpath provisioning service. As we are going to explain below, in such a scenario dynamic traffic has to use resources that are sparse in the network. This is much different from the typical situation considered so far in most of the papers on dynamic traffic in which dynamic connections occupy an initially empty network with the same amount of WDM channels in all the links. In our case available capacity varies from link to link because of the presence of static traffic and because of the optimization. Therefore the simulations of dynamic traffic we are going to describe in this paper are carried out on network systems obtained as results of the design tool. We believe this is the most faithful and simplest way to model the scenario we have assumed.

The network resources available to support dynamic traffic comprise: (a) WDM channels assigned to protection lightpaths (spare WDM channels); (b) unassigned WDM channels. The two path-protection implementations we have considered leave protection lightpaths idle in absence of failure. They can thus be used to host low-priority traffic (dynamic connections in our case) [2]. The low-priority qualification is due to the fact that when a failure occurs some low-priority connections have to be sacrificed to activate the protection lightpaths for all the static working paths hit by the failure. Since dynamic connections are low-priority traffic, they are satisfied by the setup of a single lightpath, without requiring any protection technique.

The second type of resources, i.e. unassigned channels, are present in the optimized WDM network as a result of cost minimization. Due to the finite granularity given by the fixed number of wavelengths per fiber W, some fibers are not fully occupied by static traffic. Unused capacity, which tends to increase with W, is usually small and widely scattered over the network links, making its exploitation very inefficient to route dynamic lightpaths. This is the main reason why we considered protection techniques for static traffic (1:1 and shared) that offered extra capacity to host dynamic connections.

To conclude the description of our model, let us explain how dynamic traffic is managed. Dynamic requests for optical connections arrive to the network control system from the upper transport protocol layers at random time. Each request is characterized by a source node, a destination node and a finite random duration of the connection. At each arrival of a new request the

[2] The exploitation of spare WDM channels would not be possible with other protection techniques such as, for instance, 1+1 dedicated path protection, in which the signal always propagates on both the working and spare lightpaths also in absence of failures.

control system applies a heuristic RFWA algorithm trying to setup the corresponding lightpath using the available WDM channels. No disruption of high-priority static working lightpaths is admitted to accommodate the new circuit, as well as no reconfiguration of already active dynamic lightpaths. If available resources are not sufficient the request is blocked and lost forever [5], [6]. Otherwise, the lightpath is setup by allocating the suitable sequence of WDM channels that will be released after the given connection duration. The chance of being able to accept a new connection is the blocking probability parameter. The main purpose of the simulation experiments we have performed is to compare the effectiveness of different RWFA algorithms (that will be presented in Sec. IV) in terms of average blocking probability. This parameter is estimated by measuring the ratio between the number of refused connection requests and the total number of requests received by the network during the simulation time. The duration of a simulation is chosen in order to be able to observe the evolution of the system long enough to reach statistical equilibrium under a constant dynamic traffic load. In such a condition the average value of the blocking probability changes very little in time.

Beside routing algorithm comparison, a second objective of this work is the evaluation by simulation of the sensitivity of the network to the type of dynamic traffic. In Sec. III we are giving details on our traffic modelling system and better explain what we mean by type of traffic.

III. Traffic modelling

As we stated in Sec. I, ASON *dynamic lambda traffic* service is a new emerging feature for WDM networks. To our knowledge no traffic measures of real cases have been yet reported in literature. Therefore a statistical description suitable for the future scenario is very difficult to predict [7]. Because of this lack of actual traffic characterizations, traffic models developed in the traditional circuit-switching theory for telephone networks are usually employed [8].

In our work we assume that each node of the WDM network (i.e. each OXC) is a generator of dynamic optical connection requests, having the node itself as source and a destination which is randomly chosen among the other nodes of the network with equal probability. This last assumption is appropriate in the case all the nodes of the network have the same importance. The analysis of particular situations of polarized destination choice (e.g. hub-like traffic) is left for a future upgrade.

In order to be able to represent a wide range of traffic situations, we adopted the “moment-matching" technique, commonly used in tele-traffic theory to study overflow streams in telephone networks [9], [10]. The traffic offered by a generator to the network is defined by assigning two parameters which corresponds to the first two moments of x, the random number of active connections in the system having the node as source in statistical equilibrium. These two parameters, per each network node, are:

- *offered load* $A_0 = \mathrm{E}[x]$, is the average number of active connections;
- *peakedness factor*, also called Variance to Mean Ratio, $\mathrm{VMR} = \sigma_x^2/\mathrm{E}[x]$, where σ_x^2 is the variance of x.

The "moment-matching" technique then allows to model a generator choosing any *equivalent process* that yields the first two moments of the offered load defined above, independently of the real nature of the generator itself.

The earliest and most widely accepted application of moment-matching [11], [12] exploits the Bernoulli-Poisson-Pascal processes as equivalent processes. Such birth-death processes are in general characterized by the mean inter-arrival time $1/\lambda_x$ between two consecutive connection requests and the mean duration $1/\mu_x$ of each single connection. The holding time of each single connection is an exponentially distributed random variable whose mean value $\mu_x = \mu$ is independent of the state of the generator and of the arrival process. The inter-arrival generation process is instead more complicated and it varies according to the specific traffic type.

Most of the dynamic traffic models in the literature have assumed a Poisson traffic type (*regular* traffic), that in the "moment-matching" technique is obtained by choosing $\mathrm{VMR} = 1$. In this case inter-arrival time is exponentially distributed with a mean value $\lambda_x = \lambda$ that is constant and independent of the state of the generator, like the holding time. For this traffic type a simple relation holds between the average load and the two generator parameters: $A_0 = \lambda/\mu$.

Poisson process, however, may not be representative of the input traffic in a wide area optical network [7], [13], [14]. The Bernoulli and Pascal processes can be used to model *smooth* and *peaked* traffic types, respectively. While in the Poisson process births are quite regularly distributed in time, Pascal traffic is characterized by burst periods with high density of births and Bernoulli traffic, on the opposite, is characterized by burst periods of "silence". In the "moment-matching" technique the peakedness factor determines which type of process has to be used to model the generators: $\mathrm{VMR} < 1$ and $\mathrm{VMR} > 1$ correspond to the Bernoulli and Pascal processes, respectively.

The exact relations between λ_x, A_0 and VMR in the Bernoulli and Pascal cases [7] are quite complicated and will be omitted here for brevity. Qualitatively, λ_x increases with x in the *smooth* case and decreases in the *peaked* case.

In this work we have developed most of simulation experiments by assuming Poisson traffic-type. In section V-C however we are going to show some results obtained with Pascal and Bernoulli traffic types.

IV. HEURISTIC ROUTING ALGORITHMS

At the arrival of a new dynamic connection request at a given time, 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 of each link to be allocated to the new connection.

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, as we will explain later on. Therefore most of the works in literature regarding dynamic WDM networks propose heuristic methods to solve RFWA [15]. Some of these methods are based on disjoint solution first of routing and then of fiber and wavelength assignment. In these cases routing can be constrained: only a limited set of pre-computed routes for each pair of nodes in the network is considered for possible routing. This simplifies the RWFA operation but limits the routing options, potentially affecting blocking probability.

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 [16]). It is based on the *multifiber layered graph* (MLG) representation of the network, also used in our static-network design tool [4] and derived from the layered graph method, well-known from many published papers (e.g. Ref. [17] for dynamic RWA). Each WDM channel of the network is represented by an arc of the MLG, and each node by a set of image nodes. In order to jointly solve RFWA, all the arcs of the MLG are assigned proper weights prior to setup the new lightpath. Then the Dijkstra algorithm is run on the MLG. This allows to find the least-total-weight route between the image node corresponding to the source OXC and the image node corresponding to the destination OXC: the MLG arcs belonging to this route correspond to the WDM channels that must be allocated to the new lightpath.

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 lightpaths that are active at that instant (either static working lightpaths and dynamic lightpaths) plus those allocated to static protection lightpaths. Secondly the MLG weight system is used to support a wide range of RFWA heuristic criteria. 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 algorithm 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.

The focus of this paper is routing algorithm evaluation under dynamic traffic. Therefore, 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. Moreover, with all the tested routing criteria, as we will explain further below, we always used the same criterion both for fiber and for wavelength assignment. This is the FIRST FIT criterion [5], according to which weights are assigned to MLG arcs so that, during RFWA, the first idle wavelength (fiber) is selected after having sorted all the wavelengths (fibers) in each link according to an *a priori* fixed order. FIRST FIT is simple, since it does not require information about the instantaneous network state; however it proved to be a good criterion as for blocking performance.

A. Simple routing algorithms

As mentioned above, the main objective of this work is to compare different routing algorithms in terms of their effectiveness in achieving low blocking probability of the dynamic connections. The high flexibility of our network model allowed us to test several algorithms, starting from “classical” solutions and then proceeding to newly defined advanced algorithms. 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 (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 establishment. 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.

Several other algorithms have been proposed in literature [15]. We consider only the ones presented above for brevity, knowing however that they are the most frequently used.

B. An advanced heuristic routing algorithm

Most of the studies on WDM dynamic traffic presented so far in literature propose routing algorithms which take present or past network states into account [18], [5], [19], [20]. Recent works however, suggested a different approach which focus on the prediction of the future network state based on the network history. In [21] this task is accomplished by a method requiring quite a complex mathematical formulation. In this paper we try to accomplish the same task following an alternative heuristic approach, by seeking a parameter which allows to evaluate the impact of a present routing choice of an optical path on the following connection requests.

The phenomena which can potentially combine to contribute to increase blocking probability may be identified as: (a) general shortage of free WDM channels; (b) exhaustion of available resources on some particular link cut-set, leaving parts of the network disconnected; (c) saturation of all input and/or output links of a particular node. Finding an exact mathematical formulation to represent these causes is not so easy. The identification of critical cut-sets in the network, for instance, is a complex problem that cannot be exactly solved with polynomial algorithms [22]. So we have defined a global network function which can be used as a heuristic measurement of the incidence of all three combined causes. This function $\varphi(t)$, which we name Occupancy Cost Function (OCF), is defined as follows:

$$\varphi(t) = \sum_{j=1}^{L} \frac{1}{f(d_j)} \cdot \frac{b_j}{WF_j} \cdot \frac{\hat{n}_j(t)}{\hat{R(t)}\bar{S}} \tag{1}$$

where symbols have the following meanings:

- L: total number of links;
- $f(d_j)$: value of the probability density function of the network link lengths corresponding to the length d_j of link j;
- b_j: link congestion parameter of link j;
- W: number of wavelengths per fiber;
- F_j: number of fibers installed on link j;
- t: time at which the network is observed, assuming $t = 0$ as the instant from which the network, loaded only with the static lightpaths, is used to carry dynamic traffic; $t = 0$ is also the beginning of all the network simulations;
- $\hat{n}_j(t)$: number of lightpaths that were routed on link j from $t = 0$;
- $\hat{R(t)}$: total number of dynamic connections setup in the network from $t = 0$;
- $\bar{S}$: average shortest path (in number of hops) taking into account all the couples of nodes of the network

The normalized link congestion parameter $\frac{b_j}{WF_j}$ measures an instantaneous utilization state.

The term $\frac{\hat{n}_j(t)}{\hat{R(t)}\bar{S}}$ estimates which share of all the WDM channels of the network allocated to dynamic traffic until time t has been supported by link j. This term is a measure of the link utilization rate derived from the past history. The product of these two factors is a sort of "historical" link congestion parameter. Since the network model we have assumed is a pure loss system, it will reach statistical equilibrium when kept under constant mean dynamic-traffic load for a sufficiently long period. In such a condition the third factor of Eq. 1 tends to become constant in time for each link.

The factor $1/f(d_j)$ may appear unexpected at a first glance, since link lengths seems irrelevant when blocking is the concern. This factor introduces a cost of the utilization of a link of a given length which is inversely proportional to the chances of finding other links of the same length in the network. As it will be shown by examples in Sec. V, in many realistic topologies network-cut-sets are often composed of few links having similar length: in this cases a dramatic increase of OCF due a $f(d_j)$ contribution denotes high chances of cut-set exhaustion.

The most important aspect of the OCF function is that it has been defined in order to be used in an operative way for dynamic lightpath routing. For this purpose, the variation of the function due to a new lightpath setup, more than $\varphi(t)$ itself, is of interest. Based on $\varphi(t)$ variation, a new interesting routing algorithm can be defined, as explained in the following. Let t be the arrival time of a new connection request and t^+ the time after the new lightpath has been set up, assuming that the request is not blocked. Furthermore be γ the set of links crossed by new connection (i.e. its route). The value $\varphi(t^+)$ of the function after the new lightpath setup is:

$$\begin{aligned}
\varphi(t^+) &= \sum_{\forall j \notin \gamma} \frac{1}{f(d_j)} \cdot \frac{b_j}{WF_j} \cdot \frac{\hat{n}_j(t)}{\hat{R(t)}\bar{S}} + \\
&\quad + \sum_{\forall j \in \gamma} \frac{1}{f(d_j)} \cdot \frac{(b_j+1)[\hat{n}_j(t)+1]}{WF_j[\hat{R(t)}+1]\bar{S}} \\
&= \sum_{\forall j \notin \gamma} \frac{1}{f(d_j)} \cdot \frac{b_j}{WF_j} \cdot \frac{\hat{n}_j(t)}{\hat{R(t)}\bar{S}} + \\
&\quad + \sum_{\forall j \in \gamma} \frac{1}{f(d_j)} \cdot \frac{b_j \hat{n}_j(t)}{WF_j[\hat{R(t)}+1]\bar{S}} + \\
&\quad + \sum_{\forall j \in \gamma} \frac{1}{f(d_j)} \cdot \frac{[b_j + \hat{n}_j(t) + 1]}{WF_j[\hat{R(t)}+1]\bar{S}}
\end{aligned}$$

Let us consider the equation above after an initial transient time τ. In realistic traffic conditions we can assume that, for $t > \tau$, $\hat{R(t)} \gg 1$ and therefore $\hat{R(t)} + 1 \approx \hat{R(t)}$. The first two terms can be grouped together, thus obtaining $\varphi(t)$ again. In conclusion the increment of function $\varphi(t)$ due to a new lightpath setup can be written as

$$\Delta\varphi(t) = \varphi(t^+) - \varphi(t) = \sum_{\forall j \in \gamma} \frac{b_j + \hat{n}_j(t) + 1}{f(d_j) W F_j \hat{R(t)} \bar{S}} \tag{2}$$

Equation 2 gives us the hint and the opportunity to define a new routing algorithm whose optimality criterion is the minimization of the increment of the OCF itself. This algorithm can easily be implemented on our network model by assigning the following weight to each link j:

$$w_r(j,t) = \frac{1}{f(d_j)F_j} \cdot [b_j + \hat{n}_j(t) + 1]$$

The other normalization factors $W\hat{R(t)}\bar{S}$ can be omitted since they are common to all the links. It should be noted that towards the beginning of the simulations the algorithm behaves similarly to LLR, due to the presence of b_j, while as the system approaches statistical equilibrium $\hat{n}_j(t)$ becomes more and more relevant.

The function $\varphi(t)$ is obviously far from being a blocking probability. However, when $\varphi(t)$ is evaluated for a network in statistical equilibrium conditions and for different values of average load, its behavior as a function of the load is extremely similar to the corresponding behavior of the blocking probability. The exact comprehension of the relation between OCF and Π_p would require the definition of a suitable analytical model. Several analytical models for evaluating blocking probability of a WDM network under dynamic traffic have been published. Several of these models (e.g. Ref. [23]) assume fixed routing (one single possible path between each source and destination). An early model considering adaptive routing has been proposed for classical circuit-switched networks (thus also VWP WDM networks) in Ref. [24]: however in this case routing is constrained (also, the topology must be fully meshed). The most advanced analytical models for WDM networks seems today those based on link correlation. A first model was proposed in Ref. [19] for fixed routing, then it was extended in Ref. [25] to multifiber WDM networks; in Refs. [16], [26] the correlation model was applied to adaptive routing, but again considering a limited predetermined set of routes for each node pair. All the models mentioned so far require to (iteratively) solve a set of Erlang fixed-point equations: constraining the routing choices is needed in order to limit the complexity of this solution. In conclusion, none of the theoretical approaches mentioned above is directly applicable to evaluate blocking probability when routing is based on OCF. In fact this new routing criterion is unconstrained, adaptive, multifiber and takes the link length distribution into account; besides, the presence of the high-priority static traffic further increases the complexity. Thus, the present paper is based on heuristic considerations supported by simulation results: an analytical model, currently under study, will be proposed in a future work in which we wish to provide theoretical justifications to the present results.

In the next section we will compare all the routing algorithms described in this section by simulating their performance on various case-study networks.

V. Case-study results analysis

The results we are going to present in this paper were obtained by a C++ discrete-event network simulator implemented according to the network model described in the previous sections and which has been integrated with the WDM network design tool.

Three case-study networks have been considered. The first two, namely the USA National-Science-Foundation Network (NSFNET) and the European Optical Network (EON), shown in Fig. 1 and Fig. 2 respectively, have been designed, optimized (minimizing the total number of fibers) and preloaded with static traffic using the tool described in [4], assuming $W = 32$ wavelengths per fiber. Data regarding physical and virtual topology for these two realistic examples were taken from [27] and [28].

The third case-study network (Fig. 3) has been created *ad hoc* as an example of network having cut-sets composed of few links of similar length. Though it does not physically exists, its topology is realistic, since it corresponds to a global infrastructure composed of three metro-area networks interconnected by a wide-area network. For this reason we named it Wide Plus Metro Area Network (WPMNET). WPMNET has only three types of links: short (MAN links), medium and long (WAN links). The number of short links is much higher than that of medium and long links, since MAN networks usually have a larger connectivity. This particular length distribution allows us to highlight the importance of introducing the cost factor $1/f(d_j)$ in the advanced routing algorithm we have proposed in this paper. Thanks to this factor the routing algorithm will try to avoid routes such as the one shown in Fig. 3 from S to D, which unnecessarily overload long links and can bring to a quick congestion of critical cut-sets.

The particular structure of WPMNET is well shown in Fig. 4, in which the probability distribution function of the length of the links is plotted, normalizing the length to the longest link in the network. By comparison, also the probability distribution functions of the other two networks are reported.

We have performed three different sets of simulation experiments on the three chosen case-study networks, in order to analyze three different aspects of the ASON scenario: (a) effects of the protection mechanism adopted for the static connections; (b) effectiveness of the routing algorithms; (c) effects of the type of dynamic traffic. In all the cases network blocking probability Π_p has been considered as the basic performance parameter. Curves are plotted using the average offered traffic (in Erlang) *per generator* A_0 as x-axis variable. In simulations concerning WPMNET no static traffic has been pre-loaded on the network; all the links have 5 fibers with $W = 5$ wavelengths per fiber. Poisson traffic has been always used, except for the experiments presented in the last subsection, and all the OXCs have been assumed to be active independent dynamic traffic generators. Finally, all the results displayed are obtained when the network system has reached the statistical equilibrium under constant average load.

A. Dedicated and shared protection of high-priority traffic

Fig. 5 shows the blocking probability of dynamic connections for NSFNET and EON (VWP scenario) in the two cases of dedicated and shared path-protection of the high-priority static connections. LLR/SPR has been used as routing algorithm.

Curves clearly show in both cases that blocking probability is higher with shared path protection. This is quite expected. The same number of static w/p pairs are supported by the optimized networks in the dedicated and shared cases. If the number of WDM channels occupied by the working lightpaths is roughly the same; protected lightpaths require far less channels in the latter case, due to sharing of several channels by more w/p pairs. As a consequence, in a shared-protected network far less WDM channels are available to host dynamic traffic. We can conclude that for a network operator the shared protection strategy is beneficial to save on initial installation costs of the network, since the total number of fibers to support a given static demand is less than in the dedicated protection case. This saving however has the drawback of limiting the operator ability of satisfying future lambda-service customers.

As stated above, blocking events can be caused either by shortage of WDM available channels or by cut-set congestion. A lower bound of blocking probability which takes only the first cause into account is given by the following simple analytical method. The total number C of WDM channels that are initially available (at $t = 0$) for dynamic traffic is a known quantity that results from static network optimization. The total number of channels allocated to dynamic connections at any time is obviously bounded by C. All the N network nodes are identical traffic generators that are demanding connections randomly selecting destinations between all the other nodes. In the ideal case we can assume that all these connections are routed on the shortest path between source and destination in order to occupy the minimum possible amount of resources. The average accepted traffic per node is A_s, which is related to A_0 by: $A_s = (1 - \Pi_p)A_0$. Given this scenario, the minimum possible number of WDM channels allocated to dynamic lightpaths having a certain node as source is $A_s \cdot \bar{S}$, where we recall that $\bar{S}$ is the average shortest path (in number of hops) of the network. After simple math we can finally write

$$\Pi_p \geq 1 - \frac{C}{N \cdot A_0 \cdot \bar{S}} \quad (3)$$

In Fig. 5 the curves derived form Eq. 3 have been plotted for the two networks in the two dedicated and shared cases. By comparing these curves with those obtained by the simulation we can conclude that cut-set congestion is a strong cause of blocking in networks pre-loaded with static traffic.

After the comparison presented in this subsection, only dedicated path-protection will be considered for static traffic for the rest of the paper.

B. Routing algorithm comparison

Fig. 6 allows to compare the performance of the various routing algorithms considered in the paper and for the three case-study networks, in both WP and VWP wavelength-conversion scenario. As expected from the lower-bound analysis reported above, the worse routing algorithm is SPR, since it is not effective in avoiding congestion. LLR alone is a little better performing, while fair improvements are obtained when the two algorithms are combined together, giving LLR a higher priority. The better behavior of LLR compared to SPR with dynamic traffic is well known [5], [6], [16], [20] [3]. Some papers [16], [26] proposed the combined LLR/SPR

[3] Ref. [26] is an exception, showing that SPR is better than LLR. This is probably due to the fact that routes are constrained to the shortest-path length + one hop.

algorithm (or similar versions) showing their advantages.

The new algorithm we proposed, based on OCF increment minimization is the best performing algorithm, especially when the cost associated to the link length probability density function $f(d_j)$ is taken into account.

We have further analyzed this latter aspect by comparing the blocking probabilities obtained by applying the OCF based routing algorithm without and with taking the cost factor associated to $f(d_j)$ into account. The ratios displayed in Fig. 7 measures the penalty that must be paid in terms of blocking probability when the distribution of the link lengths is not considered in routing. As expected, this penalty gets worse for networks which contain cut-sets composed of few links of similar length, while is less severe for networks that have a rather uniform link length distribution (e.g. the NSFNET).

Another interesting aspect we wished to better understand is the relation between the occupancy cost function $\varphi(t)$ and the blocking probability when the algorithm based on OFC is adopted for routing. Fig. 8 compares Π_p and $\varphi(t_e)$ evaluated at a time t_e in which the network is in equilibrium. The graph clearly shows that, even if OFC assumes a completely different set of values, its dependence on A_0 is very similar to that of the blocking probability. Π_p and $\varphi(t_e)$ result to be almost proportional, especially for small loads.

As a final comment we shall add that all the graphs displayed in this subsection show that wavelength conversion is quite important for WDM dynamic traffic (while it is not so in the static case), especially for low traffic loads, for which the presence of the converters can reduce blocking probability of one order of magnitude.

C. Traffic type comparison

We have simulated the behavior of the NFSNET under the three types of dynamic traffic (Bernoulli, Poisson and Pascal) described in Sec. III. All these simulations are carried out adopting the OCF based algorithm for routing. In the case of Bernoulli and Pascal the chosen values of the peakedness ratio VMR are 0.5 and 5 respectively.

In Fig. 9 the results of the simulations are displayed in three cases: (a) with a single active generator; (b) with 5 active generators; (c) when all the 14 generators are active. Results with one single active generator (which could model the real situation of a large hub node connected to small customers) indicates that blocking probability is strongly dependent on the type of traffic. Most of the blocking events are probably due to the saturation of the links connected to the active generator. With a higher number of independent generators the blocking probability becomes more and more insensitive to the type of traffic. This behavior is probably due to the fact that the network links aggregate uncorrelated traffic from many different sources which are characterized by "classical" random processes such as those we employed for our simulations.

It should be observed that though the global blocking probability tends to be the same, the dynamic behavior of a network loaded with the three types of traffic is different, even with a large number of active generators. In fact with Bernoulli process blocking events are regularly distributed in time, with Poisson process losses occur less regularly, while with Pascal process there are periods in which the system accepts all the connection requests and some others in which loss is very high (further results regarding this aspect are not reported here for brevity).

VI. CONCLUSIONS

We have considered the future scenario of WDM networks designed and optimized for static traffic and then employed to provide lambda-connection service on demand. This leads dynamic low-priority optical connections to co-exist together with static high-priority connections on the same optical network. This paper simulates and compares the performance of several well-known algorithms for dynamic lightpath routing in such a network environment. We have proposed and tested an advanced routing algorithm able to reduce blocking of future connections in different ways. By means of dynamic traffic simulations we have shown the performance improvement of the advanced routing algorithm compared to other well-known classical solutions. Our study also includes an evaluation of the behavior of WDM networks under non-Poissonian traffic type, as well as a comparison between cases in which high-priority static connections are protected by shared and dedicated WDM path-protection, respectively.

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List of Figures

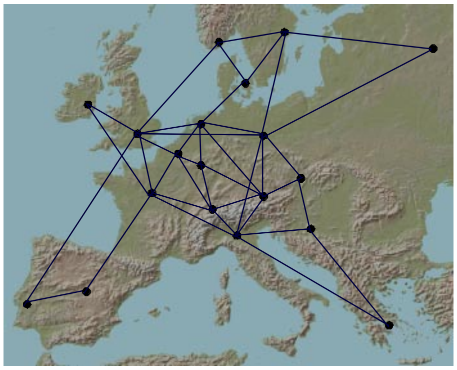


Figure 1. European Optical Network (EON).

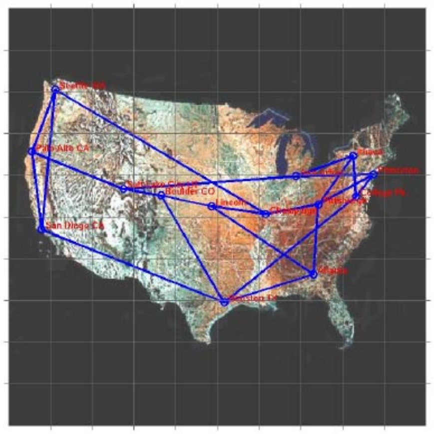
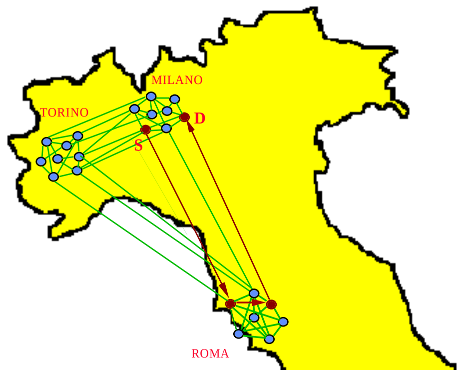


Figure 2. National Science Foundation Network (NSFNET).



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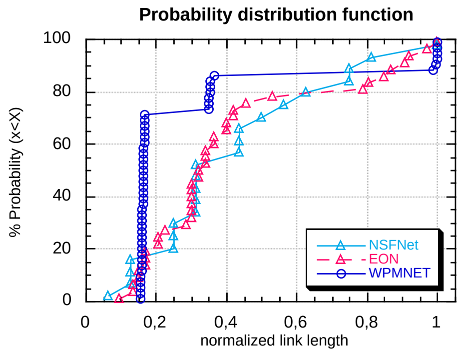

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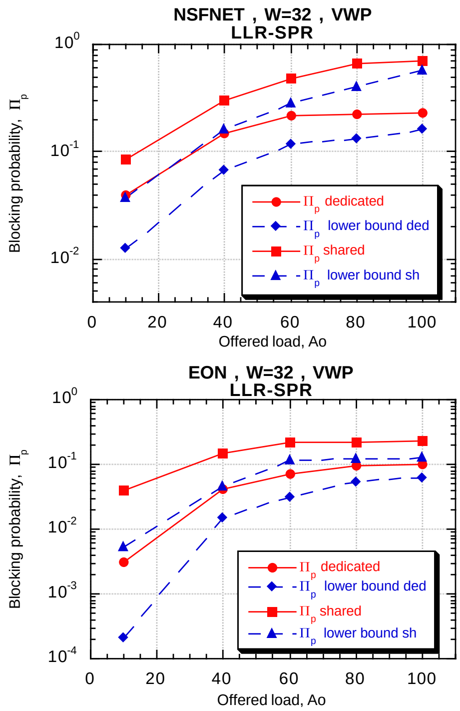
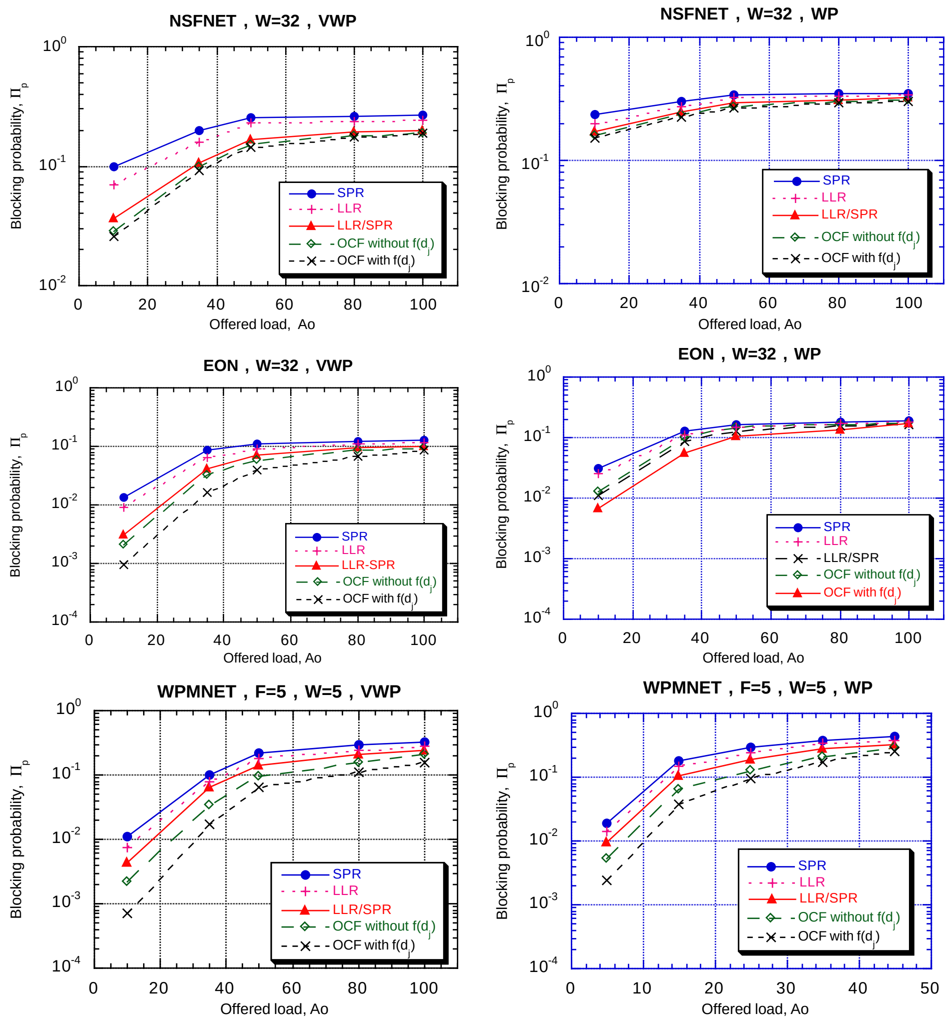


Figure 5. Blocking probability of dynamic connections in NSFNET and EON in the two cases of dedicated and shared path-protection of the static traffic. Lower-bound curves are also plotted



(a) (b)

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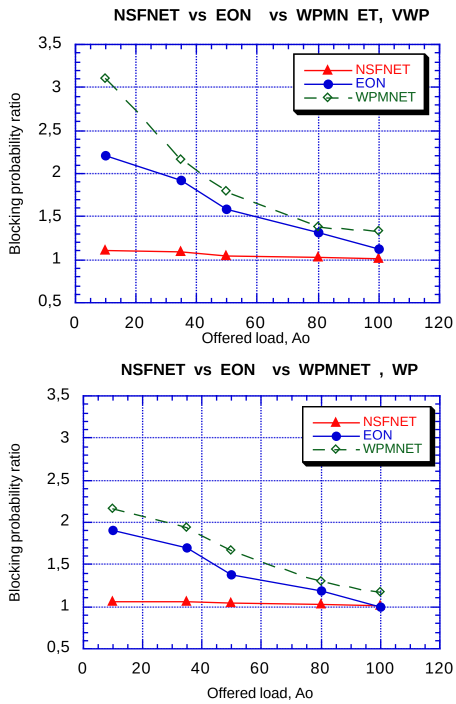

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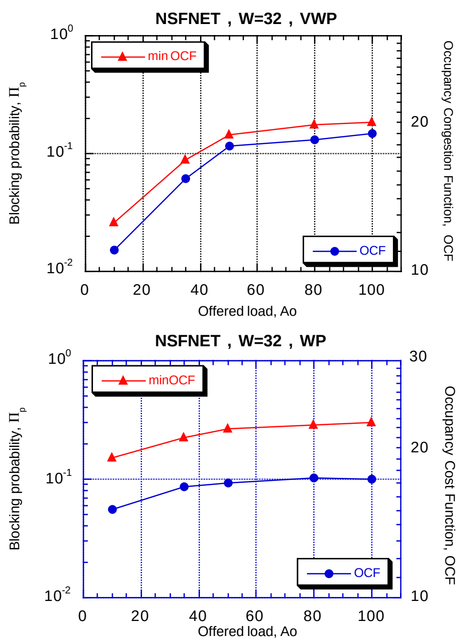

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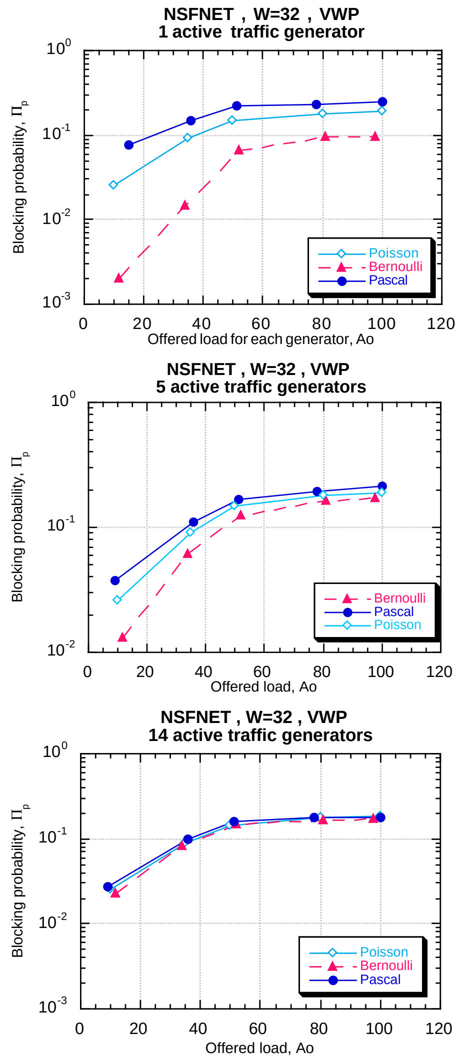

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