Highlights on a Study of Bicriteria Routing Methods with Protection for WDM Networks with Dynamic Traffic

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***Abstract*—Dedicated path protection is a robust and efficient way to increase the resiliency of a telecommunication network. Two variants of a bi-criteria dedicated path protection model for wavelength division multiplexing (WDM) networks in a dynamic traffic scenario, are presented. The proposed routing approach is based on a bi-criteria optimization model for the calculation of disjoint lightpath pairs in WDM networks with dedicated protection. A performance analysis study of the proposed routing method considering two different metric pairs as objective functions and using an exact resolution approach, in a reference test network, is highlighted. The presented simulation results show the potential advantages of this approach when compared with single criteria optimization approaches.**

Keywords-optical networks; multicriteria optimization; routing; protection.

I. INTRODUCTION

Given the enormous transfer rate available in the links of a WDM network, a single failure potentially results in huge data losses and service disruptions to many customers. To circumscribe this potential problem and ensure a high degree of availability, network operators adopt protection and/or restoration schemes [1]. In protection mechanisms, an optical connection (or *lightpath*) can be protected against failures by a precomputed backup route. Alternatively, in restoration schemes, the necessary resources to recover a failed connection are only determined and reserved after a failure occurs. Usually, restoration mechanisms are more resource efficient since they do not reserve resources in advance, and provide recovery against different types of failures (including multiple failures), but they need more time for resource determination and reservation, and the recovery will only be successful if there are sufficient resources in the network. Conversely, protection schemes have faster recovery times and can insure resource availability in the failure scenarios for which they have been designed, at the expense of more resources.

In path protection against any single failure, it is necessary to calculate a pair of disjoint paths - the *Active Path* (AP) to be used in normal conditions and the *Backup Path* (BP) to be used if a failure occurs. With dedicated path protection, both the resources of the AP and the BP are assigned to the connection and will only be released when connection ends.

The problem of finding two link disjoint paths can be solved in polynomial time using *Suurballe*'s algorithm [2].

Optical WDM networks consist of optical fiber links, interconnected by optical nodes (routers). Each fiber link comprises several channels, with different wavelengths, and each optical node supports wavelength based switching or routing. The configuration of these optical nodes allows the establishment of point-to-point optical paths (lightpaths), between node pairs. A lightpath may span several links and consist of a wavelength channel in each of these links, interconnected at the nodes by means of optical routing. In order to set up a lightpath, the network needs to decide on the topological path and the wavelength(s) assigned to the lightpath - the so-called Routing and Wavelength Assignment problem (RWA). In the absence of wavelength converters at the optical nodes, a lightpath must use the same wavelength on all the links of its route (the wavelength continuity constraint), but wavelengths can be reused by different lightpaths in the network, as long as they do not share any fiber link.

In a dynamic traffic scenario (Dynamic Lightpath Establishment problem – DLE), a lightpath is set up for each connection request as it arrives, and is released after some finite amount of time. The objective is usually to choose routes and assign wavelengths in a manner that minimizes the overall blocking. To overcome the high complexity of this problem, the routing sub-problem and the wavelength assignment sub-problem are solved separately.

Concerning dedicated path protection in WDM networks (Survivable Routing and Wavelength Assignment – SRWA), the problem of finding a pair of disjoint paths under the wavelength continuity constraint is *NP*-complete [3].

Even though, in general, the routing methods try to optimise only one metric, typically using some variant of a shortest path algorithm, optical networks are characterised in terms of performance by multiple metrics. Furthermore, the design of real networks involves multiple, often conflicting objectives and constraints.

In this context, it seems potentially advantageous to develop multicriteria models that explicitly represent the different performance objectives to be optimised, enabling to treat in a consistent manner the trade offs among these objectives. In this type of models, the concept of optimal solution is replaced by the concept of non-dominated solution. A feasible solution is said to be non-dominated if it is not possible to find any other

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feasible solution which enables one criteria to be improved without sacrificing, at least, one of the remaining criteria.

Reference [4] presents a state-of-art review on multicriteria approaches in communication networks and includes a section dedicated to routing models. A survey of multicriteria routing models can be seen in [5].

In this paper, we focus on the problem of dedicated path protection against link and node failures with dynamic traffic, and present a performance analysis study of two variants of a bicriteria model for the route calculation problem using an exact resolution approach. The first variant of the model was initially proposed in [6], but in a context of incremental traffic.

The two major contributions of this work in progress will be: *i*) the consideration of specific variants of a bi-criteria model for dynamic traffic instead of incremental traffic (which is a fundamental change in the underlying assumptions of the model) using an exact resolution method; *ii*) an extensive performance comparison of the bi-criteria model variants with the associated single-criterion models using reference test networks. The analysis in this paper considers relevant network performance measures, namely, the global blocking probability, the carried traffic and percentage of used bandwidth. A dynamic traffic model in a benchmark network will be considered.

The remaining of this paper is organised as follows. In Section II, the bicriteria model is presented, the metrics are introduced and two versions of the bicriteria model are considered. Section III identifies the relevant parameters for performance assessment of the model, presents the simulation results and a comparative study of the models. Finally, some conclusions are drawn in Section IV.

II. Model Description

In this section, we describe the features of the proposed bicriteria routing model associated with the Dynamic Lightpath Establishment problem (DLE) with dynamic traffic in WDM networks. The model was developed for application in large WDM networks, with multiple wavelengths per fiber and multifibers per link. Network reliability is improved through dedicated path protection, so a node disjoint path pair must be obtained for each connection request. In order to cover a wide variety of networks, different types of nodes are considered (with complete wavelength conversion capability, limited range conversion or no wavelength conversion capability) in the model. Due to the real-time nature of the intended application, solutions should be obtained in a short time. This requirement lead to the separation of the routing and wavelength assignment problems, also having in mind an automatic selection of the solution (among the non-dominated solutions, previously identified). The wavelength assignment problem is solved separately, after the bicriteria routing problem.

Let the WDM network be represented by $R = \{N, L\}$ where N is the set of nodes and L is the set of links. A *topological path*, p, in the network is defined by: a source node s, a destination node t and an ordered sequence of nodes and links from s to t. In addition to the ordered sequence of nodes and links, a *lightpath* p^λ also comprises the fiber used in each link and the wavelength in each of the fibers.

A. Bicriteria Model

In a first variant of the model (*BiC_A Model*), we consider two additive metrics for the active and the protection paths as objective functions (*o.f.*). The first *o.f.* is the sum of the inverse of the free bandwidth in the links of each path:

$$\min_{z\in D}\left\{c_1(z)=\sum_{l\in z}\frac{1}{b_l^T}=\sum_{l\in p}\frac{1}{b_l^T}+\sum_{l\in q}\frac{1}{b_l^T}\right\} \quad (1)$$

where D represents the set of topological path pairs $z \equiv (p, q)$ for the origin–destination node pair (s, t) such that p and q are node disjoint and correspond to viable optical lightpaths (taking into account the availability of wavelengths in the links and the wavelength conversion capabilities of the nodes), and b_l^T is the total available capacity in link l, in terms of free wavelengths. This criterion aims to avoid more congested links, promoting a balanced distribution of the traffic throughout the network, hence decreasing the blocking probability and increasing the expected revenue.

The second objective consists of minimizing the number of links of the two paths (hop count), and is intended to avoid bandwidth waste, hence favouring global efficiency in the use of network resources:

$$\min_{z\in D}\{c_2(z)=h(p)+h(q)\} \quad (2)$$

In many cases, whenever the objective functions are conflicting, there is no feasible solution which optimises the two *o.f.* simultaneously. The algorithmic approach described in section II-B is used to obtain a good compromise solution among the non-dominated solutions of the bicriteria problem:

$$(\mathcal{P}_A)\quad \begin{cases}\min_{z\in D}\left\{c_1(z)=\sum_{l\in p}\frac{1}{b_l^T}+\sum_{l\in q}\frac{1}{b_l^T}\right\}\\ \min_{z\in D}\{c_2(z)=h(p)+h(q)\}\end{cases} \quad (3)$$

Another version of the bicriteria model (*BiC_B Model*) was also implemented. As in the previous model, the second *o.f.* is the hop count, but the first one is a load cost function suggested in [7] for IP/MPLS networks. This load cost function is an additive metric where the cost of a link is modeled through a piecewise linear increasing and convex function, the value of which is inversely proportional to the free capacity. The main goal of this metric is to avoid congestion, i.e., overloading of links, and obtain a balanced distribution of the traffic throughout the network.

The *load cost*, LC_l, of a link l is defined by [7]:

$$LC_l=\begin{cases}\rho_l & \text{if}\quad 0<\rho_l<\frac{1}{3}\\ 3\rho_l-\frac{2}{3} & \text{if}\quad \frac{1}{3}\le\rho_l<\frac{2}{3}\\ 10\rho_l-\frac{16}{3} & \text{if}\quad \frac{2}{3}\le\rho_l<\frac{9}{10}\\ 70\rho_l-\frac{178}{3} & \text{if}\quad \frac{9}{10}\le\rho_l<1\end{cases} \quad (4)$$

where ρ_l denotes the relative occupancy of the link (the ratio between the occupied bandwidth and the total bandwidth on the link). The second bicriteria problem, considering dedicated path protection, is now:

$$(\mathcal{P}_B) \quad \begin{cases} \min_{z\in D}\left\{c_1(z)=\sum_{l\in p} LC_l+\sum_{l\in q} LC_l\right\} \\ \min_{z\in D}\left\{c_2(z)=h(p)+h(q)\right\} \end{cases} \tag{5}$$

B. Resolution Approach

Reference [8] proposes an exact algorithm for finding non-dominated shortest pairs of disjoint paths that uses the *k*-shortest path algorithm MPS [9]. Given an origin-destination node pair (s, t), the algorithm starts by making a network topology modification, where all nodes and links of the graph, (N, L), representing the network topology are duplicated and a new link, with null cost, is added between node t and node s' (the duplicate of s). In this new modified graph, (N', L'), each path from s to t' (the duplicate of the destination node t) will correspond to a pair of paths from s to t in the original topology [8]. Finally, the adapted version of MPS is used for ranking by non-decreasing order of cost the pairs of paths $z \equiv (p, q)$, such that p and q are node disjoint. In order to select the best compromise solution, priority regions are defined in the objective function space [10]. The final solution is chosen among the non dominated solutions in the highest priority region, by using a weighted Chebyshev distance to a reference point (bottom left corner of the region). Further details of the topological path pair selection can be seen in [6].

C. Wavelength selection

Having selected a node disjoint path pair, we use the maximization of the *wavelength bottleneck bandwidth*, which corresponds to the choice of the Least Loaded wavelength (LL) along the links of each of paths in the pair, to make the wavelength and fiber selection. Further details and an illustrative example of this selection heuristic can be seen in [11]. Note that, if all the nodes of the network enable full wavelength conversion, once a viable topological path is chosen, the choice of the wavelength(s) to be used is irrelevant in terms of network performance. If the nodes have no conversion capability, the proposed criterion of wavelength selection is known in the literature (see, e.g., [12]) to give good results. In any case, it is also known that in these cases the critical factor in terms of network performance is the selection of topological paths, the choice of wavelength having a minor impact [12].

III. Performance Analysis Study

A. Network Performance parameters

Highlights of the results obtained using the two variants of the bicriteria model, *BiC_A* corresponding to $\mathcal{P}_A$ (3) and *BiC_B* corresponding to $\mathcal{P}_B$ (5), will be analysed and compared with the results obtained using single objective formulations, namely, the shortest path in terms of either the number of hops *SP_hop* (2), the inverse of the free bandwidth *SP_BW* (1), or the load cost *SP_LC* ($c_1(z)$ in (5)), by recurring to relevant network global performance metrics. The considered network metrics are: the global blocking probability (fraction of connection requests that are blocked); the carried traffic; the percentage of used bandwidth in the network and the point-to-point blocking probabilities.

B. Comparative Study

This section presents the simulation results in the NSFNET network [13], with 14 optical nodes and 21 multifiber links (with 16 wavelengths per fiber). The results were obtained from discrete events stochastic simulations, with Poisson traffic generated with intensities proportional to the traffic matrix presented in [13], which takes into account the distance and population of the nodes. Concerning the wavelength conversion capabilities, simulations were conducted considering three different scenarios: all nodes without conversion capability, five nodes with total conversion capability, (central nodes were chosen with this capability), and total conversion capability in all the nodes.

Figure 1 shows the global blocking probability and the percentage of used bandwidth for several values of the offered traffic, with no conversion capability in the network. Clearly, the single criterion routing model based on hops (*SP_hop*) has the worst performance, which confirms that choosing the path pair based only on the hop count is a poor strategy, in this type of networks. Model *BiC_A* presents the lower blocking, and hence more carried traffic and expected revenue. Thus, *BiC_A* outperforms SP_hop and SP_BW, the corresponding single objective formulations. Concerning *BiC_B*, its blocking is quite similar to that presented by *SP_LC*. However, *BiC_B* uses slightly less bandwidth (see Figure 1).

Although not shown here, the results with total wavelength conversion in the network or with 5 nodes with conversion exhibit the same behavior pattern: *BiC_B* and *SP_LC* have similar performance, which is better than *SP_BW*, but worse than *BIC_A*. Again, the single objective *SP_hop* exhibits the worst performance. As expected, it turns out that the presence of wavelength conversion enables a slight improvement in the global blocking probability. Furthermore, much more important than this improvement in global blocking, an additional advantage provided by the conversion capability is a substantial improvement in QoS fairness. Indeed, comparing the point-to-point blocking probabilities in both cases, it is noted that, for 1000 *Erlangs* of offered traffic, *BIC_A* has mean blocking probability of 0.63% without wavelength conversion and 0.53% with total conversion, but the maximum point-to-point blocking probability (usually observed between farther away nodes) is 2.44% in the former case and 1.42% with total conversion. For higher values of the offered traffic, without wavelength conversion, the QoS among node pairs is even more unbalanced. For example, with *BIC_A* and 1050 *Erlangs* the global blocking probability is 3.16% without conversion and 2.67% with total conversion, but there are pairs of nodes for which blocking is 11.8% without conversion and 6.21%

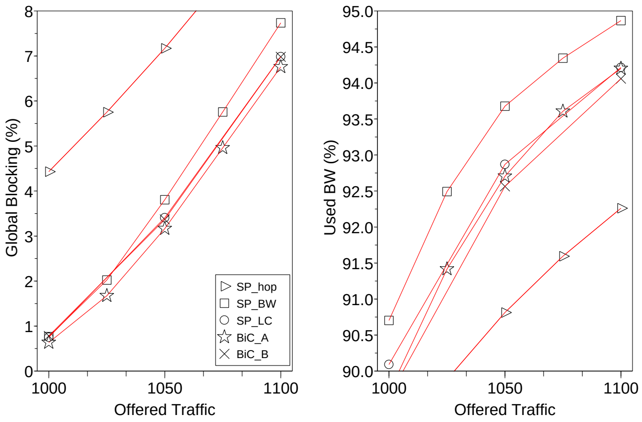

Figure 1. Global Blocking and Used Bandwidth.

with total conversion. The maximal point-to-point blocking is even worse in single criterion models.

IV. Conclusion and Further Study

A multicriteria approach of the type proposed can explicitly represent the different performance objectives, enabling to address, in a mathematically consistent manner, the trade offs among the various criteria. Two variants of a bicriteria model for obtaining a topological path pair for every lightpath request in a WDM network with dynamic traffic were presented. The proposed resolution approach uses an exact bicriteria shortest path pair algorithm and an automated solution selection procedure. Having obtained a non-dominated topological path pair, a heuristic procedure was then used to assign wavelengths to the links.

The performance of two variants of the bicriteria model was analysed in comparison with the corresponding single objective approaches. The model *BiC_B* did not show a significant advantage in comparison with *SP_LC*. But the *BiC_A* exhibits better performance than any of the single objective models. Furthermore, in conjunction with wavelength conversion, *BiC_A* also allows a higher fairness regarding the point-to-point blocking probabilities.

Further experimental studies of similar type, with other reference test networks, will be carried out.

It is important to note that, from a methodological point of view, the used modeling approach, as indeed any other shortest path based approach, is a flow oriented optimization approach. That is, the path pairs are calculated for each node-to-node connection request at a time, so that the objective functions do not integrate explicitly the combined effect of all possible connections offered to the network. This is an inherent limitation of this type of approaches, as analysed in depth in [14] in the context of multicriteria routing models for MPLS networks. This is an additional reason why it is so important to make extensive performance analysis studies with flow oriented models, using relevant network performance global metrics as in the present work. A more in depth analysis of these issues in the context of WDM networks, both at methodological and experimental level (considering different objective functions and other networks), deserves further research.

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