Paper

Performance Analysis of a Bi-Objective Model for Routing with Protection in WDM Networks

Carlos Simões, Teresa Gomes, José Craveirinha, and João Clímaco

Abstract—The operation of wavelength division multiplexing (WDM) networks involves not only the establishment of lightpaths, defining the sequence of optical fibres and the wavelength in each fibre for traffic flow, but also a fault management scheme in order to avoid the huge loss of data that can result from a single link failure. Dedicated path protection, which establishes two end-to-end disjoint routes between the source–destination node pair, is an effective scheme to preserve customers' connections. This paper reviews a bicriteria model for dedicated path protection, that obtains a topological path pair of node-disjoint routes for each lightpath request in a WDM network, developed by the authors. An extensive performance analysis of the bicriteria model is then presented, comparing the performance metrics obtained with the monocriterion models using the same objective functions, in four different reference networks commonly used in literature.

Keywords—multicriteria optimization, protection, routing in WDM networks.

1. Introduction

1.1. Background Concepts

In modern all-optical networks based on wavelength division multiplexing (WDM), one single fiber can provide an enormous bandwidth (up to tens of terabits per second) by multiplexing many non-overlapping wavelength channels. Each wavelength can be operated transparently, at speeds compatible with the lower capacity of the end-users devices.

The high capacity of a single fibre in optical networks, however, has the drawback that a failure on a link can potentially lead to a huge amount of data loss (and revenue), and service disruption for a large number of customers. In this scenario, network survivability becomes a critical concern for service providers (both in the network design phase and in the real-time network operation) and fast and efficient fault-recovery mechanisms are then needed to ensure a high degree of network resilience and minimize losses. Survivability of a network refers to the network capability to provide continuous service in the presence of failures.

Fibre cuts are usually the most frequent failure event in optical networks, and lead to the disruption of all the lightpaths that transverse the failed fibre. But other network equipments (such as OXC, amplifiers, etc.) may also fail. These two basic types of failures in the network can be categorized as either link (mostly cable cuts) or node failures (equipment malfunctions).

Essentially, there are two types of fault-recovery mechanisms. A lightpath can be protected against failures by pre-computing a backup route and reserving resources along the route in advance [1]. We call this approach a protection scheme. Alternatively, the resources necessary to restore a disrupted lightpath can be discovered dynamically and signaled (reserved) only after a failure occurs. This approach is referred to as dynamic restoration (or just restoration) [1]. Usually, dynamic restoration schemes are more resource-efficient because they do not allocate spare capacity in advance and provide resilience against different kinds of failures (including multiple failures), but they need more time to discover free resources and reroute the disrupted connection. On the other hand, a protection scheme has faster recovery time and can guarantee resource availability for a backup path in the fault scenarios for which it was designed [2], but it needs more resources.

A protection method can protect the end-to-end path (path protection), protect the failed link (link protection) or protect a segment of a path (subpath protection) [2]. In path protection, in order to recover from any single link failure in the network, a link-disjoint path is needed as the backup path to reroute the traffic on the active path (primary path). The primary and backup paths for a connection between a node pair must be link disjoint so that no single link failure can affect both paths. Note that node failures can also be considered by calculating node disjoint routes. In link protection, the traffic is rerouted only around the failed link. While path protection leads to efficient utilization of backup resources and lower end-to-end propagation delay for the recovered route, link protection provides shorter protection switching time. The concept of subpath protection has been proposed as a tradeoff between the path and link protection schemes, and consists in the division of the primary path into a sequence of segments, each one protected separately [3]. In dedicated protection there is no sharing between backup resources, while in shared protection backup wavelengths can be shared on some links as long as their protected segments (links, subpaths, paths) are mutually diverse. Consequently, shared protection is more resource efficient, but the backup paths can not be configured until the failure occurs and, thus, recovery time is longer than with dedicated protection.

1.2. Routing and Wavelength Assignment

A lightpath may span several fibre links and consist of wavelength channels in the sequence of these links, interconnected at the nodes by means of optical routing. In order to establish a lightpath, the network needs to decide on the topological route and the wavelength(s) for the lightpath. If the optical cross-connects have wavelength converters (wavelength-convertible network), a lightpath can be assigned to different wavelengths in each link of its route. However, since wavelength converters are costly and may cause signal quality degradation, often no wavelength converters are used or only some nodes have this capability. In the absence of wavelength conversion (wavelength-continuous network), the same wavelength must be allocated on all links in the path (*the wavelength continuity constraint*), but wavelengths can be reused by different lightpaths in the network, as long as they do not share any fibre.

Given a set of connection requests, the routing and wavelength assignment (RWA) problem consists of deciding the path and assign a wavelength to each of its links, for every request, given a desired objective and a set of constraints [4]. Wavelength assignment must satisfy two constraints, namely, no two lightpaths on the same physical link can be assigned the same wavelength, and if wavelength conversion is not available, then wavelength continuity constraint must be satisfied on all the links that a lightpath traverses.

Obviously, wavelength conversion leads to lower blocking probabilities, but, in practice, some works have shown that with only a small number of converters placed in strategic locations, a significant performance improvement can be achieved [5].

The RWA problem is known to be NP-complete [6]. Hence, most approaches presented in the literature decouple the problem into its two underlying sub-problems – routing and wavelength assignment – which are solved separately. However each sub-problem is still NP-complete [6]. Therefore, the proposed methods in the literature are generally based on heuristics that allow obtaining a feasible solution in acceptable computation time. Generally, the routing scheme has a much a higher impact in the blocking probability of the connections than the wavelength assignment scheme [4].

1.3. Survivable Routing and Wavelength Assignment

In a WDM network employing path protection, the problem of finding a disjoint primary-backup path pair and assigning wavelength(s) to each path is known as the survivable routing and wavelength assignment (S-RWA) problem and has been extensively studied [1], [2], [7], [8], [9].

Typically, routing heuristics prefer the path pair with least cost from a source to a destination to carry the traffic, where the path cost is defined to be the sum of the costs of all the links along the path. The path cost of a dedicated path-protected connection is the sum of the costs of the primary and backup lightpaths.

Concerning shared path protection, the path cost of a connection is the sum of the cost of the primary lightpath and the costs of the additional backup links on which the wavelength is reserved but is not shared by existing connections. The path pair can be either selected from a set of preplanned alternate routes or dynamically computed according to current network state. Depending on different traffic engineering considerations, different cost functions can be applied to network links, such as constant 1 (to minimize hop distance), length of the links (to minimize delay), fraction of available capacity on the links (to balance traffic load), network cost (total equipment cost plus operational cost) on the links (to minimize cost), and so on. Wavelength assignment can be considered only after the routing of the primary-backup path pair. Several wavelength assignment heuristics have been proposed in the literature [4]. Wavelength assignment can also be jointly considered with the route computation of both primary and backup paths.

In dedicated path protection, two disjoint routes are needed between the source node and the destination node – one for the primary path and the other for the backup path. The simplest way to compute disjoint paths consists in two steps [7]–[10]. In the first step the primary path is computed using a shortest-path algorithm. Then, in the second step, the links and nodes used in the primary path are removed and the backup path is calculated in the remaining topology. This approach is referred to as the two-step approach and has some drawbacks because of the sequential nature of paths' calculation. First, although the primary path is the shortest one (minimal cost), the sum of the costs of the two disjoint paths may not be optimal (minimal). Worst than that, in some scenarios, since erasing the first path can isolate the source node from the destination node, this procedure may not find a pair of disjoint paths even if such a pair of paths exist (trap topology). This can happen even in highly connected topologies [10].

To find two disjoint paths with minimal total cost, Suurballe's algorithm [11] can be applied. This algorithm guarantees to find the disjoint path-pair in polynomial time if such pair exists.

1.4. Multicriteria Models

Typically, routing protocols try to optimize a single metric, using some variant of a shortest path algorithm. Nevertheless, all-optical WDM networks can be characterized in terms of performance by multiple metrics, and the design of real networks usually involves multiple, often conflicting objectives and various constraints. Clearly, since single objective approaches can not express this multiplicity of metrics, it seems potentially advantageous to develop multicriteria models that explicitly represent the different performance objectives, enabling to treat in a consistent manner the trade off among the various criteria.

Note that in models involving explicitly multiple criteria, there is no guarantee that a solution that optimizes all the criteria exists, and the concept of optimal solution is replaced by the concept of non-dominated solutions. A non-dominated solution is a feasible solution such that no improvement in any criterion may be achieved without sacrificing at least one of the other criteria.

Reference [12] presents a state-of-art review on multicriteria approaches in communication networks, including a section dedicated to routing models. For a more recent review on multicriteria routing models see [13].

A bicriteria model for obtaining a topological path (unidirectional or symmetric bidirectional) for each lightpath request in a WDM network with multi-fibre links and an exact resolution approach for that model was presented by the authors in [14], and an extensive performance analysis of the bicriteria model in several reference WDM networks can be found in [15]. In order to provide dedicated path protection to lightpaths, against node failures, an extension of the bicriteria model that allows to obtain a topological pair of node disjoint paths for each request was developed in [16]. The first criterion is related to bandwidth usage in the links of the network, and the second criterion is the number of links (hops) of the path. The resolution approach of this model uses a k-shortest path algorithm for the determination of non-dominated shortest pairs of disjoint paths proposed in [17]. Furthermore, preference thresholds, defined in the objective function's space, combined with a Chebyshev distance to a reference point [18] are used for selecting the final solution. The solution of this bicriteria model is a non-dominated topological (optically feasible) disjoint path pair. A heuristic procedure is then used to assign the wavelengths in the links of the two disjoint paths.

In this paper we focus on the problem of dedicated path protection against node failures, and present an extensive and systematic performance analysis study of the bicriteria model with dedicated protection developed in [16]. This analysis considers relevant network performance measures and compares the corresponding results for the bicriteria model with the results of the associated single objective models, one related to the bandwidth usage and the other consisting of the total number of links in the two paths (active and protection path). An incremental traffic model (where the duration of the connections is assumed unlimited) and several benchmark networks commonly used in this research area will be considered. Essentially, the network performance measures envisaged are: the frequency of rejected requests (an estimate of the global blocking probability), the total used bandwidth, the mean hop count of accepted requests, the percentage of links with minimal free bandwidth, the average CPU time per request, and the percentage of non-optimal solutions.

The paper is organized as follows. In Section 2 the model with dedicated protection is described, together with the resolution approach of the bicriteria model. Performance analysis of the results obtained using several network topologies are presented and discussed in Section 3, enabling to compare the network performance (under the prescribed metrics) of the bicriteria with the monocriterion models, with dedicated protection. Finally, some conclusions of practical and methodological nature are drawn in Section 4.

2. The Bicriteria Routing Model with Dedicated Protection

2.1. Model Description

In this section we describe the features of the proposed bicriteria routing model associated with the dynamic lightpath establishment problem (DLE) with incremental traffic, and a mixture of unidirectional and bidirectional (symmetric) connections requests, in WDM networks. The model was developed for application in large WDM networks, with multiple wavelengths per fibre and multi-fibres per link. 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, 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 $R = \{N,\ L,\ C,\ T_N\}$ represent the WDM network, where:

- Set of nodes, $N = \{v_1, v_2, \ldots, v_n\}$, $n = \#N$.
- Set of directed arcs, $L = \{l_1, l_2, \ldots, l_m\}$, $m = \#L$.
- Set of wavelengths, $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$, $W = \#\Lambda$.
- Set of fibres, $F = \{f_1, f_2, \ldots, f_k\}$, $k = \#F$.
- Let $l_i = (v_a, v_b, \bar{o}_{l_i})$, $\bar{o}_{l_i} = (o_{l_i1}, o_{l_i2}, \ldots, o_{l_ik})$, $v_a, v_b \in N$. If $o_{l_ij} = (1, \bar{a}_j)(j = 1,2,\ldots,k)$, then fibre f_j belongs to arc l_i and contains the wavelengths signalled in $\bar{a}_j$, $\bar{a}_j = (a_{j1}, a_{j2}, \ldots, a_{jW})$, where $a_{ju} = 0,1,2$ $(u = 1,2,\ldots,W)$:

$$a_{ju} = \begin{cases} 0, \text{ if } \lambda_u \text{ does not exist in fibre } f_j\,, \\ 1, \text{ if } \lambda_u \text{ exists and is free in fibre } f_j\,, \\ 2, \text{ if } \lambda_u \text{ exists but is busy in fibre } f_j\,. \end{cases} \quad (1)$$

  If $o_{l_ij} = (0, \bar{a}_j)$ $(j = 1,2,\ldots,k)$, fibre f_j does not belong to arc l_i.

- C is the arc capacity, $C(l_i) = (\bar{n}_{l_i}, \bar{b}_{l_i})$, with $\bar{n}_{l_i} = (n_{l_i1}, n_{l_i2}, \ldots, n_{l_iW})$ and $\bar{b}_{li} = (b_{l_i1}, b_{l_i2}, \ldots, b_{l_iW})$, where n_{l_ij} is the total number of fibres in arc l_i with wavelength λ_j and b_{l_ij} is the number of fibres where that wavelength is free in arc l_i.

- $T_N(v_i)$ is a table for each node $v_i \in N$ which represents the wavelength conversion capability of the nodes, that is the possibility of transferring the optical signal from one input λ_i to an output λ_j in the node:

$$T_N(v_i) = [t_{uv}], \quad \forall v_i \in N; u,v = 1,2,\ldots,W\,, \quad (2)$$

where $t_{uv} = 1(0)$ whether (or not) λ_u can be converted into λ_v, in node v_i.

A *topological path*, p in R, is described by: a source node, a destination node ($v_s, v_t \in N$) and the ordered sequence of nodes and arcs in the path, $p = \langle v_1, l_1, v_2, \ldots, v_{i-1}, l_{i-1}, v_i\rangle$, such that the tail of arc l_k is v_k and the head of l_k is v_{k+1}, for $k = 1,2,\ldots,i-1$ (all the v_i in p are different).
Besides the ordered sequence of nodes and arcs, a *lightpath* p^λ also comprises the fibre used in each arc and the wavelength on the fibres:

$$p^\lambda = \langle l_c^*, \ldots, l_d^*\rangle = \langle (v_s, v_u, f_i, \lambda_\alpha), \ldots, (v_x, v_t, f_j, \lambda_\beta)\rangle\,, \quad (3)$$

where $f_i, \ldots, f_j \in F$, $\lambda_\alpha, \ldots, \lambda_\beta \in \Lambda$, represent fibres and wavelengths, respectively.
Note that l_c^* corresponds to $l_c = (v_s, v_u, \bar{o}_{l_c})$ which implies $o_{l_c i} = (1, \bar{a}_i)$ and if $a_{i\alpha} = 1$ then $a_{i\alpha}$ will change from 1 to 2 if p^λ is selected.
With dedicated protection, each connection is supported by two lightpaths (the active lightpath and the protection lightpath), whose topological paths are node disjoint.

2.2. Determination of Node Disjoint Pairs of Topological Paths

Let path $p = \langle v_1, l_1, v_2, \ldots, v_{i-1}, l_{i-1}, v_i\rangle$, be given as an alternate sequence of nodes and arcs from R, such that the tail of l_k is v_k and the head of l_k is v_{k+1}, for $k = 1,2,\ldots,i-1$ (all the v_i in p are different). Assuming that $N^*(p)$ represents the set of nodes in p, two paths $p = \langle v_1, l_1, v_2, \ldots, v_{i-1}, l_{i-1}, v_i\rangle$ and q are node-disjoint if $\{v_2, \ldots, v_{i-1}\} \cap N^*(q) = \emptyset$.
An algorithm for ranking node disjoint pairs of paths by non-decreasing order of cost, based on an adaption of the MPS algorithm [19], is proposed in [17]. Given an origin-destination node pair, *s*–*t*, the algorithm starts by making a network topology modification (see Fig. 1), where all nodes and links of the graph, (N, L), representing the network topology are duplicated and a new link, of null cost, is added by linking node t to node s' (the duplicate of s): $N' = N \cup \{v_i' : v_i \in V\}$ and $L' = L \cup \{(v_i', v_j') : (v_i, v_j) \in L\} \cup \{(t, s')\}$. In this new augmented graph, (N', L') each path z, from s to t' will correspond to a pair of paths from s to t in (N, L):

$$z = p \diamond (t, s') \diamond q \quad (4)$$

where p is a path from s to t in (N, L) and q is a path from s' to t' in (N', L').
Finally, the adapted version of MPS is used for ranking by non-decreasing order of cost the paths z, such that p and q are node disjoint. Let the set of paths from a source node s to a destination node t in (N, L) be $\mathscr{P}_{st}$. Note that each path z from s to t' in (N', L') is given by (4), with $p \in \mathscr{P}_{st}$ and $q \in \mathscr{P}'_{s't'}$.

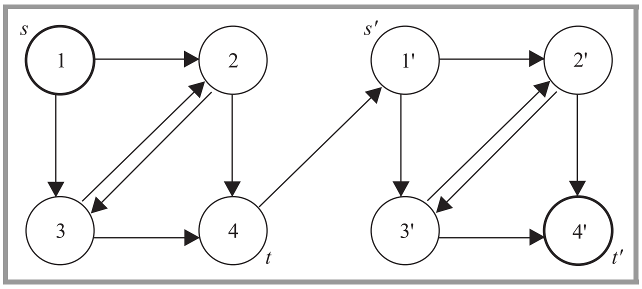

Fig. 1. Topology modification [17].

2.3. Bicriteria Approach

Having in mind a bicriteria optimization model, we consider two additive objective functions for the active and the protection path – the first one is the sum of the inverse of the available bandwidth in the links of each path and the second is the number of links (or hop count) of the paths. The duplicated links in the augmented graph, (N', L') also have the same costs and the two costs of link (t, s') are null. The first objective function, $c_1(z)$ is related to the bandwidth usage in the links of the path z and is expressed in the inverse of the available bandwidth in the links:

$$\min_{z \in D} \left\{ c_1(z) = \sum_{l \in z} \frac{1}{b_l^T} = \sum_{l \in p} \frac{1}{b_l^T} + \sum_{l \in q} \frac{1}{b_l^T} \right\}, \quad (5)$$

where D is the set of topological paths for the origin–destination node pair (s, t') and b_l^T is the total available capacity in link l, in terms of available wavelengths. This criterion seeks to avoid already congested links, favoring a balanced distribution of traffic throughout the network, and hence decreasing the blocking probability and therefore increased the expected revenue. The same criterion was used in the model without protection analyzed in the related paper [15]. The values of the available bandwidths b_l^T to be used in each instance of the resolution of the bi-objective optimization problem are calculated from the vector $\bar{b}_l$ in $C(l)$:

$$b_l^T = \sum_{j=1}^{W} b_{lj}, \quad \forall l \in L. \quad (6)$$

The second objective consists of minimizing the sum of the number of links of the two paths, $h(p) + h(q)$, seeking to avoid bandwidth waste, hence favoring global efficiency in the use of network resources:

$$\min_{z \in D} \left\{ c_2(z) = h(p) + h(q) \right\}. \quad (7)$$

Note that in many cases there is no feasible solution which optimizes the two objective functions, $c_1(z)$ and $c_2(z)$, simultaneously. A certain amount of conflict is therefore expected between c_1 and c_2, and no optimal solution (in most cases) will exist for this problem. Therefore the candidate solutions to the topological RWA multicriteria model are topological paths which are non-dominated solutions to the bi-objective problem:

$$(\mathscr{P}) \quad \begin{cases} \min_{z\in D_T} c_1(z) \\ \min_{z\in D_T} c_2(z) \end{cases} . \tag{8}$$

The set of admissible solutions, D_T, consists of all topological paths between the source-destination node pair (s,t') in (N',L') which correspond to node disjoint paths pairs (p,q) in (N,L) and to *viable lightpaths* (p^λ,q^λ), that is, lightpaths with the same arcs as p and q and with a free and usable wavelength (according to T_N) in every arc. The topological paths in these conditions (elements of D_T) will be designated as *viable topological paths*, for the given origin-destination node pair. Firstly, for obtaining D_T, the free wavelengths in each arc will have to be identified, taking into account the wavelength conversion capabilities specified by T_N, then the set of viable node disjoint paths pairs (p^λ,q^λ) for the origin-destination node pair becomes implicitly defined.

This model was extended to bidirectional connections between nodes s and t by considering a bidirectional lightpath $z^\lambda = (z^\lambda_{st'}, z^\lambda_{t's})$ supported by a bidirectional topological path $z = (z_{st'}, z_{t's})$ which is a pair of symmetrical topological paths in (N',L'). In this case the set D^b_T of feasible solutions to the bicriteria model will be the set of viable bidirectional topological paths z, i.e., characterized by the fact that both (unidirectional) topological paths $z_{st'}$ and $z_{t's}$ are viable. Therefore the bi-objective bidirectional routing optimization problem is formulated as:

$$\min_{p\in D^b_T}\left\{c_1(z) = \sum_{l\in p_{st}} \frac{1}{b^T_l} + \sum_{l\in q_{s't'}} \frac{1}{b^T_l} + \sum_{l\in p_{ts}} \frac{1}{b^T_l} + \sum_{l\in q_{t's'}} \frac{1}{b^T_l}\right\}, \tag{9}$$

$$\min_{p\in D^b_T}\{c_2(z) = h(p_{st}) + h(q_{s't'}) + h(p_{ts}) + h(q_{t's'})\} . \tag{10}$$

We will assume the most common situation in real networks where the two paths $z_{st'}, z_{t's}$ are topologically symmetrical, thence $c_2(z) = 2[h(p_{st}) + h(q_{s't'})]$. Note that this does not imply that the wavelengths used in the two opposite directions are necessarily symmetrical.

2.4. Resolution Method

The addressed problem is: given a source-destination pair of nodes, $s-t$, find a pair (p,q) of node disjoint paths which minimises $c_i(z) = c_i(p) + c_i(q)$, $i = 1,2$.

As in [17], we will say that, given two node disjoint path pairs (p_j,q_j) $(j = 1,2)$ from s to t in R, pair (p_1,q_1) dominates (p_2,q_2), denoted by $(p_1,q_1)_D(p_2,q_2)$, if and only if $c_i(p_1)+c_i(q_1) \le c_i(p_2)+c_i(q_2)$ $(i = 1,2)$ and at least one of the inequalities is strict. A node disjoint path pair (p,q) is a non dominated solution if no other feasible node disjoint path pair dominates it.

The aim of the resolution procedure is to find a *good* compromise node disjoint path pair from the set of non-dominated solutions, according to certain criteria, previously defined. Secondly, one must note that path calculation and selection have to be fully automated, having in mind the nature of a telecommunication network routing mechanism, so that an interactive decision approach is precluded.

Topological paths $z = p \diamond (t,s') \diamond q$ that are candidate solutions of the problem are generated in the modified graph according to the algorithm in [17], using as path cost a convex combination of the two objective functions $f(z) = \alpha c_1(z) + (1-\alpha)c_2(z)$ – recall that the arc (t,s') has null cost in both metrics. The value of α is not relevant and only defines the order by which solutions will be obtained by the algorithm for ranking node disjoint pairs of paths by cost f. Every generated solution will have to be evaluated to determine if it can correspond to a viable lightpaths and then a dominance test is used to determine whether or not it is non-dominated with respect to all the previously generated solutions. Only viable lightpaths which are non-dominated solutions will be stored.

The selection of the final solution follows a procedure perfectly analogous to the one used for the bicriteria model without protection [14], [15]. It is based on the definition of preference thresholds for both functions in the form of requested and acceptable values, and on a reference point like approach (see detailed description in [16]). These thresholds enable the specification of priority regions in the objective function's space.

Let $z^{c_1} = p^{c_1} \diamond (t,s') \diamond q^{c_1}$ be the shortest path with respect to the first objective function, and z^{c_2} the shortest path with respect to the second objective function (computed by solving the associated shortest path problems). This leads to the ideal solution, $\mathscr{O}$, in the objective functions' space:

$$z^{c_1} = \arg\min_{z\in D_T}\{c_1(z)\} , \tag{11}$$

$$z^{c_2} = \arg\min_{z\in D_T}\{c_2(z)\} . \tag{12}$$

The objective functions space, where non-dominated solutions will be searched, is defined by the points (c_{1m}, c_{2M}) and (c_{1M}, c_{2m}):

$$c_{1m} = c_1(z^{c_1}) = c_1(p^{c_1}) + c_1(q^{c_1}) , \tag{13}$$

$$c_{2M} = c_2(z^{c_1}) = c_2(p^{c_1}) + c_2(q^{c_1}) , \tag{14}$$

$$c_{1M} = c_1(z^{c_2}) = c_1(p^{c_2}) + c_1(q^{c_2}) , \tag{15}$$

$$c_{2m} = c_2(z^{c_2}) = c_2(p^{c_2}) + c_2(q^{c_2}) . \tag{16}$$

The preference thresholds $c_{1\text{req}}$, $c_{2\text{req}}$ (requested values) and $c_{1\text{acc}}$, $c_{2\text{acc}}$ (acceptable values) that circumscribe the priority regions are defined (taking into account the discrete nature of $c_2(z)$) by the following expressions:

$$c_{1\text{acc}} = c_{1M} , \tag{17}$$

$$c_{2\text{acc}} = c_{2M} , \tag{18}$$

$$c_{1\text{req}} = \frac{c_{1m} + c_{1M}}{2} , \tag{19}$$

$$c_{2\text{req}} = \left\lfloor \frac{c_{2m} + c_{2M}}{2} \right\rfloor , \tag{20}$$

which result in four priority regions in the objective functions' space (as in [15]).

The selection of the final solution, when there is more than one non-dominated solution in a region S, uses a reference point based procedure of the type proposed in [20]. In the present context we used a weighted Chebyshev metric [18] proportional to the size of the "rectangle" S:

$$\min_{z \in S} \max_{i=1,2} \{w_i |c_i(z) - \underline{c}_i|\}, \quad (21)$$

where $(\underline{c}_1, \underline{c}_2)$ is the reference point, which is chosen as the left down corner of region S; the right upper corner is given by $(\bar{c}_1, \bar{c}_2)$, and the weights w_i $(i = 1, 2)$ are:

$$w_i = \frac{1}{|\bar{c}_i - \underline{c}_i|}. \quad (22)$$

Details of this selection procedure can be seen in [14], [20].

This resolution method seeks to make the most of the very great efficiency of the used shortest path ranking algorithm [21], [17] (used to calculate candidate solutions) and the inherent superiority of the use of a reference point-based procedure, as a solution selection mechanism. Note that the automated nature of the routing mechanism (with protection) requires a solution in a very short time period. The final stage of the resolution method is the selection of the wavelengths along the arcs of the selected path, described in the next subsection.

The proposed resolution approach can be applied straightforwardly to the calculation and selection of bidirectional lightpaths, with the necessary adaptation to the objective functions, according to the definitions in (9) and (10).

2.5. Wavelength Assignment Heuristic

After the selection of the pair of topological node disjoint paths (unidirectional or bidirectional), the second stage is the assignment of wavelengths (and corresponding fibres) along the links of the paths, hence completing the lightpaths specification. Wavelength selection seeks to maximise the *wavelength bottleneck bandwidth*, $b_j(p)$ $(\lambda_j \in \Lambda)$:

$$\max_{\lambda_j \in \Lambda} \left\{ b_j(p) = \min_{l \in p \wedge b_{lj} > 0} b_{lj} \right\}, \quad (p \in D_T). \quad (23)$$

This procedure corresponds to the choice of the least loaded wavelength (LL) along the arcs of the path p. 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., [4]) 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.

In the present model this choice of wavelength will correspond to specify λ_{j^*} in arc l^*:

$$b_{l^* j^*} = \max_{\lambda_j \in \Lambda} \left\{ b_j(p) = \min_{l \in p \wedge b_{lj} > 0} b_{lj} \right\} : \ \exists \text{ viable } p^{\lambda} \text{ which uses } \lambda_{j^*} \text{ in } l^* \in p. \quad (24)$$

Further details and an illustrative example of this selection heuristic can be seen in [14].

The same procedure is used for wavelength and fibre selection along the links of the node disjoint path q.

For bidirectional connections, once a non-dominated solution $z \in D_T^b$ has been selected, the wavelengths (and fibres) to be used along $z_{st'}$ and $z_{t's}$ are chosen applying the same procedure to each path. Note that the chosen wavelength(s) in each path can be different.

3. Performance Analysis of the Bicriteria Model with Protection

Extensive simulations with the model were made on several typical WDM networks found in literature. This section presents the simulation results in four of such networks, namely, the NSFNET [22] (see Fig. 2), the Pan-European network COST 266BT [22] (Fig. 3), a typical core network presented in [23] – Kodialam network (KL) (Fig. 4), and a typical network provider network presented in [24] – ISP network (Fig. 5). Table 1 summarizes the main characteristics of these networks. All the networks were dimensioned for about one thousand bidirectional lightpaths (1084 for

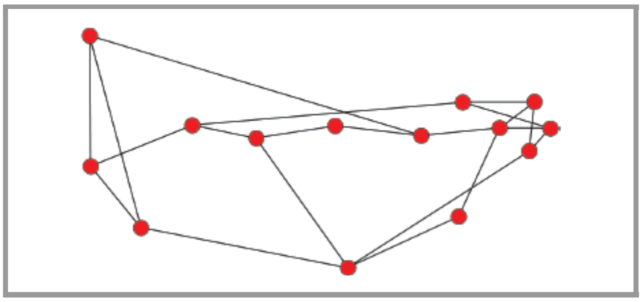

Fig. 2. NSFNET network (14 nodes and 21 links) [22].

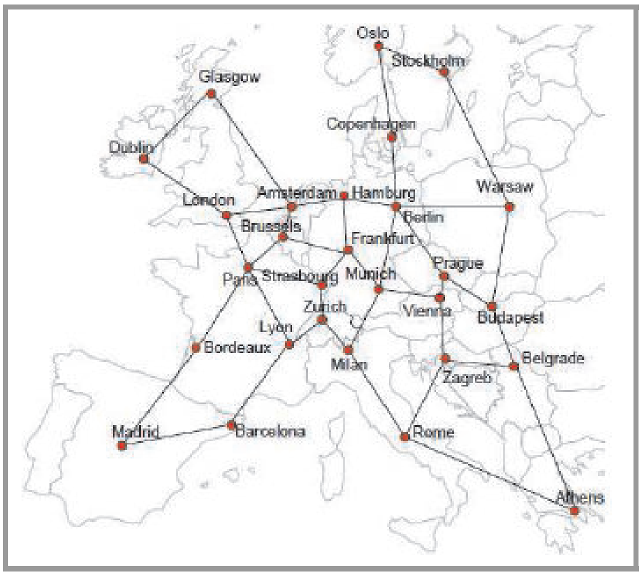

Fig. 3. COST 266BT Pan-European network (28 nodes and 41 links) [22].

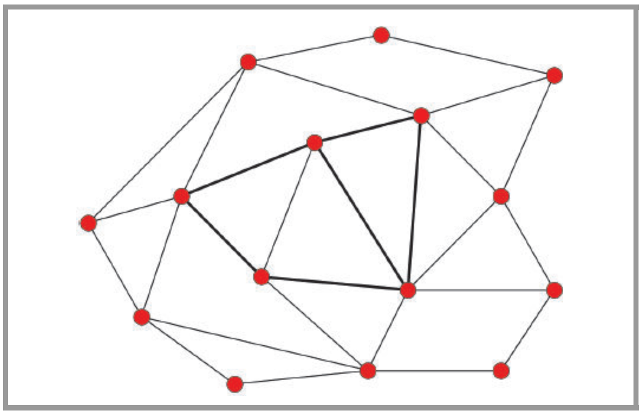

Fig. 4. KL network (15 nodes and 28 links) [23].

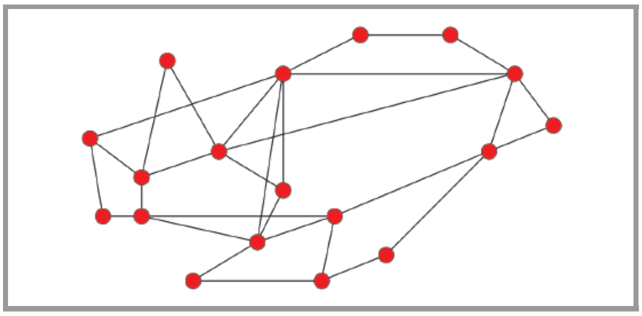

Fig. 5. ISP network (18 nodes and 30 links) [24].

NSFNET, 1008 for COST 266BT, 1050 for KL network, and 918 for ISP network) and each fibre has 16 wavelengths.

Table 1
Networks characteristics

Network	Number of nodes	Number of links	Nodal degree
NSFNET [22]	14	21	3.00
COST266BT [22]	28	41	2.93
KL [23]	15	28	3.73
ISP [24]	18	30	3.33

Two different scenarios of conversion capability were considered in simulations: all nodes without conversion capability (first scenario) and only five nodes with total conversion capability (central nodes were chosen with this capability) – second scenario.

Simulations were run up to 1200 requests (incremental traffic) in two different cases: with 100% bidirectional requests and with 5% unidirectional requests (usually, most of the connection requests for lightpaths are bidirectional).

The simulations showed that the performance variation due to presence of five nodes with total conversion capability is negligible. Therefore, from now on, we only present the scenario without conversion.

For performance assessment purposes, the results in several relevant network performance measures obtained with the bicriteria model (BiC) will be compared with the corresponding results of the single objective formulations, namely, the first objective function related with the bandwidth usage (SP_c1), and the second objective function, concerning hop count (SP_c2).

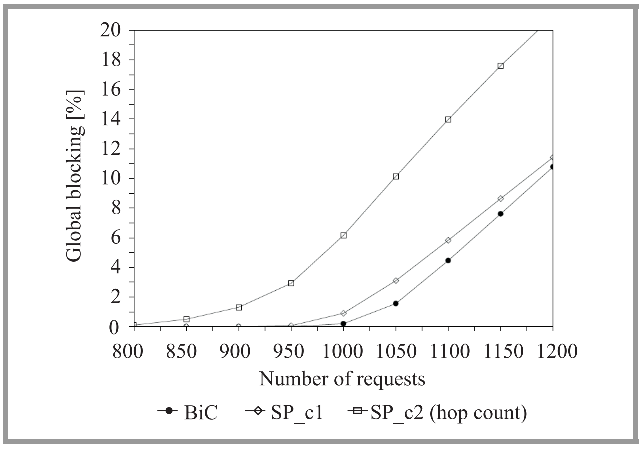

Fig. 6. Global blocking – NSFNET network.

Figure 6 shows that the blocking probability in the NSFNET for the BiC model has a value significantly lower than in the SP_c2 model. It is also lower than the blocking

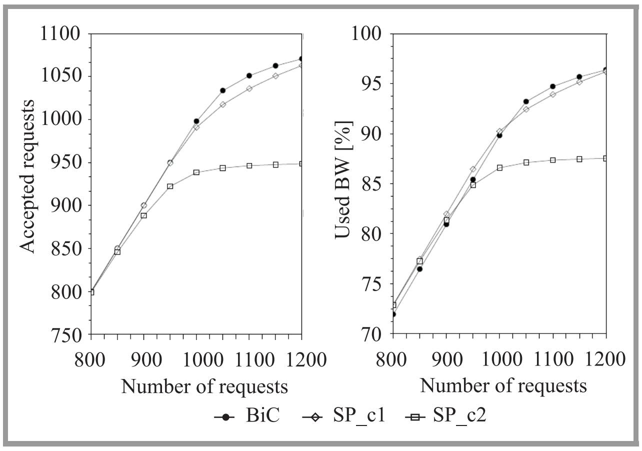

Fig. 7. Accepted requests versus used bandwidth – NSFNET network.

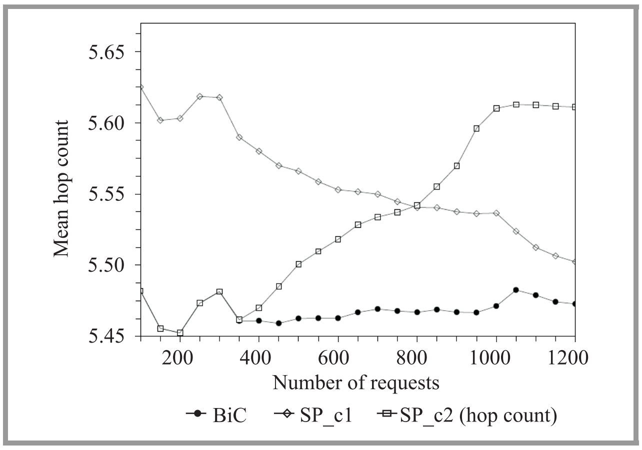

Fig. 8. Mean hop count – NSFNET network.

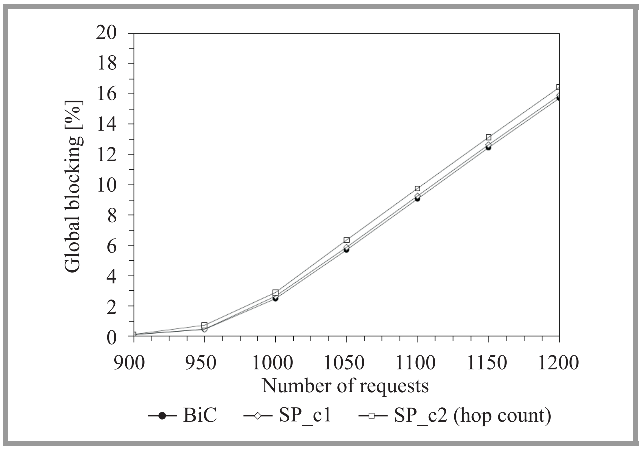

Fig. 9. Global blocking – COST 266BT network.

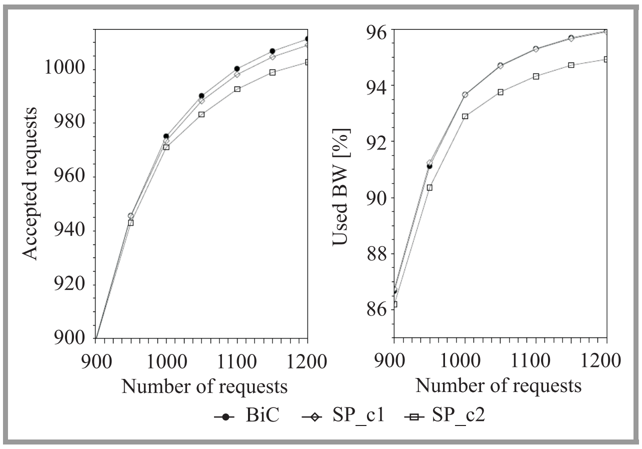

Fig. 12. Accepted requests versus used bandwidth – COST 266BT network.

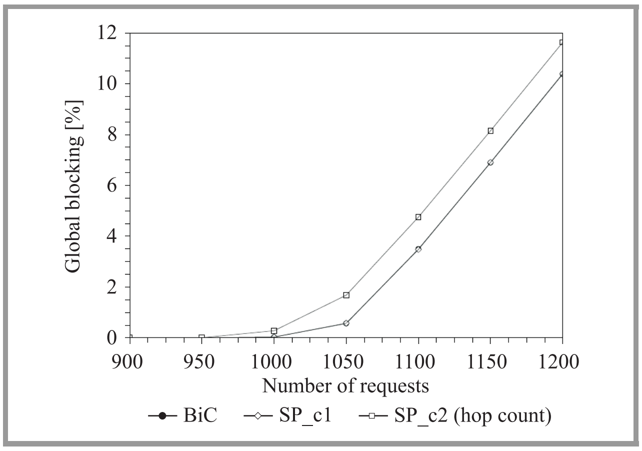

Fig. 10. Global blocking – KL network.

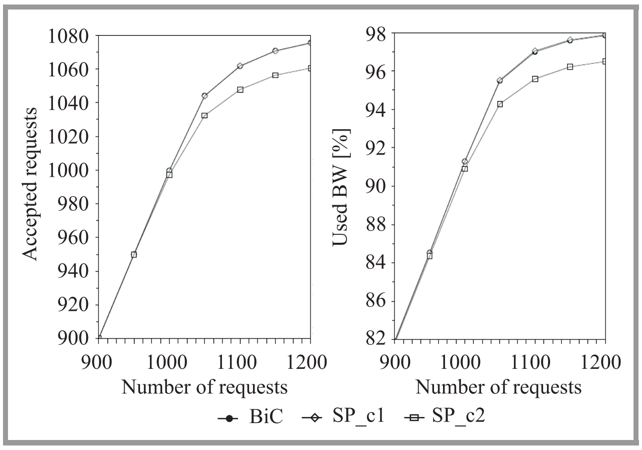

Fig. 13. Accepted requests versus used bandwidth – KL network.

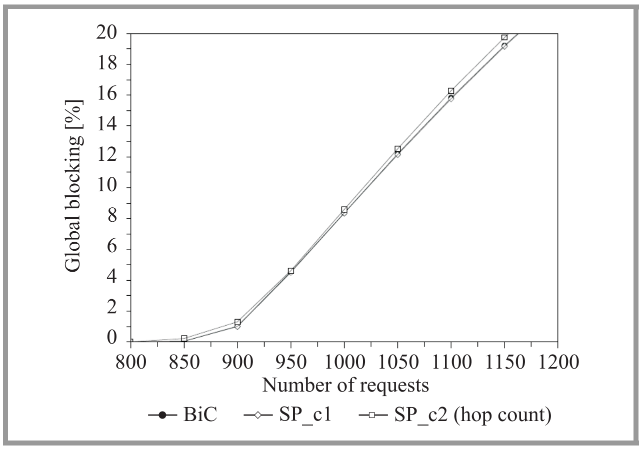

Fig. 11. Global blocking – ISP network.

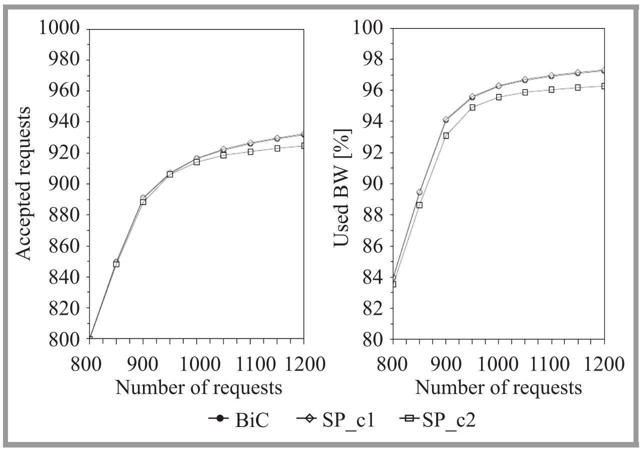

Fig. 14. Accepted requests versus used bandwidth – ISP network.

probability observed in SP_c1, although the difference is smaller. The BiC and SP_c1 models do not exhibit blocking until 950 connection requests. SP_c2 performs worse, as blocking appears for approximately 850 connection requests.

As it can be seen in Fig. 7, for moderate traffic loads (up to 1000 requests), although the number of accepted connections is higher in BiC, it uses less bandwidth than SP_c1. Above 1000 requests, the SP_c1 model requires less bandwidth than BiC, but this happens because SP_c1 accept less requests. The lowest average number of hops per connection (see Fig. 8) also shows the efficiency of the BiC formulation – BiC normally chooses shorter paths.

Figure 7 shows that the used network bandwidth in BiC and SP_c1 exceeds 95%, above approximately 1050 accepted requests, a value similar to the number of connections for which the network was dimensioned (1084 in NSFNET network).

Although not shown in the figures, the topologies with five nodes with complete conversion capability offers a negligible performance improvement. The results obtained when 5% of the requests were unidirectional are similar to the ones with 100% bidirectional connections.

The global blocking probability for the COST 266BT[1], KL and ISP networks with protection is shown in Figs. 9–11. Figures 12–14 show the number of accepted requests and the used bandwidth for the same topologies (Figs. 9, 10, 12, and 13 only show the results above 900 connection requests because, below this value, the blocking probability for KL and COST 266BT networks is almost zero).

Regarding the blocking probability on these networks, BiC model clearly exhibits a better performance than SP_c2. On the COST 266BT network the blocking in BiC model is only slightly lower than in SP_c1. Figure 12 shows that BiC and SP_c1 use the same amount of bandwidth but the number of accepted lightpaths in the BiC model is slightly larger. But, contrary to the results obtained without protection [15], the BiC and SP_c1 approaches applied to KL and ISP networks with protection have roughly the same performance. So the BiC model for dedicated path protection has not always a better performance than the SP_c1 – in some topologies, the single criterion model based on the bandwidth usage in the links of the path has a global blocking probability similar to the bicriteria model.

Regarding the traffic distribution capability of the three models, Fig. 15 shows the number of arcs with less than 10% free bandwidth in the NSFNET network. Until 1000 requests in the NSFNET network (the only one where BiC is clearly better than SP models) the BiC model provides a lower number of arcs with less than 10% free bandwidth (Fig. 15), although it has a slightly higher number of accepted requests. For COST 266BT, KL and ISP networks this measure has a similar behavior in BiC and SP_c1 models.

Concerning CPU times in an AMD 64X2 processor at 2.4 GHz, they are very low. In NSFNET the CPU time is approximately 0.25 ms for single objective formulations and 0.5 ms for BiC (Fig. 16). Note that these CPU times are roughly twice those obtained in the model without protection (see [15]). In COST 266BT network the BiC uses less than 1 ms below 900 requests while single objective approaches use about 0.5 ms (see Fig. 17). When the number of requests exceeds 900 the CPU time grows up to 2.4 ms in BiC, 2.1 ms in SP_c1 and up to 1 ms in SP_c2. In the KL network up to 1000 requests, SP_c1 and SP_c2 use about 0.27 ms per connection request, while BiC uses 0.5 ms (roughly twice the CPU time obtained without protection [15]). In the ISP network the CPU times are slightly higher, about 0.3 ms for the SP_c1 and SP_c2 approaches and 0.5 ms for BiC, until 900 requests. The CPU time

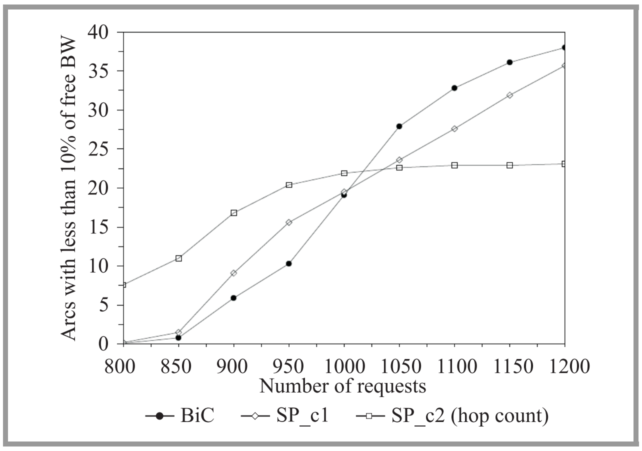

Fig. 15. Arcs with less than 10% of free BW – NSFNET network.

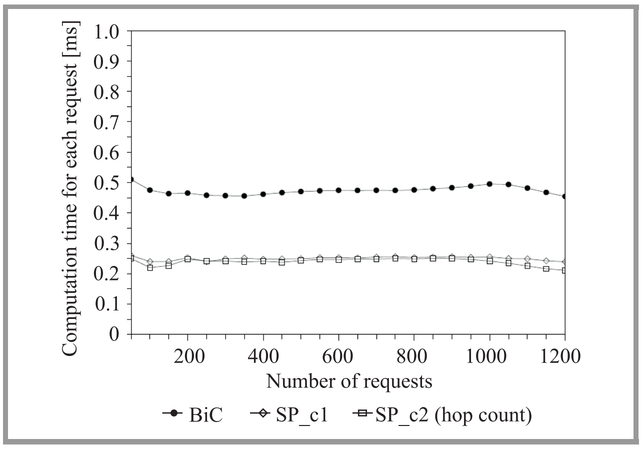

Fig. 16. Computation time for each request – NSFNET network.

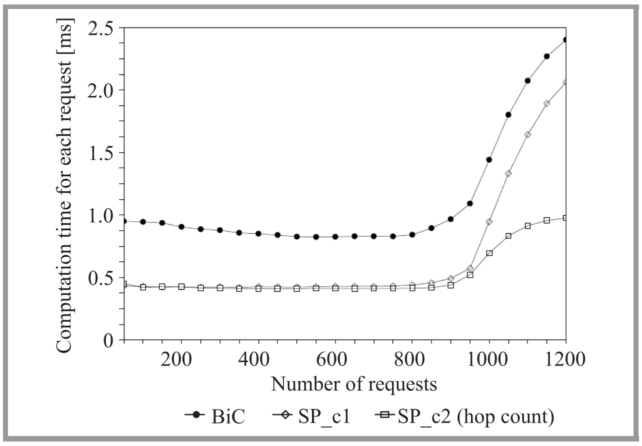

Fig. 17. Computation time for each request – COST 266BT network.

[1]Comparing the results for global blocking probability in the COST 266BT network with those presented in [16], apparently for the same network, a significant performance improvement can be verified. This is due to a different network dimensioning. The simulations in [16] use the network dimensioning presented in [22], which results in a total of 1066 fibres of 16 wavelengths each, while here we use a dimensioning method in line with the routing scheme. The total resources are only slightly different – 1094 fibres – but their distribution in the 41 bidirectional links of the network is substantially different.

increase, verified in COST 266BT, KL, and ISP networks coincides with the starting of visible blocking.

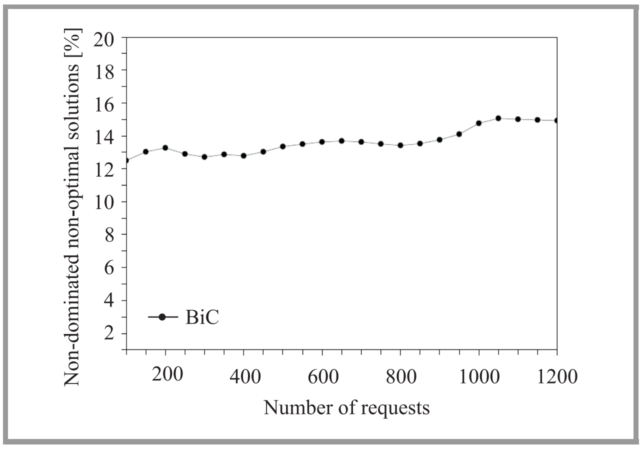

Fig. 18. Non-dominated non-optimal solutions – NSFNET network.

To assess the degree of conflict between the two objective functions involved in the bicriteria model, the number of accepted requests with optimal solution was measured. Figure 18 shows the number of requests without an optimal solution in the NSFNET network. This number of non-dominated solutions is relatively low, which indicates a relatively low degree of conflict between the functions c_1 and c_2, but, at least in some networks/topologies, the bicriteria model exceeds the performance of the single criteria approaches.

4. Conclusions

The routing and wavelength assignment problem in WDM networks involves multiple objectives and constraints, so, multicriteria approaches like the one analyzed in this paper enable an explicit representation of the different performance objectives and the addressing, in a mathematically consistent manner, of the trade offs among the various criteria.

A bicriteria model for obtaining a topological pair of node-disjoint paths unidirectional or symmetric bidirectional for each connection request in WDM networks was analyzed in terms of relevant network performance metrics. The optimization model considers two criteria – one concerning the bandwidth usage in the links of the network and the other the number of links of the paths. All the non-dominated solutions are identified using an efficient k-shortest path algorithm, applied to a modified topology. The automated selection of final solution uses preference thresholds defined in the objective function's space, combined with a Chebyshev distance to a reference point. Having obtained the "best" non-dominated topological path pair, a heuristic procedure was then used to assign wavelengths to the links of the paths.

Several benchmark networks were used to perform extensive network performance assessment of this bicriteria model, considering a comparison with the results of the two single criterion approaches corresponding to each of the criteria used in the BiC model. The impact of having five nodes with wavelength conversion capability was negligible in the simulated situations. The BiC model leads to a performance better than the monocriteria model SP_c2 (based on the hop count metric).

Regarding the comparison between BiC and SP_c1 approaches, only in one of the simulated networks the performance of BiC was clearly better than SP_c1. This happens in the smaller network (NSFNET). In all other cases, and contrary to what happens in the model without protection, with dedicated protection the BiC and SP_c1 approachs have similar performance in some cases. So the bicriteria model (with these two criteria) for dedicated path protection does not seem to provide additional benefits in all networks topologies as compared to the single criterion model based on link usage costs.

Although the BiC model uses more CPU time than the monocriteria approaches its values are quite low, even when the networks are congested.

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Teresa Gomes, José Craveirinha – for biographies, see this issue, p. 12.