Instituto de Engenharia de Sistemas e Computadores de Coimbra

Institute of Systems Engineering and Computers INESC - Coimbra

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No. 12 2010

ISSN: 1645-2631

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www.inescc.pt

A Bi-Objective Model for Routing and Wavelength Assignment in Multifiber WDM Networks – Performance Analysis [1]

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Abstract

Establishing end-to-end connections on Wavelength Division Multiplexing (WDM) networks requires setting up lightpaths, defining the sequence of optical fibers and the wavelength in each fiber (the Routing and Wavelength Assignment problem) for traffic flow. All-Optical Networks are characterized by multiple metrics, but generally routing algorithms only optimize one metric. Firstly, this report reviews a bi-objective model for obtaining a topological path (unidirectional or symmetric bidirectional) for each lightpath request in a WDM network, developed by the authors, and presents a performance analysis of the model by considering important network performance measures. The first criterion considered in the model is related to bandwidth usage in the network links, while the second criterion is the number of links (hops) of the path.

Secondly, the extension of the routing models to dedicated protection schemes is considered, in order to ensure a high degree of network routing resilience. An extensive performance analysis of the two bi-objective models (with and without protection path) is presented. Also a study comparison (using relevant network metrics) with the performance obtained with the monocriterion models using the same objective functions, in five different reference networks commonly used in literature, is described.

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

[1] Work partially supported by programme POSI of the III EC programme cosponsored by FEDER and national funds. C. Simões also thanks the FCT and IPV by the grant of the PhD scholarship SFRH/BD/49739/2009.

1 Introduction

1.1 Background Concepts

All-optical networks based on wavelength division multiplexing (WDM) have emerged as a promising technology for network operators to respond to an increased demand for broadband services, exploiting the huge bandwidth of optical fibers. All-optical networks based on wavelength division multiplexing (WDM) consist of optical fiber links and nodes, and the WDM scheme divides the optical bandwidth into independent channels, each one with a different wavelength, operating at transmission rates compatible with the lower capacity of the end user's devices. Each node in a all-optical network has a dynamically configurable optical switch or router which supports wavelength based switching or routing. Configuring these optical devices across the network enables node pairs to establish point-to-point all-optical connections, or lightpaths, for information transfer. A lightpath may span several fiber links and consist of wavelength channels in the sequence of this 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.

In the absence of wavelength converters, 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.

1.2 The RWA problem

Given a set of connection requests, the problem of setting up lightpaths by defining a path and assigning a wavelength to each of its links for every connection is called the Routing and Wavelength Assignment (RWA) problem.

If the networks nodes have wavelength converters, it is possible to assign different wavelengths on the multiple links of the lightpath. As a result, the wavelength continuity constraint is relaxed, thereby increasing the possible number of lightpaths that can simultaneously be established in the network. 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. The converter configuration of the network is called full if all nodes have wavelength converters and sparse if only a part of the nodes have them. 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 [1]. On the other hand, when a node is capable of converting a wavelength to any other wavelength, the node is said to have complete conversion capability. If a node is able to convert an incoming wavelength to only a subset of available wavelengths, the node is said to have limited or partial conversion capability. A wavelength converter is said to have a conversion degree D, if it can shift any wavelength to one of D wavelengths.

Another approach for improving the average number of established lightpaths is to use several fibers per link (multi-fiber networks). In the absence of wavelength converters, multi-fiber networks also have to satisfy the wavelength continuity constraint, however, the chances of finding the same wavelength free on all the links along the path is higher, as it can choose the free wavelength on any of the fibers in a link. A multi-fiber network with F fibers per link and W wavelengths per fiber is functionally equivalent to a single-fiber network with $F \times W$ wavelengths and conversion degree of F [2].

Typically, the representation of connection requests may be of three types: static, incremental, and dynamic [3]. In the case of static traffic, the entire set of connections is known in advance and remain unchanged, and the problem is then to set up lightpaths for these connections in a global fashion while minimising network resources such as the number of wavelengths or the number of fibers in the network. Alternatively, one may attempt to set up as many of these connections as possible for the number of wavelengths that exists in the network.

The RWA problem for static traffic is known as the Static Lightpath Establishment (SLE) problem. In the incremental-traffic case, connection requests arrive sequentially, a lightpath is established for each connection, and the lightpath remains in the network indefinitely. As for dynamic traffic, it is assumed that a lightpath is set up for each connection request as it arrives, and the lightpath is released after some finite amount of time. The objective in the incremental and dynamic traffic cases is to set up lightpaths and assign wavelengths in a manner which minimizes the amount of connection blocking, or that maximizes the number of connections that are established in the network at any time. This problem is referred to as the Dynamic Lightpath Establishment (DLE) problem.

The SLE problem can be formulated as an Integer Linear Program [4], which is NP-complete [5]. To make the RWA problem more tractable, it can be partitioned into two subproblems - (1) routing and (2) wavelength assignment, and each sub-problem can be solved separately. However each sub-problem is still NP-complete [5].

Routing schemes in WDM networks can be classified into two groups: static routing and adaptive routing. Static routing includes fixed routing and fixed-alternate routing. Fixed routing always chooses the same fixed route for a given source-destination pair. The fixed-alternate routing scheme pre-computes a set of paths between each source-destination pair, and for each request, a route from this pre-computed set is chosen. On the other hand, adaptive routing dynamically searches for a path when a connection request arrives, taking into account the actual state of the network. As a consequence, generally, adaptive routing gives better blocking performance than fixed-alternate routing [3].

The wavelength assignment algorithm determines the wavelengths to use along the route chosen in the routing step. Many wavelength assignment algorithms have been suggested such as random, first fit, most-used, least-used, least-loaded, max-sum, min-product, and relative capacity loss schemes [3].

1.3 Related work

In most approaches presented in the literature, routing and wavelength assignment are 'optimized' separately by considering a decomposition of the global RWA problem, through heuristic algorithms, because these problems are NP-complete. However, some algorithms consider the routing and the wavelength assignment jointly [6, 7].

Many different integer linear programming (ILP) formulations have been proposed for the RWA problem in WDM optical networks, under different objectives. However, although those formulations lead to exact solutions, most of the times they have not been used for developing solution schemes except for very small networks, or as a basis for obtaining approximate solutions, derived from the results of the LP-relaxation of the ILP formulation [8].

Some of the objectives considered in the literature are: – *minimising the number of used wavelengths* (called *min-RWA* problem), ensuring the establishment of all connections [6, 7]; – *maximising the number of accepted connections* (called *max-RWA* problem), when there is not enough transport capacity, i.e., enough available wavelengths, to accommodate all connection requests [4, 3, 9, 10, 11]; – *minimising the maximum number of lightpaths going through a single fiber*, in order to distribute the lightpaths on the links in a uniform manner (hence seeking to minimize the congestion), assuming again that all connections can be granted [3, 12]; – *minimising the network load*, i.e., the fraction of the number of wavelengths used on the overall set of fiber-links in the network [13].

For large networks, when finding exact solutions is too computationally intensive, different techniques are used to find near optimal solutions, based on the relaxation of integer variables in the ILP formulations. Some of this techniques are: *Linear Programming (LP) relaxation* [6, 9, 11]; *Randomized Rounding* [6, 9, 12]; *Column Generation* [14]; and *Lagrangean relaxation* [10, 7].

Due to the computational complexity of the ILP approach, heuristics, which are widely applied in solving various combinatorial optimization problems, have begun to surface as alternatives. Some of the heuristics and meta-heuristics already proposed include: *Greedy Heuristics* [15]; *Tabu Search* [16]; *Simulated Annealing* [17]; *Genetic Algorithms* [18]; *Iterative Approach* [15]; and *Layered Graph Approaches* [15].

1.4 Dedicated protection routing

Given the high rates in any optical connection, network providers must ensure a high degree of network resilience by using protection schemes. This can be achieved with dedicated protection, where a protection path, disjoint with the active path, is calculated for each active path, which is used in case of a failure.

Essentially, there are two types of fault-recovery mechanisms. A lightpath can be protected against failures by precomputing a backup route and reserving resources along the route in advance [19]. This approach is designated by protection scheme. Another form of protection consists in discovering and signalling a backup path only after a failure occurs. This approach is commonly referred to as dynamic restoration (or just restoration). Schemes that use this restoration concept are more resource-efficient, but they need more time to discover free resources for redirecting the disrupted lightpath. A protection scheme ensures that resources are available to recover from any single failure in a given specific fault scenario (link, node, path, segment failure) – see [20]. 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 (segment protection). In path protection, in order to recover from any single link (node) failure in the network, a link-disjoint (node-disjoint) path is needed as the backup path to reroute the traffic on the active path.

In path protection, a backup path can share resources with other backup path as long as their respective active paths do not have any protected network element in common (no single failure affects the two paths simultaneously). This is designated as shared path protection [21]. If no resource sharing is allowed among backup paths, the scheme is called dedicated path protection. Shared protection results in a more effective use of network resources, but has a slower response time than dedicated protection (protection paths are not reserved in advance). Algorithms for shared protection can be found in [22, 23].

1.5 Multicriteria Models

All-optical WDM networks can be characterized in terms of performance by multiple metrics but in general routing protocols only optimize one metric, typically using some variant of a shortest path algorithms. Nevertheless, the design of real networks usually involves multiple, often conflicting objectives and various constraints. Having in mind the inherent limitations of single objective approaches it seems potentially advantageous the development of 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 and conflicting criteria, 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.

A state-of-art review on multicriteria approaches in communication networks was presented in [24], including a section dedicated to routing models. A recent review on multicriteria routing models can be seen in [25].

The routing algorithm presented in [26] considers two different criteria, namely path length and congestion in the network, but they are applied sequentially. The second metric is only used if a tie occurs in the first one. Two algorithms for dynamic traffic were suggested: Least Congested Shortest Hop Routing where priority is given to efficient resource utilization (the algorithm selects the least congested among all shortest hop paths currently available); and Shortest Hop Least Congested Routing in which priority is given to maintaining the load balance in the network (it selects the shortest hop path among all the least congested paths). This type of models may be considered as a first-tentative multicriteria approach as analysed in [24].

In [27] the weighted least-congestion routing and first-fit wavelength assignment algorithm also includes two criteria (hop count and free wavelengths), but combined in a single weighted metric, calculated for a set of pre-computed link disjoint routes for each node pair, in a network with dynamic traffic. The same approach was proposed earlier in [28], which tries to minimize the resource utilization while simultaneously maintaining the traffic load among the links as balanced as possible. However, [28] only considers networks with full wavelength conversion.

Note that the approach used in these an similar models, that consists of taking as solution of the bicriteria problem the optimal solution of the single objective function resulting from the weighted sum of the considered criteria, does not take full advantage of the possibilities of multicriteria approaches and may lead to less effective solutions or even unbalanced solutions.

A bi-objective model for obtaining a topological path (unidirectional or symmetric bidirectional) for each lightpath request in a WDM network with multi-fiber links and an exact resolution approach for that model was presented by the authors in [29]. The first criterion is related to bandwidth usage in the links (or arcs) of the network. The second criterion is the number of links (hops) of the path. The resolution approach [29] uses an exact procedure to calculate non-dominated topological paths based on a k-shortest path algorithm [30] which is based on an adaptation of the MPS algorithm [31]. Furthermore, preference thresholds, defined in the objective function space, combined with a Chebyshev distance to a reference point [32] are used for selecting the final solution. The solution of this bi-objective model is a non-dominated topological (optically feasible) path. A heuristic procedure is then used to assign wavelengths to the links.

In order to provide dedicated path protection to lightpaths, an extension of the bi-objective model that allows to obtain a topological pair of node disjoint paths for each request was developed in [33]. 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 [34], as well as preference thresholds defined in the objective function space, combined with a Chebyshev distance to a reference point, already mentioned. The solution of this bi-objective model extension is a non-dominated topological (optically feasible) disjoint path pair. Again, an heuristic procedure is then used to assign wavelengths to the links of the path.

The focus of this paper is to present an extensive and systematic performance analysis study of the two bi-objective models (without and with dedicated protection) with respect to certain network performance measures by comparison of their results with the results of the associated single objective models, one related to the bandwidth usage and another that minimizes the number of used links (hop count). An incremental traffic model (where the duration of the connections is assumed unlimited) will be considered in several benchmark networks used in previous works in the area of WDM networks. The selected network performance measures are: the frequency of rejected requests (global blocking probability estimate), total used bandwidth, mean hop count of accepted requests, 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 without protection is described, together with the resolution approach of the bi-objective model. Performance analysis of the results obtained using several network topologies are presented and discussed in section 3. The model extension to dedicated path protection is reviewed in section 4. Performance analysis of the results for the dedicated path protection are presented and discussed in section 5. Finally, some conclusions are drawn in section 6.

2 The bi-objective routing model

2.1 Model description

In this section we describe the features of the proposed bi-objective routing model associated with the Dynamic Lightpath Establishment problem (DLE) with incremental traffic, in a WDM network. The model was developed for application in large WDM networks, with multiple wavelengths per fiber and multi-fibers per link. The bi-objective routing model considers the DLE problem with incremental traffic, and a mixture of unidirectional and bidirectional (symmetric) connections. 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.

It is even possible to individually indicate which wavelengths in the model can be (or not) converted to which others. 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 bi-objective routing model considers a flow oriented optimization formulation, that is, the topological lightpath establishment problem is formulated for each connection request at a time. The wavelength assignment problem is solved separately, after the bi-objective routing problem.

2.2 WDM network and lightpaths representation

Let $R = \{N, L, C, T_N\}$ represent the WDM network where:

- N is the set of nodes, $N = \{v_1, v_2, \ldots, v_n\}$, $n = \#N$.
- L is the 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 fibers, $F = \{f_1, f_2, \ldots, f_k\}$, $k = \#F$.
- 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 fiber 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 $a_{ju} = 0, 1, 2$ $(u = 1, 2, \ldots, W)$:

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

  If $o_{l_ij} = (0, \bar{a}_j)$ $(j = 1, 2, \ldots, k)$, fiber 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 fibers in arc l_i with wavelength λ_j and b_{l_ij} is the number of fibers 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 fiber used in each arc and the wavelength on the fibers:

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

where $f_i, \ldots, f_j \in F$, $\lambda_\alpha, \ldots, \lambda_\beta \in \Lambda$, represent fibers 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.

A *bidirectional lightpath* $p^\lambda = (p^\lambda_{st}, p^\lambda_{ts})$ is supported by a *bidirectional topological path* $p = (p_{st}, p_{ts})$, which is a pair of symmetrical topological paths.

2.3 Bi-objective Routing Model

Firstly we will describe the bi-objective model used for calculating topological paths.

The first objective function, $c_1(p)$ is related to the bandwidth usage in the links of the path p and is expressed in the inverse of the available bandwidth in the links:

$$\min_{p \in D} \left\{ c_1(p) = \sum_{l \in p} \frac{1}{b_l^T} \right\} \quad (4)$$

where D is the set of topological paths for the origin–destination node pair 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, favouring a balanced distribution of traffic throughout the network, and hence decreasing the blocking probability and therefore increasing the expected revenue.

Note that 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 directly calculated from the vector $\bar{b}_l$ in $C(l)$:

$$b_l^T = \sum_{j=1}^{W} b_{lj}, \quad \forall l \in L \quad (5)$$

The second objective consists of minimizing the number of arcs of the path, $h(p)$, seeking to avoid bandwidth waste, hence favouring global efficiency in the use of network resources as well the reliability of optical connections (longer paths are more prone to failure).

$$\min_{p \in D} \{ c_2(p) = h(p) \} \quad (6)$$

Note that in many cases there is no feasible solution which optimizes the two objective functions, $c_1(p)$ and $c_2(p)$, simultaneously. In fact, objective $c_2(p)$ will favour shorter paths and $c_1(p)$ may choose longer paths (using more bandwidth), but selecting links with more residual free bandwidth. A certain amount of conflict is therefore expected between c_1 and c_2, and, in a relevant number of cases, no optimal feasible solution 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:

$$(\mathcal{P}) \quad \begin{cases} \min_{p \in D_T} c_1(p) \\ \min_{p \in D_T} c_2(p) \end{cases} \tag{7}$$

Given two paths p_1 and p_2, from s to t in R, path p_1 dominates p_2, denoted by $p_1{}_D p_2$, if and only if $c_i(p_1) \leq c_i(p_2)$ $(i = 1, 2)$ and at least one of the inequalities is strict. A path p is a non dominated solution if no other feasible path dominates it.

The set of admissible solutions, D_T, consists of all topological paths between the source-destination node pair which correspond to *viable lightpaths* p^λ, that is, lightpaths with the same arcs as p 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. For obtaining D_T firstly the free wavelengths in each arc will have to be identified, taking into account the wavelength conversion capabilities specified in T_N, then the set of viable paths p^λ for each pair of origin-destination nodes becomes implicitly defined

2.4 Extension for bidirectional connections

This model was extended to bidirectional connections between nodes s and t by considering a bidirectional lightpath $p^\lambda = (p^\lambda_{st}, p^\lambda_{ts})$ supported by a bidirectional topological path $p = (p_{st}, p_{ts})$ which is a pair of symmetrical topological paths. In this case the set D^b_T of feasible solutions to the bi-objective model will be the set of viable bidirectional topological paths p, i.e., characterized by the fact that both (unidirectional) topological paths p_{st} and p_{st} are viable.

Therefore the bi-objective bidirectional routing optimization problem is formulated as:

$$\min_{p \in D^b_T} \left\{ c_1(p) = \sum_{l \in p_{st}} \frac{1}{b^T_l} + \sum_{l \in p_{ts}} \frac{1}{b^T_l} \right\} \tag{8}$$

$$\min_{p \in D^b_T} \{ c_2(p) = h(p) = h(p_{st}) + h(p_{ts}) \} \tag{9}$$

We will assume the most common situation in real networks where the two paths p_{st}, p_{ts} are topologically symmetrical, thence $h(p) = 2h(p_{st})$. Note that this does not imply that the wavelengths used in the two opposite directions are necessarily symmetrical.

2.5 Resolution approach

The first stage of the resolution approach is an exact algorithm enabling the calculation of non-dominated viable topological paths and the selection of a path according to an automatic procedure that uses preference thresholds defined in the objective function space and reference points obtained from those thresholds. This algorithmic approach will be reviewed in this subsection.

The second stage is the assignment of wavelengths (and corresponding fibers) along the arcs of the selected path p, and will be reviewed in the next subsection.

The aim of the resolution procedure is to find a 'good' compromise path 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.

The candidate solutions are computed according to an extremely efficient k-shortest path algorithm, MPS [31, 35], by using a version adapted to paths with a maximum number of arcs as described in [30]. The algorithm is applied to a convex combination of the two objective functions and the selection of a solution is based on the definition of preference thresholds for both functions in the form of requested and acceptable values for each of them. These thresholds enable the specification of priority regions in the objective function's space, as illustrated in Figure 1.

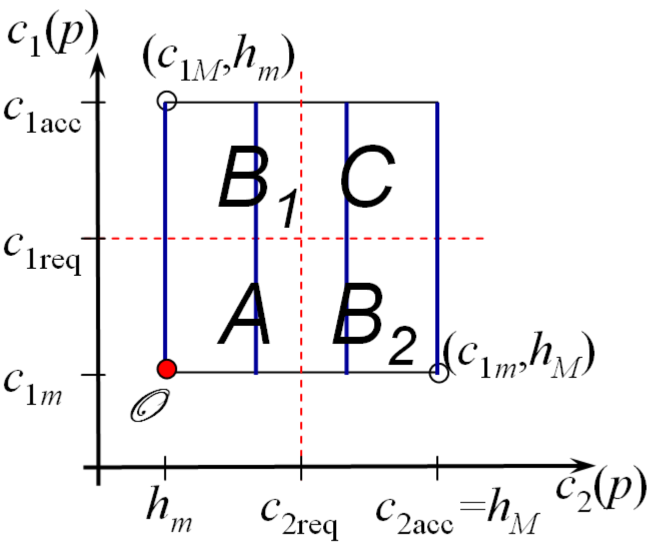


Figure 1: Preference Regions.

In the first step, vertex solutions p^{c_1} and p^{c_2} (viable topological paths) which optimize each objective function, $c_1(p)$ and $c_2(p) = h(p)$, respectively, are computed by solving the associated shortest path problems. This leads to the ideal solution, $\mathcal{O}$, in the objective functions space.

$$p^{c_1} = \arg\min_{p \in D_T} c_1(p) \tag{10}$$

$$p^{c_2} = \arg\min_{p \in D_T} \{c_2(p) = h(p)\} \tag{11}$$

The preference thresholds $c_{1\text{req}}$, $c_{2\text{req}}$ (requested values) and $c_{1\text{acc}}$, $c_{2\text{acc}}$ (acceptable values) for the two metrics are given, taking into account the discrete nature of $c_2(p) = h(p)$, according to the following expressions:

$$c_{1m} = c_1(p^{c_1}) \quad \wedge \quad c_{2M} = h_M = c_2(p^{c_1}) \tag{12}$$

$$c_{1M} = c_1(p^{c_2}) \quad \wedge \quad c_{2m} = h_m = c_2(p^{c_2}) \tag{13}$$

$$c_{1\text{acc}} = c_{1M} \tag{14}$$

$$c_{2\text{acc}} = h_M \tag{15}$$

$$c_{1\text{req}} = \frac{c_{1m} + c_{1M}}{2} \tag{16}$$

$$c_{2\text{req}} = \left\lfloor \frac{h_m + h_M}{2} \right\rfloor \tag{17}$$

Therefore we define priority regions in the objective functions' space according to Figure 1 in which non-dominated solutions are searched for. Region A (Figure 1) is the first priority region where the requested values for the two functions are satisfied simultaneously. Concerning the second priority regions, B_1 and B_2, only one of the requested value is guaranteed while the acceptable value for the other function is also satisfied. A further preference order between these regions was introduced by giving preference to solutions with less arcs, that is solutions in B_1 are giving preference over solutions in B_2. In region C only the acceptable values, $c_{1\text{acc}}$ and $c_{2\text{acc}}$, are satisfied and it is the last priority region to be searched for.

As previously mentioned, the candidate solutions are computed by an extremely efficient length constrained k-shortest path algorithm given in [30], an adaptation of the MPS algorithm in [35], that is applied to the convex combination:

$$f(p) = \alpha c_1(p) + (1-\alpha) c_2(p) \qquad 0 \leq \alpha \leq 1 \tag{18}$$

The value of α just defines the order in which the solutions are found, and its choice is purely instrumental. Finally it will be necessary to select a solution among the non-dominated solutions in the highest priority region, with at least one non-dominated solution, $S \in \{A, B_1, B_2, C\}$. This implies that if no such solutions were found in A, then non-dominated solutions in B_1, B_2, C, in this order would be searched for.

As for the selection of a solution when there is more than one non-dominated solution in a region S, a form of ordering such solutions is to use a reference point type approach and consider that the 'form' of the region where solutions are located reflects the user's preferences. This leads to the use, at this step, of a reference point based procedure of the type proposed in [36], by considering as reference point the 'left bottom corner' of S (this point coincides with the optimal point if $S = A$).

In general, reference type approaches minimize the distance of the solutions to a specific point by using a certain metric, recurring to a scalarizing function [32]. In the present context we used a weighted Chebyshev metric proportional to the size of the 'rectangle' S. Therefore one will select the solution p^*:

$$p^* = \arg \min_{p \in S_N^c} \max_{i=1,2} \{w_i |c_i(p) - \underline{c}_i|\} \tag{19}$$

where S_N^c is the set of non-dominated paths which correspond to points in S and $(\underline{c}_1, \underline{c}_2)$ is the considered reference point which corresponds to the 'left bottom corner' of region S. The weights w_i of the metrics are chosen in order to obtain a metric with dimension free values:

$$w_i = \frac{1}{\bar{c}_i - \underline{c}_i} \tag{20}$$

where $(\bar{c}_1, \bar{c}_2)$ is the 'right top corner' of S, so that $\underline{c}_i \leq c_i(p) \leq \bar{c}_i$ $(i = 1, 2)$ for all p such that $(c_1(p), c_2(p)) \in S$. An illustrative example is in Figure 2, where the number assigned to each bullet is the computation order of the corresponding solution, and solution (2) would be the one to be selected, since it has the shortest distance to the reference point.

The combination, in this resolution method, of a weighted sum procedure to calculate candidate solutions with a reference-point based procedure to select a solution in a higher priority region, seeks to make the most of the very great efficiency of the used shortest path ranking algorithm, based on the MPS algorithm [35] and the inherent superiority of the use of a reference point-based procedure, as a solution selection mechanism. Note that in the present context the computational efficiency is a major factor taking into account the automated nature of the routing mechanism, requiring a solution in a very short time period, a factor which becomes critical in networks of higher dimension. Nevertheless a 'pure' reference point approach, as the one in [36] might be more advantageous in a routing model where more than two criteria were used since it is not critically sensitive to

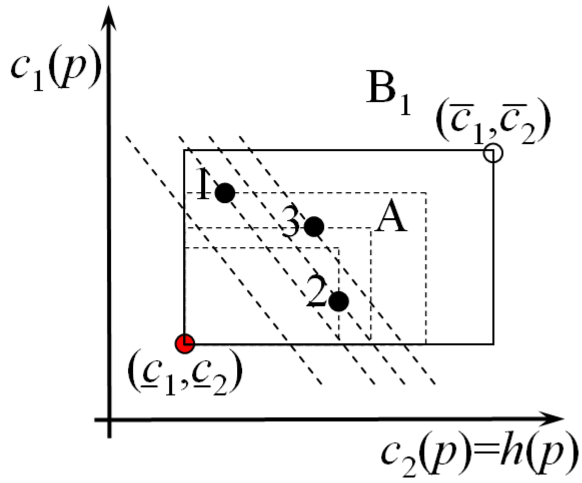


Figure 2: Choosing the final solution.

the different number of criteria unlike the present approach. This sensitivity of the present approach to the number of criteria stems from the fact that this type of method has the disadvantage of finding, in some cases, solution(s) outside the currently searched priority region before all solutions inside this region have been calculated, taking into consideration that solutions are found along the dashed lines illustrated in 2. This implies the current solutions have to be stored until that priority region has been completely analyzed, for possible further solution reordering, which is a source of computational inefficiency.

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 (8) and (9).

2.6 Wavelength assignment heuristic

The second stage is the assignment of wavelengths (and corresponding fibers) along the arcs of the selected path p. For this purpose we will use the maximization of the *wavelength bottleneck bandwidth*, $b_j(p)$ $(\lambda_j \in \Lambda)$:

$$\max_{\lambda_j \in \Lambda} \left\{ b_j(p) = \min_{l \in p \wedge b_{lj} > 0} b_{lj} \right\} \quad (p \in D_T) \tag{21}$$

This procedure corresponds to the choice of the Least Loaded wavelength (LL) along the arcs of the path. 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 eg. [3]) 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^*:

$$b_{l^*j^*} = \max_{\lambda_j \in \Lambda} \left\{ b_j(p) = \min_{l \in p \wedge b_{lj} > 0} b_{lj} \right\} : \begin{array}{l} \exists \text{ viable } p^\lambda \text{ which} \\ \text{uses } \lambda_{j^*} \text{ in } l^* \in p \end{array} \quad (22)$$

An illustrative example is shown in Table 1, where $b_{l^*j^*} = 5$, and we could choose either λ_5 in arc l_3 or λ_6 in arc l_4.

λ_j	$b_j(p)$	l_u	b_{lj}, $l_u \in p$				
			l_1	l_2	l_3	l_4	l_5
1	3	l_1	3	4	5	0	6
2	2	l_1, l_2, l_3	2	2	2	4	7
3	3	l_2, l_3	4	3	3	8	0
4	4	l_1	4	5	5	6	9
5	5	l_3	9	6	5	7	8
6	5	l_4	6	7	7	5	6

$p = \langle l_1, l_2, l_3, l_4, l_5 \rangle$, $l_u \in L_W$.

Table 1: Example of wavelength choice.

If there is more than one pair (l^*, λ_{j^*}) satisfying the above condition the first one found by the procedure will be selected. In in the example the choice would be (λ_5, l_3). Finally, in each arc, the fiber with the lowest identification number with the free selected wavelength λ_{j^*}, would be chosen, hence completing the full specification of the selected lightpath.

For bidirectional connections, once a non-dominated solution $p \in D_T^b$ has been selected, the wavelengths (and fibers) to be used along p_{st} and p_{ts} 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 model

Extensive simulations with the model were made on several typical WDM networks found in literature. This section presents the simulation results for five such networks, namely, the Pan-European Network COST 266BT [37, 38] (Figure 3(a)), the denser version of this network [38] - COST 266TT Network (Figure 3(b)), a typical core network presented in [39] - KL Network (Figure 3(c)), a typical internet provider network presented in [40] - ISP Network (Figure 3(d)), and the NSFNET [37] (Figure 3(e)). Table 2 summarizes the main characteristics of these networks. All the networks were dimensioned for about one thousand bidirectional lightpaths (1084 for NSFNET, 1008 for both COST 266BT and COST 266TT, 1050 for KL Network, and 918 for ISP Network) and each fiber has 16 wavelengths.

network	number of nodes	links	nodal degree
COST266BT [37, 38]	28	41	2.93
COST266TT [38]	28	61	4.36
KL [39]	15	28	3.73
ISP [40]	18	30	3.33
NSFNET [37]	14	21	3.00

Table 2: Networks characteristics.

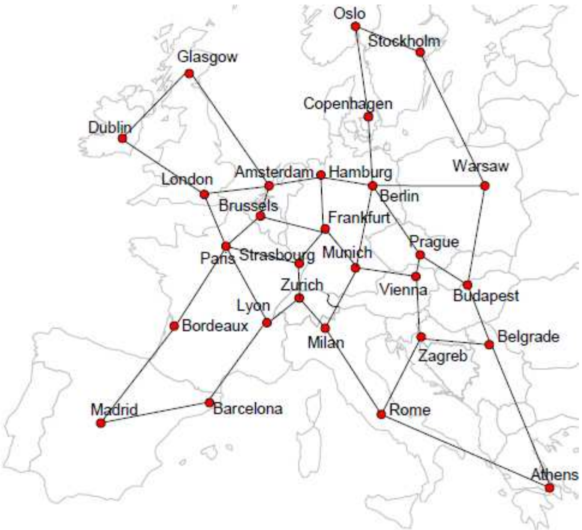
Concerning the wavelength conversion aspect, simulations were conducted considering two different cenarios: all nodes without conversion capability and five nodes with total conversion capability (central nodes were chosen with this capability).

Simulations considered 1200 connection requests (incremental traffic) in two different cases: with 100% bidirectional requests and with 5% unidirectional requests (because most of the connection requests for lightpaths are bidirectional).

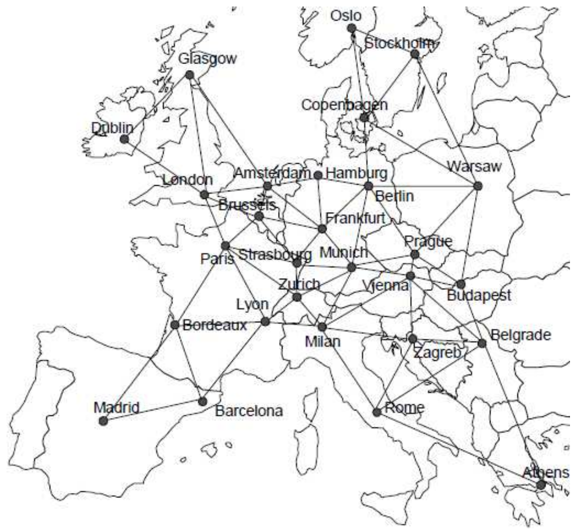
For performance assessment purposes, results obtained using the bi-objective model (BiC) will be compared with the corresponding results using the single objective formulations, namely, the first objective function related with the bandwidth usage (SP_c1), and the shortest path concerning hop count (SP_c2). Several relevant network performance measures will be used in this comparison.

Figure 4 shows the global blocking probability in the NSFNET network, for 100% bidirectional requests, both for the network where five nodes have total conversion capability and for the network without conversion. The first inference to be drawn from the figure is that the performance of the network where five nodes have total conversion capability is nearly the same as for the network without conversion. Simulation results showed that this is also true for the remain network topologies - only in COST 266TT network (shown later) a small difference is visible. Therefore, from now on, we only present the "no conversion" scenario, unless there is a noticeable difference. Discussion and conclusions remain true for the second scenario.

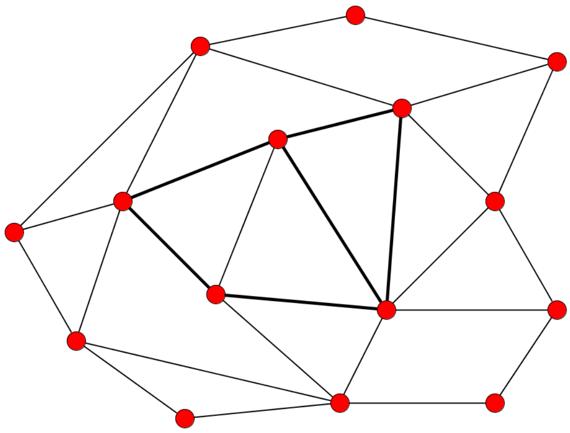
As we can see in Figure 4, the bi-objective approach (BiC) leads to a blocking probability lower than that in the single objective formulations. The difference is significantly higher with the shortest path approach SP_c2. Also note that until 1000 requests both BiC and SP_c1 do not exhibit any blocking. The SP_c2 model rejects requests much earlier, and this clearly confirms that choosing the shortest path based only on the hop count is a poor strategy in this type of networks.



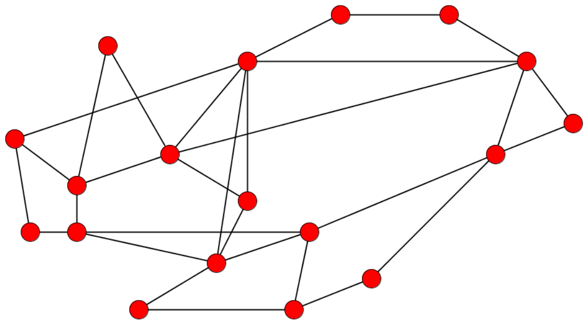
(a) Cost 266BT Pan-European Network
(28 nodes and 41 links) [37, 38].



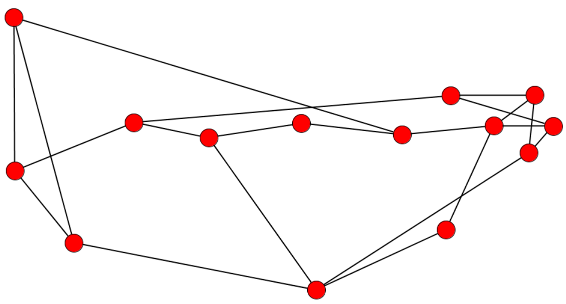
(b) COST 266TT Network
(28 nodes and 61 links) [38].



(c) KL Network(15 nodes and 28 links) [39].



(d) ISP Network(18 nodes and 30 links) [40].



(e) NSFNET Network
(14 nodes and 21 links) [37].

Figure 3: Tested Networks.

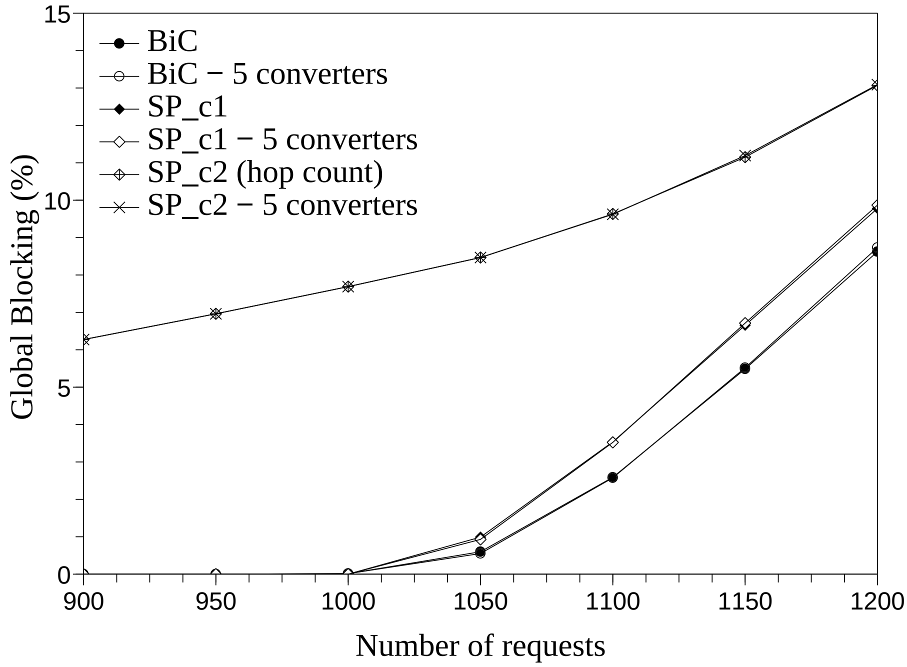


Figure 4: Global Blocking (%) - NSFNET Network.

In Figure 5, the number of accepted requests is shown together with the used bandwidth and with the mean hop count per accepted request. When the number of requests is high, the used bandwidth exceeds 95%, but this corresponds to approximately 1100 accepted requests in BiC, a value that surpasses the number of connections for which the network was dimensioned (1084 for the NSFNET). Although the BiC model uses more bandwidth than the SP_c2, it should be noted that BiC supports a significantly higher number of connections. In fact, as it can be seen in the mean hop count graph, (rightmost graph of Figure 5), BiC allows a lower average number of hops per connection. Another interesting conclusion that emerges from the analysis of Figure 5 is that the BiC, while accepting more requests than SP_c1, when traffic load is high, always uses less bandwidth, which shows its superior performance.

Although not shown here, the results obtained when 5% of the requests were unidirectional are rather similar to the ones with 100% bidirectional connections.

The results in the other networks exhibit the same behaviour. In the COST 266BT Network, BiC also has lower blocking than SP_c1 and SP_c2 (more accepted requests) but always uses an amount of bandwidth smaller than SP_c1 (see Figure 6). For moderated traffic loads (until 950 connection requests), BiC even uses less bandwidth than SP_c2, despite allowing the establishment of many more lightpaths.

In Figures 7, 8, and 9 the same performance measures (number of accepted requests,

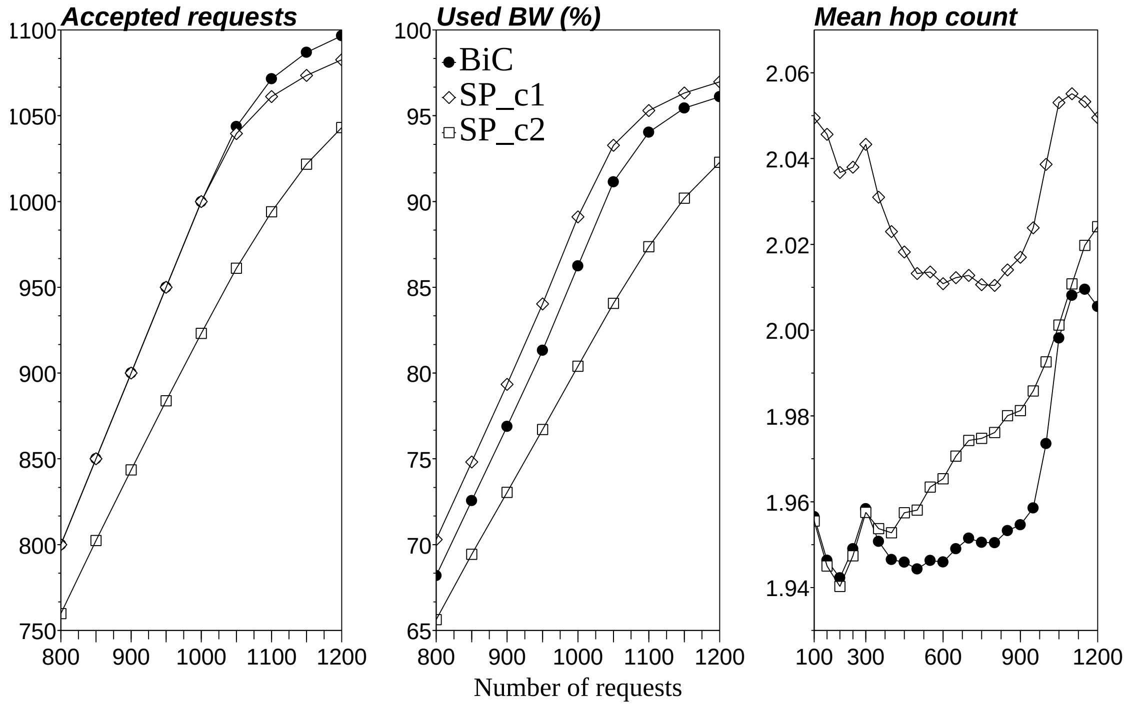


Figure 5: Accepted requests *vs.* used bandwidth *vs.* mean hop count - NSFNET Network.

used bandwidth and mean hop count) are shown for COST 266TT, KL, and ISP networks, respectively. The superior performance of the BiC model is consistent in all tested networks:

In COST 266TT network the BiC model outperforms SP_c1 since it accepts more lightpaths and uses less bandwidth (Figure 7). BiC also outperforms SP_c2 because, despite using more bandwidth, many more lightpaths were accepted. On KL network the BiC model, in addition to outperform both monocriterion models in number of accepted requests, even uses less bandwidth than the minimum hop count approach - SP_c2 - for moderate traffic load (until 1000 requests). Similar results are obtained for the ISP network (Figure 9). Despite the BiC always accept more requests, it uses less bandwidth than SP_c1 model and, up to 900 requests, also uses less bandwidth than SP_c2.

The average number of hops per established lightpath is an interesting network performance measure. As it can be seen in Figures 5, 6, 7, 8 and 9 (for NSFNET, COST 266BT, COST 266TT, KL and ISP Networks, respectively), BiC uses in average a smaller number of links in all ranges of traffic loads. This happens because it takes advantage of the characteristics of the two metrics. For light traffic, the BiC model chooses shorter connections and, in fact, achieves paths as short as SP_c2. But, unlike SP_c2, BiC is concerned with the load already present in the network links. On the other hand, SP_c1

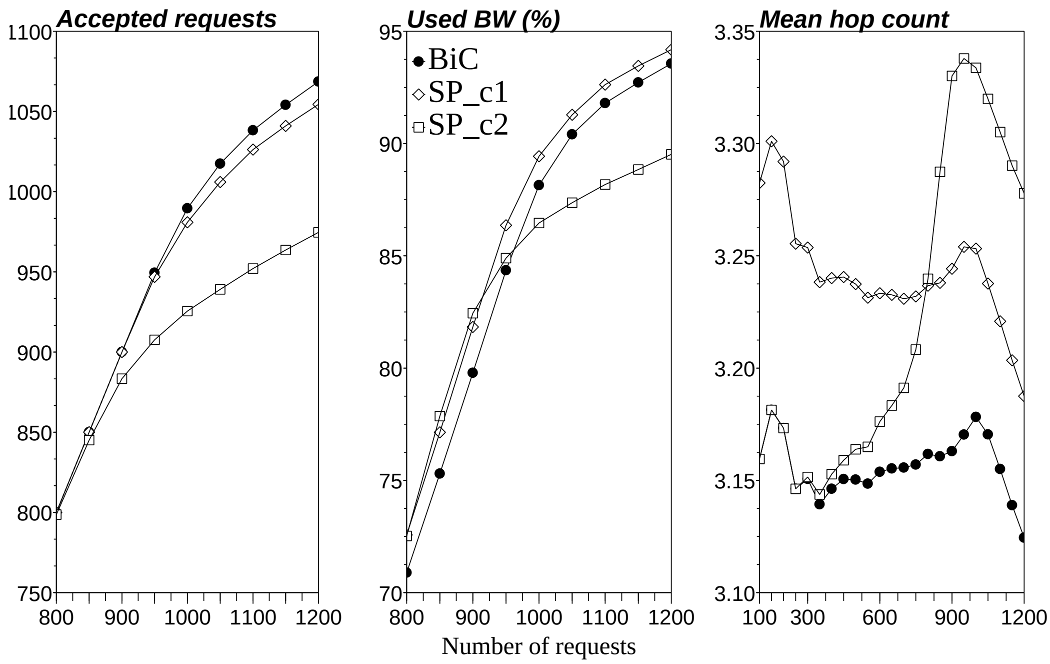


Figure 6: Accepted requests *vs.* used bandwidth *vs.* mean hop count - COST 266BT Network.

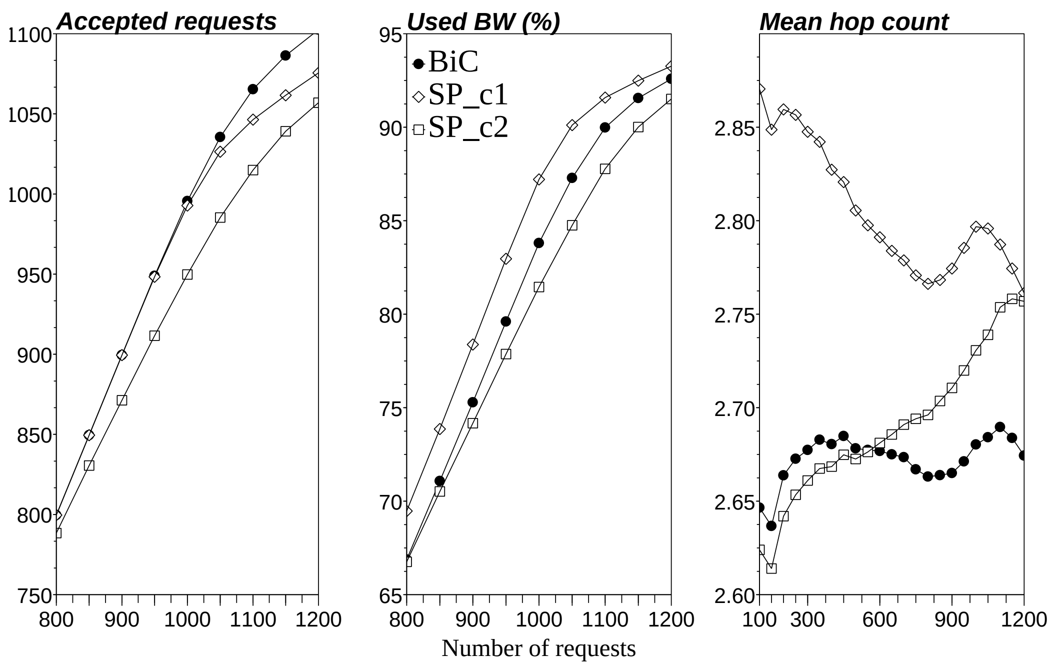


Figure 7: Accepted requests *vs.* used bandwidth *vs.* mean hop count - COST 266TT Network.

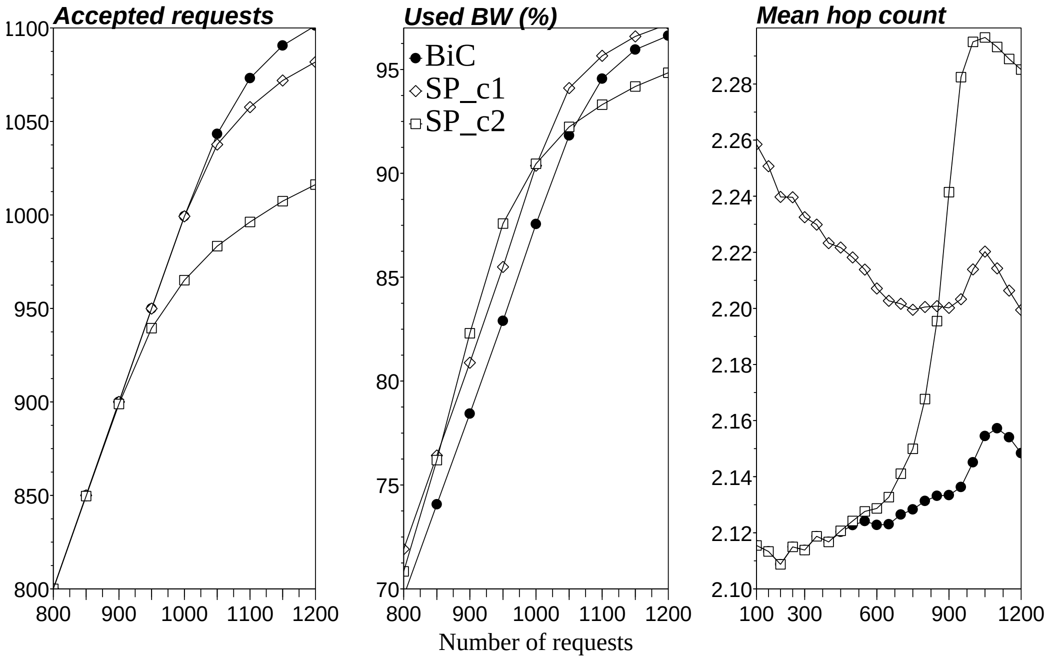


Figure 8: Accepted requests *vs.* used bandwidth *vs.* mean hop count - KL Network.

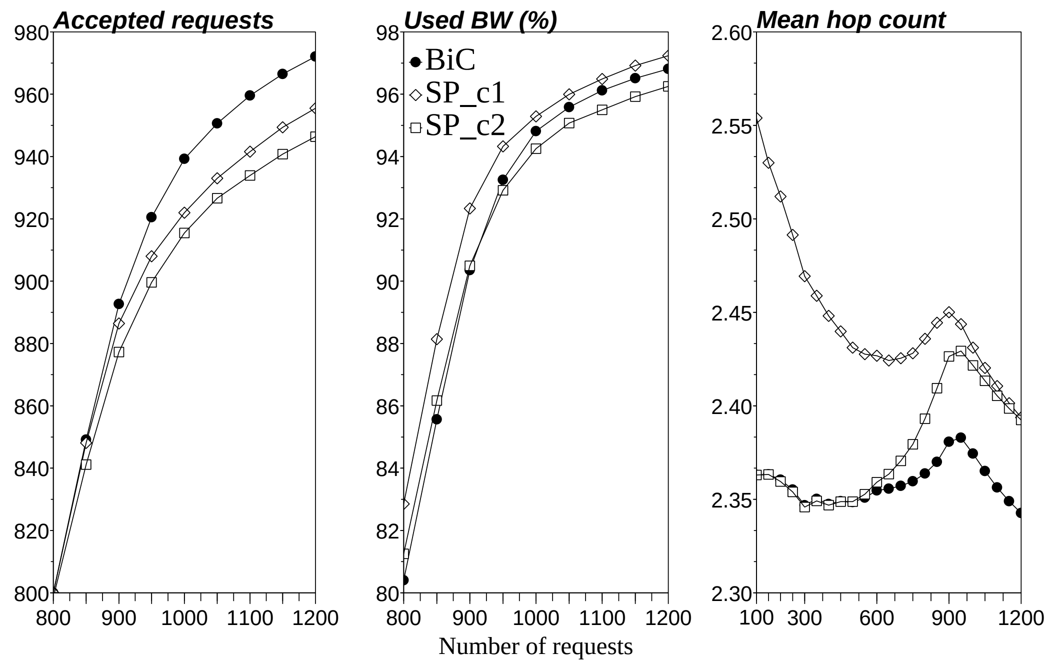


Figure 9: Accepted requests *vs.* used bandwidth *vs.* mean hop count - ISP Network.

does not take into account the hop count, leading to longer paths, even when the network is nearly 'empty'. As the traffic load increases, the worst choice of the initial paths in SP_c2 leads to bottlenecks in some links. This results in the selection of longer paths, and in higher blocking probability. In the COST 266BT and KL networks (Figures 6 and 8), above approximately 850 requests, the average number of hops per lightpath in SP_c2 is even greater than in SP_c1 - the traffic distribution is more effective in this model. Also note that when the number of connection requests exceeds approximately 1000, the mean hop count decreases in the three approaches. With this traffic load the network is already congested and node pairs topologically distant are experiencing greater difficulties in establishing a successful connection. So only some 'short' connection requests obtain a service, lowering the mean hop count.

Figure 10 shows the global blocking probability on the COST 266TT network. As mentioned earlier, COST 266TT network is the only case where the five nodes with complete conversion capability have a visible effect on the network performance, although insignificant.

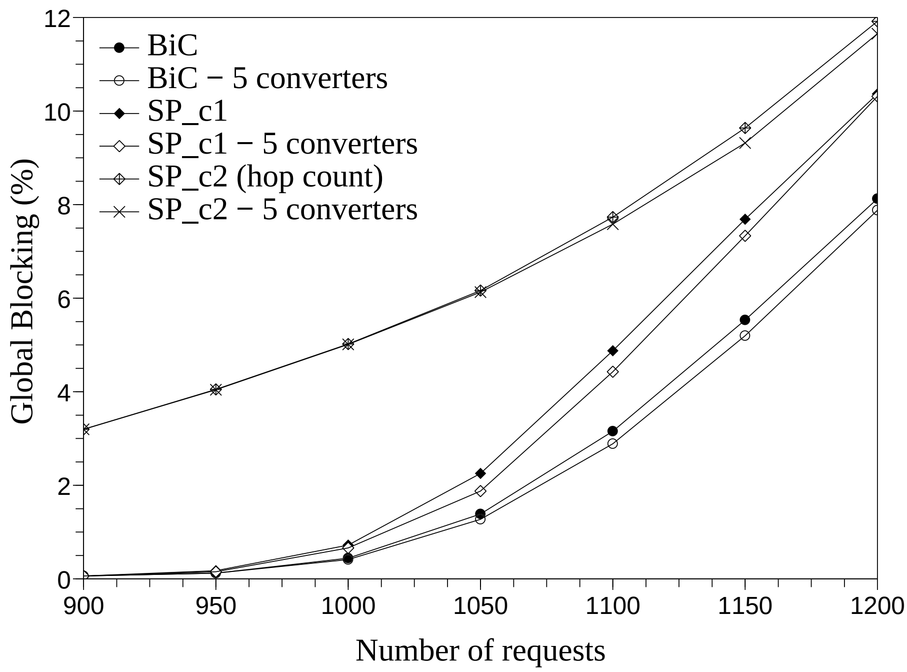
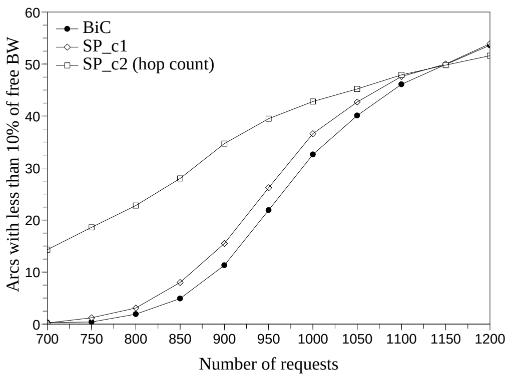
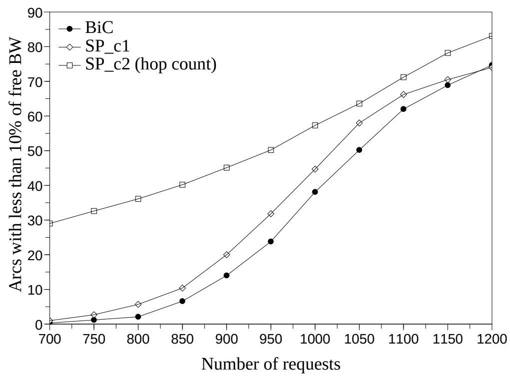


Figure 10: Global Blocking (%) - COST 266TT Network.

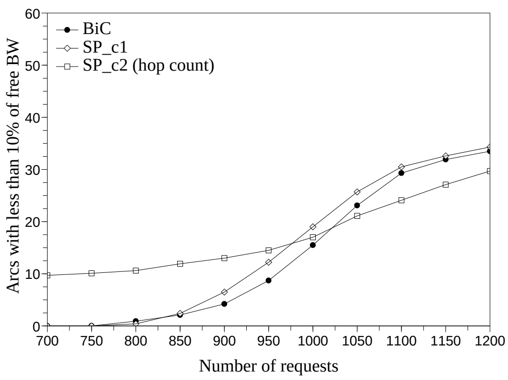
It is also interesting to analyze the ability of the different approaches to distribute traffic over the network. Figure 11(a) plots the number of links in the COST 266BT network with less than 10% of free bandwidth. BiC leads to a lower number of links with less than 10% free bandwidth than SP_c1 and SP_c2. Knowing that the number of accepted request is also higher, we can conclude that BiC has a performance significantly better than the single objective counterparts. The same behavior was observed in the remaining simulated networks. Figures 11(b), 11(c), and 11(d) shown the performance metric for the COST 266TT, NSFNET and KL networks, respectively (results from ISP network are not shown). Although the number of congested arcs above 1050 connection requests in the NSFNET network with BiC approach became higher than in the SP_c1 approach (see Figure 11(c)), we have to note that BiC significantly accepts more requests than SP_c1 (see Figure 5).



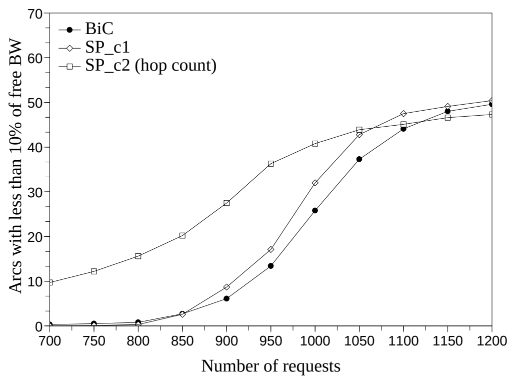
(a) Cost 266BT Network.



(b) Cost 266TT Network.



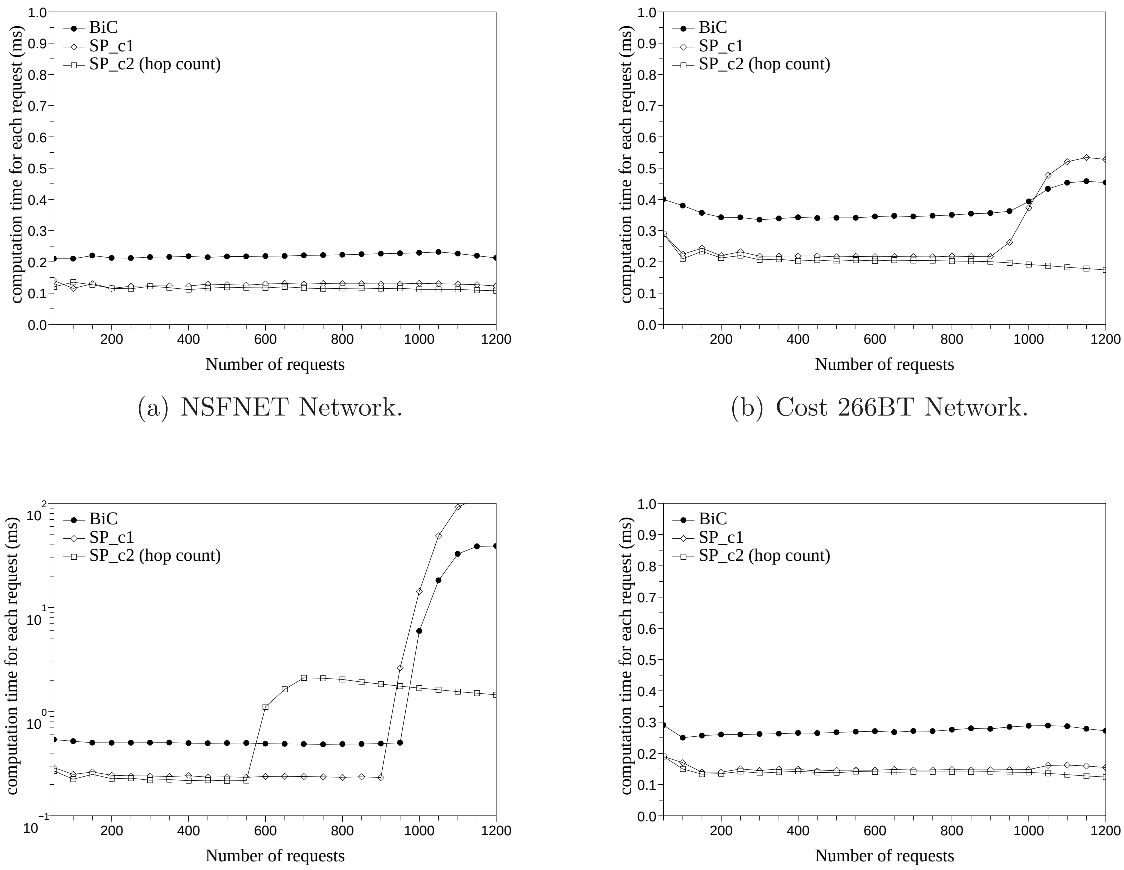
(c) NSFNET Network.



(d) KL Network.

Figure 11: Arcs with less than 10% of free BW.

Regarding CPU time, the BiC approach requires more CPU, as would be expected, but CPU times are still very low, not exceeding 0.25 ms in NSFNET, 0.45 ms in COST 266BT, 0.3 ms in KL network, and 0.35 ms in ISP network. In the COST 266TT network CPU time remains under 0.6 ms until 950 connection requests. Figures 12(a), 12(b), 12(c) and 12(d) show the CPU time per connection request, obtained in an AMD 64X2 4800 2.4 GHz computer, for NSFNET, COST 266BT, COST 266TT and KL networks, respectively. The CPU times remain stable as the traffic load grows in the NSFNET, ISP (not shown), KL and COST 266BT networks. In COST 266TT network (see Figure 12(c)), above 950 connection requests, the mean CPU time for BiC and SP_c1 models increases considerably, and can be as high as 40 *ms*. This effect occurs when the traffic load is very high and coincides with the starting of visible blocking in the network. Note that this substantial increase in CPU time is even larger in SP_c1.



(a) NSFNET Network.

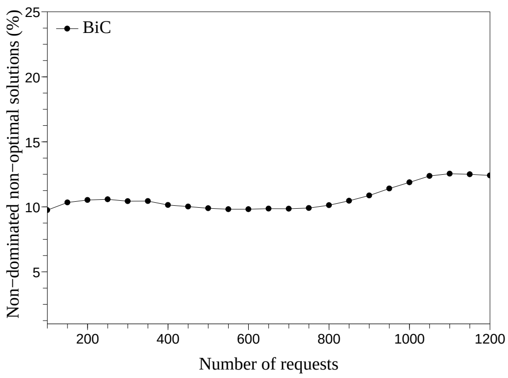
(b) Cost 266BT Network.

(c) Cost 266TT Network.

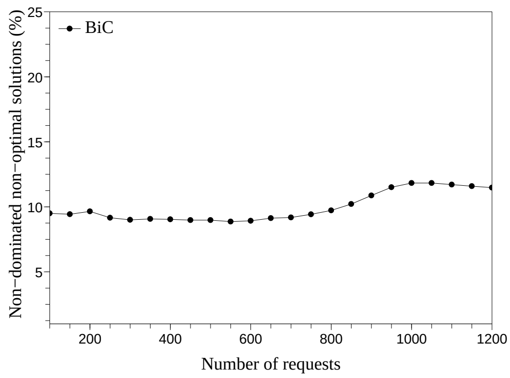
(d) KL Network.

Figure 12: Computation time for each request.

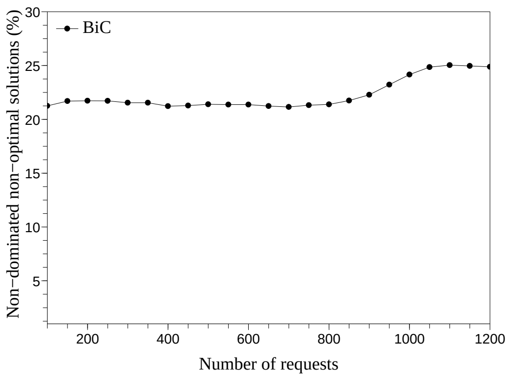
In order to assess the degree of conflict between the two objective functions of problem $\mathcal{P}$ used in the BiC model, the number of requests without an optimal solution was calculated. Figure 13 show the percentage of non-dominated non-optimal solutions for NSFNET, COST 266BT, COST 266TT and KL networks. Although the number of non-dominated solutions is relatively low this does not compromise the interest in using a bi-objective model. In fact many of the ideal solutions of the bi-objective model might possibly have not been found by the single objective models because they correspond to alternative optimal solutions in one of the objective functions.



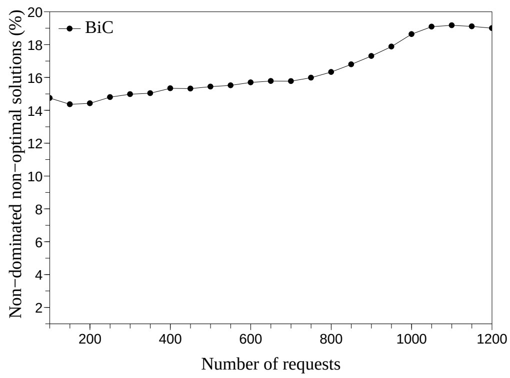
(a) NSFNET Network.



(b) Cost 266BT Network.



(c) Cost 266TT Network.



(d) KL Network.

Figure 13: Non-dominated non-optimal solutions (%).

4 The bi-objective routing model with dedicated protection

This section reviews an extension to the model previously described that is intended for obtaining a pair of node disjoint topological paths for each connection request, ensuring dedicated protection.

4.1 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 $\{v_2, \ldots, v_{i-1}\} \cap N^*(q) = \emptyset$.

Reference [34] proposes an algorithm for ranking node disjoint pairs of paths by non-decreasing order of cost, based on an adaption of the MPS algorithm [31]. Given an origin-destination node pair, s-t, the algorithm starts by making a network topology modification (see Figure 14), 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):

$$z = p \diamond (t, s') \diamond q \tag{23}$$

where p is a path from s to t in (N, L) and p' is a path from s' to t' in (N', L').

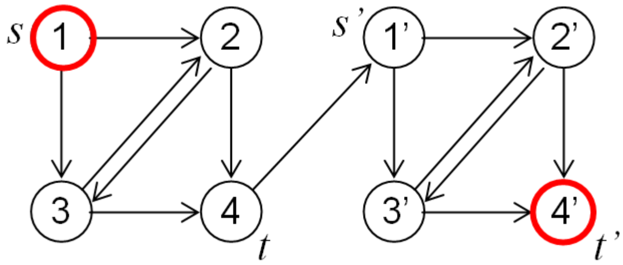


Figure 14: Topology Modification [34].

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 the source node s to the destination node t in (N, L) be $\mathcal{P}_{st}$. Note that each path z from s to t' in (N', L') is given by (23), with $p \in \mathcal{P}_{st}$ and $q \in \mathcal{P}'_{s't'}$.

4.2 Bi-objective Approach and 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 minimizes $c_i(p) + c_i(q)$, $i = 1, 2$.

As in [34], 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 $c_i(p_1) + c_i(q_1) \leq c_i(p_2) + c_i(q_2)$ $(i = 1, 2)$ and at least one of the inequalities is strict.

Topological paths $z = p \diamond (t, s') \diamond q$ are generated in the modified graph, using as path cost $f(z) = \alpha c_1(z) + (1 - \alpha) c_2(z)$ – 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 optical path 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 optical paths which are non dominated solutions will be stored.

Preference thresholds will now be defined. 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.

$$c_{1m} = c_1(z^{c_1}) = c_1(p^{c_1}) + c_1(q^{c_1}) \tag{24}$$

$$c_{2M} = c_2(z^{c_1}) = c_2(p^{c_1}) + c_2(q^{c_1}) \tag{25}$$

$$c_{1M} = c_1(z^{c_2}) = c_1(p^{c_2}) + c_1(q^{c_2}) \tag{26}$$

$$c_{2m} = c_2(z^{c_2}) = c_2(p^{c_2}) + c_2(q^{c_2}) \tag{27}$$

The preference thresholds (requested and acceptable values) are defined by equations 14-17 and circumscribe the priority regions in the objective functions' space (see Figure 1), where non-dominated solutions will be searched.

The final solution is chosen by using the aforementioned weighted Chebyshev distance to a reference point of a preference region.

$$\min_{z \in S} \max_{i=1,2} \{w_i |c_i(z) - \underline{c}_i|\} \tag{28}$$

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:

$$w_i = \frac{1}{|\bar{c}_i - \underline{c}_i|} \tag{29}$$

After selecting the pair of topological node disjoint paths (unidirectional or bidirectional), a fiber and a wavelength must be chosen for every link of the paths, hence completing the lightpath specification.

As previously, the wavelength selection seeks to maximize the wavelength bottleneck bandwidth (21), $b_j(p)$ $(\lambda_j \in \Lambda)$.

$$\max_{\lambda_j \in \Lambda} \left\{ b_j(p) = \min_{l \in p \wedge b_{lj} > 0} b_{lj} \right\} \tag{30}$$

For bidirectional requests, the same procedure will be used for each of the four paths which define a protected bidirectional lightpath.

5 Performance analysis of the model with dedicated protection

In order to assess its performance, the bi-objective routing model with dedicated protection was applied to the WDM networks already presented in section 3. All the networks were dimensioned taking into account the extra capacity needed to ensure protection. Again, we considered incremental traffic by simulating up to 1200 connection requests and the scenarios with 100% bidirectional requests and 5% unidirectional requests. Also, the situations without any conversion ability and five nodes with total conversion were considered. Like before, having 5 nodes with complete conversion capability has a marginal influence on the results, so, in almost all figures, only the case without conversion will be shown.

Figure 15 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 probability observed in SP_c1, although the difference is smaller. As it can be seen in Figure 16, although the number of accepted connections is higher, for moderate traffic loads (up to 1000 requests) BiC uses less bandwidth than SP_c1. Above 1000 requests, BiC uses more bandwidth than SP_c1, but this happens because BiC accepts more lightpaths. The lowest average number of hops per connection (see rightmost graphic on Figure 16) also shows the efficiency of the BiC formulation.

The global blocking probability for the COST 266BT, KL and ISP networks with protection is shown in Figures 17, 18, and 19. Figures 17 and 18 only show the results above 900 connection requests because below this value the blocking is almost zero. The number of accepted requests, the used bandwidth and the mean hop count for these networks are presented in Figures 20, 21, and 22.

Regarding the blocking probability on these networks, BiC model clearly exhibits a better perfomance than SP_c2. On the COST 266BT network the blocking in BiC model is only slightly lower than in SP_c1. Figure 20 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, the BiC and SP_c1 approaches applied to KL and ISP networks with protection have roughly the same performance. As can be seen in figures 18 and 19, in KL and ISP networks, the blocking probability of the BiC approach is coincident with the blocking probability of the SP_c1 approach. So the BiC model for dedicated path protection not always has 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 bi-objective model.

Regarding the traffic distribution, Figure 23 shows the number of arcs with less than

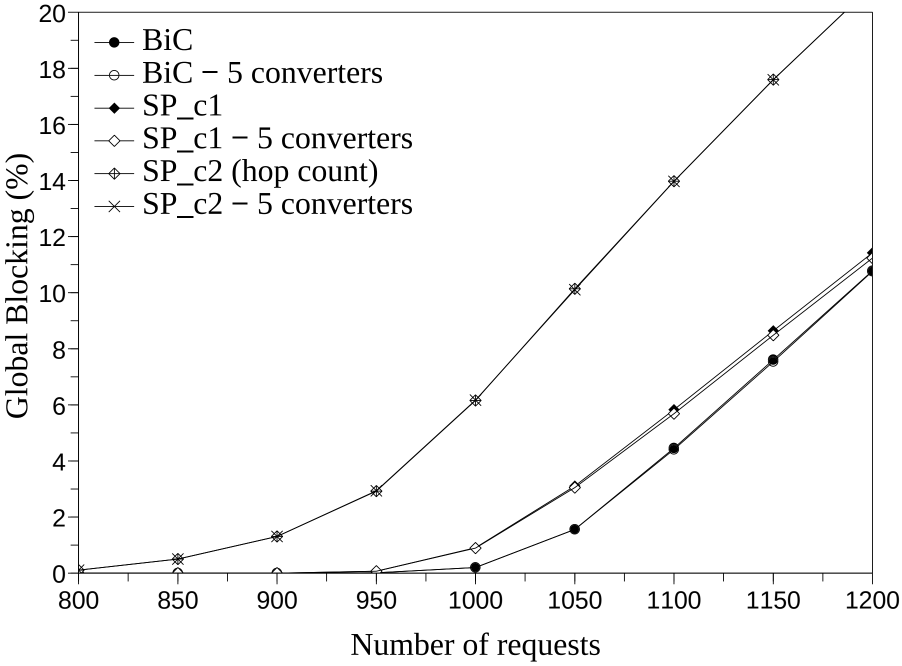


Figure 15: Global Blocking (%) - NSFNET Network.

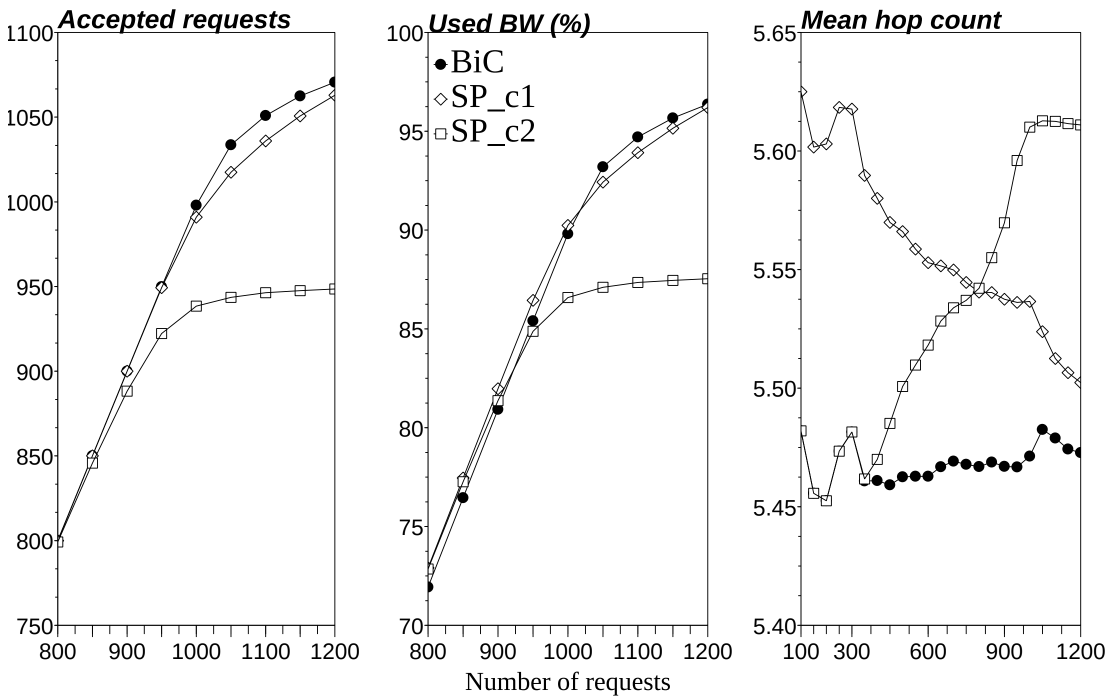


Figure 16: Accepted requests *vs.* used bandwidth *vs.* mean hop count - NSFNET Network.

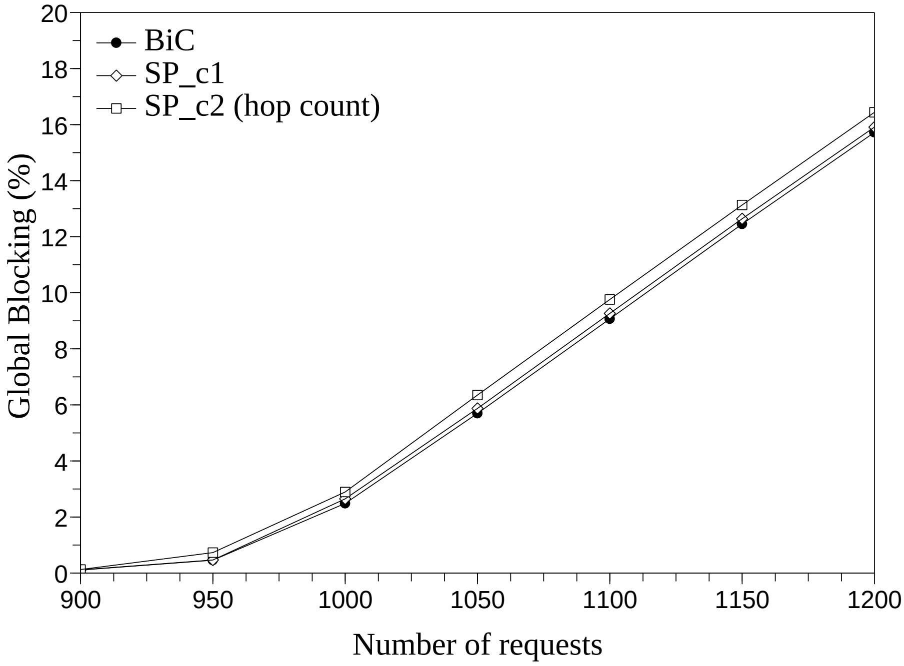


Figure 17: Global Blocking (%) - COST 266BT Network.

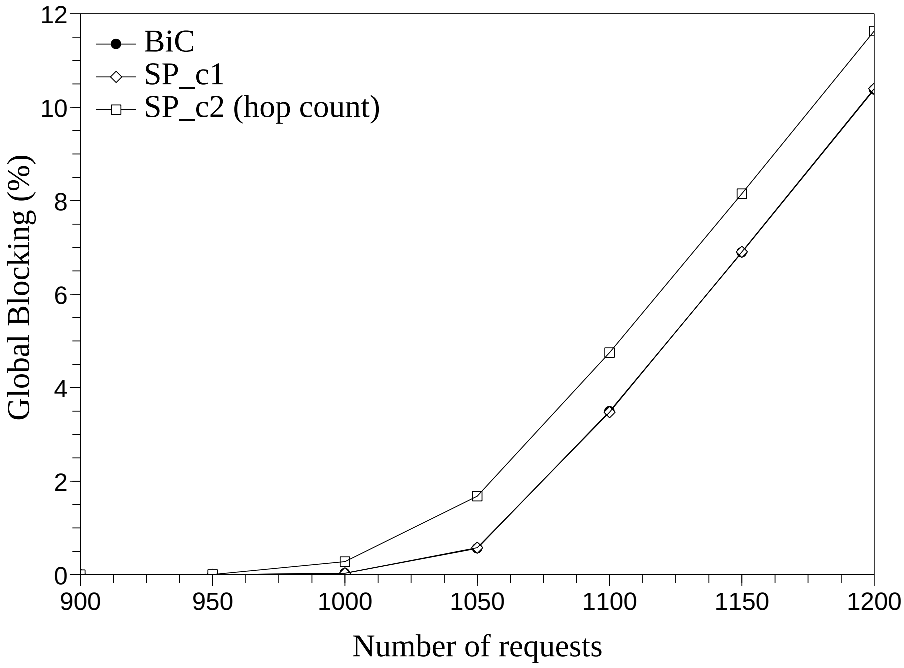


Figure 18: Global Blocking (%) - KL Network.

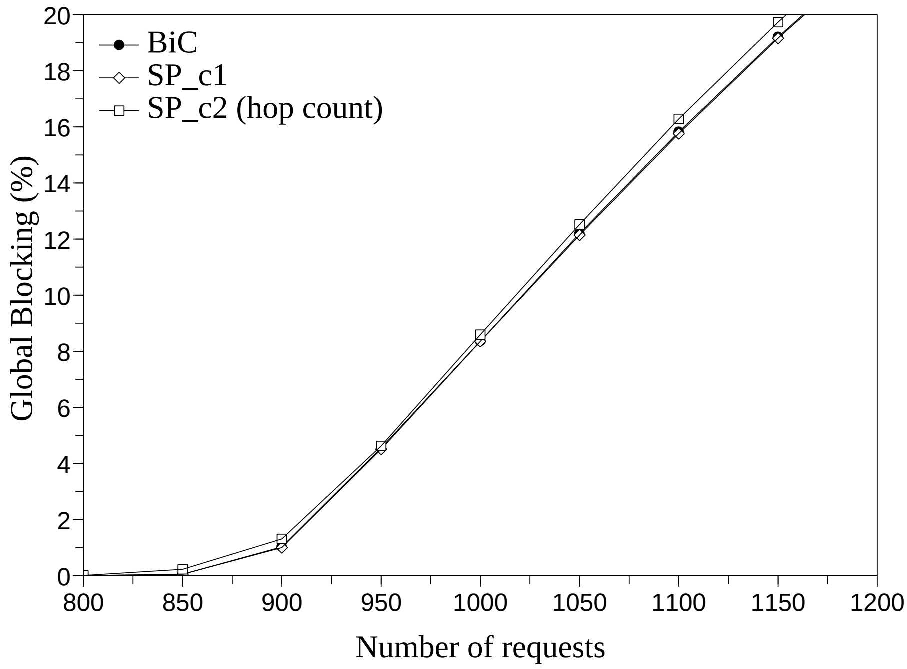


Figure 19: Global Blocking (%) - ISP Network.

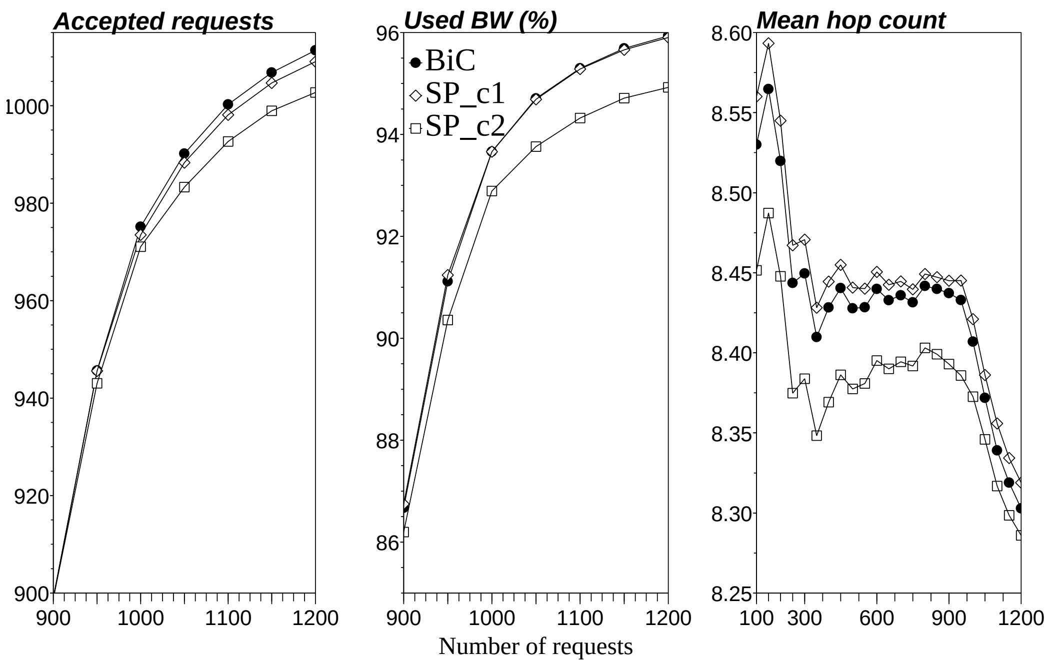


Figure 20: Accepted requests *vs.* used bandwidth *vs.* mean hop count - COST 266BT Network.

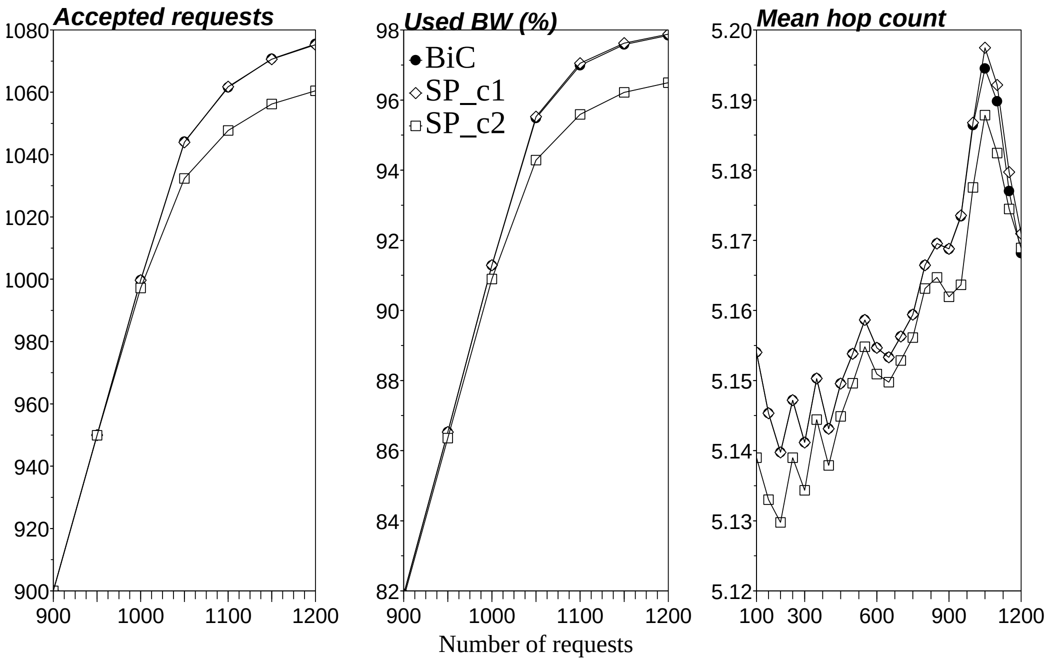


Figure 21: Accepted requests *vs.* used bandwidth *vs.* mean hop count - KL Network.

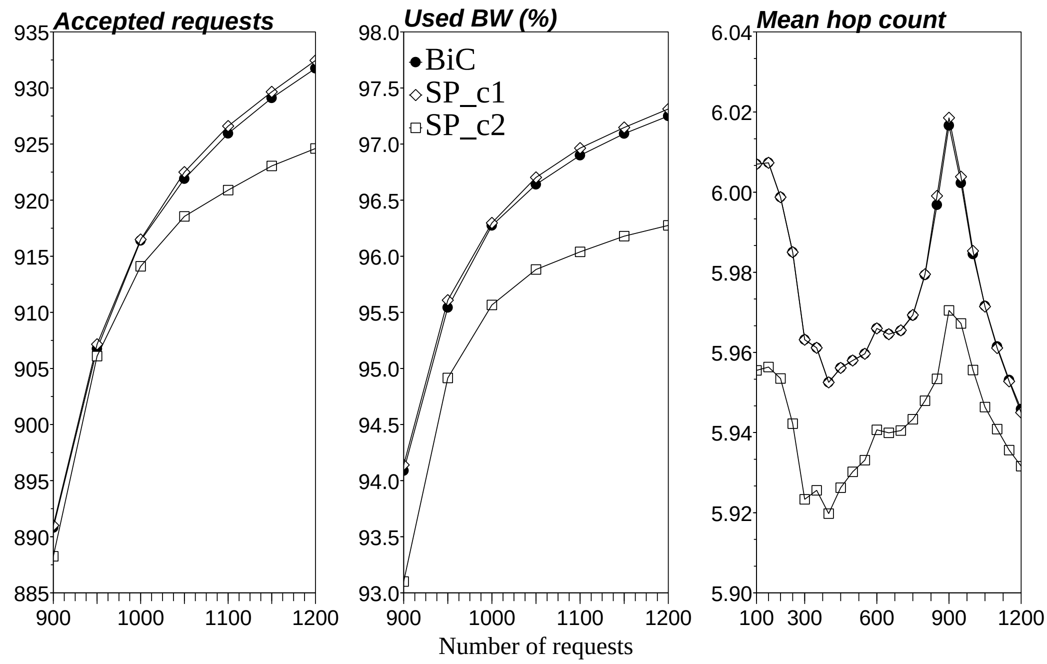
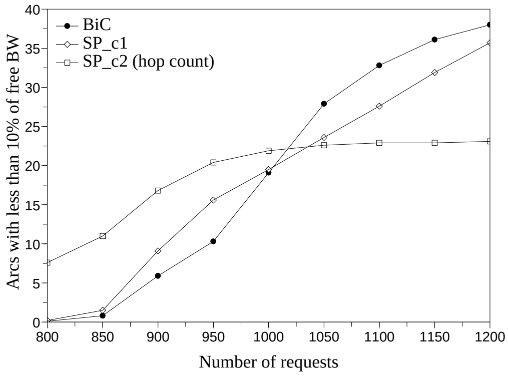
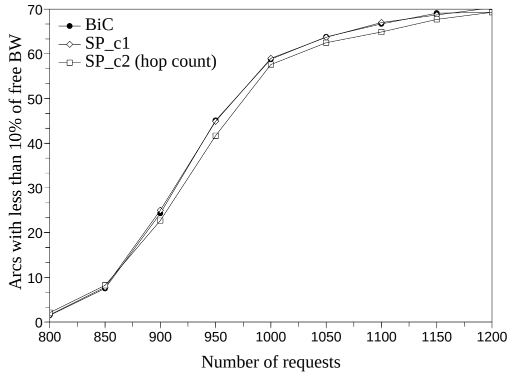


Figure 22: Accepted requests *vs.* used bandwidth *vs.* mean hop count - ISP Network.

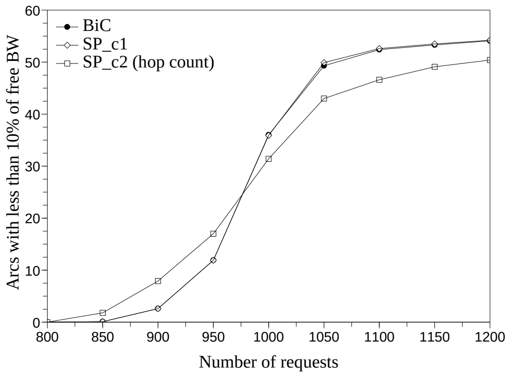
10% free bandwidth in the networks with protection. For networks COST 266BT, KL and ISP, this measure has a similar behavior in models BiC and SP_c1. For NSFNET network (the only one where BiC model is clearly better than the SP) BiC provides a lower number of arcs with less than 10% free bandwidth until 1000 requests (Figure 23(a)), although it has a slightly higher number of accepted requests. Above 1000 connection requests, BiC have more congested arcs, but the number of accepted requests is also higher.



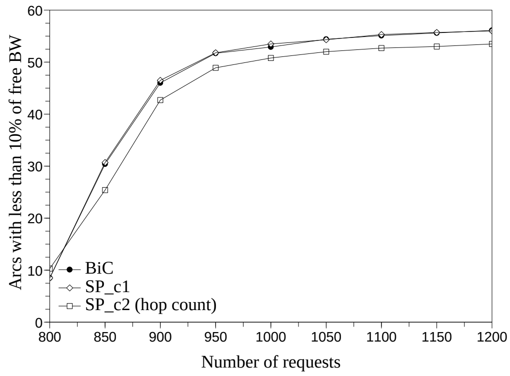
(a) NSFNET Network.



(b) Cost 266BT Network.



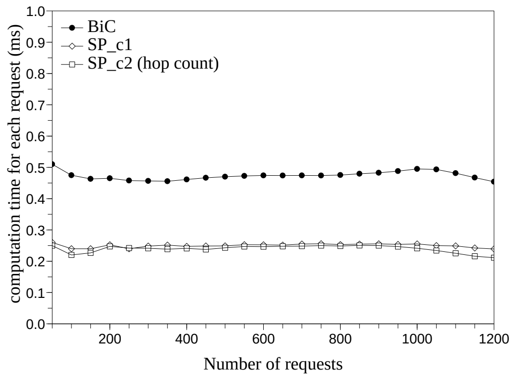
(c) KL Network.



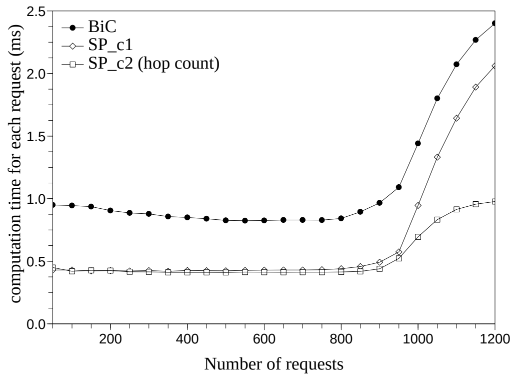
(d) ISP Network.

Figure 23: Arcs with less than 10% of free BW.

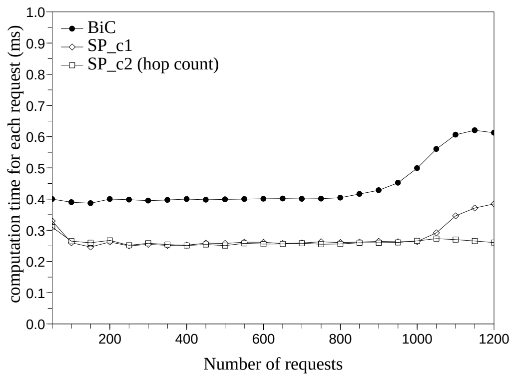
Concerning the CPU times, they still are very low. In NSFNET the CPU this time is approximately 2.5 *ms* for single objective formulations and 5 *ms* for BiC (Figure 24(a)). Note that these CPU times are roughly twice those obtained without protection (see Figure 12(a)). In COST 266BT network the BiC uses less than 1 *ms* below 900 requests while single objective approaches use about 0.5 *ms* (see Figure 24(b)). 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). In the ISP network the CPU times are slightly higher, about 0.3 ms for SP_c1 and SP_c2 approaches and 0.5 ms for BiC, until 900 requests.



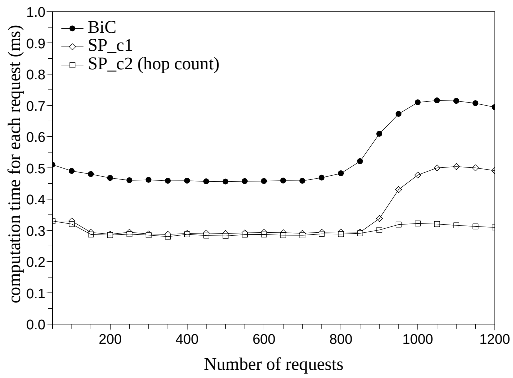
(a) NSFNET Network.



(b) Cost 266BT Network.



(c) KL Network.



(d) ISP Network.

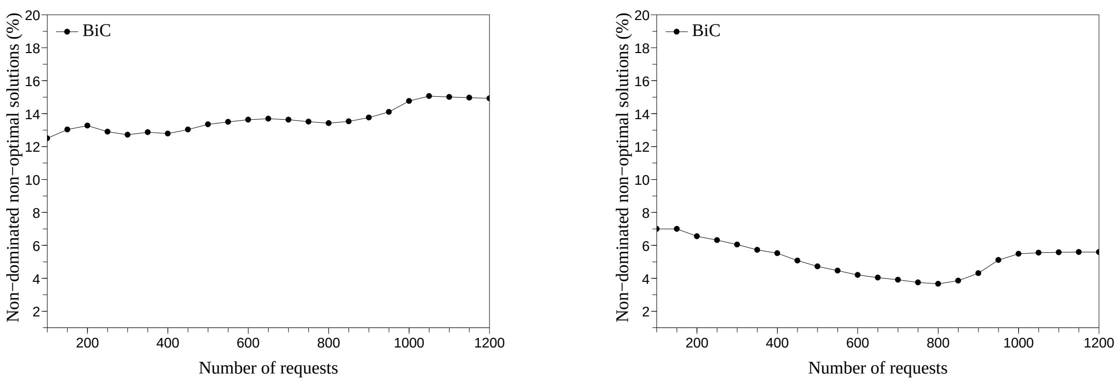
Figure 24: Computation time for each request.

The number of requests without an optimal solution is shown in Figure 25 for the NSFNET and COST 266BT networks. Again the number of non-dominated solutions is relatively low, but, at least in some networks/topologies, the bi-objective model exceeds the performance of the single objective approaches.

6 Conclusions

The Routing and Wavelength Assignment problem in WDM networks involves multiple objectives and constraints, so, multicriteria approaches like the one presented enable to explicitly represent the different performance objectives and to address, in a mathematically consistent manner, the trade off among the various criteria.

A bi-objective model for obtaining a topological path (unidirectional or symmetric



(a) NSFNET Network.

(b) Cost 266BT Network.

Figure 25: Non-dominated non-optimal solutions (%).

bidirectional) for each lightpath request in a WDM network was reviewed. The model considers two criteria – the first one takes into account the bandwidth usage in the links of the network and the second one the number of links of the path. The automated resolution approach uses a k-shortest path algorithm, as well as preference thresholds defined in the objective function space, combined with a Chebyshev distance to a reference point (which changes with the analysed preference region). Having obtained a non-dominated topological path, a heuristic procedure was then used to assign wavelengths to the links.

The performance of this bi-objective model was analysed using several benchmark networks, and considering a comparison with the results of the two single criterion approaches corresponding to each of the criteria used in the BiC model. Concerning the model without protection, the BiC approach resulted in lower global blocking than SP_c1 and SP_c2. This is due to an initial better choices of paths and a more balanced distribution of traffic load. At moderate load, although BiC approach accepts more requests, BiC uses less bandwidth than SP_c1. SP_c2 uses less bandwidth than the BiC but it leads to a significant lower number of successful connections.

The impact of having five nodes with wavelength conversion capability was negligible in the simulated situations.

Although the BiC approach uses more CPU time per request its performance was nevertheless quite good – below 0.5 ms except in the denser network (COST 266BT) when traffic load is high.

Concerning dedicated protection, an extension of the previous model that obtains a pair of node disjoint lightpaths for each connection request was also reviewed.

The performance of this bi-objective model was evaluated by comparing it with the results of the single criterion approaches corresponding to the two criteria used.

The BiC model leads to a better performance than the monocriteria model SP_c2 (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 bi-objective model (with these two objectives) 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.

Acknowledgements

This study was partially supported by PT Inovação and by programme POSC of the EC programme cosponsored by national funds.

C. Simões also thanks the FCT and IPV by the grant of the PhD scholarship SFRH/-BD/49739/2009.

References

[1] X. Chu, J. Liu, and Z. Zhang, "Analysis of sparse-partial wavelength conversion in wavelength-routed WDM networks," in *Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM'2004*, vol. 2, pp. 1363–1371, Mar. 2004.

[2] S. Bandyopadhyay, A. Jaekel, A. Sengupta, and W. Lang, "A virtual wavelength translation scheme for routing in all-optical networks," *Photonic Network Communications*, vol. 4, pp. 391–407, July 2002.

[3] H. Zang, J. P. Jue, and B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks," *Optical Networks Magazine*, vol. 1, pp. 47–60, Jan. 2000.

[4] R. Ramaswami and K. N. Sivarajan, "Routing and wavelength assignment in all-optical networks," *IEEE/ACM Transactions on Networking*, vol. 3, pp. 489–500, Oct. 1995.

[5] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: An approach to high bandwidth optical WAN's," *IEEE Transactions on Communications*, vol. 40, pp. 1171–1182, July 1992.

[6] D. Banerjee and B. Mukherjee, "A practical approach for routing and wavelength assignment in large wavelength-routed optical networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 903–908, June 1996.

[7] A. E. Ozdaglar and D. P. Bertsekas, "Routing and wavelength assignment in optical networks," *IEEE/ACM Transactions on Networking*, vol. 11, pp. 259–272, Apr. 2003.

[8] B. Jaumard, C. Meyer, and B. Thiongane, "Comparison of ILP formulations for the RWA problem," *Optical Switching and Networking*, vol. 4, pp. 157–172, Nov. 2007.

[9] R. M. Krishnaswamy and K. N. Sivarajan, "Algorithms for routing and wavelength assignment based on solutions of LP-relaxations," *IEEE Communications Letters*, vol. 5, pp. 435–437, Oct. 2001.

[10] M. E. M. Saad and Z.-Q. Luo, "A lagrangean decomposition approach for the routing and wavelength assignment in multifiber WDM networks," in *IEEE Global Telecommunications Conference, GLOBECOM'02*, vol. 3, pp. 2818–2822, Nov. 2002.

[11] M. E. M. Saad and Z.-Q. Luo, "On the routing and wavelength assignment in multifiber WDM networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, pp. 1708–1717, Nov. 2004.

[12] R. M. Krishnaswamy and K. N. Sivarajan, "Design of logical topologies: A linear formulation for wavelength-routed optical networks with no wavelength changers," *IEEE/ACM Transactions on Networking*, vol. 9, pp. 186–198, Apr. 2001.

[13] B. Jaumard, C. Meyer, and B. Thiongane, *Handbook of Optimization in Telecommunications*, ch. 23, ILP formulations for the routing and wavelength assignment problem: Symmetric systems, pp. 637–677. Springer Science + Business Media, Apr. 2006.

[14] K. Lee, S. Park, K.-I. Choe, and C. Park, "Routing and wavelength assignment in WDM all-optical networks," *IEEE Electronics Letters*, vol. 36, pp. 964–966, May 2000.

[15] Z. Zhang and A. S. Acampora, "A heuristic wavelength assignment algorithm for multihop WDM networks with wavelength routing and wavelength re-use," *IEEE/ACM Transactions on Networking*, vol. 3, pp. 281–288, June 1995.

[16] B. Jaumard, C. Meyer, and X. Yu, "How much wavelength conversion allows a reduction in the blocking rate?," *Journal of Optical Networking*, vol. 5, pp. 881–900, Dec. 2006.

[17] A. K. Katangur, Y. Pan, and M. D. Fraser, "Simulated annealing routing and wavelength lower bounds estimation on wavelength-division multiplexing optical multistage networks," *Optical Engineering*, vol. 43, pp. 1080–1091, May 2004.

[18] N. Banerjee, V. Mehta, and S. Pandey, "A genetic algorithm approach for solving the routing and wavelength assignment problem in WDM networks," in *3rd IEEE/IEE International Conference on Networking, ICN'2004*, pp. 70–78, Feb. 2004.

[19] J. Zhang, K. Zhu, L. H. Sahasrabuddhe, S. J. B. Yoo, and B. Mukherjee, "On the study of routing and wavelength assignment approaches for survivable wavelength routed WDM mesh networks," *Optical Networks Magazine*, vol. 4, pp. 16–28, November/December 2003.

[20] J. Zhang and B. Mukherjee, "A review of fault management in WDM mesh networks: Basic concepts and research challenges," *IEEE Network*, vol. 18, pp. 41–48, March/April 2004.

[21] Y. Xiong, D. Xu, and C. Qiao, "Achieving fast and bandwidth-efficient shared-path protection," *IEEE Journal of Lightwave Technology*, vol. 21, pp. 365–371, Feb. 2003.

[22] P.-H. Ho, J. Tapolcai, and H. T. Mouftah, "On achieving optimal survivable routing for shared protection in survivable next-generation internet," *IEEE Transactions on Reliability*, vol. 53, pp. 216–225, June 2004.

[23] T. Li and B. Wang, "Efficient online algorithms for dynamic shared path protection in WDM optical networks," *Photonic Network Communications*, vol. 9, pp. 207–222, Mar. 2005.

[24] J. Clímaco and J. Craveirinha, *Multiple Criteria Decision Analysis: State of the Art Surveys*, vol. 78 of *International Series in Operations Research & Management Science*, ch. Multicriteria Analysis in Telecommunication Planning and Design - Problems and Issues, pp. 899–951. New York: Springer Science, 2005.

[25] J. C. N. Clímaco, J. M. F. Craveirinha, and M. M. B. Pascoal, *Advances in Multiple Criteria Decision Making and Human Systems Management*, ch. Multicriteria Routing Models in Telecommunication Networks - Overview and a Case Study, pp. 17–46. IOS Press, 2007.

[26] A. Todimala and B. Ramamurthy, "Congestion-based algorithms for online routing in optical WDM mesh networks," in *IASTED International Conference on Communications, Internet, and Information Technology, CIIT'03*, pp. 43–48, Nov. 2003.

[27] X. Chu and B. Li, "Dynamic routing and wavelength assignment in the presence of wavelength conversion for all-optical networks," *IEEE/ACM Transactions on Networking*, vol. 13, pp. 704–715, June 2005.

[28] C.-F. Hsu, T.-L. Liu, and N.-F. Huang, "On adaptive routing in wavelength-routed networks," *Optical Networks Magazine*, vol. 3, pp. 15–24, January/February 2002.

[29] T. Gomes, J. Craveirinha, J. Clímaco, and C. Simões, "A bicriteria routing model for multi-fibre WDM networks," *Photonic Network Communications*, vol. 18, pp. 287–299, Dec. 2009.

[30] T. Gomes, L. Martins, and J. Craveirinha, "An algorithm for calculating the k shortest paths with a maximum number of arcs," *Investigaço Operacional*, vol. 21, no. 2, pp. 235–244, 2001.

[31] E. Martins, M. Pascoal, and J. Santos, "Deviation algorithms for ranking shortest paths," *International Journal of Foundations of Computer Science*, vol. 10, no. 3, pp. 247–263, 1999.

[32] A. P. Wierzbicki, "The use of reference objectives in multiobjective optimization," *Theory and Application, Proceedings, Lecture Notes in Economics and Mathematical Systems*, vol. 177, pp. 468–487, 1980.

[33] T. Gomes, C. Simões, J. Craveirinha, and J. Clímaco, "A bi-objective model for routing and wavelength assignment in resilient WDM networks," in *Safety, Reliability and Risk Analysis: Theory, Methods and Applications*, vol. 4, pp. 2627–2634, Sept. 2008.

[34] J. C. N. Clímaco and M. M. B. Pascoal, "Finding non-dominated bicriteria shortest pairs of disjoint simple paths," *Computers & Operations Research*, vol. 36, pp. 2892–2898, Nov. 2009.

[35] E. Martins, M. Pascoal, and J. Santos, "An algorithm for ranking loopless paths," Tech. Rep. 99/007, CISUC, 1999. http://www.mat.uc.pt/˜marta/Publicacoes/mps2.ps.

[36] J. C. N. Clímaco, J. M. F. Craveirinha, and M. M. B. Pascoal, "An automated reference point-like approach for multicriteria shortest path problems," *Journal of Systems Science and Systems Engineering*, vol. 15, pp. 314–329, Sept. 2006.

[37] A. Betker, C. Gerlach, M. Jäger, M. Barry, S. Bodamer, J. Späth, C. M. Gauger, and M. Köhn, "Reference Transport Network Scenarios," tech. rep., MultiTeraNet Report, July 2003.

[38] S. D. Maesschalck, D. Colle, M. P. I. Lievens, P. Demeester, C. Mauz, M. Jaeger, R. Inkret, B. Mikac, and J. Derkacz, "Pan-European Optical Transport Networks: An availability-based comparison," *Photonic Network Communications*, vol. 5, pp. 203–225, May 2003.

[39] M. Kodialam and T. V. Lakshman, "Dynamic routing of bandwidth guaranteed tunnels with restoration," in *Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies, IEEE INFOCOM'2000*, vol. 2, pp. 902–911, Mar. 2000.

[40] G. Apostolopoulos, R. Guérin, S. Kamat, and S. K. Tripathi, "Quality of service based routing: A performance perspective," in *Proceedings of the ACM SIGCOMM 98 Conference*, pp. 17–28, 1998.