Paper

Performance Analysis of a Bi-Objective Model for Routing and Wavelength Assignment in WDM Networks

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

Abstract—Establishing end-to-end connections on wavelength division multiplexing (WDM) networks requires setting up lightpaths, defining the sequence of optical fibres and the wavelength in each fibre (the routing and wavelength assignment problem) for traffic flow. This paper reviews a bicriteria 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. An extensive performance analysis of the two bicriteria model is presented, comparing the performance metrics obtained with the monocriterion models using the same objective functions, in five different reference networks commonly used in literature.

Keywords—multicriteria optimization, routing in WDM networks.

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 fibres. All-optical networks based on wavelength division multiplexing consist of optical fibre 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 that node pairs can establish point-to-point all-optical connections, or lightpaths, for information transfer. A lightpath may span several fibre 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 fibre link.

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 network 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.

Multi-fibre networks use several fibres per link. Considering that the nodes have no wavelength converters, the possibilities of finding a lightpath satisfying the wavelength continuity constraint is higher than in single fibre networks. A multi-fibre network with F fibres per link and W wavelengths per fibre is functionally equivalent to a single-fibre network with $F \times W$ wavelengths and conversion degree of F [2].

Connection requests are usually considered to be of three types: static, incremental, and dynamic [3]. Regarding static traffic, the entire set of connections is known in advance, and the problem is then to set up lightpaths for these connections seeking to minimize network resources such as the number of wavelengths or the number of fibres in the network. In this case the RWA problem is known as the static lightpath establishment (SLE) problem. Concerning incremental-traffic, connection requests arrive sequentially, a lightpath is established for each connection, and the lightpath remains in the network indefinitely. In the case of dynamic traffic, 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 seeking to minimize the amount of connection blocking, or to maximize the number of connections that are established in the network at any time. This problem is designated as the dynamic lightpath establishment (DLE) problem. The SLE problem can be formulated as an integer linear program [4], which is known to be NP-complete [5].

In order to make the RWA problem more tractable, it can be divided into two sub-problems – routing and wavelength assignment, so that each sub-problem can be solved separately. Nevertheless note that each sub-problem is still NP-complete [5].

Routing methods in WDM networks can be classified into two types: static routing and adaptive routing. Static routing encompasses fixed routing and fixed-alternate routing. In fixed routing the same fixed route for a given source-destination pair remains unchanged throughout time. The fixed-alternate routing scheme pre-computes a set of paths between each source-destination pair, and for each request, a path from this pre-computed set is chosen. Adaptive routing involves a dynamical search for a path when a connection request arrives, taking into account the current state of the network. Therefore in general, adaptive routing gives better blocking performance than fixed-alternate routing [3].

A wavelength assignment algorithm is used to determine the wavelengths in the arcs along the path chosen in the routing step. Many wavelength assignment algorithms have been proposed such as random, first fit, most-used, least-used, least-loaded, max-sum, min-product, and relative capacity loss schemes [3].

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 for some rounding off procedures [8]. Examples of monocriterion approaches to the RWA problem, considering different metrics as objective functions are in the references: [3], [4], [6], [7], [9]–[12].

1.2. Multicriteria Models

In general routing protocols only optimize one metric, typically using some variant of a shortest path algorithm. However all-optical WDM networks can be characterized in terms of performance by multiple metrics. Also the design of real networks usually involves multiple, often conflicting objectives and various constraints. 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, seems to be potentially advantageous in face of the inherent limitations of single objective approaches.

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 [13], including a section dedicated to routing models. A recent review on multicriteria routing models can be seen in [14].

In [15] two different criteria, path length and congestion in the network, are considered and applied sequentially (the second metric is only used if a tie occurs in the first one). Two algorithms for dynamic traffic were proposed: least congested shortest hop routing where priority is given to efficient resource utilization (the algorithm selects the least congested path 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 analyzed in [13].

In [16] a set of link disjoint routes for each node pair, in a network with dynamic traffic, is pre-computed. Then the weighted least-congestion routing and first-fit wavelength assignment algorithm, which includes two criteria (hop count and free wavelengths), combined in a single weighted metric, is used to rank the paths. The same approach was proposed earlier in [17], which tries to minimize the resource utilization while simultaneously balancing the traffic load in the links. Nonetheless [17] only considers networks with full wavelength conversion. These models, which consider as solution of the bicriteria problem the optimal solution of the single objective function resulting from the weighted sum of the considered criteria, do not take full advantage of the possibilities of multicriteria approaches and may lead to less effective solutions.

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 [18]. 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 [18] uses an exact procedure to calculate non-dominated topological paths based on a k-shortest path algorithm [19] which is based on an adaptation of the MPS algorithm [20]. Furthermore, preference thresholds, defined in the objective function's space, combined with a Chebyshev distance to a reference point [21] are used for selecting the final solution. The solution of this bicriteria model is a non-dominated topological (optically feasible) path. A heuristic procedure is then used to assign wavelengths to the links.

The focus of this paper is to present an extensive and systematic performance analysis study of the bicriteria routing model [18] 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 bicriteria model. Performance analysis of the results obtained using several network topologies are presented and discussed in Section 3. Finally, some conclusions are drawn in Section 4.

2. The Bicriteria Routing Model

2.1. Model Description

In this section we review the features of the bicriteria routing model associated with the dynamic lightpath establishment problem with incremental traffic, in a WDM network, proposed in [18]. The model was developed for application in large WDM networks, with multiple wavelengths per fibre and multi-fibres per link. The bicriteria 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. 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:

- 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 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 $o_{l_ci} = (1, \bar{a}_i)$ and if $a_{i\alpha} = 1$ then $a_{i\alpha}$ will change from 1 to 2 if p^λ is selected.

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

Firstly we will describe the bicriteria 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:

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

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, favoring a balanced distribution of traffic throughout the network, and hence decreasing the blocking probability and therefore increased 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 $C(l)$:

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

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).

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

Note that in many cases there is no feasible solution which optimizes the two objective functions, $c_1(p)$ and $c_2(p)$, simultaneously. 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:

$$(\mathscr{P})\quad\left\{\begin{array}{l}\min_{p\in D_T}c_1(p)\\ \min_{p\in D_T}c_2(p)\end{array}\right.. \tag{7}$$

Given two paths p_1 and p_2, from s to t in R, path p_1 dominates p_2, denoted by $p_{1D}p_2$, 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.

This model was extended to bidirectional connections between nodes s and t by considering a bidirectional lightpath $p^\lambda=(p_{st}^\lambda,p_{ts}^\lambda)$ 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_T^b of feasible solutions to the bicriteria 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_{ts} are viable.

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

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

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

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.

2.2. 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's 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 fibres) along the arcs of the selected path p. For this purpose we will use the maximization of the *wavelength bottleneck bandwidth*, $b_j(p)$ $(\lambda_j\in\Lambda)$:

$$\max_{\lambda_j\in\Lambda}\left\{b_j(p)=\min_{l\in p\wedge b_{lj}>0}b_{lj}\right\}\quad(p\in D_T). \tag{10}$$

Note that this procedure is equivalent to the choice of the least loaded wavelength (LL) along the arcs of the path. Moreover, if all the nodes of the network enable full wavelength conversion, once a viable topological path is selected, the choice of the wavelength(s) in the arcs is irrelevant in terms of network performance. When the nodes have no conversion capability the proposed scheme of wavelength selection is known to give good results (see, e.g., [3]). In any case it can be concluded from many studies that 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^*:

$$b_{l^*j^*}=\max_{\lambda_j\in\Lambda}\left\{b_j(p)=\min_{l\in p\wedge b_{lj}>0}b_{lj}\right\}:\ \exists\text{ viable }p^\lambda\text{ which uses }\lambda_{j^*}\text{ in }l^*\in p \tag{11}$$

For bidirectional connections, once a non-dominated solution $p \in D_T^b$ has been selected, the wavelengths (and fibres) 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.

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. It must be stressed that path calculation and selection have to be fully automated, as part of a telecommunication network routing mechanism, therefore the use of an interactive decision approach is precluded.

The candidate solutions are computed according to an extremely efficient k-shortest path algorithm, MPS [20], [22], by using a version adapted to paths with a maximum number of arcs (length constrained k-shortest paths) as described in [19]. The algorithm is applied to the convex combination of the two objective functions:

$$f(p) = \alpha c_1(p) + (1-\alpha)c_2(p) \qquad 0 \le \alpha \le 1\,. \tag{12}$$

Note that the value of α just determines the order in which the solutions are found, and its choice is purely instrumental, since all non-dominated solutions can be calculated.

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 Fig. 1.

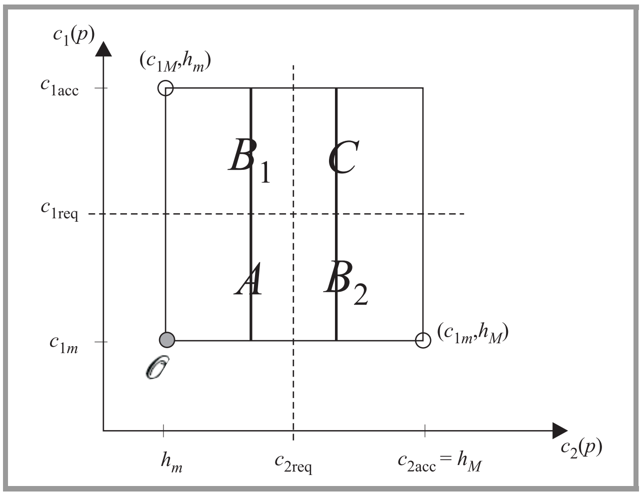

Fig. 1. Preference regions.

In the first step, vertex solutions p^{c_1} and p^{c_2} (viable topological paths) which optimise 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.

$$p^{c_1} = \arg\min_{p \in D_T} c_1(p) \tag{13}$$

$$p^{c_2} = \arg\min_{p \in D_T} \{c_2(p) = h(p)\} \tag{14}$$

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:

$$c_{1m} = c_1(p^{c_1}) \quad \wedge \quad c_{2M} = h_M = c_2(p^{c_1})\,, \tag{15}$$

$$c_{1M} = c_1(p^{c_2}) \quad \wedge \quad c_{2m} = h_m = c_2(p^{c_2})\,, \tag{16}$$

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

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

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

$$c_{2\text{req}} = \left\lfloor \frac{h_m + h_M}{2} \right\rfloor. \tag{20}$$

Priority regions are defined in the objective functions' space according to Fig. 1, in which non-dominated solutions are searched for. Region A (Fig. 1) is the first priority region where the requested values for the two functions are satisfied simultaneously. In the second priority regions, B_1 and B_2, only one of the requested value is satisfied while the acceptable value for the other function is also guaranteed. Concerning these two regions we will give preference to solutions with less arcs, that is, preference is given to solutions in B_1 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.

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.

Concerning the selection of a solution when there is more than one non-dominated solution in a given region S, the used method for ordering such solutions is a reference point type approach that considers that the 'form' of the region where solutions are located "reflects" in some manner the user's preferences. At this step a reference point based procedure of the type proposed in [23] is used, by considering as reference point the 'left bottom corner' of region S. This point coincides with the ideal optimum if $S = A$.

Reference type approaches minimize the distance of the solutions to a specific point by using a certain metric, recurring to a scalarizing function [21]. In the present context a weighted Chebyshev metric proportional to the size of the "rectangle" S (see Fig. 2) is used. Therefore, one will select the solution p^*:

$$p^* = \arg\min_{p \in S_N^c} \max_{i=1,2} \{w_i |c_i(p) - \underline{c}_i|\}\,, \tag{21}$$

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:

$$w_i = \frac{1}{\bar{c}_i - \underline{c}_i}, \qquad (22)$$

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 Fig. 2, where the number assigned to each bullet is the computation order of the corresponding solution (according to Eq. (12)), and solution (2) would be the one to be selected, since it has the shortest distance to the reference point.

Details of this selection procedure can be seen in [18], [23].

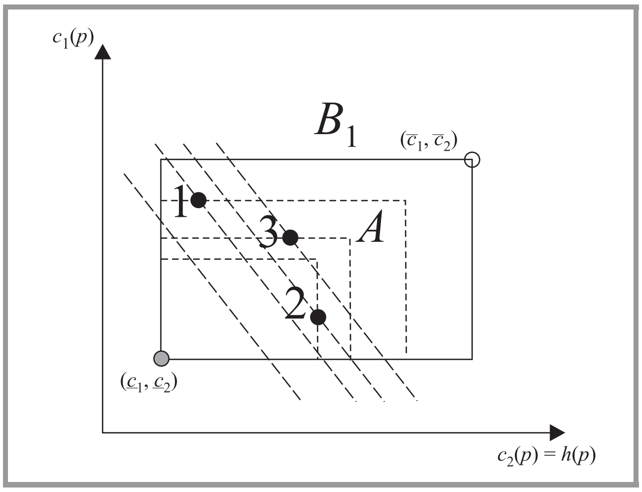

Fig. 2. Choosing the final solution.

In this resolution method, we combine a weighted sum procedure to obtain candidate solutions with a reference-point based method to select a solution in a higher priority region. In this form we sought to make the most of the very great efficiency of the used shortest path ranking procedure, based on the MPS algorithm [22] and of the inherent superiority of the use of a reference point-based procedure, as a solution selection method. Furthermore, note that in the present context, the computational efficiency is a very important aspect taking into account the automated nature of the routing mechanism, which requires a solution in a very short time period. This factor becomes more critical in networks of higher dimension.

The final step of the resolution method is the choice of wavelengths along the arcs of the selected path. This steps follows the procedure described in Subsection 2.2 which is based on the maximization of the wavelength bottleneck bandwidth.

The described resolution method can be applied straightforwardly to the calculation and selection of bidirectional lightpaths, considering the necessary adaptations to the objective functions, specified in Eqs. (8) and (9).

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 net-

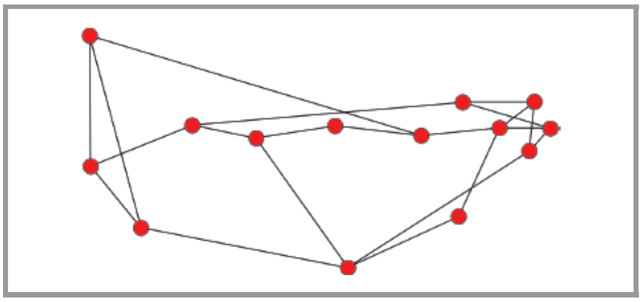

Fig. 3. NSFNET network (14 nodes and 21 links) [24].

works, namely, the NSFNET [24] (see Fig. 3), the Pan-European network COST 266BT [24], [25] (Fig. 4), the denser version of this network [25] – COST 266TT network (see Fig. 5), a typical core network presented in [26] – KL network (Fig. 6), and a typical network provider network presented in [27] – ISP network (Fig. 7). Table 1 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 fibre has 16 wavelengths.

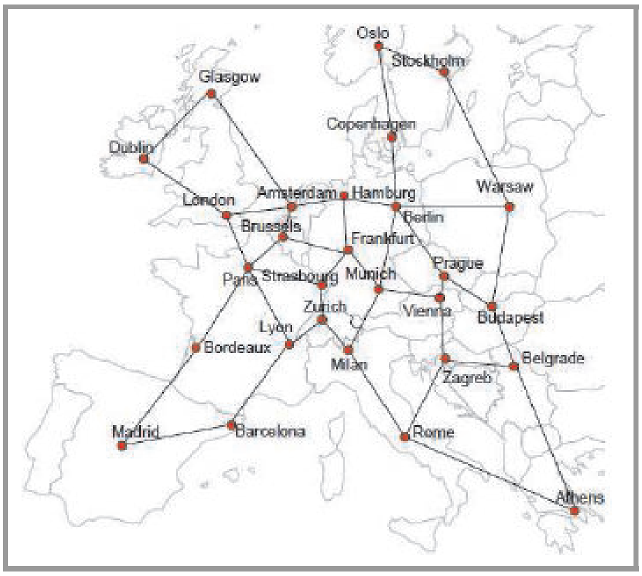

Fig. 4. COST 266BT Pan-European network (28 nodes and 41 links) [24], [25].

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

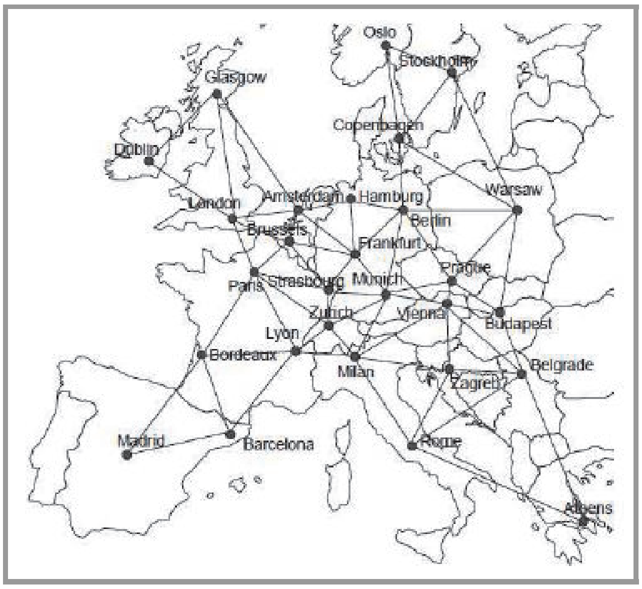

Fig. 5. COST 266TT network (28 nodes and 61 links) [25].

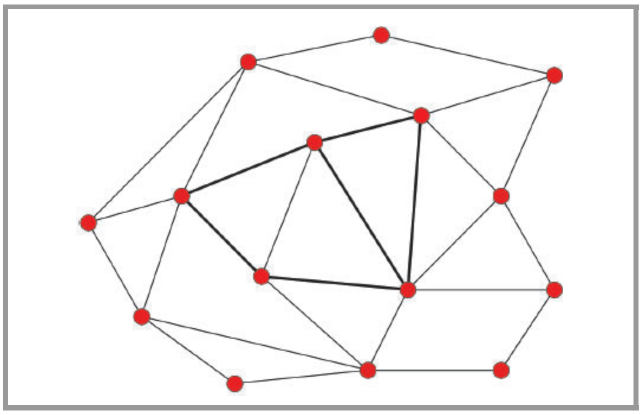

Fig. 6. KL network (15 nodes and 28 links) [26].

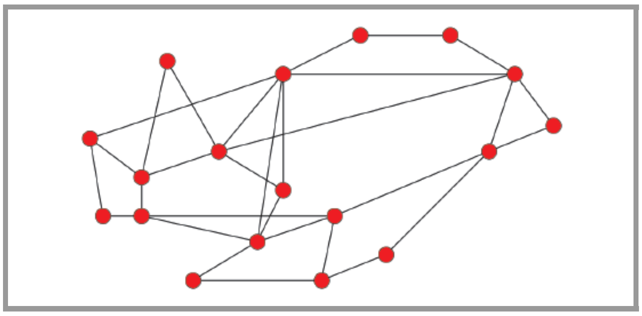

Fig. 7. ISP network (18 nodes and 30 links) [27].

Table 1
Networks characteristics

Network	Number of		Nodal
	nodes	links	degree
NSFNET [24]	14	21	3.00
COST266BT [24, 25]	28	41	2.93
COST266TT [25]	28	61	4.36
KL [26]	15	28	3.73
ISP [27]	18	30	3.33

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).

Simulation results showed that the performance of the networks where five nodes have total conversion capability is nearly the same as for the networks without conversion. Therefore, from now on, we only present the "no conversion" scenario. Discussion and conclusions remain true for the second scenario.

For performance assessment purposes, results obtained using the bicriteria (BiC) model 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.

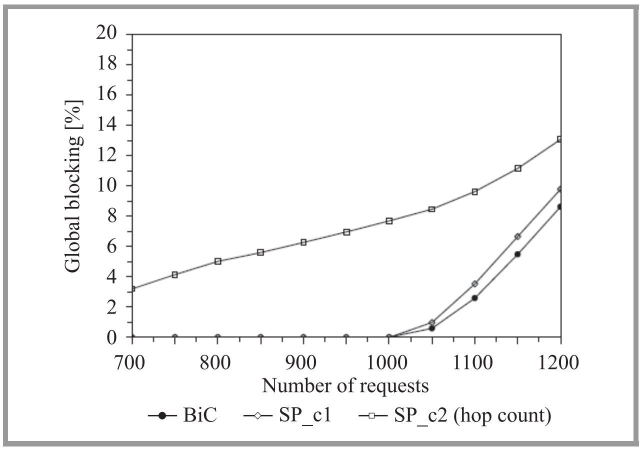

Fig. 8. Global blocking – NSFNET network.

Figure 8 shows the global blocking probability in the NSFNET network, for 100% bidirectional requests. As we can see, the bicriteria approach 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 Fig. 9, the number of accepted requests is shown together with the used bandwidth (BW). 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 Fig. 10, BiC allows a lower average number of hops per connection. Another interesting conclusion that emerges from the analysis of Fig. 9 is that the BiC, while

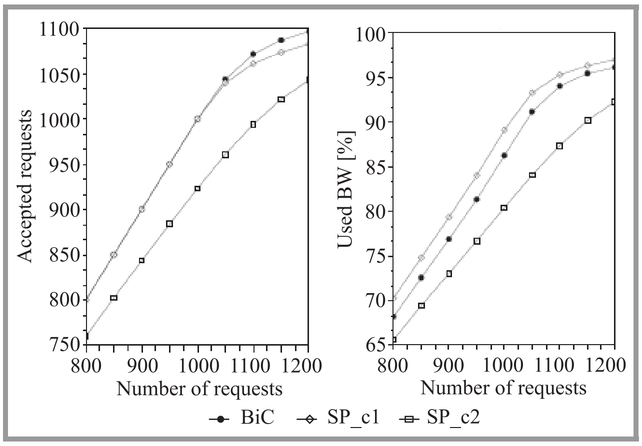

Fig. 9. Accepted requests versus used bandwidth – NSFNET network.

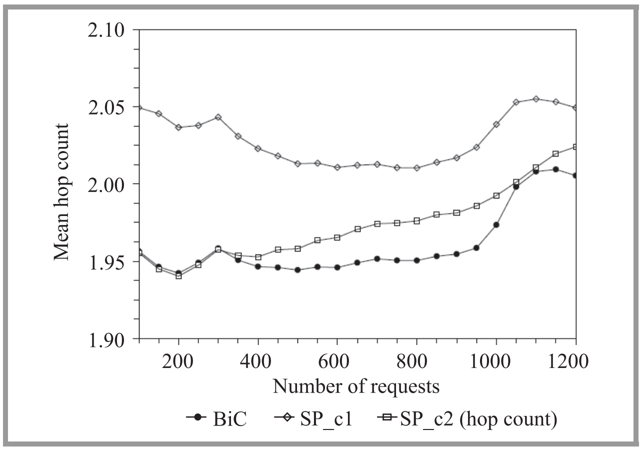

Fig. 10. Mean hop count – NSFNET network.

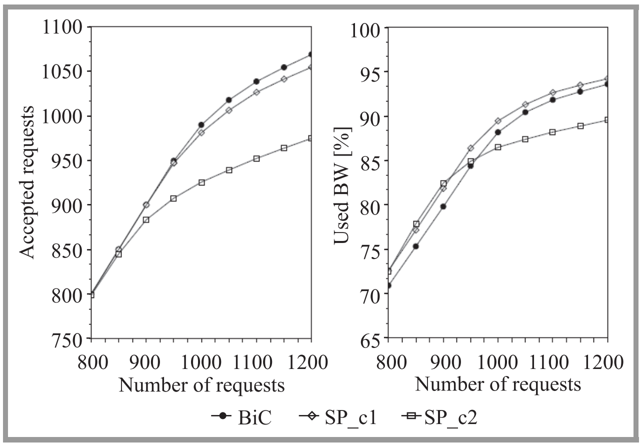

Fig. 11. Accepted requests versus used bandwidth – COST 266BT network.

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.

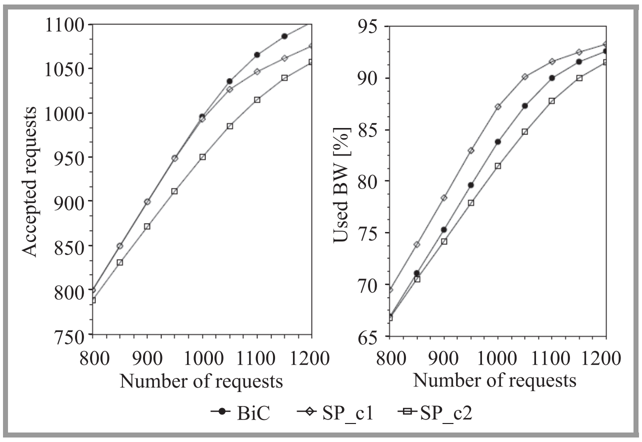

Fig. 12. Accepted requests versus used bandwidth – COST 266TT network.

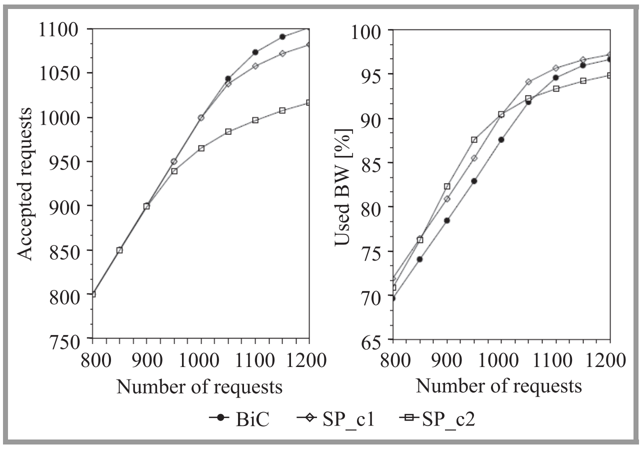

Fig. 13. Accepted requests versus used bandwidth – KL network.

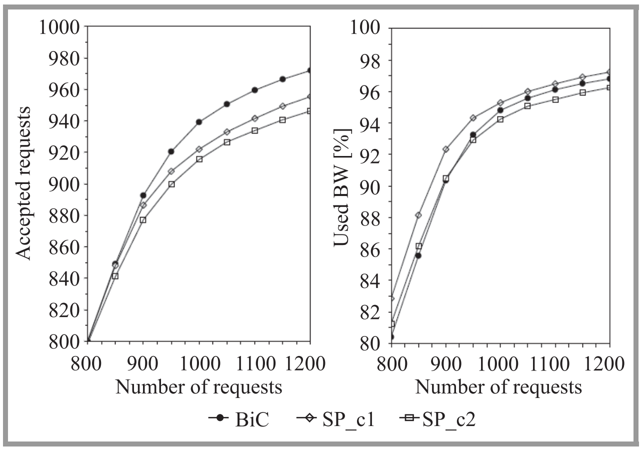

Fig. 14. Accepted requests versus used bandwidth – ISP network.

The results in the other networks exhibit the same behavior. 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 Fig. 11). For moderated traffic loads (until 950 connection requests), BiC even uses less bandwidth

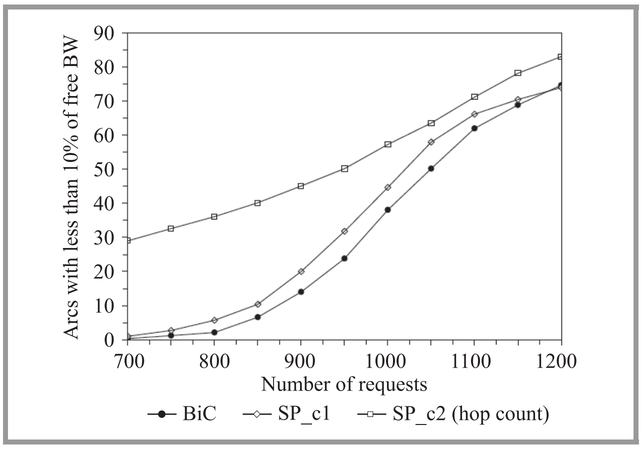

Fig. 15. Arcs with less than 10% of free bandwidth – COST 266TT network

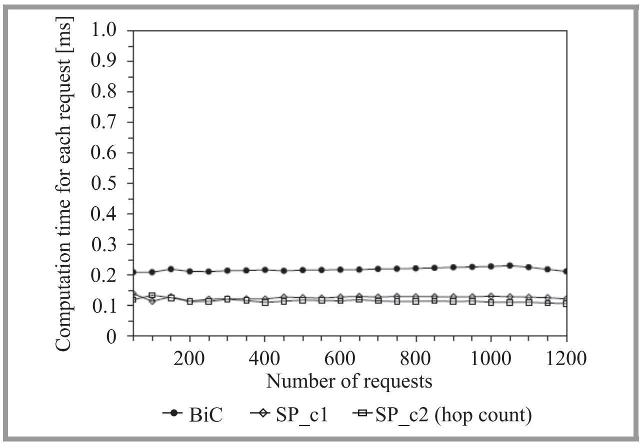

Fig. 18. Computation time for each request – NSFNET network.

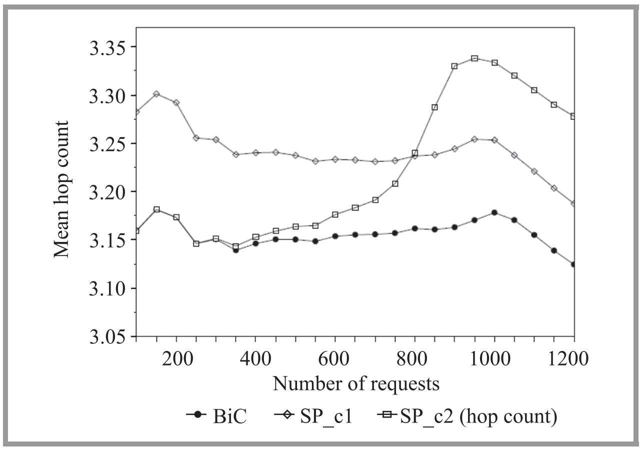

Fig. 16. Mean hop count – COST 266BT network.

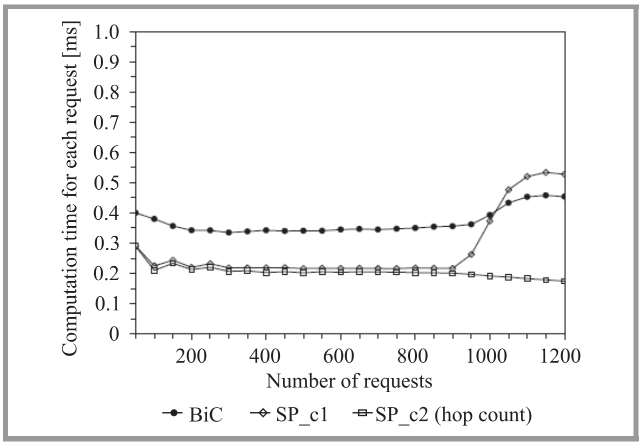

Fig. 19. Computation time for each request – COST 266BT network.

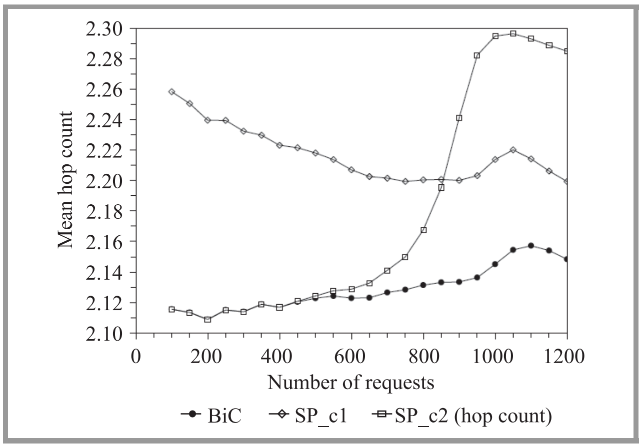

Fig. 17. Mean hop count – KL network.

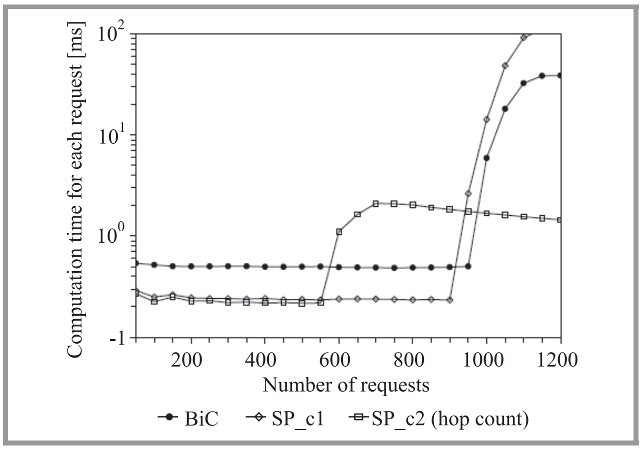

Fig. 20. Computation time for each request – COST 266TT network.

than SP_c2, despite allowing the establishment of many more lightpaths.

In Figs. 12, 13, and 14 the same performance measures are shown for COST 266TT, KL, and ISP networks, respectively. The superior performance of the BiC model is consistent in all tested networks.

It is also interesting to analyze the ability of the different approaches to distribute traffic over the network. Figure 15 plots the number of links in the COST 266TT 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 (although not shown here).

Another interesting network performance measure is the average number of hops per established lightpath. As it can be seen in Figs. 10, 16, and 17 (for NSFNET, COST 266BT and KL 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 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. Above approximately 800 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.

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 18, 19, and 20 show the CPU time per connection request for NSFNET, COST 266BT and COST 266TT networks, respectively. The CPU times remain stable as the traffic load grows in the NSFNET, ISP, KL and COST 266BT networks. In COST 266TT network (see Fig. 20), above 950 connection requests CPU time for BiC and SP_c1 approaches 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.

In order to assess the degree of conflict between the two objective functions used in BiC approach, the number of requests without an optimal solution was calculated. Figures 21 and 22 show the percentage of non-dominated non-optimal solutions in COST 266BT and COST 266TT networks. Although the number of non-dominated solutions is relatively low this does not compromise the interest in using a bicriteria model. In fact many of the ideal solutions of the bicriteria model might possibly have not

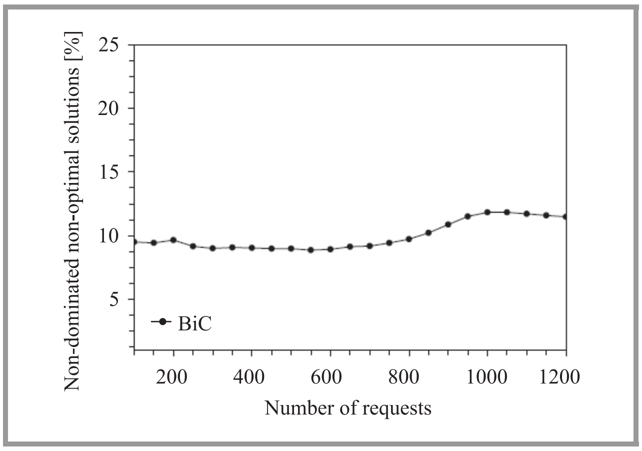

Fig. 21. Non-dominated non-optimal solutions – COST 266BT network.

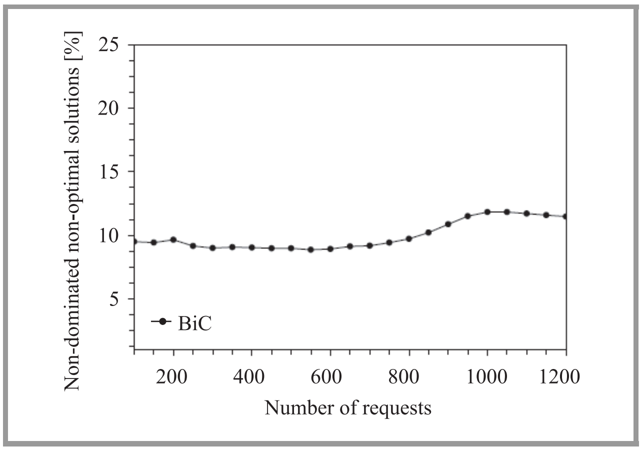

Fig. 22. Non-dominated non-optimal solutions – COST 266TT network.

been found by the single objective models because they correspond to alternative optimal solutions in one of the objective functions.

4. Conclusions

The routing and wavelength assignment problem in WDM networks, as seen from a full traffic engineering perspective, involves multiple metrics, to be optimized, and specific constraints. Therefore multicriteria approaches like the one described in this paper enable to explicitly represent the various performance objectives and to address, in a consistent manner, the trade offs among the various criteria.

A bicriteria model for obtaining a topological path (unidirectional or symmetric 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's space, combined with a Chebyshev distance to a reference point (which changes with the analyzed 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 bicriteria model was analyzed 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. Clearly, the BiC approach resulted in lower global blocking than the single criterion models 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 266TT).

In a following paper we will address the network performance analysis issues of an extension of the bicriteria model that provides dedicated path protection, in the event of failures. This is an issue of great importance having in mind the great amount of traffic carried in these optical networks. To provide the necessary network resiliency, while preserving the multicriteria nature of the developed model, this extension (see [28]) enables to obtain a topological pair of node disjoint paths for each connection request. The developed performance analysis study will consider the same type of experimentation and performance measures as in this paper and will present interesting conclusions concerning the potentialities (put in evidence in this paper) and limitations of the use of multicriteria approaches in this context.

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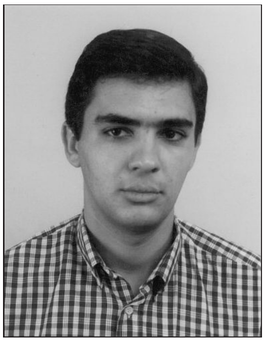
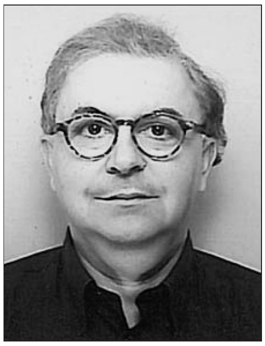


Carlos Simões obtained an undergraduate diploma in electrical engineering science- telecommunications and electronics in 1995 and a M.Sc. degree in systems and automation-telecommunications in 1999, both from the University of Coimbra, Portugal. Since 1998, he has been an Assistant at the Polytechnic Institute of Viseu, Portugal, and a researcher at INESC-Coimbra R&D Institute. He is currently working towards his Ph.D. degree in electrical engineering and informatics at the University of Coimbra and is involved in the research of multicriteria models for routing in optical networks.

e-mail: csimoes@ipv.pt
School of Technology and Management of Viseu
Polytechnic Institute of Viseu
Campus Politecnico de Repeses
P-3504-510 Viseu, Portugal

Institute of Computers and Systems Engineering
of Coimbra (INESC-Coimbra)
Rua Antero de Quental, 199
P-3000-033 Coimbra, Portugal



João Clímaco is Full Professor at the Faculty of Economics of the University of Coimbra and President of the Scientific Committee of the INESC-Coimbra. He obtained the M.Sc. degree in control systems at the Imperial College of Science and Technology, University of London (1978); the "Diploma of Membership of the Imperial College of Science and Technology" (1978); the Ph.D. in optimization and systems theory, Electrical Engineering Department, University of Coimbra (1982) and the title of "Agregação" at the University of Coimbra (1989). He served in the past as the Vice-President of ALIO- Latin Ibero American OR Association and Vice-President of the Portuguese OR Society. He belongs to the editorial board of the following scientific journals: Investigação Operacional (Journal of the Portuguese OR Society), Journal of Group Decision and Negotiation, International Transactions in Operational Research (ITOR), ENGEVISTA and Rio's International Journal on Sciences of Industrial and Systems Engineering and Management. He is also member of the editorial board of the University of Coimbra Press. His current interests of research include multicriteria decision aiding, multiobjective mathematical programming, location analysis and telecommunication network planning and management.

e-mail: jclimaco@inescc.pt
Faculty of Economics University of Coimbra
Av. Dias da Silva 165
P-3004-512 Coimbra, Portugal

Faculty of Economics
Institute of Computers and Systems Engineering
of Coimbra (INESC-Coimbra)
Rua Antero de Quental, 199
P-3000-033 Coimbra, Portugal

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