Paper

Traffic splitting in MPLS networks – a hierarchical multicriteria approach

José M. F. Craveirinha, João C. N. Clímaco, Marta M. B. Pascoal, and Lúcia M. R. A. Martins

Abstract—In this paper we address a new hierarchical multicriteria routing model associated with a two-path traffic splitting routing method in MPLS networks whereby the bandwidth required by a given node-to-node traffic flow is divided by two disjoint paths. The model has two levels of objective functions and several constraints. An algorithmic approach is presented for calculating non-dominated solutions and selecting good compromise solutions to this problem. Also a number of computational experiments are presented.

Keywords— multicriteria optimization, multicriteria shortest paths, routing telecommunication networks, Internet/MPLS.

1. Introduction

Routing problems in modern multiservice communication networks involve the calculation of paths satisfying various technical constraints (usually quality of service (QoS) related constraints) and seeking simultaneously to "optimize" relevant metrics. The multiplicity of QoS metrics and cost functions which may be involved in the models and the potential conflicts among such metrics/functions make that there are potential advantages in developing multicriteria routing models in this area, which depend on the features of the network functionalities and the adopted routing framework. An overview of applications of multicriteria decision analysis (MCDA) tools to important telecommunications network planning and negotiation problems can be seen in [7]. A state of art review on applications of MCDA to telecommunication network planning and design problems, including a section on routing models is in [1], while an overview and a case study on multicriteria routing models in telecommunication networks is presented in [2].

In particular the multiprotocol label switching (MPLS) platform for IP networks enables the implementation of advanced routing schemes, namely explicit routes satisfying QoS requirements, and is prepared for dealing with multipath routing, including traffic splitting. MPLS is a recent multiservice Internet technology based on the forwarding of packets using a specific packet label switching technique. Among other advanced routing mechanisms the utilization of explicit – routes is characterized by the fact the path, designated as label switched path (LSP), followed by each node-to-node packet stream of a certain type, is entirely determined by the ingress router (corresponding to the originating node). This technological platform is prepared to deal with *multi-path routing*, using the concept of *traffic splitting* that consists of the division of the packet stream of each flow, along two or more disjoint paths such that the sum of the bandwidths available in those paths satisfies the bandwidth requirement of each type of flow, depending on the service class.

In this work we address a new hierarchical multicriteria routing model associated with a two-path traffic splitting routing method in MPLS networks whereby the bandwidth required by a given node-to-node traffic flow is divided by two disjoint paths.

In telecommunication routing models the objective functions are concerned with the necessity of minimizing the consumption of (transmission) resources along a path and to obtain a minimum negative impact on all traffic flows that may use the network. The specific models of these cost functions and of the QoS constraints depend on the type of service associated with the connections which are being routed from origin to destination, as it is the case in the MPLS networks.

The proposed model has two levels of objective functions and several constraints. The formulated multicriteria problem involves the calculation of a pair of disjoint paths for a given node-to-node traffic flow such that the sum of the minimal available bandwidths in the paths (usually designated as "bottleneck bandwidths") is not less than the bandwidth required for that traffic flow (two-path traffic splitting constraint); in the considered problem formulation for real-time traffic a constraint on the maximal number of arcs per path also has to be satisfied. The upper-level objective functions are a "load balancing" cost function that is the sum of the load balancing costs associated with the two paths (the load balancing cost being an additive metric, which seeks to achieve an optimal distribution of traffic throughout the network) and the sum of the number of arcs of both paths (which seeks to optimize the number of used resources and favours path reliability). The two lower-level objective functions are the minimal bottleneck bandwidth in both paths and the maximal estimated delays in the two paths.

An algorithmic approach is presented for calculating non-dominated solutions and selecting good compromise solutions to this problem, taking into account the two optimization levels. The resolution approach begins with the calculation of non-dominated solutions with respect to the first level objective functions by using a new algorithm [4] and includes the definition of preference thresholds for these functions in order to establish a flexible preference system in the first level. The second level objective functions are then just used to obtain bounds for "filtering" a certain number of the most preferred non-dominated solutions of the first level. Also a number of computational experiments were performed with an application model focusing on a video traffic routing application, to show the effectiveness of the proposed algorithm. The application platform used the "GT-ITM Georgia Tech Internetwork Topology Models" software[1] which enabled to generate and analyse a significant variety of randomly generated Internet network topologies, following certain probabilistic laws.

This paper is organized as follows. In Section 2 we describe in detail the proposed multicriteria routing model for two-path traffic splitting and the corresponding mathematical formulation. Section 3 presents the developed resolution approach, including a brief description of the algorithm developed for finding non-dominated pairs of disjoint loopless paths as well as the preference system model. The application model for traffic routing in randomly generated Internet topologies and some computational results are shown in Section 4. Finally in Section 5 we put forward some conclusions and outline future work on this model.

2. Hierarchical multicriteria routing model with traffic splitting

This is an area where there are potential advantages in introducing multicriteria routing approaches, taking into account the network major functional features and the nature of the multiple QoS metrics. Here we will begin by describing the nature and aim of the specific objective functions involved in this new hierarchical multicriteria routing model for MPLS networks with a two-path traffic splitting mechanism.

The first objective function considered in the first optimization level is a "load balancing" cost function that is the sum of the cost associated with the two paths, where the load balancing cost of an arc is a piecewise linear function of the bandwidth used in the arc. This is a function which has been used in previous multicriteria routing models, namely in [8] and in the tricriteria model for MPLS networks in [6].

The minimization of this function aims at minimizing the negative impact on the remaining network flows resulting from the utilization of a given path by the considered node-to-node flow. This function is formalized as follows, for any pair of disjoint simple paths, q and q':

$$\Phi^*(q,q') = \Phi(q) + \Phi(q'), \qquad \Phi(p) = \sum_{(i,j)\in p} \phi_{ij},$$

where ϕ_{ij} is the load balancing cost associated with arc (i,j), given by

$$\phi_{ij} = \begin{cases} o_{ij}, & 0 \le o_{ij}/R_{ij} \le 0.5 \\ 2o_{ij} - \frac{1}{2}R_{ij}, & 0.5 < o_{ij}/R_{ij} \le 0.6 \\ 5o_{ij} - \frac{23}{10}R_{ij}, & 0.6 < o_{ij}/R_{ij} \le 0.7 \\ 15o_{ij} - \frac{93}{10}R_{ij}, & 0.7 < o_{ij}/R_{ij} \le 0.8 \\ 60o_{ij} - \frac{453}{10}R_{ij}, & 0.8 < o_{ij}/R_{ij} \le 0.9 \\ 300o_{ij} - \frac{2613}{10}R_{ij}, & 0.9 < o_{ij}/R_{ij} \le 1\,, \end{cases}$$

where $o_{ij} = R_{ij} - b_{ij}$ is the bandwidth occupied in arc (i,j), and b_{ij} is the available bandwidth in arc (i,j) with capacity R_{ij}.

As for the second objective function in the first level it is simply the sum of the number of arcs in the two paths:

$$h^*(q,q') = h(q) + h(q'),$$

where $h(p)$ denotes the number of arcs of path p. The aim of this function is to seek the minimization of the resources used by the given traffic flow hence favouring the network traffic carrying capability (specially for high loads) as well as the path reliability (under failure of links or arcs).

The optimization of these two function seeks, in an approximate manner, to minimize the negative impact of the use of the two paths, in the remaining traffic flows in the network. Next we will consider two functions for the second priority level which seek to optimize transmission related QoS parameters for the particular node-to-node flow that is being routed through the two paths. The first of these functions is the minimum of the available bandwidths in the links of the two paths (*bottleneck bandwidths*, b), that should be maximized:

$$b^*(q,q') = \min\{b(q), b(q')\} = \min_{(i,j)\in q,q'}\{b_{ij}\};\; b(q) = \min_{(i,j)\in q}\{b_{ij}\}.$$

This function aims at distributing the load of the flow through paths with the least occupied links.

The second function considered in this level is the maximal average delay experienced along the two paths, to be minimized:

$$d^*(q,q') = \max\{d(q), d(q')\};\;\; d(q) = \sum_{(i,j)\in q} d_{ij},$$

where d_{ij} is the average packet delay on link (i,j). This function seeks the choice of pairs of paths with minimal average packet delay.

[1] Available at http://www.cc.gatech.edu/fac/Ellen.Zegura/graphs.html

Concerning the constraints, the first one corresponds to the *traffic-splitting* requirement using two paths, i.e., the sum of the bottleneck bandwidths in the two disjoint paths cannot be less than the bandwidth required by micro-flows (i.e., end-to-end connections with given QoS requirements) of the considered node-to-node flow, $\Delta_{\text{bandwidth}}$:

$$\text{for any} \quad q, q' \in \mathcal{P}, \quad b(q) + b(q') \geq \Delta_{\text{bandwidth}}. \qquad (1)$$

The second constraint which may be considered in the model is a "jitter" related constraint, which may be transformed, for certain queueing disciplines (namely for weighted fair queueing discipline), into a constraint on the maximal number of arcs per path, Δ_{jitter}:

$$\text{for any} \quad q, q' \in \mathcal{P}, \quad h(q), h(q') \leq \Delta_{\text{jitter}}. \qquad (2)$$

This constraint is important for certain types of QoS traffic flows (i.e., with guaranteed levels of quality of service) as in the case of video traffic considered in the application model and may be eliminated for best effort traffic flows for which there is no such guarantee of QoS.
The considered *hierarchical multicriteria routing problem* can then be formulated, designating by $\mathcal{P}$ the set of feasible paths:

- 1st level
$$\begin{cases} \min\limits_{q,q' \in \mathcal{P}} \Phi^*(q,q') \\ \min\limits_{q,q' \in \mathcal{P}} h^*(q,q'), \end{cases} \qquad (3)$$

- 2nd level
$$\begin{cases} \max\limits_{q,q' \in \mathcal{P}} b^*(q,q') \\ \min\limits_{q,q' \in \mathcal{P}} d^*(q,q'), \end{cases}$$

subject to the constraints (1) and (2).
The addressed hierarchical multicriteria routing problem consists of finding "satisfactory" compromise solutions (q,q'), $q,q' \in \mathcal{P}$, where q and q' are disjoint loopless paths, taking into account the optimization hierarchy.

3. Resolution approach

In general problem (3) does not have an optimal solution (pair of disjoint paths) due to possible conflict between the considered first level functions.
Thus, it will be necessary to consider the set of "non-dominated" solutions, i.e., solutions such that there is no other feasible solution which improves one objective function without worsening the second objective function.
The definition of dominance in terms of two functions c and h (to be minimized) is recalled:

Definition 1: Given solutions a and b, a dominates b ($a_D b$) if and only if $c(a) \leq c(b)$, $h(a) \leq h(b)$ and at least one of the inequalities is strict. Solution b is dominated if and only if there is another solution, say a, such that $a_D b$.
$\mathcal{P}_N$ will denote the set of non-dominated solutions.

The first stage of the developed approach [4] is the creation of a modified network in which a pair of disjoint paths in the original network corresponds to a single path in the new network. This modification of the network is as follows. We will begin by introducing the basic mathematical notation. Let $(\mathcal{N},\mathcal{A})$ be a directed network where $\mathcal{N}$ is the node set and $\mathcal{A}$ denotes the arc (or link) set. A path p from $s \in \mathcal{N}$ to $t \in \mathcal{N}$ is a sequence of the form $p = \langle s = v_0, v_1, \ldots, t = v_{h(p)} \rangle$, where $(v_k, v_{k+1}) \in \mathcal{A}$, for any $k \in \{0, \ldots, h(p)-1\}$; nodes s and t are called the initial and terminal nodes of p, which correspond in our model to ingress and egress MPLS routers; p is a simple (or loopless) path if it has no repeated nodes. $\mathcal{P}_{xy}$ will denote the set of paths from node x to node y and two paths p,q from s to y are node-disjoint iff the only nodes they have in common are x and y.
The steps of the modification of the network topology are then:

- Duplicate the nodes: $\mathcal{N}' = \mathcal{N} \cup \{i' : i \in \mathcal{N}\}$.
- Duplicate the arcs and add a new arc linking t and the new s': $\mathcal{A}' = \mathcal{A} \cup \{(i',j') : (i,j) \in \mathcal{A}\} \cup \{(t,s')\}$.
- Maintain the initial node: s.
- Consider a new terminal node: t'.

Concerning the objective function coefficients $\phi_{i'j'}$ and $h_{i'j'}$ associated with each arc $(i',j') \in \mathcal{A}'$ the new coefficients are:

- $\phi_{i'j'} = \phi_{ij}$, if $(i,j) \in \mathcal{A}$, and $\phi_{t,s'} = 0$,
- $h_{i'j'} = h_{ij} = 1$, if $(i,j) \in \mathcal{A}$, and $h_{t,s'} = 0$.

Each simple path p from s to t' in $(\mathcal{N}',\mathcal{A}')$ corresponds to a pair of paths from s to t in $(\mathcal{N},\mathcal{A})$, i.e., there exist $q \in \mathcal{P}_{st}$ and $q' \in \mathcal{P}'_{s't'}$, such that

$$p = q \diamond (t,s') \diamond q'.$$

Thus, if $q \cap q' = \emptyset$, then q,q' correspond to a pair of disjoint simple paths in $(\mathcal{N},\mathcal{A})$.
Figure 1 illustrates, in a simplified manner, the construction of the modified network.

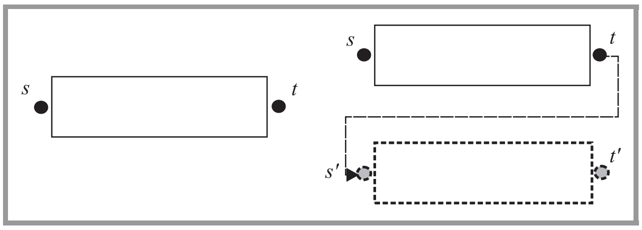

Fig. 1. Original and correspondent augmented networks.

It is also assumed that a transmission capacity $R_{ij} \in \mathbb{R}^+$ (usually expressed in bit/s) and the available bandwidth, b_{ij}, are assigned to each link (i,j).

The first stage of the approach is the resolution of the first level bicriterion problem by calculating the non-dominated solutions set by an adaptation of the algorithm in [3] based on a simple path ranking method by [9].

The resolution is based on the ranking of simple feasible (with respect to constraints (1) and (2)) paths by non-decreasing order of Φ^* in the modified network $(\mathcal{N}',\mathcal{A}')$, until the value of this function is greater than a certain value $\hat{\phi}$. Firstly this value $\hat{\phi}$ (which works as stopping criterion of the algorithm) is obtained by minimising h^*, i.e., it is the value Φ^* when h^* is optimal; if there are alternative optimal solutions to h^*, $\hat{\phi}$ is the least possible value of Φ^* among those solutions. A dominance test is then used to select the non-dominated paths of the augmented network that are calculated as explained above. The dominance test based on [3] is now presented.

Let Φ_{ca} and h_{ca} be the objective function values corresponding to the last candidate to non-dominated path in $(\mathcal{N}',\mathcal{A}')$ as expressed above. Note that the first one, in the initialization of the process, is the optimal path with respect to Φ. If there are alternative optimal paths, the one with the least value of h is selected. Let $p_k = q_k \diamond (t,s') \diamond q'_k$ be the path under test in $(\mathcal{N}',\mathcal{A}')$. Noting that $\Phi^*(q_k,q'_k) = \Phi(p_k)$ and $h^*(q_k,q'_k) = h(p_k)$:

1. If $\Phi(p_k) = \Phi_{\text{ca}}$
   - and $h(p_k) < h_{\text{ca}}$, then p_k dominates the candidate path and it is a new candidate to be non-dominated; update h_{ca};
   - and $h(p_k) = h_{\text{ca}}$, then p_k is added to the candidate path set;
   - and $h(p_k) > h_{\text{ca}}$, then p_k is dominated by the previous candidate.
2. If $\Phi(p_k) > \Phi_{\text{ca}}$
   - and $h(p_k) < h_{\text{ca}}$, then the candidate path remains in the non-dominated candidate path set and p_k is added as a new element of this set; update Φ_{ca} and h_{ca};
   - and $h(p_k) > h_{\text{ca}}$, then p_k is dominated by the previous candidate.

In order to define a system of preferences for the non-dominated solutions of the first level, the next stage of the algorithmic approach is the calculation of preference thresholds corresponding to required (aspiration level) and acceptable (reservation level) values for the objective functions Φ^* and h^*. These thresholds are used to define regions in the first level objective function space, with different priority requirements, which enable the ordering of the candidate solutions in $\mathcal{P}'_N$, the set of non-dominated paths in $(\mathcal{N}',\mathcal{A}')$. It is important to note that the consideration of these preference thresholds is a simple and efficient manner of enabling an automated decision process, as required in this multicriteria routing method.

Preference thresholds can be easily calculated in the modified network in the following manner:

- Required (aspiration level) and acceptable (reservation level) values of h, h_{req} and h_{acc}, respectively:

  $$h_{\text{req}} = \text{int}(\overline{m}_p) + 1, \quad h_{\text{acc}} = \text{int}(\overline{m}_p) + \Delta_{\text{arcs}} - 1,$$

  $(\Delta_{\text{arcs}} > 2)$, where $\text{int}(x)$ is the smallest integer greater than or equal to x, and $\overline{m}_p$ is the average value of the feasible shortest path lengths for all node pairs in the modified network.

- Required and acceptable values of Φ, Φ_{req} and Φ_{acc}, respectively:

  $$\Phi_{\text{req}} = (\overline{\Phi}_{\text{min}} + \Phi_m)/2, \quad \Phi_{\text{acc}} = (\overline{\Phi}_{\text{max}} + \Phi_m)/2,$$

  where $\overline{\Phi}_{\text{min}}$, $\overline{\Phi}_{\text{max}}$ are the average minimal and maximal feasible path costs Φ for all node pairs in the modified network, and $\Phi_m = (\overline{\Phi}_{\text{min}} + \overline{\Phi}_{\text{max}})/2$.

Therefore a region with the highest priority (region A as exemplified in Fig. 2) may be defined by the points for which both the required values Φ_{req} and h_{req} are satisfied. Second priority regions (B_1 and B_2 in Fig. 2) may also be defined by the points for which only one of the requested values is satisfied while the reservation level for the other function is not exceeded. Also a region with third priority (C) may be calculated, such that only the reservation levels for both functions are satisfied, while the aspiration levels are exceeded.

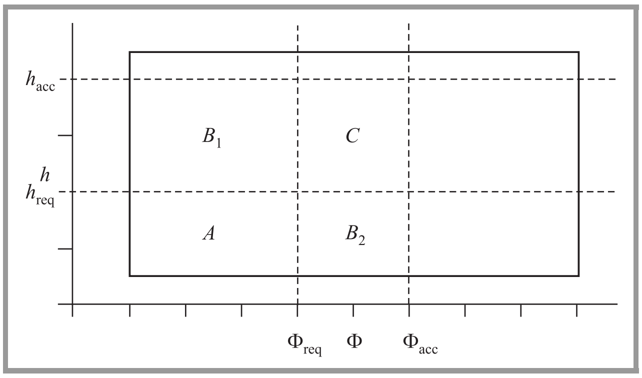

Fig. 2. Priority regions.

The final stage of the resolution approach involves the selection of the non-dominated solutions of the first level, which are filtered according to acceptance bounds defined from the second level objective functions. Therefore these bounds, b_m, a lowerbound on bottleneck bandwidth, and, d_M, an upperbound on delay, work as a filtering mechanism to the non-dominated solutions and are defined as follows.

Let $p = q \diamond (t,s') \diamond q'$, be a path in $(\mathcal{N}',\mathcal{A}')$ (corresponding to a 1st level non-dominated solution). Then:

$$b_m = \min\{b(q^*), b(q'^*)\},$$

where $p^* = \mathrm{argmin}_p\{\max\{d(q), d(q')\} : p = q \diamond (t,s') \diamond q' \in \mathcal{P}'_N\}$, and

$$d_M = \max\{d(q'), d(q'')\},$$

where $p' = \mathrm{argmax}_p\{\min\{b(q), b(q')\} : p = q \diamond (t,s') \diamond q' \in \mathcal{P}'_N\}$.

Finally the solution(s) of the first level with higher priority which satisfy these bounds will be selected as compromise solution(s) to the problem.

Note that it could be considered limitative to analyse exclusively non-dominated solutions of the first level having in mind that there is a second level of criteria evaluation. Also it may be advisable, in some cases, to widen the set of possible compromise solutions to be filtered by the final stage of the resolution approach. So, similarly to the approach in [2] we may consider ε-non-dominated solutions in the first level, the value of ε being tuned according to the specific application environment. Furthermore the consideration of ε-non-dominated solutions, in the upper optimization level enhances the model flexibility. In fact, the widening of the set of solutions under analysis can be accompanied by the tightening of the bounds obtained from the second level or *vice-versa*. Hence the combination of the variation in ε and in the bounds from the second level enables the representation of the relative importance of both levels to be "calibrated", in the solution selection stage. In this manner the flexible nature of our multicriteria model can be reinforced.

4. Application model and computational results

In order to test the hierarchical multicriteria routing model and resolution approach described in the previous sections a C language program implementing such an approach was written and some computational experiments were run for a specific application problem.

The presented model was applied to a video traffic routing problem in a MPLS type network. The network topologies used for that purpose where generated with the "GT-ITM Georgia Tech Internetwork Topology Models" software. This software allows the calculation of randomly generated Internet topologies with different architectures and using various types of laws for defining the probability of occurrence of an edge between any two given nodes, typically as an exponential function of the Euclidian distance between the nodes and some calibrating parameters. These models seek to better reflect the structure of real Internet type networks. Since we wanted to have a control over the average node degree, we used, as the more adequate edge probability distribution, the Doar-Leslie model [5]. This was calibrated, for each given number of nodes, to obtain approximately the desired average node degree. The considered networks had 30, 50, 100, 150, 200 nodes and an average node degree of 4. For each number of nodes 10 network topologies were generated and for each network 20 source-destination node pairs were considered.

In the video traffic routing problem each node is assumed to be modeled as a queueing system using weighted fair queueing (WFQ) service discipline, enabling the bound on jitter to be represented through a constraint on the number of arcs Δ_{jitter}. Each arc (i,j) was assigned with the available bandwidth b_{ij} and the average packet delay d_{ij}. Values $b_{ij} \in \{0.52,\ldots,150.52\}$ (in Mbit/s) were randomly generated according to the empirical statistical distribution:

I_0	I_1	I_2	I_3	I_4
50%	20%	15%	10%	5%

where I_i are intervals with equal amplitude defined by

$$I_i = \{0.52 + 2k : k = 15i,\ldots,15(i+1)-1\},\ i = 0,1,2,3,$$

$$I_4 = \{0.52 + 2k : k = 60,\ldots,75\},$$

and considering a fixed total link capacity of 155.52 Mbit/s. Values d_{ij} were obtained by an empirical model and depend on the Euclidean distance between the nodes i and j, on the bandwidth capacity $R_{ij} = 155.52$ Mbit/s and on parameters associated with the generation rate of a leaky bucket as in [10].

The constraints for these experiments were $\Delta_{\text{bandwidth}} = 1.5$ Mbit/s, $\Delta_{\text{delay}} = 60$ ms, and $\Delta_{\text{jitter}} = m_p(s,t) + \Delta_{\text{arcs}}$, where $m_p(s,t)$ denotes the minimal number of arcs of a feasible path from s to t in $(\mathcal{N},\mathcal{A})$ and $\Delta_{\text{arcs}} = 6$.

The computational tests performed on the instances generated under the above specifications ran on a core 2 at 1.66 GHz, with 1 MB of cache and 1 Gbit of RAM, running over SUSE Linux 10.2. Figure 3 depicts the solutions found for two problems in 100 node networks and one problem for a 200 node network, respectively. The bullets correspond to the non-dominated solutions of the 1st level set accepted after the 2nd bounds level have been applied, while the points marked with "×" correspond to non-dominated solutions which did not satisfy the bounds of the 2nd level.

Tables 1, 2 and 3 show the function values associated with the solutions, as well as the required and acceptable values for the 1st level objective functions (also represented in the pictures), and the bounds d_M and b_m obtained from the 2nd level and used for filtering the 1st level solutions. Here the best bandwidth and delay values are marked in italic, and the value of the other function, that defines one of the bounds, is shown in bold.

In the first example of the 100 node network (Fig. 3a) all the solutions found at the 1st level, (1), (2) and (3), are accepted through the bounds of the 2nd level. Therefore solution (2) in the higher priority region is selected.

In the example of Table 2 and Fig. 3b (in a network with $n = 100$) only solution (1) was accepted while (2) was

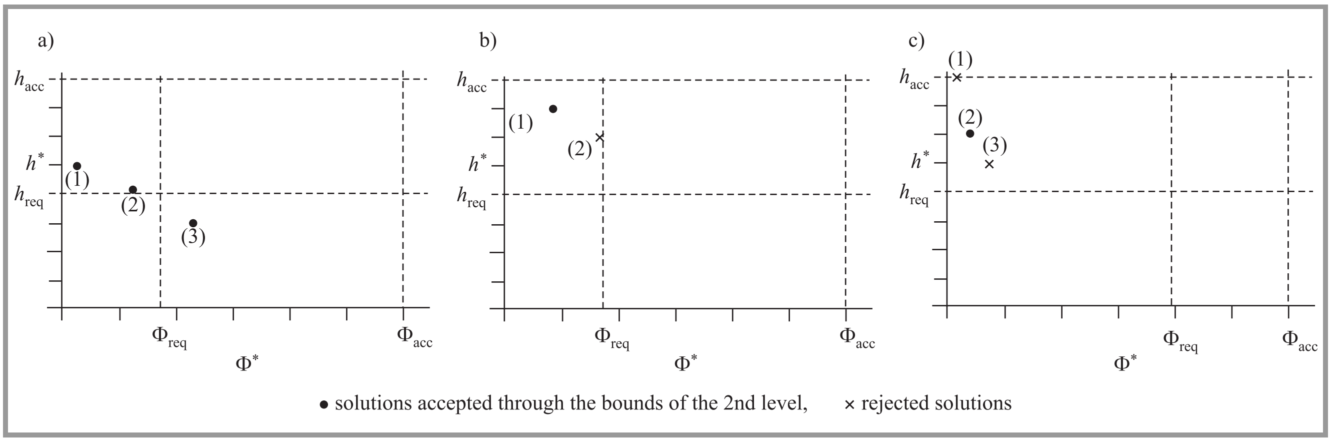

Fig. 3. First level solution for: (a) first and (b) second source-destination pair of 100 node network; (c) of 200 node network.

Table 1
Solutions for the first source-destination pair of nodes ($n = 100$), case Fig. 3a

• 1st level solutions (in the augmented network)

Sol.	Φ^*	h^*	b^*	d^*
(1)	567.24005	5	*72.52*	**6.42697**
(2)	760.20813	4	44.52	4.87697
(3)	940.87207	3	**40.52**	*3.59157*

	h^*	Φ^*
Req.	4	894.10822
Acc.	8	1622.09253

• Solutions accepted through bounds d_M and b_m (in the original network)

Sol.	Path	Φ	h	b	d
(1)	1	267.00003	3	80.52	4.82696
	2	300.24005	2	72.52	6.42697
(2)	1	471.96802	2	44.52	3.09157
	2	288.24005	2	70.52	4.87697
(3)	1	468.90405	2	40.52	3.59157
	2	471.96802	1	44.52	3.09157

	d_M	b_m
Bounds	6.42697	40.52

Table 2
Solutions for the second source-destination pair of nodes ($n = 100$), case Fig. 3b

• 1st level solutions (in the augmented network)

Sol.	Φ^*	h^*	b^*	d^*
(1)	685.24005	7	**62.52**	**6.26236**
(2)	833.14404	6	44.52	6.26236

	h^*	Φ^*
Req.	4	894.10822
Acc.	8	1622.09253

• Solution accepted through bounds d_M and b_m (in the original network)

Sol.	Path	Φ	h	b	d
(1)	1	364.00006	3	82.52	5.96236
	2	321.24002	4	62.52	6.26236

	d_M	b_m
Bounds	6.26236	62.52

Table 3
Solutions for a source-destination pair of nodes ($n = 200$), case Fig. 3c

• 1st level solutions (in the augmented network)

Sol.	Φ^*	h^*	b^*	d^*
(1)	749.72009	9	62.52	7.63314
(2)	787.72003	7	**62.52**	**5.96236**
(3)	861.50409	6	60.52	6.16236

	h^*	Φ^*
Req.	5	1487.28198
Acc.	9	2029.37366

• Solution accepted through bounds d_M and b_m (in the original network)

Sol.	Path	Φ	h	b	d
(2)	1	401.24005	4	62.52	5.96236
	2	386.48007	3	64.52	5.46236

	d_M	b_m
Bounds	5.96236	62.52

rejected. Note that in this case both solutions have the same d^* and we have chosen as bound b_m the most demanding value of b^* (62.52). In the example of Table 3 out of the 3 solutions only solution (2) was accepted through the bounds obtained in the 2nd level, since we have considered (analogously to the previous example) the most demanding value of d^* as bound, for the two solutions (1) and (2) with equal maximal b^*.
Finally, note that when solutions with the same value of one of the metrics appear in the list of selected paths, if required, they can be reordered according to the metric which distinguishes those solutions.

5. Conclusions

A new hierarchical multicriteria routing model associated with a two-path traffic splitting routing method in MPLS networks whereby the bandwidth required by a given node-to-node traffic flow is divided by two disjoint paths, was presented. An algorithmic approach for calculating non-dominated solutions (or ε non-dominated) in the first level and selecting good compromise solutions to this problem, taking into account the objective functions of the second level, was proposed. The resolution approach begins with the calculation of non-dominated solutions with respect to the first level objective functions by using a new algorithm [4] and includes the definition of preference thresholds for these functions in order to establish a flexible preference system in the first level. The second level objective functions are then just used to obtain bounds for "filtering" a certain number of the most preferred non-dominated solutions of the first level. This approach seems highly adequate to an automated decision process, as required by a communication network routing system, having in mind its efficiency and flexibility.
Some computational experiments with an application model focusing on a video-traffic routing problem in randomly generated Internet type topologies were presented, to show the effectiveness of the proposed approach. The calculation of ε non-dominated solutions in the first level combined with variable "filtering" bounds defined in the second level, can be used in the context of the developed procedure in order to increase the flexibility of the approach.

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José Manuel Fernandes Craveirinha is full Professor in telecommunications at the Department of Electrical Engineering and Computers of the Faculty of Sciences and Technology of the University of Coimbra, Portugal, since 97. He obtained the following degrees: undergraduate diploma in electrical engineering science (E.E.S.) – telecommunications and electronics at IST, Lisbon Technical University (1975); M.Sc. (1981) and Ph.D. in E.E.S. at the University of Essex (UK) (1984) and Doct. of Science ("Agregado") in E.E.S. telecommunications at the University of Coimbra (1996). Previous positions were: Associate Professor and Assistant Professor at FCTUC, Coimbra Univ., Telecommunication R&D Engineer (at CET-Portugal Telecom). He coordinated a research group in Teletraffic Engineering & Network Planning at INESC-Coimbra R&D Institute since 1986 and was Director of this institute in 1994–99. He is author and co-author of more than 100 scientific and technical publications in teletraffic modeling, reliability analysis, planning and optimization of telecommunication networks. His main present interests are in reliability analysis models and algorithms and multicriteria routing models for optical and multiservice-IP/MPLS networks.

e-mail: jcrav@deec.uc.pt
Departamento de Engenharia Electrotécnica
e Computadores
Polo II da Universidade de Coimbra
Pinhal de Marrocos
3030-290 Coimbra, Portugal

Instituto de Engenharia de Sistemas
e Computadores – Coimbra
Rua Antero de Quental, 199
3000-033 Coimbra, Portugal

João Carlos Namorado Clímaco is full Professor at the Faculty of Economics of the University of Coimbra, Portugal, 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, University of Coimbra (1982); and the title of "Agregado" at the University of Coimbra (1989). He was, in the past, Vice-President of ALIO – Latin Ibero American OR Association, Vice-President of the Portuguese OR Society and Member of the International Executive Committee of the International Society on Multiple Criteria Decision Making. Actually he is Member of the IFIP WG 8.3 on Decision Support Systems. He belongs to the editorial board of the following scientific journals: "Journal of Group Decision and Negotiation" (JGDN), "International Transactions in Operational Research" (ITOR), "Investigação Operacional" (IO) – "Journal of the Portuguese OR Society" – and "ENGEVISTA" (a Brazilian journal). He is author and co-author of 95 papers in scientific journals and 30 papers in specialized books. His current major interests of research are: multiple criteria decision aiding, multi-objective combinatorial problems, and management and planning of telecommunication networks and energy systems.

e-mail: jclimaco@inescc.pt
Instituto de Engenharia de Sistemas
e Computadores – Coimbra
Rua Antero de Quental, 199
3000-033 Coimbra, Portugal

Faculdade de Economia da Universidade de Coimbra
Avenida Dias da Silva, 165
3004-512 Coimbra, Portugal

Marta Margarida Braz Pascoal is an Assistant Professor at the Mathematics Department of the Faculty of Science and Technology of the University of Coimbra, Portugal. She obtained the undergraduate diploma in mathematics – specialization in computer science at the University of Coimbra (1995), the M.Sc. degree in applied mathematics at the University of Coimbra (1998) and the Ph.D. in mathematics – specialization in applied mathematics at the University of Coimbra (2005). Her current major interests of research are: ranking solutions of combinatorial problems and multiobjective combinatorial problems.

e-mail: marta@mat.uc.pt
Instituto de Engenharia de Sistemas
e Computadores – Coimbra
Rua Antero de Quental, 199
3000-033 Coimbra, Portugal

Departamento de Matemática
Polo I da Universidade de Coimbra
Apartado 3008
3001-454 Coimbra, Portugal

Lúcia Martins received the Ph.D. degree in electrical engineering (telecommunications and electronics) from the University of Coimbra, Portugal, in 2004. She worked as development engineer for six years in Portugal Telecom public operator. She is an Assistant Professor at the Department of Electrical Engineering and Computers, University of Coimbra, and a Researcher at INESC Coimbra. Her research areas include multiple objective dynamic routing and quality of service analysis in multiservice telecommunications networks.

e-mail: lucia@deec.uc.pt
Departamento de Engenharia Electrotécnica
e Computadores
Polo II da Universidade de Coimbra
Pinhal de Marrocos
3030-290 Coimbra, Portugal

Instituto de Engenharia de Sistemas
e Computadores – Coimbra
Rua Antero de Quental, 199
3000-033 Coimbra, Portugal