Network Performance Improvement Through Evaluation of Bicriteria Routing Methods in Transport Networks

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***Abstract*—Bandwidth allocation and management is of paramount importance for telcos mainly in packet transport networks where bandwidth needs an even more tricky control than in the previous circuit-based SDH networks. In these new transport networks, as is the case of MPLS-TP or Carrier Ethernet networks, it is very important to balance the traffic load distribution in order to avoid localized overloads when some parts of the networks still have available bandwidth. The load balance in the network can improve the fulfillment of the service level agreements and the network performance, namely with respect to the amount of carried traffic. In point-to-point (p2p) virtual connections it is well known that the shortest paths obtained through the hop count metric can lead to an inefficient load distribution. In order to better distribute the traffic over the network other metrics that can be used in shortest paths algorithms have been proposed in the literature. In this paper we present a bicriteria approach in which the first objective has the purpose of better distribute the traffic in the network and the second objective function intends to minimize the amount of network resources involved in each virtual connection. This is a general approach that can be applied to different kind of virtual connections such as point to multipoint (p2m) or multipoint to multipoint (m2m). This paper is focused on the algorithms and the methods involved in the calculation and path selection for p2p connections and also presents a network performance study of the addressed methods, considering realistic transport networks.**

I. Introduction and Motivation

In transport networks the bandwidth can be determined through proper network design models. These models are associated with different optimization problems such as finding an optimal topology for the network depending on a given offered traffic estimative or finding the minimal bandwidth for each link in a network with a given topology and for a given offered traffic estimative in order to achieve a certain network performance level [1].

In transport network design there are also technological problems related, for instance, to the choice of the technology that better fits the kind of traffic that will be transported [2]. In this case and considering the increasing volumes of packet traffic two technologies were proposed in the last few years: Carrier Ethernet and MPLS–TP (Multiprotocol Label Switching–Transport Profile). Both technologies use the bandwidth profile proposed by MEF (Metro Ethernet Forum) [3], [4]. The bandwidth specification for each service, for each Class of Service (CoS) or for each User Network Interface (UNI) considered in [4] is no longer a fixed amount of bandwidth, as it was in the case of the previous SDH (Synchronous Digital Hierarchy) circuit-based transport networks. In Carrier Ethernet or MPLS-TP networks each service, which can be point-to-point, rooted-multipoint or a multipoint-to-multipoint virtual connection, is defined together with a Service Level Specification (SLS) which includes the Committed Information Rate (CIR) and the Exceeded Information Rate (EIR), among other parameters [4]. In order to fulfil each SLS the network service providers need to have a fine control over the carried traffic in order to take advantage of the the statistical multiplexing, inherent to the packet traffic, considering that not all network users need the maximal contracted bandwidth at the same time. However it is always possible that a set of users need, at a given moment, an amount of bandwidth which is not available in some parts of the network in spite of the traffic control mechanisms that must be implemented to minimise the network performance degradation and to avoid the decreasing of the Quality of Experience (QoE) perceived by the users in these cases. This type of localized congestion may be minimised through an adequate routing strategy that tries to balance the network load in order to avoid the existence of links with excessive utilization rates whenever there is available bandwidth in some other part of the network.

For a given transport network each virtual connection (VC) with a given bandwidth profile may be created through management mechanisms and it may be active for a relatively long time period, typically from a few months to some years. The network resources involved in each point-to-point (p2p) VC are often found through shortest path algorithms using a metric chosen according to management criteria. Sometimes,

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depending on the importance of each VC and depending on the protection mechanisms already implemented in the transport networks, instead of a single path, a pair of disjoint paths (or maximal disjoint paths) may be calculated for each p2p VC in order that one is to be used as working path and the other as a protection path (which may become the working path in case of a link or node failure).

The computation of the working path in network management systems is often obtained through shortest path algorithms using a single metric, the the hop count being one of the most frequently used. Other metrics such as delay or a load cost [5], this one with the purpose of balancing the network traffic, may be used instead. There are several classical algorithms to compute shortest paths such as the algorithms of Dijkstra, Ford-Fulkerson, or Bellman-Ford [6], [7].

There may be advantages in developing multicriteria models for various routing problems. In fact such models enable to treat in a consistent manner the trade-offs among possible conflicting metrics (to be optimised) which may be relevant in various application contexts.

State of art reviews on multicriteria routing approaches with a discussion of methodological issues were presented in [8], [9].

In multicriteria optimisation a set of objective functions are considered in the problem formulation and if they are conflicting, as it is usually the case, it is not possible to find a global optimal solution which simultaneously optimises all the objective functions, instead a set of non-dominated solutions should be calculated. A non-dominated solution is a solution such that there is no other feasible solution which may improve one objective function without worsening at least one of the other objective functions.

In complex problems where several objectives are involved, in order that the different options may be assessed more clearly, the set or a subset of non-dominated solutions are presented to a decision agent assuming that an interactive decision process is used. In routing problems where potentially conflicting objectives may be present in the problem formulation, usually related to Quality of Service (QoS) requirements, a compromise solution can be chosen from the set of non-dominated solutions by a decision agent through an interactive procedure with the resolution algorithm or in an automated manner.

In this paper a bicriteria shortest path approach will be proposed for choosing p2p VCs in transport networks for which the metrics involved are the hop count and a load cost and considering different methods for selection of a final non-dominated solution. A major focus of this work is on a systematic analysis and proposal of different methods for selecting, in an efficient manner, a non-dominated solution by considering different forms of calculating the weights of the convex combination of the path metrics, will be put forward. Also the main results of an experimental study for comparison of relevant network performance measures, with the different variants of solution selection and the single criterion optimisation solutions for the same metrics, will be presented.

This paper is organised as follows. In section II the formal description of the bicriteria routing model is presented. The algorithm that allows the computation of the set of all non-dominated solutions is presented in section III, as well as a set of variants of that algorithm involving different methods of solution selection. Besides the presentation of the set of non-dominated solutions to the decision agent, a network performance analysis is presented in section IV when a non-dominated solution was chosen automatically. Finally in the last section the conclusions are outlined.

II. Basic Bicriteria Routing Model

In the establishment of a p2p VC a management system needs to compute a 'best' path in the network to which some amount of bandwidth will be allocated. However it is important to note that this path needs to have available, in each link, at least the bandwidth that will be allocated to the VC. The links without that available bandwidth will not be considered in the path computation. If, for instance, the shortest path concerning the number of hops is chosen then the less possible amount of network resources, at the moment the VC is created, should be occupied by the VC. In packet transport networks the bandwidth profile associated with each VC, characterized by a set of parameters in which the CIR and the EIR are the most significant, must be configured throughout the network in each network element included in the VC path. However in shortest path algorithms used by the management systems the bandwidth that will be considered is the effective bandwidth [10] that may vary from link to link in the same VC. The effective bandwidth is a simplified stochastic measure of the network resources utilization which reflects the statistics multiplexing effects of different traffic flows and theirs QoS requirements.

The nature of this bandwidth allocation problem leads to the following formalization of a generic flow oriented bicriteria shortest path problem.

Notation:

- $G = (V, L)$ – directed graph representing the network topology where $V = \{v_1, v_2, \ldots, v_{|V|}\}$ is the node set and $L = \{l_1, l_2, \ldots, l_{|L|}\}$ is the directed arc (or link) set. Each arc $l_k = (v_i, v_j, C_k)$, from node v_i to node v_j, has an associated capacity (or bandwidth) C_k;
- $f_s \equiv (v_i, v_j, \gamma_s) \in F_s$; $v_i, v_j \in V$; $v_i \neq v_j$ - p2p traffic flow of the CoS $s \in S$ (the CoS set) from node v_i to node v_j where γ_s represents a traffic descriptor that includes all characteristics which enable to define completely each connection of each CoS, namely the effective bandwidth d_{ks} occupied by each flow of that CoS in the arc l_k;
- $\mathcal{F}_s$ – set of all traffic flows of the CoS s;
- $r_s \equiv r(f_s)$ – path for the traffic flow $f_s = (v_i, v_j, \gamma_s)$ composed of a sequence of nodes and links from the origin v_i to the destination node v_j with available bandwidth in each arc at least equal to the effective bandwidth d_{ks};

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- $\mathcal{D}(f_s) = \{r(f_s)\}$ – routing domain for the traffic flow f_s, i. e. the set of all loopless paths in G from v_i to v_j with enough available bandwidth for that flow;
- m_k – cost associated with the arc l_k corresponding do and additive metric for which the path cost is:

$$m(r_s) = \sum_{l_k \in r_s} m_k \tag{1}$$

For the bicriteria problem lets consider that m_k^i represents the additive metric i (with $i = 1, 2$) associated with the arc l_k. The biticriteria shortest path problem can be formulated as follows:

(Problem $\mathcal{P}^{(2)}$)

$$\min_{r_s \in \mathcal{D}(f_s)} m^n(r_s) = \sum_{l_k \in r_s} m_k^n \quad n = 1, 2 \tag{2}$$

Note that $m^i(r_s)$ is the value of the criterion related to the objective function i for the path r_s (or the value of the objective function i or simply the value of the metric i for the path r_s) and $\mathcal{D}(f_s)$ is the admissible region (which is supposed to be non empty) in the space of the decision variables r_s. The cost of a path r_s is now a bi-dimensional vector: $\overline{m}(r_s) = (m^1(r_s), m^2(r_s))$. If the objective functions are conflicting there is no solution r_s which minimizes both objective functions simultaneously, instead a set of non-dominated solutions should be calculated.

Definition 2.1: In a bicriteria problem, a path $r'_s \in \mathcal{D}(f_s)$ is non-dominated (also designated as *efficient*, *non inferior* or *Pareto optimal solution*) if and only if $\forall r_s \in \mathcal{D}(f_s)$, $(m^1(r_s), m^2(r_s)) \leq (m^1(r'_s), m^2(r'_s))$ implies that $(m^1(r_s), m^2(r_s)) = (m^1(r'_s), m^2(r'_s))$

The admissible region in the objective functions space is defined by the set:

$$\overline{M}(f_s) = \left\{\overline{m}(r_s) : \overline{m}(r_s) = (m^1(r_s), m^2(r_s)), r_s \in \mathcal{D}(f_s)\right\}$$

$\overline{M}_N(f_s)$ is the subset of $\overline{M}(f_s)$ for which all the paths r_s are non-dominated.

The non-dominated solutions can be found through the minimization of a scalar function which is a convex linear combination of the objective functions involved in the problem formulation (see [11]). A convex linear combination associates with each arc a new cost which is a non negative weighted sum of the original costs.

Therefore the non-dominated solutions of the problem $\mathcal{P}^{(2)}$ can be found by solving the problem $\mathcal{P}'$:

(Problem $\mathcal{P}'$)

$$\min_{r_s \in \mathcal{D}(f_s)} m'(r_s) = \sum_{l_k \in r_s} \mathcal{M}_k \tag{3}$$

where $\mathcal{M}_k = \sum_{n=1}^{2} \epsilon_n m_k^n$ and $\overline{\epsilon} = (\epsilon_1, \epsilon_2) \in \varepsilon = \{\overline{\epsilon} : \epsilon_n \geq 0, n = 1, 2 \wedge \sum_{n=1}^{2} \epsilon_n = 1\}$.

If different weights $\overline{\epsilon} \in \varepsilon$ were used in the minimization function (3) different non-dominated solutions could be obtained for the problem $\mathcal{P}^{(2)}$, however with this approach it is not possible to find the whole set of non-dominated solutions but only the solutions belonging to the boundary of convex hull in the objective functions space. These solutions are designated as supported non-dominated solutions of the bicriteria problem and are represented in the example of figure 1 by the solutions A, B, C and D. The non-dominated solutions belonging to the duality gaps, designated as non-supported solutions, which are dominated by a convex linear combination of two adjacent supported solutions, can not be found through this method. In figure 1 a unsupported non-dominated solution is represented by the point E which is dominated by a convex liner combination of solutions D and B. The point F represents a dominated solution (dominated by solution C), the point O represents an ideal optimal solution which, in general, is not feasible and H represents a dominated solution, outside the space of non-dominated solutions. This space of non-dominated solutions is delimited by solutions A and B which are the extreme supported solutions obtained by separately solving the single criterion minimization problem defined by each objective function (2 and 1, respectively) and which allow the definition of point G (the Nadir point) beyond which there are no more non-dominated solutions.

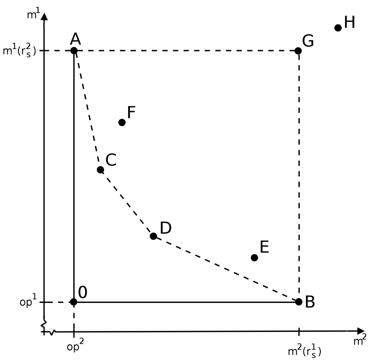

Fig. 1: Dominated and non-dominated solutions in the objective functions space.

The set of all non-dominated solutions, supported and unsupported, can be obtained by recurring to a k–shortest path algorithm [12], [13] such as the MPS [14], which is very efficient in most practical cases.

In this paper two additive metrics are proposed to compute p2p VC path in transport networks: the hop count and the load cost (4) presented in [15], [5]:

$$m_k^1(C_k, b_k) = \begin{cases} \theta_k & , \quad 0 \leq \theta'_k \leq 0.5 \\ 2\theta_k - \frac{1}{2}C_k & , \quad 0.5 < \theta'_k \leq 0.6 \\ 5\theta_k - \frac{23}{10}C_k & , \quad 0.6 < \theta'_k \leq 0.7 \\ 15\theta_k - \frac{93}{10}C_k & , \quad 0.7 < \theta'_k \leq 0.8 \\ 60\theta_k - \frac{453}{10}C_k & , \quad 0.8 < \theta'_k \leq 0.9 \\ 300\theta_k - \frac{2613}{10}C_k & , \quad 0.9 < \theta'_k \leq 1 \end{cases} \tag{4}$$

where $\theta_k = C_k - b_k$ is the occupied bandwidth, b_k is the available bandwidth and θ'_k represents the relative occupation of the arc l_k, $\theta'_k = \frac{\theta_k}{C_k}$.

This load cost is a piece-wise linear convex function which associates a cost with each link depending on the link utilization and penalising the most loaded links. In shortest path algorithms this cost tends to better distribute the traffic over the network, as it leads to the avoidance of higher loaded links.

The hop count, represented in this formulation by $m_k^2 = 1, \forall\ l_k \in A$, is as integer metric which simply counts the number of links included in each path.

The use of both metrics in the computation of each VC path intends to combine the benefits of each one. If the network is lightly loaded the hop count metric used in shortest path algorithms leads to shorter paths and thus to a minimal of network resources involved in each VC. However, for higher loads hop count leads to longer paths because some parts of the network start to become congested while at the same time other parts of the network are less loaded. On the other hand the use of a load cost in shortest path algorithms leads to a better load distribution and so, for a lightly loaded network, leads, in average, to longer paths and because of that to an higher amount of network resources allocated to each VC which, for higher loads, leads to more congestion as there are less available resources. The bicriteria model proposed in this paper intends to find compromise solutions for each VC in order to achieve load balance in the network without too much resources involved.

III. Variants of the Routing Method

The resolution approach based on the use of a k–shortest path algorithm allows the computation of the whole set of non-dominated solutions, supported and unsupported. However this may not be the adequate strategy in terms of computational efficiency for finding a final compromise solution in practical situations of networks where many non-dominated solutions may arise, namely in networks of great dimension and with high connectivity. A more efficient use of this algorithm involves to consider a convex combination of the two original objective functions (3) where the considered weights allow a quicker finding of non-dominated solutions in the desired region of the objective functions space.

Another aspect to be taken into account is the range in which each objective function may vary. If those ranges are very different from each other it is important that the weights be chosen in order to compensate this difference otherwise the solutions would be found by an order which is mainly conditioned by the objective function with lower range. In that case too many (dominated) solutions may be found by the k-shortest path algorithm conditioned by the lower range objective function before other non-dominated solution be obtained.

Next, considering that equal importance is given to each objective function included in the bicriteria problem formulation, different strategies are proposed to compute the weights used in (3) in order that the MPS algorithm can find efficiently a 'best' compromise solutions in the set of non-dominated solutions.

A. Weighting Sets

Let Op^i be the minimum value of the objective function $m^i(r_s)$ and let r_s^i be the path for which Op^i is obtained. Analogously, let Op^j be the minimum of the objective function $m^j(r_s)$ and r_s^j be the path for which Op^j is obtained. Then the range of values of the objective function $m^i(r_s)$ for non-dominated solutions is: $\Delta^i = m^i(r_s^j) - Op^i$. The Op^i values are represented in figure 1 and can be obtained for each objective function with Dijkstra algorithm, for instance.

The first set of weights can be obtained as in classical bicriteria algorithms with the aim of equalising the range of values for each objective function:

$$\begin{cases} \Delta^1 \epsilon_1 = \Delta^2 \epsilon_2 \\ \epsilon_1 + \epsilon_2 = 1 \end{cases} \tag{5}$$

which means that each weight ϵ_i is given by:

$$\epsilon_i = \frac{1}{\Delta^i} \left(\sum_{k=1}^{2} \frac{1}{\Delta^k} \right)^{-1} \tag{6}$$

As it can be seen these weights are calculated each time that a VC needs to be computed. The search direction, in this space, is approximately at 45° in the objective functions space.

The second set of weights is based on the network state. Lets consider the average of each cost for all the links in the network:

$$\overline{m}_k^i = \frac{\sum_{l_k \in L} m_k^i}{|L|} \tag{7}$$

Then, the equalisation of the variation range of both objective functions, instead of being considered for each VC computation through (5), (6), can be done in terms of the global network conditions independently of which VC is going to be computed:

$$\begin{cases} \overline{m}_k^1 \epsilon_1 = \overline{m}_k^2 \epsilon_2 \\ \epsilon_1 + \epsilon_2 = 1 \end{cases} \Leftrightarrow \begin{cases} \epsilon_1 = \frac{\overline{m}_k^2}{\overline{m}_k^1 + \overline{m}_k^2} \\ \epsilon_2 = \frac{\overline{m}_k^1}{\overline{m}_k^1 + \overline{m}_k^2} \end{cases} \Leftrightarrow \begin{cases} \epsilon_1 = \frac{1}{\overline{m}_k^1 + 1} \\ \epsilon_2 = 1 - \epsilon_1 \end{cases} \tag{8}$$

As the second metric is the hop count, $\overline{m}_k^2 = 1$ in equations (8).

It is important to note that the two sets of weights have the purpose of considering with equal importance both objective functions underlying.

B. Choice of a Compromise Solution

In the resolution of the proposed bicriteria shortest path problem all the set of non-dominated solutions may be computed in order that a solution may be chosen by a decision agent. Alternatively a single non-dominated solution may be chosen automatically by the routing management system. For the latter case two methods are going to be considered.

The first method is based on priority regions defined in the non-dominated solution space as in the models described in [16], [17] as represented in figure 2. In this case 'soft constraints', defined as required and acceptable values for each objective function, are used to define the priority regions 1, 2, 3 and 4 in figure 2 where the priority order is defined by the corresponding number. If there are no solutions in the higher priority region 1 the search is stopped whenever a non-dominated solution is found in a given priority region if all

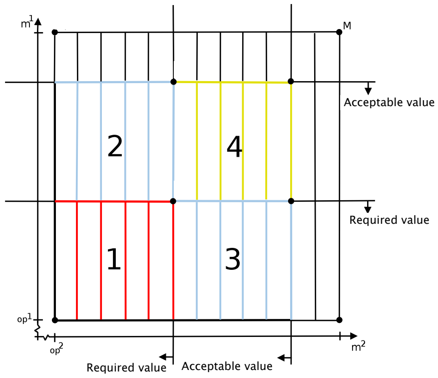

Fig. 2: Priority regions.

the higher priority regions were already completely searched without success.

The required and acceptable values for the two metrics were defined as follows:

$$m^1_{ac} = Op^1 + \frac{2}{3}\Delta^1; \quad m^1_{req} = Op^1 + \frac{1}{3}\Delta^1 \qquad (9)$$
$$m^2_{ac} = Op^2 + \frac{2}{3}\Delta^2; \quad m^2_{req} = Op^2 + \frac{1}{3}\Delta^2$$

Note that in figure 2 the discrete nature of the hop count metric is taken into account.

The second method is based on the use of a reference point, in this case the ideal optimal solution, and the choice of the non-dominated solution is based in the shortest distance to that point. Two weighted distances are going to be considered: the Euclidian distance and the Tchebycheff distance [11]:

$$\|\overline{m}_N(r_s) - \overline{Op}\|^{\epsilon}_p = \left[\sum_{i=1}^{\mathcal{N}} (\epsilon_i |m^i_N(r_s) - Op^i|)^p\right]^{\frac{1}{p}} \qquad (10)$$

where $p \in \{1, 2, ...\} \cup \{\infty\}$. For the Euclidian distance $p = 2$ and for the Tchebycheff distance $p = \infty$ as:

$$\|\overline{m}_N(r_s) - \overline{Op}\|^{\epsilon}_{\infty} = \max\{|m^i_N(r_s) - Op^i|\} \quad i \in \{1, 2\} \qquad (11)$$

Note that $\overline{m}_N(r_s) \in \overline{M}_N(f_s)$, and $\overline{Op} = (Op^1, Op^2)$ is the ideal optimal solution.

IV. Performance Analysis Results

The performance evaluation of the bicriteria approach considering different solution selection methods for choosing p2p VC in transport networks, is presented next. For that purpose a simulation study was carried out for two network topologies, presented in [18]. For each network it was considered that all the links have the same capacities C_k = 10Gbit/s. Three services were also considered for each network with three different effective bandwidths: 20, 50 and 100Mbit/s correspond to the services 1, 2 and 3, respectively. In the simulation study the p2p VC requests are randomly generated concerning origin-destination pairs and service types with a uniform distribution and are maintained indefinitely in the network, which means that the traffic is of incremental type. For each case 100 independent simulations were considered and the average values as well as the confidence interval with 95% confidence degree were registered for each network performance measurement.

The different methods for choosing a non-dominated solution as well as the weighs used in each method are summarized in the table I:

Designation	Selection Method	Weights
B1	Priority regions	$\epsilon_1 = \frac{1}{\overline{m}^1_k+1}$ $\epsilon_2 = 1 - \epsilon_1$
B2	Priority regions	$\epsilon_i = \frac{1}{\Delta^i}\left(\sum_{k=1}^{2} \frac{1}{\Delta^k}\right)^{-1}$
B3	Euclidian dist.	equal to B1
B4	Tchebycheff dist.	equal to B1
B5	Euclidian dist.	equal to B2
B6	Tchebycheff dist.	equal to B2
M7	Single criterion (Load cost)	–
M8	Single criterion (Hop count)	–

TABLE I: Methods for choosing a non-dominated solution.

In the simulation study the effect on the network concerning the use of different ways of choosing a non-dominated solution are evaluated in terms of the following network performance measurements:

- Number of p2p VC requests per service;
- Number of p2p VC established per service;
- Carried bandwidth: $B_{Carr} = \sum_s \sum_{l_k \in r_s} d_{ks}$;
- Available bandwidth: $B_{Aval} = \sum_{l_k \in L} (C_k - B_{Carr})$;
- Average number of links in each p2p VC.

The network performance measurements were registered for different bandwidth blocking percentages (i. e. the ratio between the bandwidth of non accepted VCs and the total offered bandwidth) as it can be seen in the next figures. The bandwidth blocking (see fig. 3) results from the fact that as the networks are progressively loaded some p2p VCs cannot be established as there is no enough available bandwidth in the network. The obtained results were compared with the ones obtained with the single criterion results for each metric, M7 and M8.

In figures 3 and 4 the carried bandwidth and the available bandwidth for the first network (“France” network in [18]), are represented for each method. Note that sub-figures (a) and (b) present the results for the different methods that use the two sets of weights (6) and (7), respectively. The single criterion results were repeated in each sub-figure in order to allow an easier comparison between both sets of results. As it can be seen in these figures the method that leads to more carried bandwidth (and consequently to less available bandwidth, as it can be seen in figure 4) for each blocking value, is the single criterion method M7 which uses the load cost metric. The method that leads lo less carried bandwidth (and to more available bandwidth) is the single criterion method M8 which uses the hop count metric. As expected the bicriteria approach leads in general to intermediate values, although the bicriteria methods that use the same weights as the method B1 lead to almost the same carried bandwidth as the single criterion method M7 and to more available bandwidth than M7. Another

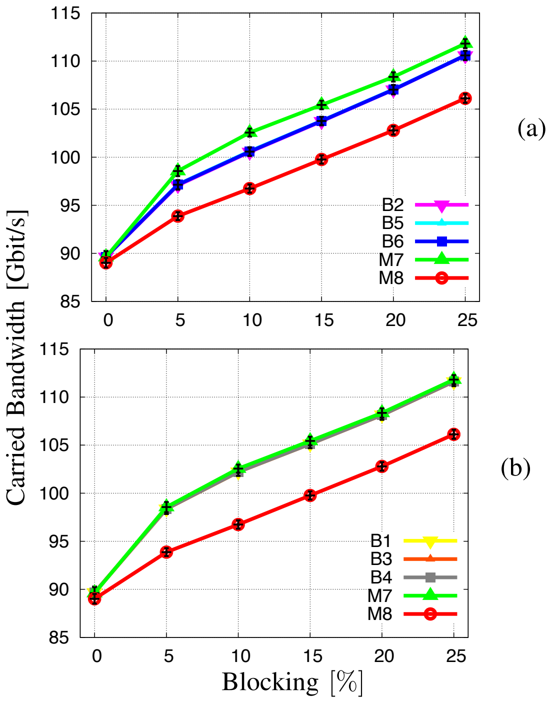

Fig. 3: Carried bandwidth in “France” network.

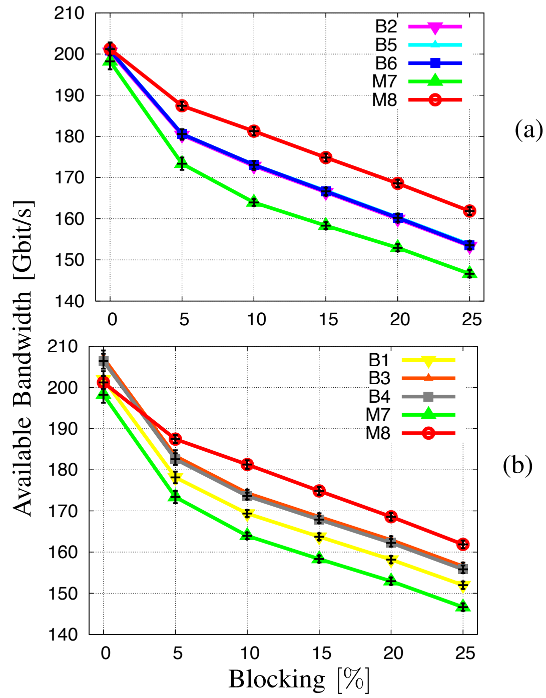

Fig. 4: Available bandwidth in “France” network.

aspect is that the bicriteria methods which use the same set of weights lead approximately to the same carried traffic but not to the same available bandwidth. In fact in figure 4(b) the method B1 leads to less available bandwidth than the other methods that are using the same weights.

In figure 5 the average number of links per path is presented for each method. As it can be seen in this figure all the bicriteria methods lead to lower average number of links values than any single criterion method. This is an important result because it was also achieved for other networks, as showed next. This result is also consistent with the maximal number of links per path obtained by each method, presented in figure 6.

Note that the decreasing in the average number of links per path for all the methods, as the blocking increases is related to the fact that some parts of networks start to be congested for higher blocking values and so, in average, the paths that can be found are smaller. Also note that the weights used in methods B1, B3 e B4 lead to the better values concerning the average and the maximal number of arcs per link.

In figure 7 the number of requests for p2p VCs which were generated and established for each method and for each service for 25% bandwidth blocking are presented. Once more the extreme values were obtained by the single criterion methods, as expected. Also note that the methods B1, B3 and B4 (which use the weights presented in equations (8)) have almost as good results as the ones obtained by the M7 method.

In order to complement the previous results, another set of the most significant results obtained with the network topology

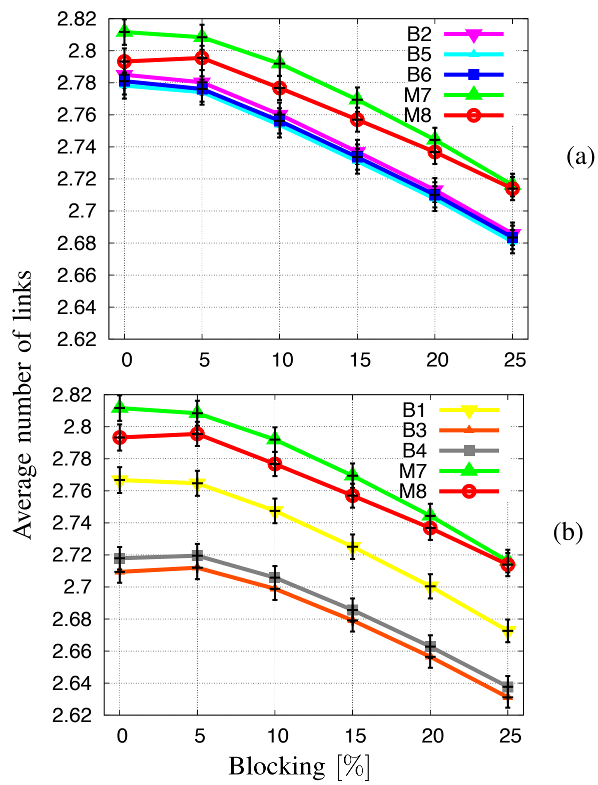

Fig. 5: Average number of links per path in “France” network.

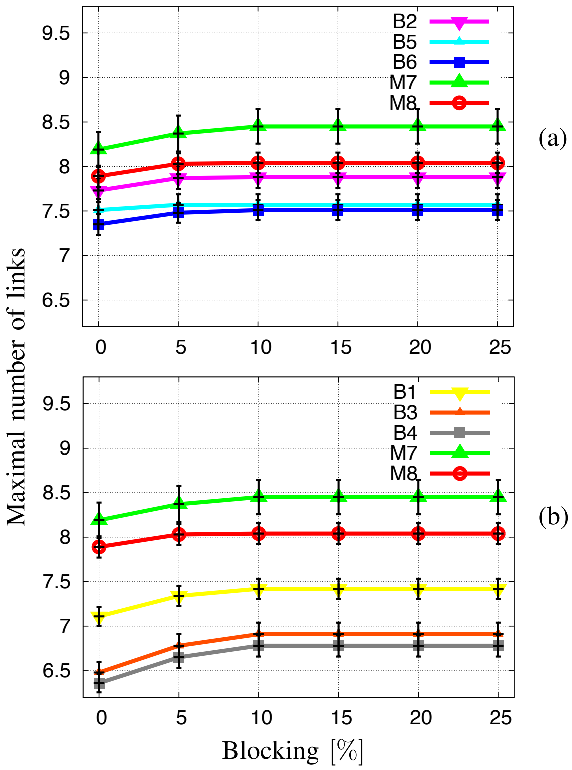

Fig. 6: Maximum number of links per path in "France" network.

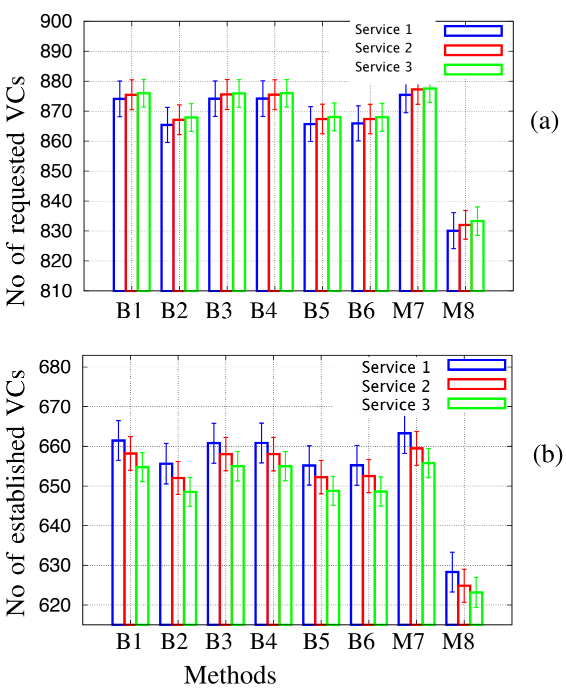

Fig. 7: In (a) and (b) the total number of the requested and established VCs are represented for 25% of bandwidth blocking percentage, respectively.

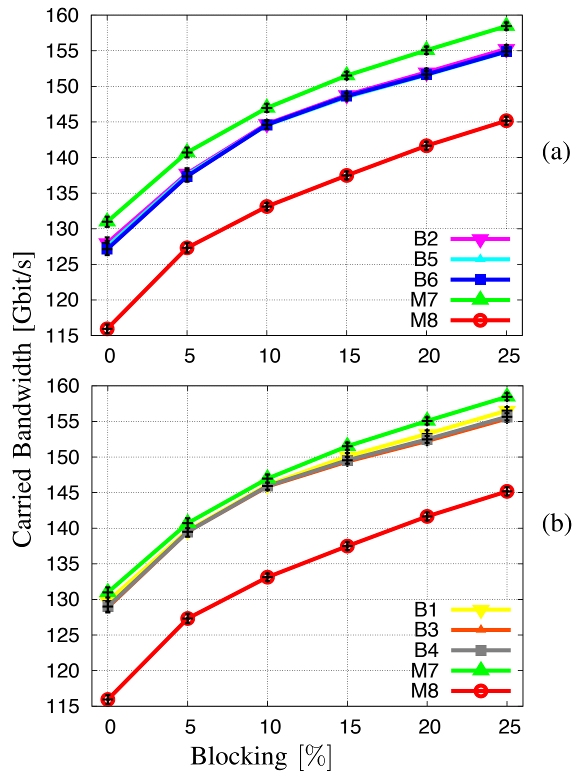

Fig. 8: Carried bandwidth in "Germany" network.

designated in [18] as the "Germany" network, are presented next. In figures 8, 9 and 10 the carried bandwidth, the available bandwidth and the average number of arcs per link obtained by each method for this network are presented. As it can be checked in these figures the results present similar patterns to the ones previously described .

V. Conclusion

In order to balance the network load in transport networks without too many resources, a bicriteria shortest path approach is proposed for choosing p2p VCs in these networks, considering the hop count and a load cost as the metrics involved and different methods for selection of a final non-dominated solution. The systematics analysis and proposal of different methods for selecting in an efficient manner a non-dominated solution by considering different forms of calculating the weights of the convex combination of the path metrics were put forward. Also the main results of an experimental study for comparison of relevant network performance measures, with the different variants of solution selection and the single criterion optimisation solutions for the same metrics, were presented. As shown in the experimental study, this approach leads to compromise solutions that can be chosen automatically by network management systems that allow the improvement of the network resources utilization. However, if the set of non-dominated solutions is presented to a decision agent other compromise solutions can be chosen that better

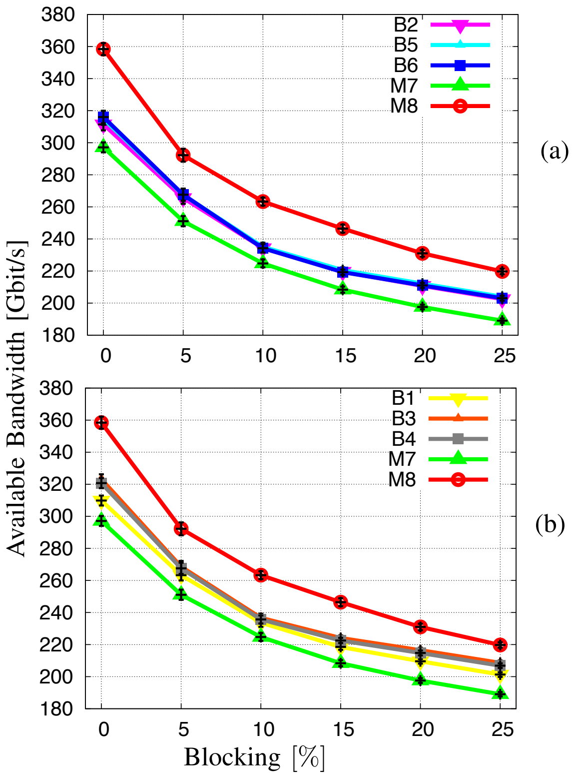

Fig. 9: Available bandwidth in “Germany” network.

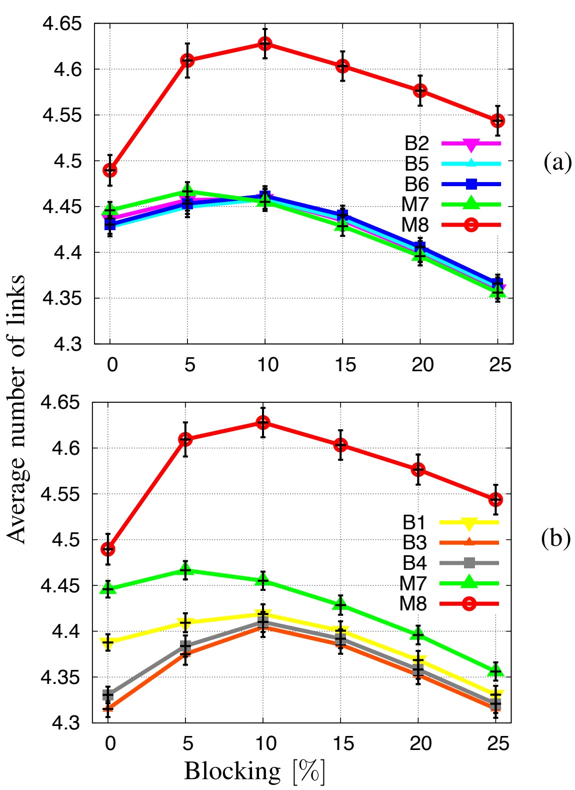

Fig. 10: Average number of links per path in “Germany” network.

fit the network state (for each p2p request) according to the network designer preferences.

The results of this work led to the integration of a bicriteria approach in a real transport network management system of Portugal Telecom.

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