Paper

Implementation and performance of a new multiple objective dynamic routing method for multiexchange networks

Lúcia Martins, José Craveirinha, João N. Clímaco, and Teresa Gomes

Abstract — The paper describes new developments of a multiple objective dynamic routing method (MODR) for circuit-switched networks previously presented, based on the periodic calculation of alternative paths for every node pair by a specialised bi-objective shortest path algorithm (MMRA). A model is presented that enables the numerical calculation of two global network performance parameters, when using MMRA. This model puts in evidence an instability problem in the synchronous path computation model which may lead to solutions with poor global network performance, measured in terms of network mean blocking probability and maximum node-to-node blocking probability. The essential requirements of a heuristic procedure enabling to overcome this problem and select "good" routing solutions in every path updating period, are also discussed.

Keywords — dynamic routing, multiple objective routing, multiexchange telecommunication network performance.

1. Introduction

The evolution of multi-service telecommunications network functionalities has led to the necessity of dealing with multiple, fine grain and heterogeneous grade of service requirements. When applied to routing mechanisms this concern led, among other developments, to a new routing concept designated as QoS routing, which involves the selection of a chain of network resources satisfying certain QoS requirements and seeking simultaneously to optimise route associated metrics (or a sole function of different metrics) such as cost, delay, number of hops or blocking probability. This trend makes it necessary to consider explicitly distinct metrics in routing algorithms such as in references [12, 13] or [11]. In this context the path selection problem was normally formulated as a shortest path problem with a single objective function, either a single metric or encompassing different metrics. QoS requirements were then incorporated into these models by means of additional constraints and the path selection problem (or routing problem in a strict sense) was solved by resorting to different types of heuristics.

Therefore there are potential advantages in modelling the routing problem of this type as a multiple objective problem. Multiple objective routing models enable to grasp the trade-offs among distinct QoS requirements by enabling to represent explicitly, as objective functions, the relevant metrics for each traffic flow and treat in a consistent manner the comparison among different routing alternatives.

On the other hand, the utilisation of dynamic routing in various types of networks is well known to have a quite significant impact on network performance and cost, namely considering time-variant traffic patterns, overload and failure conditions (see for example [6] and [2]).

In a previous paper [5] the authors presented the essential features of a multiple objective dynamic routing method (MODR) of periodic state dependent routing type, based on a multiple objective shortest path model. In its initial formulation for multiexchange circuit-switched networks the model uses implied costs and blocking probabilities as metrics for the path calculation problem. Alternative paths for each node-to-node traffic flow are calculated by a specialised bi-objective shortest path algorithm, designated as modified multiple objective routing algorithm (MMRA), as a function of periodic updates of certain QoS related parameters estimated from real time measurements on the network. In other network environments in terms of underlying technologies and supplied services other QoS metrics can be easily integrated in this type of routing model.

The main objective of this paper is to present new developments of the MODR method, for circuit-switched networks, including a model for network performance evaluation under MODR and the discussion of a path instability problem associated with the MMRA model and of its consequences in terms of global network performance measured by two criteria (network mean blocking probability and maximal node-to-node blocking probability).

The paper begins by reviewing the main features of the MODR method and of the core node-to-node route calculation algorithm MMRA, based on a bi-objective shortest path model. Then it outlines an analytical model the numerical resolution of which gives the global network performance measured in terms of total traffic carried and maximal node-to-node blocking probability, when using MMRA and periodically time varying traffic matrices, for one class of service. This model enabled to put in evidence an instability problem in the synchronous path computation module, expressed by the fact that the paths computed by MMRA for all node pairs in each period tend to oscillate between a few sets of solutions many of which lead to a poor global network performance. Having in mind to explicit this instability/inefficiency which results from the interdependencies between implied costs, blocking probabilities and computed paths and from the discrete nature of the multiple objective shortest path problem, a model (of bi-objective nature) for the global network performance evaluation, was developed. The essential requirements of a heuristic procedure enabling to overcome this problem and select "good" routing solutions in every path updating periods, are discussed. This heuristic will have to be based on an adequate selection of candidate second choice paths for possible change in each updating period. A criterion for selecting such paths will be proposed.

Finally the main conclusions from this paper will be drawn together with the presentation of the lines of undergoing developments of this work.

2. Review of the basic features of the MODR method

The MODR method [5] is based on the formulation of the static routing problem (calculation of the paths for a given pair of nodes assuming fixed cost coefficients in the objective functions) as a bi-objective shortest path problem, including "soft constraints" (that is constraints not directly incorporated into the mathematical formulation) in terms of requested and/or acceptable values for the two metrics. The formulation of the problem for circuit-switched networks uses as metrics, for loss traffic, implied cost (in the sense defined by Kelly [9]) and blocking probability. The implied cost c_k associated with arc $l_k = (v_i, v_j) \in L$ (where $v_i, v_j \in V$, L is the set of arcs of the graph (V, L) defining the network topology and V is the node set where each node represents a switching facility or exchange and each arc or link represents a transmission system) represents the expected number of the increase in calls lost (on all routes of all traffic flows using l_k) as a result of accepting a call of a given traffic flow, on arc l_k. Therefore the bi-objective shortest path problem is:

$$\min\ z^n = \sum_{l_k=(v_i,v_j)\in L} \mathcal{C}_k^n x_{ij} \quad (n = 1,2) \tag{1}$$

s.t.

$$\begin{aligned} &\sum_{v_j\in V} x_{sj} = 1 \\ &\sum_{v_i\in V} x_{ij} - \sum_{v_q\in V} x_{jq} = 0 \quad \forall v_j \in V, (v_j \neq s,t) \\ &\sum_{v_i\in V} x_{it} = 1 \\ &x_{ij} \in \{0,1\}, \quad \forall l_k = (v_i, v_j) \in L \\ &\left(\text{Problem} \quad \mathcal{P}^{(2)}\right), \end{aligned} \tag{2}$$

where

$$\mathcal{C}_k^1 = c_k \quad \text{and} \quad \mathcal{C}_k^2 = -\log(-B_k)\,.$$

B_k being the call congestion on arc l_k and the log being necessary for obtaining an additive metric.

The multiple objective dynamic routing method proposed in [5] is as a new type of periodic state dependent routing method based on a multiple objective routing paradigm. In its general formulation MODR has the following main features: i) paths are changed dynamically as a function of periodic updates of certain QoS related parameters obtained from real-time measurements, using a multiple objective shortest path model which enables to consider, in an explicit manner, eventually conflicting QoS metrics; ii) it uses a very efficient algorithmic approach, designated as modified multiple objective routing algorithm, prepared to deal with the selection of one alternative path for each node pair in a dynamic alternative routing context (briefly reviewed later in this section) by finding adequate solutions of $\left(\mathcal{P}^{(2)}\right)$; iii) the present version of the method uses estimates of implied costs as one of the metrics to be incorporated in the underlying multiple objective model; iv) it enables to specify required and/or requested values for each metric (associated with predefined QoS criteria), values which define priority regions on the objective functions space. This capability is attached to a routing management system (see [5]) and enables to respond to various network service features and to variable working conditions. As for the way in which the paths are selected in the MODR method, the first path is always the direct route whenever it exists. The remaining routes for traffic flows between an exchange pair are selected from the MMRA, taking into account the defined priority regions.

In general there is no feasible solution which minimises both objective functions of $\left(\mathcal{P}^{(2)}\right)$ simultaneously. Since there is no guarantee of the feasibility of this ideal optimal solution, the resolution of this routing problem aims at finding a best compromise path from the set of non-dominated solutions, according to some relevant criteria defined by the decision maker. Non-dominated solutions can be computed by optimising a scalar function which is a convex combination of the bi-objective functions:

$$\min\ z = \sum_{l_k\in L} \mathcal{C}_k x_{ij} \tag{3}$$

with the same constraints of $\mathcal{P}^{(2)}$ and $\mathcal{C}_k = \sum_{n=1}^{2} \varepsilon_n \mathcal{C}_k^n$, where $\varepsilon = (\varepsilon_1, \varepsilon_2) \in \varepsilon = \{\varepsilon : \varepsilon_n \geq 0,\ n = 1,2 \wedge \sum_{n=1}^{2} \varepsilon_n = 1\}$.

However, by using this form of scalarization only supported dominated paths (that is those which are located on the boundary of the convex hull) may be found. Nevertheless non-dominated solutions located in the interior of the convex hull may exist. MMRA resorts to an extremely efficient k-shortest path algorithm [10] to search for this specific type of non-dominated paths.

The basic features of MMRA are the following: i) it enables to search for and select non-dominated or dominated paths for alternative routing purposes; ii) it uses as sub-algorithm for calculating k-shortest paths a new variant of the k-shortest path algorithm in [10], developed in [7] for solving the k-shortest path problem with a constraint on the maximum number of arcs per path since this is a typical constraint considered in practical routing methods; iii) the search direction in the objective function space is a 45° straight line; this is justified by the variable nature of the metrics in an integrated service network environment and the possibility of dynamic variation of the priority regions; iv) the priority regions for alternative path selection have a flexible configuration that varies as a result of periodic alterations in the objective function coefficients.

Concerning the specification of the requested and/or acceptable values for the metrics, distinct cases should be envisaged. In the case of blocking probabilities, delays and delay jitter for example, such values can be obtained from network experimentation and/or from ITU-T standardisation or recommendations for various types of networks and services. On the other hand, in the case of costs, namely implied costs, included in the present model, it is more difficult to define a priori such values, since no general criteria are known for these quantities. In the illustrative example described in [5] the requested and acceptable values for z^1 and z^2, were obtained from calculations for the network dimensioned by the classical heuristic [3] for typical network mean blocking probabilities in nominal and overload conditions. The non-dominated and possible a dominated solution corresponding to an alternative path for a given node pair, are selected by MMRA in the higher priority regions. Further details on MMRA and the architecture of MODR method may be seen in [5].

3. Model of network performance

The MODR model described so far, overlooks a question which will be shown to have significant impact on network performance: the interdependencies between implied costs, blocking probabilities and the paths chosen between every node pair. For understanding this and other related problems a model for global network performance evaluation, is now presented.

Denote by: $A_t(f)$ the traffic offered by flow f from node v_i to node v_j at time period t (in Erlangs); $\mathcal{R}_t(f) = \{r^1(f), r^2(f), ..., r^M(f)\}$ (in the present model $M = 2$) the ordered set of paths (or routes) which may be used by traffic flow f in time t; $\overline{R}_t = \{R_t(f_1), \dots, R_t(f_{|\mathcal{F}|})\}$ ($\mathcal{F}$ is the set of all node to node traffic flows); C_k the capacity of link l_k; $R_k = \{r(f) \in R_t(f_1) \cup \cdots \cup R_t(f_{|\mathcal{F}|}) : l_k \in r(f)\}$ the set of routes which, at a given time , may use arc l_k; $\overline{A}_t$ a matrix of elements $A_t(f)$, $f = (v_i, v_j)$; $\overline{C}$ the vector of link capacities C_k; $\overline{B}$ the vector of link call blocking probabilities B_k; $\overline{c}$ the vector of link implied costs c_k and $L_{r^i(f)}$ the blocking probability of route $r^i(f)$. From the definitions and analytic results in [9] and in the previous paper [5] one may obtain a system of implicit equations in B_k and c_k, of the general form:

$$\left\{\begin{array}{lcl} B_k & = & \beta_k\left(\overline{B}, \overline{C}, \overline{A_t}, R_k\right) \qquad \text{(S1a)} \\ c_k & = & \alpha_k\left(\overline{c}, \overline{B}, \overline{C}, \overline{A}_t, R_k\right) \qquad \text{(S1b)} \\ (k & = & 1, 2, \dots, |L|) \end{array}\right.$$

First important elements of the MODR model are a fixed point iterative scheme enabling the numerical computation of $\overline{B}$ and a similar fixed point iterator to calculate $\overline{c}$ given the network topology (V, L), $\overline{C}$, $\overline{A}_t$ and $\overline{R}_t$ (therefore all R_k are also known), which resolve the systems (S1a) and (S1b) respectively, in this order. The convergence of these numerical procedures designated hereafter as fixed point iterators (or simply, iterators) is guaranteed in most cases of practical interest as a consequence of the results in [8, 9]. Taking into account that the algorithm MMRA calculates $\overline{R}_t$ at every period $t = nT$ $(n = 1, 2, \dots)$, where T is the path updating period, the functional interdependencies between the mathematical entities involved in the MODR may be expressed through:

- $\overline{R}_{t_0} = \overline{R}_0$,
- Recalculate $\overline{c}$, $\overline{B}$ with the iterators for previous $\overline{R}_t$,
- $\overline{R}_t$=MMRA($\overline{c}, \overline{B}$),

where $\overline{R}_0$, the initial route set should be defined from a suitable network dimensioning method, such as in [3], for given nominal traffic matrix $\overline{A}_{t_0}$.

The next point to be addressed is the definition of the global network performance criteria. The first criterion is the maximisation of the total traffic carried in the network A_c:

$$\max_{\overline{R}_t} A_c = \sum_{f \in \mathcal{F}} A_t(f)\big(1 - B(f)\big), \tag{4}$$

where $B(f)$ is the marginal blocking experienced by traffic flow f in the network at time t:

$$B(f) = L_{r^1(f)} L_{r^2(f)}. \tag{5}$$

The maximisation of A_c is equivalent to the minimisation of the network mean blocking probability:

$$B_m = \sum_{f \in \mathcal{F}} \frac{A_t(f) B(f)}{A_t^0}, \tag{6}$$

where $A_t^0 = \sum_{f \in \mathcal{F}} A_t(f)$ is the total traffic offered; note that (4) is the objective of all "classical" single objective routing methods. The second proposed criterion is the minimisation of the maximal marginal call congestion:

$$\min_{\overline{R}_t} B_M = \max_{f \in \mathcal{F}} \{B(f)\}. \tag{7}$$

In many situations in alternative routing networks the minimisation of B_m is associated with a penalty on $B(f)$ for "small" traffic flows $A_t(f)$, leading to an increase in B_M. In conventional single objective routing models this effect is usually limited by imposing upper bounds on $B(f)$. Note that minimising z^1 in $\mathcal{P}^{(2)}$ corresponds to maximising A_c, when searching for a path for flow f only if all the remaining conditions in the network (namely the paths assigned to all other flows and all the link implied costs) were maintained constant, which is not really the case. Similar analysis applies for the minimisation of z^2 in $\mathcal{P}^{(2)}$, concerning the search for the minimisation of B_M. It is therefore important to analyse the effects of the functional interdependencies in terms of global network performance. To illustrate these effects, with respect to z^1 and z^2 separately, and concerning the performance criteria A_c (4) some results are shown in Fig. 1 for a network designated as network B with six nodes, dimensioned according to the method in [3] and described in Appendix. These values in the graphics are the minimum, maximum and average values of A_c obtained for each traffic load factor, by performing $100 \cdot 30$ iterations of minimisation of z^1 (calculation of the shortest path in terms of implied cost) where each iteration corresponds to the calculation of the alternative path for a given node pair. Analogous results are presented in Table 1 for a network designated as network A (given in the Appendix), with the same topology as network B (six node complete graph) but different traffic matrix $\overline{A}_{t_0}$, with link capacities calculated by the same method [3].

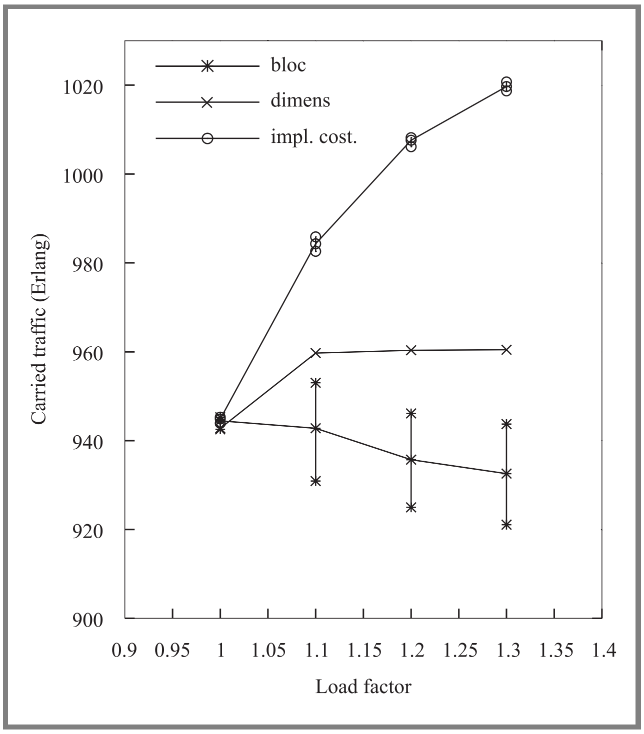

Fig. 1. Oscillations in total carried traffic when z^1 ("impl.cost") and z^2 ("bloc") are minimised separately, for network B.

The following conclusions may be drawn from these results: i) the minimisation of the path implied costs tends to maximise the network carried traffic; ii) there is an instability in the obtained solutions, leading to significant variations in the associated network performance metrics A_c (or B_m) and B_M; iii) the minimisation of the path blocking probabilities leads to relatively small (hence "poor") values of A_c. Analogous conclusions are obtained by calculating paths which minimise z^2 (shortest paths in terms of blocking probability) as illustrated in Table 1, and replacing the network criteria A_c by B_M (maximal node-to-node blocking probability). All these results (similar to those obtained for other networks) are consistent with the assumptions and implications of the model.

Table 1
Variations in B_m and B_M for network A when z^1 ("impl.cost") and z^2 ("bloc") are minimised separately; the $\min B_m$ and $\min B_M$ obtained for the two sets of experiments are indicated in bold

Overload factor [%]	Blocking probability	$\min z^2$ (bloc)		$\min z^1$ (impl.cost.)	
		min B_M	$\min B_m$	$\min B_M$	$\min B_m$
0	B_m	0.00384	**0.00368**	0.00371	0.00369
	B_M	**0.00504**	0.00605	0.00554	0.00613
10	B_m	0.0312	0.0301	0.0306	**0.0297**
	B_M	**0.0372**	0.0442	0.0395	0.0515
20	B_m	0.0946	0.0899	0.0849	**0.0796**
	B_M	**0.109**	0.169	0.140	0.209
30	B_m	0.162	0.149	0.148	**0.128**
	B_M	**0.177**	0.232	0.214	0.258

4. Path instability and network performance

Similarly to the phenomena observed in the previous section for the single objective models based either on implied cost or on blocking probability it could be expected that direct application of MMRA would generate unstable solutions, possibly leading to poor network performance (under the bi-objective approach (A_c, B_M)). In fact direct application of the previous MODR formulation (involving the determination by MMRA of the "best" compromise alternative paths for all origin-destination node pairs as a function of the network state) leads to situations where certain links or paths that were "best" candidates according to the MMRA working, will be in the following path updating period, in a "bad" condition as soon as they are selected as paths of a significant number of O-D pairs. This behaviour leads typically to situations where paths chosen by the routing calculation system may oscillate between a few sets of solutions such that in a certain updating period certain links will be very loaded (i.e. they will contribute to many paths) while others are lightly loaded and in the following period the more loaded and the less loaded links will reverse their condition. This phenomena is a new and specific "bi-objective" case of the known instability problem in single objective adaptive shortest path routing models of particular importance, for example in packet switched networks (see for example [4], Chap. 5). In our case this behaviour (which may imply inefficiency of the solutions $\overline{R}_t$, from the point of view of global network performance) results from the interdependencies between implied costs, blocking probabilities and paths computed by MMRA and from the discrete nature of the bi-objective shortest path problem.To illustrate these questions Table 2 shows the minimal, maximal and average values of B_m and B_M obtained for network B by executing MMRA 100 times for all node pairs, for each traffic matrix overload factor.

Table 2
Oscillations in B_m and B_M given by MMRA for network B

Overload factor [%]	B_m			B_M		
	Minimum	Maximum	Average	Minimum	Maximum	Average
0	0.00430	0.00748	0.00495	0.00852	0.0510	0.0192
10	0.0814	0.105	0.0925	0.176	0.321	0.243
20	0.160	0.183	0.172	0.274	0.469	0.371
30	0.223	0.250	0.238	0.350	0.599	0.452
40	0.280	0.303	0.292	0.416	0.673	0.504
50	0.327	0.349	0.338	0.444	0.690	0.557

The following conclusions may be drawn from the results: i) there is a significant range of variation in the values of B_m and B_M for each overload factor thereby confirming the instability and potential inefficiency of the solutions; ii) the MMRA solutions correspond in most cases to intermediate values in comparison with the values of $\min B_m$ and $\min B_M$ given by the corresponding shortest path models, as should be expected. Nevertheless in one apparently "odd" case the $\min B_m$ in the table was slightly less than the corresponding value obtained through the minimisation of z^1 in the same number of iterations. This situation although rare in the set of the extensive experimentation performed with the models can be explained by the complexity of the aforementioned functional interdependencies (and the discrete nature of the problem – see Section 3) there is no guarantee that by minimising z^1 (or z^2) any finite number of times, the optimal values of B_m (or B_M) might be obtained.

5. Requirements for a heuristic of synchronous route selection

A heuristic procedure will have to be developed for selecting path sets $\overline{R}_t$ $(t = nT; \quad n = 1, 2, \ldots)$ capable of overcoming the described path instability problem and guaranteeing a good compromise solution in terms of the two global network performance criteria (B_m, B_M), at every updating period. The foundation of such procedure will be to search for the subset of the alternative path set

$$\overline{R}^a_{t-T} = \left\{r^2(f), \quad f \in \mathcal{F}\right\} \tag{8}$$

the elements of which should be possibly changed in the next updating period, seeking to minimise B_m while simultaneously not letting that smaller intensity traffic flows be affected by excessive blocking probability $B(f)$. A first possible criterion for choosing candidate paths for "improvement" was suggested by Kelly [9] for use in an adaptive routing environment: $(1 - L_{r^2(f)})s_{r^2(f)}$. This corresponds to choose paths with a lower value of non-blocking probability multiplied by the corresponding path surplus per call, $s_{r^2(f)}$. Extensive experimentation with the model lead us to propose another criterion for this purpose, depending explicitly both on the first choice path $r^1(f)$ (which in MODR is the direct arc from origin to destination whenever it exists) and on the alternative path $r^2(f)$:

$$\xi(f) = F_1 F_2 = \left(2C^1_{r^1(f)} - C^1_{r^2(f)}\right)\left(1 - L_{r^1(f)} L_{r^2(f)}\right), \tag{9}$$

$$C^1_{r^i(f)} = \sum_{l_k \in r^i(f)} c_k \, . \tag{10}$$

The objective expressed by the factor F_1 is to favour (with respect to the need to change the 2nd route) the flows for which the 2nd route has a high implied cost and the 1st route a low implied cost. The factor 2 of $C^1_{r^1(f)}$ was introduced for normalising reasons taking into account that $r^1(f)$ has one arc and $r^2(f)$ two arcs, in the considered fully meshed networks. The second factor F_2 expresses the objective of favouring the flows with worse end-to-end blocking probability. The second point to be addressed in the heuristic procedure will be to specify how many and which of the second choice routes $r^2(f)$ with smaller value of $\xi(f)$ should possibly be changed by applying MMRA once again. In any case, among the recalculated routes only those which lead to lower B_m and/or lower B_M should be finally selected by the procedure as routes to be changed in each path updating period. This requires that the effect of each candidate route, in terms of network performance, be previously estimated.

Another mechanism to be introduced in MODR is a specific service protection scheme, aimed at preventing excessive network blocking degradation in overload situations, associated with the utilisation of alternative routes for all node-to-node traffic flows. This mechanism here designated as alternative path removal (APR) is based on the elimination of the alternative paths of all traffic flows for which the value of the scalar function z (3) of the multiple objective model is greater than or equal to a certain parameter z_{APR}. This parameter will have to be carefully "tunned" for each specific network by performing a previous analytical evaluation of the network performance and represents a practical absolute threshold above which the use of alternative routing is no longer justified.

6. Conclusions and ongoing work

A description has been made of new developments of a multiple objective dynamic routing method of periodic state-dependent type for circuit-switched networks, previously presented, aiming to overcome its limitations in terms of global network performance.

A model was presented the numerical resolution of which gives the global network performance measured in terms of total traffic carried and node-to-node blocking probability, when using MMRA and periodically time varying traffic matrices, for one class of service. This model enabled to put in evidence an instability problem in the synchronous path computation module, expressed by the fact that the paths computed by MMRA for all node pairs in each period tend to oscillate between a few sets of solutions many of which lead to a poor global network performance.

Also the essential requirements of a heuristic procedure aiming to overcome this instability problem and obtain acceptable compromise solutions in terms of the global network performance, were presented. Work is progressing with respect to the specification of a heuristic satisfying these requirements and enabling to obtain "good" solutions in terms of the two global network performance criteria B_m (network mean blocking probability) and B_M (maximal node-to-node blocking probability). The performance of the global routing method incorporating this heuristic (MODR-1) is being tested by comparing (for single channel traffic) the obtained global performance network metrics, in three case study networks, with the corresponding results given by a discrete event simulation model for a reference dynamic routing method, real-time network routing (RTNR) developed by AT&T, known for its efficiency and sophistication in terms of service protection mechanisms. Preliminary experiments with the current version of the heuristic, involving the comparison of the analytical results of MODR-1 with simulation results for RTNR for various test networks suggest that MODR-1 might perform better with respect to network mean blocking probability and/or maximum node-to-node blocking probabilities in a very wide variety of network overload conditions. To confirm these results an extensive simulation study with MODR-1 will be carried out for three test networks. Also some modifications are being introduced in the model of periodic recalculation of the boundary values of the priority regions of MMRA which will change dynamically in order to reflect the current loading conditions in the links.

An important conclusion of this work is that a multiple-objective (and indeed a single objective) dynamic routing method where the coefficients of the objective functions of the core multiple objective algorithm depend on the calculated paths (beyond possible intrinsic interdependencies between cost coefficients) have an inherent instability problem which can significantly degrade the "quality" of the obtained solutions in terms of global network performance. This problem, previously overlooked, is a new and specific, "bi-objective case" of the classical instability problem in single objective adaptive routing models, of particular importance, for example, in the case of packet switched networks. This phenomena results from the interdependencies between the calculated paths and the objective functions coefficients and from the discrete nature of the routing problem. To overcome its effects in MODR it is necessary to develop a suitable procedure of heuristic nature enabling to select a final solution at each updating period, with a "good" quality (in terms of the adopted network performance criteria). We think that similar type of heuristics could be applied to different dynamic routing models with similar instability problems.

Further work is also taking place concerning the extension of MODR-1 formulation to multi-service networks, based on appropriate generalisation of the concept of implied cost and appropriate multiclass traffic models, associated with adequate quality of service (traffic dependent) metrics.

Finally the "tuning" of important parameters of the method, namely the path updating period and service protection mechanism parameters, such as z_{APR} in the aforementioned alternative path removal scheme, will have to be tackled through extensive use of a simulation test-bed.

Appendix

Test networks

Calculation results for networks A and B are presented in Tables 3 and 4, respectively.

Table 3
Network A

O-D pair	Link capac.	Offered traf.	Intermediate node
1-2	36	27	3
1-3	13	6	4
1-4	33	25	5
1-5	27	20	6
1-6	31	20	2
2-3	29	25	4
2-4	17	10	5
2-5	37	30	6
2-6	25	20	1
3-4	17	11	5
3-5	14	8	6
3-6	19	13	1
4-5	13	9	6
4-6	27	20	1
6-6	18	12	1

Table 4
Network B

O-D pair	Link capac.	Offered traf.	Intermediate node
1-2	41	27.47	3
1-3	13	6.97	4
1-4	276	257.81	5
1-5	33	20.47	6
1-6	45	29.11	2
2-3	29	25.11	4
2-4	112	101.61	5
2-5	88	76.78	6
2-6	94	82.56	1
3-4	18	11.92	5
3-5	11	6.86	6
3-6	21	13.25	1
4-5	87	79.42	6
4-6	94	83.0	1
6-6	137	127.11	1

Acknowledgements

We thank Tiago Sá for the implementation of the network design model based on the algorithm [3].
This work was partially supported by FCT, project POSI/SRI/37346/2001, "Models and algorithms for treating uncertainty in decision support systems".

References

[1] C. H. Antunes, J. Craveirinha, J. Climaco, and C. Barrico, "A multiple objective routing algorithm for integrated communication networks" in *ITC-16 Teletraffic Engineering in a Competitive World*, P. Key and D. Smith, Eds., Elsevier Science B.V., 1999, vol. 3b, pp. 1291–1300.

[2] G. R. Ash, *Dynamic Routing in Telecommunications Networks*. McGraw-Hill, 1998.

[3] G. R. Ash, R. H. Cardwell, and R. P. Murray, "Design and optimization of networks with dynamic routing", *Bell Syst. Tech. J.*, vol. 60, no. 8, pp. 1787–1820, 1981.

[4] D. Bertsekas and R. Gallager, *Data Networks*. Prentice-Hall, 1992.

[5] J. Craveirinha, L. Martins, T. Gomes, C. H. Antunes, and J. Clímaco, "A new multiple objective dynamic routing method using implied costs", *J. Telecommun. Inform. Technol.*, no. 3, pp. 50–59, 2003.

[6] A. Girard, *Routing and Dimensioning in Circuit-Switched Networks*. Addison-Wesley, 1990.

[7] T. Gomes, L. Martins, and J. F. Craveirinha, "An efficient algorithm for calculating k shortest paths with a maximum number of arcs", *Invest. Oper.*, vol. 21, pp. 235–244, 2001.

[8] F. P. Kelly, "Blocking probabilities in large circuit-switched networks", *Adv. Appl. Probab.*, vol. 18, pp. 473–505, 1986.

[9] F. P. Kelly, "Routing in circuit-switched networks: optimization, shadow prices and decentralization", *Adv. Appl. Probab.*, vol. 20, pp. 112–144, 1988.

[10] E. Q. V. Martins, M. M. B. Pascoal, and J. L. E. Santos, "Deviation algorithms for ranking shortest paths", *Int. J. Found. Comput. Sci.*, vol. 10, pp. 247–263, 1999.

[11] C. Pornavalai, G. Chakraborty, and N. Shiratori, "Routing with multiple QoS requirements for supporting multimedia applications", *Telecommun. Syst.*, vol. 9, pp. 357–373, 1998.

[12] R. Vogel, R. G. Herrtwich, W. Kalfa, H. Wittig, and L. C. Wolf, "QoS – based routing of multimedia streams in computer networks", *IEEE J. Selec. Areas Commun.*, vol. 14, no. 7, pp. 1235–1244, 1996.

[13] Z. Wang and J. Crowcroft, "Quality-of-service routing for supporting multimedia applications", *IEEE J. Selec. Areas Commun.*, vol. 14, no. 7, pp. 1228–1234, 1996.

Lúcia Martins, **José Craveirinha**, **Teresa Gomes** – for biography, see this issue, p. 58.

João N. Clímaco – for biography, see this issue, p. 59.