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Modelling and Performance Analysis of a New Multiple Objective Dynamic Routing Method for Multiexchange Networks*

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Abstract

The paper describes a new version 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). An analytical model is presented that performs the numerical calculation of the 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. A heuristic procedure is presented to overcome this problem and obtain "good" routing solutions in terms of network performance. A model of dynamic calculation of the boundary values of the priority regions in MMRA is also described. The performance of MODR is compared with results from a discrete event simulation model for a reference dynamic routing method RTNR (Real Time Network Routing), using case-study networks.

Key Words: 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 ap-

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plied 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 GoS 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 [15], [16] or [14]. 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 modeling 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 treating 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 [8] and [4]).

In a previous paper [7] the authors presented the essential features of a multi-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 MMRA (Modified Multi-objective Routing Algorithm), as a function of periodic updates of certain GoS 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 first main objective of this paper is to present a new version of MODR, for circuit switched networks, including new procedures which imply some significant changes in the previous formulation, enabling to overcome its limitations in terms of global network performance. The second main objective is to analyse the performance of case study networks using this version of MODR and two relevant metrics of global network performance.

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 presents an analytical model 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 analytical 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 of the discrete nature of the multi-objective shortest path problem, an analytical model (of bi-objective nature) for the global network problem, was developed. An heuristic procedure is presented aiming to overcome this instability problem and obtain acceptable compromise solutions in terms of the global network performance. Also some changes in the model of periodic recalculation of the boundary values of the priority regions of MMRA will be explained. Finally the performance of the global routing method (MODR-1) was tested by comparing 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, RTNR (Real-Time Network Routing) developed by AT&T, [4] known for its efficiency and sophistication in terms of service protection mechanisms. This will enable to draw some conclusions concerning the potential advantages and difficulties of the model and the future developments of this work.

2 Review of the Basic Features of the MODR Method

The MODR method [7] 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 [11]) and blocking probability. The implied cost c_k associated with arc $l_k = (v_i, v_j) \in L$ (with $v_i, v_j \in V$ and L is the set of arcs of the graph

(V, L) defining the network topology, 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.

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

where

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

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 [7] 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 GoS 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 Multi-objective Routing Algorithm (MMRA), 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 ($\mathcal{P}^{(2)}$); 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) – such values define preference regions on the objective functions space, which may change in a flexible way, through variable boundary values. This capability is attached to a Routing Management System (see [7]) 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 ($\mathcal{P}^{(2)}$) 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 $\mathcal{C}_k = \sum_{n=1}^{2} \epsilon_n \mathcal{C}_k^n$ where $\epsilon = (\epsilon_1, \epsilon_2) \in \varepsilon = \{\epsilon : \epsilon_n \geq 0, n = 1, 2 \wedge \sum_{n=1}^{2} \epsilon_n = 1\}$. 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 [12] 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 [12], developed in [9] 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^{o} straight line, instead of the gradient of the plane passing through the points defined by the intersection of the requested and the optimal values of the objective functions, as in [1]; 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 the periodic alterations in the objective function coefficients; furthermore the bounds of those regions may also be changed through some of the functionalities associated with the Parametrisation Module of the Routing and Management System [7].

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 [7] 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. Such values define priority regions in the objective functions space, as shown in [7]. 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 [7].

3 Analytical 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 paths chosen between every node pair. For understanding this and other related problems we now present an analytical model for the global network performance calculation.

Denote by: $A_t(f)$ the traffic offered by flow f from node v_i to node v_j at time period t; $\mathcal{R}_t(f) = \{r^1(f), r^2(f), ..., r^M(f)\}$ (in the present model $M = 2$) the ordered set of paths (or routes) which may be used by traffic flow f in time t; $\overline{R}_t = \{R_t(f_1), \ldots, R_t(f_{|\mathcal{F}|})\}$ ($\mathcal{F}$ is the set of all node to node traffic flows); C_k the capacity of link l_k; $R_k = \{r(f) \in R_t(f_1) \cup \ldots \cup R_t(f_{|\mathcal{F}|}) : l_k \in r(f)\}$ 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 $r^i(f)$.

According to [11], assuming all traffic flows are Poissonian and statistical independence in the occupations of the links:

$$c_k = \eta_k(1 - B_k)^{-1} \left[\sum_{f:l_k \in r^1(f)} \lambda_{r^1(f)} \left(s_{r^1(f)} + c_k \right) + \sum_{f:l_k \in r^2(f)} \lambda_{r^2(f)} \left(s_{r^2(f)} + c_k \right) \right] \quad (4)$$

$$s_{r^2(f)} = w(f) - \sum_{l_j \in r^2(f)} c_j \quad (5)$$

$$s_{r^1(f)} \quad = \quad w(f) - \sum_{l_j \in r^1(f)} c_j - \left(1 - L_{r^2(f)}\right) s_{r^2(f)} \tag{6}$$

where: η_k is the increase in the blocking on the link l_k originated by a unit decrease in the arc capacity :

$$\eta_k = E(\rho_k, C_k - 1) - E(\rho_k, C_k) \tag{7}$$

ρ_k being the total traffic offered to link l_k and $E(A, C)$ the Erlang B function for traffic offered A and C channels. $\lambda_{r^i(f)}$is the marginal traffic carried in $r^i(f)$ given, for disjoint routes $r^1(f)$, $r^2(f)$:

$$\lambda_{r^1(f)} = A_t(f) \prod_{l_j \in r^1(f)} (1 - B_j) \tag{8}$$

$$\lambda_{r^2(f)} = A_t(f) L_{r^1(f)} \prod_{l_j \in r^2(f)} (1 - B_j) \tag{9}$$

$$L_{r^i(f)} = 1 - \prod_{l_j \in r^i(f)} (1 - B_j) \tag{10}$$

$$B_k = E\left(\rho_k, C_k\right) \tag{11}$$

$$\rho_k = \sum_{f: l_k \in r^1(f)} A_t(f) \prod_{l_j \in r^1(f) - \{l_k\}} (1 - B_j) + \sum_{f: l_k \in r^2(f)} A_t(f) L_{r^1(f)} \prod_{l_i \in r^2(f) - \{l_k\}} (1 - B_i) \tag{12}$$

$w(f)$ is the expected revenue for an accepted call of traffic flow f and $s_{r^i(f)}$ is the surplus value of a call on route $r^i(f)$.

The relations (4)-(12) define implicitly a system of equations in B_k and c_k:

$$\begin{cases} B_k & = \beta_k \left(\overline{B}, \overline{C}, \overline{A_t}, R_k\right) \qquad (S1a) \\ c_k & = \alpha_k \left(\overline{c}, \overline{B}, \overline{C}, \overline{A_t}, R_k\right) \qquad (S1b) \\ (k & = 1, 2, \ldots, |L|) \end{cases}$$

First important elements of the analytical 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 according to [10], [11]. Taking into account that the algorithm MMRA calculates $\overline{R}_t$ at every period $t = nT$ $(n = 1, 2, \ldots)$ 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 $\overline{A}_{t_0}$. These interdependencies may be illustrated trough the diagram in figure 1.

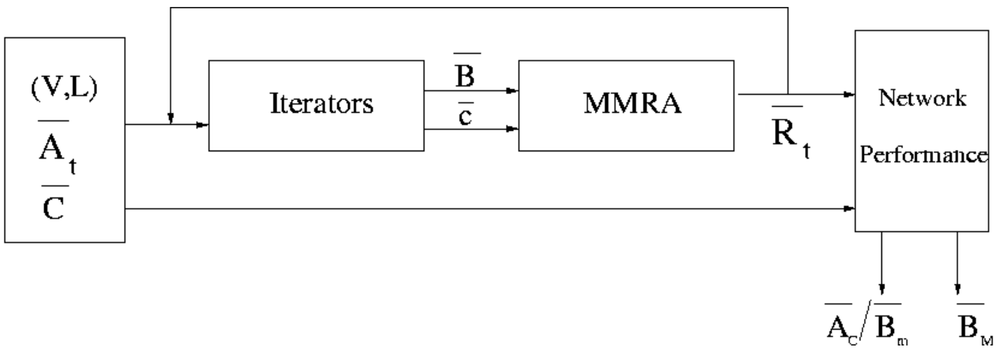

Figure 1: Functional relations in the MODR model

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:

$$\max_{\overline{R}_t} A_c = \sum_{f \in \mathcal{F}} A_t(f)\,(1 - B(f)) \tag{13}$$

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

$$B(f) = L_{r^1(f)} L_{r^2(f)} \tag{14}$$

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

$$B_m = \sum_{f \in \mathcal{F}} \frac{A_t(f)B(f)}{A_t^0} \tag{15}$$

where $A_t^0 = \sum_{f \in \mathcal{F}} A_t(f)$ is the total traffic offered; note that (13) is the objective of all “classical” single objective routing methods. The second proposed criterion is the minimisation of the maximal marginal call congestion:

$$\min_{\overline{R}_t} B_M = \max_{f \in \mathcal{F}} \{B(f)\} \tag{16}$$

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 (13) some results are shown in figure 2 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 $100 * 30$ 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.

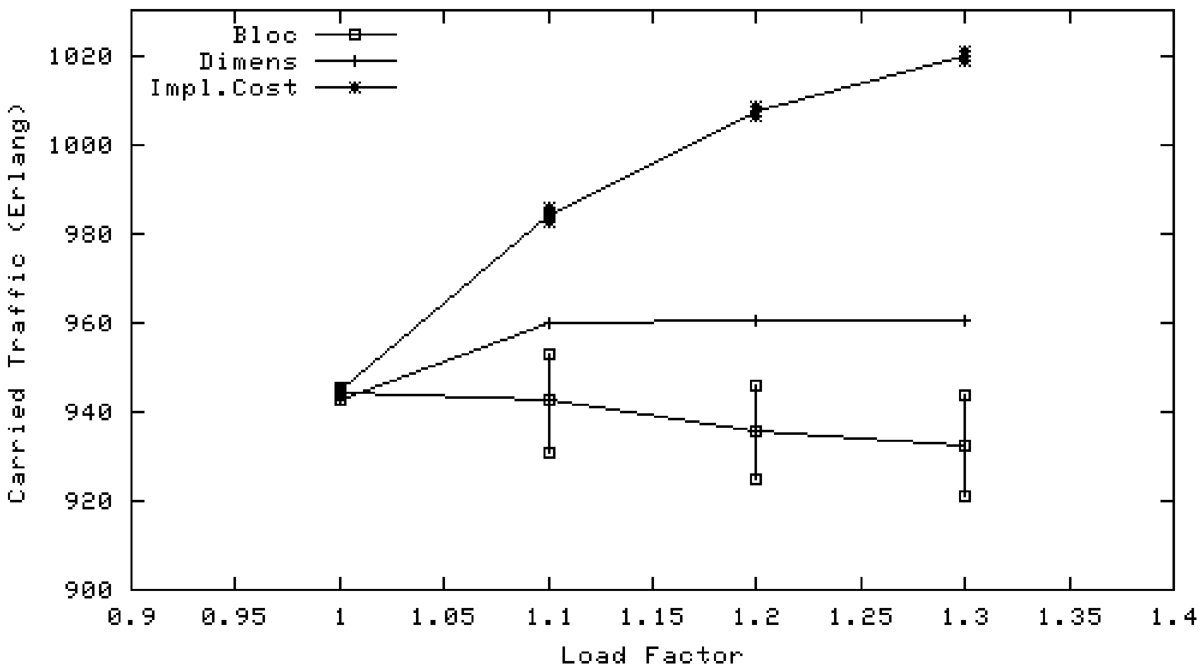

Figure 2: Oscillations in total carried traffic when z^1 ("impl.cost") and z^2 ("bloc") are minimised separately

The following conclusions may be drawn from these results: i) the minimisation of the path implied cost 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 metric A_c; iii) the minimisation of the path blocking probabilities leads to relatively small (hence "poor") values of A_c. Analogous conclusions could be obtained by calculating paths which minimise z^2 (shortest paths in terms of blocking probability)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 analytical model.

4 Heuristic for Path Selection

4.1 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 [6], 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 1 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.

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

Table 1: Oscillations in B_m and B_M given by MMRA for network B

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.

4.2 Heuristic for Synchronous Route Selection

A heuristic was developed for selecting path sets $\overline{R}_t$ ($t = nT; \quad n = 1, 2, \ldots$) capable of 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 this procedure is to search for the subset of the alternative path set

$$\overline{R}^a_{t-T} = \left\{ r^2(f), \quad f \in \mathcal{F} \right\} \tag{17}$$

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 [11] 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. Extensive experimentation with the model led 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 $r^2(f)$:

$$\xi(f) = F_1F_2 = \left(2C^1_{r^1(f)} - C^1_{r^2(f)}\right)\left(1 - L_{r^1(f)}L_{r^2(f)}\right) \tag{18}$$

$$C^1_{r^i(f)} = \sum_{l_k \in r^i(f)} c_k \tag{19}$$

The objective expressed by the factor F_1 is to favour (with respect to the need to change the 2^{nd} route) the flows for which the 2^{nd} route has a high implied cost and the 1^{st} 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. In a more general case where $r^1(f)$ has n_1 arcs and $r^2(f)$ n_2 arcs ($n_1 \leq n_2$):

$$F_1 = (n_2 - n_1)c'_1 + C^1_{r^1(f)} - C^1_{r^2(f)} \tag{20}$$

c'_1 being the average implied cost of the arcs in $r^1(f)$. 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 is to specify how many and which of the second 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 by solving the corresponding analytical model. The procedure uses two variables, $Npaths$ paths and $Mpaths$ that define the current number of candidate paths for improvement in the two main cycles of heuristic. $Npaths$ is used in the internal cycle where one seeks to obtain new alternative paths able of improving B_m while $Mpaths$ controls an external cycle where, for the current solution $\overline{R}_t$ with minimum B_m obtained in the internal cycle, one seeks solutions with smaller value of the other global network performance criterion, B_M.

Heuristic for Route Selection (MODR–1)

Denote for $t = nT \quad (n = 1, 2, \ldots)$: $\overline{R}^{(n)}_o$ the initial set of alternative paths, for which $\overline{B}$, $\overline{c}$ are the corresponding links metrics, B_m and B_M the network performance metrics and $N = |V|$, the number of nodes. One will also consider the current sets of alternative paths, $\overline{R}^*_m$, for which B_m is minimum, $\overline{R}^*_M$, for which B_M is minimum and the current set $\overline{R}^a$ of alternative paths to be tested.

1. $\overline{R}^*_M \leftarrow \overline{R}^{(n)}_o$, $\overline{R}^a \leftarrow \overline{R}^{(n)}_o$
2. Compute $\overline{B}$, $\overline{c}$, B_m and B_M for $\overline{R}^a$ by the iterators
3. $minB_{m_{ini}} \leftarrow B_m$, $minB_{M_{ini}} \leftarrow B_M$ and $minB_M \leftarrow B_M$
4. $Mpaths = N(N-1)$
5. While(1) $Mpaths > 0$ Do
   (a) $Ncycle \leftarrow 2$
   (b) $Npaths \leftarrow Mpaths$
   (c) $\overline{R}^a \leftarrow \overline{R}^{(n)}_o$, $\overline{R}^*_m \leftarrow \overline{R}^a$
   (d) Compute $\overline{B}$, $\overline{c}$, B_m and B_M for $\overline{R}^a$ by the iterators
   (e) $minB_m \leftarrow B_m$
   (f) While(2) ($Npaths > 0$ and $Ncycle > 0$) Do
      i. Search for the $Npaths$ with lower $\xi(f)$
      ii. Compute with MMRA new paths for the corresponding O–D pairs and define a new set of alternative paths for the network – $\overline{R}^a$
      iii. Compute the new $\overline{B}$, $\overline{c}$, B_m and B_M by the iterators
      iv. If $B_m < minB_{m_{ini}}$ and $B_M < minB_{M_{ini}}$ Do
         A. $minB_{M_{ini}} = B_M$ and $minB_{m_{ini}} = B_m$ (which means that the last obtained solution dominates the initial one for the considered network performance metrics)
         B. $\overline{R}^*_M \leftarrow \overline{R}^a$
         C. $minB_M = B_M$
      v. If $B_m < minB_m$ Do
         A. $minB_m \leftarrow B_m$
         B. $\overline{R}^*_m \leftarrow \overline{R}^a$ (save the best solution with respect to B_m, obtained so far)
      vi. If not

A. $Npaths \leftarrow Npaths - 1$

B. $\overline{R}^a \leftarrow \overline{R}^*_m$

C. <u>If</u> ($Npaths = 0$ <u>and</u> $Ncycle = 2$) <u>Do</u>

$Ncycle \leftarrow Ncycle - 1$

$Npaths \leftarrow N(N-1)$

D. Compute $\overline{B}$, $\overline{c}$, B_m and B_M for $\overline{R}^a$ by the iterators

(end of while (2))

(g) <u>If</u> $B_M \ < minB_M$ <u>Do</u>

i. $\overline{R}^*_M \leftarrow \overline{R}^*_m$ (save the best solution with respect to B_M, obtained so far

ii. $minB_M \leftarrow B_M$

(h) $Mpaths \leftarrow Mpaths - 1$

(end of while(1))

6. $\overline{R}^{(n+1)}_o \leftarrow \overline{R}^*_M$ (set of alternative paths selected for the network in this path update cycle)

Note that $Ncycle = 2$ guarantees that the internal cycle (search for minimal B_m) is executed twice; in most cases one execution of the cycle was shown to be sufficient for improving B_m and more than 2 cycles would serve no purpose as a result of the oscillatory behaviour of the solution set. Also note that the solution corresponding to the current minimal B_m depends on the routes which one seeks to change initially and on the initial path set.

4.3 Further Improvements in MODR

In the initial version of MODR [7] the boundary values of the priority regions of MMRA ("soft" constraints of the objective functions) that is acceptable and required values for the two path metrics, M^i_{acc}, M^i_{req} $\quad (i = 1, 2)$ were obtained from reference networks engineered for standard global network blocking probabilities in nominal and overload conditions; the changes in the preference regions would only result from alterations in the ideal solution (Op^1, Op^2). A more flexible and effective scheme of boundary value specification was now introduced. Let:

$$B_{av} = \frac{1}{|L|} \sum_{l_k \in L} B_k, \qquad c_{av} = \frac{1}{|L|} \sum_{l_k \in L} c_k \tag{21}$$

$$\Delta B_k = \frac{B_{av} - \min\{B_k\}}{2}, \qquad \Delta c_k = \frac{c_{av} - \min\{c_k\}}{2} \tag{22}$$

$$B^+_k = B_{av} + \Delta B_k, \qquad B^-_k = B_{av} - \Delta B_k \tag{23}$$

$$c_k^+ = c_{av} + \Delta c_k, \qquad c_k^- = c_{av} - \Delta c_k \tag{24}$$

Then the required and acceptable values for the two path metrics z^1 (implied cost) and z^2 (blocking probability) are:

$$C_{req} = Dc_k^-, \qquad C_{acc} = Dc_k^+ \tag{25}$$

$$B_{req} = 1 - \left(1 - B_k^-\right)^D, \qquad B_{acc} = 1 - \left(1 - B_k^+\right)^D \tag{26}$$

where D is the number of arcs of the paths ($D = 2$ in our case). The main advantage of this scheme, confirmed by extensive experimentation is the fact that it enables the priority region boundaries to adapt dynamically to different overload situations thereby overcoming the rigidity of the previous bounds which may lead in many overload situations to less efficient solutions from the point of view of global network performance. Overall the solutions obtained with this scheme are tendentially more efficient than the previous ones, since the varying boundaries reflect the current situation of the links as a result of the updates of B_k and c_k performed in each iteration of the heuristic.

Another mechanism introduced in MODR was 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 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 multi-objective model is greater than or equal to a certain parameter z_{APR}. This parameter will have to be carefully "tuned" 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.

5 Network Performance of MODR–1

In order to evaluate the potential improvement obtained by the introduction of the heuristic of synchronous route calculation and the relative performance of this new formulation of the MODR method (designated hereafter as MODR–1) extensive computational experimentation was carried out, using three test networks: the network in [13] widely used in studies of dynamic routing method evaluation (network M for short) and two other networks with the same topology (six nodes, fully meshed) designated as network B and A. Network B was obtained by recalculating the arc capacities of network M (while maintaining the same matrix of nominal traffic offered $\overline{A}_{t_0}$), with a standard design method for dynamic routing circuit-switched networks [3]. Note that network M has strong asymmetries in many arc capacities, with respect to the direct traffic offered to them. Network A has a different matrix of nominal traffic offered with a smaller variation in traffic intensities than in network B and M, and its arc capacities were calculated as in network B. The characteristics of each of these networks, including the initial route set $\overline{R}_{t_0}$ computed by the mentioned method [3], are shown in Appendix. For assessing the potential of MODR–1 in terms of global network performance a comparative study with a known reference in dynamic routing, the RTNR method (Real Time Network Routing [2], [5], [4]) developed by AT&T, was performed for the three mentioned networks. Note that the RTNR method is well known for its efficiency and remarkable network performance under overload conditions, largely resulting from the extensive use of very sophisticated hierarchical and dynamically adaptive service protection mechanisms, able of quickly and effectively responding to link overloading, traffic traffic intensity fluctuations and degradation of node-to-node blocking probabilities. Results of global network performance measured by B_m and B_M are presented in tables M, B and A for different overload factors. The results for RTNR were obtained by a discrete-event simulator developed with a OMNET++ simulation platform and are the mid points of a 95% confidence intervals obtained by the method of the batch means. Results are given for MODR–1 with and without APR service protection mechanism, obtained from the developed analytical model.

Overload Factor	MODR–1 without APR		MODR–1 with $z_{APR} = 1$		RTNR	
	B_m	B_M	B_m	B_M	$B_m \pm \Delta$	$B_M \pm \Delta$
0%	$6.65.10^{-5}$	0.000544	$6.65.10^{-5}$	0.000544	$\mathbf{2.08.10^{-5} \pm 9.8.10^{-6}}$	$\mathbf{0.000240 \pm 1.5.10^{-4}}$
10%	0.00121	0.00941	0.00121	0.00941	$\mathbf{0.000615 \pm 1.1.10^{-4}}$	$\mathbf{0.00501 \pm 1.1.10^{-3}}$
20%	0.00519	0.0346	0.00519	0.0346	$\mathbf{0.00424 \pm 3.0.10^{-4}}$	$\mathbf{0.0253 \pm 2.4.10^{-3}}$
30%	**0.0198**	**0.0747**	**0.0198**	**0.0747**	$0.0265 \pm 1.5.10^{-3}$	$0.144 \pm 1.3.10^{-2}$
40%	**0.0576**	**0.134**	**0.0576**	**0.134**	$0.0625 \pm 1.6.10^{-3}$	$0.257 \pm 5.5.10^{-3}$
50%	**0.0931**	0.321	0.103	**0.177**	$0.101 \pm 1.8.10^{-3}$	$0.335 \pm 3.3.10^{-3}$
60%	**0.134**	0.362	0.141	**0.321**	$0.138 \pm 1.5.10^{-3}$	$0.397 \pm 3.7.10^{-3}$
70%	0.168	0.423	**0.166**	**0.398**	$0.173 \pm 1.7.10^{-3}$	$0.446 \pm 2.9.10^{-3}$
80%	0.202	0.507	**0.201**	**0.474**	$0.204 \pm 1.6.10^{-3}$	$0.479 \pm 1.4.10^{-3}$
90%	0.238	0.584	**0.234**	0.508	$\mathbf{0.234 \pm 1.5.10^{-3}}$	$\mathbf{0.506 \pm 4.2.10^{-3}}$
100%	0.303	**0.396**	0.279	0.500	$\mathbf{0.262 \pm 1.6.10^{-3}}$	$0.533 \pm 3.2.10^{-3}$

Table 2: Global network performance for network M

The value of the parameter z_{APR} was defined empirically taking into account that we assumed $w(f) = 1, \quad \forall f \in \mathcal{F}$ and the fact that network M is poorly engineered and alternative paths with high "combined cost" z may still be worth considering in the sense that they may be useful for improving network performance in certain overload conditions. In the cases of networks B and A

Overload Factor	MODR–1 without APR		MODR–1 with $z_{APR} = 0.5$		RTNR	
	B_m	B_M	B_m	B_M	$B_m \pm \Delta$	$B_M \pm \Delta$
0%	**0.00457**	**0.0143**	**0.00457**	**0.0143**	$0.00744 \pm 6.7.10^{-4}$	$0.0294 \pm 6.4.10^{-3}$
10%	0.0664	0.227	0.0596	**0.121**	$\mathbf{0.0580 \pm 1.1.10^{-3}}$	$0.180 \pm 9.7.10^{-3}$
20%	0.130	0.376	0.113	**0.150**	$\mathbf{0.111 \pm 1.3.10^{-3}}$	$0.257 \pm 1.2.10^{-2}$
30%	0.179	0.487	**0.165**	**0.193**	$\mathbf{0.165 \pm 1.5.10^{-3}}$	$0.296 \pm 3.8.10^{-3}$
40%	0.247	0.503	**0.214**	**0.246**	$0.216 \pm 1.2.10^{-3}$	$0.315 \pm 7.7.10^{-3}$
50%	0.298	0.547	**0.259**	**0.293**	$0.262 \pm 1.3.10^{-3}$	$0.321 \pm 5.7.10^{-3}$

Table 3: Global network performance for network B

Overload Factor	MODR–1 without APR		MODR–1 with $z_{APR} = 0.5$		RTNR	
	B_m	B_M	B_m	B_M	$B_m \pm \Delta$	$B_M \pm \Delta$
0%	0.00387	0.00565	0.00387	0.00565	$\mathbf{0.00303 \pm 5.3.10^{-4}}$	$\mathbf{0.00557 \pm 1.5.10^{-3}}$
10%	**0.0311**	**0.0473**	**0.0311**	**0.0473**	$0.0405 \pm 2.9.10^{-3}$	$0.0613 \pm 4.4.10^{-3}$
20%	0.0881	0.134	**0.0817**	**0.125**	$0.0898 \pm 2.7.10^{-3}$	$0.133 \pm 8.9.10^{-3}$
30%	0.139	0.221	**0.120**	**0.165**	$0.129 \pm 2.2.10^{-3}$	$0.186 \pm 8.7.10^{-3}$
40%	0.190	0.287	**0.157**	0.242	$0.167 \pm 1.8.10^{-3}$	$\mathbf{0.226 \pm 1.1.10^{-2}}$
50%	0.244	0.349	**0.194**	0.282	$0.202 \pm 2.3.10^{-3}$	$\mathbf{0.267 \pm 1.1.10^{-2}}$

Table 4: Global network performance for network A

the same argument does not apply, since they are "correctly" engineered, therefore the value z_{APR} was lowered to 0.5.

The following main conclusions may be drawn from these results (and other results not presented here): i) the heuristic of path selection beyond stabilising the final solution $\overline{R}_t$ in each updating period enabled improved solutions from a global network performance point of view; ii) in general MODR–1 with APR performs better than without APR, as expected; iii) excepting for the case of the poorly engineered network M for low and moderate overload (where B_m and B_M were in general very low and below standardised acceptable values) MODR–1 with APR performed better than RTNR – in fact the estimated solutions of MODR–1 dominate those of RTNR in network A and in network B the MODR–1 solutions either dominate the RTNR solutions or are non-dominated with respect to the latter, cases in which they enable a reduction in maximum marginal blocking probability at the cost of a light increase in network mean blocking probability. Overall these results seem very encouraging with respect to the potential of MODR–1 in terms of global network performance, specially when the preservation of the GoS of more "sensitive" traffic flows of low intensity is an important concern.

6 Conclusions and Further Work

We have described a new version of a multiple objective dynamic routing method of periodic state-dependent type for circuit-switched networks, previously presented, enabling to overcome its limitations in terms of global network performance. In the method alternative paths for each node to node traffic flow are calculated by a specialised bi-objective shortest path algorithm, designated as MMRA (Modified Multi-objective Routing Algorithm) as a function of periodic updates of certain GoS related parameters estimated from real time measurements in the network.

An analytical 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 analytical 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 an heuristic procedure was presented aiming to overcome this instability problem and obtain acceptable compromise solutions in terms of the global network performance. Also some changes were introduced in the model of periodic recalculation of the boundary values of the priority regions of MMRA which are now dynamically changed thereby reflecting the current loading conditions in the links. The performance of the global routing method (MODR-1) was 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, RTNR (Real-Time Network Routing) developed by AT&T, known for its efficiency and sophistication in terms of service protection mechanisms.

An important conclusion of this work is that a multi-objective (and indeed a single-objective) dynamic routing method where the coefficients of the objective functions of the core multi-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 was 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.

Concerning the potential relative performance of MODR–1, by comparison with RTNR, the analytical results suggest that it 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 the test networks. Note that the analytical model includes some simplifications in terms of traffic modelling which may give biased results in some situations and has also intrinsic numerical errors, factors of special importance in very low blocking probability working conditions. 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, will have to be tackled through extensive use of the simulation test-bed.

A Test Networks

O-D Pair	Link Capac.	Offered Tráf.	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 5: Network A

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O-D Pair	Link Capac.	Offered Tráf.	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

Table 6: Network B

O-D Pair	Link Capac.	Offered Tráf.	Intermediate node
1-2	36	27.47	3
1-3	24	6.97	5
1-4	324	257.81	–
1-5	48	20.47	3
1-6	48	29.11	5
2-3	96	25.11	–
2-4	96	101.61	3
2-5	108	76.78	3
2-6	96	82.56	3
3-4	12	11.92	1
3-5	48	6.86	6
3-6	24	13.25	2
4-5	192	79.42	1
4-6	84	83.0	5
6-6	336	127.11	–

Table 7: Network M

[3].

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