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A New Multiobjective Dynamic Routing Method for Multiservice Networks – modelling resolution and performance

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Abstract

There are potential advantages in formulating the routing problems in modern multiservice networks as multiple objective problems. This paper presents a novel hierarchical bi-level multiobjective dynamic routing model for multiservice networks. It is based on a bi-objective shortest path algorithm, with dynamically adapted soft-constraints, to compute alternative paths for each node pair and on a heuristic to synchronously select alternative routing plans for the network in a dynamic alternative routing context. It is a routing method which periodically changes alternative paths as a function of periodic updates of certain QoS related parameters obtained from real-time measurements. The performance of the proposed routing method is compared with two reference dynamic routing methods namely RTNR and DAR by means of a discrete-event simulator, in terms of relevant network average performance and service performance parameters.

keywords Dynamic Routing, Multicriteria Analysis, Network Performance, Quality of Service.

1 Introduction

1.1 Background and Motivation

Modern multiservice network routing functionalities lead to the necessity of dealing with multiple, multifaceted and heterogeneous quality of service requirements. This concern led to the routing concept designated as QoS (Quality of Service) based routing which involves the selection of a sequence of network resources satisfying certain QoS requirements and seeking simultaneously to optimise relevant route associated metric(s) or a sole function of different metrics. Examples of such metrics are cost, delay, blocking probability or number of hops [34, 21]. In this context the path selection problem has been usually formulated as a shortest path problem with a single objective function, either a single metric or a combination of different metrics. QoS requirements are then incorporated into these models by means of additional constraints and the path selection problem (or routing problem in a strict sense) is solved by resorting to different types of heuristics usually based on Dijkstra or Bellman-Ford shortest path algorithms. For a comprehensive review of QoS routing models and algorithms see [19, 20]. Since this type of mathematical models, namely in shortest path problems, have inherently a network structure, the introduction of additional constraints (side constraints) destroys some properties underlying the specialised and quite efficient algorithms used to solve them. This leads to the necessity of using resolution approaches with heavier computational cost. Also the ‘classical’ types of QoS routing models don’t enable a fully explicit representation of potentially conflicting routing objectives.

Having all this in mind we think there are potential advantages in modelling many path selection problems of that (or similar) type as multiple objective problems. Multiple objective routing models enable the trade-offs among distinct QoS requirements to be pursued in a fully consistent manner by enabling to represent explicitly, as objective functions, the relevant metrics for each traffic flow. Also the comparison among different routing alternatives can be treated in a consistent and systematic manner by using appropriate multicriteria analysis models. In this

methodological framework paths are normally selected in the set of non-dominated paths, i. e. the set of paths for which, in minimisation problems, it is not possible to decrease the value of an objective function without increasing on at least the value of one of the other objective functions.

Also it is well known in traffic engineering that the utilisation of dynamic routing in various types of networks has a quite significant impact on network performance and cost, namely considering time-variant traffic patterns, overload and failure conditions (see eg. [3, 6]). A study that presents a framework for QoS routing computation with path caching relevant to dynamic routing models in Internet, is in [27].

The numerous routing optimisation models for multiservice networks that have been proposed in the literature in recent years can be viewed from distinct points of view. A very important aspect is the routing optimisation framework. In this respect we may distinguish network-wide optimisation models, where the objective function(s) which we seek to maximise or minimise (example: total traffic carried, total network revenue, average packet delay) are formulated at the network level, and flow-oriented optimisation models where the objective function(s) are formulated at the level of each node-to-node flow or call (where ‘call’ is viewed in its widest meaning as a connection request of any service/application type) – for example average packet delay on each packet stream or marginal call blocking probability). Examples of network-wide optimisation models with application to MPLS networks can be seen in [30, 29] and in [8] for application to GMPLS networks. Concerning recent contributions on flow oriented routing models for application to packet networks we refer to the works on the cognitive packet network (CPN) routing protocol which is based on a novel framework for adaptive routing control using random neural network reinforcement learning, namely in references [10, 11].

The MODR-S model presented in this paper is based on a new type of network-wide alternative routing optimisation model, where several objective functions of two levels (network and service levels) are explicitly incorporated in the mathematical formulation of the route calculation problem.

Two major motivation factors for this model were the interest in the explicit representation of QoS objectives at network and service levels in the optimisation model (hence enabling a mathematically based search for ‘compromise’ global routing solutions) and the explicit introduction in the model of fairness objectives concerning service types and traffic flows of each service type.

1.2 Contents of the Paper

In previous papers [7, 25] the essential features of a multiobjective dynamic alternative routing method (MODR-1) for single service networks, of periodic state dependent type, based on a bi-objective shortest path model with “soft constraints”, were presented. In its initial formulation for circuit-switched networks the model uses implied costs and blocking probabilities as metrics for the route calculation problem. Also an analytical model and a heuristic were developed [26] for synchronous selection of a first choice path and an alternative path between every pair of nodes, seeking to obtain a set of routes which is a satisfactory compromise solution from the point of view of two global network performance objectives, namely the network mean blocking probability and the maximal end-to-end blocking probability (for all traffic flows). In [26] the performance of the global routing method (MODR-1) for single channel traffic was compared in terms of two global network performance metrics, with the corresponding results given by a discrete event simulation model for a reference dynamic routing method, RTNR. This study revealed that the method globally performed well in most situations.

The present paper presents the essential features of a multiple objective dynamic routing method for multiservice networks (MODR-S) that is founded on the formulation of an alternative routing problem at the global network level as a bi-level hierarchical multiple objective network optimisation problem.

The major contributions of this paper are the following:

1. The generalisation of a multiobjective routing optimisation framework proposed by the authors in [7, 25, 26] from single-service networks to multiservice networks. The main innovative aspects of the proposed multiservice routing optimisation model are the particular multiobjective nature of the formulation involving the consideration in the mathematical model of network level objectives and service level objectives such that the former have priority over the latter, and the inclusion of fairness objectives as objective functions at the network level (minimisation of the maximal mean blocking probability of all service types) and service level (minimisation of the maximal blocking probability of all traffic flows of each service type). This leads to a new type of approach for the formulation of dynamic routing in multiservice networks, expressed through a bi-level network multiobjective dynamic alternative routing optimization problem including fairness objectives.
2. The proposal of a resolution approach for tackling the very complex dynamic routing

problem referred to in 1.

This involves the specification of the essential features of a heuristic for calculating “good” routing compromise solutions for all traffic flows which may be considered as the extension to multiservice networks of the requirements of the heuristic developed in [26] for single service networks. This also involves the extension to a dynamic multiservice environment of a bi-objective shortest path algorithm previously developed for resolving an auxiliary problem for each particular traffic flow [7] namely by incorporating time-varying preference thresholds which are used to select candidate alternative routes in the context of the heuristic. Finally, a “tailor-made” service protection mechanism (APR - Alternative Path Removal), adapted to the multiobjective and multiservice nature of the MODR-S model, is developed.

3. The presentation of a performance comparison study of the method, with two reference dynamic routing methods, RTNR and DAR (multiservice) in two fully meshed networks of a type previously considered in the literature on multiclass loss traffic networks. This performance comparison was carried out using a discrete-event simulation platform. This experimental study enabled to conclude that in this type of networks, the MODR-S method has better relative performance than RTNR and DAR-S in most cases. This performance improvement was also shown to be particularly relevant in overload conditions and for the more bandwidth demanding traffic classes.

The essential requirements of the heuristic of synchronous route selection are here analysed having in mind the inherent instability of the procedure associated with successive application to every pair of nodes of a bi-objective shortest path algorithm that is the basis of the end-to-end route calculation procedure. This type of instability problem was studied by the authors in [25] in the context of MODR-1, for single service networks, and can be considered as a new form of the known instability problem in single objective adaptive shortest path routing models, namely used in packet switched networks (see for example [4], chap.5). Instability phenomena were also studied in some single-objective alternative routing models as reported in [18] and [12]. The heuristic in question incorporates a specialised service protection scheme aimed at preventing excessive network blocking degradation in overload situations which will also be characterised. Note that the procedures used to aggregate the preferences involve the different objective functions of the routing optimisation model and are of course more elaborated than in standard single objective approaches.

The proposed model may be applied to strongly meshed networks which may be modelled at the traffic level as circuit-switched multirate loss-networks. These include ATM networks with VC (Virtual Channel) connections and MPLS networks using explicit routes, by using the concept of effective bandwidth, as suggested in [30]. Note that in this text the term ‘call’ is used as synonymous to a connection request that may be represented in the traffic plane by an equivalent multirate circuit in a circuit-switched network. This is made possible by using the concept of effective bandwidth (see for example [28]). This concept is a simplified stochastic measure of the utilisation of network transmission resources reflecting the variability of the rates of the different traffic sources as well as effects of statistical multiplexing of different traffic flows and possibly QoS requirements. The effective bandwidth enables traffic behaviour and QoS features at cell (in ATM based networks) and packet level (in IP based networks) to be ‘encapsulated’ in a simplified manner. The hiding of the cell and packet dynamic details is essential for obtaining tractability in network-wide routing optimisation models, as in MODR-S.

The paper is organised as follows. Section 2 presents the bi-level multiobjective dynamic alternative routing optimisation model for multiservice networks that is the basis of the MODR-S method. An analytical model that enables the relations and interdependencies among the various mathematical entities to become explicit, is also presented; a short review of the bi-objective shortest path algorithm used as a core of the MODR-S route calculation procedure is also included in this section. Section 3 presents the main features of a heuristic for synchronous path selection enabling to select “good” compromise solutions in terms of the global network and service performance criteria as well as a service protection mechanism developed in the context of the heuristic for preventing excessive network blocking degradation in overload conditions. Section 4 analyses the relative performance of the routing method by recurring to a discrete event simulation platform enabling to compare the global network and service performance criteria values with those obtained with two reference dynamic routing methods RTNR [2, 3] (Real Time Network Routing) developed by AT&T and DAR (Dynamic Alternative Routing) developed by BT [13] for a given test network. Finally some conclusions and further developments of this work will be outlined.

2 Multiobjective Dynamic Routing for Multiservice Networks

MODR-S is a state dependent alternative routing method which periodically updates routing tables based on periodic estimates of offered end-to-end traffic flows. It is based on a hierarchical bi-level multiobjective network routing optimisation model described in the present section. The core of the method for resolving this model is an algorithm to compute end-to-end alternative paths, the modified multiobjective routing algorithm (MMRA) [7], which is here adapted (section 2.2) for multiservice environments. A heuristic for synchronous selecting alternative routing plans (i.e. alternative paths for all traffic flows in the network in each updating cycle) that is based on this algorithm is used for seeking a compromise routing plan solution, in terms of the global network metrics.

The routing problem is here formulated as a hierarchical bi-level multiobjective optimisation problem which, at the network level, aims to maximise network expected revenue and minimise the maximum service mean blocking probability B_{Mm} and, at the service level, to minimise the service mean blocking probability B_{ms} and the service maximal point-to-point blocking probability B_{Ms} for each service $s \in S$. Note that in this manner fairness objectives concerning important QoS objectives at network and service levels are explicitly incorporated as objective functions of the routing optimisation model, in parallel with other objective functions (total revenue and mean blocking probability of each service type).

Denote by: V, L the node and arc sets; $A_t(f_s)$ the mean of the traffic offered by flow f_s of service type $s \in S$ from node v_i to node $v_j \in V$ at time period t (in Erlang); $R_t(f_s) = \{r^1(f_s), r^2(f_s), \dots, r^M(f_s)\}$ (in the present implementation $M = 2$) the ordered set of paths (or routes) which may be attempted by traffic flow f_s in time t ; $R_t(s) = \cup_{all f_s \in F_s} R_t(f_s)$ (F_s is the set of all point-to-point traffic flows for service type s); $\overline{R}_t = \cup_{s=1}^{|S|} R_t(s)$ the routing plan for the network; $B(f_s)$ the mean point-to-point blocking probability for traffic flow f_s ; d_{ks} the bandwidth required by service s calls on link l_k which may be interpreted as its effective bandwidth; $A_s^o = \sum_{f_s \in F_s} A_t(f_s)$ the total offered traffic by service s ; A_s^c the total carried traffic for service type s ; $w(f_s)$ the expected revenue for an accepted call of traffic flow f_s , Then

$$W_s = \sum_{f_s \in F_s} A_t(f_s)(1 - B(f_s))w(f_s) \quad (1)$$

is the service s expected revenue and

$$W_T = \sum_{s=1}^{|S|} W_s \quad (2)$$

is the network total expected revenue. For tractability purposes lets consider $d_{ks} = d_s$ ($\forall l_k \in L \wedge \forall s \in S$) and $w(f_s) = d_s$, ($\forall f_s \in F_s \wedge \forall s \in S$), as in [30], implying:

$$W_s = d_s A_s^c \text{ and } W_T = \sum_{s \in S} d_s A_s^c$$

with

$$A_s^c = \sum_{f_s \in F_s} A_t(f_s)(1 - B(f_s)) \quad (3)$$

Now the *multiple objective dynamic alternative routing problem for multiservice networks* is formulated as follows:

(Problem \mathcal{P}_{G-S})

$$NL : \min_{\bar{R}_t} -W_T = - \sum_{s \in S} d_s A_s^c = - \sum_{s \in S} d_s A_s^o (1 - B_{ms}) \quad (4)$$

$$\min_{\bar{R}_t} B_{Mm} = \max_{s \in S} \{B_{ms}\} \quad (5)$$

$$SL : \min_{\bar{R}_t(s)} B_{ms} = (A_s^o)^{-1} \sum_{f_s \in F_s} A_t(f_s) B(f_s), \quad s = 1, 2, \dots, |S| \quad (6)$$

$$\min_{\bar{R}_t(s)} B_{Ms} = \max_{f_s \in F_s} \{B(f_s)\}, \quad s = 1, 2, \dots, |S| \quad (7)$$

s.t.

equations of the teletraffic model enabling to calculate $\{B(f_s)\}$ in terms of $\{A_t(f_s)\}$ and \bar{R}_t (see sect. 2.1)

This is a bi-level hierarchical multiple objective network optimisation problem with $2(1+|S|)$ objective functions where the first level is associated with objectives of the routing model at the network level (NL) and the second level (SL) incorporates the objectives concerning the different service types. The objective function in (5) represents a fairness objective at network level, concerning all service types and the objective functions in (7) represent the fairness objectives within each service type. It is important to note that the first level (NL – network level) of objective functions (o. f. s in short) has priority over the second level (SL – service level). Finally, note the strong interdependencies among all the objective functions which further enhance the complexity of this routing problem.

2.1 Analytical Model

In order to make it explicit the fundamental relations between the various mathematical entities in MODR-S the underlying teletraffic model is now outlined. Denote by: C_k the capacity of link $l_k \in L$; \overline{C} the vector of link capacities C_k ; \overline{B} the matrix of link call blocking probabilities B_{ks} ; \overline{c} the matrix of link implied costs c_{ks} and $L_{r^i(f_s)}$ the blocking probability on route $r^i(f_s)$. We assume Poissonian arrivals, negative exponential call durations and independence in link occupations. Let B_{ks} denote the loss probability of service s calls on link l_k , ρ_{ks} the traffic offered to link l_k by service s calls. Let $\overline{d}_k = (d_{k1}, \dots, d_{k|S|})$ and $\overline{\rho}_k = (\rho_{k1}, \dots, \rho_{k|S|})$, then,

$$B_{ks} = \mathcal{L}_s(\overline{d}_k, \overline{\rho}_k, C_k) \quad (8)$$

The functions \mathcal{L}_s represent the traffic calculation model that enables the marginal blocking probabilities on the links, B_{ks} , to be computed in terms of \overline{d}_k , $\overline{\rho}_k$ and C_k . This calculation procedure should be based on an approximate stochastic model adequate to the MODR-S method. Having in mind that the traffic calculation subroutines have to be used a very large number of times in the context of the heuristic of selection of routes (involving the resolution of the system of equations S1 given below) we adopted a simplified model based on the Kaufman (or Roberts) algorithm [16, 32] for small values of C_k and on the uniform asymptotic approximation (UAA) [28] for large values of C_k (typically for $C_k \geq 80$). This approximation, suggested by Mitra in [30] (in the context of a single-objective off-line routing optimisation model for multiservice networks) enables a robust and efficient calculation of B_{ks} which is absolutely critical in a model of the MODR-S type.

The concept of implied cost of accepting a call on a link of a circuit-switched network was firstly formalised by Kelly [17] and later extended to multirate networks (without alternative routing) in [30, 9]. This parameter, c_{kt} , represents the cost of the acceptance of a call of type t on a link l_k expressed through the expected value of the loss of revenue in all network traffic flows which may use link l_k , associated with the decrease in the capacity of link l_k (the so called ‘knock-off’ effect of the acceptance of a type t call). Here we have adapted the definition of c_{kt} to multirate loss networks with alternative routing by extending the corresponding expression given for single-service networks in [17]. Hence c_{kt} is given by:

$$c_{kt} = \sum_s (1 - B_{ks})^{-1} \zeta_{kts} \left[\sum_{f_s: l_k \in r^1(f_s)} \lambda_{r^1(f_s)} (s_{r^1(f_s)} + c_{ks}) + \sum_{f_s: l_k \in r^2(f_s)} \lambda_{r^2(f_s)} (s_{r^2(f_s)} + c_{ks}) \right] \quad (9)$$

$$s_{r^2(f_s)} = w(f_s) - \sum_{l_j \in r^2(f_s)} c_{js}; \quad s_{r^1(f_s)} = w(f_s) - \sum_{l_j \in r^1(f_s)} c_{js} - (1 - L_{r^2(f_s)}) s_{r^2(f_s)} \quad (10)$$

where $s_{r^i(f)}$ is the surplus value of a call on route $r^i(f_s)$, $\lambda_{r^i(f)}$ is the marginal traffic carried on $r^i(f_s)$ considering that $r^1(f_s)$ and $r^2(f_s)$ are disjoint paths and

$$\zeta_{kts} = \mathcal{L}_s(\bar{d}_k, \bar{\rho}_k, C_k - d_{kt}) - \mathcal{L}_s(\bar{d}_k, \bar{\rho}_k, C_k)$$

is the increase in the congestion for type s calls on link l_k originated by a decrease in the arc capacity because of the acceptance of a type t call.

Let $\psi(\bar{\gamma}_s, \bar{\eta}_j)$ be a function which represents (in probability terms) the mechanism of access control to link l_j for service s calls in terms of the parameters $\bar{\gamma}_s$ and $\bar{\eta}_j$ (vectors representing traffic engineering attributes associated with service s calls and with link l_j , respectively). Then the reduced load values ρ_{ks} are given by

$$\begin{aligned} \rho_{ks} = & \sum_{f_s: l_k \in r^1(f_s)} A_t(f_s) \prod_{l_j \in r^1(f_s) - \{l_k\}} \psi(\bar{\gamma}_s, \bar{\eta}_j)(1 - B_{js}) + \\ & \sum_{f_s: l_k \in r^2(f_s)} A_t(f_s) L_{r^1(f_s)} \prod_{l_i \in r^2(f_s) - \{l_k\}} \psi(\bar{\gamma}_s, \bar{\eta}_i)(1 - B_{is}) \end{aligned} \quad (11)$$

Hereafter we will assume for simplifying reasons that the access is complete, $\psi(\bar{\gamma}_s, \bar{\eta}_j) = 1$ ($\forall s \in S, l_j \in L$). Therefore:

$$L_{r^i(f_s)} = 1 - \prod_{l_j \in r^i(f_s)} (1 - B_{js}) \quad (12)$$

$$\lambda_{r^1(f_s)} = A_t(f_s) \prod_{l_j \in r^1(f_s)} (1 - B_{js}) \quad (13)$$

$$\lambda_{r^2(f_s)} = A_t(f_s) L_{r^1(f_s)} \prod_{l_j \in r^2(f_s)} (1 - B_{js}) \quad (14)$$

Then, it is defined implicitly a system of non-linear equations in B_{ks} and c_{ks} , designating by \bar{A}_t , the traffic matrix with elements $A_t(f_s)$:

$$\begin{cases} B_{ks} = \beta_{ks} \left(\bar{B}, \bar{C}, \bar{A}_t, \bar{R}_t \right) & \text{(S1a)} \\ c_{ks} = \alpha_{ks} \left(\bar{c}, \bar{B}, \bar{C}, \bar{A}_t, \bar{R}_t \right) & \text{(S1b)} \end{cases} \quad (k = 1, 2, \dots, |L|; s = 1, 2, \dots, |S|)$$

It should be emphasised the interdependencies between $\{c_{ks}\}$ and $\{B_{ks}\}$ and between these two sets of parameters and the current total route set \bar{R}_t . First important elements of the resolution of the analytical model are a fixed point iterative scheme enabling the numerical computation of \bar{B} and a similar fixed point iterator to calculate \bar{c} given the network topology (V, L) , \bar{C} , \bar{A}_t and \bar{R}_t , which resolve the systems (S1a) and (S1b) respectively, in this order. Note that this system has to be resolved in the context of the heuristic of synchronous selection of routes, discussed in

section 3, whenever the effect of the possible change in any route for any traffic flow has to be evaluated, which may occur a very large number of times. Hence the aforementioned necessity of having a very efficient traffic calculation procedure (albeit introducing simplifications and corresponding approximation errors), for tractability reasons.

2.2 MMRA – Multiservice

The resolution of the routing model \mathcal{P}_{G-S} at each path updating period is performed by a heuristic, characterised in the next section, that uses as core sub-algorithm an algorithm for solving the following bi-objective static routing problem. This static routing problem, i. e. the calculation of the paths $r_s \equiv r^i(f_s)$ for any traffic flow f_s between an ordered pair of nodes, assuming fixed cost coefficients in the objective functions (o.f.s), is formulated as a bi-objective shortest path problem including preference thresholds, also designated as “soft constraints” (that is constraints not directly incorporated into the mathematical formulation). The path metrics are blocking probability and implied cost. The first metric tends (at a network level) to minimise the maximal node-to-node blocking probability while the second tends to minimise the network mean blocking probability as seen in [7, 25]. It is assumed that the arcs are undirected and the paths for each flow f_s from v_o to v_t (belonging to the feasible path set $\mathcal{D}(f_s)$) are node disjoint, loopless, and have a predefined maximal number of arcs. Denote by $m^n(r_s)$ the value of an additive metric m^n for the path r_s and m_{ks}^n the corresponding value for arc l_k ($l_k \in r_s$). The bi-objective shortest path problem can then be formulated as:

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

$$\min_{r_s \in \mathcal{D}(f_s)} m^n(r_s) = \sum_{l_k \in r_s} m_{ks}^n \quad n = 1, 2 \quad (15)$$

where $m_{ks}^1 = c_{ks}$ and $m_{ks}^2 = -\log(1 - B_{ks})$. The log is used to transform blocking probability into an additive metric.

In general there is no feasible solution which minimises both o.f.s 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 previously defined. In this context since path computation and selection has to be fully automated such criteria are embedded in the working of MMRA via preference regions in the o. f. space, defined from preference thresholds on the two metrics.

The MMRA algorithmic approach for single service networks [7, 25] was adapted straightforwardly for a multiservice environment. The purpose of the MMRA version used in the present context is to calculate solutions for problem $\mathcal{P}^{(2)}$ and is a new variant of the algorithm proposed in [1] for a bi-objective shortest path problem of the same type, adapted to the requirements and specificities of the MODR-S method. The approach given in [1] (inspired by the one presented in [33] and [5] concerning a procedure to search interactively non-dominated paths) enables the calculation and selection of non-dominated paths in the framework of a routing control mechanism. The procedure satisfies this requirement by integrating the k-shortest paths algorithm [22] and a special concept designated as “soft constraints” (that is constraints not directly incorporated into the mathematical model). The main features of this approach are: i) the representation of QoS requirements through soft constraints corresponding to *requested* and *acceptable thresholds* for each QoS metric; ii) the consideration of this type of soft constraints defines priority regions in the objective function space in which non-dominated solutions are searched for; iii) the non-dominated paths are computed by means of an extremely efficient k-shortest path algorithm proposed in [22], designated as MPS algorithm.

MMRA–multiservice (see details in [7]) follows the same procedures as in the reviewed approach with the exception of the following aspects: i) the sub-algorithm used for calculating k-shortest paths it is a new variant [14] of the MPS algorithm [22] which calculates k-shortest paths with a maximal number¹ of arcs per path in a very efficient manner; ii) the solution selection procedure accepts, in particular conditions, dominated solutions corresponding to a second-choice route $r^2(f_s)$ situated in higher priority region(s) of the o. f. space; iii) the boundaries of the preference regions (corresponding to acceptable(*acc*) and required (*req*) values for each o. f.) vary dynamically enabling an adaptation to variable network loading conditions.

This mechanism of dynamic preference regions is now performed according to the following scheme which is more flexible and efficient than the one in [7]:

$$C_{req}(s) = Dc_k^-(s), \quad C_{acc}(s) = Dc_k^+(s) \quad (16)$$

$$B_{req}(s) = 1 - \left(1 - B_k^-(s)\right)^D, \quad B_{acc} = 1 - \left(1 - B_k^+(s)\right)^D \quad (17)$$

$$B_k^+(s) = B_{av}(s) + \Delta B_k(s), \quad c_k^+(s) = c_{av}(s) + \Delta c_k(s) \quad (18)$$

$$B_k^-(s) = B_{av}(s) - \Delta B_k(s), \quad c_k^-(s) = c_{av}(s) - \Delta c_k(s) \quad (19)$$

$$\Delta B_k(s) = (B_{av}(s) - \min\{B_{ks}\})/2, \quad \Delta c_k = (c_{av}(s) - \min\{c_{ks}\})/2 \quad (20)$$

¹In a fully meshed network it is usually considered a maximum of two arcs in each alternative path.

The parameters $B_{av}(s) = \frac{1}{|L|} \sum_{l_k \in L} B_{ks}$, $c_{av}(s) = \frac{1}{|L|} \sum_{l_k \in L} c_{ks}$ are the current average values of the link blocking probabilities and the link implied costs for type s calls, respectively, and D is the number of arcs of the second-choice paths. In this manner the boundaries of the preference regions vary dynamically through updates in c_{ks} and B_{ks} , thereby reflecting changing network working conditions.

3 A Heuristic for Synchronous Path Selection

In [25] an instability problem was identified in the synchronous path selection procedure (that would result from successive applications of MMRA to every traffic flow) expressed by the fact that the route sets \overline{R}_t tend to oscillate between a few solutions some of which may lead to poor global network performance. This is associated with the complex non-linear interdependencies between the two o. f. s in (15) (see S1) and the interdependencies between \overline{R}_t and the o. f. s coefficients. To overcome this problem a heuristic was developed for selecting path sets \overline{R}_t ($t = n\mathcal{T}$; $n = 1, 2, \dots$) capable of guaranteeing a good compromise solution in terms of the two global network performance criteria (W_T, B_{Mm}) and the additional service performance criteria at every updating cycle. The foundation of this procedure (similarly to MODR-1 [25]) is to search for the subset of the alternative path set

$$\overline{R}_{t-\mathcal{T}}^a = \cup_{s=1}^{|S|} \overline{R}_{t-\mathcal{T}}^a(s) \quad : \quad \overline{R}_{t-\mathcal{T}}^a(s) = \left\{ r^2(f_s), \quad f_s \in F_s \right\} \quad (21)$$

the elements of which should be possibly changed in the next updating cycle. Extensive analysis and experimentation with the model led us to propose the following criterion for choosing candidate paths for possible routing improvement. The criterion depends explicitly on the first choice path $r^1(f_s)$ (which in MODR-S is the direct arc from origin to destination whenever it exists) and on the alternative path $r^2(f_s)$:

$$\xi(f_s) = F_{1s} F_{2s} = \left(2c_{r^1(f_s)} - c_{r^2(f_s)} \right) \left(1 - L_{r^1(f_s)} L_{r^2(f_s)} \right) \quad (22)$$

$$c_{r^i(f_s)} = \sum_{l_k \in r^i(f_s)} c_{ks} \quad (23)$$

The objective of the factor F_{1s} is to favour (concerning 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 $C_{r^1(f_s)}^1$ was introduced for normalising reasons taking into account that $r^1(f_s)$ has one arc and $r^2(f_s)$ two arcs, in the considered fully (or strongly) meshed networks. In a general when

$r^1(f_s)$ has n_1 arcs and $r^2(f_s)$ n_2 arcs ($n_1 \leq n_2$), $F_{1s} = (n_2 - n_1)c'_{1s} + c_{r^1(f_s)} - c_{r^2(f_s)}$, c'_1 being the average implied cost of the arcs in $r^1(f_s)$. The second factor F_{2s} has the objective of favouring the flows with worse end-to-end blocking probability. In the case where overload conditions led to the elimination of the alternative path, as it is mentioned next, $\xi(f_s) = c_{r^1(f_s)} (1 - L_{r^1(f_s)})$. A second point to be tackled by the heuristic procedure is to specify how many and which of the second routes $r^2(f_s)$ with smaller value of $\xi(f_s)$ should possibly be changed by applying MMRA-S once again. This requires that the effect of each candidate route, in terms of network and service performance, be anticipated by solving the corresponding analytical model. For that purpose, the proposed heuristic procedure uses two variables, $Npaths$ and $Mpaths$ that define the current number of candidate paths for improvement in the two main cycles of the heuristic. $Mpaths$ is initialised to the total number of node pairs. $Npaths$ is used in an internal cycle where one seeks to obtain new alternative paths able of improving B_{ms} and B_{Ms} for the service s and also W_T and B_{Mm} for the network, while $Mpaths$ controls an external cycle where $Npaths$ is re-initialised. A variable $Ncycle$ guarantees that the internal cycle (search for minimal B_m) is executed twice, by re-initialising the values of $Npaths$; 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. Also note that the solution found in the inner cycle depends on the number of routes which one seeks to change and on the initial route set.

Also 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, was introduced in the heuristic. 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 each objective function $m^i(r_s)$ ($i = 1, 2$) of the bi-objective shortest path model (15) is greater than certain values:

$$m^1(r_s) > d_s * z_{APR} \quad \wedge \quad m^2(r_s) > -\log(1 - 0.3) * z_{APR} \quad (24)$$

where z_{APR} is a parameter which varies dynamically between 0 and 1. The first factor in the condition on $m^2(r_s)$ corresponds to a path with blocking greater than 0.3 and the factor d_s in the condition on $m^1(r_s)$ corresponds to a cost equal to the revenue per call of f_s . The decrease in z_{APR} only may occur in the second internal cycle of the heuristic and up to a value M_{sup} of $Mpaths$ since the application of the APR mechanism for greater values of $Mpaths$ may prevent the consideration as candidate paths of “good” solutions in the initial iterations of the external cycle, which could be particularly negative in low overload conditions. Note that typically the

final selected solution is obtained in most cases in the two initial iterations of the external cycle, for the test networks.

Finally it was necessary to properly initialise the heuristic in order to enable that the initial set of alternative paths be a “good” initial solution which is related with the fact that the obtained solution is dependent from the initial one – which is a consequence of the routing problem, as it is here formulated, be NP-complete. So, in order to find a “good” initial solution some alternative paths must be eliminated from the initial set, which is specially importante is overload conditions, according to the following criteria. It will be eliminate from the initial set, the alternative paths $r^2(f_s)$, for which:

$$B(f_s) > \frac{\sum_{f_s=1}^{|F_s|} B(f_s)}{|F_s|} \quad \vee \quad B(f_s) > 10\% \quad (25)$$

This procedure allows that better alternative paths be found for the services with more bandwidth demand which improves the service performance and, as a consequence, the network performance. Note that, in spite of not beeing applied in single services networks, the experience has proved that this procedure could improve the network performance in that case too. As can be seen in the following description of the heuristic, if the final solution does not dominate the initial one, before the elimination of some alternative paths, than it is the initial solution that is adopted in the next updating path period. Nevertheless this case was never found during the analitical study of the heuristic. Also note that the initial solution without any alternative paths for all services was not a “good” initial solution as the experience has proved for single and multiservice networks.

Finally, as it was already said, it is in the two or three prime cicles of the *Mpaths* variable that the heuristic usually finds solutions which are very similar to the ones which are found after total number of cicles of *Mpaths*. This fact could reduce the total number of iterations in the heuristic for 1/4 of the original number.

Next the heuristic is formalised and its main steps are described in more detail.

Heuristic for Route Selection (MODR–S)

Denote, for $t = nT$ ($n = 1, 2, \dots$): $\overline{R}_o^{(n)} = \cup_{s=1}^{|S|} \overline{R}_o^{(n)}(s)$ the initial set of routes (for the set of services S such that $\{d_s\}$ is ordered by bandwidth ascendent order) for which \overline{B} , \overline{c} are the corresponding link metrics, B_{ms} and B_{M_s} the services performance metrics, W_T e B_{Mm} the network performance metrics and $N = |V|$, the number of nodes. Also denote by

$\overline{R}_e = \cup_{s=1}^{|S|} \overline{R}_e(s)$ the initial route set where the alternative paths were obtained from $\overline{R}_o^{(n)}$, after the elimination of some alternative paths according to (25) and $\overline{R}^* = \cup_{s=1}^{|S|} \overline{R}^*(s)$ the set of routes with alternative paths for which W_T and B_{Mm} are both current minima which means that \overline{R}^* dominates (or is equal to) the initial path set solution \overline{R}_e . Finally denote by $\overline{R} = \cup_{s=1}^{|S|} \overline{R}(s)$ the current set of alternative to be tested.

- I. $\overline{R} \leftarrow \overline{R}_o^{(n)}$
- II. Compute \overline{B} , \overline{c} , W_T e B_{Mm} for \overline{R} by the iterators
- III. $W_T^o \leftarrow W_T$, $B_{Mm}^o \leftarrow B_{Mm}$
- IV. Eliminate the $r^2(f_s)$ paths in \overline{R} according with (25)
- V. $\overline{R}_e \leftarrow \overline{R}$
- VI. Compute \overline{B} , \overline{c} , W_T and B_{Mm} for \overline{R} by the iterators
- VII. $\max W_T \leftarrow W_T$, $\min B_{Mm} \leftarrow B_{Mm}$
- VIII. For ($s = |S|$ To $s = 1$)
 1. $\overline{R}(s) \leftarrow \overline{R}_e(s)$, $\overline{R}^*(s) \leftarrow \overline{R}_e(s)$
 2. Compute \overline{B} , \overline{c} , B_{ms} and B_{Ms} for \overline{R} by the iterators
 3. $\min B_{ms_{ini}} \leftarrow B_{ms}$, $\min B_{Ms_{ini}} \leftarrow B_{Ms}$
 4. $Mpaths \leftarrow N(N - 1)/2$, $z_{APR} \leftarrow 1$
 5. While(1) ($Mpaths > 0$) Do
 - (a) $Ncycles \leftarrow 2$
 - (b) $Npaths \leftarrow Mpaths$
 - (c) $\overline{R}(s) \leftarrow \overline{R}_e(s)$
 - (d) Compute \overline{B} , \overline{c} , B_{ms} and B_{Ms} for \overline{R} by the iterators
 - (e) $\min B_{ms} \leftarrow B_{ms}$
 - (f) While(2) ($Npaths > 0$) Do
 - i. Search for $Npaths$ alternative paths with lower $\xi(f_s)$
 - ii. Compute with MMRA new paths for the corresponding O–D pairs and define a new set of alternative paths for the service s which define $\overline{R}(s)$, using z_{APR}
 - iii. Compute the new \overline{B} , \overline{c} , B_{ms} and B_{Ms} by the iterators
 - iv. If ($B_{ms} < \min B_{ms_{ini}}$ and $B_{Ms} < \min B_{Ms_{ini}}$) Then

(which means that the last obtained solution for the service s dominates the best previous solution for the considered service performance metrics)

A. Compute W_T e B_{Mm}

B. If ($W_T > \max W_T$ and $B_{Mm} < \min B_{Mm}$) Then

$$\text{B.1 } \min B_{Ms_{ini}} \leftarrow B_{Ms}, \min B_{ms_{ini}} \leftarrow B_{ms}$$

$$\text{B.2 } \min B_{Mm} \leftarrow B_{Mm}, \max W_T \leftarrow W_T$$

$$\text{B.3 } \bar{R}^*(s) \leftarrow \bar{R}(s)$$

(which means that the last obtained solution dominates the best previous one for the considered network performance metrics)

v. If ($B_{ms} < \min B_{ms}$) Then

A. $\min B_{ms} \leftarrow B_{ms}$ (which means that $|F'_s| = Npaths$ does not change in this case)

vi. Else

A. $Npaths \leftarrow Npaths - 1$

B. If ($Npaths = 0$ and $Ncycles = 2$) Then

$$Ncycles \leftarrow Ncycles - 1$$

$$Npaths \leftarrow N(N - 1)/2$$

C. If ($Npaths < 10$ and $Ncycles = 1$ and $Mpaths < M_{sup}$) Then

$$z_{APR} \leftarrow Npaths * 0.1$$

D. Else $z_{APR} \leftarrow 1$

(End of While(2))

(g) $Mpaths \leftarrow Mpaths - 1$

(End of While(1))

6. $\bar{R}(s) \leftarrow \bar{R}^*(s)$

(End of For)

IX. If ($\max W_T < W_T^o$ or $\min B_{Mm} > B_{Mm}^o$) Then

1. $\bar{R}_o^{(n+1)} \leftarrow \bar{R}_o^{(n)}$

(which means that the obtained network solution does not dominate the best initial one for the considered network performance metrics)

X. Else $\bar{R}_o^{(n+1)} \leftarrow \bar{R}^*$ (set of paths selected for the network in this path update cycle)

The application of this heuristic to fully meshed networks with three types of services (telephone, data and video), using a discrete-event simulation platform was presented in [23] together

with a comparison with reference dynamic routing methods deployed in various countries. This enabled the conclusion that the performance of MODR was globally better than those methods for most network and service metrics. In particular it led to solutions which dominated the ones from the reference methods in the vast majority of overload conditions.

In the first set of instructions the heuristic is initialized by calculating the relevant model parameters and the objective functions values for the initial route set \overline{R}_e obtained according to (25). Next it starts the procedures for seeking an improvement of the current solutions, by changing alternative routes of the flows of each service, considering the services by decreasing order of bandwidth (step VIII). After initializing the auxiliary route sets $\overline{R}(s)$ and $\overline{R}^*(s)$ with \overline{R}_e and the variables $Mpaths$ and z_{APR} with the maximal values (the number of node pair and 1, respectively) the external cycle of the heuristic (step 5), controlled by $Mpaths$ is executed. Then the auxiliary variables $Ncycles$ and $Npaths$ that control the internal ‘optimization’ cycle are initialised. In the internal cycle (step 5f) the heuristic analyses the effect of changing a number, $Npaths$, of alternative routes the ones with lower $\xi(f_s)$. The new candidate alternative paths are obtained by applying the bi-objective shortest path algorithm MMRA, leading to a set of candidate alternative paths which define the set $\overline{R}(s)$. Note that some of these candidate alternative paths can be eliminated according to the APR criterion (24) defined for the current value of z_{APR} . This value is decremented of 0.1 following the decrement in $Npaths$ but only if $Mpaths < Msup$ (step 5(f)viC). If the currently tested solution dominates the current best ($\overline{R}^*(s)$) with respect to the service metrics (B_{ms} and B_{Ms}) and if it also dominates the latter with respect to the network metrics (W_T and B_{Mm}) then the new current ‘best’ solution will be $\overline{R}(s)$ (5(f)ivB). These procedures are then repeated for all the types of traffic flows. After the cycles of the heuristic are completed a final dominance test concerning the network metrics is performed between the obtained solution (\overline{R}^*) and the initial solution $\overline{R}_o^{(n)}$. Note that in some situations the solution supplied by the cycles of the heuristic is dominated by the initial one or is not comparable in a multicriteria sense. In the latter case the heuristic is conservative and retains the previous solution that is the solution which was found ‘best’ in the previous route updating cycle $(n - 1)\tau$.

For better understanding the working of the heuristic we present in figure 1 a simplified fluxogram:

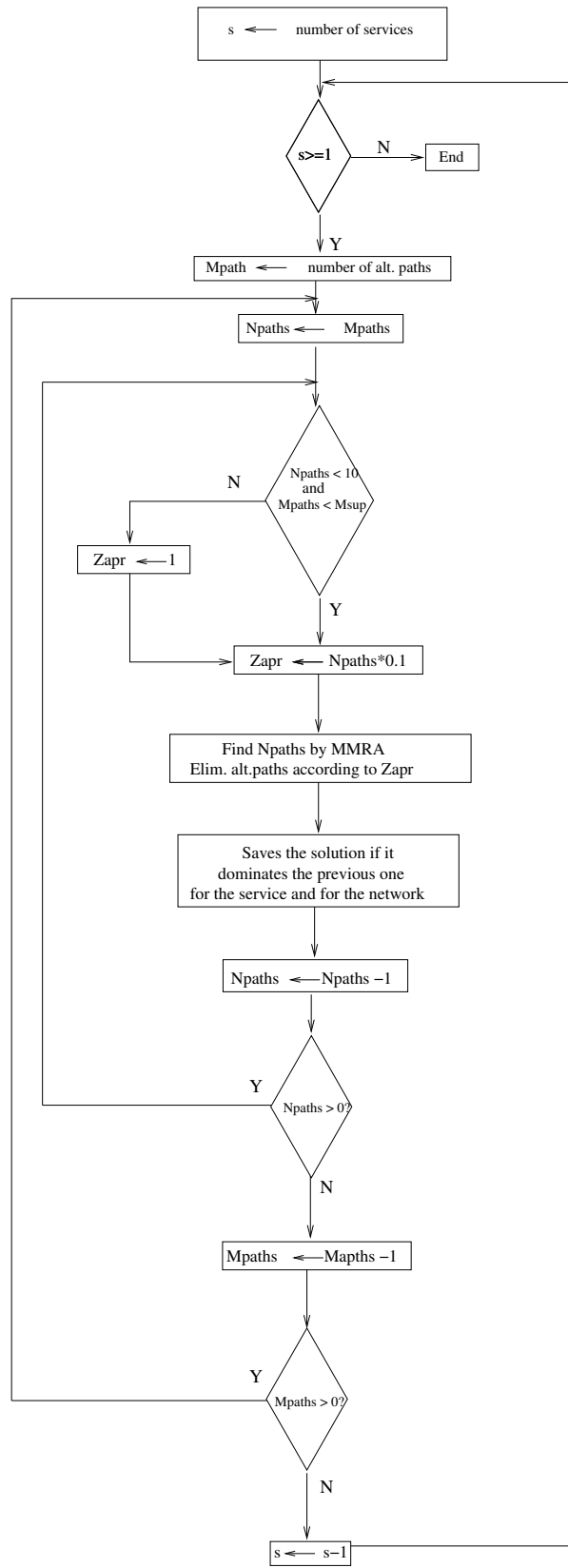


Figure 1: Simplified Fluxogram of the Heuristic for Route Selection

4 MODR-S Network Performance

In order to evaluate the MODR-S performance, a network (see table 1) based on the one presented in [31] was engineered with three services: telephone, data and video with $\bar{d} = [1, 6, 10]$

O-D Pair	Link Capac.	Offered Traf.		
		$s = 1$	$s = 2$	$s = 3$
1-2	851	27.47*3	27.47*2	27.47
1-3	195	6.97*3	6.97*2	6.97
1-4	6585	257.81*3	257.81*2	257.81
1-5	616	20.47*3	20.47*2	20.47
1-6	937	29.11*3	29.11*2	29.11
2-3	688	25.11*3	25.11*2	25.11
2-4	2602	101.61*3	101.61*2	101.61
2-5	3013	76.78*3	76.78*2	76.78
2-6	2288	82.56*3	82.56*2	82.56
3-4	342	11.92*3	11.92*2	11.92
3-5	192	6.86*3	6.86*2	6.86
3-6	356	13.25*3	13.25*2	13.25
4-5	2212	79.42*3	79.42*2	79.42
4-6	2187	83.0*3	83.0*2	83.0
5-6	3456	127.11*3	127.11*2	127.11

Table 1: Test Network

and call durations of 1, 5 and 10 minutes respectively. A discrete-event simulator has been used for a comparative study with RTNR [2, 3] (Real Time Network Routing) developed by AT&T and DAR (Dynamic Alternative Routing) developed by BT [13]. In the later method, adapted for the multiservice case, a dynamic trunk reservation mechanism based on the one used in RTNR was introduced to improve its performance in overload conditions. This version of DAR was designated as DAR-S (see [15]). In order to prevent very high blocking probability, the overload factor of $X\%$ corresponds to the offered traffic $A_s^o(1 + \frac{X}{100d_s})$ for service s .

For the MODR-S method, the estimated offered traffic \tilde{x} in the n^{th} time interval for traffic flow f is obtained from an estimate $\tilde{X}(n-1)$ of the offered traffic in the previous interval calculated from on-line measurements, for the same traffic flow, by using a first order moving average iteration: $\tilde{x}_{f_s}(n) = (1-b)\tilde{x}_{f_s}(n-1) + b\tilde{X}_{f_s}(n-1)$ (as suggested in [17]) with $b = 0.9$. It was considered $\mathcal{T} = 1$ minute but different values of \mathcal{T} , one for each service, could be easily integrated in the heuristic.

The simulation results presented in tables 2, 3 and 4 are the mid points of a 95% confidence intervals obtained by the method of the independent replications. The best results for each

Overload Factor	MODR-S		RTNR		DAR-S
	Analytical Model		Simulation Model		
	W_T		$W_T \pm \Delta$		
-20%	22588.8	22588.7 \pm 31.67	22596.5 \pm 29.12	22583.1 \pm 30.18	
-10%	23146.8	23108.3 \pm 25.43	23113.6 \pm 28.58	23097.8 \pm 26.56	
0%	23526.8	23510.8 \pm 46.66	23378.9 \pm 63.23	23470.7 \pm 34.42	
10%	23692	23762.7 \pm 32.61	23450.7 \pm 55.87	23604.2 \pm 54.16	
20%	23965.9	23966.6 \pm 36.00	23503.1 \pm 44.65	23594.1 \pm 37.04	
30%	23909.4	24133.2 \pm 39.35	23606.6 \pm 33.39	23733.2 \pm 38.22	
40%	24145.7	24266.5 \pm 48.92	23704.1 \pm 32.76	23840.8 \pm 40.03	
	B_{Mm}		$B_{Mm} \pm \Delta$		
-20%	0.00061	0.0009 \pm 2.9×10^{-4}	0.0007 \pm 2.4×10^{-4}	0.0016 \pm 3.2×10^{-4}	
-10%	0.001	0.0030 \pm 5.4×10^{-4}	0.0031 \pm 3.7×10^{-4}	0.005 \pm 4.0×10^{-4}	
0%	0.010	0.011 \pm 2.0×10^{-3}	0.017 \pm 3.2×10^{-3}	0.015 \pm 1.6×10^{-3}	
10%	0.036	0.028 \pm 1.1×10^{-3}	0.042 \pm 2.9×10^{-3}	0.032 \pm 1.9×10^{-3}	
20%	0.068	0.045 \pm 1.7×10^{-3}	0.078 \pm 5.4×10^{-3}	0.117 \pm 2.0×10^{-3}	
30%	0.104	0.063 \pm 2.6×10^{-3}	0.140 \pm 1.1×10^{-3}	0.183 \pm 8.0×10^{-4}	
40%	0.133	0.084 \pm 1.9×10^{-3}	0.188 \pm 1.2×10^{-3}	0.240 \pm 2.3×10^{-4}	

Table 2: Global Performance

Overload Factor	MODR-S		MODR-S		RTNR	
	Analytical Model		Simulation Model		Simulation Model	
	B_{ms}	B_{Ms}	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$
	Service $s = 1$					
-20%	0.002	0.009	0.002 \pm 2.6×10^{-4}	0.009 \pm 2.8×10^{-3}	$< 10^{-3}$	$< 10^{-3}$
-10%	0.003	0.013	0.003 \pm 6.3×10^{-4}	0.009 \pm 1.6×10^{-3}	0.001 \pm 3.3×10^{-4}	0.003 \pm 8.5×10^{-4}
0%	0.004	0.018	0.004 \pm 6.1×10^{-4}	0.014 \pm 2.6×10^{-3}	0.005 \pm 4.9×10^{-4}	0.014 \pm 2.9×10^{-3}
10%	0.004	0.020	0.005 \pm 9.5×10^{-4}	0.017 \pm 3.6×10^{-3}	0.019 \pm 3.9×10^{-3}	0.053 \pm 1.4×10^{-2}
20%	0.005	0.017	0.006 \pm 4.0×10^{-4}	0.017 \pm 2.6×10^{-3}	0.069 \pm 6.9×10^{-3}	0.164 \pm 1.4×10^{-2}
30%	0.006	0.020	0.008 \pm 9.3×10^{-4}	0.021 \pm 6.4×10^{-3}	0.131 \pm 1.6×10^{-3}	0.257 \pm 7.8×10^{-3}
40%	0.008	0.031	0.009 \pm 1.2×10^{-3}	0.022 \pm 3.3×10^{-3}	0.178 \pm 1.6×10^{-3}	0.307 \pm 1.1×10^{-2}
	Service $s = 2$					
-20%	0.001	0.002	0.003 \pm 1.2×10^{-3}	0.011 \pm 3.5×10^{-3}	0.003 \pm 2.1×10^{-3}	0.008 \pm 4.3×10^{-3}
-10%	0.004	0.007	0.012 \pm 2.7×10^{-3}	0.032 \pm 9.7×10^{-3}	0.021 \pm 4.0×10^{-3}	0.040 \pm 7.5×10^{-3}
0%	0.029	0.092	0.025 \pm 4.6×10^{-3}	0.051 \pm 7.6×10^{-3}	0.054 \pm 7.4×10^{-3}	0.094 \pm 2.0×10^{-2}
10%	0.044	0.103	0.043 \pm 4.4×10^{-3}	0.082 \pm 7.4×10^{-3}	0.089 \pm 1.1×10^{-2}	0.157 \pm 3.0×10^{-2}
20%	0.038	0.106	0.062 \pm 4.4×10^{-3}	0.111 \pm 1.0×10^{-2}	0.117 \pm 6.7×10^{-3}	0.215 \pm 2.3×10^{-2}
30%	0.048	0.121	0.080 \pm 6.3×10^{-3}	0.152 \pm 1.1×10^{-2}	0.132 \pm 8.0×10^{-3}	0.251 \pm 1.0×10^{-2}
40%	0.067	0.177	0.101 \pm 6.9×10^{-3}	0.184 \pm 2.2×10^{-2}	0.145 \pm 9.0×10^{-3}	0.255 \pm 3.5×10^{-2}
	Service $s = 3$					
-20%	0.003	0.005	0.004 \pm 1.8×10^{-3}	0.017 \pm 8.5×10^{-3}	0.006 \pm 4.5×10^{-3}	0.023 \pm 1.5×10^{-2}
-10%	0.011	0.019	0.011 \pm 2.9×10^{-3}	0.031 \pm 6.8×10^{-3}	0.036 \pm 7.4×10^{-3}	0.078 \pm 1.3×10^{-2}
0%	0.022	0.032	0.026 \pm 3.6×10^{-3}	0.062 \pm 1.5×10^{-2}	0.077 \pm 1.5×10^{-2}	0.153 \pm 2.7×10^{-2}
10%	0.044	0.136	0.046 \pm 4.3×10^{-3}	0.103 \pm 2.8×10^{-2}	0.115 \pm 1.1×10^{-2}	0.209 \pm 2.1×10^{-2}
20%	0.087	0.180	0.068 \pm 4.8×10^{-3}	0.129 \pm 1.6×10^{-2}	0.138 \pm 4.6×10^{-3}	0.265 \pm 2.2×10^{-2}
30%	0.117	0.203	0.090 \pm 7.2×10^{-3}	0.161 \pm 2.2×10^{-2}	0.145 \pm 4.3×10^{-3}	0.272 \pm 2.7×10^{-2}
40%	0.139	0.285	0.114 \pm 1.0×10^{-2}	0.195 \pm 2.3×10^{-2}	0.149 \pm 4.4×10^{-3}	0.265 \pm 1.7×10^{-2}

Table 3: Service Performance - Comparison with RTNR

metric are indicated in bold. Concerning the two global network performance metrics, MODR-S solutions always dominate² DAR-S solutions and, except for two cases, RTNR solutions as can be seen in table 2. The comparison with results from RTNR for the different services are in table 3. Concerning service 1 and excepting for the very low blocking probability zone (where RTNR outperforms MODR-S) the solutions from MODR-S dominate RTNR solutions with respect to the service performance objectives in problem \mathcal{P}_{G-S} . As for the two other services (2 and 3) MODR-S solutions are consistently better than RTNR solutions with respect to both service performance criteria. The comparison with results from the DAR-S method for the different services are in table 4. For service 1 DAR-S solutions dominate MODR-S solutions while for service 2 the relative performance of the solutions from the two methods is overall similar (in most cases the solutions from each method are non-dominated with respect to the solutions of the other and of the same order of magnitude). In the case of service 3, the one with higher bandwidth requirement and call duration, MODR-S solutions lead to much better performance than DAR-S with respect to both metrics. This means that in order to obtain better global network performance (corresponding to higher priority objectives in model \mathcal{P}_{G-S}) MODR-S had to allow a better blocking probability for service 3 in comparison with DAR-S, at the cost of a slight worsening on the performance of services 2 and 1. Also note some discrepancies between the analytical and simulation results for MODR-S, specially important for low overload where the analytical model tends to underestimate the values of the network blocking probability parameters. A major factor that explains these errors, beyond the intrinsic numerical imprecision of the analytical solution and the uncertainty in the simulation results (particularly important for very low blocking, where even for many hundreds of thousands of simulated calls a “rare event” is at stake), has to do with the assumed simplifications in the stochastic traffic model of the links (superposition of independent Poisson traffic flows and independent occupations in the path links). Note that this simplification (usually assumed in the analytical models of dynamic routing methods) is necessary to cope with the inherent complexity of the model, which otherwise could easily become intractable as discussed in section 2.1. Other factor that has to be taken into account for explaining those discrepancies is the fact that the simulation results represent average performance measures over a large number of

²In multicriteria analysis (assuming a multiple objective minimisation problem) a solution s_1 dominates s_2 with respect to criteria f^i ($i = 1, \dots, n$) iff $f^i(s_1) \leq f^i(s_2), \forall i$ and $f^j(s_1) < f^j(s_2)$ for at least one $j \in \{1, 2, \dots, n\}$. In the present context criteria, metric or objective function have equivalent meaning.

routing updating periods while the analytic results assume perfectly stationary traffic conditions. One could use more realistic representations of the traffic flows namely based on their mean and variance, enabling to obtain better estimates of the blocking probabilities (without the biasing towards underestimation for zero or low overload) obtained from known models in teletraffic theory. In any case this, or other eventually more realistic traffic representations based on higher order moments, would turn the analytical model rapidly intractable, having in mind that it has to be solved numerically a very large number of times in the context of the heuristic of synchronous path selection. Note that the importance of the accuracy of the results given by the traffic calculation model, in the context of the MODR-S, is in terms of relative values of the associated route metrics (since the aim is just to compare routing solutions with respect to those metrics) rather than in terms of absolute errors.

Extensive results for this and other test networks have been obtained and confirm the better relative performance of MODR-S in comparison with RTNR and DAR-S in most cases (see [24]). In many cases results from MODR-S in other test networks were even more favourable than for the mentioned test network.

Overload Factor	MODR-S		DAR-S	
	Simulation Model		Simulation Model	
	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$
Service $s = 1$				
0.8%	$0.002 \pm 2.6 \times 10^{-4}$	$0.009 \pm 2.8 \times 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
0.9%	$0.003 \pm 6.3 \times 10^{-4}$	$0.009 \pm 1.6 \times 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
0%	$0.004 \pm 6.1 \times 10^{-4}$	$0.014 \pm 2.6 \times 10^{-3}$	$0.001 \pm 1.8 \times 10^{-4}$	$0.002 \pm 1.3 \times 10^{-4}$
10%	$0.005 \pm 9.5 \times 10^{-4}$	$0.017 \pm 3.6 \times 10^{-3}$	$0.002 \pm 1.5 \times 10^{-4}$	$0.004 \pm 2.4 \times 10^{-4}$
20%	$0.006 \pm 4.0 \times 10^{-4}$	$0.017 \pm 2.6 \times 10^{-3}$	$0.003 \pm 3.2 \times 10^{-4}$	$0.006 \pm 5.8 \times 10^{-4}$
30%	$0.008 \pm 9.3 \times 10^{-4}$	$0.021 \pm 6.4 \times 10^{-3}$	$0.004 \pm 4.7 \times 10^{-4}$	$0.008 \pm 1.4 \times 10^{-3}$
40%	$0.009 \pm 1.2 \times 10^{-3}$	$0.022 \pm 3.3 \times 10^{-3}$	$0.005 \pm 5.1 \times 10^{-4}$	$0.010 \pm 7.8 \times 10^{-4}$
Service $s = 2$				
0.8%	$0.003 \pm 1.2 \times 10^{-3}$	$0.011 \pm 3.5 \times 10^{-3}$	$0.003 \pm 9.0 \times 10^{-4}$	$0.013 \pm 5.0 \times 10^{-3}$
0.9%	$0.012 \pm 2.7 \times 10^{-3}$	$0.032 \pm 9.7 \times 10^{-3}$	$0.009 \pm 1.9 \times 10^{-3}$	$0.029 \pm 3.2 \times 10^{-3}$
0%	$0.025 \pm 4.6 \times 10^{-3}$	$0.051 \pm 7.6 \times 10^{-3}$	$0.023 \pm 4.5 \times 10^{-3}$	$0.053 \pm 1.0 \times 10^{-2}$
10%	$0.043 \pm 4.4 \times 10^{-3}$	$0.082 \pm 7.4 \times 10^{-3}$	$0.040 \pm 2.6 \times 10^{-3}$	$0.084 \pm 1.1 \times 10^{-2}$
20%	$0.062 \pm 4.4 \times 10^{-3}$	$0.111 \pm 1.0 \times 10^{-2}$	$0.061 \pm 5.6 \times 10^{-3}$	$0.120 \pm 1.0 \times 10^{-2}$
30%	$0.080 \pm 6.3 \times 10^{-3}$	$0.152 \pm 1.1 \times 10^{-2}$	$0.084 \pm 7.4 \times 10^{-3}$	$0.155 \pm 6.3 \times 10^{-3}$
40%	$0.101 \pm 6.9 \times 10^{-3}$	$0.184 \pm 2.2 \times 10^{-2}$	$0.108 \pm 7.6 \times 10^{-3}$	$0.191 \pm 1.4 \times 10^{-2}$
Service $s = 3$				
0.8%	$0.004 \pm 1.8 \times 10^{-3}$	$0.017 \pm 8.5 \times 10^{-3}$	$0.009 \pm 3.6 \times 10^{-3}$	$0.035 \pm 7.7 \times 10^{-3}$
0.9%	$0.011 \pm 2.9 \times 10^{-3}$	$0.031 \pm 6.8 \times 10^{-3}$	$0.023 \pm 4.8 \times 10^{-3}$	$0.055 \pm 7.8 \times 10^{-3}$
0%	$0.026 \pm 3.6 \times 10^{-3}$	$0.062 \pm 1.5 \times 10^{-2}$	$0.051 \pm 7.8 \times 10^{-3}$	$0.122 \pm 7.9 \times 10^{-3}$
10%	$0.046 \pm 4.3 \times 10^{-3}$	$0.103 \pm 2.8 \times 10^{-2}$	$0.088 \pm 6.6 \times 10^{-3}$	$0.201 \pm 3.3 \times 10^{-2}$
20%	$0.068 \pm 4.8 \times 10^{-3}$	$0.129 \pm 1.6 \times 10^{-2}$	$0.132 \pm 1.0 \times 10^{-2}$	$0.258 \pm 4.5 \times 10^{-2}$
30%	$0.090 \pm 7.2 \times 10^{-3}$	$0.161 \pm 2.2 \times 10^{-2}$	$0.177 \pm 1.2 \times 10^{-2}$	$0.312 \pm 3.2 \times 10^{-2}$
40%	$0.114 \pm 1.0 \times 10^{-2}$	$0.195 \pm 2.3 \times 10^{-2}$	$0.219 \pm 1.4 \times 10^{-2}$	$0.361 \pm 3.6 \times 10^{-2}$

Table 4: Service Performance - Comparison with DAR-S

5 Conclusions and Further Work

A novel multiobjective dynamic alternative routing model of periodic type for multiservice networks has been presented. It is based on a new type of network-wide alternative routing optimisation model where objective functions are formulated at network and service levels, including the explicit incorporation of fairness objectives. The model is adequate to strongly meshed networks and can be applied to networks which are equivalent, in the traffic plane, to multiclass traffic loss networks, namely ATM networks with VC connections and MPLS networks using explicit routes. The underlying analytical model was presented and the features of a heuristic approach for resolving in an efficient manner the multiobjective routing optimisation model, by calculating and selecting ‘good’ compromise routing solutions, were put forward.

Globally the performance of the presented MODR-S method is good compared with RTNR and DAR specially in overload conditions. The major added-value of this novel approach to dynamic routing is its particular multiobjective nature enabling the explicit incorporation in the mathematical model of several QoS objectives as well as fairness objectives. This enables the trade-offs among these objectives to be explored to the maximum extent, in a dynamic alternative routing environment. This modelling framework is in principle adaptable to various types of metrics relevant to different network environments. The major limitation of the method is its inherent complexity and the associated computational burden. The tuning of the path updating period having in mind this limitation and the possible decentralisation of MODR-S in fully meshed networks as well as the consideration of possible refinements in the heuristic and in the traffic calculation procedures deserve further investigation.

The possible developments in all these aspects must have in mind to reinforce the effectiveness (i. e. the capability to select ‘good’ routing solutions) of the method in various application environments, namely MPLS, and improve its tractability.

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