Formulation of a Multiple Objective Dynamic Routing Method using Implied Costs – Architecture and Algorithms

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Abstract

There are advantages in considering the routing problem in integrated communication networks as a multiobjective shortest path problem, having in mind to grasp eventual conflicts and trade-offs among distinct objectives and QoS constraints. On the other hand the utilization of dynamic routing methods in various types of networks is well known to have significant impact on network performance and cost, namely in overload and failure conditions. This paper presents the detailed formulation of a proposal of a multiple objective dynamic routing method (MODR) of periodic state dependent routing type, enabling to represent distinct QoS related metrics and requirements in a consistent manner. The MODR method present formulation is based on a multiple objective shortest path model with constraints and is prepared to use implied costs as one of the metrics. Alternative paths for each traffic flow are changed as a function of periodic updates of certain GoS related parameters estimated from real time measurements on the routes and trunks of the network. Such paths are computed by a specialised and efficient variant of a bi-objective shortest path constrained algorithm, developed for the MODR, enabling to incorporate flexible requirements on the QoS metrics. The architecture of the routing system is discussed together with the features of its main modules. An illustrative example of application of the MODR path calculation module to a circuit-switched type network using blocking probability and implied cost as metrics, is also presented, considering different overload conditions.

Key Words: Dynamic Routing, Quality of Service, Traffic Management and Control.

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1 Introduction

The evolution of multiservice network functionalities leads, in terms of teletraffic engineering, to the necessity of dealing with multiple, fine grain end heterogeneous GOS requirements. When applied to routing mechanisms this concern led, among other developments, to a new routing paradigm 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 (see [9]). Other interesting papers following this concern such as [13], [14] or [12], could be mentioned. In this context the path selection problem is normally formulated as a shortest path problem with a single objective function, either a single metric or encompassing 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, normally based on classical shortest path algorithms such as Dijkstra algorithm. Since the mathematical models have inherently a network structure which renders them to be tackled in an effective way by specialized and efficient algorithms, the introduction of additional constraints destroys some underlying properties and implies a heavier computational burden.

Therefore there are advantages in considering the routing problem of this type, subject to multiple constraints as a multiple objective problem. Besides cost, other aspects such as delay, blocking probability or bandwidth may be addressed explicitly by the mathematical model as objective functions which could be pursued to their optimum extent. Note that in a multiple objective context, involving multiple, potentially conflicting, incommensurate objective functions, the concept of optimal solution in single objective problems (unique in general) gives place to the concept of non-dominated solutions (feasible solutions for which no improvement in any objective function is possible without worsening at least one of the other objective functions). Multiple objective routing models thus enable to grasp the trade-offs among distinct QoS requirements by treating in a consistent manner the comparison among different routing alternatives. This type of approach was proposed in [1] by solving a static routing problem, formulated as a multiple objective shortest path problem, by using a particularly efficient algorithm approach. The global objective of this algorithm was to find a best compromise non-dominated solution (path) enabling simultaneously that QoS requirements might be expressed as additional (soft) constraints on the objective function values, which defined preference regions on the objective functions space.

On the other hand, the utilization 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 [5] and [4]).

The objective of this paper is to present a detailed formulation of a proposal of a Multiple Objective Dynamic Routing Method (or MODR) that may be envisaged as new type of Periodic State Dependent Routing (PSDR) method. The MODR method is based on a multiple objective routing paradigm and incorporates a dynamic alternative routing principle, as well as the utilization of the concept of implied cost in [8] as one of the metrics of the routing problem model. Other feature of MODR is the capability of defining preference regions (concerning the search for alternative paths) on the objective functions space which may change dynamically, through variable boundary values. The paper is organised as follows. Section 2 is a concise review of the Multiple Objective static routing model in [1] and of the general multiple-objective shortest path problem. The main features of the proposed MODR method are presented in section 3 and the main modules and functionalities of a centralized MODR architecture, are discussed. The characteristics of the route calculation algorithm developed for the MODR, are presented in section 5. Section 6 gives the model proposed for calculating dynamically changing estimates of the coefficients needed by a bi-objective version of the MODR method, namely certain GoS related parameters obtained from the periodic measurements on the network links and the implied costs associated with the links. An example of application of the MODR method to a fully meshed circuit-switched network is shown is section 7 in order to illustrate relevant features of the proposed alternative route calculation method and its inherent capabilities. Finally some conclusions and lines for further work on this matter will be outlined in the conclusion section.

2 Review of a Multiple Objective Routing Principle

The static routing principle and the basic algorithm, from which the MODR routing method was derived was proposed in [1]. This approach formulates the static routing problem as a multiple objective shortest path problem and uses a particularly efficient algorithmic approach. This algorithm computes non-dominated paths by optimizing weighted-sums of the multiple objective functions, to determine solutions which belong to the boundary of the convex hull of the union of the set $\mathcal{Z}$ of the non-dominated solutions with $\{z \in \mathbb{R}^K | z \geq 0\}$, namely vertex solutions. It uses a very efficient k-shortest path algorithm [10], to search for unsupported non-dominated solutions within duality gaps (which are solutions located to the inside of the convex hull). Also it enables that QoS requirements may be expressed as additional (soft) constraints on the objective functions values in terms of requested and acceptable thresholds for each metric, which define preference regions in the objective functions space. Recall the general formulation of the multiple objective shortest path problem with K-objective functions, where each function is associated with a particular metric:

$$\min\ z^n = \sum_{l_k=(v_i,v_j)\in L} C_k^n x_{ij} \quad (n = 1, \ldots, K) \tag{1}$$

s.t.

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

where C_k^n is the cost associated with metric n $(n = 1, 2, \ldots, K)$ on arc $l_k = (v_i, v_j) \in L$ of the graph (V, L), V being the node set and L the arc set of the network structure. The variables x_{ij} enable to define a solution (path) p from node s to node t by taking the value 1 if the arc $(v_i, v_j) \in p$ and 0 otherwise. Note that the cost of a path is a real-valued vector $\mathcal{C}_p = (\mathcal{C}_p^1, \ldots, \mathcal{C}_p^K)$ with $\mathcal{C}_p^n = \sum_{l_k\in p} C_k^n$ being the cost associated with metric n. In general there is no feasible solution which minimizes all objective functions simultaneously. Since there is no guarantee of the existence of this ideal optimal solution, the resolution of this static Multiple Objective 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 optimizing a scalar function which is a convex combination of the K-objective functions:

$$\min\ z = \sum_{l_k\in L} C_k x_{ij} \tag{3}$$

with the same constraints of $\mathcal{P}^{(K)}$ and $C_k = \sum_{n=1}^{K} \epsilon_n C_k^n$ where $\epsilon = (\epsilon_1, \epsilon_2, \ldots, \epsilon_K) \in \varepsilon = \{\epsilon : \epsilon_n \geq 0, n = 1, \ldots, k \wedge \sum_{n=1}^{K} \epsilon_n = 1\}$. 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. The mentioned algorithmic approach implemented for two objective functions, designated hereafter as Basic Multi-objective Routing Algorithm (BMRA) resorts to an extremely efficient k-shortest path algorithm [10] to search for this specific type of non-dominated paths. Note that direct application of the BMRA requires the metrics to be additive such as in the case of delay, hop-count and cost (in strict sense). Blocking probability is a key metric to be considered in the case of traffic flows working on a loss basis. This metric can be easily transformed into an additive metric by associating with each arc l_k, $-\log(1-B_k)$, B_k being the blocking probability on l_k. The other main features of the BMRA, the details of which are described in [1] are:

- it enables QoS requirements to be expressed as additional (soft constraints) on the objective function values in terms of requested and acceptable thresholds for each metric, which define preference regions in the objective functions space;
- it performs a very efficient search for non-dominated solutions both in the boundary and in the interior of the convex hull according to a search direction defined by the gradient of the plane passing through the points obtained by the intersection of the requested and the optimal values for each function. The details of the way in which BMRA works and an illustrative example of its application using as metrics cost and delay were also shown in [1].

3 The MODR Method

The multiple objective dynamic routing method proposed in this paper may be envisaged as a new type of Periodic State Dependent Routing (PSDR) method based on a Multiple Objective routing paradigm. The PSDR class of routing methods were formulated for circuit-switched networks in [7] by the ITU-T group 2 and were based on a centralized type of control which provides routing decisions for each pair of exchanges based on periodical updates of the number of free circuits in each trunk of the network using a typical update period of $10s$. In its general formulation the MODR here discussed has the following main features:

1. Paths are changed dynamically as a function of periodic updates of certain GoS related parameters obtained from real-time measurements, using a Multiple Objective principle which enables to consider, in a consistent manner, eventually conflicting QoS metrics;

2. It uses a very efficient version of the BMRA, designated hereafter as Modified Multiobjective Routing Algorithm (MMRA), prepared to deal with the selection of alternative paths in a dynamic alternative routing context;

3. The present version of the method uses implied costs in the sense defined by Kelly in [8] as one of the metrics to be incorporated in the underlying Multiple Objective model;

4. It enables to specify required and/or requested values for each metric (associated with pre-defined QoS criteria) as in the BMRA. Such values define preference regions on the objective functions space, which may change dynamically, in a flexible way, through variable boundary values. This capability is attached to a Routing Management System (described in the next section) 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. This may be easily formalised in the following manner.

Let R be the number of routes attempted by a call of each traffic flow $(r^1(f), r^2(f), \ldots, r^R(f))$ and $S(f)$ be the ordered set of solutions selected by MMRA $\{s_1, s_2, \ldots, s_R\}$ for flow f as a function of the defined priority regions for flow f and $r_d(f)$ the possible direct route:

1st Case:

$$r_d(f) = \emptyset \Rightarrow r^i(f) = s_i, \quad (i = 1, 2, \ldots, R) \tag{4}$$

2nd Case:

$$r_d(f) \neq \emptyset \Rightarrow \begin{cases} r^1(f) & = & r_d(f) \\ r^i(f) & = & s'_{i-1}, \quad (i = 2, \ldots, R) \end{cases} \tag{5}$$

with $S'(f) = S(f) \backslash \{r_d(f)\} = \{s'_1, \ldots, s'_{|S'(f)|}\}$

All these features aim at turning more effective and flexible the application of the Multiple Objective routing approach to a dynamic routing method, having in mind the multifaceted nature of traffic flows and the variability of a network working conditions.

4 Architecture of the MODR System

Here the main features and functionalities of a centralized version of the MODR method architecture, will be analysed. A periodic centralized routing technique[1] must be able of computing, every T seconds, for every traffic flow f associated with each exchange pair of the network, the routing tables better fitted to the network state, having in mind to obtain the best possible network performance according to the routing method. For this purpose the MODR routing system must receive from the network nodes, the necessary GoS related measurements.

As can be seen in figure 1, there are the two following main subsystems:

- **Routing Control / Real Time Management**, which is the core of the MODR method architecture.

  The core of this subsystem is the MMRA (Modified Multiobjective Routing Algorithm) path calculation algorithm (it constitutes the basis of the Alternative Path Calculation Module), described in the next section. The inputs to the MMRA are the current values of the coefficients of the objective functions and the associated (soft) constraints which define preference regions in the objective function space. The updates of the alternative paths for each traffic flow between a pair of exchanges are performed with period T (typical time scale of $10s$ for example).

  The routing control also includes a *Network Data* module that contains all the necessary information about the network configuration that is important for the coefficient calculation.

- **Routing Management System** which operates on a wider time scale as compared with the previous subsystem.

  The main functions of this subsystem are the following:

  - The specification of relevant parameters for the routing control such as the path update period T and the frequency $1/\tau$ of real time measurements of GoS related parameters needed for the calculation of the objective functions coefficients. A change in the maximum number R of alternative paths is also possible.
  - The specification of threshold values for the route metrics (typically required and/or acceptable values) which enable to define the preference regions for alternative path se-

[1]Here the term routing technique is considered as synonym of a particular implementation of a certain routing method in terms of control, circuit reservation, traffic routing management, etc.

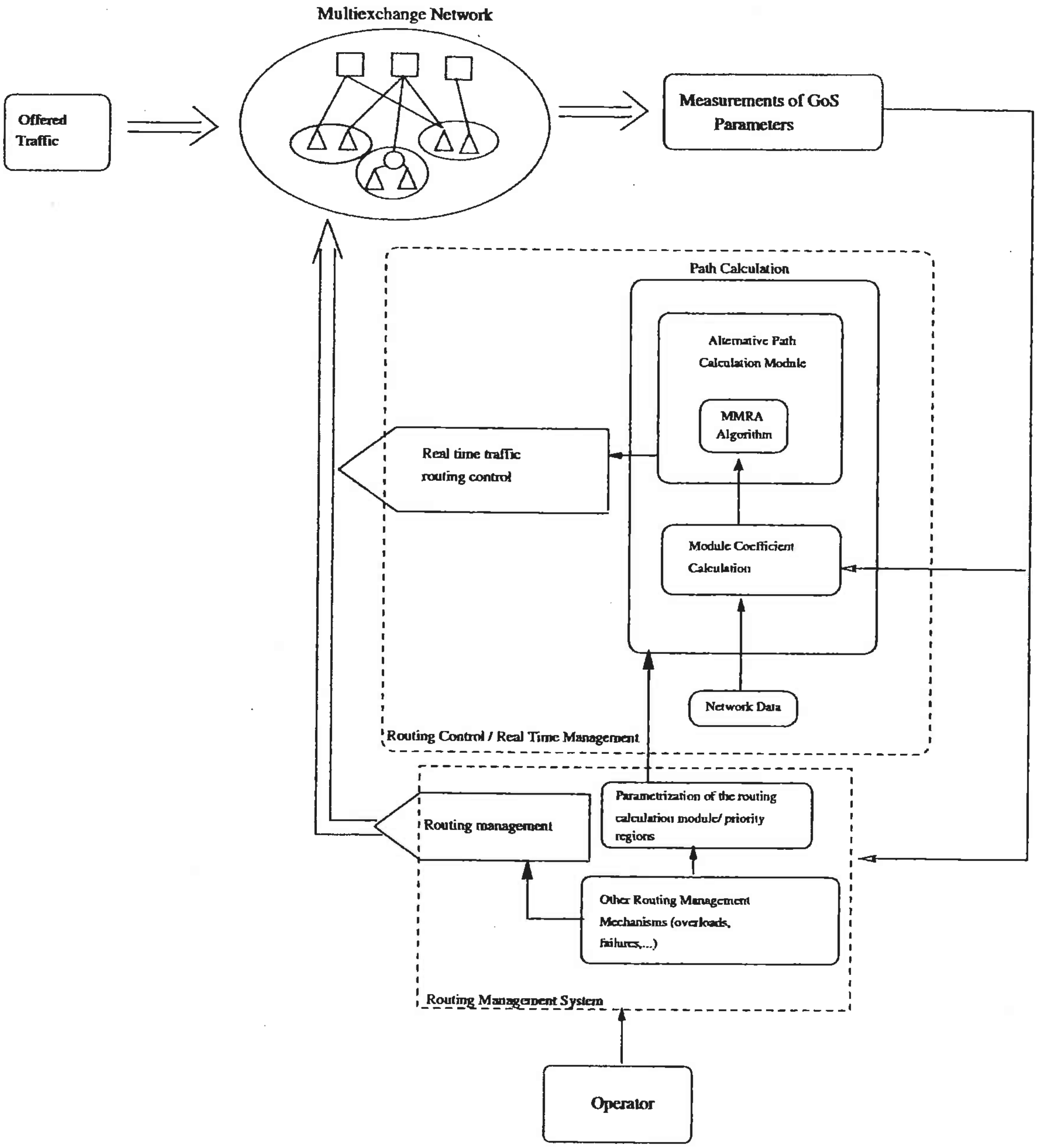

Figure 1: Architecture of the MODR System

lection according to the MMRA (see section 5). Such values may be modified empirically at any time, as a result of the intervention of the operator of the Routing Management System (an essential part of any Traffic Management System). Those values, namely the required (or "desirable") values, also may vary periodically (with period T) as a result of the changes in the marginal optimal of the objective functions using a criterion as the one defined in section 5 for the priority regions. These functions are associated with the Parametrisation Module in figure 1.

Also, other, more specialised mechanisms, namely related to the functional and/or transport network levels, may also be included in this subsystem in order to reinforce the network survivability under particular failure or overload conditions through the module designated in figure 1 as Other Routing Management Mechanisms.

Finally the parametrisation of service protection mechanisms such as circuit reservation could be performed through this module.

Note that those mechanisms are strongly dependent on the characteristics of the network and traffic flows in terms of basic technologic features, provided services and global QoS targets defined/negotiated by the network operator or service provider.

The core of the MODR method, i.e., the Routing Control / Real Time Management subsystem, can be, in principle, decentralized to the network nodes without too much effort when the network is totally meshed, assuming each node has an associated Path Calculation Module. In this case, some additional signalling messages, which must include the values of the implied costs and blocking probabilities on the links, must be exchanged between the nodes, because each node must have information about these data related to all the links, in order to be able to compute the shortest multi-objective paths via the MMRA. It must be noted that the implied cost for the adjacent links of each node can be computed in this case because each node knows the implied cost for all links in the network needed for its path calculations.

5 The Route Calculation Algorithm MMRA

The Modified Multiobjective Routing Algorithm is a new variant of the BMRA proposed in [1], adapted and optimised to the needs of the MODR method. It's basic features and differences with respect to the BMRA are the following:

1. It enables to search for and select non-dominated or dominated paths for alternative routing purposes.

2. It uses as sub-algorithm for calculating k-shortest paths (in order to find possible solutions in the interior of the convex hull) a new variant of the k-shortest path algorithm in [10], developed in [6] by some of the authors 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.

3. The search direction in the objective function space is a 45° 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 the BMRA. This is justified by the need of giving no precedence to any of the two objective functions in terms of the search for possible solutions, having in mind the variable nature of the metrics in an integrated service communications environment and the possibility of variation of the priority regions configuration as pointed out in the next point.

4. The priority regions for alternative path selection have a flexible configuration that varies dynamically 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

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, 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 application example described in section 7 for a circuit-switched network with loss traffic, using call blocking probability and implied cost as metrics the following approach was used. As for the path blocking probabilities, having in mind that alternative routing is used, the value required for path blocking, B_{req} is obtained from an approximation based on the mean call blocking on the trunks, calculated when the network is dimensioned for a typical end-to-end blocking probability such as 0.5%:

$$B_{req} = 1 - \prod_{k=1}^{D} (1 - B_{kmed}) = 1 - (1 - B_{kmed})^D \tag{6}$$

by considering

$$B_{kmed} = \frac{1}{|L|} \sum_{l_k \in L} B_k^d \tag{7}$$

B_k^d being the calculated average call congestion on link l_k resulting from the dimensioned network and D the maximum number of links per path. Note that this criterion intends to guarantee that the constraint B_{req} is satisfied by any path selected by the MMRA in the priority regions for which $B \leq B_{req}$.

As for the implied costs obtained from the model described in section 6, analogous criterion leads to the required implied cost path value:

$$c_{req} = \sum_{k=1}^{D} c_{kmed} = Dc_{kmed} \tag{8}$$

by considering

$$c_{kmed} = \frac{1}{|L|} \sum_{l_k \in L} c_k^d \tag{9}$$

c_k^d being the implied cost value obtained for link l_k, using an adequate form of numerical fixed point iteration for the engineered network. For obtaining the acceptable values B_{acc} and c_{acc} for the associated path metrics an analogous procedure was used by dimensioning the network for a typical end-to-end blocking value such as 1%.

Taking into account the variability in time of the marginal optimum Op^n of each objective function z^n, the following cases may occur regarding the priority regions in the bi-objective model, designating by M a generic metric:

i) $M_{req}^n > Op^n$ for $(n = 1, 2)$ in which case there are 5 priority regions, analogously to the static routing example in [1]

ii) If $Op^n < M_{req}^n < M_{acc}^n$ for one of the objective functions and $M_{req}^m < Op^m < M_{acc}^m$, $(m \neq n)$ then there are 3 priority regions as illustrated in figure 2.

iii) If $M_{req}^n < Op^n < M_{acc}^n$ for $(n = 1, 2)$ then there are two priority regions only, of type C and D.

iv) If $M_{acc}^n < Op^n$ for $(n = 1, 2)$, case in which there is only region D for searching for last chance route(s), defined by the intervals $[Op^n, M_L^n]$.

It is assumed the following convention: A_n is a region which satisfies both requirements (M_{req}^n and M_{acc}^n) for z^n ($A \equiv A_1 \cap A_2$); B_n a region which satisfies M_{req}^n and M_{acc}^n but doesn't satisfy M_{req}^m although satisfying M_{acc}^m $(m \neq n)$; C a region which satisfies M_{acc}^n $(n = 1, 2)$ but not M_{req}^n $(n = 1, 2)$ and D is the last priority region, corresponding to search for a last chance route in the cases where particularly unfavorable network conditions occur (resulting for example from certain overloads or component failures such that not even M_{acc}^n is satisfied for any of the metrics); M_L^n is the more relaxed bound considered for z^n.

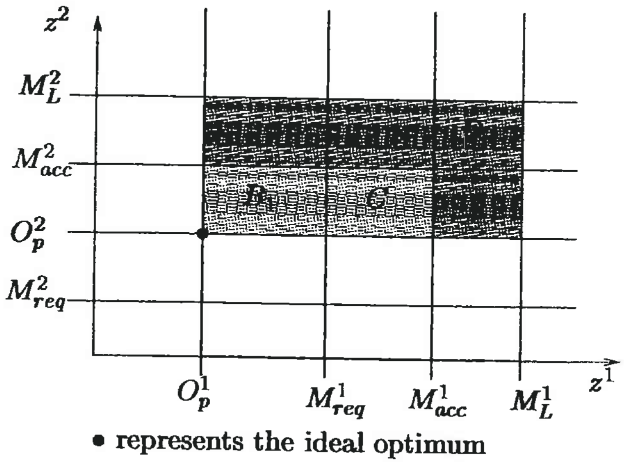

Figure 2: Case *ii*) for dynamic priority regions (B_1, C, D)

6 Estimates of the Model Coefficients

6.1 Parameter Dynamic Estimates

The periodical computations for updating the node routing tables for the n^{th} time interval, of duration T are based on GoS related measurements obtained from the nodes (associated with the exchanges) in the $(n-1)^{th}$ time interval and possibly on values obtained in previous time intervals. These values are used in the estimation of the GoS parameters needed for obtaining the routing tables for the n^{th} time interval. Moving-average iterations, as suggested in [8], may be used for that purpose as will be explained next.

One of the parameters to be estimated is the blocking probability on each link l_k. In the time interval, $[(i-1)\tau, i\tau[$ – τ is the measurement period – an estimate of the blocking probability is $\mathcal{B}_k(i-1) = N^T_{i_{loss}}/N^T_i$ where $N^T_{i_{loss}}$ is the number of lost calls and N^T_i is the number of call attempts in that interval. For simplicity, it will be assumed that the updating period τ of the measurements coincides with the routing updating period T.

If $\beta_k(n)$ is an estimator of blocking probability for link l_k for the n^{th} time interval then it can be calculated through the first order moving-average iteration:

$$\beta_k(n) = (1-b)\beta_k(n-1) + b\mathcal{B}_k(n-1) \tag{10}$$

where $b \in [0,1]$ reflects a balance between accuracy of estimation and speed of response. This estimation is carried out in the module **Measurements of GoS Parameters**. The information concerning the values $\beta_k(n)$, obtained at one of the adjacents nodes of l_k should then be conveyed to the centralized routing system.

The forecasted carried traffic on link l_k for the n^{th} time interval, $y_k(n)$, can also be estimated in a similar manner, i.e., $y_k(n) = (1-b')y_k(n-1)+b'Y_k(n-1)$, where $Y_k(n-1)$ is the estimate for the average carried traffic in the $[(n-1)T, nT[$ period, which was communicated to the **Measurements of GoS Parameters** module.

The carried traffic estimate for a path $r^i(f)$, $x_{r^i(f)}(n)$, associated with traffic flow f between a certain pair of nodes can be, in principle, estimated in a way similar to the two previously mentioned parameters. Nevertheless, in dynamic routing, the set of routes available for each pair of nodes may change in successive periods, so the moving-average iterations must be adapted to cope with this: if a path was selected as a possible route in the $(n-1)^{th}$ time interval but not in the $(n-2)^{th}$ interval, then only the measurements in the $(n-1)^{th}$ interval should be used in the estimation scheme for the n^{th} interval. Therefore b should be made equal to 1 in this situations. The details of the easy adaptation of these estimation schemes to the cases in which it is used a measurement updating period τ shorter than T, are explained in [11].

6.2 Implied Costs Estimates

Two possible approaches for calculating implied costs estimates in the context of MODR with $R = 2$, are now presented for a circuit-switched type network with single circuit calls.

The first one, using a moving-average iteration, as in the previous sub-section, will be described next.

Let $c_k(n)$ be an estimate for c_k, the implied cost[2] [8] associated with link l_k and $s_{r^i(f)}(n)$ be an estimate for $s_{r^i(f)}$, the surplus value of a call on route $r^i(f)$ $(i = 1, 2)$, for the n^{th} time interval. Designating by $w(f)$ the expected revenue obtained from an accepted call of traffic flow f, then one may easily obtain (see details in [11]) from equation (7.11) in [8] the following iterative scheme:

$$\begin{aligned}
c_k(n) &= (1-a)c_k(n-1) + aF_k(n)\Bigg[\sum_{f:l_k\in r^1(f)} \frac{x_{r^1(f)}(n)}{y_k(n)}\Big(c_k(n-1)+s_{r^1(f)}(n-1)\Big) + \\
&\quad + \sum_{f:l_k\in r^2(f)} \frac{x_{r^2(f)}(n)}{y_k(n)}\Big(c_k(n-1)+s_{r^2(f)}(n-1)\Big)\Bigg] \qquad (11)\\
s_{r^2(f)}(n) &= w(f) - \sum_{l_j\in r^2(f)} c_j(n-1)\\
s_{r^1(f)}(n) &= w(f) - \sum_{l_j\in r^1(f)} c_j(n-1) - \Big(1-L_{r^2(f)}(n)\Big)\, s_{r^2(f)}(n)
\end{aligned}$$

[2] As shown by Kelly in [8], c_k is the mean increase in the value of lost calls in the network as a result of removing one circuit for unit time, from link l_k.

where

$$F_k(n) = z_k(n)[E(z_k(n), C_k - 1) - E(z_k(n), C_k)] \tag{12}$$

$E(A, C)$ is the value of the Erlang-B function for offered traffic A and C circuits, and $z_k(n)$,the estimate of the offered traffic on link l_k given by $y_k(n)/(1 - \beta_k(n))$ for the n^{th} time interval. The meaning of the auxiliary parameter a is analogous to b in the previous sub-section.

The second approach, more rigorous, although heavier in terms of required numerical calculations, is based on the execution of a fixed point iteration at the beginning of each period of duration T. Let $c_k^{j_n}(n)$ designate an estimate for c_k, and $s_{r^i(f)}^{j_n}(n)$ an estimate for the surplus value of a call on route, $r^i(f)$, for the n^{th} time interval, using this approach. Then the calculation procedure is the following:

$$\begin{aligned}
c_k^{j+1}(n) &= (1-a')c_k^j(n) + a'F_k(n)\Bigg[\sum_{f:l_k\in r^1(f)} \frac{x_{r^1(f)}(n)}{y_k(n)}\left(c_k^j(n) + s_{r^1(f)}^j(n)\right) + \\
&\quad + \sum_{f:l_k\in r^2(f)} \frac{x_{r^2(f)}(n)}{y_k(n)}\left(c_k^j(n) + s_{r^2(f)}^j(n)\right)\Bigg] \\
s_{r^2(f)}^{j+1}(n) &= w(f) - \sum_{l_j\in r^2(f)} c_j^j(n) \\
s_{r^1(f)}^{j+1}(n) &= w(f) - \sum_{l_j\in r^1(f)} c_j^j(n) - \left(1 - L_{r^2(f)}(n)\right) s_{r^2(f)}^{j+1}(n)
\end{aligned} \tag{13}$$

with $j = 0, 1, \ldots, j_n - 1$ and $c_k^0(n) = c_k^{j_{n-1}}(n-1)$, where j_n is the number of iterations used to calculate $c_k(n)$. The parameter a', in this approach is the damping parameter of the fixed point iteration scheme. Here a' should be chosen in order to guarantee the convergence of the iterations in (13).

7 Application Example

A fully-meshed 6 node circuit-switched network with single circuit calls was dimensioned according to the method in [3], for 0.005 end-to-end blocking probability, assuming one alternative path to the direct route. The obtained network is characterised in table 1.

For the definition of the priority regions bounds, the required values for each metric of the paths, are given according to (6), (8) :

$$B_{req} = 1 - (1 - B_{k_{med}})^2 \tag{14}$$

$$c_{req} = 2c_{k_{med}} \tag{15}$$

Node pair	Direct link capac.	Offered traffic	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 1: Network of the application example

where $B_{k_{med}}$ is the average link blocking probability and $c_{k_{med}}$ is the average implied cost of the links, both obtained for the network in table 1, using fixed point iteration schemes.

The acceptable bounds are obtained by a similar approach for the same network topology dimensioned for end-to-end blocking probability of 0.01 (for the same traffic offered as in table 1).

These bounds are marked in figures 3 (a) and (b) where the search direction is a 45° straight line.

Two examples for illustrating the application of the MMRA model have been selected, showing the results of the search for two paths, with at most two links. The following notes may be drawn from this experimental study.

- Blocking probability and implied cost may be conflicting criteria, although in general they are not orthogonal. In example (a) described in table 2 (network with 5% overload) it is shown that the three first generated solutions are non-dominated. In example (b) described in table 3 (network with 10% overload in all traffic flows from node 1) although the first feasible solution is the ideal optimal solution (meaning that in this case the two metrics are not conflicting and lead to the same optimal solution), the second and the third solutions are dominated solutions not comparable in a multicriteria sense. In fact, in various fully meshed networks, dimensioned by the same algorithm as the network in table 1, more than 50% of node pairs, for the first and/or the second path, path blocking probability and path implied cost were conflicting objectives. This fully justifies the potential advantages of the MODR principle.

- In both examples represented graphically in figure 3 (a) and (b) in the objective function space, the number of generated paths depends on the fact that the MMRA algorithm does not stop searching for paths while there is the possibility of finding a solution in a lower preference region not yet fully covered.

- The MMRA algorithm selects in first place the direct path, regardless of its priority region as can be seen in table 2, following rule (5).

The results in tables 2 and 3 are graphically presented in figures 3 (a) and (b) with the preference regions clearly marked. Note that the last choice region D is not represented in these graphics.

i	Blocking	Implied Cost	Generated paths	Selected paths	Type	Preference region type
1	0.119621	0.371881	$2 \to 3$	$r^1(f)$	non-dominated	C
2	0.112106	0.410792	$2 \to 1 \to 3$		non-dominated	C
3	0.0953536	0.471365	$2 \to 5 \to 3$	$r^2(f)$	non dominated	B_1
4	0.164738	0.521878	$2 \to 6 \to 3$		dominated	C
5	0.167548	0.563675	$2 \to 4 \to 3$		dominated	C

Table 2: Network with 5% overload

i	Blocking	Implied Cost	Generated paths	Selected paths	Type	Preference region type
1	0.0292787	0.0950544	$5 \to 3$	$r^1(f)$	**ideal solution**	A
2	0.137195	0.493963	$5 \to 2 \to 3$	$r^2(f)$	dominated	C
3	0.152468	0.487164	$5 \to 6 \to 3$		dominated	C
4	0.149753	0.541269	$5 \to 1 \to 3$		dominated	C
5	0.218845	0.562676	$5 \to 4 \to 3$		dominated	C

Table 3: Network with 10% overload in traffic flows from node 1

8 Conclusions and Further Work

The detailed formulation of the proposal of a Multiple Objective Dynamic Routing method of PSDR type, was presented. The method is based on a multiple objective shortest path model resolved in its present version, by a specialised and very efficient algorithm which enable to find a pre-defined number of alternative paths, which may change periodically as function of GoS related

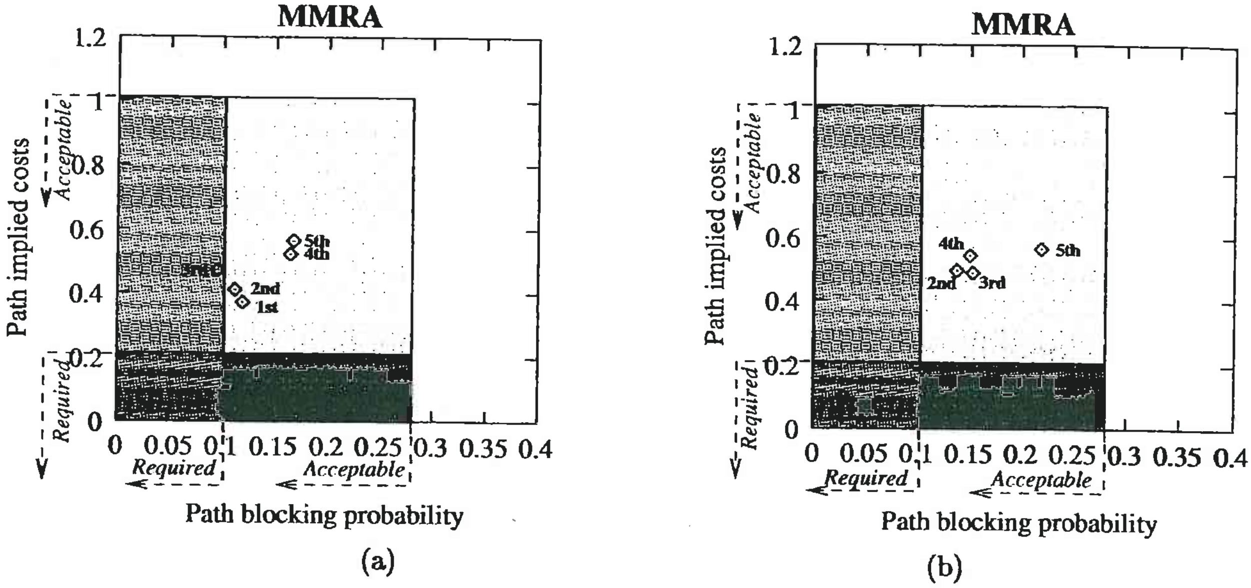

Figure 3: (a) Network with 5% overload (b) Network with 10% overload in all traffic flows from node 1

parameter measurements. The present formulation of the method uses implied costs as one of the metrics, which enables to represent the knock-on effects of accepting a call on a given route upon the other routes (see [8]), in the context of the MODR. The modules and functionalities of a MODR centralised architecture were also outlined as well as the possibility of decentralising some of its basic functions in the case of fully meshed networks. Other important feature of the method is the capability of defining in a dynamic and flexible way, preference regions for selection of alternative routes between every pair of nodes as a function of required and/or requested values for each metric. An application example of the MODR principle to a fully meshed circuit-switched network was also presented which showed that path implied cost and blocking probability may be conflicting objectives in many practical network working conditions, namely in cases of global or local overload. This fully justifies, in our opinion, potential advantages of a MODR type method.

Further work should be focused on a number of open issues, namely: the evaluation of network performance under MODR in different traffic conditions using an appropriate simulation platform, and its comparison with other PSDR methods, in the context of multiservice networks. Also the parametrisation of the method namely in terms of the tunning of the updating periods for the measurements and routing tables should be addressed through simulation. Also the potential effects of the parameter estimation models should be investigated, having in mind a reasonable trade-off between the costs in terms of call processing and signalling requirements and the eventual impact on network performance. Also the incorporation of service protection mechanisms, already foreseen in the routing architecture should be addressed in the near future having in mind the known significant impact of these mechanisms in network performance, as shown in [2] in the case of adaptative dynamic routing. The extension of the MODR principle to broadband networks is being developed at the present.

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