Paper

A new multiple objective dynamic routing method using implied costs

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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 quality of services (QoS) constraints. On the other hand the utilisation 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 QoS 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.

Keywords — dynamic routing, multicriteria decision support systems, traffic management.

1. Introduction

The evolution of multiservice network functionalities leads, in terms of teletraffic engineering, to the necessity of dealing with multiple, fine grain and heterogeneous QoS 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 QoS requirements and seeking simultaneously to optimise route associated metrics (or a sole function of different metrics) such as a cost, delay, number of hops or blocking probability. This trend makes it necessary to consider explicitly distinct metrics in routing algorithms such as in references [1, 2, 3] or [4]. 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. Since the mathematical models have inherently a network structure which renders them to be tackled in an effective way by specialised 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. 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 previously proposed by the authors [5] to solve a static routing problem, formulated as a multiple objective shortest path problem, and using a particularly efficient algorithmic approach.

On the other hand the utilisation of dynamic routing in various types of networks is well known to have a quite significant impact on network performance and cost, namely considering time-variant traffic patterns, overload and failure conditions (see for example [6] and [7]).

The objective of this paper is to present a formulation of a multiple objective dynamic routing method (or MODR) that may be envisaged as a 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 utilisation 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) 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 [5]. The main features of the proposed MODR method are presented in Section 3 and the main modules and functionalities of a centralised 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. 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, were proposed in [5]. 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 optimising 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 [9], 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. Recalling the general formulation of the multiple objective shortest path problem with K-objective functions, where each function is associated with a particular metric:

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

s.t.

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

where $\mathcal{C}_k^n$ 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 is 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 $\mathcal{C}_p^n = \sum_{l_k\in p} \mathcal{C}_k^n$ being the cost associated with metric n. In general there is no feasible solution which minimises 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 optimising a scalar function which is a convex combination of the K-objective functions:

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

with the same constraints of the original problem and $\mathcal{C}_k = \sum_{n=1}^K \varepsilon_n \mathcal{C}_k^n$ where $\varepsilon = (\varepsilon_1,\varepsilon_2,\ldots,\varepsilon_K) \in \mathcal{E} = \{\varepsilon : \varepsilon_n \geq 0, n = 1,\ldots,K \wedge \sum_{n=1}^K \varepsilon_n = 1\}$. However, by using this form of scalarization only supported non-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 [9] to search for this specific type of non-dominated paths. It must be noted that in the calculation of non-dominated solutions, namely unsupported non-dominated solutions, it seems useful considering reference point approaches. However in the case of shortest-path problems, the recent development of an extremely efficient algorithm (the MPS algorithm [9]) for the *k*-shortest path problem, creates the possibility of developing very efficient techniques for calculating supported and unsupported non-dominated solutions in this particular context.

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 (as required by the algorithm) by associating with each arc l_k, $-\log(1 - B_k)$, B_k being the blocking probability on l_k. Other common metrics such as cost, delay and hop-count follow the additive aggregation function. Also path bandwidth may be a metric of the model by using the concave aggregation rule [5]. The other features and the details of the BMRA, are described in [5].

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 [10] method based on a multiple objective routing paradigm. The PSDR class of routing methods [10] is based on a centralised 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 10 s.

In its general formulation the MODR here discussed has the following main features: i) paths are changed dynamically as a function of periodic updates of certain QoS related parameters obtained from real-time measurements, using a multiple objective principle which enables to consider, in a consistent manner, eventually conflicting QoS metrics; ii) it uses a very efficient version of the BMRA, designated hereafter as a modified multiobjective routing algorithm (MMRA), prepared to deal with the selection of alternative paths in a dynamic alternative routing context; iii) 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; iv) it enables to specify required and/or requested values for each metric (associated with predefined 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:

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

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

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

A periodic centralised routing technique 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 QoS related measurements. As can be seen in Fig. 1, there are 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 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 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 QoS related parameters; 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 selection 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 values 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 Fig. 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 Fig. 1 as other routing management mechanisms. Finally the parametrisation of service protection mechanisms such as circuit reservation could be performed through this module.

The core of the MODR method, i.e., the routing control/real time management subsystem, can be, in principle, decentralised 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 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.

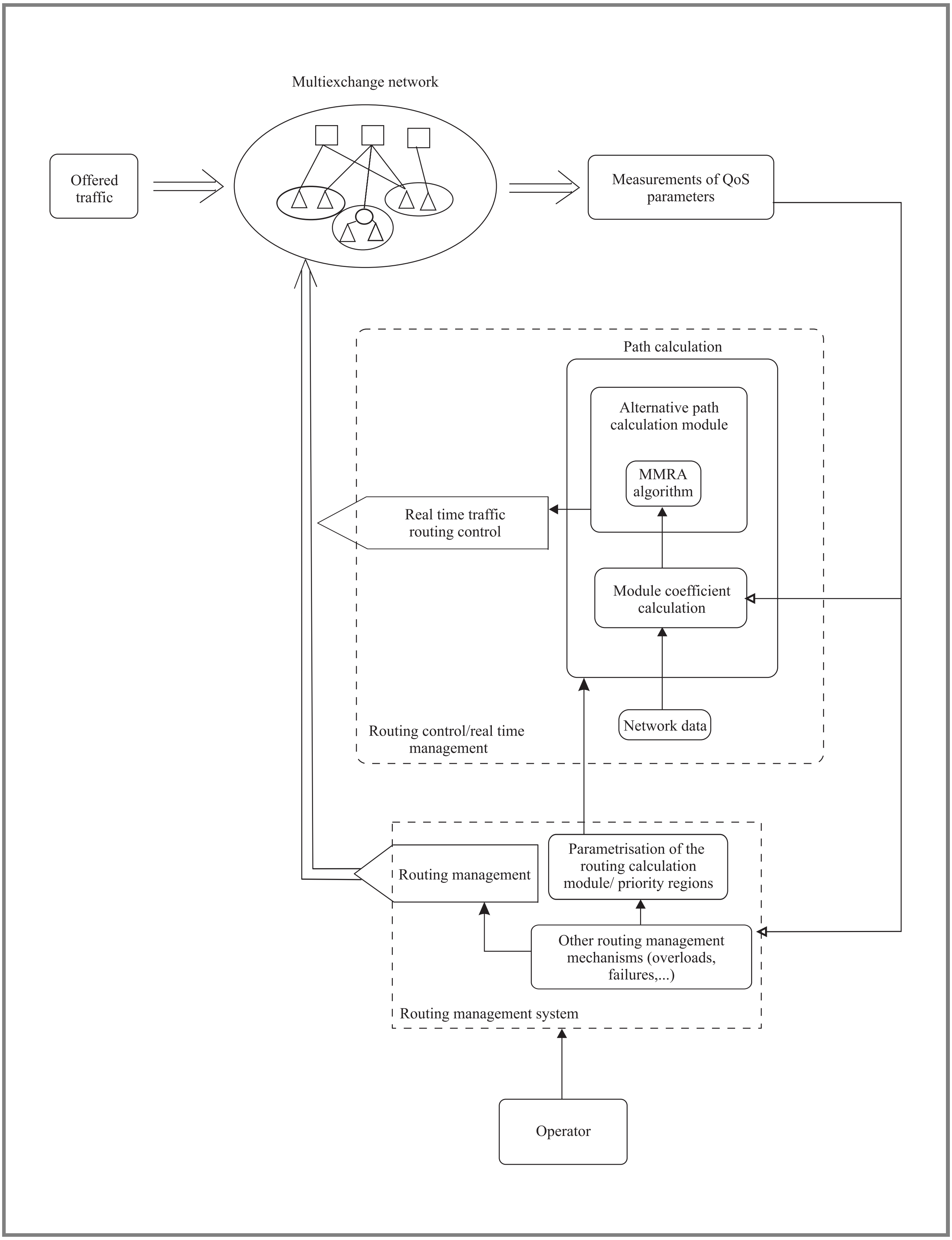

Fig. 1. Architecture of the MODR system.

5. The route calculation algorithm MMRA

The modified multiobjective routing algorithm is a new variant of the BMRA proposed in [5], adapted and optimised to the needs of the MODR method. Its basic features and differences with respect to the BMRA are the following: i) it enables to search for and select non-dominated or dominated paths for alternative routing purposes; ii) it uses as sub-algorithm for calculating k-shortest paths a new variant of the k-shortest path algorithm in [9], developed in [11] 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; iii) the search direction in the objective function space is a 45° straight line; this is justified by the variable nature of the metrics in an integrated service network environment and the possibility of dynamic variation of the priority regions; iv) the priority regions for alternative path selection have a flexible configuration that varies 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 and delay jitter for example, such values can be obtained from network experimentation and/or from ITU-T standardisation or recommendations for various types of networks and services. On the other hand, in the case of costs, namely implied costs, included in the present model, it is more difficult to define a priori such values, since no general criteria are known for these quantities. In the application example described in Section 7 for a circuit-switched network with loss traffic, 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%:

$$B_{req} = 1 - \prod_{k=1}^{D}\left(1 - B_{k_{med}}\right) = 1 - \left(1 - B_{k_{med}}\right)^{D} \quad (6)$$

$$\text{by considering } B_{k_{med}} = \frac{1}{|L|}\sum_{l_k \in L} B_k^d \,, \quad (7)$$

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:

$$c_{req} = \sum_{k=1}^{D} c_{k_{med}} = D c_{k_{med}} \quad (8)$$

$$\text{by considering } c_{k_{med}} = \frac{1}{|L|}\sum_{l_k \in L} c_k^d \,, \quad (9)$$

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) $M^n_{req} > Op^n$ for $(n = 1,2)$ in which case there are 5 priority regions, analogously to the static routing example in [5]; ii) if $Op^n < M^n_{req} < M^n_{acc}$ for one of the objective functions and $M^m_{req} < Op^m < M^m_{acc}$, $(m \neq n)$ then there are 3 priority regions as illustrated in Fig. 2; iii) if $M^n_{req} < Op^n < M^n_{acc}$ for $(n = 1,2)$ then there are two priority regions only, of type C and D; iv) if $M^n_{acc} < Op^n$ for $(n = 1,2)$, case in which there is only region D for searching for last chance route(s), defined by the intervals $[Op^n, M^n_L]$.

It is assumed the following convention: A_n is a region which satisfies both requirements (M^n_{req} and M^n_{acc}) for z^n $(A \equiv A_1 \cap A_2)$; B_n a region which satisfies M^n_{req} and M^n_{acc} but does not satisfy M^m_{req} although satisfying M^m_{acc} $(m \neq n)$; C a region which satisfies M^n_{acc} $(n = 1,2)$ but not M^n_{req} $(n = 1,2)$ and D is the last priority region, corresponding to search for a last chance route in the cases where particu-

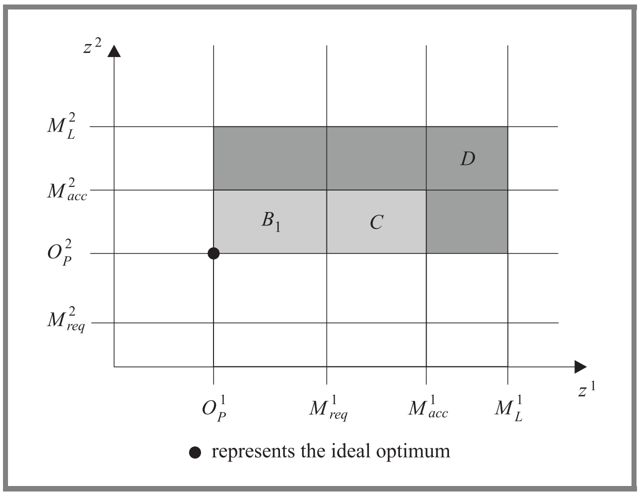

Fig. 2. Case $ii)$ for dynamic priority regions (B_1, C, D).

larly unfavorable network conditions occur. M_L^n is the more relaxed bound considered for z^n.

6. Estimates of the model coefficients

The periodical computations for updating the node routing tables for the nth time interval, of duration T, are based on QoS related measurements obtained from the network nodes in the $(n-1)$th time interval and possibly on values obtained in previous time intervals. Moving-average iterations, as suggested in [8], may be used for this 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 $\mathcal{B}_k(i) = N^T_{i_{loss}}/N^T_i$, 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 nth 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 QoS 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 centralised routing system. The forecasted carried traffic on link l_k for the nth 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 $Y_k(n)$ is the estimate for the average carried traffic in the $[(n-1)T, nT]$ period, which was communicated to the **measurements of QoS 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 similar manner. 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 nth interval. Therefore b should be made equal to 1 in this situation. 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 [12].

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 will be described next. Let $c_k(n)$ be an estimate for c_k, the implied cost 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 nth 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 [12]) from equation (7.11) in [8] the following iterative scheme:

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

where

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

Here $E(A,C)$ is the value of the Erlang-B function for offered traffic A and C circuits, $z_k(n)$ is the estimate of the offered traffic on link l_k given by $y_k(n)/(1-\beta_k(n))$ and $L_{r^i(f)}(n)$ the blocking probability estimate of $r^i(f)$, for the nth time interval. The meaning of the auxiliary parameter a is analogous to b.

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 $s^{j_n}_{r^i(f)}(n)$ an estimate for the surplus value of a call on route $r^i(f)$, for the nth time interval, using this approach.

Then the calculation procedure is the following:

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

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 [13] 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 Eqs. (6), (8): $B_{req} = 1 - (1 - B_{k_{med}})^2$, $c_{req} = 2c_{k_{med}}$, 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).

Table 1
Network of the application example

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

These bounds are marked in Figs. 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

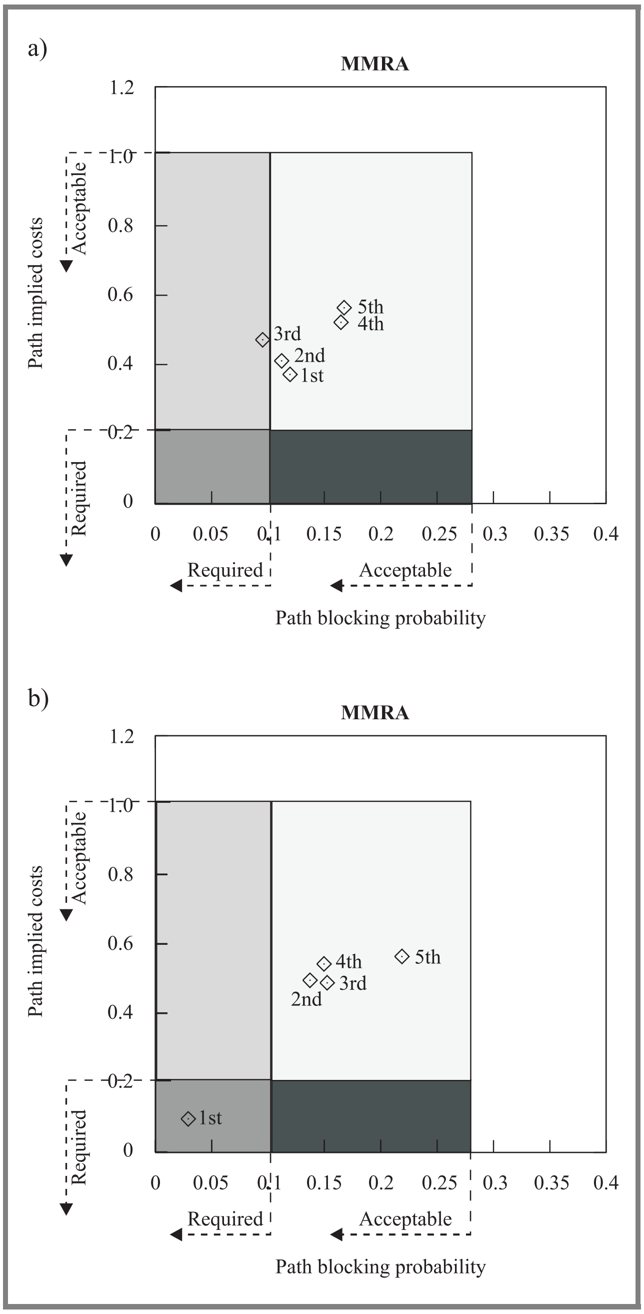

Fig. 3. (a) Network with 5% overload; (b) network with 10% overload in all traffic flows from node 1.

Table 2
Network with 5% overload

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

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

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

8. Conclusions and further work

A new MODR method is proposed having as basis a multiple objective shortest path model, tackled by a specialised and very efficient algorithm which enables to find a predefined number of alternative paths which may change periodically as function of QoS related parameter measurements. The present formulation of the method uses implied costs as one of the metrics, which enable 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.

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, 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 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 [14] 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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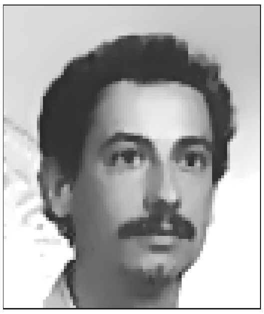

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