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A multiple objective routing algorithm for integrated communication networks

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Traditional routing algorithms are aimed at computing the optimal network path based on a single metric (or a function which is a combination of different metrics). However, in integrated communication networks distinct quality of service (QoS) requirements are at stake. This paper presents a new algorithmic approach to deal with the routing problem in integrated networks, which is modelled as a multiple objective shortest path problem explicitly considering distinct metrics and corresponding QoS requirements.

1. INTRODUCTION

Routing is a key element of any communication network functional structure, which has a decisive impact on network traffic performance and cost. A routing method is primarily concerned with the definition of a route, or set of routes, between a pair of nodes satisfying some optimality criteria. The formulation of such criteria, expressed through an appropriate objective function and/or constraints, depends on the nature of the network in terms of provided services and information transfer modes. In circuit-switched networks the routing method also encompasses, in general, an ordered selection of the routes (in the pre-defined set) which may be attempted by a given call between an origin and a destination switch (alternative routing). Classical formulations of the routing problem seek to optimize network cost while satisfying certain grade of service (GoS) constraints (such as loss probability or delay) or, alternatively, to optimise GoS criteria under network cost constraints, usually leading to nonlinear mathematical programming problems of great complexity requiring decomposition techniques. In traditional packet-switched data networks routing aims at optimising a single metric, such as hop count or delay, over available paths and it is generally based on shortest path algorithms.

The increasing demand for a new wide range of network services, namely multimedia applications, as well as the very rapid pace of networking technology evolution leads to the need of modern multiservice network functionalities, dealing with multiple, fine grain, and heterogeneous GoS requirements. When applied to routing control mechanisms this leads to a new routing paradigm, designated as QoS routing, which involves a selection of a chain of network resources along an acceptable path satisfying certain GoS requirements and seeking simultaneously to optimise the associated metrics (or a sole function of different metrics) such as cost, delay, number of hops and loss probability.

Therefore, in this context, network operators cannot continue to rely on routing techniques for path selection which are based on a single metric, but it is necessary to consider explicitly distinct metrics in routing algorithms (Lee et al., 1995). Path selection is generally formulated as a shortest path problem with a single objective function (either a single metric or a single function encompassing different metrics). QoS requirements can be incorporated into these mathematical models by means of additional constraints. 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 interesting properties and implies a heavier computational burden.

There are some advantages in considering the routing problem subject to multiple constrains as a multiple criteria problem, ill which a path constraint is transformed into a routing objective function to be optimised. Besides cost, other aspects such as delay (or blocking probability), bandwidth, etc. must be addressed explicitly by the mathematical models as objective functions which could be pursued to their optimum extent. On the other hand, the consideration of distinct aspects of evaluation as constraints, rather than objective functions, would reduce the range of (l1ondominated) solutions (paths) which can be computed. In a multiple objective context (involving multiple, conflicting, incommensurate objective functions) the concept of optimal solution in single objective problems (unique, in general) gives place to the concept of nondominated solutions (feasible solutions for which no improvement in any objective function is possible without sacrificing on at least one of the other objective functions). Multiple objective routing models thus enable to grasp the trade-offs among distinct QoS requirements, which can eventually be application-dependent, by rationalising the comparison among distinct routing alternatives in a way to balance the conflicting criteria involved in the evaluation in order to select a path. In this way models become more realistic, assuming the multiple objective nature of the problem, thus enabling to grasp the inherent conflicts and trade-offs among the distinct objectives in selecting a best compromise plan from the set of nondominated solutions.

The proposed methodological approach models the routing problem in integrated communication networks as a multiple objective shortest path problem, therefore explicitly incorporating the distinct evaluation aspects into the formulation. The developed algorithm computes nondominated paths by optimising weighted-sums of the multiple objective functions to determine vertex solutions (that is, those which belong to the boundary of the convex hull), and using a computationally effective k-shortest path algorithm to search for unsupported nondominated solutions within duality gaps (that is, solutions located inside the convex hull). QoS requirements may 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 function space.

2. MULTIPLE OBJECTIVE SHORTEST PATH

Consider a network G=(N,A), consisting of a finite set N of n nodes and a set A of m arcs ($A \subset N \times N$). Each arc a_{ij} connecting nodes i and j ($i, j \in N$) is assigned K real values c_{ij}^k (k=1,...,K), which denote the cost per unit flow on that arc for metric k. A path p from an origin node $s \in N$ to a destination node t is a sequence of arcs : $p = (a_{si}, a_{ij}, a_{jl}, \ldots, a_{mt})$.

The value of a path p is a real-valued vector $v_p = (v_p^1, v_p^2, \ldots, v_p^K)$, where $v_p^k = \sum_{a_{ij} \in p} c_{ij}^k$. That is, each component of this vector is the sum of all costs associated with the arcs along the path p, for each metric k.

The multiple objective shortest path problem simultaneously considers K metrics, each one associated with an objective function to be minimized. For a given k the problem becomes the usual (scalar) shortest path problem from node s to node t, with respect to metric k only.

Since, in general, no solution (path from s to t) exists which minimizes all objective functions simultaneously, an optimal solution does not exist for the multiple objective shortest path problem. A nondominated solution is a feasible path for which no other feasible path exist which improves the value of one objective function without worsening, at least, the value of another objective function.

Nondominated solutions can be computed by optimising a scalar function which is a convex combination of the K objective functions, where the cost coefficient c_{ij} associated with each arc a_{ij} is a non-negative weighted-sum of the corresponding cost coefficients with respect to each metric:

$$c_{ij} = \sum_{k=1}^{K} \lambda_k c_{ij}^k, \text{ where } \lambda = (\lambda_1, \lambda_2, \ldots, \lambda_K) \in \Lambda = \{ \lambda : \lambda_k \geq 0, k=1,\ldots,K; \sum_{k=1}^{K} \lambda_k = 1 \}$$

It must be remarked that whenever alternative optima exist with any λ_K=0 (in particular, regarding the individual optima of the K objective functions) solutions which are not strictly nondominated may be found. However, this can be avoided by using a small non-archimedian ε rather than zero in the weighted-sum objective function.

The optimal solution to the weighted-sum shortest path problem, if unique, yields a nondominated vertex path. However, by using this form of scalarization (that is, transforming the multiple objective problem into the weighted-sum scalar problem) only nondominated vertex paths can be computed. These are the solutions belonging to the boundary of the convex hull of the nondominated solution set in the K-dimensional objective function space.

Nondominated solutions located in the interior of the convex hull (i.e., those which are not vertices) cannot be reached using the weighted sums program because they are dominated by a convex combination of vertex solutions, and hence cannot be optimal solutions to the weighted-sum shortest path problem (no $\lambda \in A$ exists which define a supporting hiperplane for them). For this reason, though they are nondominated, they are generally called convex dominated solutions or unsupported (nondominated) solutions. But, since those solutions are actually nondominated, they must be-considered as potential compromise solutions and consequently the algorithms must accommodate for their computation. In the proposed approach these solutions are computed by means of a k-shortest path algorithm, which is used to search for nondominated solution within duality gaps, as described in section 2.1.

These concepts are illustrated in fig. 1 for the two-objective case, where delay and cost have been considered as objective functions to be minimized. Solutions 1 and 2 are the nondominated solutions which minimize cost and delay objective functions, respectively. Solutions 3 and 4 are two other vertex nondominated solutions. Solutions 5 and 6 are nondominated, even though they are dominated by a convex combination of solutions 3 and 4, which belong to the nondominated boundary of the convex hull. The same happens with solution 7 with respect to solutions 2 and 4. Solutions 8 is dominated by solutions 4 and 7, and solution 9 is dominated by 3. 0 is the ideal solution: - the so-called ideal solution is the one that would optimise all the objective functions simultaneously (its path value is obtained by optimising each objective function separately), which is not feasible whenever the objective functions are conflicting.

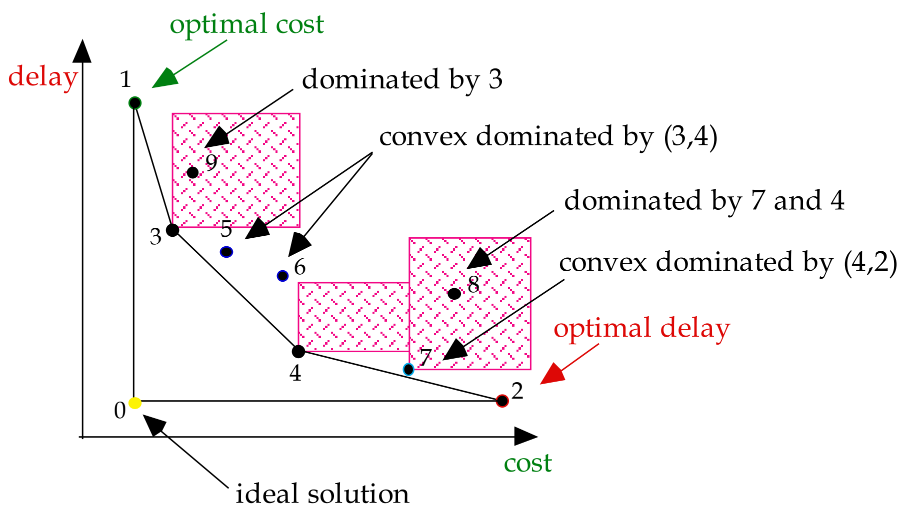


Figure 1 - Nondominated, convex dominated, dominated and ideal solution

2.1. A multiple objective shortest path approach

This approach to multiple objective shortest path problems is suited to be implemented both in an interactive manner (by requiring from the DM some input to guide the search for more nondominated solutions which more closely correspond to the DM's preferences) and in an automatic manner (by following pre-specified search rules). This later approach is well suited for application in the context of a routing control mechanism (see section 3). The algorithm optimizes weighted-sum objective functions to compute nondominated solutions which belong to the boundary of the convex hull, and a computation ally efficient k-shortest path algorithm to search for unsupported nondominated solutions within duality gaps, that is the solutions located inside the convex hull (see also Rodrigues et al., 1998).

The main steps of the algorithm are as follows:

(1) The nondominated solutions which optimise each objective function are computed, by solving K scalar shortest path problems using Dijkstra's algorithm, or any of its implementations. This yields information regarding the value range of each objective function over the nondominated solution set.

(2) A weighted-sum scalar function is constructed where the weights are the normalized components of the gradient of the hyperplane passing through those nondominated solutions in he objective function space.

(3) If the optimization of this weighted-sum function (again a scalar shortest path problem) leads to a weighted objective function value lower than the corresponding value of the hyperplane passing through the nondominated solutions, then the obtained optimal solution is a nondominated vertex solution. Otherwise all K nondominated solutions (which are the individual

optimum of each objective function) are obtained as alternative optima of the weighted-sum function. This means that no other solutions defining the convex hull exist.

(4) Let us suppose that a new vertex nondominated solution has been found in step (3). Again a K-tuple of nondominated vertex solutions is selected, a weighted-sum objective function is constructed by computing the gradient of the hyperplane passing through these solutions, and this function is optimised.

(5) The method resorts to the k-shortest path algorithm whenever the optimum of a weighted-sum objective function constructed in this manner yields all K solutions as alternative optimal solutions. This means that only solutions located inside the convex hull may exist. The k-shortest path with the weighted-sum objective function is then called to compute these solutions. The k-shortest path is a very effective algorithm which computes 500 000 loopless paths in an euclidean network with 10 000 nodes and 100 000 arcs in about 0.35 seconds of CPU time for undirected networks (and less than that for directed networks). Further details about this algorithm may be found in Martins et al. (1997). Unsupported nondominated solutions will be found in ascending order (worse values) of this function. Note that, whenever a new nondominated solution is found the upper bound on the weighted-sum function beyond which it is not necessary to proceed the search can be updated (see 2.2).

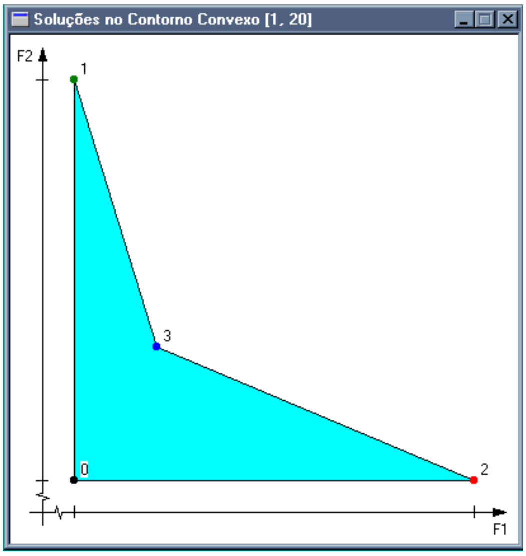
2.2. An illustrative example

This approach to compute nondominated solutions for multiple objective shortest path problems is now illustrated by means of an example with two objective functions.

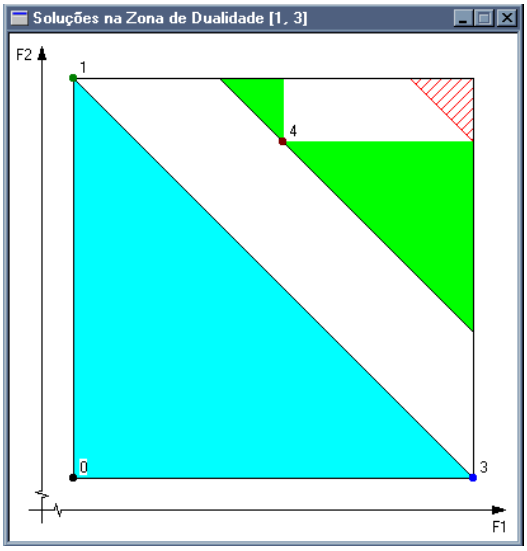
Firstly, the nondominated solutions which optimise each objective function are computed (solutions, 1 and 2, respectively; fig. 2a). A weighted-sum function is constructed where the weights are the normalized components of the gradient of the plane passing through those nondominated solutions in the objective function space. The optimization of this function leads to (supported) solution 3 (fig. 2a). The region between solutions 1 and 3 is selected to be searched for new nondominated solutions. The optimization of the weighted-sum function constructed using solutions 1 and 3 enables to conclude that no supported nondominated solutions exist between them. By resorting to the k-shortest path algorithm (using that weighted-sum function) to search for nondominated solution in duality gaps, solution 4 is found (fig. 2b). New nondominated solutions can only be found in the doted regions (otherwise they would be dominated by 4). Also, this enables to have an updated upper bound on the weighted-sum objective function which is being used in the k-shortest path algorithm. This upper bound is represented by the hatched region in the upper right corner (fig. 2b).

Unsupported nondominated solutions will be successively computed by the k-shortest path algorithm within the duality gap region defined by supported nondominated solutions 1 and 3. Note that both the regions (where new nondominated solutions can be located) and the new upper bound are updated, once a new solution is found. When this upper bound is reached no more solutions exist and the k-shortest path algorithm can terminate (figs. 2e-d).

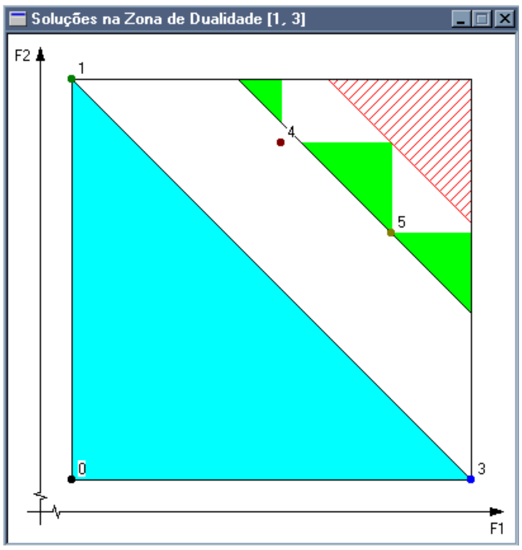
The same procedure is then applied to the region between supported nondominated solutions 2 and 3, which enables solutions 7, 8 and 9 to be computed (fig. 2e). All (supported and unsupported) nondominated solutions to this problem are displayed in fig. 2f.



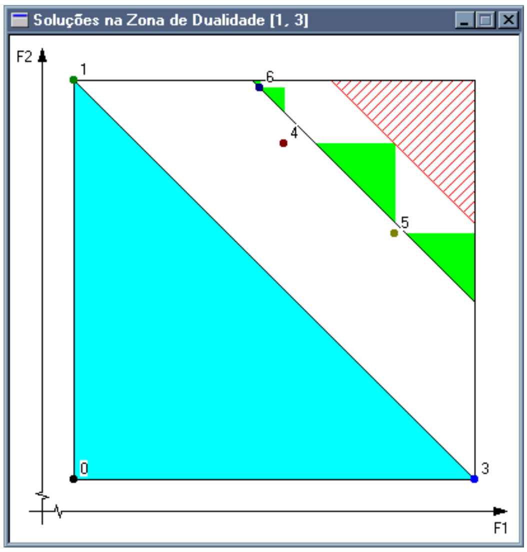
(a)



(b)



(c)



(d)

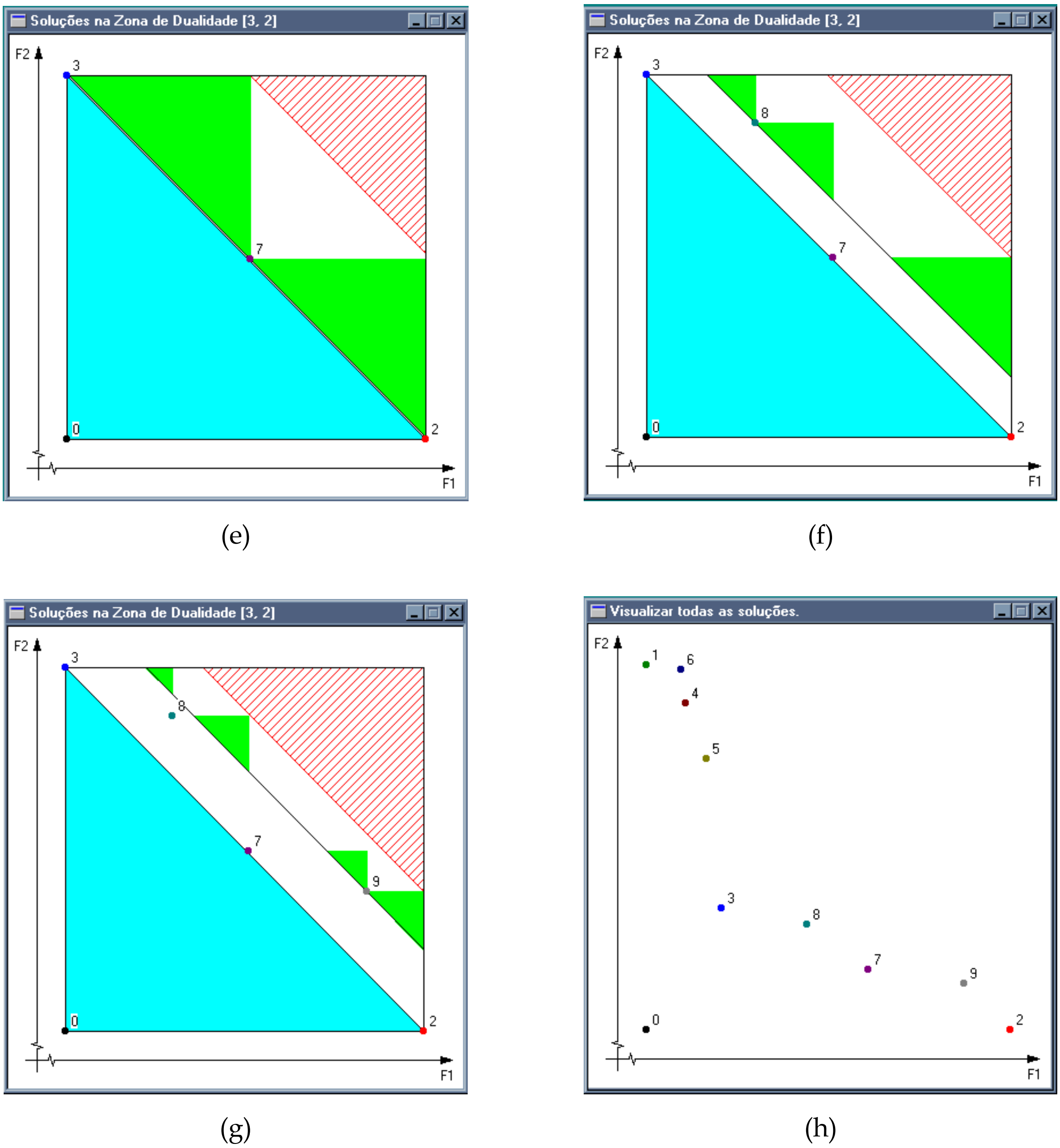


Figure 2 - An example of computing supported and unsupported nondominated solutions (screen copies)

3. A MULTIPLE OBJECTIVE APPROACH TO THE ROUTING PROBLEM

The routing problem in integrated communication networks is modeled as a multiple objective shortest path problem. In this way the distinct evaluation aspects are explicitly incorporated into the problem's formulation, emphasizing the search for satisfactory compromise paths with respect to various QoS requirements.

Routing metrics generally considered are delay, cost, hop-count, loss probability, error rate, and bandwidth (Lee et al., 1995; Wang and Crowcroft, 1996; Vogel et al., 1996). The aggregation function to compute the value of path p depends on the metric:

- the metric is additive if $v_p = \sum_{a_{ij} \in p} c_{ij}$
- the metric is multiplicative if $v_p = \prod_{a_{ij} \in p} c_{ij}$
- the metric is concave if $v_p = \min_{a_{ij} \in p} (c_{ij})$

The loss probability (and error rate) metrics follow the aggregation function

$$v_p = 1 - \prod_{a_{ij} \in p} (1 - c_{ij})$$

Delay, hop-count and cost follow the additive aggregation function. Path bandwidth (and throughput) is computed by using the concave aggregation rule.

The loss probability (and error rate) metric can be transformed into an additive metric (and hence comply with the shortest path approach requirements) in the following way:

$$1 - v_p = \prod_{a_{ij} \in p} (1 - c_{ij})$$

This is the probability of non-blocking, which follows the multiplicative aggregation function. Furthermore $\log(1 - v_p) = \sum_{a_{ij} \in p} \log(1 - c_{ij})$

To maximize the probability of successful transmission is then algebraically equivalent to

$$\max \log(1 - v_p) = \max \sum_{a_{ij} \in p} \log(1 - c_{ij})$$

which is equivalent to $\min \sum_{a_{ij} \in p} -\log(1 - c_{ij})$

Since c_{ij} is a probability, the coefficient associated with a_{ij} is $-\log(1-c_{ij})$ which is positive.

The shortest path approach can be used with an additive metric. Therefore, the proposed multiple objective shortest path approach can be used whenever additive, multiplicative and loss probability metrics are to be considered, by transforming the two latter into the additive case.

The general algorithmic approach is described below for the two-objective case in order to facilitate its graphical illustration.

(1) The nondominated solutions which optimise each objective function are computed, by solving K scalar shortest path problems using Dijkstra's algorithm, or any of its implementations.

This yields information regarding the value range of each objective function over the nondominated solution set.

(2) QoS requirements for each of those metrics are specific by means of the thresholds:

requested value (aspiration level)- M_{req} ;

acceptable value (reservation level): M_{acc} ($M_{req} < M_{acc}$).

The addition of this type of *soft* constraints (that is, constraints not directly incorporated into the mathematical formulation) defines priority regions, in which nondominated solutions are searched for according to the underlying QoS requirements (see fig. 3). Region A is a first priority region where both requested values are satisfied. Regions B1 and B2 are second priority regions where only one of the requested values is met and the acceptable value for the other metric is also satisfied. A further distinction can be made between these second priority regions by establishing a preference order on the objective functions. For instance, stating that cost is more important than delay, would give privilege to region B1. Region C is a third priority region where only acceptable values for all metrics are satisfied.

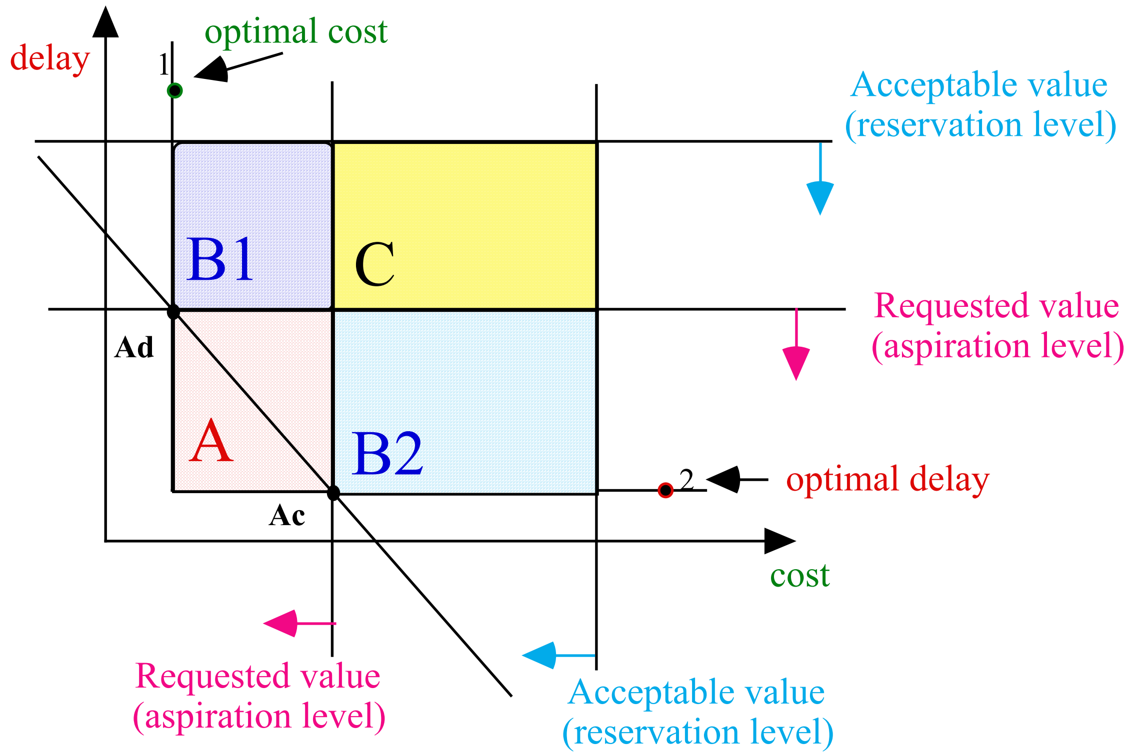


Figure 3 - QoS requirements are used to define priority regions

A weighted-sum scalar function is constructed where the weights are the normalized components of the plane passing through points A_c and A_d, defined by the intersection of the requested values and the optimal values. The first solution found within (first priority) region A is selected. This is solution 3 (fig. 4). Note that any solution in region A dominates any solution in region C. It must be remarked that from a value of that gradient corresponding to a level line passing through A_c and A_d, solutions within (second priority) regions B1 and B2 may be found. These solutions are stored but not reported until the 1st priority region is entirely searched (this corresponds to the value of the weighted sum gradient passing through point X; fig. 4). If there are no nondominated solutions within region A, the search proceeds to 2nd priority regions. The previously computed solutions in regions B1 and B2, if any, are now reported. Solutions 5, 6 and 8 would have been found within second priority regions.

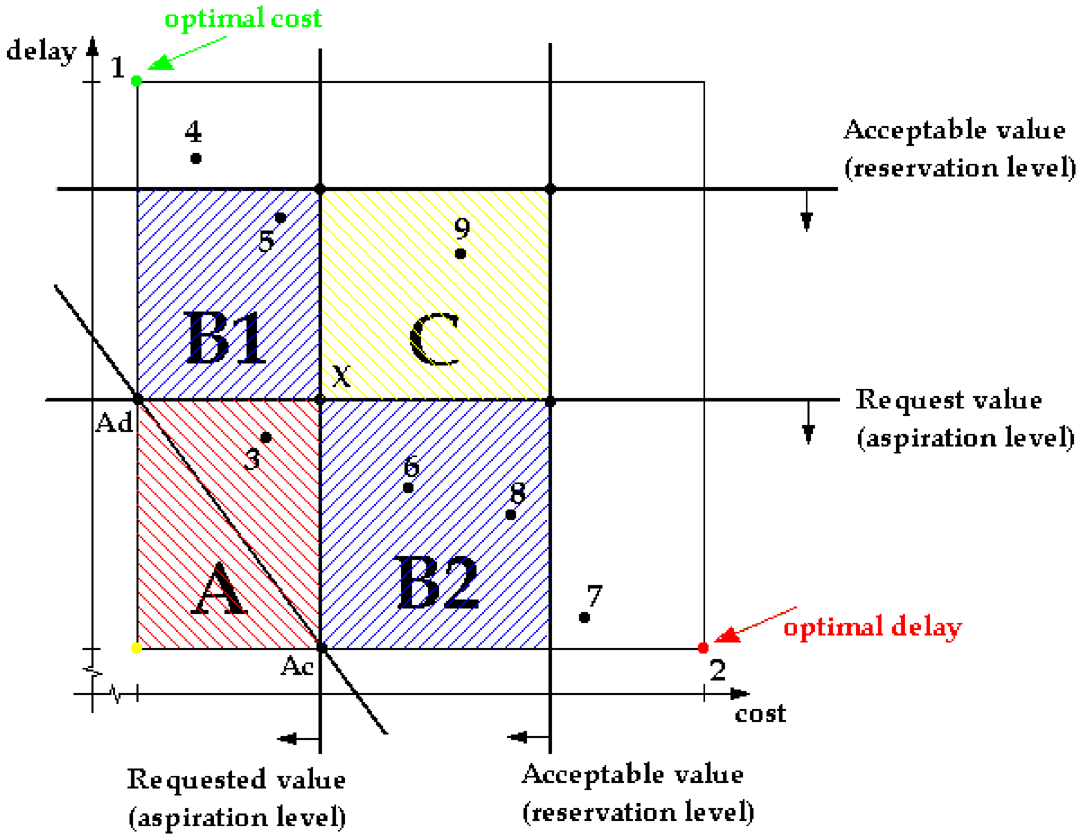


Figure 4 – Computing nondominated solutions in priority regions

From now on it is (again) possible to obtain solutions in (third priority) region C before all (2nd priority) regions B1 and B2 are searched. Again these solutions are stored and reported only when regions B are completely searched without finding any nondominated solutions within them. If the algorithm proceeds to this point it means that no paths exist satisfying at least one of the requested QoS values and only acceptable values can be met.

If there are no nondominated solutions within 2nd priority regions B1 and B2 the search proceeds to 3rd priority region C. The previously computed solutions in region C are now reported. The search then proceeds until the weighted gradient attains the value of a plane passing through point Y. Beyond this point even acceptable values for QoS requirements cannot be met. Eventually nondominated solutions may exist outside the priority regions (such as solutions 4 and 7, or even 1 and 2, in fig. 4), which can be used as "last chance" routes.

If bandwidth (or throughput) requirements must be considered then, since this is a concave metric (that is, $b_{st} = \min(b_{si}, b_{ij}, b_{jl}, ..., b_{mn}, b_{nt})$) a QoS requirement for bandwidth in terms of the same thresholds - requested value (aspiration level) b_{req} and acceptable value (reservation level) b_{acc} ($b_{acc}<b_{req}$) - can be dealt with in the following way: - a new network is constructed by removing arcs a_{ij} for which $b_{ij} < b_{req}$; - if the resulting network remains connected then a path between the origin node and the destination node exists satisfying the requested bandwidth (aspiration level); - otherwise (if the resulting network turns out to be not connected) then the arcs a_{ij} for which $b_{ij} < b_{acc}$ only are removed; - if this network is connected then a path between the origin node and the destination node exists satisfying the acceptable bandwidth (reservation level); - otherwise no path exists for the specified bandwidth QoS parameters. The previously described methodology is then applied to the resulting network.

4. CONCLUSIONS AND FURTHER WORK

A multiple objective approach to computing routing strategies in integrated communication networks has been presented. The routing problem is modelled as a multiple objective shortest path problem. Distinct evaluation aspects are explicitly incorporated into the problem's formulation, emphasizing the search for satisfactory compromise paths with respect to heterogeneous QoS requirements. The algorithmic approach optimizes weighted-sum objective functions to compute vertex nondominated solutions, and uses a computationally effective k-shortest path algorithm to search for unsupported nondominated solutions. QoS requirements may 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 function space. These regions are then searched to determine paths (if they exist) satisfying those requirements. The use or this capability of the model to incorporate such soft constraints is strongly dependent on the application environment of the routing approach, in terms of network technological constraints and/or capabilities, functional and QoS requirements, types of traffic and characteristics of provided services. For example, in conventional NB-ISDN, only constraints concerning "acceptable" levels of GoS need to be considered, which should follow standard ITU recommendations. On the other hand, in A TM networks where traffic sources of quite different nature and a multiplicity of requirements may occur, the connection oriented approach allows the user to indicate the communication needs during the connection set-up phase and the network may tailor the transfer properties of the connection to specific user needs. This gives rise, in particular, to the concept of traffic contract (see related ITU-T, Recommendations 1.371 and 1.356) with its inherent flexibility in terms of resource management. In this framework both types of (soft) constraints, concerning "acceptable" and "requested" values become significant. In this context, it must be noted that the (possible) occurrence of nondominated paths which lead to a better value than the one "requested" by the user raises questions regarding their admissibility as outcomes of the algorithm, since they correspond to an over-utilization (albeit temporary) of network resources. This type of questions, which does not bring any further algorithmic or computational complexity to the proposed approach, nevertheless requires further analysis, which will be necessarily dependent on the network features.

Concerning the application of the proposed approach two possible scenarios are envisaged. Firstly it could be applied as a new variant of a Periodic State Dependent Routing (PSDR) type method for circuit-switched networks. Originally this dynamic routing method, described in the document D.42 (1997) of the ITU-T group is based on a centralized type of control which provides routing decisions based on periodical updates of the number of free circuits in each trunk of the target network, using a typical update period of 10 sec. The envisaged variant based on the multiple objective shortest path approach would use an automated version of the algorithm for computing a number of nondominated solutions corresponding to the number of alternative paths selected for each pair of nodes. Such paths would be changed dynamically as a function of periodic updates of the measurements of the GoS metrics on the links, namely blocking probability, delay or available bandwidth (in an ISDN environment, for example), depending on the nature of the offered traffic. This method would require an *a-priori* study of the signaling requirements and the architecture of the traffic routing control and the routing management mechanisms. A second line of application would be the routing of continuous media streams (such as audio and video in packet-switched networks) where the basic problem is to find, for each flow, a path satisfying multiple, conflicting objectives and constraints, which was the original motivation of the QoS routing paradigm. In this context an automated version of the multiple objective shortest path algorithm could, in principle, be applied having in mind the extreme efficiency of the algorithm. Further investigation would be needed on the architecture of the associated routing system and the requirements of the routing protocol.

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