BFC Heuristic Approach for Constraint-Based Path Selection in QoS Routing

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Abstract - **In DiffServ networks QoS-based routing for only one QoS measure (e.g. constrained bandwidth) is known as the restricted shortest path (RSP) problem. It can be treated as the minimum cost network flow problem in the multi-commodity single source multiple destination network. For constrained-based path selection in QoS routing with *N* quality of service levels in function to serve predicted traffic demands, an efficient heuristic algorithm is being developed. The algorithm approach is of BFH (backward-forward heuristic) type. The optimal flow theory enables separation of these extreme flows which can be a part of an optimal expansion solution from those which cannot be. Algorithm is compared with algorithm based on exact approach. In all numerical test-examples the best possible result is achieved, but with significant reduction of complexity and computation savings.**

Index Terms - **QoS-based routing, constraint-based path selection in DiffServ networks, MPLS-based traffic engineering.**

I. Introduction

Internet evolves toward the global multi-service network of the future, and the main task is the support for services with guaranteed quality of service (QoS). IPSs see service management as a new product with greater potential service differentiation than a pure connectivity service. The proposed differentiated services (DiffServ) technology is the main tool to achieve this. Service-level specifications (SLSs) are used to describe the appropriate QoS parameters in such approach. Multi protocol label switching (MPLS) ensure extensive configuration in label switching routers (LSRs) so traffic demands have to be routed in an optimal way, to avoid congestion on the path between edge routers.

One of the key issues in all of these frameworks is how to identify efficient path that can satisfy the given QoS constraints, commonly known as the QoS-based routing.

Routing protocols capture the network state information (e.g. available resources) and disseminate it trough the network, while routing algorithms use that information to compute appropriate paths. While current best-effort routing simply performs these tasks based on a single, relatively static measure, QoS routing take into account both applications' requirements and the availability of network resources. Limitation of trunk capacity on the path are in firm correlation with predicted traffic demands, that is result of service level agreements (SLAs) made with customers.

It means that QoS routing has to deal with some challenging issues that are not present in best-effort routing, including scalable dissemination of dynamic (state-dependent) information, state aggregation, and computation of constrained paths. The basic motivation for sophisticated QoS routing arises from the fact that shortest-path-based traffic routing leads to congestion on certain trunks while others remain relatively unused.

In section 2 explanation of the constraint-based path selection problem is given. The mathematical model for restricted shortest path (RSP) problem is formulated in section 3. QoS routing problem is seen as the capacity expansion problem for predicted traffic demands.

II. Explanation Of The Constraint-Based Path Selection Problem

Let $G(A,E)$ denote a network topology, where A is the set of nodes and E the set of trunks. The source and destination nodes (edge routers in domain) are denoted by s and d, respectively. The number of QoS measures (e.g. bandwidth, delay) is denoted by z. QoS measures can be roughly classified into additive (e.g. delay) and nonadditive (e.g. available bandwidth). In case of an additive measure, the QoS value of the path is equal to the sum of the corresponding weights of the trunk along that path. For a nonadditive measure, the QoS value of the path is the minimum (or maximum) trunk weight along the path. In algorithm approach it is assumed that the network state information (e.g. traffic demands, trunk capacities) is temporary static and can be disseminated throughout the network using the underlying QoS based routing protocols.

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Consider a network $G(A,E)$ where each trunk is characterized by z-dimensional trunk weight vector, consisting of z nonnegative QoS weights ($w_i\ (k,l)$, $i = 1, \ldots, z$, $(k,l) \in E$) as components. Given z constraints are denoted by L_i, $i = 1, \ldots$, z. Definition of the multi-constrained problem (MCP) is to find a path P from s to d such that:

$$w_i(P) def \sum_{(k,l)\in P} w_i(k,l) \le L_i \qquad (2.1)$$

for $i = 1, \ldots z$.

A path obeying the above conditions is said to be feasible. Note that there may be multiple feasible paths between s and d. A modified version of the MCP problem is to retrieve the shortest "length" path among the set of feasible paths. Such problem is known as the Multi-Constrained Optimal Path (MCOP) problem and is attained by adding a second condition on the path P in definition 2.1(I): $I(P) \le I(Q)$ for any feasible path Q between s and d, where I(.) is a path length (or cost) function. A solution to the MCOP problem is also a solution to the MCP problem, but not necessarily vice versa; see [2].

In this paper we dealt about only one dimensional trunk weight vector, with only one constraint denoted with L. Given constraints are limited bandwidth on each trunk on the path: L_m, $m = 1, \ldots, M$; see fig. 2. Such problem is special case of the MCP problem, known as Restricted Shortest Path (RSP) problem; see [5]. The trunk weight (cost) is the function of used capacity: lower used capacity (smaller bandwidth) gives lower weight (cost), taking care that given traffic demands can be satisfied (sufficient capacity on the trunk without shortages). Nonlinear cost function is necessary if trunk weights are not positively correlated.

Appropriate network resources (e.g. bandwidth) may be provisioned along the routes according to predicted of measured traffic requirements. For example, the customers operate stub networks and shall be able to order VPN connectivity with guaranteed QoS between those sub-nets; see fig 1.

A. RSP problem solved with expansion problem with only one constrained QoS measure

On each communication trunk in the network traffic demands can be satisfied on different QoS levels, depending on used bandwidth for appropriate transmission speed. Given traffic demands can be routed through appropriate or higher quality level (but not lower) to achieve QoS guarantees (SLA- Service Level Agreement with customers).

RSP problem can be solved with different algorithms; see an overview in [3]. In this paper we try to solve it effectively through capacity expansion problem. We are looking for an optimal expansion sequence that is the capacity assignment problem and the inventory problem in the same time. Capacity Expansion Problem (CEP) in the network with common source but with constrained trunk resources (shortages are not allowed), is looking for shortest path with minimal capacity on the path. Traffic demand increments (relative value) for any QoS level on the interior router can be positive or negative, that depends of traffic direction; see fig. 3.

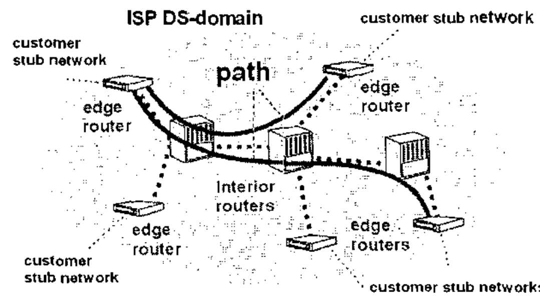

Figure 1. The service provider operates an IP network with VPN-enabled edge routers and a core network that suport resource reservation mechanisms.

If the optimal routing sequence between edge routers (see fig. 2) has any expansion on the trunk with amount that exceeds allowed limits (bandwidth constraint for each trunk is L_i), it means that given traffic demands cannot be routed without congestion. With such approach in QoS routing for the constraint-based path selection can be done effectively, helping in traffic engineering (TE) to achieve end-to-end QoS guarantees.

If idle capacity on the trunk exists, conversion of traffic demands from one QoS level to another (only toward higher quality level) could be a good solution for the customer, but it might not be the optimal solution for the network operator. Because of that the proposed optimization process is necessary.

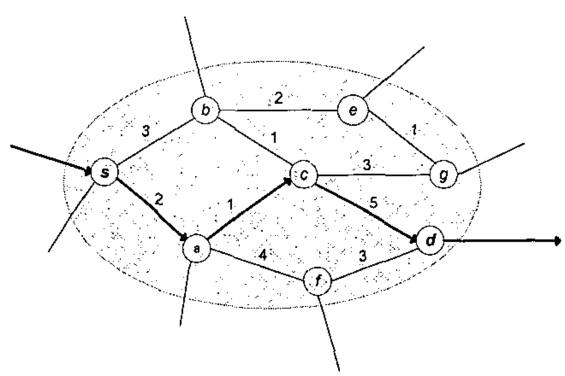

Figure 2. The shortest path routing between two edge routers in domain. Each trunk in the network has an integer weight.

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Such problems exist in the networks with two, three or more different QoS levels and with finite number of interior routers. Some very important papers in that field are [1] Biswas, Ganguly & Izmailov and [4] Braun, Guenter & Khail, but many other authors are investigating that problem.

III. Mathematical Model And Heuristic Approach

Transmission trunk capacities on the path between routers are capable to serve traffic demands for N different QoS levels (called *facilities*), for $i = 1,2, \dots, N$. With more traffic demands we have to use more capacity (more bandwidth). If expansion exceed given limits it causes extra penalty cost. Facility i is used primarily to serve demands for QoS level i, but it can be used to satisfy traffic demands for QoS level j ($j>i$). Re-routing of traffic demands towards higher QoS level is the same thing as facility conversion toward lower QoS level, see fig. 3. and fig. 5. Normally, it does not require physical modifications, it can be done by traffic routing mechanisms and with no cost. Once converted from i to j, the amount of facility i becomes an integral part of facility j, but it can be rearranged to its original type at any time without cost. In this model conversion of traffic demand is permitted only in the direction toward higher QoS level. Usage of the new capacity (expansion), same as re-routing of traffic demands, can be used as stand alone strategies or can be combined together. If both strategies are necessary they are not substitutes but complements.

The objective is to find optimal routing-policy that minimizes the total cost incurred over the whole path between edge routers (M interior routers and $M+1$ transmission trunks) and to satisfy given traffic demands.

The expansion problem can be represented by a flow diagram. In fig. 3 we have the *Multi-Commodity Single Source Multiple Destination Network*, and the problem can be treated as the *Minimum Cost Network Flow Problem*. The flow theory enables separation of these extreme flows which can be a part of an optimal expansion solution from those which cannot be. Important papers in that field are Lee & Luss [6] and Luss [7]. With such heuristic approach we obtain optimal result with significant computational savings. Fig. 3 gives a network flow representation of CEP for three QoS levels ($N = 3$) and LSRs included in the shortest path solution.

On that diagram the m-th row of nodes represents a possible capacity state of each transmission trunk between routers for i-th QoS level. Capacity values are positive only (idle capacity), and shortages are not allowed. Horizontal links between them represent the traffic flow between routers. Common node "O" is the source for used capacity (expansions), introducing the new capacity on the trunk (routing capacity). Vertical links represent re-routing of traffic demands (capacity conversion of facility).

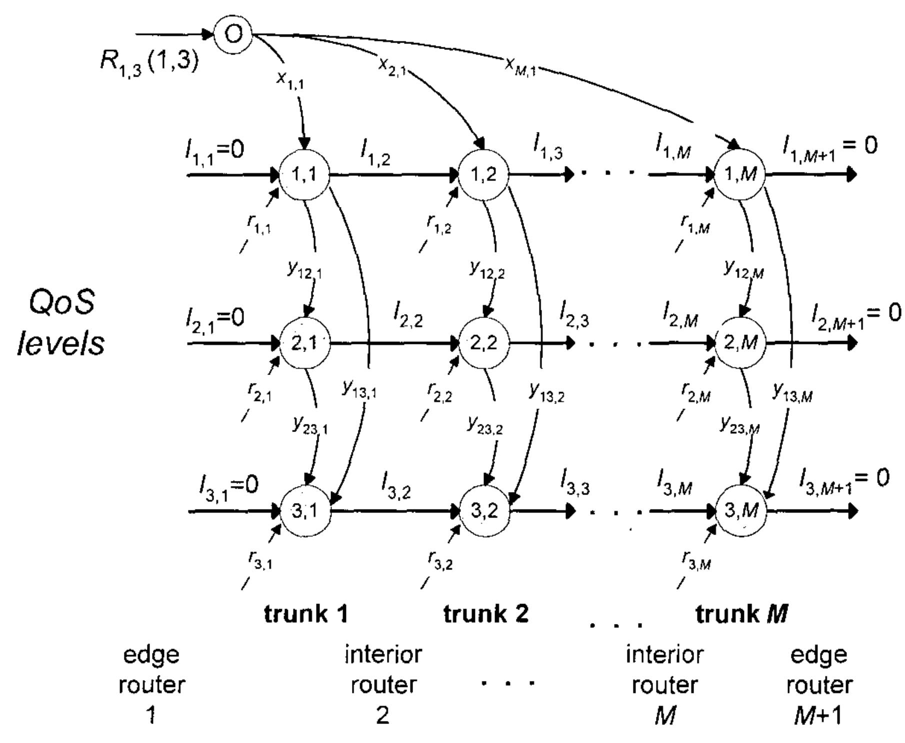

Figure 3. A network flow representation of the expansion problem on the path for three QoS levels. The shortest path consists of M trunks and $M+1$ routers.

In the mathematical model of CEP the following notation is used:

i, j and k = QoS level. The N levels are ranked from 1,2,..., N, and quality decreases with higher number.

m = the order number of transmission trunk on the path, connecting two successive routers. Path consists of M transmission trunks ($m = 1, \dots, M$) between M+1 routers.

u,v = the order number of capacity point that define transmission sub-problem, $1 \le u, \dots, v \le M+1$.

r_{im} = traffic demand increment for additional capacity of facility i (appropriate QoS level) on transmission trunk m. For convenience, the r_{im} are assumed to be integer. The demands can also be satisfied by facility with higher QoS level (lower i).

I_{im} = the relative amount of idle capacity of facility i on the trunk m, related on the trunk before. We assumed that initially there is no idle capacity or capacity shortage between edge router and the neighbor interior router, that means that capacity is sufficient $I_{i1} = 0$, $I_{i,M+1} = 0$.

kl_i = the lowest step of possible capacity change of facility i (QoS level).

x_{im} = the amount of used capacity for facility i on the transmission trunk m.

L_m = upper limit of trunk capacity (bandwith) on the transmission trunk m.

y_{ijm} = the amount of re-routing capacity (conversion) of facility i on the trunk m, redirected to satisfy the traffic demands of lower QoS level j.

The CEP problem can be formulated as follows:

$$\min\left(\sum_{l=1}^{M}\left\{\sum_{i=1}^{N} c_{im}(x_{im}) + h_{im}(I_{i,m+1}) + \sum_{j=i+1}^{N} g_{ijm}(y_{ijm})\right\}\right) \tag{3.1}$$

so that we have:

$$I_{m+1} = I_{im} + x_{im} - \sum_{j=i+1}^{N} y_{ijm} - r_{im} \tag{3.2}$$

$$I_{im} = I_{i,M+1} = 0 \tag{3.3}$$

for $m = 1, 2, \dots, M$; $i = 1, 2, \dots, N$; $j = i + 1, \dots, N$.

The total cost on the path from edge to edge router includes some costs: the cost for capacity expansion $c_{im}(x_{im})$, the idle capacity cost $h_{im}(I_{i,m+1})$ as penalty cost to force the usage of the minimal trunk capacity, and the re-routing cost of traffic demands $g_{ijm}(y_{ijm})$ that can be set to constant or to zero. For expansion of trunk in allowed limits we can set the cost to zero, too. Costs are often represented by the fix-charge cost or with constant value. We assume that all cost functions are concave and non-decreasing, , reflecting economies of scale, and they can change for appropriate trunk. With costs parameters we can influence on the optimization process, looking for the most appropriate routing solution. Cost functions can be nonlinear if it is necessary.

A. Definition of the Capacity Point

Generalizing the concept of the capacity state for transmission trunk m (capacity on the input of interior router) in which the capacity state of each trunk is known within defined limits and which at least one capacity state satisfies I_{im} = 0, we define as *a capacity point.* In (3.4) α_m denotes the vector of capacities I_{im} for all QoS levels (facility types) on trunk m, and we call it capacity point.

$$\alpha_m = (I_{1m}, I_{2m}, \dots, I_{Nm}) \tag{3.4}$$

$$\alpha_1 = \alpha_{M+1} = (0, 0, \dots, 0) \tag{3.5}$$

Each column in the flow diagram from fig. 3 represents a capacity point, consisting of N capacity state values.

(3.5) implies that idle capacities are not allowed on the trunk between edge and interior router.

B. Solving of the Sub-problem (CES)

Associated value between two capacity points, that represents minimum cost $d_{uv}(\alpha_u, \alpha_{v+1})$ we denoted as CES (*Capacity Expansion Sub-problem*). In CEP we have to find many cost values $d_{uv}(\alpha_u, \alpha_{v+1})$ that emanate two capacity points, from each node (u, α_u) to node (v+1, α_{v+1}) for $v \ge u$. Most of the computational effort is spent on computing the sub-problem values. Any of them, if it cannot be a part of the optimal sequence, is set to infinity.

Supposing that all d_{uv} values are known, the optimal solution for CEP can be found by searching for the optimal sequence of capacity points and their associated values. The problem can be formulated as the shortest path problem between edge routers for an acyclic network in which the nodes represent all possible capacity state values of interior routers. BFC approach starts from the end, so it determines the last trunk on the path with minimal weight (cost) and the least

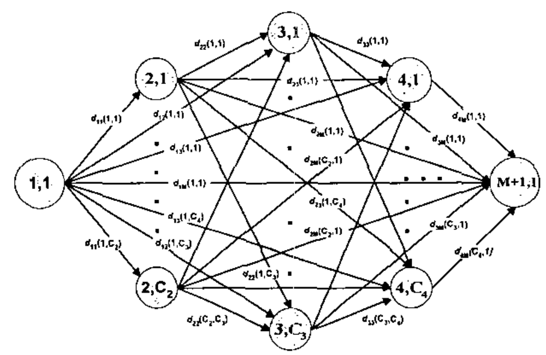

Figure 4. The expansion problem can be solved as the shortest path formulation using Dijkstra's algorithm, but values of all possible sub-problems (links on the graph) have to be calculated before.

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cost trunk from every node u (intermediate node) to d. BFC then starts from u to s and explores the graph as in Dijkstra's algorithm; see fig. 4.

Let the generalized capacity expansion sub-problem CES (α_u, α_{v+1}) be the expansion problem for N facilities $i = 1,2, .., N$ on the path between routers u, $u + 1$, .., v. $d_{uv}(\alpha_u,\alpha_{v+1})$ is as follows:

$$\min\left\{\sum_{m=u}^{v}\left(\sum_{i=1}^{N} {}_{im}(x_{im})+h_{im}(I_{i,m+1})+\sum_{j=m+1}^{N} g_{ijm}(x_{ijm})\right)\right\} \qquad (3.6)$$

$$\text{where} \quad I_{i,v+1} = I_{iu} + D_i - R_i(u,v) \qquad (3.7)$$

$$R_i(m_1,m_2) = \sum_{m=m_1}^{m_2} r_{im} \qquad (3.8)$$

$$D_i = \sum_{m=u}^{v}\left(x_{im} - \sum_{j=1}^{N} y_{ijm}\right); \quad i \neq j \qquad (3.9)$$

for $i = 1, 2, \dots, N$; $m = 1, 2, \dots, M$

C. Single Location Expansion Problem

The approach described above requires solving repeatedly a certain single location expansion problem (SLEP). Let $SLEP_{iN}(m, D_i, \dots D_N)$ be associated with router location m for facility i, i+1, ... , N and corresponding values of *capacity change value* (see relation 3.9) denoted with D_i, D_{i+1}, ... , D_N.

Solving $SLEP_{13}$ for three different QoS levels we have many changing solutions. Changes of all three facility types depend on each other because the channel resources are in firm correlation (channel speed). Traffic re-routings to higher QoS level is allowed (or capacity conversion to lower QoS level), that can be seen from fig. 5.

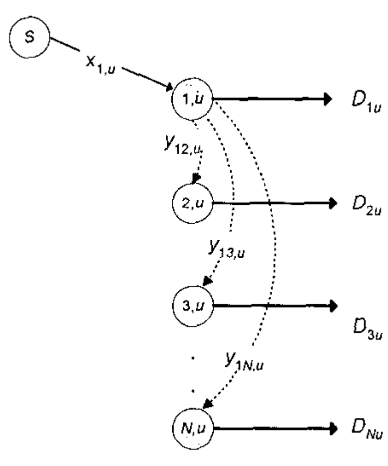

Figure 5. Presentation of $SLEP_{1N}$ problem on router location (u) for different QoS levels

Many different expansions and re-routing solutions can be derived, depending on D_i polarity; see [7]. Lot of them are not acceptable and are not part of the optimal sequence, that is the key for the heuristic approach. The heuristic algorithm in all test-examples can achieve the best possible result (near-optimal expansion sequence), but requires the computation effort of $O(M^3N^4R_i^{2(N-1)})$, that is few times that of Dijkstra's algorithm. The required effort for one sub-problem is $O(N^2M)$. The number of all possible d_{uv} values depends on the total number of capacity points, same as on granularity of trunk weights.

IV. CONCLUSION

The problem of constraint-based path selection for QoS routing in DiffServ networks was investigated. In MPLS-based networks predicted traffic with N QoS levels can be routed through LSRs in an optimal way if existing trunk capacities are sufficient. In traffic engineering we need an optimization tool to avoid congestion and to achieve end-to-end QoS guarantees. In this paper we dealt with only one constraint QoS measure (bandwidth), so the problem is known as Restricted Shortest Path (RSP) problem. QoS routing can be solved with heuristic algorithm based on the capacity expansion problem (CEP) without shortages and with constrained trunk bandwidth. Algorithm is of BFH type. Expansion solutions can be made in allowed limits and at no cost, but traffic demands have to be satisfied (no shortages). If it is not possible, we have congestion on at least one trunk. If there is no congestion on the path, QoS routing is successful; see fig. 6. Using optimal flow theory in multi-commodity single source multiple destination network, we applied the heuristic approach, eliminating extreme flows that cannot be a part of an optimal solution (shortest path).

Algorithm was tested through many numerical test-examples and in all cases it was possible to find the best routing scheme (expansion sequence with minimal cost), in the same way as with the algorithm based on the exact approach. At the same time this heuristic approach shows significant complexity savings that is proportionally reflected on computation time savings. It means that such heuristic approach can be successfully applied for QoS-based routing in DiffServ networks.

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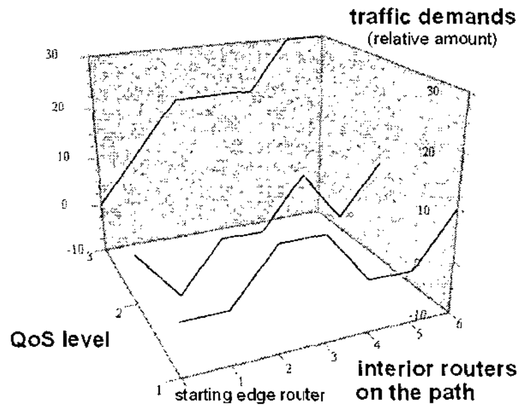

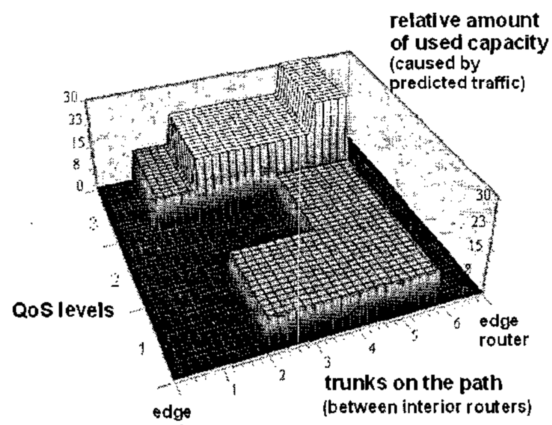

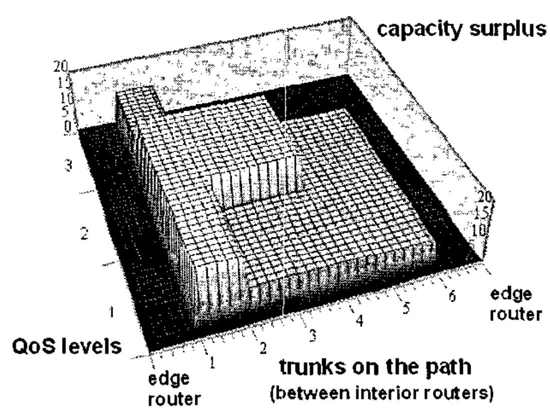

Figure 6. With such resource management tool we can analyse the capacity situation on the path. In this numerical test-example used capacites don't exceed given limits, that means no congestion on the path exists for predicted traffic demands. Capacity resources for three QoS levels are in firm correlation. Conversion of traffic demands in router toward higher quality level is possible.

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