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An Efficient Algorithm for Congestion Control in Highly Loaded DiffServ/MPLS Networks

Srećko Krile *srecko.krile@unidu.hr*
University of Dubrovnik
Department of Electrical Engineering and Computing, Dubrovnik

Dario Krešić *dario.kresic@foi.hr*
University of Zagreb
Faculty of Organization and Informatics, Varaždin

Abstract

Optimal QoS path provisioning of coexisted and aggregated traffic in networks is still demanding problem. All traffic flows in a domain are distributed among LSPs (Label Switching Path) related to *N* service classes, but the congestion problem of concurrent flows can appear. As we know the IGP (Interior Getaway Protocol) uses simple on-line routing algorithms (e.g. OSPFS, IS-IS) based on shortest path methodology. In QoS end-to-end provisioning where some links may be reserved for certain traffic classes (for particular set of users) it becomes insufficient technique. On other hand, constraint-based explicit routing (CR) based on IGP metric ensures traffic engineering (TE) capabilities. But in overloaded and poorly connected MPLS/DiffServ networks the CR becomes insufficient technique. As we need firm correlation with bandwidth management and traffic engineering (TE) the initial (pro-active) routing can be pre-computed in the context of all priority traffic flows (former contracted SLAs) traversing the network simultaneously. It mean that LSP can be pre-computed much earlier, possibly during SLA (Service Level Agreement) negotiation process. In the paper a new load simulation technique for load balancing control purpose is proposed. The algorithm proposed in the paper may find a longer but lightly loaded path, better than the heavily loaded shortest path. It could be a very good solution for congestion avoidance and for better load-balancing purpose where links are running close to capacity. Also, such technique could be useful in inter-domain end-to-end provisioning, where bandwidth reservation has to be negotiated with neighbor ASes (Autonomous System). To be acceptable for real applications such complicated routing algorithm can be significantly improved. Algorithm was tested on the network of *M* core routers on the path (between edge routers) and results are given for *N*=3 service classes. Further improvements through heuristic approach are made and results are discussed.
Keywords: intra-domain routing, inter-domain routing, traffic engineering in DiffServ/MPLS networks, constraint-based routing

1. Introduction

With capability in service differentiation techniques (DiffServ networks) the network operator can ensure the traffic priorization, specialy to quality voice (VoIP) and video calls (premium traffic), as same as for truly differentiated data services. It means that DiffServ classifies individual flows in a small number of service classes (at network edges). Also it enables ‘’soft’’ reservation (allocation) of resources and special handling of packets in the core. Together, MPLS (Multi Protokol Label Switching) and DiffServ provide a scalable QoS solution for the core of the network; see [1] and [2].

MPLS uses extensions to Resource Reservation Protocol (TE-RSVP) and the MPLS forwarding paradigm to provide explicit routing; see [3], [4] and [5]. With OSPF (*Open Shortest Path First*), widely-used IGP routing protocol, some paths may become congested while others are underutilized. Such intra-domain routing can be appropriate only for under loaded networks. For highly loaded networks we need prediction of congestion probability and it has to be done much before the moment of service utilization. Constraint-based routing (CR) as a extension of explicit routing allows an originating (ingress) router to compute a path (LSP) to egress router (sequence of intermediate LSRs), taking care of constraints such as bandwidth, delay and administrative policy; see [12]. With constraint-based label distribution protocol (CR-LDP) we can ensure the bandwidth provisioning directives and other information (list of router's neighbors, attached networks, actual resource availability and other relevant information). It can be distributed for each service class at each link along the path (LSP); see [6]. CR process can be incorporated into each ingress router and co-exists with the conventional routing technique.

MPLS/DiffServ aware TE (DS-TE) allows constraint-based routing of IP traffic with final task to adjust class load to actual class capacity. But the routing approach above can be effective in under loaded networks or in fully connected networks only. For them the WRED (Weighted Random Early Detection) is effective congestion avoidance technique. But in some networks dropping packets can lead to customer dissatisfaction and SLA violation.As we need firm correlation with bandwidth management and traffic engineering (TE) the initial (pro-active) routing can be pre-computed in the context of all priority traffic flows (former contracted SLAs) traversing the network simultaneously; see fig. 1. It could be a very good solution for congestion avoidance and for better load-balancing purpose in core network where links are running close to capacity. If we want to obtain quantitative end-to-end guarantees the QoS provisioning has to be in firm correlation with bandwidth management; see [7] and [8]. Similar approach we need in bandwidth reservation from neighbour ASes (Autonomous System), see [14]. It is th main element for optimal end-to-end provisioning. Detail explanation of new constraint-based routing approach is given in section 2. CR routing technique can be seen as the capacity expansion problem (CEP) in given limits. The mathematical model explanation is given in the section 3. In the section 4 we have CEP algorithm development and heuristic approach. The comparison of results for different algorithm options we can see in the section 5.

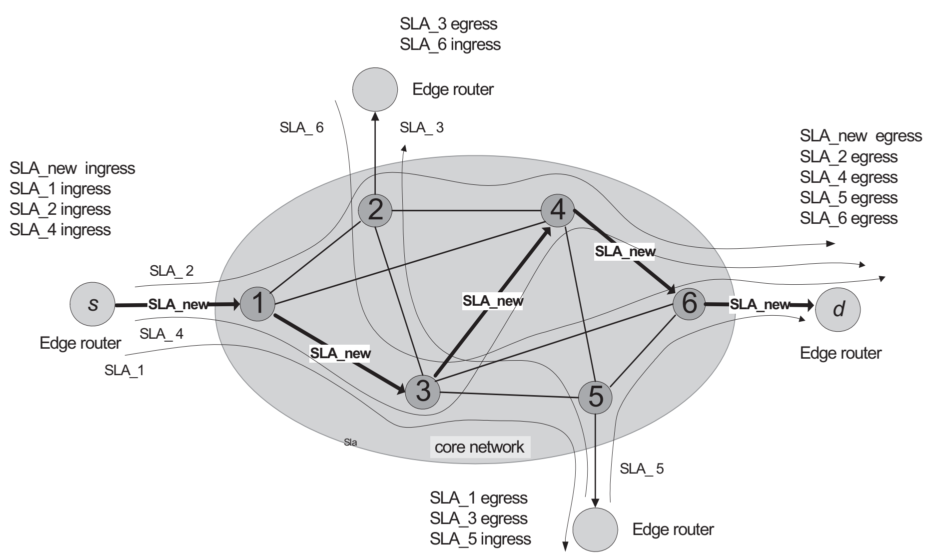

Figure 1. An example of number of SLAs in the context of new SLA creation.

2. LSP Creation During SLA Negotiation

The service provider in domain (e.g. ISP) wants to accept new SLA that results with priority traffic flow between edge routers. A traffic trunk is defined as a logical pipeline within an LSP, with reservation of certain amount of capacity to serve the traffic associated with a certain SLA. So it is clear that LSP between an ingress/egress pair may carry multiple traffic trunks associated with different SLAs; see [10]. In fig. 2 we have situation on the path for the example of simultaneous SLA flows from fig. 1. All traffic flows on the path are participating possibly in the same time (the worst case). In that sense the network operator (e.g ISP) has to find the optimal LSPs for aggregated flows without any possible congestion in the core network; see [9]. Each traffic demand can be satisfied on appropriate or higher QoS level. The main condition is: the sufficient network resources must be available for the priority traffic at any moment.

During SLA negotiation process the RM (Resource Manager) module has to determine the main parameters that characterize the required flow (i.e., bandwidth, QoS class, ingress and egress IP router addresses); see [13]. At first RM can apply any shortest path-based routing algorithm (e.g. OSPF - Open Shortest Path First) to get initial LSP. The BB (Bandwidth Broker) will therefore check if there are enough resources on the calculated path to satisfy the requested service class, taking care of all existing flows in the same time (caused by former SLAs).

With such congestion control algorithm the RM can predict sufficient link resources to satisfy all traffic demands. If the optimal routing sequence has any link that exceeds allowed capacity limits (maximal bandwidth) possible congestion exists; see [15]. It means that link capacity on the path cannot be sufficient for such traffic. Such congested link has to be eliminated from the path and procedure starts again with next path configuration. Alternatively, adding capacity arrangement can be done (if possibly) but it can produce significant extra cost.

If calculation finds the path without any congestion the new SLA can be accepted and related LSP is assigned to that flow and stored in database of BB. In opposite the new SLA cannot be accepted or must be re-negotiated. In the moment of service invocation such calculated and stored LSP can be easily distributed from BB to the MPLS network to support explicit routing, leveraging bandwidth reservation and prioritization; see [16].

In that way the LSP creation should be in co-relation with SLA, to enable better load-balancing and congestion avoidance in domain. In such CR approach we can observe the main difference from usual on-line routing techniques (e.g. OSPF): the optimal LSP need not to be necessarily the shortest path solution.

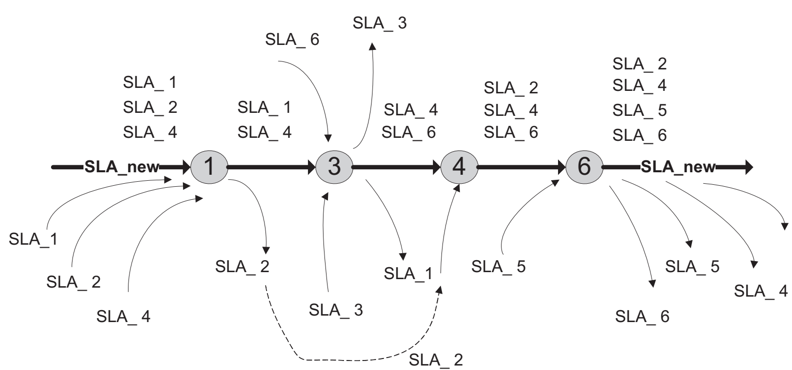

Figure 2. Simultaneous flows with possibly congestion on the path.

Such technique can be appropriate for inter-domain end-to-end path provisioning in the part of optimal bandwidth reservation from neighbor ASes. Capacity reservations are made in the most effective way in order to provide bandwidth guarantees for the predicted traffic; [11]. Having purchased access to sufficient bandwidth from downstream ASes, the AS needs to utilize both: purchased bandwidth and its own network capacity.

3. Mathematic Model of CEP for Congestion Control and Load Balancing Purposes

The congestion control technique explained above can be seen as the capacity expansion problem (CEP) with or without shortages. For full traffic satisfaction we talk about CEP without shortages. Transmission link is capable to serve traffic demands for N different QoS levels (service class) for $i = 1, 2, ..., N$. For each load we need appropriate bandwidth amount, so it looks like bandwidth expansion. Bandwidth portions on the link can be assigned to appropriate service class up to the given limit (maximal capacity). Used capacity can be increased in two forms: by expansion or by conversion. Expansions can be done separately for each service class or through conversion (redirected amount) to lower quality class. It means that it can be reused under special conditions to serve the traffic of lover quality level. Bandwidth usage for each service class can be a part of resource reservation strategy. Fig. 2 gives an example of network flow representation for multiple QoS levels (N) and M core routers (LSR) on the path. In the CEP model the following notation is used:

Fig. 3 gives an example of network flow representation for multiple QoS levels (N) and M core routers (LSR) on the path. In the CEP model the following notation is used:

i, j and k = QoS level. We differentiate n service classes (QoS levels).The N levels are ranked from $i = 1, 2,..., N$, from higher to lower.

m = the order number of the link on the path, connecting two successive routers, $m = 1, …., M+1$.

u,v = the order number of capacity points in the sub-problem, $1 \le u, ..., v \le M+1$.

$r_{i,m}$ = traffic demand increment for additional capacity for each router on the path. Any traffic demand can also be satisfied by converted capacity from any capacity type k with higher quality level. For convenience, the $r_{i.m}$ is assumed to be integer. The sum of traffic

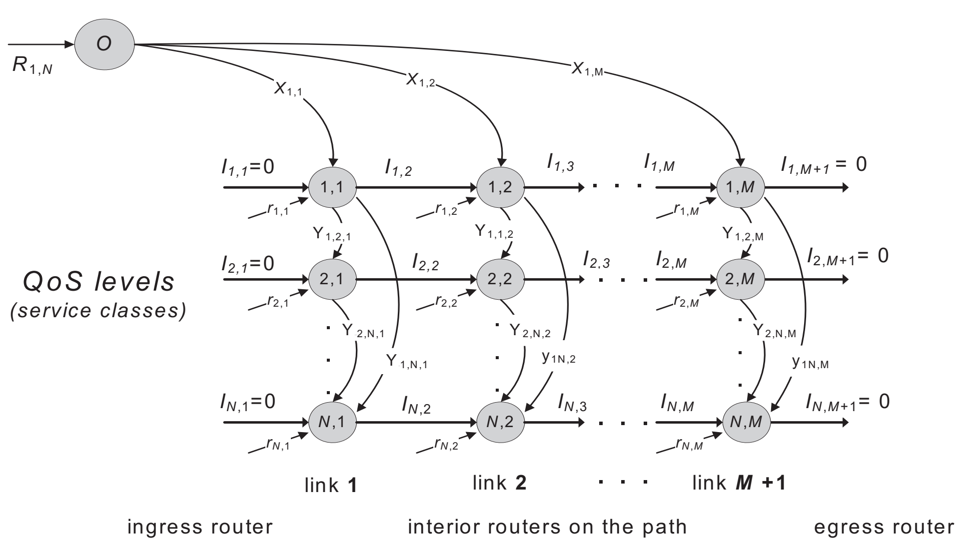

Figure 3. The network flow representation of the CEP model for congestion control purposes.

demand for capacity type i between two routers:

$$R_i(m_1, m_2) = \sum_{m=m_1}^{m_2} r_{i,m} \tag{3.1}$$

The sum of demands for whole path and for all capacity types has to be positive or zero:

$$\sum_{i=1}^{N} R_i(1, M) \geq 0 \tag{3.2}$$

It means that we don't expect reduction of total capacity on the path toward egress router, in other words we presume the increase of capacity. Traffic demand can also be satisfied by converted capacity from one capacity type to another, partially in combination with expansion or in total amount.

$I_{i,m}$ = amount of capacity (idle capacity or shortage) on the link m, connecting two neighbor routers. Possibly positive or negative values. $I_{i1} = 0$, $I_{i,M+1} = 0$ that means: no adding capacity is necessary on the links toward edge routers. Those links are not the mater of optimization.

$x_{i,m}$ = the amount of adding capacity for each service class on the link m. Possible negative values (decrease).

$L_{i,m}$ = bandwidth constraints for link capacity values on the link m and for appropriate service class i ($L_{1,m}$, $L_{2,m}$, … $L_{N,m}$).

$y_{i,j,m}$ = the amount of capacity for quality level i on the link m, redirected to satisfy the traffic of lower quality level j.

$w_{i,m}$= weight for the link m and appropriate service class i (QoS level).

$del_{i,m}$= delay on the link m for appropriate service class i. Maximal delay on the path is denoted with DEL_i .

As we have nonlinear cost functions (showing the economy of scale) the CEP can be solved by any nonlinear optimization technique. Instead of a nonlinear convex optimization, that can be very complicated, the network optimization methodology is efficiently applied; see [17]. The main reason on such approach is the possibility of discrete capacity values for limited number of QoS classes, so the optimization process can be significantly improved. The problem can be formulated as Minimum Cost Multi-Commodity Flow Problem (MCMCF). Such problem (NP-complete) can be easily represented by multi-commodity the single (common) source multiple destination network; see fig. 3.

Let G (V, E) denote a network topology, where V is the set of vertices/nodes, representing link capacity states and A, the set of arcs representing traffic flows between routers. Each link on the path is characterized by z-dimensional link weight vector, consisting of z-nonnegative QoS weights. The number of QoS measures (e.g. bandwidth, delay) is denoted by z. In general we have multi-constrained problem (MCP) but in this paper we talk about one-dimensional link weight vectors for M+1 links on the path $\{w_{i,m}, m \in A, i = 1, \ldots, N\}$. E.g. the capacity constraint for each link on the path is denoted with $L_{i,m}$ ($L_{1,m}$ $L_{2,m}$, … $L_{N,m}$). For a non-additive measure (e.g. bandwidth) definition of the single-constrained problem is to find a path from ingress to egress node with minimal link weight along the path.

In the context of MCP we can introduce easily the adding constraint of max. delay on the path (end-to-end). As it is an additive measure (more links on the path cause higher delay) it can be used as criteria to eliminate any unacceptable routing solution from calculation.

The flow situation on the link depends of expansion and conversion values ($x_{i,m}$, $y_{i,j,m}$). It means that the link weight (cost) is the function of used capacity: lower amount of used capacity (capacity utilization) gives lower weight. If the link expansion cost corresponds to the amount of used capacity, the objective is to find the optimal routing policy that minimizes the total cost on the path.

Definition of the single-constrained problem is to find a path P from ingress to egress node such that:

$$w(P) = \min \sum_{m=1}^{M+1} \sum_{i=1}^{N} w_{i,m}(I_{i,m}, x_{i,m}, y_{i,j,m}) \tag{3.3}$$

where: $I_{i,m} \leq L_{i,m}$ (3.4)

$$\sum_{m_1}^{m_2} del_{i,m} \leq DEL_i \tag{3.5}$$

satisfying condition: max. delay of $P \leq DEL_i$ (3.6)

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

A path obeying the above conditions is said to be feasible. Note that there may be multiple feasible paths between ingress and egress node. Generalizing the concept of the capacity states for each quality level of transmission link m between LSRs in which the capacity states for each service class (QoS level) are known within defined limits we define *a capacity point* - α_m.

$$\alpha_m = (I_{1,m}, I_{2,m}, \dots, I_{N,m}) \tag{3.7}$$

$$\alpha_1 = \alpha_{M+1} = (0, 0, \dots, 0) \tag{3.8}$$

In formulation (3.7) α_m denotes the vector of capacities $I_{i,m}$ for each service class on link m, and we call it capacity point. On the flow diagrams (fig. 2.) each column represents a capacity point of the node, consisting of N capacity state values (for i-th QoS level). Link capacity is capable to serve different service classes. Capacity amount labeled with i is primarily used to serve traffic demands of that service class but it can be used to satisfy traffic of lower QoS level j ($j > i$).

Formulation (3.8) implies that idle capacities or capacity shortages are not allowed on the beginning and on the end of optimization. It means that process is starting with new SLA flow that must be fully satisfied through the network (to egress node).

The objective function for CEP problem can be formulated as follows:

$$\min\left(\sum_{m=1}^{M+1}\left\{\sum_{i=1}^{N} c_{i,m}(x_{i,m}) + h_{i,m}(I_{i,m+1}) + g_{i,j,m}(y_{i,j,m})\right\}\right) \tag{3.9}$$

so that we have:

$$I_{i,m+1} = I_{i,m} + x_{i,m} - \sum_{j=i+1}^{N} y_{i,j,m} - r_{i,m} \tag{3.10}$$

$$I_{i,1} = I_{i,M+1} = 0 \tag{3.11}$$

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

In the objective function the total cost (weight) includes some different costs. Expansion cost (adding capacity) is denoted with $c_{i,m}$ ($x_{i,m}$). For the link expansion in allowed limits we can set the expansion cost to zero. We can differentiate expansion cost for each service class. We can take in account the idle capacity cost $h_{i,m}$ ($I_{i,m+1}$), but only as a penalty cost to force the usage of the minimum link capacity (prevention of unused/idle capacity). Also we can introduce facility conversion cost $g_{i,j,m}$ ($y_{i,j,m}$) that can control non-effective usage of link capacity (e.g. usage of higher service class capacity instead). 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 differ from link to link. The objective function is necessarily non-linear cost. With different cost parameters we can influence on the optimization process, looking for benefits of the most appropriate expansion solution.

4. Algorithm Development

The network optimization can be divided in two steps. At first step we are calculating the minimal expansion weights $d_{u,v}$ for all pairs of capacity points in neighbor links on the path. The calculation of weight value between capacity points we call: capacity expansion sub-problem (CES); see (4.1). The expansion sub-problem for N facilities $i = 1, 2, \dots, N$ on the path between routers u and v is as:

$$d_{u,v} = \min\left\{\sum_{m=u}^{v}\left(\sum_{i=1}^{N} c_{i,m}(x_{i,m}) + h_{i,m}(I_{i,m+1}) + \sum_{j=m+1}^{N} g_{i,j,m}(y_{i,j,m})\right)\right\} \tag{4.1}$$

where:

$$I_{i,v+1} = I_{i,u} + D_i(u,v) - R_i(u,v) \tag{4.2}$$

$$R_i(u,v) = \sum_{m=u}^{v} r_{i,m} \tag{4.3}$$

$$D_i(u,v) = \sum_{m=u}^{v}\left(x_{i,m} - \sum_{j=1}^{N} y_{i,j,m}\right); \quad i \neq j \tag{4.4}$$

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

Let C_m be the number of capacity point values at router position m (for link between core routers). Only one capacity point for the link that connects to the edge router: $C_1 = C_{M+1} = 1$.

The total number of capacity points is:

$$C_p = \sum_{m=1}^{M+1} C_m \tag{4.5}$$

In the CEP we have to find many cost values $d_{u,v}(\alpha_u, \alpha_{v+1})$ that emanate two capacity points, from each node (u, α_u) to node $(v+1, \alpha_{v+1})$ for $v \geq u$. The total number of all possible connections (CES) is:

$$N_d = \sum_{m=1}^{M} C_m \cdot C_{m+1} \tag{4.6}$$

For every CES calculation of many different solutions can be derived depending on D_i value. Many combinations exist and each of them consists of expansion and conversion amount solutions for each capacity type.

The most of the computational effort is spent on computing of the sub-problem values. The number of all possible $d_{u,v}$ values depends on the total number of capacity points.

Suppose that all links (sub-problems) are calculated, the optimal solution for CEP can be found by searching for the optimal sequence of capacity points and their associated link state values. The number of all possible $d_{u,v}(\alpha_u, \alpha_{v+1})$ values depends on the total number of capacity points. It is very important to reduce that number (C_p) and that can be done through imposing of appropriate capacity bounds or by introduction of adding constraints (e.g. max. delay). Through numerical test-examples we'll see that many expansion solutions cannot be a part of the optimal expansion sequence. It is the way how algorithm can be significantly improved. So we can obtain the near-optimal result with significant computational savings.

4.1. Single Location Expansion Problem

Approach described in chapter above requires solving repeatedly a certain single location expansion problem (SLEP) in all possible modifications, looking for the best result. Let $\text{SLEP}_{i,j}$ (m, D_i, ... D_j) be a *Single Location Expansion Problem* associated with link m for facility (capacity) type i, i+1, ... , j and corresponding values of *capacity change intention* D_i, D_{i+1}, ... , D_j.

For example, in solving $\text{SLEP}_{1,3}$ for three different capacity types we have many expansion solutions divided into three different scenarios (expansion strategies):

A. capacity changes of one capacity type are not correlated with changes of others;

B. capacity changes of two capacity types depend on each other, but change of the third is independent;

C. capacity changes for all of three capacity types depend on each other.

From three expansion scenarios (expansion strategy) many different expansion solutions can be derived, depending on D_i value. A lot of them are not acceptable and are not part of optimal sequence. For this problem an acceptable expansion solution has to satisfy some basic properties:

$$x_{i,m} \cdot D_{i,m} \geq 0 \tag{4.1.1}$$

$$y_{i,j,m} \cdot D_{i,m} \leq 0 \tag{4.1.2}$$

$$y_{i,j,m} \cdot D_{j,m} \geq 0 \tag{4.1.3}$$

Property (4.1.1) implies that the expansion (increase) of capacity type i cannot be acceptable if that facility has intention to be reduced on location (link) m ($D_{i,m} < 0$). Similar stays for negative values.

Expansion (increase) is also possible through conversion, so (4.1.2) and (4.1.3) imply the similar restriction as (4.1.1). Zero value of any capacity type means that any change of capacity is allowed.

In scenario A. we have only one possible expansion solution. In scenario B. we can combine all three capacity types in couples. In scenario C. we can see that only one expansion solution exists. Totally, we have five different expansion solutions with many variations.

In scenarios B. and C. we have expansion solutions with conversions of capacity from one type to another. It can be done as stand-alone expansion or together with expansion. That means that the conversion is just complementary with the expansion in satisfying of traffic demands.

Conversions can be applied only when idle capacities are noticed or negative demand increments are present. Special case is occurred when conversion $y_{i,j,m}$ eliminates both: eliminating idle capacity of type i plus satisfying traffic demands of capacity type j. Also we can make distinction between two options: the partial expansion and the excessive expansion. The partial expansion $x_{j,m}$ means that demands are satisfied by expansion of appropriate capacity type j plus by conversion $y_{i,j,m}$ of capacity type i with higher quality level, but only if shortage of facility i is not occurred.

The excessive expansion means that the expansion amount $x_{i,m}$ is used to partially expand facility i and to satisfy demands for lower capacity type j, with conversion amount $y_{i,j,m}$.

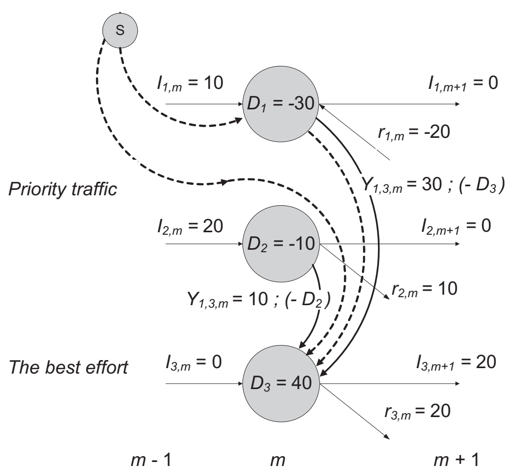

Figure 4. An example of single location expansion solution that cannot be a part of the extreme solution.

4.2. Adding properties (the improvement of CEP algorithm)

The most of the computational effort is spent on computing the $d_{u,v}$ sub-problem values. A lot of expansion solutions are not acceptable and they are not part of the optimal sequence. The key for this very effective approach is in fact that extreme flow theory enables separation of these extreme flows which can be included in optimal expansion solution from those which cannot be. Any of them, if it cannot be a part of the optimal sequence, is set to infinity. It can be shown that a feasible flow in the network given in fig. 4. corresponds to an extreme point solution of CEP if and only if it is not the part of any cycle (loop) with positive flows, in which all flows satisfy given properties; see [18]. One may observe that the absence of cycles with positive flows implies that each node has at most one incoming flow from the source node (positive or negative). This result holds for all single source networks. That means that optimal solution of $d_{u,v}$ has at most one expansion (or reduction) for each facility.

Using a network flow theory approach, adding properties of extreme point solution are identified. These properties are used to develop an efficient search for the link costs $d_{u,v}$. Absence of such cycles with positive flows implies that extreme point solutions for CEP satisfy the following properties:

$$I_{i,m} \cdot x_{i,m} \leq 0 \tag{4.2.1}$$

$$I_{i,m} \cdot y_{i,j,m} \geq 0 \tag{4.2.2}$$

$$I_{j,m} \cdot y_{i,j,m} \leq 0 \tag{4.2.3}$$

$$I_{j,m} \cdot x_{i,m} \cdot y_{i,j,m} = 0 \quad \text{if } x_{i,m} \cdot y_{i,j,m} \neq 0 \tag{4.2.4}$$

$$I_{i,m} \cdot I_{j,m} \cdot y_{i,k,m} \cdot y_{j,k,m} = 0 \text{ if } \; y_{i,k,m} \cdot y_{j,k,m} \neq 0 \tag{4.2.5}$$

for: $i, j, k = 1, 2, 3 \; i \neq k \neq j$; $m = 1, \ldots, M+1$

Properties (4.2.1) to (4.2.5) imply that the capacity of any capacity type is changed through an expansion, reduction or by conversion only if it doesn't make cycles with positive flows.

(4.2.1) and (4.2.2) imply that the capacity of any capacity type can be increased by an expansion or by a conversion only if there is no idle capacity. Similar rule exists for reduction of idle capacity.

(4.2.3) implies that capacity can be reduced only if there is no capacity shortage.

(4.2.4) implies that incoming flow of facility, going to be converted (reduced) in partially or excessive expansion solution, has to be zero. If not, cycles with positive flows can be occurred; see fig. 4. On that diagram we have idle capacity from previous link (for first and second class). The third class is satisfied with capacity conversions of higher classes. On that diagram dotted lines mark a cycle with positive flows from the common source. It means that such solution is not allowed. One of the capacity values ($I_{2,m}$ or $I_{3,m}$) must be zero.

Property (4.2.5) is used for simultaneous multi-conversion solution from scenario C. Only one incoming flow of converted (reduced) facility can exist. It means that two incoming flows are not allowed in the same time. In the case of simultaneous conversions, incoming flows have to be zero.

We can say that any acceptable $SLEP_{1,3}$ expansion solution for any CES have to satisfy properties (4.1.1) - (4.1.3) and (4.2.1) - (4.2.5). So many expansion solutions are not a part of optimal sequence and could be eliminated from further computation; see [19]. It means that any of sub-problem value if it cannot be a part of the optimal sequence is set to infinity.

5. Testing Results and Comparison of Different Algorithm Options

The proposed algorithm is tested on many numerical test-examples, looking for optimal routing sequence on the path. Between edge routers there are maximum M core routers (LSR) and the path consists of maximum M+1links. Traffic demands (former contracted SLAs) are given in relative amount for each interior router on the path. Demands are overlapping in time and are defined for each capacity type (service class). Results obtained by improved algorithm (reduction of unacceptable expansion solutions) are compared with results obtained by referent algorithm that is calculating all possible expansion solutions for each CES.

For each test-example we know the total number of capacity points. The number of possible CES is well-known, so it is the measure of the complexity for the CEP-problem.

Also, for each test-example we can see the number of acceptable sub-problems, satisfying basic and additional properties of optimal flow. For all numerical test-examples with improved algorithm (denoted with Basic_A) the best possible result (near-optimal expansion sequence) can be obtained, same as with referent algorithm (without reduction of unacceptable expansion solutions). For N=3 and M=6 algorithm complexity savings in percents are on average near 40 % that is proportionally reflected on computation time savings; see fig. 5.

The number of all possible CES values depends on the total number of capacity points as resultant of traffic demands. So CEP requires the computation effort of $O(NMN_d)$ with linear influence of N. In real application we normally apply definite granularity of capacity values through discrete values (only integer) of traffic demands R_i. It reduces the number of the capacity points significantly. Because of that the lowest step of possible capacity change ($step\_I_i$) has strong influence on the algorithm complexity.

In real situation we can introduce some limitations on the capacity state values, talking about heuristic algorithm options:

a) Only one negative capacity value in the capacity point. Such option is denoted with M_H *(Minimal-shortage Heuristic option*);

b) Total sum of the link capacity values (for all quality levels) is positive A_H *(Acceptable Heuristic option*);

c) Total sum is positive but only one value can be negative. Such option is denoted with R_H (*Real Heuristic option*);

d) Algorithm option that allows only non-negative capacity state values is denoted with P_H (*Positive Heuristic option*);

e) Only null capacity values are allowed. A trivial heuristic option (denoted with T_H) allows only zero values in capacity point (only one capacity point).

We compared the efficiency of algorithm in above mentioned options. In figure 5. we can see the average values of results for N=3 and M=6. Only for few test-examples any algorithm option can find the best expansion sequence, providing the minimal cost no matter of algorithm option we use. For the most examples algorithm option M_H can obtain the best result with average saving of 60 %. For other algorithm options the significant reduction of complexity is obvious but deterioration of result appears. Only for some of them the final results are still in acceptable limits (see fig. 5). In the most cases the trivial algorithm option (T_H) shows the significant deterioration of results. A very good fact for all algorithm options is that efficiency rises with increase of value M; see fig. 6.

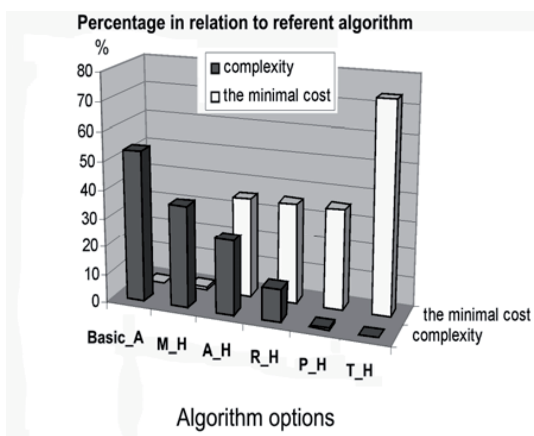

Figure 5. Trends of algorithm complexity and comparison of results (minimal cost).

6. Conclusion

In this paper we propose a efficient algorithm for congestion control that can help in network and traffic dimensioning. Traffic engineering (TE) can improve QoS capabilities as an effective mean for bandwidth guarantee provisioning while optimizing network resource utilization. Inappropriate bandwidth reservation or wrong traffic assignment could result in, respectively, high cost or poor resource utilization.

We can check congestion probabilities on the path with algorithm of very low complexity first (e.g. P_H algorithm option). It means that only if congestion possibility appears we need optimization with more complex algorithm (e.g. A_H). With the most complex algorithm option (Basic_A) we can get the best possible result, so we can be sure if congestion on the path could appear or not. In the case of congestion appearance new SLA cannot be accepted or adding capacity arrangement should be done. It means that SLA re-negotiation has to be done and customer has to change the service parameters: e.g. bandwidth (data speed), max. delay or period of service utilization.

The proposed algorithm for congestion control (with different options) can be efficiently incorporated in explicit intra-domain and inter-domain routing for DiffServ/MPLS networks. Routing process can be in firm correlation with bandwidth management and admission control only if it starts much earlier, possibly during SLA negotiation process.

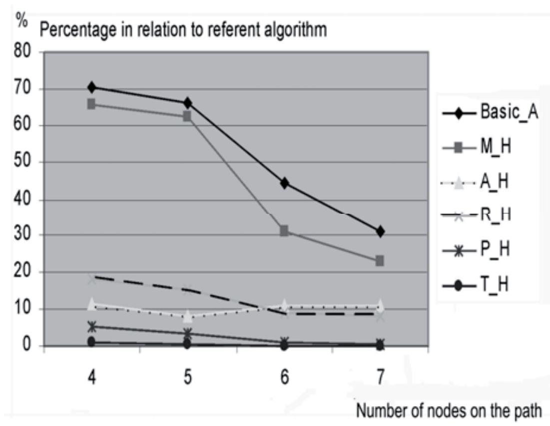

Figure 6. The complexity savings increase with value *M.*

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