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Self-Management Principles in Autonomic Service Architecture Supported by Load Balancing Algorithm

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Original scientific paper

This paper is about the role of a heuristic algorithm for load balancing that can be incorporated in Multi-Protocol Label Switching/ Differentiated Services (MPLS/DS) networks based on self-management principles for automated traffic configuration. Delivery of Quality of Services (QoS) differentiation according to specific service level agreements, Service Level Agreement (SLA), has to be in relation to resource management and bandwidth allocation, to ensure better end-to-end QoS provisioning and to avoid traffic congestion. To ensure simultaneous traffic flows with different priorities we need some load-balancing procedure. It could start much earlier than usual, possibly during SLA negotiation. If SLA creation is supported by load control mechanism it can ensure better performances of the network in the moment of service invocation. LSP (Label Switching Path) creation could be influenced by former contracted SLAs and such approach could be more effective than pure routing technique based on the shortest path algorithm (LSP creation in the moment of service invocation). So we propose application of heuristic algorithm tested on numerical examples with maximum M routers on the path and with differentiation of N service classes. Further, we introduced some capacity state restrictions in the process of network optimization, considering different algorithm options. We compared their performances, especially the algorithm complexity that is very important for efficient load control in huge networks.

Key words: Constraint-based routing, End-to-end QoS provisioning, Load control and congestion avoidance self-management systems, SLA negotiation, Traffic engineering in MPLS/DiffServ networks

Samoorganiziranje u autonomnoj arhitekturi za pružanje diferenciranih usluga primjenom algoritma za balansiranje prometa. Članak opisuje ulogu heurističkog algoritma za balansiranje opterećenja i dimenzioniranje prometa u MPLS/DiffServ mreži na načelu samoorganizacije i automatske konfiguracije. Ostvarenje QoS usluga mora biti u skladu s postojećim ugovorom za kvalitetu usluge (SLA), sklopljenim između korisnika i operatera, ali tako da se omogući upravljanje resursima mreže izbjegavajući moguća zagušenja. Da bi osigurali simultane prometne tokove uz razlikovanje kvalitativne razine, nužno je osigurati balansiranje prometa. Takvo balansiranje mreže može započeti i znatno ranije, moguće već u trenutku pregovaranja pri sklapanju SLA. Ako je ono podržano kontrolom mogućeg zagušenja mogu se značajno poboljšati QoS jamstva i uravnoteženost mreže. Kreiranje LSP puta s obzirom na prijašnje ugovoren (rezerviran) promet bilo bi bolje od samog usmjeravanja na načelu najkraćeg puta (usmjeravanje u trenutku pokretanja usluge). Za tu je namjenu u radu predložena primjena heurističkog algoritma testiranog na mnogim numeričkim primjerima s maksimalno M usmjerivača na putu s kraja-na kraj domene i s maksimalno tri vrste (N=3) različitih kvalitativnih razina (klase prometa). Razmatrana su daljnja poboljšanja algoritma u ograničavanju stanja kapacitivnih točaka u postupku mrežne optimizacije, tj. testirane su i uspoređene razne opcije algoritma. Neke od njih pokazuju značajno smanjenje složenosti uz zadovoljavajuću kvalitetu ostvarenih rezultata, što je važno za kontrolu opterećenja u velikim mrežama.

Ključne riječi: kontrola zagušenja i izbjegavanje sukoba, osiguranje QoS s-kraja-na-kraj, prometno inženjerstvo u MPLS/DiffServ mrežama, samo-organizirajući sustavi, placeSLA pregovaranje, višekriterijsko određivanje puta

1 INTRODUCTION

In MPLS/DS (Multi-Protocol Label Switching/ Differentiated Services) domain traffic flows are defined with LSPs (Label Switching Path). The traffic aggregation in intermediate routers, LSRs (Label Switching Routers), is related to service classification made in an edge (ingress) router by (CoS) bits in the packet header [1]. PHB (Per Hop Behavior) for a FEC (Forward Equivalence Class) between neighboring LSRs is usually defined using the shorts path principle, so all LSPs (Label Switching Paths) for the same QoS level are built in the same way. It means that many different LSPs could simultaneously use the same link and create congestion. Some links could be congested while the others could be underutilized. There are some congestion avoidance techniques such as RED (Random Early Detection) or WRED (Weighted Random Early Detection), but in some QoS networks dropping packets can lead to customer dissatisfaction and SLA (Service Level Agreement - between a customer and service provider) violation [2, 3]. In the context of simultaneous flows (the existing SLAs and new SLA) bandwidth overbooking is possible and a congestion problem can occur.

QoS provisioning in MPLS/DS networks has load balancing issues, especially in networks where overprovisioning of bandwidth (link capacity) is not acceptable [4, 5]. All traffic traversing an ingress/egress pair has to be distributed among these LSPs but in optimal way, taking care of load balancing purposes. We have to compute the LSP (a sequence of LSRs) with constraints such as bandwidth, delay and administrative policy [6, 7]. TE (Traffic engineering) offers CR (Constrained Routing) option that can be incorporated into each edge router to co-exist with usual routing technique [8]. But it is obvious that technique could be insufficient if it is not correlated with SLA negotiation process and bandwidth/resource reservation processes.

The resource management problem is in fact an optimization problem subject to the set of constraints: the total bandwidth has to be allocated to parallel traffic trunks associated to simultaneous SLAs without exceeding the physical link capacity [9]. We assume that there exists a routing algorithm which can set up several parallel paths for each ingress/egress pair, one for each service class, and the paths are fixed as LSPs. The paths are not necessarily the same for different service classes. Total bandwidth allocation for each link on the path must be less than the sum of bandwidth for all flows (different traffic classes) simultaneously traversing the same link. For traffic routing of lower service class (FEC) instead of the shortest path we can use the alternative paths. Such approach can result in change of PHB (Per-Hop Behavior) for some QoS class. That approach opens the possibility of sophisticated off-line routing that can be done in advance, possibly during SLA creation. It provides a foundation for firm corelation between SLA negotiation process and bandwidth/resource management [5]. The load balancing control, as a part of DS-TE (DiffServ TE), can help with optimal bandwidth reservation, i.e. to predict sufficient resources and to ensure better end-to-end QoS provisioning [10].

The efficient bandwidth utilization in a scalable, flexible, and automatic way can be seen as a part of autonomic service architecture (ASA) through interoperability of many functional elements. Section 2 provides related work and describes some existing approaches to bandwidth management and centric resource distribution. Off-line technique for load balancing as a part of SLA negotiation process is explained in Section 3. Bandwidth distribution and load control can be viewed as the capacity expansion problem (CEP) of *N* capacity types where simultaneous flows influence each other. We are looking for fair distribution of bandwidth portions for each (*N*) service (QoS) classes respectively to each SLA (LSP) and for each link on the path. The mathematical model of CEP in context of load-balancing is described in Section 4. Further the heuristic algorithm implementation is discussed. Section 5 discusses the results for different algorithm options.

2 RELATED WORK

ASA for MPLS/DS networks is based on TEQUILA architecture that provides a framework for resource bandwidth and TE in MPLS/DS networks [11]. In SLA management architecture after the customer and SP (service provider) negotiate the service (with corresponding SLA), ASA has to manage that service in order to ensure quality service delivery without SP's intervention. In such ASA approach "*a service*" is defined as the engagement of resources for a period of time during which the contract on relations between a customer and an SP is valid. Resources can be physical or logical components used to construct services. When customers purchase a service from an SP, they can also offer it to other customers, becoming SPs to those customers (upstream AS). This is the crucial part of inter-SP resource allocation in end-to-end (E2E) QoS support.

An example of SLA management architecture can be seen in [12]. The approach is based on virtual partitioning for efficient resource utilization. At each link, virtual partitioning is implemented for resource sharing among overloaded and underloaded SLAs. The problem of virtual partitioning is that the QoS of the underloaded SLAs can not be guaranteed. SLA violation for underloaded SLAs is a serious problem. Therefore, Bouillet et al. propose to use a "penalty payment" from the service provider to the customer to compensate possible QoS or SLA violations. However, from the customers' perspective the penalty scheme is not a completely satisfying solution. Customers would always prefer to have guaranteed QoS as well as a fair billing system.

Cheng et al. [11] describe a SLA-centric management model where the bandwidth resources are shared by all SLAs over the network. They propose an autonomic bandwidth borrowing scheme for efficient inter-SLA resource sharing in a MPLS/DS network. With bandwidth borrowing, the network can automatically adjust the resource allocation to each SLA so that the spare capacity can be exploited and QoS specifications of all SLAs are always guaranteed. However, the proposed bandwidth borrowing is consistent with SLA-centric manage principle and works as adaptive adjustment of resource allocation.

As previously discussed, the SLA management scheme based on ”virtual partitioning” is efficient in resource utilization, but may lead to SLA violation. Cheng et al. approach we have an adaptively self-configuring and self-optimizing resource sharing technique called *”bandwidth borrowing”* for MPLS/DS networks. In that approach the crucial element is algorithm for optimal bandwidth borrowing from the common source. It must ensure eficient resource allocation which can be able to set up several parallel paths for each ingress/egress pair, and to find out the optimal paths – known as LSPs.

In basic ASA approach all management functions (resource, policy, SLA, accounting and billing management) are performed by autonomic entities called Autonomic Resource Broker (ARB), which are self-managing, and whose role is to ensure automated delivery of services. For further discussion we refer to standard ARB architecture (Figure 1). The Service Composition and Resource Management normally ensure network dimensioning when large customers are considered, or participate in connection admission control (per-flow resource management) when smaller customers are loading the network. The Resource/Operation Manager ensures that the appropriate actions are taken by allocation of appropriate amount of resources (bandwidth portions) for each link and each quality level (service class). The aggregation size depends on issues such as management overhead and scalability. Resource Info. supports the extraction of badwidth portion from the existing resource pool. It controls the available resources at the SP’s disposal, obtained from the Resource Information Base.

TEQUILA is an architecture for MPLS/DS network management built on the self-management principles. It is mapped to the ARB architecture to function as the core network - CARB (Figure 1). MPLS/DS network provides IP transport service to multiple VNs (Virtual Networks). Each VN negotiates a SLA with the network provider to purchase a certain amount of bandwidth with certain QoS guarantee between some ingress/egress pairs of the core network. The SLA interpreter (or SLA translator) will map the boundary resources according to the MPLS trunk deployment. The SLAs and the corresponding internal resource requirements will be saved as Service Info in separate database.

The CARB module can estimate the long-term traffic load in each DS service class based on the current and some historical SLA subscription information (saved in the Service IB), and forward such traffic load information to the network dimensioning module. By knowing the network topology and present load, the network dimensioning can automaticaly determine the label switched path (LSP) in the network and calculate the bandwidth provisioning PHB directives for each class at each link [13]. The network dimensioning directives are forwarded to the admission control and routing module as "soft" resource partitions and can be activated in the moment of service invocation.

3 OFF-LINE ROUTING AS A PART OF SLA NEGOTIATION

Based on the DS (DiffServ) terminology, a centralized entity, the bandwidth/resource broker (BB), takes care of resource management and network configuration. The bandwidth broker is the core network CARB in the DS context. In the path-oriented environment, admission control and routing are under control of the same module (Figure 1). Each time a new connection request arrives at a certain ingress router, it is forwarded to the bandwidth broker. This ensures that former contacted SLA-a can influence the decision in LSP creation. By checking the stored status information, the controller will select a traffic trunk according to the routing algorithm and make an admission decision according to the resource availability of the selected trunk. Decision will then be delivered back to the corresponding ingress router. If accepted, flow related information is stored in the Service IB associated with each edge router. The bandwidth usage information is updated in Resource IB.

Autonomic inter-SLA resource sharing technique proposes the efficient resource utilization and QoS guarantees. In such path-oriented approach, all the per-VN, per-class, per-ingress/egress resource commitments are mapped to bandwidth allocation at each traffic trunk by network dimensioning. Such ”bandwidth borrowing” technique [12] can be realized through the “link resource sharing” approach. In this context we propose implementation of heuristic algotiham explained in [14] that can be a very effective tool for load balancing and dimensioning of the network based on self-management principles.

So the proposed scenario is: during SLA negotiation process the RM (Resource/Operation Manager) module has to determine the main parameters that characterize the required flow (i.e., bandwidth, QoS class, ingress and egress IP router addresses, time of service utilization); see [15]. At first RM can apply simply routing algorithm to get the initial LSP. It can be done with any shortest path-based routing algorithm (e.g. OSPF). It is possible that all PHBs on the path are previously well known. Also, from RM and Resource IB we can get statistical details for each SLA flow traversing the network simultaneously, e.g.

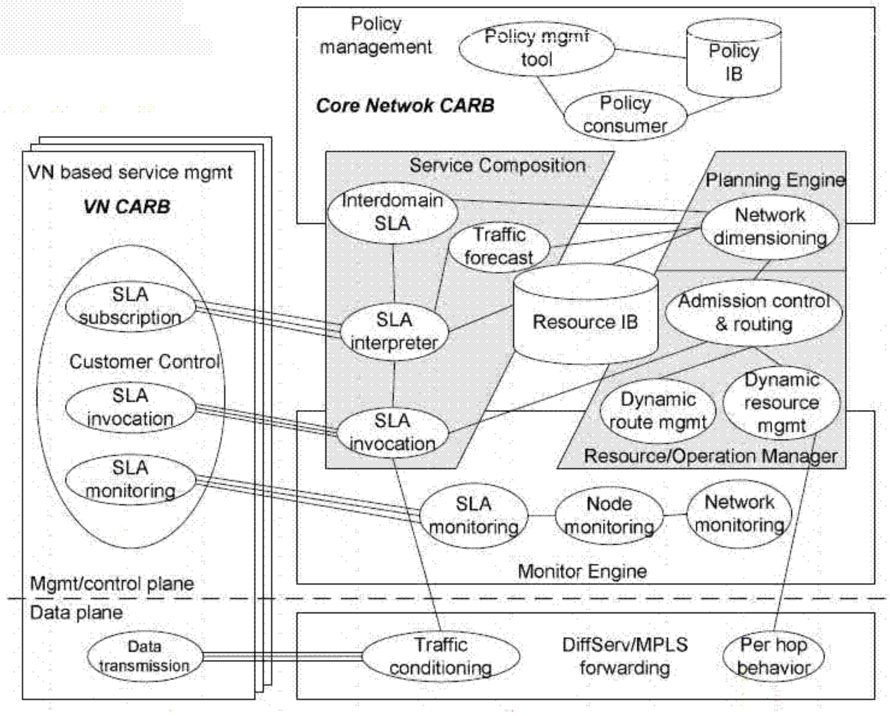

Fig. 1. Elements of CARB participating in resource management process [11]

ingress node, egress node, service class, bandwidth etc.). Now we use very effective algorithm to simulate such traffic loads for all LSRs on the path (for all service classes) and detect congestion possibility. Such optimization is a multi-constrained problem (MCP).

That algorithm in CARB (Resource/Bandwidth Broker) will check if there are enough bandwidth resources on the calculated path to satisfy the requested service class. In the MPLS/DS transport network, the bandwidth broker determines on which traffic trunk the accepted flow should be placed. If such calculated path has any link that exceeds allowed capacity limits (maximal bandwidth for appropriate service class) possible congestion exists [16]. This means that link capacity on the path cannot be sufficient for new traffic load. Alternatively, adding capacity arrangement (dynamic bandwidth reservation) for congested link has to be done but it may produce significant extra costs. More details about dynamic bandwidth reservation mechanism are provided in [17, 18].

For an acceptable LSP creation the alternative path must be defined. The congested link has to be eliminated and replaced by another one. The load control process is repeated until we get acceptable solution without congestion. If calculation finds that proposed path has no congestion, the new SLA can be accepted and the related LSP is assigned to that traffic flow (SLA). The data is stored in the RM (Resource Manager) database (Resource IB). Conversely, if there is congestion, the new SLA cannot be accepted or must be re-negotiated. In the moment of service invocation such calculated (and stored) LSP (sequence of PHBs) can be easily distributed from RM to the MPLS/DS network to support explicit routing, leveraging bandwidth reservation and prioritization [19].

Similarly, load balancing technique can be a part of an optimal bandwidth reservation from the neighboring ASes (Autonomous Systems) in inter-domain routing [20]. The capacity reservation has to be done in the most effective way. Having enabled access to sufficient bandwidth from downstream ASes, home AS can utilize both: purchased bandwidth and its own network capacity (Figure 2).

4 EXPLANATION OF CEP MODEL AND ALGORITHM IMPLEMENTATION

The proposed model for congestion control can be seen as the capacity expansion problem (CEP) on the path with or without shortages for N different QoS levels (service class) for i = 1, 2, ..., N. For each traffic load we need the appropriate bandwidth amount, i.e. bandwidth expansion. Bandwidth portions on the link can be assigned to a traffic flow of the appropriate service class up to the given limit of the bandwidth sub-pool (maximal capacity for defined service class). Used capacity can be increased in two ways: by expansion or by conversion. Expansions can be done separately for each service class or through conversion (redirected amount) to a lower quality class. It means that capacity can be reused to serve the traffic of lower quality level under special conditions. For example, if capacity predefined for priority traffic is unused, it can be redirected to support best effort services. Bandwidth usage for each service class (sub-pool) can be a part of resource reservation strategy but sum of all sub-pools has to be equal/less than link capacity. Figure 2 gives an example of a network flow representation for multiple QoS levels (*N*) and maximum *M* core routers (LSRs) and M+1 links on the path. Network has *V* core routers, $M \leq V$, and *A* links connecting all of them, including edge routers.

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 indexed *i* = 1, 2,..., *N*, from higher to lower quality levels.

m – link on the path, connecting two successive routers; *m* = 1, . . . , *M*+1.

u,*v* - indices for the starting and ending links on the path; $1 \leq u < v \leq M+1$.

$r_{i,m}$– traffic demand increment for additional capacity on the link *m* from an appropriate sub-pool *i*. For convenience, the $r_{i,m}$ is assumed to be integer. For the flow going out from the path $r_{i,m}$ is negative. The sum of the traffic demands for capacity type *i* on the path between two edge routers is:

$$R_i(u,v) = \sum_{m=u}^{m=v} r_{i,m}. \tag{1}$$

$x_{i,m}$ -the amount of adding capacity for appropriate service class *i* on the link *m*. In case that we have idle (sufficient) capacity, negative values (reduction) are possible. The sum of the capacity changes is:

$$X_m = \sum_{i=1}^{N} x_{i,m}. \tag{2}$$

The sum of traffic demands for whole path and for all capacity types has to be positive or zero (including new SLA):

$$\sum_{i=1}^{N} R_i(1, M+1) \leq \sum_{m=1}^{M+1} X_m \geq 0. \tag{3}$$

From this formulation it is obvious that the sum of traffic demands on the path has to be equal or less to capacity amount used to satisfy them. 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.

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

Any traffic demand can also be satisfied by converted capacity from any capacity type $k < i$ with higher quality level. In Fig. 2 such flows are marked with doted lines.

$I_{i,m}$ – relative amount for the capacity type *i* on the link *m*, connecting two neighbor routers. Idle capacity is represented with positive value. If shortages are not allowed, negative value cannot exist. $I_{i,1} = 0$, $I_{i,M+1} = 0$ that means: no adding capacity is necessary on the link toward edge routers. It means that the capacity for that link is always sufficient.

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

$w_{i,m}$ -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 .

4.1 Minimal Usage of Bandwidth Resources for Known Traffic Load

The CEP for nonlinear expansion functions (showing the economy of scale) can be efficiently solved by the network optimization methodology. The main reason on such approach is the possibility of discrete capacity values for limited number of QoS classes, so the optimization can be significantly improved. The problem is formulated as Minimum Cost Multi-Commodity Flow Problem (MCMCF). Such problem can be represented by multi-commodity the single (common) source multiple destination network (Figure 2).

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 expansion 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:

$$w_P = \min \sum_{m=1}^{M+1} \sum_{i=1}^{N} w_{i,m}(I_{i,m}, x_{i,m}, y_{i,j,m}), \tag{4}$$

where:

$$I_{i,m} \leq L_{i,m}. \tag{5}$$

satisfying condition of maximal delay for *P*:

$$\sum_{m=1}^{m=M+1} del_{i,m} \leq DEL_i \tag{6}$$

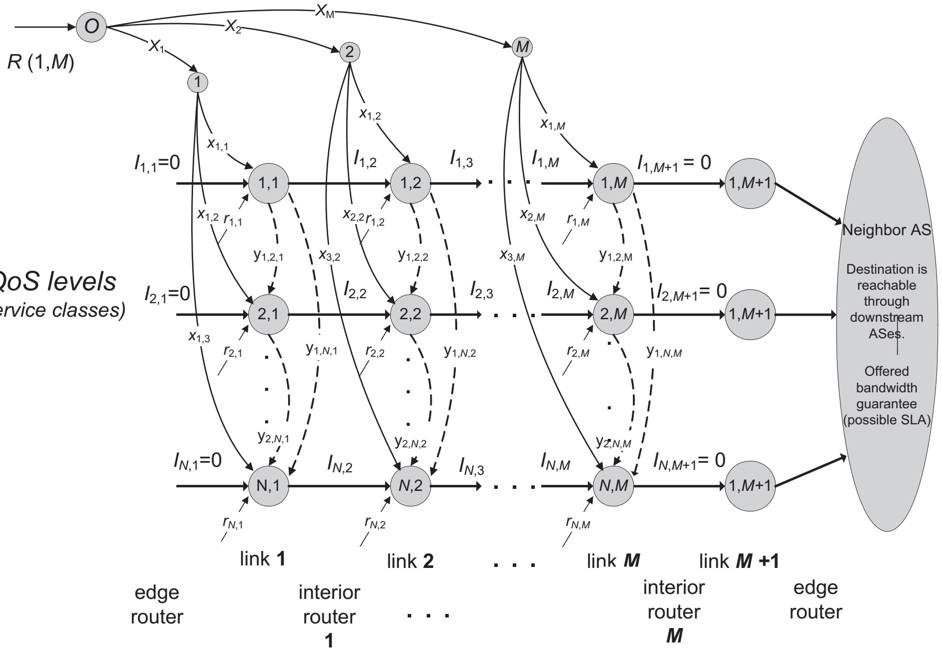

Fig. 2. The network flow representation of the CEP for Russian Dolls bandwidth allocation model

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

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:

$$\alpha_m = (I_{1,m}, I_{2,m}, \ldots, I_{N,m}), \tag{7}$$

$$\alpha_1 = \alpha_{M+1} = (0, 0, \ldots, 0). \tag{8}$$

In formulation (7) α_m denotes the vector of capacities $I_{i,m}$ for each service class on link *m*, and we call it capacity point. In Figure 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 (8) implies that idle capacities or capacity shortages are not allowed at the beginning and at the end of the path. It means that process is starting with new SLA flow that must be fully satisfied through the network (from ingress to egress node).

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

$$w_P = \min \left(\sum_{m=1}^{M+1} \left\{ \sum_{i=1}^{N} c_{i,m}\left(x_{i,m}\right) + h_{i,m}\left(I_{i,m+1}\right) + \right. \right. \\ \left. \left. + g_{i,j,m}\left(y_{i,j,m}\right) \right\} \right) \tag{9}$$

so that we have:

$$I_{i,m+1} = I_{i,m} + x_{i,m} - \sum_{j=i+1}^{N} y_{i,j,m} - r_{i,m} \tag{10}$$

$$I_{i,1} = I_{i,M+1} = 0 \tag{11}$$

for *m* = 1, 2, ..., *M*+1; *i* = 1, 2, ... , *N*; *j* = i + 1, ... , *N*.

In the objective function (9) the total cost (weight) includes some different costs. Expansion cost (adding capacity) is denoted with $c_{i,m}\left(x_{i,m}\right)$. 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 $h_{i,m}\left(I_{i,m+1}\right)$, 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 by constant value.

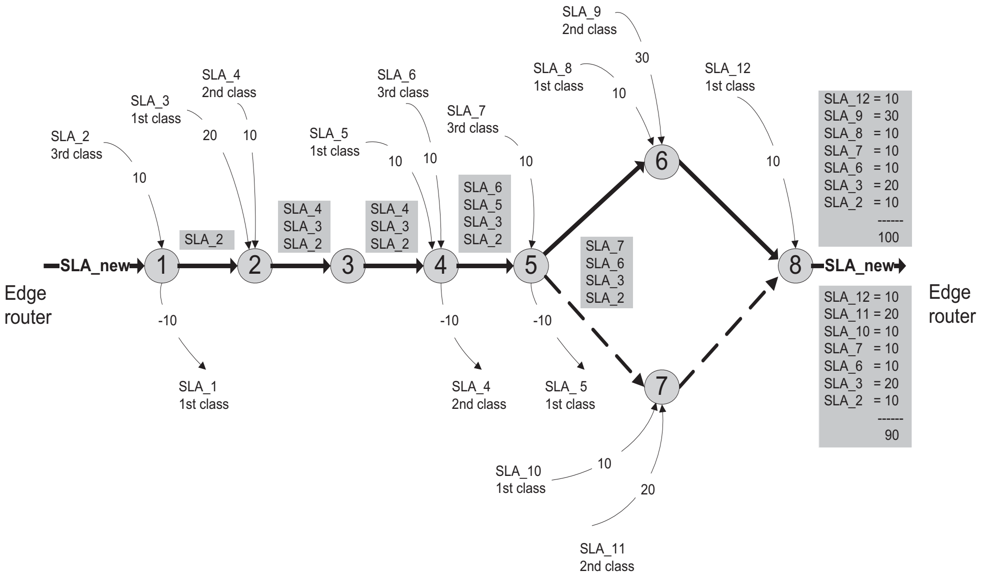

Fig. 3. Simultaneous traffic flows and alternative routing paths for example in Figure 4

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 the optimization process, looking for benefits of the most appropriate expansion solution.

4.2 Algorithm Solution and Heuristic Approach

The network optimization can be divided in two steps. In the first step we calculate the minimal expansion weight $d_{u,v}$ for capacity expansion between two capacity points (neighboring SLRs). We call the calculation of that value: capacity expansion sub-problem (CES). It has to be done for all capacity points and for all pairs of neighbor routers interconnected. In the second step we look for optimal (the shortest) path in the network with calculated weights between nodes. Detailed explanation of algorithm can be seen in [14].

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

The total number of capacity points is:

$$C_p = \sum_{m=1}^{M+1} C_m \qquad (12)$$

In the CEP we have to find many cost values $d_{u,v}(\alpha_u, \alpha_v)$ that emanate two capacity points, from capacity state (u, α_u) to capacity state (v, α_v) for $v \geq u$. The calculation of weight value $d_{u,v}(\alpha_u, \alpha_v)$ is called: Capacity Expansion Sub-problem (CES). The number of all possible CES values can be pretty large:

$$N_d = \sum_{m=1}^{M} C_m \cdot C_{m+1}. \qquad (13)$$

For every CES the calculation of many different expansion solutions can be derived from D_i value - *capacity change intention*. Many combinations are influenced by different expansion and conversion amounts [14]. The most of the computational effort is spent on computing of the CES values. The number of all possible $d_{u,v}$ values depends on the total number of capacity points (Table 1).

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. On that level the CEP problem can be seen as a shortest path problem for an acyclic network in which the nodes represent all capacity state values, and branches represent CES values. Then Dijkstra's algorithm or any similar algorithm can be applied.

The number of all possible $d_{u,v}(\alpha_u, \alpha_v)$ 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). Lot of expansion solutions are not acceptable and they cannot be a part

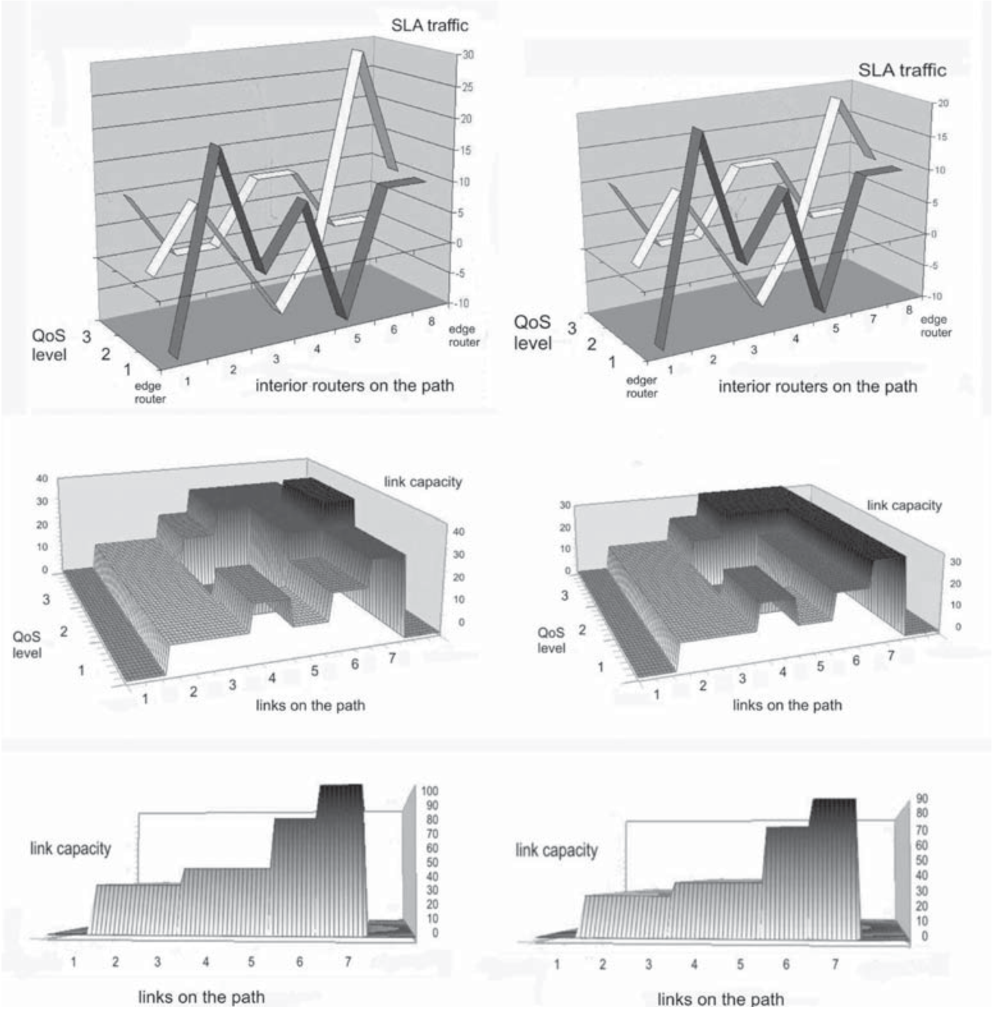

Fig. 4. An example from it is obvious how algorithm for congestion detection works. On the left side diagram for the link 7 the congestion on the path exists. There is no free capacity for new SLA (more than 100). On the right side diagram still free capacity on the path exists

of the optimal expansion sequence [21,22]. 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 $d_{u,v}$ value, 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. 2. 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 [15]. 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. So CEP requires the computation effort of $\mathcal{O}(NMN_d)$ with linear influence of *N*. In real application we normally apply definite granularity of capacity values through discrete values (integer) of traffic demands R_i. It reduces the number of the capacity points significantly. Because of that the minimal step of capacity change (*step_*I_i) has strong influence on the algorithm complexity.

5 EXAMPLE OF ALGORITHM APPLICATION AND COMPARISON OF DIFFERENT ALGORITHM OPTIONS

We tested the proposed algorithm on many numerical test-examples to find an optimal expansion sequence [14].

Traffic demands (the existing, previously contracted SLAs) are given as relative amounts 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 the results obtained by referent algorithm that is calculating all possible expansion solutions for each CES. For all numerical test-examples, the best possible result (near-optimal expansion sequence) can be obtained by the improved algorithm (denoted with Basic_A), same as with the referent algorithm (without reduction of unacceptable expansion solutions). Complexity savings in percents are on average more that 40% that is proportionally reflected on computation time savings (Figure 5).

From diagrams in Figures 3 and 4 it is clear how algorithm works. In Figure 3 we have alternative paths from nodes 1 to 8. We compared two load situations in the context of the new_SLA creation.

The top diagrams in Figure 4 illustrate simultaneous traffic demands for each router on the path and for three different service classes (*N*=3). Only one difference is in the incoming traffic flows on routers 6 and 7 (the second QoS level). On the left slide we can see the higher traffic increment (30 instead of 20).

The middle diagrams in Figure 4 illustrate minimal capacities for such traffic load. On the left slide we need more bandwidth on the links 6 and 7 for second QoS level (class 2), so we can see if it is in given bounds (bandwidth constraints).

The bottom diagrams in Figure 4 show the sum of capacities on the path for all QoS levels (total link capacity). On the left slide the capacity value for the link 7 exceeds the limited amount (100) so we cannot accept new traffic (new_SLA). It means there is no available capacity for the new_SLA (no matter of which QoS level). On the right slide the input traffic is slightly lower, so congestion doesn't exist if new load is less then 10.

For each test-example we know the total number of capacity points. The number of possible CES is known, so it can be used as a measure of the complexity for the CEP-problem. We can also see the number of acceptable subproblems, satisfying basic and additional properties of optimal flow (Table 1). Many of them cannot be a part of the optimal expansion sequence. The number of all possible CES values depends on the total number of capacity points C_p.

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

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

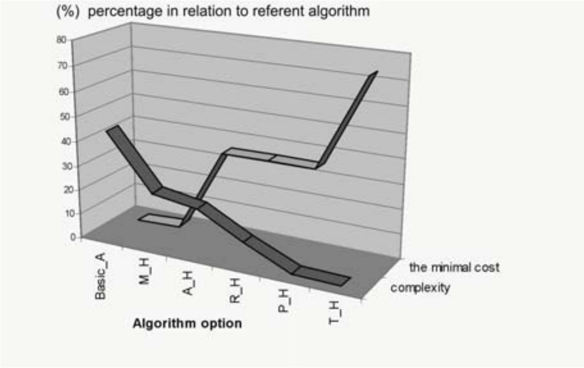

Fig. 5. The comparison of algorithm options

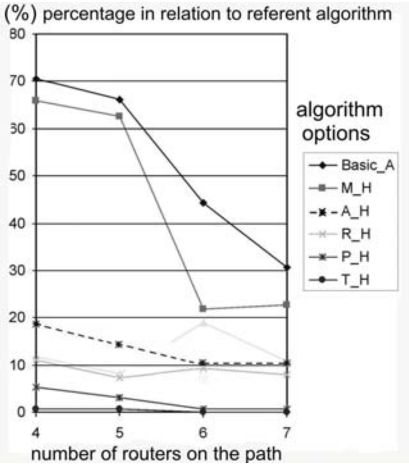

Fig. 6. The comparison of complexity for different algorithm options in dependency of number of routers on the path

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 labeled R_H (*Real Heuristic option*);

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

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

We compared the algorithm efficiency for different options [14]. Figure 5 shows the average values of results. Only for few test-examples (Table 1) we can find the best expansion sequence, providing the minimal cost, no matter of algorithm option we use. For the most examples the algorithm option M_H can obtain the best result with average saving more than 60%. For other algorithm options the

Table 1. The comparison of results for a numerical test-example

Traffic demands (increment)				Algorithm option	The best possible result (minimal cost)	Number of capacity points	Number of sub-problems satisfying properties	Computational savings in perc. (%)
LSR Routers on the path	$r_{1,m}$	$r_{2,m}$	$r_{3,m}$					
1	-10	0	10	Full approach	10 399,46	839	30 133	-
2	10	10	0	Basic_A	10 399,46	839	17 869	40,70 (59,30)
3	0	0	0	M_H	10 399,46	590	12 249	59,35 (40,65)
4	10	-10	10	A_H	10 399,46	424	11 146	63,01 (36,99)
5	-10	0	0	R_H	10 399,46	394	5 324	82,31 (17,69)
6	10	10	0	P_H	10 399,46	91	963	96,80 (3,20)
7	10	10	0	T_H	10 399,46	7	6	99,99 (0,01)

$c_{i,m}(x_{i,m}) = f_i^{\,m-1}(A_i+B_i x_{i,m}^{\,ai})$, $A_1=3000$, $B_1=25$, $a_1 = 0.9$, $A_2=1000$, $B_2=20$, $a_2=0.85$, $A_3=2000$, $B_3=30$, $a_3=0.95$
For negative expansions ($x_{i,m} < 0$) $c_{i,m}(x_{i,m}) = - f_i^{\,m-1}(B_i\, abs(x_{i,m})^{ai})$. For all positions and for all quality levels it is the same value $f_i = 0.9$. So expansions are forced to the end of the path, but reductions are stimulated to happen as early as possible.
$h_{i,m}(I_{i,m+1}) = f_i^{\,m-1} H_i\, I_{i,m+1}$, $H_i = 400$ $(I_{i,m} > 0)$ for $i = 1, 2, 3$. Shortages ($I_{i,m} < 0$) are not allowed;
$g_{i,t}(y_{i,j,m}) = G_i\, y_{i,j,m}$, $G_i = 100$ for $y_{i,j,m} > 0$, $i < j$. Conversions in opposite direction ($y_{i\,j,,m} < 0$) are not allowed;
For all links and for all three capacity types the limitation $L_{i,m} \leq 30$. Maximum of total link capacity is 100.

Optimal usage of the capacity (expansion sequence):
$y_{1,3,1} = 10$, $x_{1,2} = 10$, $x_{2,2} = 10$, $x_{1,4} = 10$, $y_{2,3,4} = 10$, $x_{1,5} = -10$, $x_{1,6} = 10$, $x_{2,6} = 10$
Minimal cost: 10 399,46

significant reduction of complexity is obvious but deterioration of result appears. In the most cases the trivial algorithm option (T_H) shows the significant deterioration of final result. A good characteristic of all algorithm options is that efficiency rises with increase of value *M* (number of routers on the path), Figure 6.

6 CONCLUSION

New SLA in context of former contacted SLAs can load the network with possible congestion (inappropriate or wrong traffic load). SLA creation has to be in relation to resource management and bandwidth allocation. Here we present a path-oriented implementation for bandwidth management, based on an autonomic inter-SLA resource sharing scheme and automatic bandwidth reservation. Ideally, the bandwidth should be distributed respectively to QoS in such a way that leads to the maximum resource utilization. It could be very difficult to derive a centralized, optimal on-line bandwidth distribution technique [23]. Therefore, we propose a distributed off-line algorithm implemented during SLA negotiation, to adjust the optimal LSP when new SLA is created.

In this paper we explained the role of proposed algorithm for congestion control and load balancing purpose during SLA negotiation process. 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 appears we need further path 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, 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), period of service utilization etc. The proposed algorithm for load control (with different options) can be efficiently incorporated in SLA negotiation process and can be used for automated traffic configuration of MPLS/DS networks on self-management principles. It may improve end-to-end QoS provisioning, especially for overloaded and poorly connected networks where over-provisioning is not possible.

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