

OPTIMIZATION STRATEGIES FOR MPLS TRAFFIC ENGINEERING

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Lucrarea de față analizează strategiile de optimizare folosite în Multiprotocol Label Switching (MPLS) Traffic Engineering în trei arii: încorporarea informațiilor de servicii diferențiate, încorporarea informațiilor referitoare la starea rețelei și construcția algoritmilor de rutare. Sunt analizate evoluțiile recente în domeniu și sunt identificate principalele posibilități de echilibrare a cerințelor conflictuale în interiorul fiecărei arii de optimizare precum și între arii.

The paper analyzes optimization strategies for Multiprotocol Label Switching (MPLS) Traffic Engineering in three different areas: Quality of Service awareness, network awareness and the design of routing algorithms. Recent developments in MPLS technology are discussed while identifying the main balancing possibilities within and between the three areas.

Keywords: MPLS, Traffic Engineering, Quality of Service, network awareness, computational complexity, heuristic algorithms

Abbreviations:

ATOM – Any Transport Over MPLS
DiffServ – Differentiated Services architecture
IETF – Internet Engineering Task Force
LSP – Label Switched Path
LSR – Label Switched Router
MIRA – Minimum Interference Routing Algorithm
MPLS – Multiprotocol Label Switching
PHB – Per Hop Behavior
QoS – Quality of Service
SA – Simulated Annealing
SLA – Service Level Agreement
TE – Traffic Engineering
VPN – Virtual Private Network

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1. Introduction

The relevance of Traffic Engineering for network administration has been gradually increasing due to several concurrent processes. On one hand, congestion problems persist despite significant technological advances that improve overall network resources. One reason is that application requirements have also increased, especially given the generalization of voice and video traffic. Another reason lies with the instability of Internet, which may lead to unpredicted patterns of traffic in networks.

Traffic Engineering refers to policies of mapping traffic flows onto a given physical topology such as to maximize a set of objectives [1]. These objectives may refer to efficient use of network resources, in a network aware TE strategy, or to user demands for various Quality of Service levels, in a QoS aware TE strategy. The two strategies may be combined. Specific challenges appear when QoS requirements necessitate a fine granularity of traffic or when the ratio of guaranteed service traffic to best-effort traffic grows faster than the increase in network resources.

Recent improvements in MPLS technologies have addressed the increased need for Traffic Engineering strategies that differentiate among levels of service. The DiffServ model in itself is not able to guarantee a level of service, independently of TE policies. QoS differentiations are a zero-sum game of differential priorities and drop probabilities allocated to various types of traffic, impacting on the access of various traffic trunks to network resources. The use of QoS TE policies allows the creation of a positive-sum game in which the overall network performance and level of service are increased.

MPLS has been widely considered to introduce significant improvements in TE over IGP strategies [2]. The main challenge of IP routing for TE refers on its exclusive reliance on the destination address and the low level of information included in the routing decisions. While destination-based routing is highly scalable, it also leads to the creation of aggregated traffic trunks that aggravate the challenge of balancing loads in the network. IP routing does not take into consideration any information on available resources in the network, such as residual bandwidth or the probability that a given link may be used by future traffic, thus optimizing on criteria which may not be ultimately relevant for the performance of the network, such as the number of hops. There are two types of constraints for more efficient routing: network constraints and user constraints [3]. The first refer to network topology, link state and other indicators such as link availability or inclusion in shared risk link groups, bandwidth resources, and estimated future traffic matrices. The second refer to requirements of bandwidth, packet delay, jitter and loss, broader QoS issues, administrative groups, cost of services etc.

2. Solutions for Traffic Engineering in IP networks

MPLS has significantly improved the possibilities for traffic engineering in IP networks. TE relies on the possibility of aggregating traffic into flows of controllable size, depending on the granularity level required by a given task, and to route these flows explicitly through the network. There are several features of the MPLS technology that contribute to its appeal for TE:

- (1) It introduces a connection-oriented perspective in packet-switched networks, facilitating explicit routing;
- (2) It has a strict separation of the data plane and the control plane;
- (3) It operates between the conventionally defined layer 2 (data link) and layer 3 (network layer) and it can be used for configurations at both levels (such as level 2 or level 3 virtual private networks);
- (4) It allows an easy incorporation of QoS markings and its mapping to traffic engineering;
- (5) It improves scalability in the network;
- (6) It allows for swift traffic restoration.

MPLS works in conjunction with IP and its IGP, and it gives IP networks capabilities for facile TE, the ability to transport Layer 3 (IP) VPNs with overlapping address spaces, and support for Layer 2 pseudowires (with Any Transport Over MPLS, or ATOM). The strict separation of the data plane and the control plane means that multiple control planes can operate in an MPLS environment – such as multicast or unicast routing, RSVP, virtual private networks, frame relay and of course Traffic Engineering.

MPLS allows for PHB (Per Hop Behavior) classification of packets. This information is included in the three EXP bits of the MPLS shim header. Therefore, it is possible to mark at most eight types of PHB, or even less in case that some values are reserved. Given the fact that in most cases only three or four PHB are used, this restriction may not be an impediment. Still, for situations that require a finer granularity of classification, new methods of signaling QoS have been recently put into place. MPLS allows now for two types of markings: the Exp-LSP (E-LSP) and the Label inferred LSP (L-LSP), according to the field that included the classification information.

MPLS improves scalability in the network, in comparison with the overlay solution to traffic engineering. When using a layer 2 network to manage the bandwidth by a full mesh of virtual circuits, the downsides occur due to the fact that virtual circuits are advertised and that IP ignores the real topology, being aware only of the virtual topology. This means that, in the case of a link failure, dozens of virtual circuits are affected and IP routing protocols must adjust, based only on information about the virtual topology. On one hand, the new routes may depart significantly from optimal choices, because of lack of physical topology

information. On the other hand, flooding updates about the virtual circuits in the network escalates to a number of updates of a magnitude of $O(n^3)$ [2], which is unscalable. MPLS addresses these issues by not advertising LSP tunnels: they are only known to the head-end router. IP is aware of the real topology of the network. In the case of a link failure in the overlay model, IP understands it as the failure of dozens of (virtual) links; in the case of MPLS paths, a single link failure is understood by IP as a single link failure, thus dramatically decreasing flooding and leading to a faster convergence.

MPLS allows both hop-by-hop routing and explicit routing, but the latter is the general norm. The explicit routes are defined by the ingress nodes, and paths include a series of hops defined by the ingress Label Switched Routers. A given hop may be a traditional interface, an autonomous system, or an LSP. Explicit paths may be either configured by users manually, specifying each hop in the path, or defined dynamically by a routing protocol such as IS-IS or OSPF. Such protocols use topological information produced by a link-state database in order to compute the path between the ingress and egress nodes.

In MPLS a single engineered tunnel may accommodate traffic from several control planes, and this also contributes to enhancing the scalability of the network.

3. Optimization strategies in Traffic Engineering

Based on a comprehensive analysis of optimization strategies in MPLS based traffic engineering the following areas can be differentiated: Quality of Service awareness in TE, network awareness in TE and path computation strategies. Each of the three dimensions is discussed below.

The unifying factor refers to computational complexity, the reverse side of any increase in the amount of information that is used in routing decisions. The information required for traffic engineering may originate in several areas:

(1) Classification of traffic according to QoS requirements; information about classes of traffic may be used to compute a path or do dynamically allocate resources on a path. QoS integration in TE policies refers to traffic segregation, routing based on priority levels, and pre-emption. The finer the granularity of traffic flows, the larger the amount of information that must be handled by routing protocols. Since classification of traffic does not by itself affect the total amount of network resources, there is a tradeoff between packet priority and probability of rejection.

(2) Estimates of future traffic matrices, produced by statistical analysis of previous traffic flows [4], or by Service Level Agreements (SLA) [5]. Statistical analysis may aim to detect abnormalities, due to large fluctuations or to link failures, or to detect trends in flow evolutions.

(3) Topological information – such as the interdependence of paths due to sharing of common links, the inclusion of links in Shared Risk Link Groups (SRLG), or various link attributes. Link attributes [6] are distributed to all LSRs in the MPLS domain, as part of each router's Link State Advertisement (LSA).

Table 1

Link attributes in MPLS TE

Link attributes	Description
Maximum link bandwidth	True link capacity (in the neighbor LSR direction): the maximum amount of bandwidth that can be used on the link
Reservable link bandwidth	Maximum bandwidth that can be reserved on the link (in the neighbor LSR direction); if it is larger than the maximum bandwidth, the link is overbooked
Unreserved bandwidth	Available bandwidth at each of the eight preemption priority levels (in the neighbor LSR direction); they are initially set at the maximum reservable bandwidth level.
Path attribute	Whether the path of the LSP should be manually specified or dynamically computed by Constraint-Based Routing
Setup Priority	The attribute specifies which LSP will acquire a certain resource if multiple LSPs compete for it
Holding Priority	The attribute specifies whether resources can be withdrawn from an established LSP in order to accommodate requests for a new LSP
Resource class or link coloring	Administrative group membership of the link, associated with the link for inclusion/exclusion policies
Traffic engineering metric	Specifies the link metric for TE purposes. This metric is not necessarily the same as the IGP metric.
Adaptability	Whether to switch the LSP to a new path whose metrics are closer to optimality values (when one becomes available)
Resilience	The attribute that decides whether to reroute the LSP when the current path is affected by failure

In order to address issues of computational complexity, routing procedures must be simplified. There are two main strategies:

(1) Layering: deciding whether to separate or to integrate in routing decisions information on multiple network levels;

(2) The use of heuristic algorithms, such as Tabu search, genetic algorithms or simulated annealing.

MPLS traffic engineering must face confronting requirements [3]:

(1) The routing process is complicated by including additional information on user and network constraints and by information on heterogeneous network elements. This leads to complicated functions that are to be optimized in the routing decision. Routing may be simplified by reducing the scope of decision-making (layering), reducing the amount of information, or by using heuristic algorithms to process it.

(2) Information needs to be transmitted by signaling the updated link state of the entire network, especially when dynamic routing decisions are key to

optimizing network performance. The larger the amount of information transmitted, and the higher the update frequency, the larger the information flood through the network. A tradeoff may be reached by increasing the interval between updates, by decreasing the information included in the update, and by simplifying the interpretation procedures for the update information.

(3) Networks must react promptly to changes in traffic patterns, based on their detection and interpretation. Still, immediate reactions may translate into suboptimal routing, which needs to be subsequently corrected by rerouting. Dynamic routing facilities must be combined with static routing.

4. Quality of Service awareness in MPLS Traffic Engineering

We can distinguish broadly between traffic oriented TE, aiming to enhance the QoS of traffic flows (such as minimization of packet loss and delay), and resource oriented TE, aiming to the efficient use of network resources (bandwidth management, minimizing congestion) [7]. In TE policies the two are usually interdependent, since resources are matched to QoS requirements. Still, QoS issues focus attention on distribution decisions in a zero-sum game, while resource management issues focus attention on optimization procedures in a positive-sum game.

DiffServ-aware Traffic Engineering (MPLS DS-TE) is a recent mechanism which enables privileged resource reservation for classes of guaranteed traffic. The RFC 3564 introduces the concept of Class Type – CT, defined as the set of traffic trunks traversing a given link and subject to common bandwidth constraints [8]. A traffic trunk will be defined by a same class type for all links that it traverses. IETF stipulates a maximum number of 8 class types. CSPF has been modified to take into account the bandwidth allocated to each traffic type, for each level of priority. There are 64 possible combinations of CT and priority level; still, the IETF has decided to limit the total number of allowed combinations to 8. These combinations are called TE classes. The 8 TE classes are selected among the 64 possible TE classes via configuration options. The classic MPLS TE is thus equivalent with implementing MPLS TE with 8 TE classes obtained from a single class type and 8 priority levels.

MPLS DS-TE is usually based on limiting the weight of guaranteed traffic within a link's bandwidth. It therefore becomes possible to have different policies of overbooking for normal traffic and for guaranteed traffic. Guaranteed traffic may even be under-booked, thus providing a high level of QoS throughout the LSP even though best-effort traffic is overbooked [9], [21-22].

5. Network awareness

Network awareness refers to the type and extent of information on network resources and utilization that are incorporated in routing decisions. We can distinguish preventive TE, which aims to prevent congestion, to balance traffic load and to achieve QoS objectives, from reactive TE, which aims to reroute LSP's from the most congested links or to dynamically adapt the LSP bandwidth [10], [17-20].

Network congestion may be defined in terms of residual bandwidth, when the load on certain links is close to overall link capacity, or in terms of rejected LSP requests – either because no route is found, or because the available route is too long compared to a standard of acceptability.

Network information may be processed off-line or on-line. Off-line optimization aims to match explicit routes to traffic matrices, while on-line optimization aims to respond swiftly to modifications in traffic patterns – either due to variations in packet inflows, or to changes in network topology (such as link failure or depreciation). While off-line optimization requires additional network management efforts, on-line optimization requires complex data structures in nodes and it produces a significant overhead due to signaling [10].

Off-line optimizations are based on traffic matrices that are the result of storing information on previous traffic flows. This means that their relevance is higher for networks with stable data flows, and it decreases for networks which have highly variable patterns of traffic – such as Internet traffic. On-line routing may be required to adapt paths to changing needs, but extensive on-line path computation may induce network instability when the time necessary to route a data flow and the time in which the requests are produced have the same order of magnitude [3]. Due to time and information constraints, on-line routing may also depart significantly more from optimal routes than off-line solutions. Combined solutions are usually implemented in order to match network resources to changing patterns of traffic.

The dominant decision criterion used when incorporating network awareness in routing procedures consists in finding paths which have a minimum impact on the rejection of future requests [11]. These algorithms are generally identified as minimum interference routing algorithms, following the terminology deployed by [12] in their work on MIRA (Minimum Interference Routing Algorithm). An already substantial body of research has been dedicated to improving these algorithms [11], all addressing the same fundamental question: finding a path for the establishment of an LSP from a source to a destination node such as that the residual capacity of each link along the path is equal or greater than the requested bandwidth, while maximizing the number of paths which will be available for future LSP requests.

While the first version of MIRA aimed to interfere minimally with potential future LSP requests between other pairs of ingress-egress routers, subsequent work also addressed the potential interference with future LSPs among the same ingress-egress router, and the degree of criticality of a link for a particular ingress-egress pair or groups of pairs [13].

A special topic in network awareness relates to recovery from error. There are several key issues that relate policies on recovery to Traffic Engineering. Fast recovery is essential to prevent delay and packet loss. Backup paths need to be as close to optimal paths as possible, and if they are temporary, their advertisement should not impose a significant overhead. Another important challenge is the “make before break” feature [2], enabling secondary paths to be established on links that currently do not have enough resources due to bandwidth consumption on the primary path. The primary and the secondary path are not actual competitors for resources, since they are never active simultaneously; if the secondary path is recognized as such, it is no longer necessary to interrupt the primary path in order to establish the backup one. This feature enables a smooth transition from the old to the new path.

MPLS labels may be stacked, with no upper limit of labels in the stack. This allows for fast recovery from error, since predefined backup paths may be computed and associated with a traffic flow.

Another challenge in establishing pre-planned alternative paths is that they may be significantly sub-optimal due to changes in traffic patterns between the moment of their computation and the moment of their activation. Recent solutions have been developed to search for new optimal alternative paths while the protected path is still active, combining fast rerouting and dynamic routing approaches [10]. If the new LSP proves to be better than the protected one, roles may be reversed.

6. Path computation strategies

There are two main strategies to reduce the burden of computational complexity in routing decisions: layering the network, or using heuristic algorithms.

The issue of layering is relevant for optical networks based on GMPLS. There are two main strategies that can be deployed [3]: layering (the server model) and unification (the peer model). In the server model, the IP/MPLS network requests a connection while the optical network makes routing decisions according to the corresponding SLA. In the peer model, a single control plane is in charge of the entire network, and routing decisions are based on a shared topological awareness. While the peer model allows for greater flexibility, it is more computationally intensive. A review of single-layer and two-layer routing

algorithms [14] concludes that each may outperform the other under different circumstances and that there is a significant difference of computational challenge.

The amount of information used in routing decisions may also be increased by using heuristic algorithms [23-29], such as the Tabu search, simulated annealing or genetic algorithms. Simulated annealing (SA) is an algorithm based on a metallurgical analogy. The industrial annealing process involves repeated heating and slow cooling of a metal to reduce defects in its internal structure. The algorithm also uses random selection of solutions, whose similarity to the current one increase as the parameter of “temperature” decreases. High values of the “temperature” parameter allow the disruption of local minima which may trap the algorithm. SA has been used in optimization proposals for MPLS Traffic Engineering algorithms, such as [15] and [16].

Genetic algorithms are based on a biological analogy, using a genetic representation of the solution domain, a fitness function that is used to evaluate the solutions and a procedure for “breeding” new generations from the current generation. This procedure also uses a degree of randomness to allow the overcoming of local minima. A genetic algorithm has been proposed in [1].

7. Conclusions

There are three main optimization areas in MPLS traffic engineering. Quality of service awareness increases the information used in routing decisions by classifying traffic flows according to Per Hop Behaviors. High traffic priority is matched by high drop probabilities, leading to distinct profiles of traffic that can be matched with specific routing policies. Network awareness incorporates information on current traffic patterns and topology changes into routing decisions, thereby also increasing routing complexity, especially for online path computation.

In order to control the complexity of path computation, two strategies are usually deployed. When possible and appropriate, single layer routing procedures may be replaced with multi-layer procedures. At the same time, heuristic algorithms may be used to approximate global optima.

The three areas are represented in the figure below. While they allow for mutual balancing, each area has its own trade-offs that must be addressed by optimization processes. This is an important factor to be taken into account in designing Traffic Engineering policies.

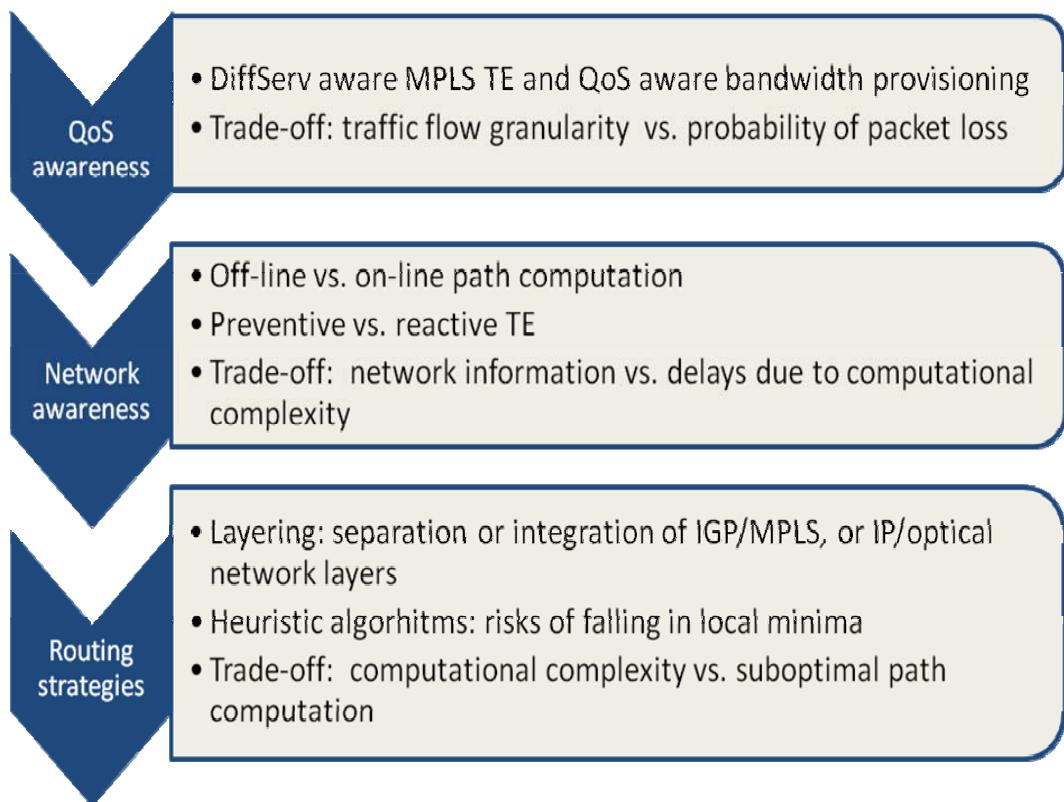


Fig. 1. Optimization areas in Traffic Engineering

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