Classification and Evaluation of Constraint-Based Routing Algorithms for MPLS Traffic Engineering

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Multiprotocol Label Switching (MPLS) is experiencing a growing interest mainly due to the flexible support of traffic engineering and Quality of Service (QoS). The efficient routing of Label Switched Paths (LSP) is an active research field where Constraint-Based Routing (CBR) appears to be a major building block. CBR can be seen as the decision entity that calculates the explicit paths for LSPs. The path calculation process can be constrained by different criteria, such as QoS requirements and particularly bandwidth guarantees considered in this paper. Special attention has been given to on-line solutions for CBR that process LSP establishment demands on the fly without any information on future demands. Currently, many proposals are formulated for CBR algorithms for bandwidth guaranteed tunnels, often compared to prove the effectiveness of one method over another. Nevertheless, no coherent evaluation has been clearly established for the general CBR problem, pointing out the different trade-offs involved in many solutions.
In this article, we investigate the different objectives of CBR algorithms. We establish clear and general criteria for these algorithms, namely: reducing blocking probability, minimizing network costs, and load balancing. An effort of classification is made in order to map existing proposals to the proposed criteria. The study, performed to evaluate the influence of these parameters with simulations, shows the drawbacks of partial considerations, and the need for a global solution. Finally, we propose an integrating solution that encompasses the different criteria presented in the paper.

Keywords: MPLS, Constraint-Based Routing, Traffic Engineering, Performance Evaluation, Quality of Service

1 Introduction

Multi-Protocol Label Switching (MPLS) is seen as a promising solution for future core networks. According to the label switching paradigm, traffic is transported in tunnels called Label Switched Paths (LSP). MPLS offers the possibility of explicit LSP routing with the help of extended signaling protocols. OSPF-TE enables the flooding of extended traffic engineering attributes (e.g. reserved bandwidth, maximal bandwidth, ...) which will be used by a decision engine to choose the appropriate path for LSPs. Moreover, RSVP-TE enables resource reservation along the explicit path.

Several design models exist for the routing engine: off-line solutions dealing with traffic matrices expressing the demands between end-nodes. These solutions optimize the use of network resources, while trying to satisfy the demands. On-line solutions try to find the best feasible path for each single demand using information on the actual state of the network. In this article, we investigate the design process of an on-line Constraint-Based Routing (CBR) algorithm for bandwidth guaranteed tunnels. By definition, on-line CBR does not require any a priori knowledge of future demands and can be implemented in a decentralized manner. We find this very appropriate considering many networking paradigms based on on-line and decentralized solutions. Moreover, the bandwidth guaranteed tunnels assumption does not restrict the scope of the study, since many Quality of Service (QoS) requirements (e.g. delay and loss) can be translated into equivalent bandwidth guarantees.

In this article, we investigate the different objectives of CBR algorithms. We establish clear and general criteria for these algorithms, namely: reducing blocking probability, minimizing network costs, and load balancing. An effort of classification is made in order to map existing proposals to the stated criteria. The study, performed to evaluate the influence and the correlation between these parameters with simulations, shows the drawbacks of partial considerations, and the need for a global approach. Finally, we propose an integrating solution that encompasses the different criteria presented in the paper.

2 MPLS traffic engineering objectives for CBR

CBR is a major building-block in the traffic engineering architecture for MPLS [1]. Usually, traffic requirements are expressed in terms of QoS parameters such as bandwidth, delay, loss, ... However, these requirements can be easily translated into bandwidth guarantees [2]. In this section, we define the different objectives of traffic engineering mechanisms in MPLS networks. After a deep study of the standardization efforts [1] and current solutions proposed by the scientific community, we found that three main criteria illustrate the relevant trade-offs involved in a traffic engineering scheme for MPLS: reducing blocking probability, minimizing network cost and load balancing.

2.1 Reducing blocking probability

One goal of traffic engineering is to reduce the blocking probability, ensuring that a maximal number of requests is accepted in the network; hence it maximizes operator revenues and enhances client satisfaction.

Minimum Interference Routing Algorithm (MIRA) [7] is one important proposal for CBR that deals with the reduction of blocking probability. The main idea is based on the correlation between the maxflow [3] value between two nodes, and the maximum amount of bandwidth that can be routed between them. Thus, a decrease of maxflow can be an interference indicator (due to LSPs routed between the same two nodes or other pairs). MIRA defines critical links as the links that cause a decrease in maxflow values between node pairs. Therefore, weights are attributed to links proportionally to their criticality. Finally, a shortest-path-like algorithm is used to calculate the minimum interference path (i.e. the path with minimum critical links). Results show that MIRA outperforms MinHop [4] algorithms considering LSP rejection. However, MIRA suffers from computational complexity: a maxflow computation is costly and is frequently done in this algorithm.

2.2 Minimizing network costs

Static metrics, such as hop count or link static costs, have been traditionally incorporated in routing algorithms in order to achieve a minimum network cost objective. MinHop [4] algorithms are one example of strategies minimizing network costs (e.g. the number of hops) for traffic engineering purpose. Moreover, some improvement has been added to MinHop with the definition of Widest Shortest Path (WSP) and Shortest Widest Path (SWP) [5] algorithms: these algorithms introduce some bandwidth requirement in shortest path calculation. MinHop algorithms are simple and computationally efficient. However, they suffer from bad performance [2] in terms of rejection ratio in a highly loaded network. From another point of view, link static costs can be used as a metric in these algorithms for a basic traffic engineering, since they usually correspond to the physical link length. Although it is not foreseen that link length will have a big influence in future networking architectures (especially optical ones), it can still be considered as a static way of expressing operator preference to choose some favorite links.

2.3 Load balancing

Load balancing is an important factor for network congestion reduction. The idea is to have some equilibrated load distribution in the network that improves the overall situation. However, [2] shows that in lightly loaded network load balancing has some undesirable effects such as routing LSPs on longer paths. In this paper, we consider the simple way of doing load balancing in traffic engineering by routing LSPs over the least loaded links. We should point out that this strategy is a basic form of load balancing [6] and is better qualified as load minimization.

Model:
G=(V,E) is a directed graph representing the network, with :
V the set of vertices (MPLS routers) and *E* the set of edges (physical links)
Main loop:
Foreach LSP request of bandwidth *b* between nodes *O,D*
Given the capacity *cap(e)* and the load *load(e)* on each edge $e \in E$
Action:
Determine the optimal set of binary variables *x(e)* and *y(e)*, that:

$$\text{Minimize} \quad : \quad \sum_{e \in E} cost(e) \times [x(e) + y(e)], \qquad (1)$$

$$\text{Subject to} \quad : \quad \sum_{e \in Out(v)} [x(e) - y(e)] - \sum_{e \in In(v)} [x(e) - y(e)] = \varepsilon(v), \qquad for\ v \in V \qquad (2)$$

$$: \quad [x(e) + y(e)] \times [load(e) + b] \leq cap(e), \qquad for\ e \in E \qquad (3)$$

$$With : \varepsilon(v) = \begin{cases} +1 & v = O \\ -1 & v = D \\ 0 & v \notin \{O,D\} \end{cases} \quad cost(e) = \begin{cases} 1 & MinHop \\ length(e) & MinLength \\ \frac{load(e)}{cap(e)} & load\ balancing \\ criticality(e) & MIRA \end{cases} \qquad (4)$$

Results:
Optimal path: LSP is routed on edge e in the same (resp. opposite) direction of the edge if $x(e) = 1$ (resp. $y(e) = 1$)

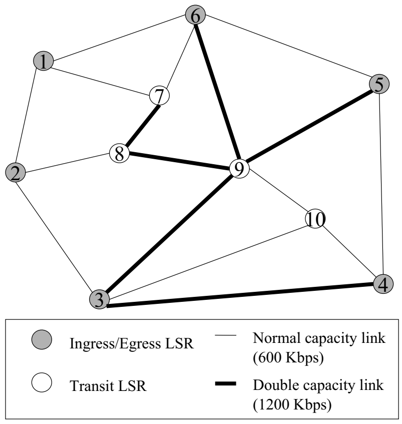

Fig. 1: Simulation model and topology

3 Comparative study using traffic engineering criteria

The study of existing methods proposed by the scientific community helped us to identify the blocking probability reduction, the network cost minimization, and the load balancing as relevant criteria for CBR for MPLS traffic engineering. In this section, we investigate the relevant design elements involved in many of these works. However, we do not intend to conduct an exhaustive evaluation of all the proposed solutions. We use our predefined set of objectives for CBR in MPLS networks to evaluate the different approaches and we clearly point out the different trade-offs. Hence, we show the limitation of these 'partial' solutions for solving the global traffic engineering problem.

3.1 Simulation environment

In the following, MinHop and MinLength refer respectively to a minimal hop [4] and a minimal length algorithm minimizing respectively the number of hops and the physical length of the chosen path. Whereas, MIRA and load balancing refer respectively to the approaches described in sections 2.1 and 2.3. These four algorithms are evaluated in a simulation environment described in figure 1. Traffic demands are uniformly distributed between all ingress/egress pairs and the associated bandwidth request is uniformly distributed between [0,10] Kbps. We perform series of static simulations where LSPs that are routed in the network are established until the end of the simulation. We use an integer linear programming (ILP) approach detailed in figure 1 to calculate the LSP route according to each algorithm. The objective (Eq. 1) is to find the path with minimal cost where the cost function is giver by (Eq. 4). Note that for MinLength the cost is equal to the link length (proportional to the euclidean distance between nodes in figure 1), while the MIRA cost is consistent with the definition introduced in [7]. A flow conservation constraint (Eq. 2) ensures that the algebraic sum of the flows at each node is null except (Eq. 4) for the source and destination nodes of the LSP. Moreover, a capacity limitation constraint (Eq. 3) ensures that the resulting bandwidth on each link does not violate the edge capacity.

3.2 Blocking probability

Figure 2 shows the best overall performance of MIRA in terms of reducing the blocking probability for new requests. This confirms the correlation between increasing maxflow and reducing request rejection [7]. On the contrary, MinHop and MinLength have a relatively high rejection ratio. As the two algorithms only take network costs into account for choosing the best path, shortest links will become very rapidly congested, and will cause a high rejection probability for concerned edge nodes. Load balancing has a fair

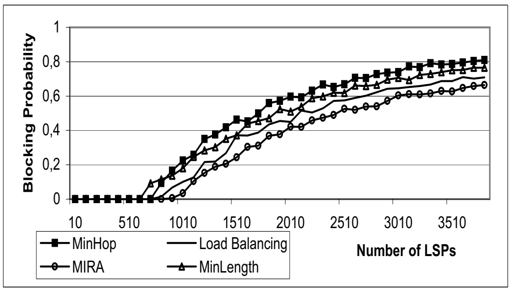

Fig. 2: Blocking Probability

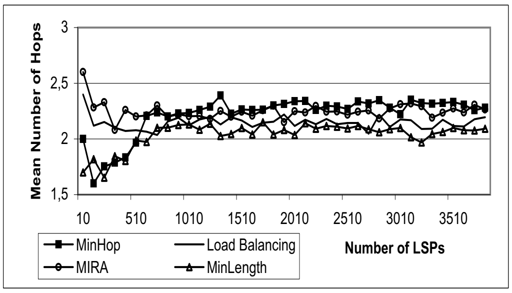

Fig. 3: Mean number of hops

performance. In fact, the distribution of demands over low congestion links ensures that bottlenecks are not easily created and thus reduces rejection probability compared to MinHop or MinLength.

3.3 Network cost

Figure 3 shows that load balancing and MIRA methods are not efficient in terms of minimizing hop number in a lightly loaded network. We can see that MinHop and MinLength are very efficient: LSPs are always routed on shortest paths (respectively least number of hops and shortest length), thus ensuring network cost minimization. However, load balancing and MIRA choose longer paths in order to minimize the rejection ratio or the load dispersion for future LSP demands. Although each method was presented as a complete solution for traffic engineering, they address only part of the global criteria. When the network becomes more loaded, performance is inversed. Shortest paths suffer from congestion problems with MinHop and MinLength. Hence, these algorithms are obliged to choose longer paths and their performance is altered. Nevertheless, the difference between load balancing/MIRA and MinLength/MinHop is not significant in a high loaded network since MinLength/MinHop are now rejecting requests and the average hop value is not seriously altered.

3.4 Load balancing

We evaluate the different approaches by comparing the mean load in the network (Fig. 4) and its standard deviation (Fig. 5). Standard deviation is a good measure of load dispersion; it shows how the load is distributed among network links. In figures 4 and 5, MIRA achieves the highest mean load with the smallest standard deviation. This shows that MIRA takes advantage of load dispersion to achieve its main goal of minimizing interference. Moreover, load balancing reaches the best overall performance. While keeping the average load at a lower value compared to MIRA, it achieves a good standard deviation objective. This can be explained by the fact that load balancing preferably chooses links with bigger residual bandwidth. Considering MinHop and MinLength, it is clear that they do not reach the load balancing objective: by choosing shortest paths according to static metrics, the network ends up with a low mean load (short paths are more congested than longer ones), but with a high deviation value.

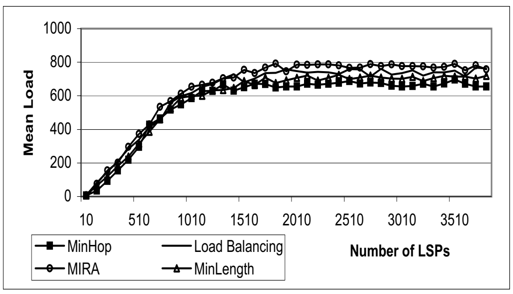

Fig. 4: Mean Load

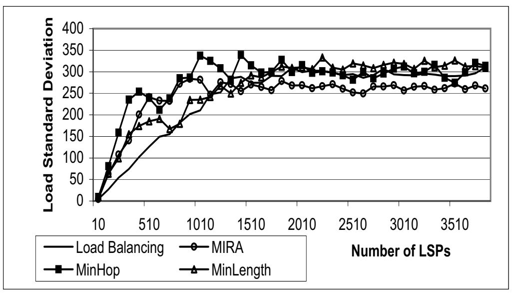

Fig. 5: Load standard deviation

4 Integrating solution

This section presents an integrating solution for on-line CBR based on the combination of load balancing, MIRA and MinHop. Our goal is to show the importance of the joint consideration of the corresponding criteria. Thus, the main challenge is to define the optimal weighting (T1, T2, T3) for each element in the integrating cost function given by (Eq. 5). Some theoretical work with extensive simulation should enable us to get the optimal values. However, since we only intend to justify the simultaneous importance of our fixed objectives, we will restrict to finding a good feasible solution. A close analysis of our simulation results presented in section 3 points out general trends that can help for weight characterization.

First, the weight associated with MinHop should be increased to emphasize its good performance under light load. For instance, according to (Eq. 6), T1 is inversely proportional to the total network load. We can see that T1 is predominant under light load and starts to decrease as the total network load increases to reach the total network capacity. Second, MIRA should really get involved when links criticality is changing (links are getting rapidly loaded). We choose T2 (Eq. 6) to be proportional to the network load. For these T1, T2 values, MIRA becomes prevailing compared to MinHop when the network load passes the quarter of the total capacity (due to the multiplicative constant 16). Third, we introduce in (Eq. 7) a new parameter for the load metric element that will control load balancing influence in the overall cost function by limiting its undesirable effects under light load. Moreover, constants a, b and c are used in order to scale the numeric values to a comparable range.

In figures 6-8, we can see that the performance of our integrating method is good in overall situation. The blocking probability (Fig. 6) of the integrating scheme is comparable with MIRA results. The load standard deviation (Fig. 7) values are comparable with values for load balancing under light load. Under high load, the integrating scheme achieves performance bounded by load balancing (upper standard deviation) and MIRA (lower standard deviation) due to the equally combined effect of these algorithms. Finally, we see the influence of the MinHop element under light load; the integrating solution has good performance compared to MinHop (Fig. 8). Therefore, these results justify our weighting approach. Even with a set of intuitive weights, we show the relevancy of the three objectives, and the benefit of their combination. Hence, further advanced studies based on our approach would determine the set of optimal weights for the integrating traffic engineering CBR solution.

$$Cost(e) = T1 + T2 \times criticality(e) + T3 \times load(e) \tag{5}$$

$$T1 = a \times \frac{total\_cap}{total\_load}\,;\; T2 = 16 \times b \times \frac{total\_load}{total\_cap}\,;\; T3 = c \tag{6}$$

$$load(e) = \begin{cases} 0 & \text{if } load(e) < threshold = cap(e)/3 \\ \frac{reserved\,bandwidth(e)}{cap(e)} & \text{otherwise} \end{cases} \tag{7}$$

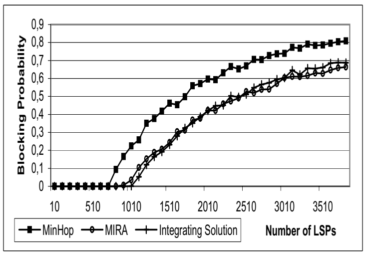

Fig. 6: Blocking probability

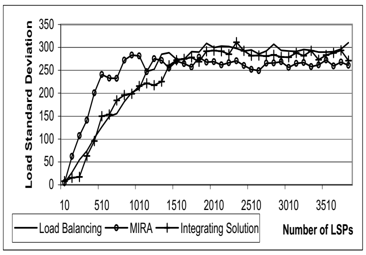

Fig. 7: Load standard deviation

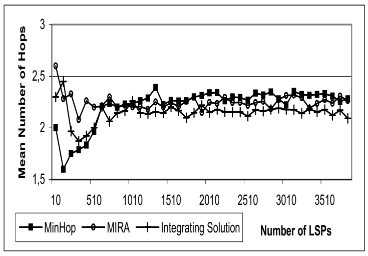

Fig. 8: Mean number of hops

5 Conclusion

In this article, we identify relevant objectives for CBR for MPLS traffic engineering. We establish clear and general criteria for these algorithms, namely: reducing blocking probability, minimizing network costs, and load balancing. We classify and evaluate the relevant approaches for this problem. The study shows the drawbacks of partial considerations, and the need for a global solution. Finally, we propose an integrating solution that encompasses the different criteria presented in the paper. Our formulation helps in clarifying all the trade-offs involved in CBR, thus enables the design of more complete solutions. Our integrating scheme shows that combination of our set of objectives achieves better overall satisfying results. The simulations presented in this article could be extended to encompass a discrete-event approach taking into account limited life-time LSPs. Moreover, the objectives we fixed can be the basis for further studies of CBR with emphasis on techniques for on-line design of survivable networks with multi-priority traffic.

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