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Comparison of IP-Based and Explicit Paths for One-to-One Fast Reroute in MPLS Networks

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Abstract Primary and backup paths in MPLS fast reroute (FRR) may be established as shortest paths according to the administrative link costs of the IP control plane, or as explicitly calculated arbitrary paths. In both cases, the path layout can be optimized so that the maximum link utilization for a specific traffic matrix and for a set of considered failure scenarios is minimized. In this paper, we propose a linear program for the optimization of the path layout for explicitly calculated paths, which can either produce single paths and route entire traffic along those paths, or generate multiple paths and spread the traffic among those paths providing load balancing. We compare the resulting lowest maximum link utilization in both cases with the lowest maximum link utilization that can be obtained by optimizing unique IP-based paths. Our results quantify the gain in resource efficiency usage provided by optimized explicit multiple paths or explicit single paths as compared to optimized IP-based paths. Furthermore, we investigate if explicit path layouts cause an increased configuration effort compared to IP-based layouts and if yes, to what extend.

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1 Introduction

Multiprotocol label switching (MPLS) enables connection-oriented communication in connectionless communication networks. Virtual connections, so-called label-switched paths (LSPs), can be established between any two points in the network by installing packet-label-based forwarding states in the nodes. To be able to quickly react to failures in the network, MPLS provides fast reroute (FRR) capabilities. These are local mechanisms that enable the failure-detecting node to switch packets to preconfigured backup LSPs. This yields faster reaction than end-to-end protection where the source node detects a failure along the primary path and then switches the traffic to the backup path.

To establish primary and backup LSPs, the routing of an associated IP control plane may be used. As an alternative, primary and backup LSPs may be set up according to arbitrary explicit paths that are pre-calculated, e.g., by a path computation element (PCE) [2]. Traffic engineering in terms of routing optimization is possible with both approaches. In this paper, we consider the maximum link utilization for the failure-free case and for a set of considered failure scenarios as an important performance metric that should be minimized.

If the MPLS path layout is based on IP routing, each primary and backup LSP is established along the least-cost path (according to the administrative link costs) between its source and destination. Adjusting the administrative link costs is the only way to influence the routing. In [3], we have shown that it is an $\mathcal{NP}$-hard problem to find optimal link costs even for the failure-free case. Therefore, often heuristic methods are used for routing optimization. We proposed such a heuristic in [4]. When there are several equal-cost paths between two nodes, it is uncertain which of the paths is actually selected. This uncertainty can be avoided by using link cost settings that lead to unique shortest paths (USP). We extended our heuristic to generate optimized routing with USP in [5].

If LSPs follow explicit paths, arbitrary paths can be chosen as primary and backup paths. In this paper, we propose a mathematical formulation for optimizing the path layout in two steps. First, a number of possible paths are calculated. Then, the best set of these paths is chosen by solving an appropriate linear program (LP). Integer solutions of the LP produce single paths while non-integer solutions yield multiple paths over which traffic is spread according to a load balancing function.

IP-based paths are a proper subset of explicit single paths, which in turn are a proper subset of explicit multiple paths. Therefore, we compare the quality of those distinct path layouts after optimization.

This paper is an extended version of our previous publication [1]. The main contribution of this version is an extended evaluation and comparison of the different path layouts concerning the configuration effort they impose. Therefore, a new metric for the evaluation of the configuration effort for explicit and IP-based MPLS paths is introduced. Furthermore, examples have been added to illustrate the different path layouts and metrics.

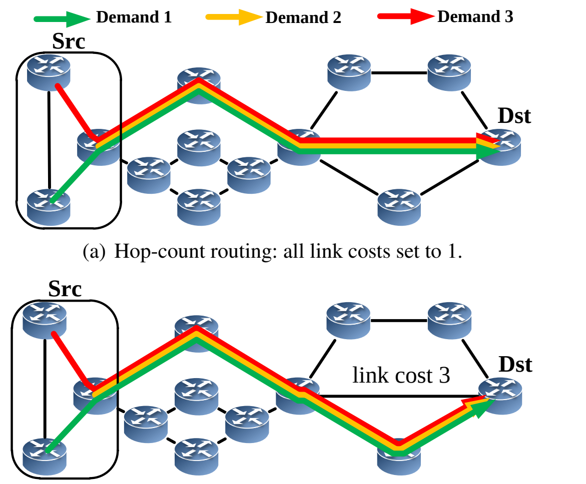
This paper is structured as follows. Section 2 gives an overview of MPLS LSP layout options and the MPLS FRR mechanism. In Section 3, we briefly explain our heuristic for the link cost optimization of IP routing, summarize previous work on this topic, and give an overview of related work in the area. In Section 4, we provide the proposed mathematical formulations for the optimization of explicit paths for MPLS one-to-one backup and differentiate our approach from related work. Section 5 compares the performance of the optimized IP-based layout of primary and backup paths with the optimal path layouts of explicit single paths and explicit multiple paths. In particular, in this section, a new performance metric, more precise than the one used before ([1]), is introduced. Finally, Section 6 concludes this work.

2 MPLS LSP layout and MPLS Fast Reroute

In this section, we illustrate different options to establish primary and backup LSPs. Furthermore, we explain the basics of the MPLS fast reroute (MPLS-FRR) mechanism one-to-one backup. It is a local backup mechanism, i.e., the nodes adjacent to a failure act as so-called points of local repair (PLRs) and redirect packets over alternative local backup LSPs to the destination.

2.1 Different Path Layouts for Primary and Backup LSPs

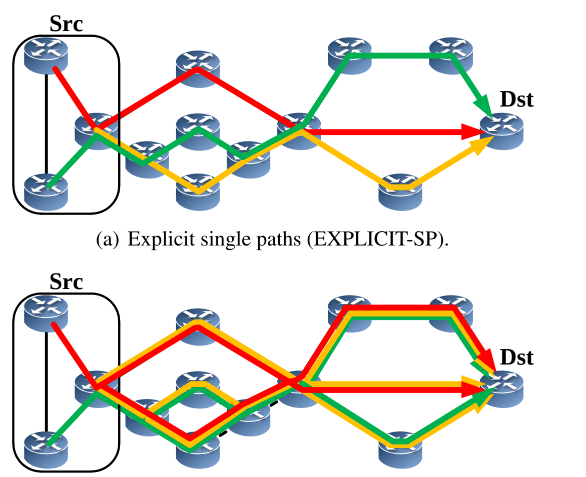
Figures 1 and 2 illustrate in a simple example network the different path layouts that can be used to establish primary and backup LSPs. In this case, only the primary paths, i.e. the paths in the failure-free case, are regarded. There are three different demands from the sources on the left hand side to the destination on the right hand side of the network (demands 1, 2, and 3).



(a) Hop-count routing: all link costs set to 1.

(b) Adjusted link costs: one link has cost 3.

Fig. 1 Illustration of LSP layouts based on IP-based single paths (IP-SP).



(a) Explicit single paths (EXPLICIT-SP).

(b) Explicit multipaths (EXPLICIT-MP).

Fig. 2 Illustration of LSP layouts based on explicit path layouts.

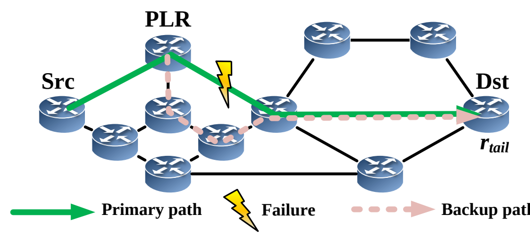
The first possibility to establish the LSPs is according to IP-based single paths (IP-SP), see Figure 1. In this case, the LSPs follow the least-cost paths to the destination according to administrative link costs. This type of routing is destination-based. That means, the different demands to the same destination have in common, that from the first node on they take the identical least-cost path to the destination. In the displayed network in Figure 1(a) all administrative link costs are set to one. In this case, the least-cost path corresponds to the path with the fewest hops (Hop-count routing). In the depicted network, there is exactly one unique least-cost path from each of the three source nodes (Src) to the destination (Dst), so all demands share a single path. The IP-SP routing can be influenced by adjusting the individual costs of the links. Figure 1(b) shows a simple example. In this case the costs of one link are modified to 3 so that the primary path is moved to other links. Still, independent of the changed path layout, all demands are sent on the same path. In Section 3, we present our heuristic method to optimize the IP-SP based path layout.

The second option to establish LSPs is to define explicit paths for each demand. Depending on the creation method and configuration, this can either be explicit single paths (EXPL-SP) for each demand or explicit multipaths (EXPL-MP). If explicit paths are used, the demands can be spread on the links independently of the path's length and link costs. Figure 2(a) illustrates this for the EXPL-SP case. Here, each demand is routed on exactly one path to the destination. EXPL-MP (Figure 2(b)) allows an arbitrary splitting of all demands to any possible paths. This offers the possibility to reach an optimal load balancing towards the destination. In the displayed example, demand 1 and 3 are split on a subset of all possible paths, whereas demand 2 is split on all existing paths from Src to Dst. If the demands are split onto multiple paths, each of these paths from Src to Dst obtains a unique LSP, i.e. a unique label. This way no splitting inside a single LSP is necessary, but the source node takes care of the entire splitting by spreading the demand onto the configured LSPs. In Section 4, we present a mathematical formulation to optimize EXPL-SP and EXPL-MP.

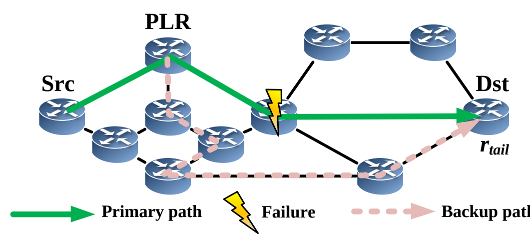
2.2 MPLS Fast Reroute: One-to-one Backup

MPLS has two different backup mechanisms. Facility backup provides a number of backup LSPs, so-called link and node bypasses, around the failed component. One-to-one backup provides for each of the LSPs individual backup paths to the LSP's destination, so-called link and node detours. In this paper, we focus on the one-to-one backup option. Further details on the facility backup and other resilience mechanisms can be found in [6].

In the case of the MPLS one-to-one backup, for each demand individual backup LSP tunnels are installed from every possible failure-detecting node on the demand's path, called point of local repair (PLR), to the demand's destination. Depending on the failure type, two different types of protection tunnels are used, as shown in Figure 3: link detour tunnels and node detour tunnels. As indicated in Figure 3(a), the failing link is protected by using a backup LSP from the PLR to the demand destination r_{tail} that does not contain the link. If a node fails as shown in Figure 3(b), the local backup path must not include the failed next node on the demand's primary path either. Therefore, a backup path from the PLR to r_{tail} that does not contain the next hop is installed.



(a) $LinkDetour(PLR, r_{tail})$.



(b) $NodeDetour(PLR, r_{tail})$.

Fig. 3 One-to-one backup uses detour tunnels.

When a failure occurs, it is difficult for a node to detect whether the adjacent node or the connecting link has failed. Therefore, we assume node failures whenever possible and use link detour only when the last link of the primary path fails (in this case, node detour cannot be applied because the next hop is already the destination).

3 Heuristic Optimization for IP Link Cost based LSP Layout

In this section, we briefly introduce intra-domain IP routing and the unique shortest path (USP) routing property. Then, we explain our heuristic optimizer and summarize the previous work on link cost optimization.

3.1 Intra-domain IP Routing and USP

IP based intra-domain routing follows least-cost paths that are determined according to administrative link costs. Between two nodes in the network, e.g., between the PLR and the destination of an LSP, there may be more than one shortest path with minimal costs. When the backup LSP is installed, only one of the paths is arbitrarily chosen by a so-called tiebreaker. The criteria used to select this path are not standardized and might even change over time. This leads to uncertainties in the path layout and can cause unexpected load shifts on different links. To avoid this problem, link cost settings can be chosen so that neither in the failure-free case nor in the considered failure scenarios multiple least-cost paths between any two destinations exist. A path layout meeting this requirement is called a unique shortest path (USP) routing.

3.2 A Heuristic Link Cost Optimizer

The path layout in intra-domain IP networks can only be influenced by appropriately choosing the administrative link costs. Obtaining the link cost setting for a given network and a given traffic matrix that leads to the lowest maximum link utilization over all links is an $\mathcal{NP}$-complete problem [3]. Therefore, heuristics are used to improve the routing. In [4], we presented the basic algorithm of the heuristic that is used in this paper. That heuristic is similar to the threshold accepting heuristic. It tries to find the link cost setting that leads to the routing with the lowest maximum link utilization over the failure free situation and a set of considered failure scenarios. Other objective functions also exist and are used throughout literature; an overview and comparison of those objective functions can be found in [7]. In [5], we extended our heuristic to optimize administrative link cost settings leading to USP routing. That publication also provides further information on the problems caused by unpredictable tiebreaker decisions.

To obtain good results, our heuristic is run several times with random initial link cost settings. We take the best solution of all optimization runs as the final best link cost setting.

3.3 Related Work

There is a lot of literature about link cost optimization. Different heuristic and mathematical approaches are used to solve the problem. Furthermore, different objective functions are being addressed [7]. Some work considers only the failure free routing, while other work has been extended to include the optimization of link costs for a certain set of failure scenarios. Due to the limited space, we do not provide an in-depth discussion of that literature but refer to the extensive summaries in our previous publications [5, 7].

4 Mathematical Program Formulation

4.1 Preliminaries

An MPLS/IP network is modeled using a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with the set of nodes $\mathcal{V}$ and the set of directed links (i.e., arcs) $\mathcal{E} \subseteq \mathcal{V}^2 \setminus \{(v,v):\ v \in \mathcal{V}\}$. The nodes correspond to the MPLS/IP routers while the arcs correspond to the directed IP links. For each $e \in \mathcal{E}$, $a(e)$ will denote the originating node, $b(e)$ the terminating node, and c_e the capacity of link e. For each $v \in \mathcal{V}$, the sets of links outgoing from node v and incoming into node v will be denoted by $\delta^+(v)$ and $\delta^-(v)$, respectively.

Let $\mathcal{D}$ be the set of demands. For each $d \in \mathcal{D}$, let $o(d)$ and $t(d)$ denote, respectively, the originating node and the terminating node of demand d, and let h_d denote the volume of demand d, which is the required bandwidth of the corresponding LSP connection.

Let $\mathcal{S}$ be the set of failure states. In the paper we consider all single, complete failures of the links, thus $\mathcal{S} \equiv \mathcal{E}$.

For each $e \in \mathcal{E}$, let variable X_e define the total load of link e in the normal state, i.e., the state with all links operating. Further, for each $e \in \mathcal{E}$ and $s \in \mathcal{S}$, let variable Y_e^s define the total load of link e in the network state corresponding to the failure of link s. The objective of the problem of optimizing the routing of LSP connections and the layout of their primary and backup paths can now be shortly defined as follows:

$$\min \quad Z \tag{1a}$$

$$s.t. \quad Z \geq X_e / c_e \qquad e \in \mathcal{E} \tag{1b}$$

$$Z \geq Y_e^s / c_e \qquad e \in \mathcal{E}, s \in \mathcal{S} \setminus \{e\}. \tag{1c}$$

We now introduce a formal model of the problem, (FRR-LP), which is based on the link-path formulation (for the notion of link-path formulation see [8]).

4.2 Link-path Formulation

Link-path (LP) formulation considers the paths of LSP connections explicitly, both in the normal state (primary paths) and in each failure state (backup paths). The paths are handled through appropriate path lists that are predefined in any instance of (FRR-LP). In effect, the path lists define an instance of (FRR-LP) when other input parameters (as the network's graph, demand, etc.) are fixed and given.

For each $d \in \mathcal{D}$, let $\mathcal{P}_d$ be a set of candidate primary paths from $o(d)$ to $t(d)$ for the LSP connection of demand d, and for each $p \in \mathcal{P}_d$, let x_{dp} be a binary path variable that is equal 1 if, and only if, path p is selected for demand d as its primary path. For each $e \in \mathcal{E}$, let P^e denote the set of all candidate primary paths that use link e, and for each

$d \in \mathcal{D}$ and $e \in \mathcal{E}$, let $\mathcal{P}_d^e \subseteq \mathcal{P}_d$ denote the set of all candidate primary paths from $\mathcal{P}_d$ that use link e.

Further, for each $s \in \mathcal{S}$, $d \in \mathcal{D}$ and $p \in \mathcal{P}_d^s$, let $\mathcal{Q}_{dps}$ be a set of candidate backup paths for the primary path p in failure state s, i.e., when link s fails; each path $q \in \mathcal{Q}_{dps}$ starts in node $a(s)$ and terminates in node $t(d)$. Note that each primary path $p \in \mathcal{P}_d$ has its own set of candidate backup paths for each failure state s. For each $q \in \mathcal{Q}_{dps}$, let y_{dpsq} be a binary path variable that is equal 1 if, and only if, for demand d path p has been selected as the primary path, and path q is selected as the backup path for p in the network state corresponding to the failure of link s. For each $s \in \mathcal{S}$, $d \in \mathcal{D}$, $p \in \mathcal{P}_d^s$ and $e \in \mathcal{E}$, let $\mathcal{Q}_{dps}^e \subseteq \mathcal{Q}_{dps}$ denote the set of all candidate backup paths from $\mathcal{Q}_{dps}$ that use link e. Finally, let $\mathcal{W}_d^{es}$ denote the set of such paths p in $\mathcal{P}_d^e$ that link e belongs to that part of p which is not affected by the failure of link s. Note that if $p \in \mathcal{P}_d^e$ and $s \notin p$, then $p \in \mathcal{W}_d^{es}$. The path selection constraints of (FRR-LP) are as follows:

$$\sum_{p \in \mathcal{P}_d} x_{dp} = 1 \qquad d \in \mathcal{D} \tag{2a}$$

$$\sum_{q \in \mathcal{Q}_{dps}} y_{dpsq} = x_{dp} \qquad s \in \mathcal{S}, d \in \mathcal{D}, p \in \mathcal{P}_d. \tag{2b}$$

Constraint (2a) says that for each demand d exactly one primary path must be selected, and constraint (2b) says that exactly one backup path must be selected for primary path p if p is selected as the primary path of demand d. Then, variables X_e and Y_e^s specifying the total load of every link in each network state (normal or failure) are quite straightforwardly defined by the path variables:

$$X_e = \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}_d^e} h_d x_{dp} \qquad e \in \mathcal{E} \tag{3a}$$

$$Y_e^s = \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{W}_d^{es}} h_d x_{dp} + \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}_d^s} \sum_{q \in \mathcal{Q}_{dps}^e} h_d y_{dpsq} \qquad e \in \mathcal{E}, s \in \mathcal{S}. \tag{3b}$$

Altogether constraints (1) and (2)-(3) define the link-path formulation (FRR-LP) of the FRR design problem.

In the link-path formulation all structural properties of the paths are controlled by the path generation method (for explanation of path generation in network design problems see [8]). Basically, the paths are shortest paths with respect to the optimal values of the dual variables corresponding to the constraints of the (FRR-LP) (see Section 4.4), but they must also satisfy additional conditions implied by the nature of the studied problem, mainly that a backup path may not go through the end node of the failed link: for $p \in \mathcal{P}_d$ such that $s \in p$, a path $q \in \mathcal{Q}_{dps}$ must start in $a(s)$, end in $t(d)$, and omit node $b(s)$ ($a(s)$ is the point of local repair in this context). As explained in the Section 4.4, the most difficult task is generating primary paths.

4.3 Discussion

The basic problem dealt with in this paper could also be formulated in the node-link formulation [8]. We do not present this formulation for the lack of space. The advantage of such a formulation, referred to as (FRR-NL), is that it is compact. The number of its variables is proportional to $|\mathcal{E}|^2|\mathcal{D}|$, and not exponential with the size of the problem as in (FPR-LP). (Observe that the number of variables in (FRR-LP) is exponential as the number of paths is exponential.) This allows for solving the problem directly; the disadvantage is that we can do that only for tiny networks (e.g., to have a benchmark solution for another method). Clearly, the linear relaxation of the node-link formulation (FRR-NL) provides a lower bound of the considered objective function value, but, because of the $\mathcal{NP}$-hardness of the linear relaxation, it does not provide the solution of the problem in terms of multiple (bifurcated) explicit paths.

On the contrary, the linear relaxation of the (FRR-LP) formulation does provide a valid optimal solution in the case of multiple explicit paths, and at the same time delivers a lower bound of the considered single-path objective function value; this lower bound is in general better than the bound provided by the liner relaxation of (FRR-NL). The linear relaxation of (FRR-LP) is solved with the path generation method. While the resulting set of paths is usually very small (as already mentioned, the set of all paths is extremely large since the number of paths is exponential in the size of the graph), this set is, in general, not sufficient to solve the (FRR-LP) to optimality. Thus solving the MIP of the (FRR-LP) with that set of paths provides an upper bound (hopefully of good quality, i.e., near-optimal) of the objective function value.

When the MIP of the (FRR-LP) is solved by the branch and bound approach, in each node of the branch and bound tree (such a node is a linear relaxation of the problem with additional constraints stating which paths on the current lists must be used and which must not be used; the linear relaxation of the original problem is the root node of the tree) an attempt must be made to generate additional paths, resulting in the so called branch and price method. Such a capability is not supported by every commercial solver (in particular it is not supported by the CPLEX solver), and potentially must be implemented by hand.

The process of generating new paths at the node of the branch and bound tree (in particular at the root node of the tree) is iterative: the current solution is used to provide the values of the dual variables that correspond to the constraints of the formulation (the values measure how tightly the constraints are satisfied, or what is the impact of the constraints on the objective function). Those values of the dual variables are the metrics for path computation. The intuition behind that process is as follows: if a constraint (e.g. a capacity/utilization constraint of a link) has low impact, then there is fair amount of capacity that could be used by new paths and the value of the metric is low. It should be noted, that those metrics are solely used in the process of generating candidate paths (also explicit paths) and have nothing to do with IP link metrics.

4.4 Solution Methods

As already mentioned, (FRR-NL) is a compact formulation of the FRR design problem, which could be used to solve problem FRR directly with a commercial MIP solver. Since the number of binary variables in such a MIP is huge, problem (FRR-NL) can be efficiently solved only for small network instances. For medium- and large-size networks only the LP relaxation of (FRR-NL) can be solved efficiently, providing a lower bound for the optimal objective function value.

Formulation (FRR-LP) is not compact because the number of paths grows exponentially with the size of the network graph. The formulation is based on pre-specified path sets $\mathcal{P}_d$ and $\mathcal{Q}_{dps}$, and as such it should be solved by column (path) generation and the branch and price approach (see [8]).

As stated in Section 4.3, the branch and price approach is difficult to implement. Hence, we propose a simplified method. The idea of our method is first to solve the linear relaxation (LR) of problem (FRR-LP) through path generation and then to use the (short) path lists $\mathcal{P}_d, d \in \mathcal{D}$, $\mathcal{Q}_{dps}, d \in \mathcal{D}, p \in \mathcal{P}_d, s \in \mathcal{S}$ defined by non-zero flows in the optimal solution of the considered LR. Then, in the second phase, we solve problem (FRR-LP) in binary path variables using a MIP solver. The rationale behind this approach is that the total number of binary variables in an instance of (FRR-LP) is equal to $\sum_{d\in\mathcal{D}} |\mathcal{P}_d| + \sum_{d\in\mathcal{D}} \sum_{p\in\mathcal{P}_d} \sum_{s\in\mathcal{S}} |\mathcal{Q}_{dps}|$ which can be a reasonable number provided the path sets are small.

Path generation required to solve the linear relaxation of (FRR-LP) is done in the following way (for explanation of path generation see [8], and for more complex cases [9]). Let λ_d, σ_{dps}, π_e and φ_{es} be optimal dual variables corresponding to constraints (2a), (2b), (1b) and (1c), respectively. (Observe that the values of optimal dual variables are readily obtained from the LP solver while solving an instance of LR for given path sets.) Then, to generate a new backup path for each demand $d \in \mathcal{D}$, path $p \in \mathcal{P}_d$ and failed link $s \in \mathcal{S}, s \in p$, we find a shortest path q' between nodes $a(s)$ and $t(d)$ with respect to link metrics φ_{es} (this is done easily, e.g., with Dijkstra's algorithm). If the length of q' is strictly smaller than σ_{dps}/h_d then we add path p' to the list $\mathcal{Q}_{dps}$.

Generating primary paths is more difficult. For each demand $d \in \mathcal{D}$, we have to find a path p' between $o(d)$ and $t(d)$ shortest with respect to the path length defined as:

$$\sum_{e\in p'} \pi_e + \sum_{s\in p'} \alpha_s + \sum_{s\in S} \sum_{e\in p'(s)} \varphi_{es} \tag{4}$$

where α_s is the length of the shortest, with respect to link metrics φ_{es}, path q from $a(s)$ to $t(d)$ not containing node $b(s)$, and $p'(s)$ denotes the set of links that form the part of path p' from $s(d)$ to $a(s)$ (if $s \notin p'$ then $p'(s) = p'$). Note that the values of α_s have been found while generating backup paths as described above. Certainly, path p' is added to set $\mathcal{P}_d$ only if its length (4) is strictly smaller than λ_d/h_d. In fact, the problem of generating such a path p' is difficult, most likely $\mathcal{NP}$-hard. Still, in practice it can be solved pretty effectively by means of a specialized binary programming problem (BP) with a reasonable number of binary flow variables.

In the BP for generating a primary path p' for a fixed demand $d \in \mathcal{D}$ we use binary variables $x_e, y_{es}, z_{es}, e, s \in \mathcal{E}$. Their meaning is as follows: $x_e = 1$ if, and only if, link e belongs to the path p' that we are looking for; $y_{es} = 1$ if, and only if, e belongs to a shortest backup path (from $a(s)$ to $t(d)$ omitting node $b(s)$) of path p' in the case of the link s failure ($s \in p'$); $z_{es} = 1$ if, and only if, e belongs to the part of path p' that is not affected by the failure of link s. The BP in question is as follows:

$$\min \quad \sum_{e\in\mathcal{E}} \pi_e x_e + \sum_{s\in\mathcal{E}} \sum_{e\in\mathcal{E}} \varphi_{es} y_{es} + \sum_{s\in S} \sum_{e\in\mathcal{E}} \varphi_{es} z_{es} \tag{5a}$$

$$s.t. \quad \sum_{e\in\delta^+(v)} x_e - \sum_{e\in\delta^-(v)} x_e = 0, \quad v \in \mathcal{V} \setminus \{o(d), t(d)\} \tag{5b}$$

$$\sum_{e\in\delta^+(v)} x_e - \sum_{e\in\delta^-(v)} x_e = 1, \quad v = o(d) \tag{5c}$$

$$\sum_{e\in\delta^+(v)} x_e - \sum_{e\in\delta^-(v)} x_e = -1, \quad v = t(d) \tag{5d}$$

$$\sum_{e\in\delta^+(v)} y_{es} - \sum_{e\in\delta^-(v)} y_{es} = 0, \quad s \in \mathcal{E},\ v \in \mathcal{V} \setminus \{a(s), t(d)\} \tag{5e}$$

$$\sum_{e\in\delta^+(v)} y_{es} - \sum_{e\in\delta^-(v)} y_{es} = x_s, \quad s \in \mathcal{E},\ v = a(s) \tag{5f}$$

$$\sum_{e\in\delta^+(v)} y_{es} - \sum_{e\in\delta^-(v)} y_{es} = -x_s, \quad s \in \mathcal{E},\ v = t(d) \tag{5g}$$

$$y_{es} \le 1 - x_e, \quad e, s \in \mathcal{E} \tag{5h}$$

$$y_{es} = 0, \quad e, s \in \mathcal{E},\ b(s) \ne t(d),\ b(e) = b(s) \tag{5i}$$

$$\sum_{e\in\delta^+(v)} z_{es} - \sum_{e\in\delta^-(v)} z_{es} = 0 \quad s \in \mathcal{E},\ v \in \mathcal{V} \setminus \{o(d), a(s)\} \tag{5j}$$

$$\sum_{e\in\delta^+(v)} z_{es} - \sum_{e\in\delta^-(v)} z_{es} = x_s \quad s \in \mathcal{E},\ v = o(d) \tag{5k}$$

$$\sum_{e\in\delta^+(v)} z_{es} - \sum_{e\in\delta^-(v)} z_{es} = -x_s \quad s \in \mathcal{E},\ v = a(s) \tag{5l}$$

$$z_{es} \le x_e, \quad e,s \in \mathcal{E}. \tag{5m}$$

The solution of the above problem delivers a shortest path $p' = \{e \in \mathcal{E} :\ x_e = 1\}$, possibly after elimination of loops which can happen when some π_e and φ_{es} are equal to 0. (Path elimination is effective.)

5 Comparison of differently optimized path layouts for MPLS One-to-One Backup

In this section, we compare differently optimized path layouts for MPLS fast reroute. We investigate explicit multipath (EXPLICIT-MP) and single path (EXPLICIT-SP) path layouts as well as the single path layout based on IP link costs (IP-SP). First, we explain the experimental setup, then, we discuss the complexity of the linear programs, and finally, we provide numerical results about the quality of the obtained path layouts in terms of maximum link utilization. Additionally, we study the number of paths needed for the different path layouts.

5.1 Experimental Setup

The networks under study are displayed in Table 1. They include the research networks Cost239 [10], Geant [11], and Labnet [12] as well as the popular Rocketfuel topologies [13]. The traffic matrices used for the optimization were created resembling real-world data with the method proposed in [14] and extended in [15]. All entries in the traffic matrices except for the diagonal are strict positive, i.e., there is a demand d with volume $h_d > 0$ between each arbitrary pair of nodes $v, w \in (V), v \neq w$ in the network. Thus, the total number of demands in a network is $|\mathcal{D}| = |\mathcal{V}|\,|\mathcal{V}-1|$.

The maximum link utilization values for EXPLICIT-MP and EXPLICIT-SP were obtained using path generation methods as explained in Section 4. Depending on the network instance at least one and at most 42 iterations of the path generation algorithm were performed including both the generation of backup and primary paths. The values for IP-SP were obtained using the heuristic optimizer for link cost optimization presented in Section 3. For each topology the heuristic was run at least 50 times with random initializations. Depending on the topology the average number of evaluations during an optimization run is between 100,000 and 600,000.

5.2 Complexity of the Linear Programs

The complexity of the linear programs significantly increases with the number of demands and links in the network.

The path generation providing EXPLICIT-MP could be optimally solved for the smallest considered networks, Cost 239, Geant, and Labnet (upper part of Table 1) so that the optimal objective value represents a lower bound for the optimal solution of EXPLICIT-SP. Abovenet (AB) has the same number of nodes and demands as Labnet, still due to the much larger number of links an optimal solution could not be reached in acceptable computation time. The same holds for the even larger networks (AT&T, EB, EX, SP and TI). The path generation algorithm (*Python* code run on PCs with CPU powers between 1.7 GHz and 2.8 GHz and memory of 500 MB to 2.5 GB RAM) was stopped after a preconfigured time limit set at most to seven days for the largest networks. Therefore, for these larger networks the provided EXPLICIT-MP solutions are not guaranteed to represent a lower bound to the maximum link utilization for EXPLICIT-SP.

All results obtained for EXPLICIT-SP are based on the paths provided by EXPLICIT-MP. Thus, in general, they are suboptimal and provide an upper bound to the optimal objective value for the single path MPLS-FRR one-to-one backup problem.

5.3 Numerical Results

In this section, we present the numerical results of the IP-based and explicit path layouts. First, the different layouts are compared concerning the quality in terms of maximum link utilization. Second, the configuration effort imposed by the different layouts is studied. Therefore, two metrics are introduced and the path layouts are compared concerning both of these metrics. Finally, the main findings of the numerical comparison are aggregated and summarized. All results referred to in this section can be found in Table 1 and Table 2.

5.3.1 Comparison of Maximum Link Utilization

First, the optimized maximum link utilization is compared for the IP link cost based single path LSP layout and for the explicit single path LSP layout (Table 1). In general, the results show that the relative difference between IP-SP and EXPL-SP values depends on the network topology. As EXPLICIT-SP are optimized mathematically, the results for maximum link utilization are slightly better than for IP-SP in most networks. In the Labnet network, the calculated values for EXPLICIT-SP are even only half of those for IP-SP, but this is rather an exception that is due to the special topology of the Labnet network. For the networks AB and EB,

Table 1 Performance metrics for optimized primary and backup path layout using IP-based single paths (IP-SP), explicit single paths (EXPLICIT-SP), and explicit multipaths (EXPLICIT-MP).

Network				Maximum link utilization			Number of primary paths $\lvert\mathcal{P}_d\rvert$			Number of backup paths $\lvert\mathcal{Q}_{dps}\rvert$		
ID	Name	$\lvert\mathcal{V}\rvert$	$\lvert\mathcal{E}\rvert$	IP-SP	EXPL.-SP	EXPL.-MP	IP-SP	EXPL.-SP	EXPL.-MP	IP-SP	EXPL.-SP	EXPL.-MP
CO	Cost239	11	52	87.60%	83.7%	64.19%	110	110	127	174	226	324
GE	Geant	19	60	92.93%	79.1%	71.64%	342	342	355	874	958	1005
LA	Labnet	20	53	68.93%	45.4%	38.79%	380	380	483	878	1012	1928
AB	Abovenet	20	156	90.31%	90.6%	22.99%	380	380	479	728	865	2917
AT	AT&T	28	120	87.72%	73.4%	47.78%	756	756	803	1982	2233	3013
EB	Ebone	25	126	64.55%	65.4%	30.92%	600	600	690	1353	1586	2614
EX	Exodus	22	102	68.52%	66.6%	33.35%	462	462	538	1041	1156	2033
SP	Sprintlink	33	190	71.03%	65.3%	53.71%	1056	1056	1127	2613	3679	4183
TI	Tiscali	38	232	85.52%	79.22%	71.73%	1406	1406	1422	3091	4214	4259
Average proportion (Avg)				**182%**	**172%**	**100%**	100%	100%	113%	**100%**	**121%**	**196%**

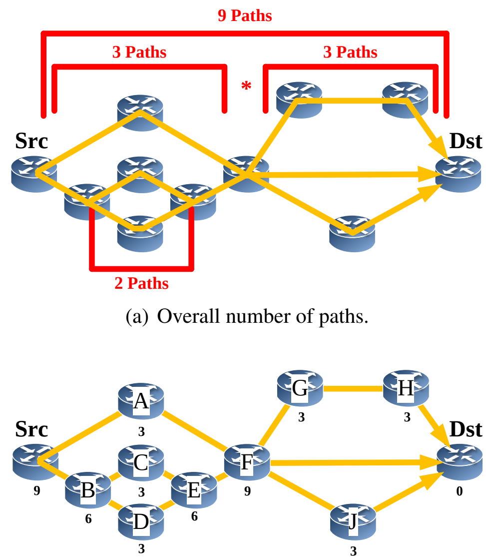
we observe smaller link utilizations with IP-SP than with EXPLICIT-SP. This is counterintuitive as the former results are produced by heuristic algorithms while the latter results stem from a mathematical optimization. However, this optimization also produces only suboptimal results since it operates on a pre-selected set of possible paths.

Next, we compare the maximum link utilization of explicit multipath and single path LSP layouts. The results show that multiple paths can significantly reduce the maximum link utilization of the networks. For the AB, EB, and EX networks the maximum link utilization can be improved by more than 50%, for the other networks by at least 10%. The last row of Table 1 shows the average over all networks under study of the relative difference between the different layout options. On average, EXPL-SP maximum link utilization values are about 72% higher than those of EXPL-MP, IP-SP values are about 182% higher than those of EXPL-MP.

5.3.2 Comparison of the Number of Paths

In previous work [16], we analyzed the necessary backup capacity for MPLS-FRR also in terms of the necessary configuration overhead. In the conference version of this paper [1], we compared this overhead for EXPLICIT-SP, IP-SP and EXPLICIT-MP by considering the overall number of LSP primary paths ($\lvert\mathcal{P}_d\rvert$ and backup paths $\lvert\mathcal{Q}_{dps}\rvert$). In this extended version, we add a second metric, the average and maximum number of paths per node. In the following, first the metrics are defined and illustrated. Afterwards, the different path layouts are compared concerning both metrics and the significance of both metrics is discussed.

Metrics Figure 4 illustrates the different metrics used in this paper to study the configuration effort. For simplification, only the primary path metric of a single multipaths demand is illustrated. The extension of these metrics to multiple demands and to the failure case is however very intuitive.



(a) Overall number of paths.

(b) Number of paths per node.

Fig. 4 Illustration of different metrics to study the configuration effort.

The first considered metric is the overall number of used paths. In the primary path case, this corresponds to the value $\lvert\mathcal{P}_d\rvert$ of the mathematical formulation, in the backup path case to $\lvert\mathcal{Q}_{dps}\rvert$. For a single path EXPL-SP or IP-SP demand the number of primary paths is always 1 by definition since there is exactly one single path from source to destination. In case of multipaths, this metric is more complicated. Figure 4(a) illustrates the number of paths for a connection over multiple different paths. At each splitting point where several paths are used to forward the demand the number of paths is multiplied by the possible number of next hops. In the displayed example, there are three paths to the middle node, one along the upper links, two on the lower links. From the middle node to the destination there are again three possibilites. As the first and the second three possibilities are chosen subsequently they can be arbitrarily combined and thus the overall number of paths from Src to Dst has to be calculated by multiplying these possibilities[1]. This leads to a total number of $3 \cdot 3 = 9$ possible paths. This describes the maximum number of paths in the EXPL-MP layout. A demand does not necessary need to use all of these nine paths, but can also use any subset of these nine paths.

Figure 4(b) illustrates the information for the second considered metric: the average and maximum number of paths per node. This metric offers additional information on the control plane complexity concerning the single nodes of a network. Figure 4(b) shows the number of paths per node for a single example demand. We only count the paths that are passing through or starting from a node. Paths that terminate at a node are not taken into account. This metric provides an upper bound to the number of necessary LSP entries per node when the LSPs have to be configured in the network[2]. In the depicted example, Src has nine paths for the considered demand as all paths of the demand start there. Dst has no paths for the demand as all paths terminate at this node. At all other nodes, the depicted value describes the number of paths that pass through the corresponding node, e.g. node A has three paths for the considered demand (Src-A-F-Dst, Src-A-F-J-Dst, and Src-A-F-G-H-Dst). As said before, in this picture only the failure-free case, i.e. primary paths of the demand are considered. If the metric is extended to the failure case, the number of paths per node for a demand is increased by the number of backup paths for this demand leaving from this node.

Comparison of the Overall Number of Paths First, the different path layouts are compared regarding the overall number of paths. These values are included in Table 1. Obviously, as indicated before, the number of primary paths is identical for IP-SP and EXPL-SP and equals the number of demands $|\mathcal{D}| = |\mathcal{V}|\,|\mathcal{V}-1|$ because the routing uses only single paths in both cases. But the number of backup paths is often much higher for EXPLICIT-SP than for IP-SP. This is probably due to the fact that while IP-SP is based on the shortest path principle, EXPLICIT-SP tends to accept longer paths (with more necessary backup paths) if they provide smaller maximum link utilization.

The use of multipath LSP layouts EXPL-MP compared to EXPL-SP can significantly increase the number of primary and backup paths, e.g., in AB even by more than 200%. On average over all networks under study, EXPL-SP has about 21% more and EXPL-MP even about 95% more backup paths than IP-SP. This means that even if EXPL-MP might bring a significant gain in resource efficiency the operators have to accept an increased control plane complexity in terms of number of used paths.

Comparison of the Average and Maximum Number of Paths Table 2 provides the values for the average and maximum number of paths per node. Analogeously to Table 1, the last row of the table contains the values of the average over all networks under study of the relative difference between the different layout options. E.g. the average number of paths per node when EXPL-MP is used is 234% of the average number of paths per node for IP-SP.

Table 2 Average and maximum number of paths per node.

Network ID	Number of paths per node (Average / Maximum) IP-SP	EXPL-SP	EXPL-MP
CO	50.91 / 73	81.55 / 150	113.18 / 200
GE	203.84 / 675	259.74 / 736	274.16 / 764
LA	151.15 / 347	234.90 / 459	403.35 / 822
AB	120.60 / 231	151.70 / 419	532.30 / 1418
AT	290.00 / 829	393.29 / 1153	538.00 / 1665
EB	204.52 / 649	315.44 / 900	497.16 / 1367
EX	177.82 / 564	225.46 / 778	428.68 / 1330
SP	315.00 / 675	579.33 / 1674	654.82 / 1920
TI	310.42 / 1162	500.37 / 2751	504.79 / 2757
Avg	**100% / 100%**	**148% / 170%**	**234% / 267%**

Similar to the first considered metric, the values in Table 2 show that explicit LSP layouts tend to cause a much higher configuration effort than a path layout based on an IP control plane. Especially the last row containing the averages shows, that the relative differences are even higher than for the number of paths considered before. The number of paths per node is higher for EXPLICIT-SP than for IP-SP because the former requires more backup paths and the established paths are also longer than those for IP-SP. Of course, this behavior is further increased, if not the average but maximum values are considered. There is one further interesting finding resulting from the observation of the number of paths per node. Obviously, the number of paths per node is limited by the number of all primary and backup paths since the maximum possible number of paths in a node is the overall number of all paths. It is however interesing that in the EXPL-MP case in some of the networks, there are single nodes where the maximum number of paths in this node is indeed larger than 40% of the number of all paths. E.g. in the CO network the overall number of paths for EXPL-MP including primary and backup paths is $127 + 324 = 451$. The maximum number of paths per node is 195.

[1] There might be possibilities to merge several LSPs with the same destination and equal subpath to reduce the total number of LSPs. However, this demands a lot of additional configuration effort including case studies and additional computations. Therefore, in this paper we do not consider any LSP merging. As mentioned in Section 2, all different subpaths from Src to Dst are unique LSPs with a unique label.

[2] As mentioned before, the number of actual LSP entries per node might be smaller than the number of paths per node if merging is used. However, in this paper due to the reasons explained before we do not consider any LSP merging.

This means that there is a single node that can be part of 43% of all paths because they can theoretically start at or pass through this node in the primary or backup case. On average, the number of paths per node is $113.18/451 = 25\%$ of the number of all paths. This finding is another indication that EXPL-MP tends to longer paths with multiple subpaths including a large amount of different links and nodes.

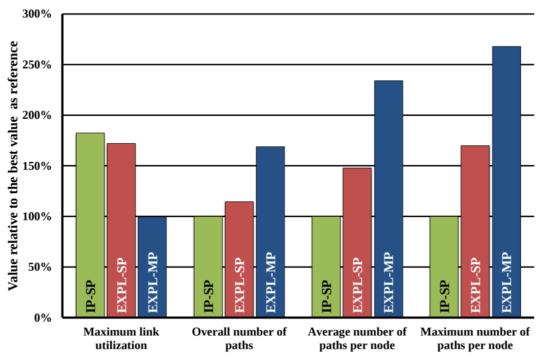


Fig. 5 Comparison of the different path layouts regarding different metrics.

To conclude the discussion of the results Figure 5 aggregates the metrics considered before into a single chart. The three path layout options are compared regarding the maximum link utilization, the overall number of paths, the average number of paths per node, and the maximum number of paths per node. For each metric, the best of the three path layouts is displayed as 100%. The values of the other two layouts are displayed relative to the best path layout. These values correspond to the values printed in bold in the last rows of Table 1 and Table 2. This graph visualizes the tradeoff between low maximum link utilizations and low configuration effort. On the one hand, EXPL-MP offers the lowest maximum link utilization values with an increased configuration effort of up to 267%. On the other hand, the IP-SP and EXPL-SP maximum link utilization values are similar while EXPL-SP has a clearly higher control plane complexity.

6 Conclusion

In this paper, we have discussed two alternatives for establishing primary and backup paths for the one-to-one backup option in MPLS fast reroute. One alternative uses explicit arbitrary paths and the other uses the paths that are induced by an IP control plane. To minimize the maximum link utilization for a specific traffic matrix and a set of considered failure scenarios, the layout of the explicit paths can be directly optimized. In contrast, the layout of the paths depending on the IP control plane can be optimized only indirectly by setting appropriate administrative link costs.

We presented a linear program for obtaining (1) optimal explicit primary and backup paths if flows may be bifurcated. We used those multipath structures as input for another linear program providing (2) optimized unique explicit primary and backup paths. And we used the heuristic from [5] to obtain (3) optimized unique primary and backup paths that satisfy IP routing constraints. We produced optimized paths according to (1) – (3) for various networks and traffic matrices.

A comparison has shown that in some cases (i) multiple explicit primary and backup paths allow for significantly lower maximum link utilization than unique explicit paths, and that (ii) unique primary and backup paths satisfying IP routing constraints may lead to significantly higher maximum link utilization. On the other hand, the use of explicit path layouts may significantly increase the resulting configuration effort.

Thus, explicit path layouts in protected MPLS networks provide a considerable improvement of the resource efficiency usage as compared to the simple setup of primary and backup paths with the IP control plane. However, this gain in resource efficiency is traded for the price of increased control plane complexity required for establishing optimized explicit paths and potential load balancing.

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