Compact node-link formulations for the optimal single path MPLS Fast Reroute layout

Cezary Żukowski, Artur Tomaszewski, Michał Pióro, David Hock, Matthias Hartmann and Michael Menth

***Abstract*—This paper discusses compact node-link formulations for MPLS fast reroute optimal single path layout. We propose mathematical formulations for MPLS fast reroute local protection mechanisms. In fact, we compare one-to-one (also called detour) local protection and many-to-one (also called facility backup) local protection mechanisms with respect to minimized maximum link utilization. The optimal results provided by the node-links are compared with the suboptimal results provided by algorithms based on non-compact linear programming (path generation) approach and IP-based approach.**

I. Introduction

MULTIPROTOCOL Label Switching (MPLS) technology enables configuration of end-to-end virtual connections in communication networks, especially in networks without connection-oriented capabilities. Labeled packets can be sent over the connections and forwarded according to the labels over so-called LSPs (Label Switched Paths).

MPLS is able to detect network failures (link failures) locally and thus a failure-detecting router can quickly switch all packets from failing primary LSP path to a backup LSP path just after a failure is detected. This is so-called fast reroute (FRR) capability and the failure-detecting router is the so-called point of local repair (PLR).

The way the backup LSPs are rerouted (from the PLR) depends on the FRR mechanism. Two mechanisms are possible: one-to-one backup (OOB) [1] and many-to-one backup (MOB) [2]. Many-to-one backup is also called facility backup as in [3]. In OOB and MOB backup LSP paths are rerouted over the next hop router (NHR) and terminated in NHR if and only if the failing link is the last one on the failing primary LSP path.

For instance, in Figure 1 the primary path originates in router A, it goes through routers A, B, C, D, and terminates in router D. Link A-B fails, router A is the PLR, router B is the NHR, and router C is the next next hop router (NNHR). In the MOB a backup path is rerouted from the PLR router to the NNHR. On the other hand, in the OOB a backup path is rerouted from PLR to router D.

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When the OOB is used, backup LSP paths originate in the PLR and terminate in the destination node of the corresponding primary LSP path.

When the MOB is used, backup LSP paths originate in the PLR and terminate in the NNHR. In MOB, all primary paths that go exactly through the same PLR, NHR, NNHR are rerouted from the PLR to the NNHR on a single LSP backup path.

Individual demands can be sent (between any pair of network nodes) on single primary and single backup LSP paths (single path layout) or split on multiple primary and multiple backup LSP paths (multipath layout). The single or multipath layout we select, impacts on the minimized maximum link utilization value and network configuration complexity as explained in our previous paper [1].

In this paper, we focus on compact node-link (NL) formulations for the single LSP paths layout as they provide the optimal solutions for this layout, they can be easily implemented (e.g. with CPLEX package), and they haven't been presented before. We show and describe the NL formulation for the one-to-one backup as well as the NL formulation for many-to-one backup.

We use applicable size networks to show the efficiency of OOB and MOB. We provide example results related to running times, the number of used continuous and binary variables to show the performance of OOB and MOB formulations according to the network sizes. We provide results for minimized maximum link utilization values and networks configuration complexities to compare OOB and MOB solutions qualities.

Additionally, we use the same networks to generate suboptimal solutions for the single path layout. To do this, non-compact linear programming (LP) based approach and IP-based approach were applied. Detailed explanations of these methods and related work can be found in [1], [4], [5], [6], [7] and [8].

Then, we discuss the gap between optimal and suboptimal solutions. Exactly, we compare the minimized maximum link

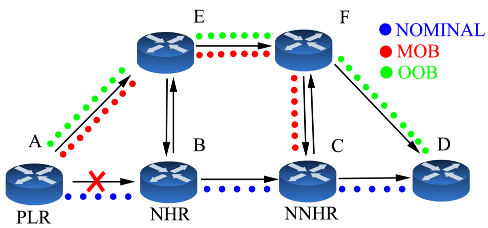

Fig. 1. Explanation of one-to-one backup and many-to-one backup

utilization values to show optimal and suboptimal solutions qualities. Finally, we present conclusions summarizing the results.

II. Node-link formulations

The section discusses the common part of OOB and MOB formulations.

A. Used symbols

An MPLS/IP network is modeled as a graph $G=(V,E)$ comprising a set V of nodes and a set E of directed edges ($E \in V^2 \setminus \{(v,v) : v \in V\}$). The nodes correspond to the MPLS/IP routers and edges correspond to IP links. Symbols $a(e)$ and $b(e)$ denote the source and the destination node of link $e \in E$. Sets $\delta^-(v)$ and $\delta^+(v)$ denote the incoming and the outgoing edges for node $v \in V$. A constant C_e is the capacity of link $e \in E$.

Set D denotes the set of demands. Symbols $o(d)$ and $t(d)$ denote source and destination node of demand d. A constant h_d is the rate of demand $d \in D$.

Set S denotes the set of failure states. In the paper only the failures of single links are considered, thus $S \equiv E$.

In both OOB and MOB formulations, the paths of the LSP connections (in normal state and in each failure state) are modeled as unitary non-bifurcated flows between appropriate pairs of nodes.

Variables x_{ed} indicate whether link e belongs to the primary path for demand d.

The Z denotes the objective function value. It minimizes maximum link utilization.

B. Feasible and infeasible solutions provided by node-links

Notice that there is no capacity constraints in the formulations for OOB and MOB. Instead, we use relative link utilization by addition of the constant $(1/C_e)$ to the NL formulations.

In the case when we get an optimal solution with $Z > 1$ it means the solution is infeasible in terms of required capacity. On the other hand, when we get some optimal solution with $Z \leq 1$ it means the solution is feasible in terms of required capacity.

III. Node-link formulation for one-to-one backup

In this section, a compact NL formulation for one-to-one backup is described. For each $s \in S$ and each $d \in D$, both the primary and its backup path that is used in the network state corresponding to the failure of link s can be viewed as consisting of two subpaths – the path between the source node of d and the PLR (which is the originating node $a(s)$ of link s), and the path between the PLR and $t(d)$ – the destination node of d. Since, according to the FRR mechanism, the primary and the backup paths share the subpaths that is upstream from the PLR and differ in the subpaths that are downstream from the PLR, the backup path can be described in terms of the primary path and those two downstream subpaths between the PLR and the destination node of the demand.

The formulation is as follows:

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

$$Z \geq \sum_{d \in D} (h_d/C_e) x_{ed}, \forall e \in E \tag{1b}$$

$$Z \geq \sum_{d \in D} (h_d/C_e)\left(x_{ed} - y_{des} + z_{des}\right), s \neq e, \forall e \in E, \forall s \in E \tag{1c}$$

$$\sum_{e \in \delta^+(v)} x_{ed} - \sum_{e \in \delta^-(v)} x_{ed} = \begin{cases} 1, & v = o(d) \\ -1, & v = t(d), \quad \forall d \in D \\ 0, & \text{otherwise} \end{cases} \tag{1d}$$

and for each $d \in D$, $s \in E$:

$$y_{des} \leq x_{ds}, \forall e \in E \tag{2a}$$

$$\sum_{e \in \delta^+(v)} y_{des} - \sum_{e \in \delta^-(v)} y_{des} = \begin{cases} x_{ds}, & v = a(s) \\ -x_{ds}, & v = t(d) \\ 0, & \text{otherwise} \end{cases} \tag{2b}$$

$$y_{des} \leq x_{de}, \forall e \in E \tag{2c}$$

$$z_{des} \leq x_{ds}, \forall e \in E \tag{2d}$$

$$\sum_{e \in \delta^+(v)} z_{des} - \sum_{e \in \delta^-(v)} z_{des} = \begin{cases} x_{ds}, & v = a(s) \\ -x_{ds}, & v = t(d) \\ 0, & \text{otherwise} \end{cases} \tag{2e}$$

$$z_{dss} = 0 \tag{2f}$$

$$z_{des} = 0, \forall e \in \delta^+(b(s)), b(s) \neq t(d) \tag{2g}$$

We cannot write conservation constraints for variables y_{de} with flow equal to 1 (the right-hand side of (2b)) because if x_{ds} is equal to 0 then from (2c) all y_{de} are equal to 0 and we would arrive at a contradiction. It only makes sense to look for the backup path described with y_{ds} (and also with variables z_{ds} described in the sequel) if the primary path fails in state s. That we know from x_{ds}: if x_{ds} is equal to 1 the primary path uses link s and thus fails in state s. Thus, putting x_{ds} in conservation constraints (2b) allows us to look for the backup path and write the constraints somewhat 'conditionally' upon the failure of the primary path.

The subpath of the backup path that is downstream from the PLR can be modeled as a unitary flow between the PLR and the destination node of the demand that must not use neither the failing link nor the terminating node of that link. For each $e \in E$, let z_{des} be a binary variable that equals 1 if, and only if, link s belongs to the primary path of demand d, and link e belongs to the segment of the backup path that this downstream from the PLR. This is satisfied by constraints (2d), (2e), (2f) and (2g).

Similarly to conditions (2a)-(2c) that describe subpath y, conditions (2d)-(2e) say that we must find subpath z between the PLR and the destination node; the form and the role of (2e) is the same as that of (2b). And the conditions for both types of subpaths paths – y must be embedded into the primary path and z must detour the failure – are given by (2c), (2f) and (2g). Constraints (2f) and (2g) say that we cannot use either the failed link or the links that originate at the terminating node of the failed link. Although we therefore cannot transit the terminating node of the failed link, this does not mean that we cannot enter such a node. Thus, in particular, the last hop of the primary path is also protected since the destination node of the demand need not be used as a transit node for the backup path.

It should be noted that although only link failures are assumed explicitly in the formulation, the determined backup paths provide protection of the primary paths against both link and node failures. But only in terms of flow routing; network capacity is not sufficient and the flows in fact are not protected. The meaning of this can be explained with the following example. Consider the following links, all with capacity equal to 1: k and l between nodes A and B; m and n between nodes B and C; and o between nodes A and C. Consider two primary paths k-m and l-n between nodes A and C, both with flows equal to 1. Assume that each of those primary paths has path o as its backup path. Then, theoretically each primary path is protected with its backup path against the failure of node B. But there is not enough capacity on link o to reroute both primary paths at the same time, so in fact the flows are not protected. Still, if either link k or l fails the affected path can be rerouted.

IV. Node-link formulation for many-to-one backup

In this section, a compact NL formulation for many-to-one backup is described. The MOB is a restricted version of OOB. The restrictions hold for all $d \in D$ and consist in:

- backup paths terminate in NNHRs (except the case the NNHR is the terminating node of demand – then terminate in NHRs),
- backup paths originating in node $a(s)$ and terminating in node $b(q)$ are rerouted the same path, on the single path going from node $a(s)$ to node $b(q)$.

For each $s \in S$ the formulation can be shown according to its two cases. The case when $b(s) \neq t(d)$ and the case when $b(s) = t(d)$. In the first case, backup LSP paths terminate in NNHRs and in the second in NHRs. The common part of the cases is formulated below:

$$\min \quad Z \tag{3a}$$

$$\sum_{e\in\delta^+(v)} x_{ed} - \sum_{e\in\delta^-(v)} x_{ed} = \begin{cases} 1, & v = o(d) \\ -1, & v = t(d), \quad \forall d \in D \\ 0, & \text{otherwise} \end{cases} \tag{3b}$$

$$Z \geq \sum_{d\in D} (h_d/C_e) x_{ed}, \forall e \in E \tag{3c}$$

$$Z \geq \sum_{d\in D} (h_d/C_e) x_{ed} + \sum_{d\in D} \sum_{q\in\delta^+(b(s))} (h_d/C_e) z_{desq}, \forall e, s \in E \tag{3d}$$

In the case when $b(s) \neq t(d)$, the constraints for each $s \in E$, $d \in D$ are formulated as follows:

$$z_{sdq} \leq x_{sd}, \forall q \in \delta^+(b(s)) \tag{4a}$$

$$z_{sdq} \leq x_{qd}, \forall q \in \delta^+(b(s)) \tag{4b}$$

$$z_{sdq} \geq x_{sd} + x_{qd} - 1, \forall q \in \delta^+(b(s)) \tag{4c}$$

$$z_{sdq} \geq 0, \forall q \in \delta^+(b(s)) \tag{4d}$$

$$f_{sq} \geq z_{sdq}, \forall q \in \delta^+(b(s)) \tag{4e}$$

$$\sum_{e\in\delta^+(v)} f_{esq} - \sum_{e\in\delta^-(v)} f_{esq} = \begin{cases} f_{sq}, v = a(s) \\ -f_{sq}, v = b(q), \quad \forall q \in \delta^+(b(s)) \\ 0, \text{otherwise} \end{cases} \tag{4f}$$

$$\sum_{e\in\delta^+(v)} z_{desq} - \sum_{e\in\delta^-(v)} z_{desq} = \begin{cases} z_{dsq}, v = a(s) \\ -z_{dsq}, v = b(q), \quad \forall q \in \delta^+(b(s)) \\ 0, \text{otherwise} \end{cases} \tag{4g}$$

$$z_{desq} \leq f_{esq}, \forall e \in E, \forall q \in \delta^+(b(s)) \tag{4h}$$

$$z_{dess} = 0, \forall e \in E \tag{4i}$$

$$z_{desq} = 0, \forall e \in \delta^+(b(s)), \forall e \in \delta^-(b(s)), \forall q \in \delta^+(b(s)) \tag{4j}$$

The constraints (3b)-(3d) correspond to constraints (1b)-(1d). The constraint (3c) concerns links load in nominal state (without failures) and constraint (3d) concerns link load in each failure state s, where $s \in S$.

Constraints (4a)-(4e) model in fact logical 'and' operator. For each demand $d \in D$, operator takes as an input x_{sd} and x_{qd} variables and sets f_{sq} variable as a result. If a primary path goes through link s and link q ($x_{sd} = 1$ and $x_{qd} = 1$), it means that in state s the f_{sq} ($f_{sq} = 1$) backup path is selected for rerouting, for demand d. All primary paths that goes through link s and q in state s are rerouted on the same route f_{sq}.

The constraint (4f) forms a route f_{sq}. The constraint is formulated similarly as (2b) and (2e). The route f_{sq} originates in $a(s)$ (PLR) and terminates in $b(q)$ (NNHR).

Backup paths, used in a failure state $s \in E$ by demand $d \in D$, are formed by z_{desq} variables. In a feasible solution all variables $z_{desq} = 1$ indicate edges that belong to the backup path used in state s by demand d. The constraint (4h) ensures that all primary paths that go through link s and q use f_{sq} path for rerouting in the state s.

The constraints (4i) and (4j) block links that should not be used in the state s. The constraints correspond to the constraints (2f) and (2g) in MOB formulation.

In the case when $b(s) = t(d)$ ($s = q$), the constraints for each $s \in E$, $d \in D$ are formulated as follows:

$$z_{sds} \geq x_{sd} \tag{5a}$$

$$f_{ss} \geq z_{sds} \tag{5b}$$

$$\sum_{e\in\delta^+(v)} f_{ess} - \sum_{e\in\delta^-(v)} f_{ess} = \begin{cases} f_{ss}, & v = a(s) \\ -f_{ss}, & v = b(s), \\ 0, & \text{otherwise} \end{cases} \tag{5c}$$

$$\sum_{e\in\delta^+(v)} z_{dess} - \sum_{e\in\delta^-(v)} z_{dess} = \begin{cases} z_{dss}, & v = a(s) \\ -z_{dss}, & v = b(s), \\ 0, & \text{otherwise} \end{cases} \tag{5d}$$

$$z_{dess} \leq f_{ess}, \forall e \in E \tag{5e}$$

$$z_{dsss} = 0 \tag{5f}$$

$$z_{desq} = 0, q \neq s, \forall e \in E, \forall q \in \delta^+(b(s)) \tag{5g}$$

The 'and' operator is reduced to constraints (5a) and (5b) – when a primary path goes through the s link, then f_{ss} path is selected for rerouting, for this path.

The constraints (5c) and (5d) simplify (4f) and (4g) constraints – there is no need to iterate over every $q \in \delta^+(b(s))$.

Similarly (5e), (5f) and (5g) correspond to (4h), (4i) and (4j) respectively.

V. Simulations

In this section, experiments performed in the paper are explained in details. Network instances and settings used in the tests are described.

The tests are performed on standard PC computer (2.8 GHz Intel, 2.5 GB RAM). CPLEX solver (version 12) is used with non-default mixed integer programming (MIP) parameters. MIP probing level and cuts generation level are set to aggressive and MIP emphasis is set to force optimality over feasibility.

The network instances used in the tests are subnetworks of networks presented in [1]. They are randomly chosen to keep their size applicable for the tests. For example, network instance CO9 is a subnetwork of network cost-239-100 and is almost as large as cost-239-100.

Each test for the optimal NL runs no more than 24 hours. Simulations are stopped after that time. There is no time limit for path generation as it runs no more than a few seconds for networks in Table I.

Each subnetwork instance contains a full matrix of demands – for each pair of nodes (a,b) two demands exist: a directed demand from node a to b and a directed demand from node b to a. The number of demands is equal to $|V| \cdot (|V|-1)$ for each network instance.

VI. Node-link formulations complexity

In this section, NL formulations complexity for practical NL instances is described.

The sizes of the applicable networks confirm that their MIP representations are hard to solve. Even with aggressive MIP settings for CPLEX, network instances CO9 and AT9 could not be solved in 24 hours time limit, as shown for MOB.

Though presented NL formulations are compact in the number of variables, they prove to be unsolvable in reasonable time and computer memory. For example, the number of binary variables in OOB CO9 is equal to about 42000. In MOB CO9 the number of binary variables is equal to about 13000 and number of continuous variables is equal to about 50000. It shows a large size of tested MIP problems.

Additionally, we solve NL formulations with cost239-100 – the network instance with the smallest number of nodes from [1]. The test is unsuccessful as it leads to a CPLEX "out of memory" error.

VII. Numerical results

In this section, we present and discuss numerical results obtained in the tests.

A. Optimal OOB and MOB link utilization

In Table I we get the same value of minimized maximum link utilization for OOB and for MOB, for all tested networks.

B. Optimal and suboptimal link utilization

The suboptimal results for single path layout can be computed with a linear programming approach (path generation approach) and an IP-based approach. Though path generation has to solve several MIP problems it still provides solutions for large network instances in reasonable time as shown in [1]. The multipath suboptimal solutions provided by the path generation determine the lower bounds for the optimal single path layout solutions. On the other hand the results provided by the path generation for single path layout determine the upper bounds for the optimal single path layout solutions.

In Table II we compare optimal and suboptimal solutions. The results show that a heuristic path generation provides significantly different values from the optimal one. The values of multipath solutions are better 32.05% (EX8) and 27.89% (EB8) than the optimal solution. For AT8 and CO9 networks, the suboptimal single path solutions are significantly worse than the optimal solutions.

Due to the relatively small size of the network instances the maximum path lengths of the primary paths if an IP-based layout is used are rather small (in most cases not more than 3 hops per path). For these short path lengths, the destination basically always equals either the NHR or NNHR. Therefore, all OOB and MOB layouts are supposed to be identical if IP-based layouts are used. It is thus an expected behavior that the IP-based values for OOB and MOB are equal for all network instances.

C. OOB and MOB network configuration effort

The configuration effort of OOB and MOB is related to the length of the LSP paths. In Table III the maximum and average configuration effort is shown for each network. Configuration effort is calculated for each node in the network as a sum of incoming and outgoing LSP paths. If LSP path goes through the node it is treated as incoming and outgoing at the same time. Maximum configuration relates to the node with the maximum sum of incoming and outgoing LSP paths.

In Table III we observe that network configuration effort for backup paths is several times greater than for primary paths.

We observe that there is no significant difference between average primary paths configuration effort of OOB and MOB. On the other hand, for EX8 and CO8 networks, there appear significant differences in OOB and MOB configuration effort for backup paths. The situation for EX8 can be described by fact that for OOB longer backup paths are used in the optimal solution. And similarly, for CO8 shorter paths are used.

VIII. Summary and conclusions

The paper presents compact node-link formulations for MPLS Fast Reroute optimal single path layout. We test the formulations on network instances with practical sizes.

We provide optimal solutions for the single path layout for two distinct MPLS local protection mechanisms: one-to-one backup and many-to-one backup. We obtain the same value of the minimized maximum link utilization for one-to-one backup and many-to-one backup, for all tested networks. This seems to be an interesting fact, taking into account that many-to-one

TABLE I
MINIMIZED MAXIMUM LINK UTILIZATION

Network					Optimal NLs		Path generation approach		IP-based approach	
ID	Name	$\|V\|$	$\|E\|$	$\|D\|$	MOB	OOB	OOB (multipath)	OOB (single path)	OOB	MOB
CO8	cost239-100_8	8	32	56	90.90%	90.90%	90.44%	102.27%	110.7%	110.7%
CO9	cost239-100_9	9	38	72	-	70.16%	69.38%	89.37%	87.6%	87.6%
GE8	geant_8	8	22	56	62.79%	62.79%	62.78%	71.68%	71.69%	71.69%
GE9	geant_9	9	26	72	58.60%	58.60%	58.60%	71.27%	66.08%	66.08%
EX8	exodus_8	8	36	56	65.15%	65.15%	33.10%	66.62%	74.84%	74.84%
EB8	ebone_8	8	34	56	63.94%	63.94%	36.05%	65.85%	68.03%	68.03%
AT8	atnt_8	8	34	56	52.40%	52.40%	44.43%	73.36%	91.01%	91.01%
AT9	atnt_9	9	38	72	-	59.47%	59.47%	81.23%	81.74%	81.74%

TABLE II
GAPS BETWEEN OPTIMAL AND SUBOPTIMAL SOLUTIONS

	Path generation approach		IP-based approach	
ID	OOB (multipath)	OOB (single path)	OOB	MOB
CO8	0.46%	11.37%	19.8%	19.8%
CO9	0.78%	19.21%	17.44%	-
GE8	0.01%	8.89%	8.9%	8.9%
GE9	0.0%	12.67%	7.48%	7.48%
EX8	32.05%	1.47%	9.69%	9.69%
EB8	27.89%	1.91%	4.09%	4.09%
AT8	7.97%	20.96%	38.61%	38.61%
AT9	0.0%	21.76%	22.27%	-

TABLE III
NETWORK CONFIGURATION EFFORT

		Primary paths		Backup paths		All paths	
		avg.	max.	avg.	max.	avg.	max.
CO8	OOB	26.5	44	56.75	102	83.25	142
CO8	MOB	26.75	38	65.25	94	92	132
		-0.25	6	-8.5	8	-8.75	10
GE8	OOB	30	48	87	152	117	198
GE8	MOB	30	44	83.5	166	113.5	208
		0	4	3.5	-14	3.5	-10
GE9	OOB	34.67	70	106.22	212	140.89	282
GE9	MOB	35.56	60	106.22	198	141.78	250
		-0.89	10	0	14	-0.89	32
EX8	OOB	23.75	36	75.25	94	99	130
EX8	MOB	22	30	53.5	72	75.5	102
		1.75	6	21.75	22	23.5	28
EB8	OOB	25.75	32	58.5	86	84.25	118
EB8	MOB	22.75	38	55.75	78	78.5	116
		3	-6	2.75	8	5.75	2
AT8	OOB	29.75	48	75	150	104.75	194
AT8	MOB	32	60	73.25	110	105.25	170
		-2.25	-12	1.75	40	-0.5	24

backup is a restricted version of one-to-one backup. It would be interesting if we could extend this observation for larger network instances.

We compare optimal solutions for the single path layout with suboptimal solutions provided by algorithms based on path generation approach and IP-based approach. The values of the optimal solution are usually significantly better than suboptimal solutions.

Though we are able to compute optimal solutions for a set of practical network instances, for larger networks more efficient methods have to be found.

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