Università di Pisa
Dipartimento di Informatica

Technical Report: TR-08-24

A Linear Programming Model for Traffic Engineering in 100% Survivable Networks under combined IS-IS/OSPF and MPLS-TE Protocols

D. Cherubini
R&D, Tiscali International Network S.p.A.

A. Fanni
DIEE, Università di Cagliari

A. Frangioni
Dipartimento di Informatica, Università di Pisa

C. Murgia
Tiscali Italia S.p.A.

M.G. Scutellà
Dipartimento di Informatica, Università di Pisa

P. Zuddas
DIT, Università di Cagliari

September 23, 2008

ADDRESS: Largo B. Pontecorvo 3, 56127 Pisa, Italy. TEL: +39 050 2212700 FAX: +39 050 2212726

A Linear Programming Model for Traffic Engineering in 100% Survivable Networks under combined IS-IS/OSPF and MPLS-TE Protocols

D. Cherubini
R&D, Tiscali International Network S.p.A.

A. Fanni
DIEE, Università di Cagliari

A. Frangioni
Dipartimento di Informatica, Università di Pisa

C. Murgia
Tiscali Italia S.p.A.

M.G. Scutellà
Dipartimento di Informatica, Università di Pisa

P. Zuddas
DIT, Università di Cagliari

September 23, 2008

Abstract

The paper concers the problem of minimizing the maximum link utilization of IP telecommunication networks under the joint use of the traditional IS-IS/OPSF protocol and the more sophisticated MPLS-TE technology. Both working conditions and single link failure scenarios are addressed. An innovative Linear Programming mathematical model is proposed that, while optimizing the network utilization, provides optimal user performance, efficient use of network resources, and 100% survivability in case of single link failure. The hybrid approach takes advantage of both IGP and MPLS-TE technologies providing a flexible tool for IP networks traffic engineers. The proposed model is validated by a wide experimentation performed on synthetic and real networks, both in working and failure conditions. The obtained results show that the new approach considerably reduces the maximum utilization of the network, thereby allowing a more efficient use of the network resources; setting a limited number of LSPs yields better results than those obtained by simply optimizing the IGP weights. In addition, an optimized set of IGP weigths allows to further improve the network performance in case of failures. The computational time needed to solve the LP model is very limited and it well matches the real time requirements.

Keywords: *Backbone Networks, Optimization, Survivability, MPLS-TE*

1 Introduction

In the last few years, the Internet has exponentially expanded to a worldwide network connecting several millions of users. Such an explosion deeply impacts on the available bandwidth of IP backbone networks. The resulting bandwidth causes loss of performance and possible failure events, which can be technically and economically harmful. Network Engineers have been building very large scale networks at their best, trying to understand beforehand (planning) and react just in time to the network events.

Recently, new emerging Traffic Engineering (TE) techniques enable Internet Service Providers (ISP) to route the traffic along the network, offering the best service to their users in terms of throughput and latency, moving traffic from congested links to less loaded areas of the network. In particular, the Multi-Protocol Label Switching (MPLS-TE) networks enable ISPs to adopt quality-of-service (QoS) policies, setting up constrained label switched paths (LSPs). Furthermore, network survivability techniques have been developed

to guarantee seamless communication services in case of network failures. Traffic management and restoration strategies are usually adopted in order to make a backbone network survivable, i.e., the network traffic load has to be distributed in such a way that a failure has the minimum (eventually, null) impact when it occurs; moreover, the traffic demands affected by the failure have to be suitably restored.

There are two variants of the restoration routing [1]: Path (or end-to-end) restoration and Link (or Local) restoration. In the former scheme, if a failure is present along a path, the source node detects it and activates backup paths. In the absence of an Operation, Administration and Maintenance (OA&M) system, the source node learns of link failures via intradomain routing updates such as OSPF (Open Short Path First) Link-State Advertisement (LSA) packets or IS-IS (Intermediate System to Intermediate System) Link-State Packets (IS-IS LSP), and these protocols are used to re-route the commodities affected by the fault; this causes very large restoration latencies.

In the Link restoration scheme, a back-up path is found to protect the failed link, rather than the entire path failure. This achieves faster restoration. Though Link restoration may use more (bandwidth) resources, it is attractive as it can meet strict restoration latency requirements. For these reasons, in the present paper, the Link restoration scheme is considered.

The TE routing problem we address can be described as follows. Given the topology of the network to be engineered, and the traffic matrix to be routed on it, the problem is to find a routing scheme that optimizes the network usage, with the following joint goals:

- optimal user performance;
- efficient use of the network resources;
- 100% survivability in case of single link failure.

Note that the traffic matrix indicates the measured or estimated traffic demand volume between an ingress and an egress router.
Several optimization models under the MPLS-TE protocol have been presented in the literature [1, 2, 4, 5, 6, 7, 8]; a literature survey is reported in the following Section 3. Many of these papers consider only the normal (or working) condition. Some papers formalize the survivability constraint under single link failure condition as a two phases design process: the working paths are firstly chosen to optimize the routing in working condition, next, restoration (or back up) paths are chosen that protect the links along the primary LSP. Nevertheless, no paper considers at the same time the different goals of the previously described TE routing problem. This may be due to the fact that optimal routing considering failures can easily be a very difficult problems. Indeed, the model developed in this paper heavily borrows from the classical General Routing Problem (GRP) [9], which is $\mathcal{NP}$-hard [10]; details about solution methods and applications for various network routing problems (included GRP) can be found e.g. in [11]. However, under the specific network technology conditions discussed below, the optimal routing problem can be modeled as a Linear Program (LP), and therefore can be efficiently solved by means of off-the-shelf LP methods. More specifically, in the proposed model the network topology is modelled by a directed graph, whose nodes and arcs represent the routers and the bi-directional links (or edges), which means that for each link in the network there will be two opposite direct arcs in the graph. Each arc has a prefixed known capacity, and an assigned or optimized distance metric (IS-IS/OSPF metric). The traffic on the network is represented by a traffic matrix, whose components are the measured or extimated user demands from each source to each destination nodes (commodities). Furthermore, a routing matrix is assumed to be built, whose elements are the fraction of the flow of each commodity that is routed across each arc according to the IS-IS/OSPF metrics. The directed graph, the set of metrics, the traffic and the routing matrices are the input of our problem.

The TE problem is formalized here as the search for some paths for each commodity, using the available routing protocols, i.e., IS-IS/OSPF and MPLS-TE, in such a way to minimize the maximum link utilization. This is achieved by taking into account the link restoration scheme, which allows the routers to automatically re-route the traffic in case of single link failure, so guaranteeing 100% survivability. Furthermore, as shown in [12] and convalidated with the results in the present paper, minimizing the maximum link utilization tends to maximize the available bandwidth, thus balancing the load in the network. The optimal solution of the stated problem was computed making use of efficient LP solvers, with very limited computational times.

The outline of this paper is as follows. Section 2 presents some relevant backgrounds on various aspects of the TE routing problem. Section 3 summarizes related works dealing with IGP and MPLS- TE optimization approaches. In Section 4 we describe the proposed optimization model, and in Section 5 we demonstrate the suitability of the proposed optimization model by tests and comparisons on synthetic and real networks. Finally, Section 6 presents our conclusions.

2 Background

2.1 IGP routing protocols

IP backbone networks make use of IGP routing protocols, such as IS-IS and OSPF, in order to compute the routes from each origin node to each destination node of the traffic demands by associating a suitable metric value with each link of the network. Once the full topology of the network is known, the routers apply the Dijkstra algorithm [13] in order to compute the shortest path, according to the configured metrics, linking each origin-destination pair. If the network topology changes, then the protocol recalculates the shortest routes using the Dijkstra algorithm.

When Equivalent Cost Multiple Paths (ECMP) are enabled, the traffic flows is equally split among the shortest paths. Generally, the traffic splitting follows the mechanism of per packet round robin, where each packet matching a given destination is forwarded toward the egress node using the least recently used equal cost path.

2.2 MPLS-TE technology

The introduction of the Multi-Protocol Label Switching Traffic Engineering (MPLS-TE) technology has improved the dataflow management due to the traditional routing protocols. In fact, IP routing protocols, by computing routing paths assigning a single metric per link and using destination-based routing, do not provide a general and scalable method for explicitly routing traffic.

On the contrary, MPLS-TE networks can support destination-based and explicit routing simultaneously; these two different kinds of LSPs are usually refereed to as "Implicit LSP" and "Explicit LSP", respectively. MPLS-TE networks may allow to better handle problems such as network congestion and network failures, thus improving the overall network performance and increasing service availability [14].

MPLS-TE provides mechanisms to quickly find an alternate path if the primary path is no longer available (typically due to a node or link failure). This Fast Re-Route (FRR) capability is critical for allowing service providers to offer high availability and high revenue SLAs (Service Level Agreements). However, FRR requires that the operator explicitly sets secondary paths for all the possible failure scenarios, which can be excessively time consuming; besides, choosing appropriate reserve paths is nontrivial. On the contrary, link restoration is able to use Interior Gateway Protocols, such as IS-IS/OSPF, to re-route the commodities affected by the fault.

2.3 Fault Model

The backbone networks are usually well-engineered and properly provisioned, leading to very low packet losses and negligible queuing delays. However, failures occur almost every day [15]. An understanding of their characteristics, properties and effects is extremely valuable. According to [16], failures are classified into two main groups: those resulting from scheduled maintenance activities (20%) and those generated by unplanned failures (80%). This latter set is mainly composed of single link failures (70%). This is the type of failures we will address in our modeling proposal.

3 Related works

In the literature, many papers have addressed the problem of optimizing traffic routing using IS-IS/OSPF protocols. In particular, in [9] the authors adapt the General Routing Problem (GRP) formulation in [10] to the world of telecommunications. This is a minimum cost multicommodity flow problem minimizing the sum

of piecewise linear cost functions associated with the links. In the last few years, Tabu Search [17], Genetic algorithms [18, 19] and tailored heuristics [20, 21] have been proposed to solve the problem. The results of these papers show that IS-IS/OSPF routing does not perform as well as optimal MPLS-TE routing, even if optimal metrics are set.

Many papers also appeared which focus on the optimization of MPLS routing; these aim at finding an "optimal" LSPs mesh deployment according to different objective functions. In particular, in [4] a Tabu Search algorithm is proposed to find a layout of MPLS paths with the minimum number of hops, whereas in [5] the MPLS routing problem is modeled in terms of an off-line multiobjective Mixed Integer Linear Programming model that looks for the best trade-off between the minimal routing delay, the optimal load balancing, and the minimal splitting of traffic trunks. In [22] and in [23] a multipath adaptive traffic engineering mechanism is introduced which aims at avoiding the network congestion by adaptively balancing the load among multiple paths based on measurements and analysis of the path level.

Only few papers deal with hybrid IGP/MPLS scenarios for traffic engineering, and most of these employ a two phase (hierarchical) approach by optimizing separately the two technologies. In particular, in [6] the IGP optimization is firstly performed using Simulated Annealing (SA) heuristics, then a set of complementary LSP tunnels are computed to improve the previous IGP solution using a Mixed Integer Linear Programming model. The results show that the use of LSPs greatly improve the network level. In [7] the basic idea of this hybrid approach is used to combine both the simplicity and robustness of IGP routing and the flexibility of MPLS-TE; a SA meta-heuristic is used to select a small number of LSPs under different objective functions, and the authors state that the method is independent of IGP weights configuration. Finally, in [8] the facilities provided by an open source toolbox for traffic engineering methods (TOTEM) are presented. The tool contains different algorithms based on IGP and MPLS intradomain and interdomain traffic engineering techniques, and it provides robust methods for IS-IS/OSPF metrics optimization, primary and backup LSP routing, and BGP (Border Gateway Protocol) simulations. The paper summarizes the results obtained by the authors in several years, and represents a very useful reference in the field of traffic engineering, even if it does not address all the TE optimization issues together.

None of the aforementioned papers take into consideration the survivability issue embedded in the overall optimization process. In the majority of the literature, survivability is addressed by simulation and/or heuristic approaches.

Regarding IS-IS/OSPF networks, survivability has been addressed in [17, 24, 25, 26, 27]. In particular, in [17, 24, 26] Tabu Search metaheuristic approaches are used in order to determine robust metrics that guarantee survivability both in working condition and in all single link failure scenarios. In [27], the same problem has been solved using an evolutionary algorithm, addressing also the failure of the routers. In [25], a bicriteria algorithm has been used, where the working condition and failure scenarios are separately considered; basically, the authors use a local search algorithm based on Tabu Search, where the objective function "drives" the search toward Pareto optimal solutions. All the authors report that it is possible to significantly reduce the link congestion in case of single link failure, at the price of a higher maximum occupation in working conditions. The drawback of all the presented methods is the huge amount of time required in order to find a feasible solution.

Survivability under the MPLS-TE technology has been formulated in [28] in terms of the Spare Capacity Allocation (SCA) problem. The idea is to mitigate the impact of a single link failure by placing sufficient capacity on the links. Following this approach, an LSP backup path which is disjoint from the primary LSP has to be created. This goal can be unachievable for pathological network topologies [29]. In [2] the SCA problem is addressed by separate design of working and restoration paths resulting in a minimum capacity usage; for this purpose, two LP models are sequentially solved. An improvement of the model is developed to take into account load balancing. In [1], the authors address the problem of distributed routing of restoration paths introducing the concept of backtracking to bound the restoration latency. They use a two steps heuristic algorithm where primary paths and backup paths are computed in two separated steps.

All the above approaches obtain optimal solutions of simple optimization problem, or sub-optimal solutions of wider problems. Anyway, no approach addresses combined IS-IS/OSPF and MPLS-TE routing and single link failures simultaeously. To overcome these drawbacks, in the present paper an innovative optimization model is proposed, which optimizes the traffic routing by jointly considering the IS-IS/OSPF and the MPLS-TE technology, while taking into account significant survivability aspects.

4 The optimization model

Let $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ be an *undirected* graph modeling a telecommunication network, where $\mathcal{N}$ ($n = |\mathcal{N}|$) is the set of the nodes (routers) of the network, and $\mathcal{E}$ ($\mu = |\mathcal{E}|$) is the set of the edges (links) of the network. A transmission capacity c_{ij} is associated with each (undirected) link $\{i, j\}$, denoting the maximum overall flow that it is possible to send along $\{i, j\}$. Capacity is intended to be bi-directional, i.e., one can simultaneously transmit up to c_{ij} information from i to j and c_{ij} information from j to i without the two transmissions interfering with each other. In the following we will often use the *bi-direction* of $\mathcal{G}$, i.e., the *directed* graph $\mathcal{G}' = (\mathcal{N}, \mathcal{A})$ having the same set of nodes as $\mathcal{G}$, whereas $\mathcal{A}$ ($m = |\mathcal{A}|$) is the set of pairs of directed arcs (i, j) and (j, i) for each edge $\{i, j\} \in \mathcal{E}$, hence $m = 2\mu$. We will sometimes find it useful to employ the short-hand notation l for an edge $\{i, j\} \in \mathcal{E}$; in that case, the two corresponding directed arcs will be denoted by $l_+(l_+ = (i, j))$ and $l_-(l_- = (j, i))$.

Let $\mathcal{F}$ ($k = |\mathcal{F}|$) denote a set of origin-destination pairs, or *commodities*; for each $f \in \mathcal{F}$, we will denote by $s(f)$, $t(f)$ and d^f respectively the origin node, the destination node and the traffic demand of the commodity f.

Let $\mathcal{X}$ be the $m \times k$ routing matrix whose element x^f_{ij} is a rational number $\in [0, 1]$ equal to the fraction of flow of the commodity f that is routed by IS-IS/OSPF along the arc (i, j), $f \in F$, $(i, j) \in \mathcal{A}$. Hence, the rows of the routing matrix correspond to the arcs, and the columns correspond to the commodities, i.e., to the pairs of origin-destination nodes. The routing matrix is intended to be obtained after that a suitable set of IS-IS/OSPF routing metrics has been setted or optimized, e.g., with the approaches proposed in [26, 9, 17].

The problem under investigation consists of satisfying the demands of the commodities in $\mathcal{F}$, under combined IS-IS/OSPF and MPLS-TE routing protocols, in such a way to minimize the maximum *arc utilization* of the network. The utilization of an arc (i, j) is defined as the total load of (i, j) over the associated capacity c_{ij}, where the total load of (i, j) is the sum over all the demands of the amount of traffic sent over (i, j). Note that, defining the *link utilization* as the maximum of the utilization of the two directed arcs associated with that link, link utilization and arc utilization coincide. In the following we will propose a Linear Programming formulation of this problem.

The proposed model is akin to the "General Routing Problem" (GRP) [9], which is basically a minimum cost multicommodity flow problem. Differently from [9], we define the objective function in terms of maximum arc utilization. Moreover, the proposed formulation includes both the IS-IS/OSPF routing protocol and a complementary set of LSP tunnels within a unique model. An extra term can be added to the model objective function to discourage the usage of LSP tunnels, as discussed below. Survivability constraints are also introduced in agreement with the used restoration technique. Note that the objective function refers to all (faulty and faulty-free) scenarios.

In terms of network management, application of the proposed model requires the following steps:

1. computation of a proper set of IS-IS/OSPF routing metrics and the corresponding IS-IS routing, represented by matrix $\mathcal{X}$;

2. solution of the model to obtain a complementary set of LSP paths which improve the quality of the IS-IS-only solution;

3. setup of the explicit LSPs determined by the model.

All these steps can be easily automatized, and no intervention of the network operators is required to setup the restoration configuration.

4.1 LP mathematical model in working condition

In the present subsection, we will firstly present an LP mathematical model for the minimum utilization routing problem, using jointly IS-IS/OSPF and MPLS-TE protocols, under *working condition*, i.e., without considering failures. Then, the model will be enriched with survivability constraints. Two different formulations can be adopted: node-arc and arc-path formulations, which are classically used for multicommodity flow problems [29]. Both formulations present advantages and drawbacks; in particular, the arc-path formulation lends itself nicely to *column generation* techniques which can considerably speed-up the solution

of the models [30]. However, the focus of the present paper is on formulation aspects rather than on implementation aspects, and the node-arc formulation can already be solved efficiently enough with available LP solvers for the sizes typically required by practical applications. Therefore only the node-arc formulation and the corresponding results will be presented here.

To formulate the model, the following data is given:

$\mathcal{N}$: set of nodes;

$\mathcal{A}$: set of arcs;

$\mathcal{F}$: set of commodities;

c_{ij} : arc capacity, $(i,j) \in \mathcal{A}$, [bit/s];

d^f : traffic demand of commodity f, $f \in \mathcal{F}$, [bit/s];

x^f_{ij} : fraction of the traffic of commodity f carried by IS-IS/OSPF along the arc (i,j) with the known set of metrics, $f \in \mathcal{F}$, $(i,j) \in \mathcal{A}$.

The variables of the model are denoted as follows:

u_{max} : maximum utilization over all the arcs of the network;

is^f share of traffic demand d^f of the commodity f carried by IS-IS/OSPF, $f \in \mathcal{F}$, [bit/s];

w^f_{ij} share of traffic demand d^f of the commodity f carried by LSP along arc (i,j) via the MPLS-TE protocol, $f \in \mathcal{F}$, $(i,j) \in \mathcal{A}$, [bit/s].

The node-arc formulation is then stated as follows:

$$\min \; u_{max} \tag{1}$$

$$\sum_{f \in \mathcal{F}} is^f x^f_{ij} + \sum_{f \in \mathcal{F}} w^f_{ij} \leq u_{max} c_{ij} \qquad (i,j) \in \mathcal{A} \tag{2}$$

$$\sum_{j:(j,i) \in \mathcal{A}} w^f_{ji} - \sum_{j:(i,j) \in \mathcal{A}} w^f_{ij} = \begin{cases} -d^f + is^f & \text{if } i = s(f) \\ d^f - is^f & \text{if } i = t(f) \\ 0 & \text{otherwise} \end{cases} \qquad \begin{array}{l} i \in \mathcal{N} \\ f \in \mathcal{F} \end{array} \tag{3}$$

$$w^f_{ij} \geq 0 \qquad (i,j) \in \mathcal{A}\,,\; f \in \mathcal{F} \tag{4}$$

$$d^f \geq is^f \geq 0 \qquad f \in \mathcal{F} \tag{5}$$

The objective function (1) measures the maximum arc utilization, which has to be minimized. The left hand side of constraints (2) specifies the total amount of traffic demand traversing the arc (i,j): it is composed by the traffic routed via the IS-IS/OSPF protocol (first summation) and the traffic carried by the LSPs (second summation). For each arc (i,j) this value must be smaller than or equal to $u_{max} \cdot c_{ij}$, thus constraining also the maximum utilization level u_{max}. Constraints (3) ensure that the communication demand of each commodity is entirely satisfied, considering both the traffic sent via IS-IS/OSPF and that sent via MPLS-TE. Constraints (4) and (5) are the nonnegativity constraints. Note that if every commodity f could only be routed *either* by IS-IS/OSPF *or* by MPLS-TE, then is^f should be defined as binary, thus turning the problem into a (much more difficult to solve) Mixed Integer Linear Program. Fortunately, current routers operations allow to direct to an MPLS-TE path every chosen fraction of a given commodity, thereby allowing the use of the (much simpler) Linear Program.

Starting from the solution of model (1)—(5), it is easy to automatically obtain, for each $f \in \mathcal{F}$, an optimal set of paths in $\mathcal{G}'$ from the origin node $s(f)$ to the destination node $t(f)$, i.e., an optimal set of LSPs. Note that the optimal value of model (1)—(5) also provides a lower bound for the optimization process of the IS-IS/OSPF metrics in working condition [31].

4.2 Improving the model: aggregation of the commodities

In the proposed model, the number of the constraints (excluding nonnegativity ones) is $(m + nk)$, whereas the number of the variables is $(m+1)k+1$. Even if the model size can be managed by an efficient LP solver, the number of the variables can be reduced by *aggregating* the commodities by origin node, as described below.

Let $\mathcal{H}$ be the set of origin nodes. For each node $v \in \mathcal{H}$, let $\mathcal{F}(v) = \{ f \in \mathcal{F} \ : \ s(f) = v \}$ denote the set of the commodities having v as their ingress node, and define

$$w_{ij}^v = \sum_{f \in \mathcal{F}(v)} w_{ij}^f$$

as the *aggregated flow* on the arc (i, j). Then, model (1)—(5) can be rewritten in terms of the aggregated variables as follows:

$$\min \ u_{max} \tag{6}$$

$$\sum_{f \in \mathcal{F}} is^f x_{ij}^f + \sum_{v \in \mathcal{H}} w_{ij}^v \leq u_{max} c_{ij} \qquad (i,j) \in \mathcal{A} \tag{7}$$

$$\sum_{j:(j,i) \in \mathcal{A}} w_{ji}^v - \sum_{j:(i,j) \in \mathcal{A}} w_{ij}^v = \begin{cases} \sum_{f \in \mathcal{F}(v)} (-d^f + is^f) & \text{if } i = v \\ d^f - is^f & \text{if } i = t(f) \\ 0 & \text{otherwise} \end{cases} \qquad i \in \mathcal{N}, v \in \mathcal{H}, f \in \mathcal{F}(v) \tag{8}$$

$$w_{ij}^v \geq 0 \qquad (i,j) \in \mathcal{A} \ , \ v \in \mathcal{H} \tag{9}$$

$$d^f \geq is^f \geq 0 \qquad f \in \mathcal{F} \tag{10}$$

If we denote by h the cardinality of $\mathcal{H}$, then the number of the variables in the aggregated model may decrease to $(hm + k + 1)$, whereas the number of the constraints is $(m + hn)$.

The disaggregated formulation (1)—(5) offers more flexibility than the aggregated one; for example, it is possible to impose *commodity-dependent costs* or *bounds*, if these are required by the problem at hand. Nevertheless, as in our application we do not need to insert that kind of constraints, we definitely adopted the aggregated formulation (6)—(10).

The model gives as result the portion of aggregated per source node flows traversing every arc. These flows must be *decomposed into paths* in order to find the explicit LSPs to be imposed in each router. Due to the *flow decomposition theorem* [29], this is always possible using the *path decomposition algorithm*; unfortunately, the decomposition is *in general not unique*. Thus, the optimal solution of (6)—(10) may be decomposed in different ways, ultimately leading to a different number of LSP paths. Observe that the same holds true in the case of the disaggregated formulation. To the best of our knowledge, there is no polynomial time algorithm that obtains a path decomposition which is optimal with regard to performance measures such as minimizing the number of the LSPs. The problem of decomposing a given flow in such a way as to minimize the number of paths in the flow decomposition is in fact NP-hard [32].

4.3 Improving the model: controlling the number of LSPs

Both models (1)—(5) and (6)—(10) present the characteristic that their optimal solutions almost surely are *highly degenerate*. This is shown by the following proposition. As discussed in the next subsection, the statement does not hold when survivability constraints are added to the models.

Proposition 4.1 *Each instance of (1)—(5) or (6)—(10) has an optimal solution where* $is^f = 0$ *for all* $f \in \mathcal{F}$.

Proof. For any $f \in \mathcal{F}$, the flow routed on each arc (i, j) by the IS-IS/OSPF protocol for the commodity f, given by $is^f x_{ij}^f$, can be represented in terms of the flow variables w_{ij}^f in the disaggregated formulation, and in terms of w_{ij}^v in the aggregated formulation. Therefore, to any feasible solution, another feasible solution

corresponds where the share is^f of the demand routed by the IS-IS protocol is now routed by the MPLS-TE protocol. Both solutions produce the same link utilization, and hence the same value of the objective function. Obviously, this happens also for the optimal solution, and the statement thus follows. □

Thus, the above models do not control the total number of the resulting LSPs; a consequence of Proposition 4.1 is that a solution can be obtained that has the same optimal value as the IS-IS/OSPF-only routing (corresponding to the feasible solution of (1)—(5) having $w_{ij}^f = 0$ for all (i, j) and f) but that would require setting a very large number of explicit LSP paths. While having a solution with many LSPs may not have a large operational cost, it can be argued that, for the same value of the maximum network utilization, a solution using a smaller number of LSP paths could be preferred to a solution using a larger number of LSP paths, mainly because of management reasons.

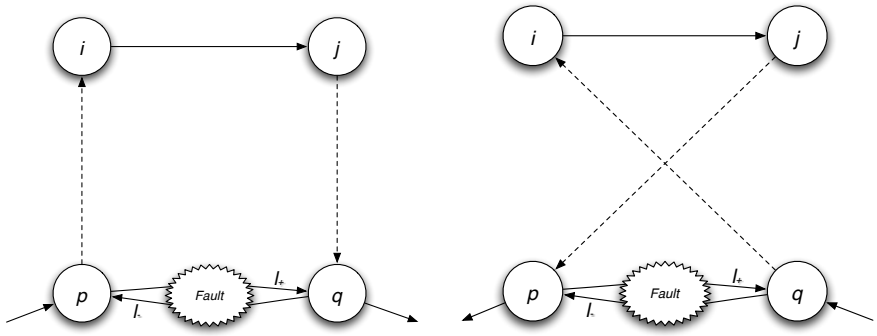
Minimizing the LSP paths at the optimum solution level generally leads to a difficult problem [32]; however, a simple technique can be used to obtain a good result in practice. For example, a reasonable objective function to replace (6) could be:

$$u_{max} + \delta \sum_{v \in \mathcal{H}} \sum_{(v,j) \in \mathcal{A}} w_{vj}^v$$

where δ is a "small" value. This penalizes each unit of flow leaving the source nodes, thereby ensuring that LSP paths are used only if they strictly decrease the maximum utilization level. A similar observation holds for the disaggregated formulation.

4.4 LP mathematical model with survivability constraints

We now extend the previous models in order to consider survivability. We consider single-link failures and define $\mathcal{L} \subseteq \mathcal{E}$ as the set of all possible link failures. Note that a link failing means that both arcs representing the link traversed in the two possible directions fail. Since we only consider single-link failures, the set of the failure scenarios coincides with the set $\mathcal{L}$ of link failures. We therefore equivalently refer to each element $l \in \mathcal{L}$ as a failed link or as a failure scenario. The models can be easily extended to multiple link failures and/or node (router) failures, at the possible cost of a substantial increase of the size of the models. Each single-link failure scenario will be addressed under the link restoration mechanism, whose backup paths are realized in terms of implicit LSPs. Recall that the operational advantage of implicit LSPs is that they are automatically determined using the conventional IS-IS/OSPF metrics and without any intervention, whereas in case of an explicit LSP each backup path has to be explicitly specified by the network operator.



(a) Rerouting flow $p \to q$ (b) Rerouting flow $q \to p$

Figure 1: *Rerouting flows in case of edge failure*

For each failure scenario, a $(m-2) \times k$ routing matrix $\mathcal{X}^l$ is defined, whose element $x_{ij}^{f,l}$ is the fraction of the flow of commodity f that is routed by IS-IS/OSPF protocol along the arc (i, j), when the link l fails. Each of these routing matrices $\mathcal{X}^l$ can be easily determined, prior to solving the model, given the fixed set of IS-IS/OSPF metrics, by computing shortest paths over a graph obtained from $\mathcal{G}'$ by removing the link

l, i.e., by removing both l_+ and l_-. We also define $x_{ij}^{l_+,l}$ and $x_{ij}^{l_-,l}$ as the fraction of the MPLS-TE traffic, routed along the arcs l_+ and l_- respectively, under the nominal working conditions, that in case of failure of the link l are rerouted along the arc (i,j), via the IS-IS/OSPF protocol, according to the link restoration strategy. Note that the rows of the routing matrices correspond to the arcs, and the columns correspond to the commodities. Hence, $x_{ij}^{l_+,l}$ is the element of the routing matrix $\mathcal{X}^l$ corresponding to the arc (i,j) and the commodity $f_+ = (p,q)$, where p and q are the starting and ending nodes of the directed arc l_+ as well as the origin and destination nodes of the commodity f_+. Similarly, $x_{ij}^{l_-,l}$ is the element of the routing matrix $\mathcal{X}^l$ corresponding to the arc (i,j) and the commodity $f_- = (q,p)$, where q and p are the starting and ending nodes of the directed arc l_- as well as the origin and destination nodes of the commodity f_-. The commodities f_+ and f_- have to be created if they do not belong to $\mathcal{F}$.

The model considering failure conditions is then formulated as follows:

$$\min \; u_{max} \tag{11}$$

$$\sum_{f\in\mathcal{F}} is^f x_{ij}^f + \sum_{v\in\mathcal{H}} w_{ij}^v \le u_{max} c_{ij} \qquad (i,j)\in\mathcal{A} \tag{12}$$

$$\sum_{f\in\mathcal{F}} x_{ij}^{f,l} is^f + \sum_{v\in\mathcal{H}} w_{ij}^v + \sum_{v\in\mathcal{H}} \left(x_{ij}^{l_+,l} w_{l_+}^v + x_{ij}^{l_-,l} w_{l_-}^v \right) \le u_{max} c_{ij} \qquad l\in\mathcal{L}, (i,j)\in\mathcal{A}\setminus\{l^+,l^-\} \tag{13}$$

$$\sum_{j:(j,i)\in\mathcal{A}} w_{ji}^v - \sum_{j:(i,j)\in\mathcal{A}} w_{ij}^v = \begin{cases} \sum_{f\in\mathcal{F}(v)} (-d^f + is^f) & \text{if } i = v \\ d^f - is^f & \text{if } i = t(f) \\ 0 & \text{otherwise} \end{cases} \qquad i\in\mathcal{N}, v\in\mathcal{H}, f\in\mathcal{F}(v) \tag{14}$$

$$w_{ij}^v \ge 0 \qquad (i,j)\in\mathcal{A} \;,\; v\in\mathcal{H} \tag{15}$$

$$d^f \ge is^f \ge 0 \qquad f\in\mathcal{F} \tag{16}$$

The $|\mathcal{L}|(m-2)$ constraints (13) are the survivability constraints, whose meaning is pictorially illustrated in Fig. 1. The failure of the (undirected) link $l = \{p,q\} \in \mathcal{L}$ means that the entire flow traversing the link in both directions, represented in the model by the two (directed) arcs $l_+ = (p,q)$ and $l_- = (q,p)$, need to be rerouted. The link restoration protocol thus re-routes all the flow traversing $l_+ = (p,q)$ using the routes defined for the commodity $f_+ = (p,q)$, and, similarly, re-routes the flow traversing $l_- = (q,p)$ using the routes defined for the commodity $f_- = (q,p)$. Of course, (11)—(16) is the aggregated formulation, but the disaggregated one is similar.

The survivability constraints (13) are the most innovative features of the proposed model. Note that they are strictly dependent on the specific re-routing technology (link restoration). In particular, once a link fails, the entire flow along that link is re-routed like a commodity that has origin and destination in the two routers at the extremes of the failed link. The routing is performed using pre-computed paths only dependent on the IS-IS/OSPF metrics. A consequence is that, in case of failure, Proposition (4.1) does not necessarily hold true. In fact, in case of failure, each arc (i,j) may behave differently depending on its usage according to the IS-IS/OSPF protocol or the MPLS-TE technology. In other words, a path P may have a different impact on the maximum arc utilization, when addressing single link failure scenarios, depending on its use according to the IS-IS/OSPF protocol (if that is possible) or in terms of a LSP path.

4.5 Technological remarks

Some technological issues may arise while trying to implement the model and its results in a real network scenario. Moreover, limitations on the routers exist that could make the obtained optimal solution not directly implementable in real world networks.

In fact, in order to correctly configure the primary/backup paths system, a tightly constrained LSP ("elementary LSP") must be configured on each link composing the primary path. Thus, each explicit MPLS-TE LSP obtained from the mathematical model can be seen as "sum" of elementary LSPs. In this way the link restoration scheme can be simply implemented configuring the backup path, on each elementary LSP, by mean of the IGP routing protocol. However, the ECMP mechanism can create implementation issues, because usually a limit of up to 16 equivalent cost paths exists; furthermore, "per-packet round

robin" technique is not implemented by the majority of the routers' vendors. This may lead to some of the model solutions not to be completely implementable in the underlying physical network. However, these technological constraints can be included in the model leading to a sub-optimum whose variation with respect to the optimal solution is easily measurable.

5 Computational results

Three different topologies of telecommunication networks are presented here as test cases of the proposed model. Two of them are synthetic networks, where we considered all possible link failures, i.e., $\mathcal{L} = \mathcal{E}$. The third one is a real backbone network and we took into account all possible fault scenarios but 3 where the failure was an inconceivable event due to strategic decisions.

The tested instances have been prepared using the Jones Lustig format [33]; they have been read using a service class for minimum cost multicommodity flow solvers called "Graph" [34]. A C++ function has been also implemented, which set up the node-arc incidence matrix associated with the graph describing the tested telecommunication networks, passing it to an Open Source solver called OsiSolver [35]. An additional C++ class, which decomposes the flows (aggregated based on their source) into disaggregated flows, has been implemented. All the results have been validated with the commercial simulation software called OPNET Modeler [36].

5.1 Random network

The first test has been performed on a randomly generated synthetic network composed by $n = 8$ nodes and $m = 36$ directed arcs, each of them having a maximum capacity of 1000 Mbps. The total number of commodities is $n(n-1) = 56$; the corresponding model (6)—(10) thus involves 345 variables and 100 constraints, whereas the model with survivability constraints (11)—(16) involves the same number of variables and 712 constraints. The network characteristics are summarized in Table 1, while the logical topology of the network is depicted in Figure 2.

Nodes	8
Arcs	36
Flows	56
Variables	345
Constraints (working condition)	100
Constraints (with survivability)	712

Table 1: Characteristics of the random synthetic network

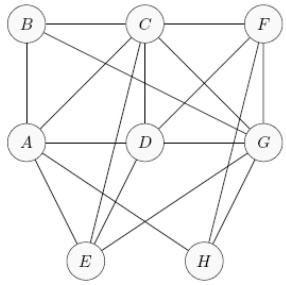


Figure 2: Logical topology of the random synthetic network

The traffic matrix used during the test has been generated aiming to produce congestion over some links in case of single link failures.

As previously mentioned, one input of the models is the set of IS-IS/OSPF metrics. In this instance, two sets of metrics are addressed. The first one consists of the metric default values suggested by the major

router vendors, i.e., unitary values. Note that, in such a case, the shortest paths are those with the minimum number of hops. The second set of metrics is obtained by performing an optimization process using the Tabu Search (TS) metaheuristics algorithm presented in [26], which considers the failure scenarios in the search process.

In Table 2, the maximum utilization is reported under "working condition" and "failure condition". In the first row, the maximum utilization has been evaluated using only the IS-IS/OSPF routing protocol, with unitary default metric values. In the second row, the maximum utilization has been evaluated using again only the IS-IS/OSPF routing protocol, but with metric values optimized by TS. The third row reports the results obtained solving the model (6)—(10) (working condition) and the model (11)—(16) (failure condition), using default metric values as input. The fourth row reports the same results (working condition and failure condition), using as input the IS-IS/OSPF metric values optimized by the TS. In the last column of Table 2, the number of explicit LSPs obtained by solving the LP model (11)—(16) with survivability is reported. The computational time required to solve model (6)—(10) and (11)—(16) is, respectively, 0.58 seconds and 0.89 seconds on a standard PC with a Pentium 4 processor.

	Working Condition	Failure Condition	# LSP
IS-IS/OSPF routing with default metrics	$u_{max} = 34\%$	$u_{max} = 70\%$	0
IS-IS routing with TS optimized metrics	$u_{max} = 29\%$	$u_{max} = 47\%$	0
LP models with default metrics	$u_{max} = 23\%$	$u_{max} = 35\%$	55
LP models with TS optimized metrics	$u_{max} = 23\%$	$u_{max} = 35\%$	48

Table 2: Comparing results for the synthetic network

The obtained results show that the application of the LP models, starting either from the default IS-IS/OSPF metrics or from the TS optimized metrics, produced the same maximum link utilization. Nevertheless, in the last case the number of LSPs reduced. It is important to note that, in case of failure condition, the use of the LSPs reduces the maximum utilization by 50% with respect to IS-IS/OSPF routing with default metrics.

5.2 The IBCN European network

The second benchmark network is part of the Zuse Institute Berlin's (ZIB) SNDlib [37], which is a library of test instances for Survivable fixed telecommunication network design. The instance, related to a capacity planning problem, has been provided by the INTEC Broadband Communication Networks research group (IBCN), which is a research institute founded by the Flemish Government, focusing on Information & Communication Technology (ICT) in general, and applications of broadband technology in particular [38].

The network consists of $n = 37$ nodes widely spread in the European territory, and $m = 114$ directed arcs. The network characteristics are summarized in Table 3, whereas the network topology is shown in Figure 3. The traffic matrix is given as part of the instance with $n(n-1) = 1332$ commodities. The corresponding model (6)—(10) involves 5551 variables and 1483 constraints, whereas the model (11)—(16) with survivability involves the same number of variables and 7867 constraints.

During the test, the capacity of the links has been fixed and the original demands values have been scaled in order to produce congestion over some links in case of single link failure, when the "default" metrics configuration is used.

Nodes	37
Arcs	114
Flows	1332
Variables	5551
Constraints (working condition)	1483
Constraints (with survivability)	7867

Table 3: Characteristics of the IBCN European network

Figure 3: The IBCN network topology

The results for this instance are shown in Table 4, which is organized exactly like Table 2 except that results for the proposed models are only reported for the optimized metrics. The computational time needed to solve model (6)—(10) on a Pentium 4 is 206s, whereas it is equal to 392s to solve model (11)—(16).

	Working Condition	Failure Condition	# LSP
IS-IS/OSPF routing with default metrics	71%	101%	0
IS-IS routing with TS optimized metrics	55%	74%	0
LP models with TS optimized metrics	41%	65%	555

Table 4: Comparing results for the IBCN network

The results show that, in working condition, using the "default" metrics results in a maximum utilization of more than 70% of the link capacity. Using the metrics obtained via the Tabu Search optimization the maximum link utilization is reduced to 55%, with a gain of 22%. Furthermore, jointly using IS-IS and MPLS-TE routing, i.e., solving the model (6)—(10), the maximum link utilization decreases to 41% of the link capacity, yielding a 41% gain with respect to IS-IS/OSPF routing with default metrics, and a 26% gain with respect to that of IS-IS/OSPF routing with TS optimized metrics. This requires setting 822 LSPs (not reported in Table 4); such an operation, however, can be performed in a supervised automatic way, as detailed in the following Subsection 4.5. Figure 4 reports the utilization in the arcs of the IBCN network for the different routing scheme.

The results are even more impressive if the arc utilization for the whole network is examined. The dotted line shows the arc utilization, for each arc, with "default" metrics; the dashed line then shows that, indeed, using optimized metrics allows reducing the peaks with respect to default metrics. However, the arc utilization is still very uneven across the network. The solid line shows that the use of an optimized set of LSPs allows both to reduce the peaks and to very evenly distributing the flows over the whole network, thereby reducing the waste of network resources.

The results follow a similar pattern when the survivability constraints are introduced (third column of

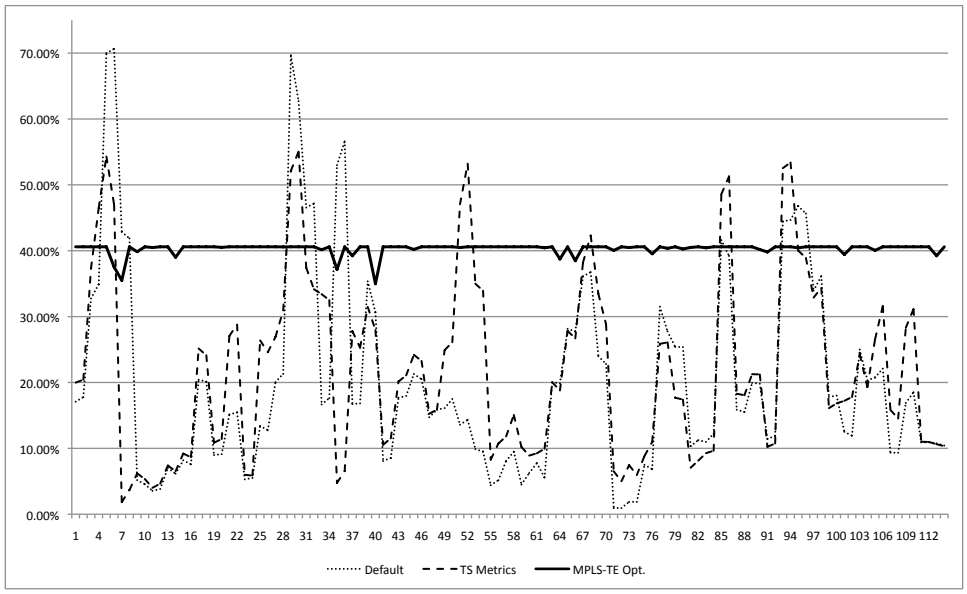


Figure 4: Link utilization using the IS-IS/OSPF routing protocol under working condition (IBCN network)

Table 4). Using only the IS-IS/OSPF routing protocol with "default" metrics results in *network congestion*, i.e., some links have utilization greater than 100%. Using TS optimized metrics already solves the network congestion by bringing the maximum link utilization down to 74%, with a gain of 27%; however, this it is still above the empiric security threshold of the 70% link occupation that is often adopted by network engineers. Finally, jointly using IS-IS/OSPF and MPLS-TE routing, i.e., solving the model (11)—(16), the maximum link utilization reduces to 65%, below the maximum empiric security threshold, with a significant gain of 11% with respect to the IS-IS/OSPF routing protocol with TS optimized metrics, and an even larger 35% gain with respect to IS-IS/OSPF routing protocol with "default" metrics.

Also, the solution provided by the joint routing model is significantly "more robust" than the others. This is shown in Figure 5 which reports, for each of the routing schemes, the objective function value u_{max} for each failure scenario (i.e., for each failed arc). The dotted line shows that, when the link #15 fails, the IS-IS/OSPF routing with default metrics produces a congestion event (u_{max} greater than 100%) with a consequent loss of performance; moreover, when the link #34 fails the maximum link utilization is over 90%. While TS optimized metrics do solve the congestion and near-congestion events (dashed line), there is still a significant difference, to the tune of 15%, between the maximum arc utilization corresponding to different failures; this means that the impact of different failures on the network performances can be rather unequal. Conversely, the solid line shows that the joint routing (with TS optimized metrics) not only further improves the maximum network utilization, but also ensures that the maximum utilizations corresponding to two distinct failures will not differ by more than 5%.

5.3 A Real Italian ISP Backbone Network

The third instance refers to the Italian portion of Tiscali International Network (TINet) [39]. The network is composed of 18 nodes and 54 arcs with different capacity ranged from 1 Gbps to 2.5 Gbps. The traffic matrix, composed of 306 commodities, has been built thanks to the willingness and the collaboration of the ISP's network operators and managers. The corresponding LP model (6)—(10) involves 1279 variables and 378 constraints, whereas the LP model (11)—(16) with survivability involves the same number of variables and 1782 constraints. The characteristics of the TINet network are summarized in Table 5, while the whole Tiscali International Network logical topology is depicted in Figure 6.

The results for this network are reported in Table 6, which has a similar structure to the previous ones except that it also reports the case where the metrics are those used, at the time of the tests, by the TINet network operators in normal working condition. The computation time needed to solve models (6)—(10) and

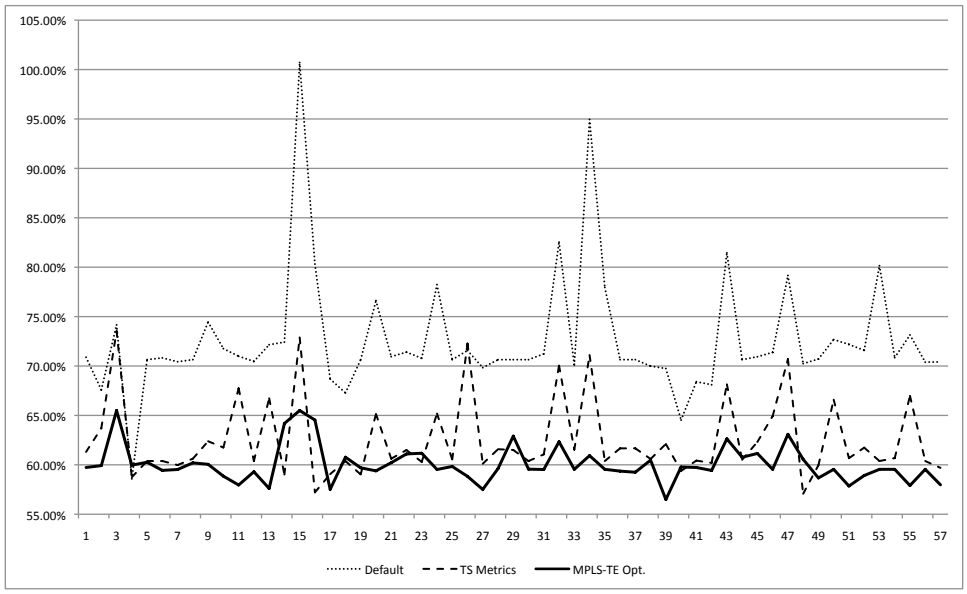


Figure 5: Objective function value u_{max} in case of single link failure (IBCN network)

(11)—(16) are, respectively, 8.09 seconds and 12.4 seconds on a standard PC with a Pentium 4 processor.

Figure 6: Tiscali International Network

Nodes	18
Arcs	54
Flows	306
Variables	1279
Constraints	378
Survivability Constraints	1782

Table 5: Characteristics of the TINet Italian backbone

The results show that a suitable choice of the metrics is necessary to avoid network congestion events if only the IS-IS/OSPF routing protocol is used, as neither the default metrics nor those set by experts can withstand all possible single-link failures. In this case, jointly using IS-IS/OSPF and MPLS-TE routing, i.e., solving the model (6)—(10), while attaining visible improvements of 13% and 7% with respect to the

	Working Condition	Failure Condition	# LSP
IS-IS/OSPF routing with default metrics	72%	128%	0
IS-IS/OSPF routing with TINet metrics	66%	117%	0
IS-IS routing with TS optimized metrics	61%	85%	0
LP models with TS optimized metrics	59%	83%	86

Table 6: Comparing results for the Tinet network

IS-IS/OSPF routing with default metrics and TINet metrics, respectively, only improves by 2%, in working conditions with respect to TS optimized metrics; all this as the "cost" of setting 105 LSPs (not shown in the Table). This is confirmed by Figure 7 which reports the utilization in the arcs of the TINet network for the different routing schemes; while link utilization is indeed slightly lower and somewhat more evenly distributed with the joint routing scheme, the effect is by far less visible than in the previous case.

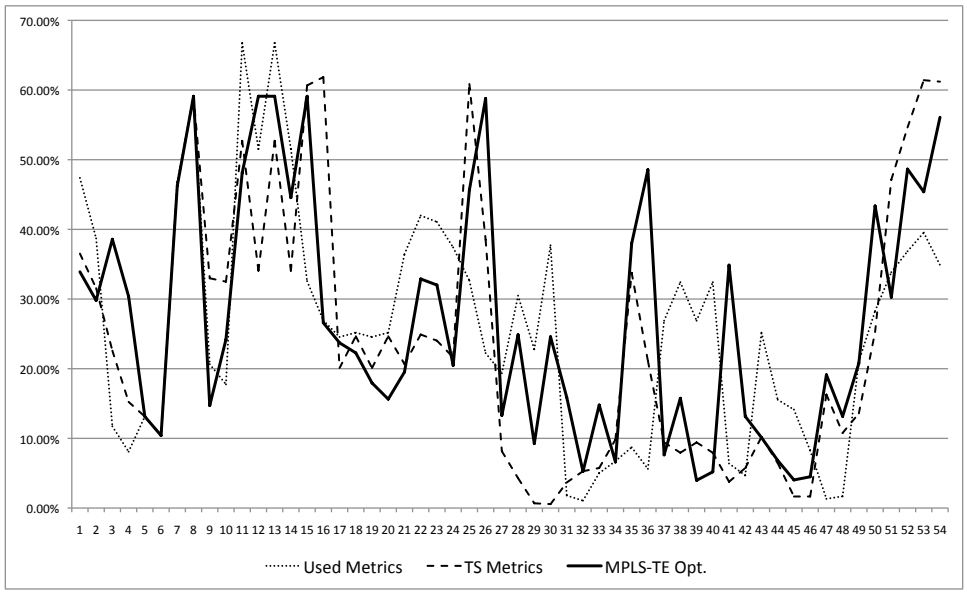


Figure 7: Link utilization under working condition (TINet network)

A similar pattern is again visible when single-link survivability is examined. TS optimized metrics offer a very substantial improvement over default and hand-tuned ones; in Figure 8 the dotted line shows that, when the links #2 and #3 fail, the network using TINet metrics suffers a severe congestion event, while the optimized metrics always attain maximum utilization under 85% (dashed line). Using the LP model (11)—(16) further slightly reduces the maximum link utilization, and "smoothes" the network response to single-link failures (solid line); however, this effect is less striking than in the IBCN network.

6 Conclusions

In this paper we addressed the problem of minimizing the maximum link utilization under the joint use of the IS-IS/OPSF routing protocol and of the MPLS-TE technology. A Linear Programming model has been formulated, which considers both working condition and single link failure scenarios. To the best of our knowledge, this is the first exact approach proposed in the literature that embeds in a unique overall model the two different technologies providing 100% survivability in failure conditions.

By using an off-the-shelf open source LP solver, optimal configurations using IS-IS/OSPF routing protocol with complementary MPLS-TE LSPs are obtained in short time on a standard PC. Hence, the model is beneficial for Quality of Service routing for traffic with particular performance requirements. Moreover,

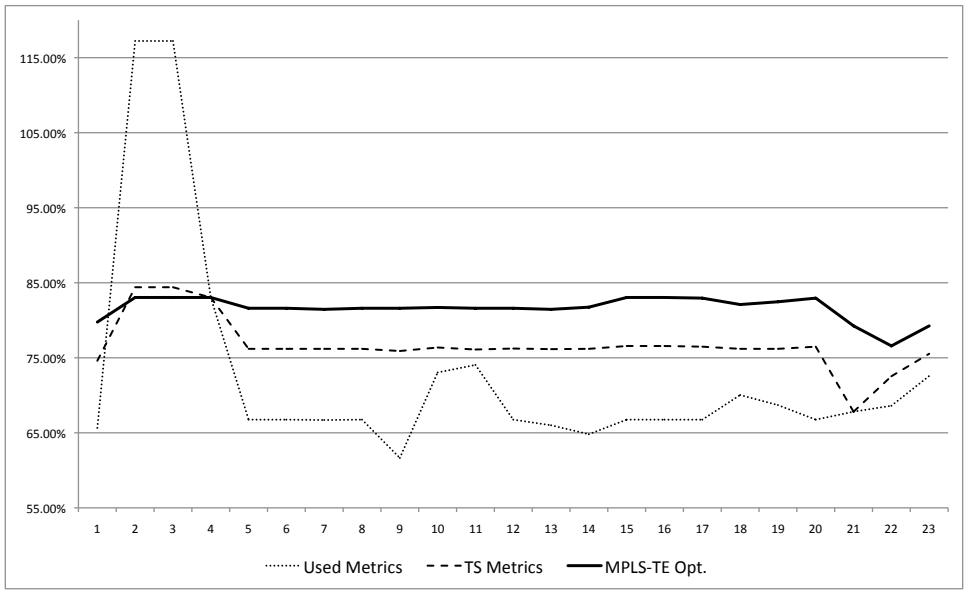


Figure 8: Objective function value u_{max} in case of single link failure (TINet network)

survivability of the service delivery is guaranteed following Link Restoration scheme. The model solution is obtained in nearly real time even for real telecommunication networks; by contrast, the time required for finding optimized IS-IS/OSPF metrics is much higher, reflecting the inherent difference in complexity between the two problems. Furthermore, it is possible to implement the results of the model with a very limited intervention of the network operators.

The obtained results show that the proposed model can attain good levels of network utilization in the tested instances, compared to the network utilization achievable via the more traditional IGP routing protocols. In fact, due to the static nature of the IGP routing algorithms, using IS-IS/OSPF protocols the traffic is mostly routed on the least cost paths, sometimes causing the congestion of some links, while leaving other links lightly loaded. On the contrary, MPLS-TE can route the traffic through explicit paths, optimizing network resources utilization and traffic performance, by distributing the flows over the whole network and reducing waste of resources.

The paper demonstrates the suitability of the proposed optimization approach, which reduces the utilization of the links with respect to configurations based on network operator experience. The use of the model may be relevant in economic terms because the better utilization of network resource it entails may reduce and/or delay the investments required to upgrade the network.

7 Acknowledgement

This work has been partially supported by Tiscali S.p.A within the framework of the ICE Lab (Information and Communications Engineering Academy joint Laboratory). The authors would like to thank Mr. Paolo Susnik and Mr. Giorgio Lembo for supporting the work, and for the useful discussions.

References

[1] L. Li, M. Buddhikot, C. Chekuri, and K. Guo, "Routing Bandwidth Guaranteed Paths with Local Restoration in Label Switched Networks," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, 2005.

[2] E. Yetginer and E. Karasan, "Robust path design algorithms for traffic engineering with restoration in mpls networks," in *ISCC '02: Proceedings of the Seventh International Symposium on Computers and Communications (ISCC'02)*. IEEE Computer Society, 2002, p. 933.

[3] M. Medrano, M. Trinidade, N. de Cheves, M. Fernandez, and H.J.M.Filho, "An Optimization Model for MPLS Networks," in *Proc. of* 11th *International Telecommunications Network Strategy and Planning Symposium, NETWORKS 2004, Vienna, Austria*, June 2004.

[4] S. Beker, N. Puech, and V. Friderikos, "A Tabu Search heuristic for the offline MPLS reduced complexity layout design problem," in *Networking*, 2004, pp. 514–525.

[5] S. C. Erbas and C. Erbas, "A multiobjective off-line routing model for MPLS networks," in *Proc. of the 18th International Teletraffic Congress*, 2003.

[6] A. Riedl, "Optimized routing adaptation in IP networks utilizing OSPF and MPLS," in *IEEE 2003 International Conference on Communications (ICC), Anchorage, USA, May 2003*, May 2003.

[7] F. Skivée, S. Balon, and G. Leduc, "A scalable heuristic for hybrid IP/MPLS traffic engineering - case study on an operational network," in *Proc. of IEEE International Conference on Networks (ICON)*. IEEE Press, September 2006.

[8] S. Balon, J. Lepropre, O. Delcourt, F. Skivée, and G. Leduc, "Traffic engineering an operational network with the totem toolbox," *IEEE Transactions on Network and Service Management (TNSM)*, vol. 4, pp. 51–61, 2007.

[9] B. Fortz and M. Thorup, "Internet traffic engineering by optimizing OSPF weights," in *in Proc. IEEE INFOCOM*, 2000, pp. 519–528.

[10] J. Lenstra and A. Rinnooy-Kan, "On general routing problems," *Networks*, vol. 6, pp. 273–280, 1976.

[11] in *Network Routing*, ser. Handbooks of Operations Research and Management Science, M. Ball, T. Magnanti, C. Monma, and G. Nemhauser, Eds. North Holland, 1995, no. 8.

[12] S. Balon, F. Skivée, and G. Leduc, "Comparing traffic engineering objective functions," in *CoNEXT '05: Proceedings of the 2005 ACM conference on Emerging network experiment and technology*. ACM, 2005, pp. 224–225.

[13] E. Dijkstra, "A note on two problem in connexion with graphs," *Numerische Mathematik*, vol. 1, pp. 269–271, 1959.

[14] "Requirements for Traffic Engineering Over MPLS," RFC 2702. [Online]. Available: http://www.ietf.org/rfc/rfc2702.txt

[15] G. Iannaccone, C. Chuah, R. Mortier, S. Bhattacharyya, and C. Diot, "Analysis of link failures in an IP backbone," in *Proc. of ACM SIGCOMM Internet Measurement Workshop 2002, Marseille, France, Nov 2002*, Nov 2002.

[16] A. Markopoulou, G. Iannaccone, S. Bhattacharyya, C. Chuah, and C. Diot, "Characterization of failures in an IP backbone," in *IEEE Infocom 2004, IRC-TR-04-015, Hong Kong, China, March 2004*, 2004.

[17] B. Fortz and M. Thorup, "Robust optimization of OSPF/IS-IS weights," in *In Proc. International Network Optimization Conference (INOC)*, 2003, pp. 225–230.

[18] M. Ericsson, M. Resende, and P. Pardalos, "A genetic algorithm for the weight setting problem in OSPF routing," *Combinatorial Optimization*, vol. 6, pp. 299–333, 2002.

[19] E. Mulyana and U. Killat, "A Hybrid Genetic Algorithm Approach for OSPF Weight Setting Problem," in *Peroc. of the* 2nd *Polish-German Teletraffic Symposium PGTS*, 2004.

[20] L. Buriol, M. Resende, C. Ribeiro, and M.Thorup, "A memetic algorithm for OSPF routing," in *Proc. of the* 6th *INFORMS Telecom*, 2002, pp. 187–188.

[21] J. Harmatos, "A heuristic algorithm for solving the static weight assignment optimisation problem in OSPF networks," in *Proc. of of Global Internet Conference*, 2002.

[22] A. Elwalid, C. Jin, S. H. Low, and I. Widjaja, "MATE: MPLS adaptive traffic engineering," in *INFOCOM*, 2001, pp. 1300–1309.

[23] A. Elwalid, C. Jin, S. Low, and I. Widjaja, "Multi-path adaptive traffic engineering," *Computer Networks*, vol. 40, pp. 695–709, 2002.

[24] A. Nucci, B. Schroeder, S. Bhattacharrya, N. Taft, and C. Diot, "IGP link weight assignment for transient link failures," in 18th *International Teletraffic Congress*, Berlin, Germany, 2003.

[25] D. Yuan, "A bi-criteria optimization approach for robust OSPF routing," in 6th *IEEE Workshop on IP Operation Management (IPOM)*, 2003.

[26] D. Cherubini, A. Fanni, and C. Murgia, "IS-IS/OSPF weights optimization for survivable backbone networks: a Tabu Search metaheuristic approach," in *OPNETWORK 2006, Washington DC*, 2006.

[27] L. S. Buriol, M. G. C. Resende, and M. Thorup, "Survivable IP network design with OSPF routing," *Networks*, vol. 49, no. 1, pp. 51–64, 2007.

[28] Y. Liu and D. Tipper, "Spare capacity allocation for non-linear cost and failure-dependent path restoration," in *Proceeding of the* 3rd *International Workshop on Design of Reliable Communication Networks, DRCN*, 2001.

[29] R. Ahuja, T. Magnanti, and J. Orlin, *Network flows: theory, algorithms, and applications.* Upper Saddle River, NJ, USA: Prentice-Hall, Inc., 1993.

[30] A. Frangioni and G. Gallo, "A Bundle Type Dual-Ascent Approach to Linear Multicommodity Min Cost Flow Problems," *INFORMS Journal on Computing*, vol. 11, no. 4, pp. 370–393, 1999.

[31] B. Fortz and M. Thorup, "Optimizing ospf/isis weights in a changing world," *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, vol. 20, pp. 756–767, 2002.

[32] G. Woeginger, *Personal Communication*, 2006.

[33] "Jones Lustig Format for Multicommodity Flow Problems." [Online]. Available: www.di.unipi.it/di/groups/optimize/Data/MMCF.html

[34] "Graph." [Online]. Available: sorsa.unica.it/crifor/it/software.php

[35] "OsiSolver." [Online]. Available: www.coin-or.org

[36] "OPNET." [Online]. Available: www.opnet.com

[37] "ZIB - SNDlib." [Online]. Available: sndlib.zib.de/home.action

[38] "INTEC Broadband Communication Networks research group (IBCN)." [Online]. Available: www.ibcn.intec.ugent.be

[39] "Tiscali International Network." [Online]. Available: www.tiscali.net