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ROUTING ALGORITHMS IN SURVIVABLE TELECOMMUNICATION NETWORKS

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PhD Thesis Summary

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1 Introduction

The modern communication networks are equipped with ultra-high speed switches to meet the dynamically changing traffic demands. In backbone networks, connection requests are launched dynamically from the upper layers, for which routing algorithms are used to derive the corresponding bandwidth guaranteed tunnels that meet all the Quality-of-Service requirements [1]. According to TeleChoice [2], offering a robust platform with strong traffic engineering mechanisms and QoS functions leads the carrier (and its customers) to a revenue-generating environment. The long-term telecom survivors will be those who can find the balance between the technological innovation, improved customer service, and the efficient allocation of network resources. Streaming video, voice and other broadband services can be pushed to the edges by receiving priority over the others for achieving better QoS services than that by less time-sensitive applications (including e-mail). Survivability has been one of the most important QoS issues, and survivable routing is recognized as one of the best strategies to equip the networks with service continuity by pre-planning link-disjoint or node-disjoint protection paths for working capacity [3, 4, 5, 6, 7, 8, 9, 10]. With a diversely routed working-protection path-pair, once the working path unexpectedly fails, the working traffic is switched to the protection path and the corresponding service is restored.

Due to the numerous QoS constraints the routing problem is NP-hard; thus, most of the papers presented approximation algorithms for solving the problem. Some of them are published in the mathematical conferences and journals; with theoretical polynomial time algorithms, which have some restrictions on topology and approximate the problem within a factor. The others are published in telecommunication conferences and journals based on effective heuristics, which solve the problem by assigning a sophisticated cost function to the edges and use shortest path search to approximate the problem.

Since the optimization problem is really complex, even the corresponding sub-problems are NP-hard, which has caused a huge gap in the research fields among different research groups.

In the theoretical papers [11, 12, 13] the network topology has to be restricted to ring, line or star to get polynomial time algorithms to solve the problem. These restrictions make the results useless in the modern mesh telecommunication networks. Some other papers investigate the approximation factors of the proposed algorithms. Due to the high complexity getting a constant approximation factor (e.g., of 2) is considered to be a significant theoretical result. Unfortunately, these methods do not perform well in the simulations. On the other hand, the reported *heuristics* do not contain many mathematical results, although they perform well in simulations [3, 4, 5, 6, 7, 8, 9, 10].

The objective of this PhD dissertation was to provide a compromise and fill up the gap between the research fields. The problems are formulated using mathematical models; with which some necessary properties of the problem can be deduced and the performance of the heuristics can be improved. Exponential algorithms to evaluate the performance of the heuristics are also introduced in the thesis. The results are classified in three areas, which are based on each other.

The thesis will firstly investigate shared protection in mesh telecommunication networks. Linear algebra is used to subdivide the whole problem into sub-problems for formulating a new heuristic. A similar topic was investigated in [14] using probability theory, however they do not restrict to the single link failure case to optimize the connection cost based on the edge costs given by Traffic Engineering.

Shared Segment Protection (SSP) is the second topic investigated in the thesis. The Integer Linear formulation for SSP used to be an open problem, and the thesis provides a solution that can derive the optimal answer. The formulation is extended to respect several QoS properties. The impacts on the performance applying different QoS constraints are also investigated.

The thesis also focuses on the distributed routing algorithms. An new algebraic way to investigate the performance of different distributed control architectures for shared protection is introduced. Using this mathematical model a classification of these results is suggested. A performance evaluation with simulation is conducted to verify the proposed distributed control architecture.

2 Research Objectives

The objective of this dissertation is to study the performance of routing algorithms in survivable mesh telecommunication networks. The complexity and mathematical models are analyzed and formulated to solve the arising open problems. Most of the algorithms introduced in this thesis have exponential running time, and they help to understand the effects of the individual QoS criteria that match the need by the modern communication industry.

This dissertation focuses on path protection in circuit switched mesh backbone networks with single failure scenario. It is mainly applicable on single-layer circuit-switched and virtual circuit-switched networks, like MPLS, ATM, SDH/SONET, Next Generation SDH/SONET and ASON.

Networks with Multi-Protocol Label Switching (MPLS) and Asynchronous Transfer Mode (ATM) are virtually circuit-switched. ATM has been largely adopted by legacy networks developed in the late 1980s and early 1990s and the MPLS architecture can be seen as an extension of ATM, and it has been used to introduce QoS schemes in the IP networks. Networks with Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH), Next Generation SDH/SONET and Dense Wavelength Division Multiplexing (DWDM) are circuit-switched, where SONET/SDH is one of the main underlying transport technologies supporting telephone systems, while DWDM is also a circuit-switched technology with optical circuit-switched connections known as lightpaths. Generalized Multi-Protocol Label Switching (GMPLS) defined by Internet Engineering Task Force (IETF) aims to cope with the extremely complex multilayer architecture that has been cobbled together to carry IP services over networks designed to support voice and fixed circuits. GMPLS can be deployed in the following two ways: either the overlay model or the peer model. In the overlay model, User-Network Interface (UNI) is defined, where the router is a client to the optical domain and interacts only with the directly adjacent optical nodes. The actual physical lightpaths are routed/initiated by the carrier of the optical core instead of by the users. Since the routing algorithms introduced in the dissertation are mainly designed to work in a single domain, they are more suitable to the network environments with the overlay model rather than that adopting the peer model. The International Telecommunications Union-Telecommunications (ITU-T) has introduced two protocol-independent framework models: the general Automatic Switched Transport Network (ASTN) and the Automatic Switched Optical Network (ASON). Since GMPLS can be mapped to ASTN/ASON models, it may well become the adopted standard for such implementations. The ASTN/ASON model focuses on providing the optical transport network with an intelligent optical control plane, incorporating dynamic network provisioning combined with network survivability, protection, and restoration.

To study diverse routing, the concepts of Shared Risk Groups (SRGs) [4] are introduced. SRG is defined as a group of network elements (i.e., links, nodes, physical devices, software/protocol identities, etc) subject to the same risk of single failure. In the single link failure scenario the task is to establish connections in the network such that there is a restoration strategy to survive one SRG failure in the network. The SRG-disjointness for both dedicated protection and shared protection is defined [4].

In summary, the main objectives of this dissertation are as follows:

- The survivable routing algorithms developed should increase the total throughput of the networks by establishing dynamic connections requests with fairness. (The target

function of routing each connection request is based on the edge costs given by the Traffic Engineering [15])

- The survivable routing algorithms should be developed for shared protection with single link failure scenario. The restoration time is a focus in the design.
- The network model should be extended to be able to deal with different cross-connect types.
- The routing algorithms developed should reduce the signaling overhead of the network.
- Test methods should be investigated for performance evaluation.
- Effective and fast approximate methods should be developed to solve the arisen sub-problems.

3 Research Methodology

The networks are modeled by graphs. Several graph algorithms (Minimum Cost Network Flow, Suurballe's algorithm [16], Dijkstra's algorithm [17, 18], Multi-commodity Network flow [19], algorithm to calculate Gomori-Hu tree [20], etc) are implemented and used in the simulations. Flows and cuts in the graphs play an important role of the design strategy of the routing algorithms.

Integer Linear Programming (ILP) [21] is used to formulate the NP-hard problems and commercial softwares e.g. CPLEX [22] and LP-Solve [23] for solving instances of ILP formulations.

In Claim 3 algorithms of linear algebra (i.e., matrix transformations like SVD [24]) are used to clarify the background of routing heuristics.

For performance evaluation I developed a simulator tool. All results of the PhD thesis have a strong motivation from the telecommunication industry, however I took the approach of complexity theory also into consideration.

4 New Results

The results are classified in three areas.

Claim 1 : Shared Path Protection (SPP) in Mesh Communication Networks with Bandwidth Guaranteed Tunnels

The key idea of shared protection is that the protection path of different working paths can reserve the same spare channels if their working paths are not involved in a common SRG. The task is to calculate the least-cost working (W) and shared protection (P) path-pair between node s and t with bandwidth $b(W)$ such that the capacity allocation is minimal weighted by given edge costs (c_e). Complete routing information scenario is applied, in other words full per-flow information (the route of working and protection path) is provided to each network node.

In shared path protection given a network $G(N, E)$ with N and E being the set of nodes and bidirectional links, respectively. The capacity along link j is categorized into the following three types as shown in Fig. 1:

1. Free capacity (denoted as f_j), which is the link capacity that can be taken as either working or spare capacity.
2. Working capacity (denoted as q_j), which is the capacity taken by some working paths and cannot be taken for any use until the corresponding working paths are torn down.
3. Spare capacity (denoted as v_j), which is the link capacity taken by some other protection paths. With the presence of W , the spare capacity along link j can be further categorized into the following two types
 - (a) Sharable spare capacity (denoted as h_j^W), which is the link capacity that has been taken by some other backup paths, and is sharable to P .
 - (b) Non-sharable spare capacity (denoted as s_j^W), which is the link capacity that has been taken by some other protection paths, and is not sharable to P due to the SRG constraints.

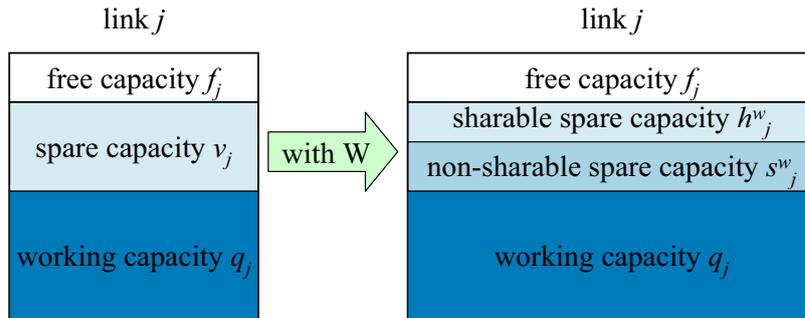


Figure 1: An illustration of categories of capacity along link j .

The spare provision matrix (denoted as \underline{S}) was introduced in [4]; it carries all pre-flow information for the dependency of working and spare capacity between each pair of links. \underline{S} is an $|E| \times |E|$ matrix, where the entry $s_{l,j}$ stands for the amount of spare capacity along link j required by the working capacity along the link l . \underline{S} can be derived off-line (i.e., before the connection request is launched); and s_j^W can also be derived by finding the maximum of the spare capacity along all the links $l \in W$, i.e.,

$$s_j^W = \max_{l \in W} \{s_{j,l}\} \quad (1)$$

I provide a compact mathematical formulation for shared protection with the most general definition of the SRG, that can consider both link- and node-protection as well. A unified expression of the cost functions for both working and protection paths is also derived. Using the formulation I proposed the following two new methods:

Claim 1.1 Two Step Approach with Asymmetrically Weighted Disjoint Path-Pair

The most widely used shared protection heuristic is a two step approach called "2D" (Two Dijkstra's) [3, 6, 8, 25]. In the first step the shortest path is routed as the working path. In the second step, an SRG-disjoint protection route is selected to permit sharing of the protection capacity on links of the protection route, if the working paths belonging to them have no SRGs in common. This scheme is currently favored in IETF deliberations for MPLS-layer protection and MPLS-controlled optical path protection [25]. It is advantageous in distributed implementation, and the protocol is less complex [3]. One of the big disadvantages of the two step approach is the existence of trap topology. In trap topology the working path may block all the possible SRG-disjoint protection paths even though the network topology is two connected. In other words the second step may fail after choosing a bad working path, since no other SRG-disjoint path is available in the network (see also simulation results in [26],[25]). The main purpose of this section to solve this dilemma.

For easier understanding in this claim we will assume to have an MPLS network model and the SRGs will be the links of the network. In other words the network is protected against link failure.

One possible solution is to use Suurballe's algorithm [16], which derives a disjoint path pair with a minimum total bandwidth allocation. Choosing the shorter route as a working path, the protection path is guaranteed. In our experience to have a short working path is more crucial than the length of the protection path, since the working path has to be allocated for the full bandwidth of the demand in the network, while the protection route may be shared with other protection routes. In [C13, 27, 28] a

problem called the asymmetrically weighted disjoint path-pair problem was defined in the following way:

$$\text{minimize: } \{\alpha \cdot \text{cost}(W) + \text{cost}(P)\}$$

where the cost of the working path is denoted by $\text{cost}(W)$, the cost of the protection path is denoted by $\text{cost}(P)$ and alpha is a given parameter.

In the claim a new two-step-approach called the "alpha method" [C12] is introduced, where in the first step an asymmetrically weighted path-pair is calculated with a pre-defined α parameter. The shorter path is chosen as a working path. According to the cost function defined in the introduction, the estimated $\frac{1}{\alpha}$ parameter will be the average of $\max\left\{1 - \frac{v_j - h_{j,l}}{b(W)}, 0\right\}$.

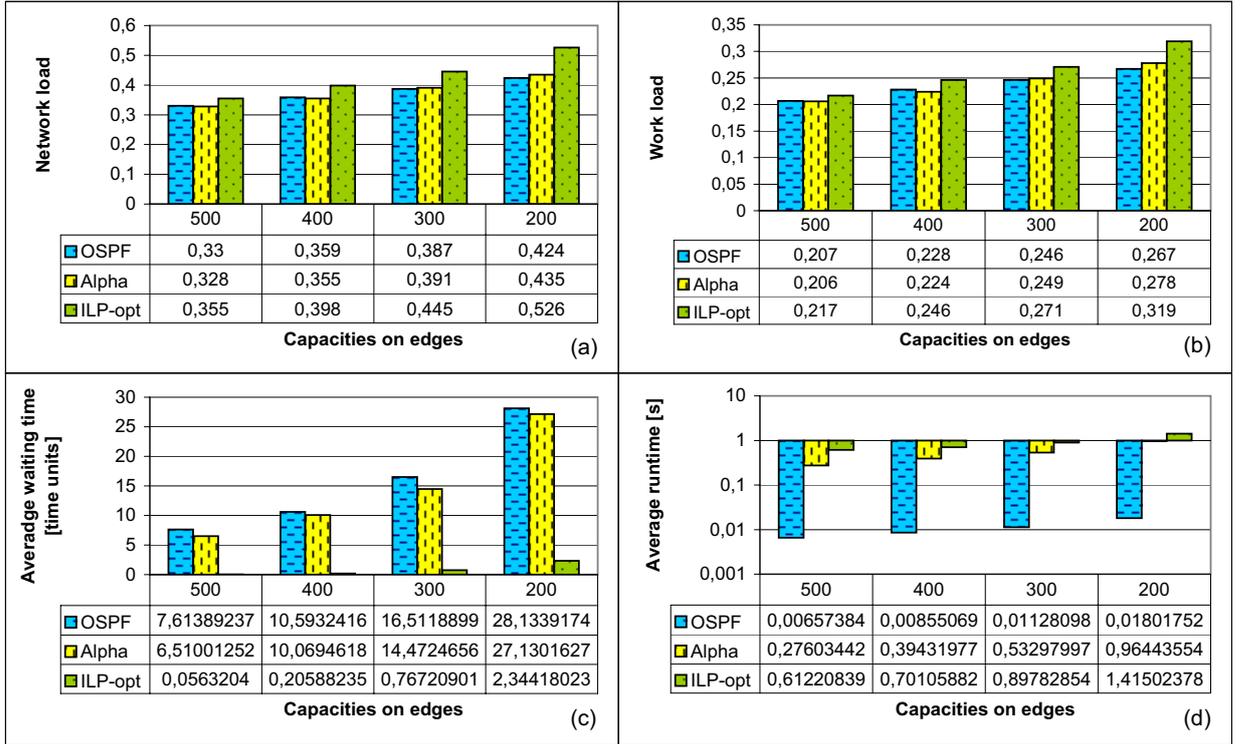


Figure 2: Simulation results of different two-step approach schemes of shared protection

Fig. 2. shows the performance comparison of the different schemes. In the simulations if a connection request cannot be established immediately, it has to wait until some other connections are taken down and the required spare capacity is available. Note that it does not necessarily mean that other connections are not established during this waiting period. As an overall performance metric the average and the maximal waiting time of establishing connections was evaluated.

Claim 1.2 Two-Step-Approach with Maximum Likelihood Relaxation (MLR)

MLR scheme is a two-step-approach, which selects the working path with a modified Dijkstra's algorithm carrying/handling some additional information during Dijkstra's relaxation process. The main idea for MLR is to select the working path such that *the number of links without enough sharable spare capacity* and the working link cost are jointly considered. The links in the network with enough sharable spare capacity for being the protection path of a working path are called "Easy Links".

During Dijkstra's relaxation process, when node n is labeled through link (x, n) by node x , a new working path segment is formed from source node s to node n passing through node x (denoted as $\pi(s, x) \cup (x, n)$). We have the following relationship:

$$s_j^{\pi(s,x) \cup (x,n)} \geq s_j^{\pi(s,x)} \quad \forall j \in A \text{ and } \forall n \in V \text{ is not on the path segment } \pi(s, x) \quad (2)$$

for the definition of $s_j^{\pi(s,x) \cup (x,n)}$ and $s_j^{\pi(s,x)}$ see Eq. (1). Eq. (2) holds since when node x gives a temporary label to node n and the resultant path segment $\pi(s, x) \cup (x, n)$, the working paths passing through link (x, n) are newly included into the SRG, which yields a fact that some sharable spare capacity in the network may become non-sharable along some Easy Links for $\pi(s, x)$.

Based on the above discussion, it is clear that during the relaxation process, the amount of sharable spare capacity less and the number of Easy Links decrease. Therefore, one of the objectives in the proposed Dijkstra's relaxation process is to find a working path, which maximizes the number of Easy Links. In addition, we need to consider the cost of each link, $c_{a,b}$, for $(a, b) \in E$, such that having a long working path is discouraged. The label (denoted as $l(n)$ for node n) given by node x in the Dijkstra's relaxation process is defined as the *link cost $c_{x,n}$ divided by the logarithm of the number of Easy Links for $\pi(s, n)$* . The label replacement at node n by node x will be performed in such a way that $l(n)$ is the minimal; i.e.,

$$l(n) = \min\{l(n), l(x) + \frac{c_{x,n}}{\log(\text{offset}(x, n) + 1)}\}, \quad (3)$$

where $\text{offset}(x, n)$ is the reduction on the number of Easy Links for $\pi(s, x) \cup (x, n)$. We have an expression for $\text{offset}(x, n)$ as follows:

$$\begin{aligned} \text{offset}(x, n) = & \left\{ \sum_{j \in A} \text{stp}(\varphi_j^{W'}) \mid \varphi_j^{W'} \leftarrow v_j - \max_{l \in W'} s_{l,j} - b(W), \text{ where } W' = \pi(s, x) \right\} - \\ & \left\{ \sum_{j \in A} \text{stp}(\varphi_j^{W'}) \mid \varphi_j^{W'} \leftarrow v_j - \max_{l \in W'} s_{l,j} - b(W), \text{ where } W' = \pi(s, x) \cup (x, n) \right\} \end{aligned}$$

where the function $\text{stp}(x)$ returns 1 if $x \geq 0$, and 0 otherwise. Both v_j and $s_{l,j}$ were introduced in the introduction of Claim 1.

The algorithm proceeds as follows: at the beginning, $l(n) = 0$ for $n = s$ and $l(n) = \infty$ otherwise. The extra information other than the ordinary Dijkstra's relaxation process required to be recorded is an $|E|$ times $|\pi(s, x)|$ size array storing $s_{l,j}$, where $l \in \pi(s, x)$ and $j \in E$. When the relaxation process attempts to replace the label of node n from node x , the "MAX" operation for the array storing $s_{l,j}$ will have to be performed for $l \in \pi(s, x)$ and $l \in \pi(s, x) \cup (x, n)$ so that Eq. (3) remain valid. In addition, when a node is relaxed, the array storing $s_{l,j}$ is also updated.

The time complexity in implementing the MLR algorithm is $O(|E| \cdot |N|^2 \cdot \log |N|)$ in the worst case. The MLR method cannot guarantee the derivation of the best working and shared protection path-pair. However, the computation efficiency can be tremendously improved compared to the other two schemes proposed in [J1].

Claim 2 : Shared Segment Protection (SSP) in Mesh Communication Networks with Bandwidth Guaranteed Tunnels

With the emergence of some commercial applications and delay-sensitive services addressing stringent requirements on data integrity and service continuity, the design of survivable routing algorithms should not only be both capacity- and computation-efficient,

but should also minimize the *restoration time* for a specific connection, such that the maximum benefits can be gained in the operation of carrier networks.

SSP is one of the best approaches to meet the above design requirements, where a connection is provisioned by concatenating a series of protection domains, each of which contains a working and protection segment-pair behaving as a self-healing unit for performing local restoration when the working segment is subject to any unexpected interruption. As shown in Fig. 3, when the working path segment of protection domain 2 is impaired unexpectedly (e.g., either link E-F, F-G, G-H, or H-I is cut), the restoration is performed locally within protection domain 2 such that the affected flow is switched over to the backup segment at node E (called switching node of the protection domain) and merges back to the original working path at node J (called merging node of the protection domain).

Compared to its counterpart – shared path protection [3, 4, 5, 6, 7, 8, 9] shared segment protection has been reported to achieve a better throughput by maximizing the extent of spare capacity resource sharing [4, 10]. It can also impose a stringent limitation on the restoration time for a specific application by constraining the length/hop-count of the working and protection segment in each protection domain.

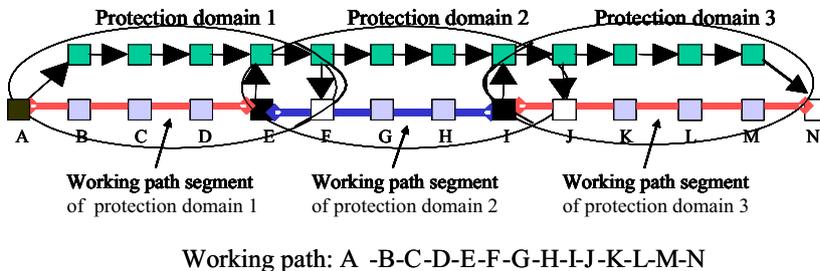


Figure 3: An illustration of SSP.

Claim 2.1 ILP Formulation of Segment Shared Protection

The benefits of SSP was well-known, however there was no method to calculate the optimal solution. The ILP formulation of SSP, which jointly optimizes the route of the working path, the location of switching and merging nodes and the route of the protection path of each segment, was an open problem. I formulated the problem in the following way [J2, C1, C10]:

The main idea is to define a path Q , called *mass protection path*, which defines the route of each protection segment as well as the switching and merging nodes of W . Similar to Suurballe’s [16] algorithm, Q is composed of the reversed links along the working path and all the backup segments. A simple example is shown in Fig. 4, where Q is (s-a-b-c-e-d). The first protection domain is formed by the working and protection segments (s-c-b) and (s-a-b), respectively; while the second is formed by (c-b-d) and (c-e-d), respectively. We allow the overlapping between the working segments of two neighbor protection domains in order to explore the largest design space so as to guarantee the optimality of the derived solution. Note that Q may contain loops to reflect the fact that spare capacity sharing can happen between two protection segments of different protection domains. Variable k_{max} is defined as a parameter of the ILP and represents maximum number of protection domains that can be possibly handled in the problem (it is $\leq n - 1$).

Three residual graphs are defined for solving this problem:

- $G_w(N, E_w)$ is composed of links with $b(W) \leq f_j$ for $j \in E_w$ (in the following formulas

x is a binary, \hat{x} is a real and x^k are k_{max} binary variables assigned to arcs of G_w , and describes the working segments.

- $G_p(N, E_p)$ is composed of all the links $b(W) \leq f_j + v_j$ for $j \in E_p$ (in the following formulas y^k is k_{max} binary and r' is real variable assigned to the arcs of G_p) and describes the protection segments. We need this graph to record the spare link-state because working and protection paths take different suites of link-state with shared protection.
- $G'_p(N, E'_p)$ is composed of all the links in E_p along with the links of E_w in a reversed direction. The “reversed” arcs corresponding to E_w in E'_p are denoted as $(\overleftarrow{a, b})$, and all the others (corresponding to E_p) are $(\overrightarrow{a, b})$. The graph is assigned to Q and handles the reverse arcs caused by the overlapping between Q and W . (in the following formulas y' is an integer, \hat{y} is a real and y is a binary variable assigned to the edges of G'_p).

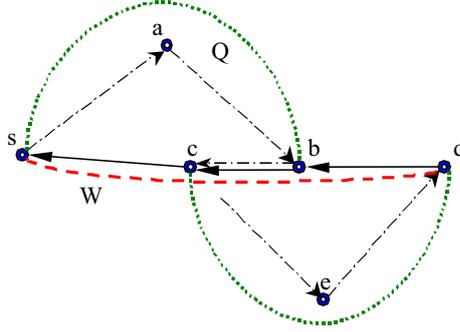


Figure 4: Design of mass protection path q .

$x_{a,b}$ and $y_{a,b}$ are flow indicators of path W and Q , and y^k is for the protection route of segment k . The target function is as follows:

$$\text{Minimize } \sum_{(a,b) \in E_w} b(W) \cdot c_{a,b} \cdot x_{a,b} + \sum_{(u,v) \in E_p} (b(W) \cdot c_{u,v} \cdot z_{u,v} + \varepsilon) \cdot y_{u,v} \quad (4)$$

where $c_{a,b}$ is the cost per unit of working bandwidth to reserve arc (a, b) and $z_{u,v}$ is a scaling factor representing the amount of capacity, which cannot be shared and need to be allocated for the protection path.

The constraints are following:

We need the flow conservation constraint for the working (on variable x) and mass protection paths (on variable y), respectively. We need to formulate the above-mentioned properties of working and mass protection path: $x_{a,b}$ and $y'_{\overleftarrow{a,b}}$ will be exclusive in terms of the SRGs they take. An arc can be taken by $y'_{\overleftarrow{a,b}}$ in a reversed direction only if $x_{a,b}$ pass through it. Besides, each reversed arc can be used only once since the algorithm only allows two working segments overlapped. Thus, Q is SRG disjoint from W except for the reversed arcs of W . Note that, reversed arcs indicates the switching/merging nodes for each protection domain along W . A pair of variables, $\hat{x}_{a,b}$ and $\hat{y}'_{a,b}$, is assigned to each link along W and Q , respectively, such that the first link from the source has a label of 1; and if a protection domain ends or starts at a node, the labels of the following arcs will be increased by 1. This labelling method is similar to that proposed in [10]. This is done by modified flow conservation constraints, where the following four situations are considered for all vertices (not the source or destination) taken by W : (a) Q merges back to W ; (b) Q switches out of W ; (c) Q merges back and switches out of W ; (d) otherwise. The amount of flow of $\hat{x}_{a,b}$ and $\hat{y}'_{a,b}$ at vertex a along W increases by 1 in

the case of situations (a) and (b), and increases by 2 in the case of situation (c), and is unchanged otherwise.

With $\hat{x}_{a,b}$ and $\hat{y}'_{a,b}$ link labels, path W is divided into segments such that each link along it is covered by at least one protection segment. This effort introduces $k_{max} \cdot |E_w|$ and $k_{max} \cdot |E_p|$ arc-domain incidence binary variables denoted as $x_{a,b}^k$ and $y_{a,b}^k$, which is 1 if link (a,b) is traversed by the working and protection segment of the k^{th} protection domain, respectively. By observing Fig. 5 one can be easily verify that the value of $\hat{y}'_{a,b}$ on Q of the first protection domain is 1; and in the second protection domain $\hat{y}'_{a,b}$ is 3; and in the k^{th} protection domain $\hat{y}'_{a,b}$ is $2k - 1$, thus $y_{a,b}^k = 1$ only when $\hat{y}'_{a,b} = 2k - 1$. The value of $\hat{x}_{a,b}$ of arc (a,b) taken by W in the first protection domain is either 1 or 2, depending on whether or not there is overlapped arc(s) between the working segments of the first and the second protection domain; while on the links of the k^{th} protection domain, we have $\hat{x}_{a,b} = 2k - 2$ on the non-overlapped links and $\hat{x}_{a,b} = 2k - 1$ on the overlapped links of the $(k - 1)^{\text{th}}$ and the k^{th} protection domain; we have $\hat{x}_{a,b} = 2k$ on the overlapped links of k^{th} and $(k - 1)^{\text{th}}$ protection domain. However this leads to more tight constraints with less integer variables (Eq. (2.4.19) of the dissertation compared to Eq. (20) in [J2]), and the runtime of the CPLEX solver can be significantly reduced since the gap between the relaxed problem and the integer solution is also reduced [29, 30].

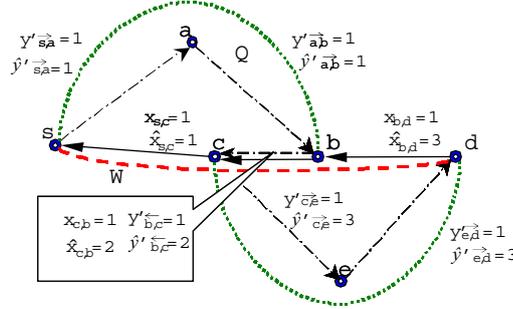


Figure 5: An example showing the variables x , y' , $\hat{x}_{a,b}$, and $\hat{y}'_{a,b}$. It is zero for the variables of the arc not shown on the figure.

The last constraints need to be defined are the SRG constraints setting the value of $z_{u,v}$ defined in the target function. It is considered using \underline{S} matrix, such that when link a and e is taken by the working and protection segments in the k^{th} protection domain, respectively, the resultant amount of scaling (i.e., z_e) is at least $1 - \frac{v_a - s_{a,e}}{b(W)}$.

The number of variables is $(K + 4) \cdot |E_w| + (K + 3) \cdot |E_p|$, and the number of rows in the constraint matrix (where the linear formulation can be expressed in a general form as $\underline{A} \cdot \underline{X} = \underline{B}$ with a target to minimize $\underline{X} \cdot \underline{C}$) is less than $K \cdot |E_w| \cdot |E_p| + 8 \cdot |E_w| + 9 \cdot |E_p| + 11 \cdot |N|$. Computation time and memory occupation are shown in [J2].

Claim 2.2 Extending the ILP of SSP with constraint on Restoration Time and with Further Network Architectures

This claim tackles the problem of dynamic survivable routing by extending the Integer Linear Program (ILP) formulation introduced in Claim 2.1. Although the formulation can effectively provide optimal solution according to a specific connection request and network-state, the following two assumptions leave space for improvement:

1. The size of each protection domain is not constrained so that the restoration time for each connection is not considered. We declare that an approach for constraining

the restoration time must be developed such that the class of service provisioning of survivable bandwidth is possible.

2. Every node can switch and/or merge restoration traffic at the same time, which may not be the case for practical applications. The major concern for this assumption is that the nodes serving as switching/merging (S/M) devices need to provide extra signalling efforts and hardware responsiveness, which may not be general to the whole network.

To improve the above two shortcomings, this claim is committed to extending the ILP formulation of the previous section, such that the constraint on restoration time in each protection domain of a connection as well as the constraint on the ability for each node to switch/merge restoration traffic are well addressed by classifying each node into two categories, each having different S/M capability.

It is important to note that the nodes serving as S/M devices for SSP must provide extra signalling efforts and hardware responsiveness especially in the transparent optical plane. Thus, equipping a network node with S/M capability in the optical domain should be taken as a network resource instead of being taken as a general assumption. The performance impact by the allocation of S/M capability in each node, therefore, turns out to be an interesting problem that is subject to further efforts of network-wide planning according to the topology, traffic pattern, and the corresponding survivable routing algorithm.

A Heuristic of Improving the runtime of solving ILP: The SSP Algorithm

Relaxation methods are widely used reduce the computation time for deriving approximate ILP solutions. Herzberg et. al. [31] formulated a linear programming (LP) model for the spare capacity assignment problem and treat spare capacity as continuous variables. A rounding process is used to obtain the final integer spare capacity solution which might not be feasible. They use hop-limited restoration routes to scale their LP problem. This technique can also be extended to input ILP formulation when Branch and Bound (BB) method is employed for searching the optimal solution [32], [33]. Lagrangian relaxation with subgradient optimization are used by Medhi and Tipper [34]. The Lagrangian relaxation [35] usually simplifies a hard original problem by dualizing the constraints and decomposing it into several easier sub-problems. Subgradient optimization is used to iteratively find the dual variables in these subproblems.

To improve the computation efficiency of the ILP, a novel approach, called SSP algorithm, is proposed to reduce the runtime in solving the proposed ILP (see also results on Fig 9.). Basically, our approach is to derive a good approximation on the parameters in the ILP by referring to the result of solving the corresponding ILP for shared path protection (SPP) such that significant reduction on the design space can be achieved by eliminating some edges in the graphs.

Evaluation of the S/M capability of the Network

To verify the proposed formulation and investigate the performance impairment in terms of average cost and success rate by the additional two constraints, extensive simulation work has been conducted on three network topologies. Two performance metrics are defined: the average increase in blocking probability caused by removing the S/M capability at a specific node (denoted by AIBP), and the average increase of cost in allocating a connection request if the S/M capability at a specific node is removed (denoted by AITC). Two realistic network topologies, European Reference Network (ERNET) and North-American Reference Network (NARNET), are adopted, where a traffic matrix in year 2005 is estimated for each network according to [36]. To evaluate the two performance metrics, two methods are discussed: the brute force method and the enhanced recursive method. In the former, the SSP algorithm solves for all the connection requests on each possible state of S/M capability; while in the latter, a novel approach is devised to reduce the computational requirement induced in the brute force method. For both of the approaches, a corresponding recursive function is developed for this purpose.

protection, we claim that this is the first study using ILP formulation yielding optimal solution.

The dissertation also investigates the performance impairment when different restoration time constraints are addressed (or having different sizes of protection domain). A comparison is made among SLP, SPP and SSP (with restoration time constraints) in terms of average cost and success rate of setting up connections. We observe that SSP can initiate a graceful compromise between average cost and network throughput under a wide range of restoration time constraints (see also results on Fig 8.). For SLP, the overall performance is not distinguished compared with the other two types of protection although an ultra-fast restoration process can be guaranteed.

With the result and analysis methodology, the modeling of the whole survivable routing process can further facilitate the deployment, and dimensioning of the network switching capacity, and can serve as a reference for setting up the pricing policy.

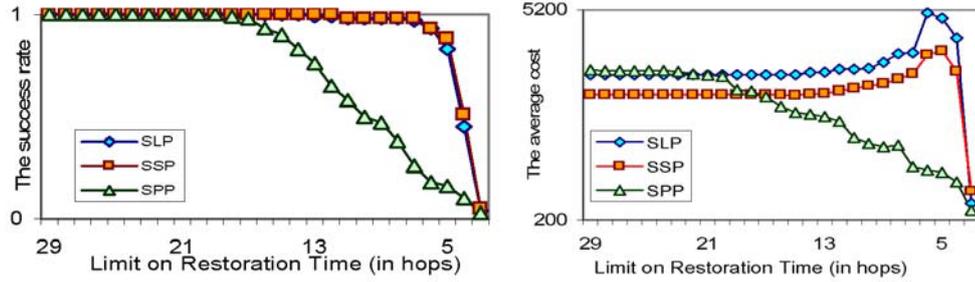


Figure 8: Performance impairment by addressing the restoration time constraint using the 61-node network at light load (19%).

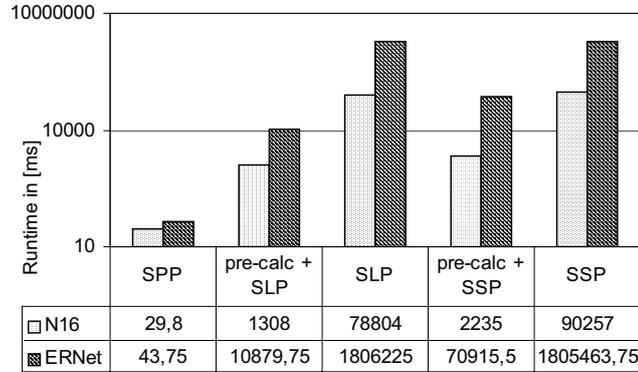


Figure 9: Runtime in solving the SPP, SLP with pre-calculation, SLP, SSP method (SSP with pre-calculation), and SSP on N16 and ERNet.

Claim 2.3 Complexity Analysis of the Segment Shared Protection Problem

A problem of Shared Segment Protection (SSP) in a mesh telecommunication network is defined as follows:

Given:

- a undirected graph $G(V, A)$, with V and A being the set of vertices and arcs, respectively,
- the free capacity (f) and the spare capacity (v) of each arc,

- the SRGs of G (the arcs of G in this case),
- the \underline{S} matrix.
- the source node s , the destination d and the bandwidth $b(W) = 1$ of the new demand,
- parameter k_{max} (≥ 1) that is an upper bound on the number of segments.

Decide whether there exists:

- a working path W , with the switching and merging nodes of each segment along W (represented in matrix \underline{W}), and the protection path of each segment (represented in matrix \underline{P}), such that
 - the number of segments (or the number of protection domains) along W is $\leq k_{max}$
 - W_k and P_k should be arc (SRG) disjoint for $\forall k$,
 - the feasible condition of the working path is $f_i \geq b(W)$ for $\forall i \in W$
 - the feasible condition of the protection path is $f_i + v_i \geq b(W) + \max_{\forall j \in W_k} s_{i,j}$ for $\forall i \in P_k$ and $\forall k$.

In the optimization version of SSP a cost function c assigned to each edge is given as well, representing the cost of allocating one unit of capacity. The task is to find the connection with minimal total capacity allocation.

Theorem 2.3. The problem of SSP is NP-hard

Note that this proof is valid both in the vertex and in the edge disjoint cases. The proof is valid if $k = 1$, so it is a proof of the SPP as well.

Claim 3 : Distributed Control Architecture for Shared Path Protection in Mesh Communication Networks with Bandwidth Guaranteed Tunnels

Studies of the dynamic survivable routing problem for shared protection have been extensively reported in the past several years, most of which focused on the schemes under the complete routing information scenario [3, 4, 5, 6, 7]. (also called Sharing with Complete Information, SCI [38]). However, in the practical operation of the Internet with a distributed control environment, the scenario may be subject to significant overhead in terms of link-state dissemination and yields a serious scalability problem. Therefore, some studies turned to solving the problem in a scenario of partial routing information (SPI) [38, 39, 40, 41, 42], in which a survivable routing protocol does not require per-flow information to make a routing decision such that both the amount of dissemination for enabling distributed control and the complexity of the routing process can be reduced at the expense of a lower degree of sharing [38, 40, 41].

Claim 3.1 Reduced Information Scenario for Shared Path Protection

An explicit and comprehensive description has been available in a number of reported routing information dissemination scenarios for shared protection [38, 40, 41], which discuss the performance of the reported scenarios in terms of link-state dissemination and routing information reconstruction. The common ideas of these papers were to reduce signaling overhead by disseminating only $O(E)$ information instead of $O(E^2)$ entries of spare provision matrix \underline{S} . In other words instead of matrix \underline{S} , vectors are disseminated. For some technical reasons matrix \underline{R} is reconstructed instead of \underline{S} , and

$$r_{j,l} = \frac{-1}{b(W)} \cdot (v_j - b(W) - s_{j,l}) \quad (5)$$

I applied the theory of SVD (Singular Value Decomposition [24]) transformation to get optimal vectors approximating \underline{S} matrix:

$$\underline{U}^T \cdot \underline{R} \cdot \underline{V} = \text{diag}(\sigma_1, \dots, \sigma_r) \in \mathfrak{R}^{m \times m}$$

$$\min_{\forall \hat{\underline{R}}, \text{rank}(\hat{\underline{R}})=1} \left\| \underline{\underline{R}} - \hat{\underline{R}} \right\|_2 = \left\| \underline{\underline{R}} - \sigma_1 \cdot \underline{U}_1 \cdot \underline{V}_1^T \right\|_2 = \sigma_2 \quad (6)$$

Let denote $\underline{S}^P = \sqrt{\sigma_1} \cdot \underline{U}_1$ and $(\underline{S}^W)^T = \sqrt{\sigma_1} \cdot \underline{V}_1^T$, where σ_1 is the first singular value and \underline{U}_1 and \underline{V}_1 are the vectors corresponding to it. Disseminating \underline{S}^P and \underline{S}^W gives the best approximation of matrix $\underline{\underline{S}}$ and the overall throughput of the network is increases [C7]. At the same time the complexity of the routing problem can be significantly reduced, with the following idea:

First I define a matrix $\underline{\underline{W}}$ representing W , where $\underline{\underline{W}}$ is a diagonal matrix with size $|E| \times |E|$. An example is given as follows. $\text{diag}(W) = \{0, 1, 0, \dots, 0, 1, 0, \dots, 0\}$ means that W traverses through two links: the second and the x^{th} link in G . In the same way a matrix $\underline{\underline{P}}$ is defined for P . The ‘‘row_max’’ operator for a matrix is defined as well, which returns a column-vector with the j^{th} entry being the maximum entry of the j^{th} row of the matrix.

Now the task is to find a SRG-disjoint path-pair such that the total cost can be formulated in the following way:

$$\begin{aligned} c_{total} &= \underline{C}^T \cdot \left\{ \underline{\underline{W}} \cdot \underline{1} + \text{row_max} \left(\underline{\underline{P}}^T \cdot \underline{\underline{R}} \cdot \underline{\underline{W}} \right) \right\} \\ &\approx \underline{C}^T \cdot \left\{ \underline{\underline{W}} \cdot \underline{1} + \text{row_max} \left(\underline{\underline{P}}^T \cdot \underline{S}^P \cdot (\underline{S}^W)^T \cdot \underline{\underline{W}} \right) \right\} \end{aligned} \quad (7)$$

where \underline{C} is the cost vector of the edges. Eq (7) can be expressed as

$$c_{total} \approx \underline{C}^T \cdot \left\{ \underline{\underline{W}} \cdot \underline{1} + \underline{\underline{P}}^T \cdot \underline{S}^P \cdot \max \left((\underline{S}^W)^T \cdot \underline{\underline{W}} \right) \right\} \quad (8)$$

where the max operation is taken on all entries of the row vector $(\underline{S}^W)^T \cdot \underline{\underline{W}}$. By Eq. (8), the cost of the working path is the summation of the cost for each link taken by W as usually, while the cost of the protection path is:

$$\max_{j \in W} \{s_j^W\} \cdot \sum_{i \in P} s_i^P \cdot c_i$$

For the routing task, the cost of each link is determined by three variables: s_i^W and c_i , for the cost of the working route, and $\left[\max_{j \in W} (s_j^W) \cdot s_j^P \right] \cdot c_j$ for the cost of protection route. Thus, I have formulated the problem as a diverse routing problem with different cost functions for working and protection paths, in which each working and protection path takes independent cost function c_j and $\left[\max_{j \in W} (s_j^W) \cdot s_j^P \right] \cdot c_j$.

The diverse routing problem with independent and different cost functions for working and protection paths can be solved with some very fast heuristics [38, 28]. The simulation results in [C7] reinforced the theoretical statements.

Claim 3.2 Reduced Information Scenario for Segment Shared Protection

Distributed Partial Information Management with Sufficient and Aggregated Information (DPIM-SAM) [1] is a scheme devised for the implementation of shared protection in a distributed control environment. In particular, DPIM-SAM allows link l to disseminate a scalar, which is the maximum entry of the l^{th} column of $\underline{\underline{S}}$. Therefore any remote ingress node, the receipt of $\max(\underline{S}^l)$ from all the other nodes will enable the reconstruction of an upper bound of the spare provision matrix for the whole network. The drawback of SSP is the enormous computation requirement, therefore there is no

need to disseminate so many link state information. Using DPIM-SAM scheme, the complexity of the survivable routing problem significantly decreases. Our simulation showed that the performance of SSP-DPIM-SAM is comparable with that of SSP-SCI, while the computation time can be reduced to one thousandth times for the network topology adopted.

I have formulated the SSP-DPIM-SAM as an ILP. Using the notation of Claim 2.1 x is a binary flow indicator of W and it is assigned to the edges of G_w . y' and z' is assigned to G'_p and y' is a binary flow indicator of Q and $z'_{a,b}$ is a variable for scaling the cost of the protection path taking spare capacity along link (a, b) .

Objective:

$$\sum_{(a,b) \in E_w} c_{a,b} \cdot x_{a,b} + \sum_{(u,v) \in E'_p} (c_{u,v} \cdot z'_{u,v} + \varepsilon) \cdot y'_{u,v}$$

The constraints mainly ensure the special structure of the working and the mass protection path, as it was described in claim 2.1.

5 Application of the Results

All the algorithms and solutions of this dissertation have a strong motivation from the telecommunication industry and mainly applicable on single layered circuit-switched and virtual circuit-switched mesh backbone networks, like MPLS, ATM, SDH/SONET, Next Generation SDH/SONET and ASON. They can equip the switches of the future survivable mesh telecommunication networks considering QoS requirements. Shared path protection and shared segment protection are recognized as two of the most promising strategies to equip networks.

I implemented simulation tools to be able to test the performance of the algorithms and to ensure their benefits. The proposed methods of Claim 1 and 3 are scalable and they were designed to meet several requirements of modern telecommunication networks. In Claim 2 I investigated the need of segment shared protection to motivate researchers developing fast heuristics.

I took into account the constructive feedback received from Ericsson and from the High-Speed Networks Laboratory (HSN*Lab*) at the Budapest University of Technology and Economics.

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