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Differentiated Quality-of-Protection in Survivable WDM Mesh Networks with p-Structures

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Abstract

Availability requirements in survivable transport networks depend on the type of costumers using the network and the supported services. Nowadays, a variety of services with different protection guarantees, also called Quality-of-Protection (QoP), are proposed through the same network at different rates. In this work, we propose a framework for optimized design of multiple quality-of-protection classes including single and dual link failure scenarios under arbitrary SRLG scenarios in survivable WDM networks that use pre-configured protection structures (i.e., p-structures).

We develop compact optimization models and propose a scalable solution method based on Column Generation (CG) where these two classes of QoP are guaranteed. Contrary to classical optimization techniques, where the shapes and protection capabilities of the potential protection structures are decided ahead of the optimization process, in our CG based approach, these characteristics are dynamically decided during the optimization process in order to effectively meet the QoP requirements of the supported users and traffic.

We test the proposed design method under several R_2 levels, and compare the optimal capacity designs of the p-structures with the p-cycles in order to gain an insight about how the shape of the protection building blocks affect the performance of the protection scheme. Furthermore, the shape and protection capability of the p-structures are studied in order to illustrate the most appropriate structures for each QoP level. The computation results show that, in some test cases, and depending on the network connectivity, an up to 150% of protection capacity can be saved throughout the use of p-structures rather than limiting the protection structures to p-cycles. This illustrate the potential of adapting the shape of the protection structures in order to meet different QoP requirements. These design methods and results can be used by network planners to evaluate the availability, flexibility, and cost of the different capacity design strategies using pre-defined shape structures (e.g., p-cycles, $p-$trees).

Key Words: Survivable WDM networks, dual link-failure, quality-of-protection, service-level agreements, column generation.

1 Introduction

Nowadays, the trends in the telecommunication business is moving toward a multi-service platform that will support diverse applications and end-users, with different requirements and needs. In order to be competitive, a business must be able to respond to the needs of as many customers as possible while minimizing its deployment and maintenance costs. However, very often, it does not really matter how versatile and diverse the provided services are if the supporting network cannot operate reliably and provide a guaranteed-availability. Indeed, reliability and availability of a network are the primordial requirements of any kind of Quality-of-Service (QoS) parameter in multimedia networks.

Optical networks based on Wavelength Division Multiplexing (WDM) have been largely deployed for the last decade to respond to the explosive growth of demand for high bandwidth in transport networks [1, 2]. In multi-channel fiber WDM networks, a physical link between two optical nodes often comprises multiple fibers, carrying each several wavelengths, and operating at a speed of up to 40Gb/s. A single network outage resulting from a link or node failure, even for a short period of time, can lead to a traffic loss of several Terabits [3].

The impact of equipment failures like fiber cuts can be mitigated by various levels of network protections ranging from dynamic restoration of traffic to pre-planned protection where redundant protection capacity is reserved ahead of failures. Pre-configured protection is the resiliency mechanism that reserves redundant resources, to be used in case of a failure, in order to recover from potential failures in a network. In the design of protection planes, the focus is usually placed on minimizing the network resource redundancy required to provide the suited service availability. Therefore, several sharing approaches, involving redundant-resources, have been studied in the literature [4–9]. Cable cuts and sharing of protection channels have been the most studied failure scenarios in survivable optical networks. Several design methods of protection schemes have been proposed in the literature to provide 100% protection against single link failures [7, 10–13]. Different network availability analysis have been proposed in order to quantify the offered availability of those schemes [14]. However, most of those studies have assumed that failures in the network are independent from each other and dual failure scenarios have not been much studied.

Providing different targeted quality-of-protection levels is a key challenge for network operators. In modern telecommunication networks, some mission-critical applications, e.g., tele-surgery, require high network availability, e.g., 100%, which is not guaranteed by a 100% single link failure protection scheme. Such a high network availability usually requires high resource redundancy, and thus high network deployment cost. Differentiated quality-of-protection, which we refer to as the different guarantees of service recovery, can be a solution approach in order to optimize the network cost while providing the suited different classes of protections. Indeed, not all the end-users and applications require the same level of resiliency against failures, some application can perform even with a low network availability, e.g., e-mail, and not all the users can afford paying the cot of a guaranteed 100% service availability. This explains why it is a challenge in order to provide different classes of protections within a possibly restricted resource budget and charging the users accordingly.

The set of specifications, including the different quality-of-service and protection parameters, are usually included in a Service Level Agreement (SLA) contract signed by the service provider with their corporative customers. The SLAs may include quantified requirements regarding for example the levels of operation, performance and availability, and penalties in case where the quality of service specifications are not met. Therefore, it is of interest to understand and quantify how much quality-of-service can be provided in order to offer safer SLAs and competitive services.

The performance of any protection scheme in survivable WDM networks is greatly defined by the shape of the used protection building blocks. Different shared protection schemes usually named after the shape of their basic building blocks e.g., $p-$cycles [12], $p-$trees [15, 16], $p-$etrees [7], p-structures [13, 17, 18] have been proposed and studied in the literature. Several studies have been performed to measure the efficiency of these pre-configured protection schemes within 100% single link failure scenarios. However, no study has yet been conducted in order to evaluate, with exact tools, how those schemes perform when higher availability (e.g., resiliency against dual-failure scenarios, $R_2 > 0$).

In this work, we propose an optimization method for optimal capacity design in link-restorable mesh networks based on p-structures that provides two quality-of-protection classes including a 100% single link failure (R_1=100%) protection and a parametrized dual failure (R_2). The novelty in this study is:

1. We use shared protection structures of unrestricted shapes, i.e., all possible protection structures (independently of their shapes) are considered as candidate structures provided that they can meet the requirements of the two classes of QoP. Both classes of protection share the same backup capacity. It constitutes the first study that considers all the possible logical protection topologies in the design of single and dual link failure scenarios.
2. We propose a quantitative design approach which guarantees different quantified and absolute service availability levels: A guaranteed single link failure recovery $R_1 = 100\%$ and several parametrized R_2 values with their associated optimized investment in terms of protection capacity.
3. We propose a design method where optimization of the selection of protection structures and their protected capacity is integrated in the optimization process. As opposed to prior study of logical protection topologies where the pre-defined shape candidate structures are partially/totally pre-enumerated and their protected capacity decided ahead of the optimization process, we adopt an integrated approach where all those steps are jointly optimized.

The article is organized as follows. Section 2 is dedicated to review the existing work on differentiated QoP and dual failure recovery. Section 3 discusses overlay protection topologies and the motivation of the paper throughout examples. In Section 4, we develop the mathematical optimization models and explain how to solve them using column generation techniques. Computational results are described in Section 5. We conclude the paper in Section 6.

2 Related work

Many factors can motivate the needs for design methods of different protection classes including dual link failures in resilient WDM networks. The occurrence of dual link failures, although less likely than single link ones, is not unusual in modern optical networks [19]. Dual link failure survivability is the dominant factor in determining the service availability after a guaranteed protection against single link failures.

Nowadays, some cooperative customers are asking in their Service Level Agreement (SLA) a service availability of the order of 99.999 or higher [20]. Therefore, it is of interest for network operators to exactly offer the required service availability in order to avoid penalties.

The problem of dual link failures has been studied within two categories: Shared Risk Link Group (SRLG) failures, i.e., a set of optical fiber links that share the same risk of failure [6, 21, 22], and arbitrary dual link failures [23, 24]. Indeed, failures on different optical fibers are not necessarily independent from each other for at least two reasons:

(1) Physical routing of optical links may differ from their logical routing counterparts, e.g., see Figure 1. The physical routing of links is dictated by different external constraints, e.g., sharing multi-purpose pipelines in cities or minimizing design costs.

(2) Fibers are linked at switching nodes, and a partial (e.g., a port) or global node failure can easily cause a dual link failure e.g., see Figure 2. This case of figure is equivalent to a failure on a fiber-bypass at a given node, which in case of a failure on one of its incident (at the node) links make the other one unusable.

Providing different classes of protection has been considered with single and dual link failures. With single link failure, Grover and Clouqueur proposed a multi QoP provisioning framework in a survivable single link failure network [9] . Four classes were presented: Guaranteed protection, best effort, unprotected, and preemptable service. The distribution of the multi QoP services and their effect on the sharing of the protection capacity were studied. An ILP based optimization was proposed based on an enumeration step of the protection paths of each working link. In [8], Tornatore *et al.* proposed a heuristic based optimization approach within dedicated and shared path protection in order to achieve two different objectives: Optimize

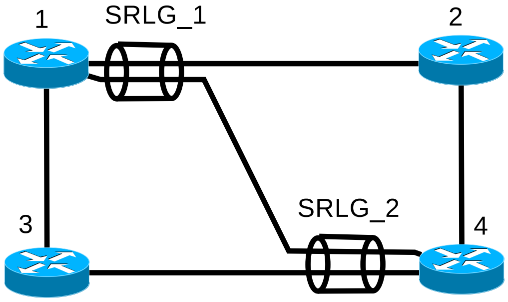


Figure 1: SRLG - physical routing

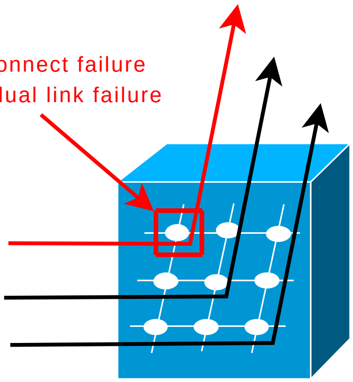


Figure 2: SRLG - switching node

the network availability, and minimize the number of fibers to provide the required QoP. However, they assumed, in their availability analysis, that the optical nodes are perfectly reliable, and fiber links are mutually failure-independent.

Regarding dual link failures, Clouqueur and Grover proposed in [25] three ILP-based optimization models based on a pre-enumeration method of candidate protection paths in order to optimize the spare capacity required in multi QoP services that can survive dual link failures. In [23], He and Somani investigated the protection capacity requirement in order to provide an arbitrary double link failure protection with path and link based protection schemes. An ILP based optimization method was proposed where three alternate backup paths between each source-destination node-pair are considered. Within the optimization conditions, they showed that, with dual link failures, the path-based protection approach is more capacity efficient than the link-based one. In [26], Shao *et al.* investigated the problem of providing differentiated QoP for surviving arbitrary double and single link failures by allowing connection requests to choose among three different protection classes. Single shared path protection (SSPP), single dedicated path protection (SDPP), and double shared path protection (DSPP) were defined as the protection classes and connections mapped to those classes. Routing algorithms were proposed, and the performance evaluation was focused on blocking probability and average QoP.

It is usually required to enumerate and manage a large number of backup paths in the design of protection schemes based on simple linear paths than on any other shaped protection structures, e.g., p-cycles, p-trees. These protection structures can be seen as combinations of elementary linear paths. However, in addition to the manageability argument, they also offer more protection capacity sharing (inter linear-path sharing) than when they are divided in simple structures. Example, a p-cycle can protect more working capacity than its two isolated component backup paths. In the next section, we review the existing pre-defined shape protection schemes and illustrate our contribution of p-structure based protection and its advantages in providing differentiated QoP, including single and dual link failures.

3 Overlay protection topologies

3.1 Literature review

The pre-configured protection cycle (p-cycles) and tree (p-trees) are two predefined shape protection structures that have been considered in the design of multi QoP including dual link failures in the literature [27–32].

The concept of p-cycles is an attractive protection approach in survivable optical mesh networks [33]. As in a shared-protection ring, a p-cycle protects the working capacity of the links it covers (on-cycle links) by providing a loop-back protection path. But, unlike rings, a p-cycle also provides protection for links whose end-nodes are on the cycle, without being on-cycle links (they are called straddling-cycle links).

Dual link restorability in mesh networks protected by p-cycles has been studied in [29, 31, 32]. In [31], Schupke et al. used directed p-cycles in the design of 100% single link failure recovery schemes, and studied the trade off between the number of p-cycles and the average dual link failure restorability. Therein, the authors proposed an ILP (Integer Linear Program) model based on a set of candidate p-cycles that are enumerated ahead of optimization. Even though the ILP was solved to optimality, it has been shown in previous studies that the best solution obtained with such a two-step optimization model can be far from the optimal one, see, e.g., [34]. In [29], different pre-selection strategies of p-cycles have been proposed in order to reduce the susceptibility of p-cycles to some specific dual link failures. p-Cycles with a lower susceptibility are selected as potential protecting structures. Failure dispersal is another strategy for selecting p-cycles in order to spread the link protection over different p-cycles [29]. However, restricting the p-cycle selection affects the optimal design and the required number of p-cycles, as well as their length (see [34]).

Except for the work in [28], there has been no accurate evaluation of the required protection capacity in order to provide an optimized level of survivability with dual link failure scenarios. Indeed, we proposed in [28] the first exact design method of p-cycle based schemes that can survive any single link and, partial as well as complete, dual link failures (R_2). We developed an optimization approach based on column generation (CG) techniques where candidate p-cycles are dynamically generated during the optimization process. Through extensive simulations, we exactly quantified the required protection capacity with different network scenarios and failure models. We also showed that although the p-cycle based approach is among the most capacity efficient protection scheme for 100% single link failure protection, its resiliency against dual link failures usually require excessive resource redundancy.

Pre-configured trees (p-trees) constitute another type of protection structures used in the design of survivable WDM networks [15,27,35]. In [27], Tang et al. proposed an ILP model to minimize the spare capacity budget in order to provide 100% protection against single link failures and a distributed provisioning algorithm for fast double-link failure restoration. Simulation results show that around 70% of the double-link failures can be restored by the restoration scheme even though the spare capacity in the network is planned for single-link failures.
In [35], Médard et al. presented a design approach to construct a pair of directed spanning trees from a common root node in a way that a failure of any single edge or node (except the root node) in the graph, leaves all the nodes connected with the root node using at least one of the trees. They named their approach the red/blue trees.
In [15], Xue et al. proposed the concept of Quality of Protection (QoP) and Quality of Service (QoS) of red/blue trees. The QoP of a pair of red/blue trees was defined as the maximum number of simultaneous link failures that can be survived in the network. Heuristic algorithms were proposed for constructing a pair of red/blue trees with enhanced QoP, low total cost, and maximum bottleneck bandwidth.

The p-cycles and p-trees have been compared in terms of spare capacity needed to provide 100% protection against single link failures in [7]. However, the effect of the shape on the performance of those pre-defined shape protection structures and others in dual link survivable networks has never been studied.

3.2 Motivation

In Figure 3, we illustrate a network topology and a set of associated potential dual link failures. The double link pairs, which are susceptible to fail at the same time, are grouped in distinct SRLGs (e.g, $SRLG_1$ contains links $1-2$ and $1-3$ which are susceptible to fail at the same time). We assume a working traffic model where each physical link is carrying a wavelength connection.

- $SRLG_1 : 1-2,\, 1-3$
- $SRLG_2 : 1-2,\, 3-4$
- $SRLG_3 : 1-2,\, 1-5$
- $SRLG_4 : 3-4,\, 4-5$
- $SRLG_5 : 3-4,\, 2-4$
- $SRLG_6 : 1-5,\, 2-5$
- $SRLG_7 : 2-5,\, 3-5$

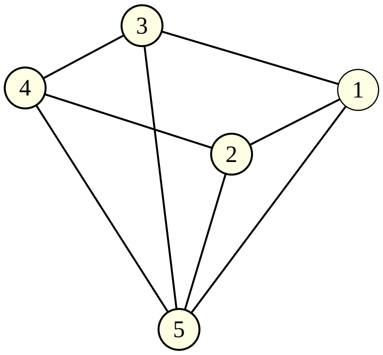


Figure 3: Arbitrary SRLG.

Let us apply the optimization solution method proposed in [28] in order to optimize the protection capacity needed to provide 100% protection against all the potential link failures in the network, i.e., all the single and dual link failures. In Figure 4, we illustrate the optimal combination of p-cycles that minimizes the protection capacity required to provide the targeted protection. The illustrated four p-cycles (dashed lines) provide protection to the eight working links (bold lines). We see that except for the first p-cycle in Figure 4-(a), which is used at its full protection capacity (protect all its on-cycle links), all the three others are used at $\sim 38\%\,(3/8)$ and $\sim 34\%\,(1/3)$ of their total protection capacity. Indeed, none of the spanned links by the first p-cycle belongs to one of the SRLGs in Figure 3. Moreover, to protect the links that belong to the same SRLG in Figure 3, it takes more protection capacity to provide 100% protection (e.g., see the other three subfigures), and shared p-cycles tend to be dedicated protection structures. The only way to protect a pair of links that belongs to the same SRLG is to get them as straddling-cycle links and not intersecting each other, e.g., Figure 4-(d) (see [28] for further explanations).

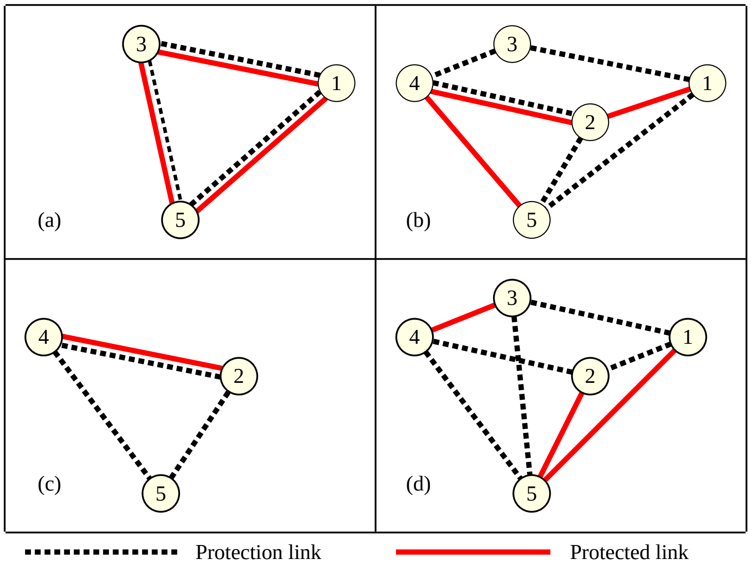


Figure 4: a p-cycle scheme

In Figure 4, we provide 100% protection against all the potential dual link failures in the network illustrated in Figure 3. However, this is only $7/\binom{8}{2}$ of all the possible combinations of dual link failures. In [28] we showed that a spare capacity budget of ~ 5.2 of the working capacity may be required in order to provide 100% dual link failure protection. The cost of this optimal p-cycle protection scheme is 16 channels, thus its capacity redundancy is $16/8 = 200\%$.

Based on the results in Figure 4 and in [28], some questions arise regarding the use of predefined shape protection structures in the design of dual link survivable WDM networks:

- How much the shape of the protection building blocks affects the efficiency of the resulting protection schemes in providing single and dual link failure protection?
- Is there any other shape that could help in designing more effective protection topologies?

In Figure 5, we illustrate another optimal design for the previous protection example based on p-structures. By p-structures we mean all the protection structures, that can provide protection for the working links.

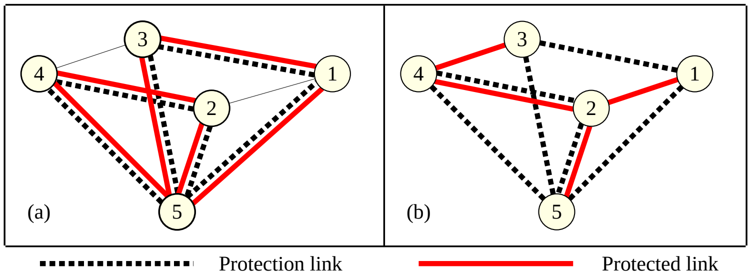


Figure 5: a p-structure scheme

The illustrated two p-structures provide 100% protection against all the single and potential dual link failures in the network. Compared to the previous p-cycle scheme in Figure 4 which requires 16 backup channels, the p-structure one, as represented in Figure 5, requires only 12. Thus, it is more capacity effective. Indeed, in the p-structure scheme, the protection topologies are more connected and can offer more routing possibilities in case of any single or dual link failure.

In the next Section 4, we propose an ILP based optimization model to optimize the spare capacity needed to provide the two QoP levels, i.e., 100% single link failures and optimized dual link failure recovery. Our optimization approach is based on a scalable decomposition approach named column generation, where the definitions of the shape and of the protection capability of each protection structure are integrated in the optimization process.

4 Mathematical Models

Prevalent ILP optimization methods of pre-defined shape protection schemes are based on pre-enumeration (explicit or selective) heuristic approaches of the protection building blocks. This approach has been shown to result in huge optimization models and non scalable solution methods [34]. In this paper, we extend the optimization approach in [28] to support all the possible protection structures independently of their shapes.

We consider a WDM network with a set $\mathcal{V}$ of nodes and a set $\mathcal{L}$ of links, indexed v and ℓ respectively. We propose a link failure model where each link can fail separately and each pair of links form a distinct SRLG. A discrete probability distribution $\mathcal{P} = (\mathcal{P}^{\ell_1,\ell_2})$ which associates a value in $\{0,1\}$ to each pair of links ℓ_1 and ℓ_2 depending on whether they are susceptible to fail at the same time ($\mathcal{P}^{\ell_1,\ell_2} = 1$) or not ($\mathcal{P}^{\ell_1,\ell_2} = 0$) is adopted.

Based on $\mathcal{P}$ we define the dual link survivability level of a protection scheme as the number of dual link failures that can be survived in the networks over the total number of possible dual link failures:

$$R_2 = \frac{\sum\limits_{\ell_1,\ell_2 \in \mathcal{L}} \mathcal{P}^{\ell_1,\ell_2}}{\binom{|\mathcal{L}|}{2}}. \tag{1}$$

Following the CG decomposition approach, our optimization problem is divided into two sub-problems: A master problem which optimizes the selection of the p-structures, and a pricing problem which dynamically generates promising candidate p-structures which provide the two classes of QoP. Based on the values of the dual variables of the master, the pricing problem generates shared p-structures that can survive both single and dual link failures. See [36] for further reading on column generation.

4.1 Master problem

The master problem consists to minimize the spare capacity requirement in order to achieve 100% single link protection and a given dual link failure protection level R_2. We assume that the working capacity w_ℓ on each link ℓ (routing of working paths) is given. We define by $\mathcal{S}$ the set of potential p-structures used in our optimization model and by s its index. Let us define the vectors of variables and parameters used to setup the optimization model:

- Variables
  - $z^s \in \mathbb{Z}^+$ is the number of copies of p-structure s.
- Parameters
  - $a^s_\ell \in \mathbb{Z}^+$ encodes the number of alternative backup paths provided by p-structure s for link ℓ.
  - b^c_ℓ equal to 1 when p-structure s spans link ℓ, 0 otherwise.

The master optimization objective consists to minimize the spare capacity (number of copies of each p-structure s) needed to provide the two QoP classes. It is written as follows:

$$\min \quad \sum_{s \in \mathcal{S}} \sum_{\ell \in \mathcal{L}} b^s_\ell z^s$$

subject to:

$$\sum_{s \in \mathcal{S}} a^s_\ell z^s \geq w_\ell \qquad \ell \in \mathcal{L} \tag{2}$$

$$z^s \in \mathbb{Z}^+ \qquad s \in \mathcal{S}. \tag{3}$$

Constraints (2) guarantee link protection for at least w_ℓ working channels along each link ℓ against all the potential link failures in the network. Resiliency against single and dual link failures are decided in the pricing problem. However, all the p-structures $s \in \mathcal{S}$ in the master problem are guaranteed to survive any failure in the network failure model i.e., both single and dual failures. Constraints (3) are integrality constraints.

Recall that the set $\mathcal{S}$ of p-structures grows after each iteration of the pricing problem (see next paragraph for its definition), which dynamically generates potential p-structures to respond to the protection needs.

4.2 Pricing problem

The pricing problem consists to minimize the reduced cost of the master problem subject to the p-structure shaping and protection constraints. Based on the dual variables of constraints (2) in the master problem, the pricing problem decides on the shape and the protection capability of each p-structure it generates.

We define the variables of the pricing problem as follows:

$$r^{\ell',\ell_j}_{\ell_1,\ell_2}(j \in \{1,2\}) = \begin{cases} 1 & \text{if } \ell' \text{ protect link } \ell_j \text{ in case of} \\ & \text{a dual failure on links } \ell_1, \ell_2 \\ 0 & \text{otherwise.} \end{cases}$$

$$x_\ell = \begin{cases} 1 & \text{if } \ell \text{ is used for protection} \\ 0 & \text{otherwise.} \end{cases}$$

$$y_\ell \in \mathbb{Z}^+ \quad \text{is the number of protected working channels}$$
$$\text{on link } \ell \text{ provided by the current } p\text{-structure.}$$

The objective function of the pricing problem, i.e., minimization of the reduced cost of the master problem is deduced as follows:

$$\min \left(\sum_{\ell \in L} b_\ell - \sum_{\ell \in L} \theta_\ell a_\ell \right)$$

where $\theta_\ell (\ell \in \mathcal{L})$ are the dual variable values associated with constraints (2). Re-expressed the objective function in terms of the pricing variables leads to the following new expression:

$$\min \left(\sum_{\ell \in L} x_\ell - \sum_{\ell \in L} \theta_\ell y_\ell \right)$$

We define the set of adjacent links to a set of nodes $V \subset N$ (so called co-cycle of V in graph theory) by:

$$\omega(V) = \Big\{ \ell = \{i,j\} \in L : i \in V, j \notin V \Big\}.$$

The constraints that shape and decide the protection capability of each p-structure are divided into two sets: The first (4)–(6) constraints are dual failure model dependent ($\mathcal{P}$ dependent), and the second set of constraints is oriented to set the protection capability and shape of each candidate p-structure.

$$\mathcal{P}^{\ell_1,\ell_2} \times r^{\ell_1,\ell_2}_{\ell_1,\ell_2} = 0 \qquad \ell_1, \ell_2, \in \mathcal{L} \tag{4}$$

$$\mathcal{P}^{\ell_1,\ell_2} \times r^{\ell_2,\ell_1}_{\ell_1,\ell_2} = 0 \qquad \ell_1, \ell_2 \in \mathcal{L} \tag{5}$$

$$\mathcal{P}^{\ell_1,\ell_2} \times (r^{\ell',\ell_1}_{\ell_1,\ell_2} + r^{\ell',\ell_2}_{\ell_1,\ell_2}) \leq 1 \qquad \ell_1, \ell_2, \ell' \in \mathcal{L}. \tag{6}$$

This set of constraints is used to avoid protection conflicts when link pairs are susceptible to fail at the same time. Constraints (4) and (5) are used to forbid inter-link protection between any pair of links ℓ_1, ℓ_2 when they belong to the same SRLG (i.e., $\mathcal{P}^{\ell_1,\ell_2} = 1$). Indeed, if ℓ_1 and ℓ_2 are susceptible to fail at the same time ($\mathcal{P}^{\ell_1,\ell_2} = 1$), then, neither ℓ_1 can protect ℓ_2 i.e., $r^{\ell_1,\ell_2}_{\ell_1,\ell_2} = 0$, nor ℓ_2 can protect ℓ_1, i.e., $r^{\ell_2,\ell_1}_{\ell_1,\ell_2} = 0$) Constraints (6) are used to avoid for any link ℓ' to protect both of links ℓ_1, ℓ_2 of any SRLG when they are susceptible to fail at the same time ($\mathcal{P}^{\ell_1,\ell_2} = 1$). In such a case, ℓ' can only protect one of the two links.

$$\sum_{\ell' (\ell' \neq \ell_j) \in \omega(\mathcal{N})} p^{\ell',\ell_j}_{\ell_1,\ell_2} \geq y_{\ell_j} \quad \mathcal{N} \subset \mathcal{V}, \ell_1, \ell_2 \in \mathcal{L}$$
$$\ell_j \in \{\ell_1, \ell_2\}, \tag{7}$$

$$r^{\ell_1,\ell_1}_{\ell_1,\ell_2} = 0 \qquad \ell_1, \ell_2, \in \mathcal{L} \tag{8}$$

$$r^{\ell_2,\ell_2}_{\ell_1,\ell_2} = 0 \qquad \ell_1, \ell_2 \in \mathcal{L} \tag{9}$$

$$p^{\ell',\ell_j}_{\ell_1,\ell_2} \leq x_{\ell'} \qquad \ell_1, \ell_2, \ell' \in \mathcal{L}, \ell_j \in \{\ell_1, \ell_2\} \tag{10}$$

$$p^{\ell',\ell_j}_{\ell_1,\ell_2} \in \{0,1\} \qquad \ell_1, \ell_2, \ell' \in \mathcal{L}, \ell_j \in \{\ell_1, \ell_2\} \tag{11}$$

$$x_\ell \in \{0,1\}, y_\ell \in \mathbb{Z}^+ \qquad \ell \in \mathcal{L}. \tag{12}$$

The second set of constraints, (7)-(12), is used to shape the p-structures and decide for their protection. Constraints (7) are used for each link pair ℓ_1, ℓ_2 (either susceptible to fail at the same time or not) to set the number of disjoint backup paths for link $\ell_j \in \{\ell_1, \ell_2\}$ to the minimum number of incident links to the minimum cut (min cut problem) separating the two end-nodes of ℓ_j. This last problem is equivalent to the max-flow min-cut problem in graph theory [37]. Constraints (8) and (9) express that a link ℓ cannot protect itself. Constraints (10) say that a link ℓ' can provide protection for ℓ_j if and only if it (ℓ') is part of the current p-structure (spanned by the p-structure). Constraints (11) and (12) are integrality constraints.

Recall that, in case where $\mathcal{P}^{\ell_1,\ell_2} = 0$ for all ℓ_1, ℓ_2, this optimization model becomes a classical 100% single link failure protection optimization model.

4.3 The solution method

In our CG solution method, we start by solving the linear programming (LP) relaxation of the restricted master problem. This is done through relaxation of constraints (3), i.e., replacing $z^s \in \mathbb{Z}^+$ by $z^s \geq 0$. The dual variables associated with the current optimal solution of the restricted master problem are used for solving the pricing problem, which consists to find a promising p-structure whenever there is one (with a negative reduced cost). This process is repeated until no promising p-structure can be identified, i.e., all remaining p-structures have a non negative reduced cost.

The cost of the optimal solution of the relaxed LP problem, denoted by z^*_{LP}, is a lower bound of the optimal ILP value (z^*_{LP}). In order to obtain the optimal solution to the ILP problem, it is usually required to integrate a branch-and-bound method within the CG approach. However, we calculated the integer solution of the ILP, also denoted $\tilde{z}_{ILP}$, with the so far generated column, and we than observed that the difference $\tilde{z}_{ILP} - z^*_{LP}$ (i.e., the optimality gap (%)) was in the interval $[0, 3\%]$ in all performed experiments. Though, we refrained from embedding our CG solution method within a branch-and-bound framework.

5 Computational results

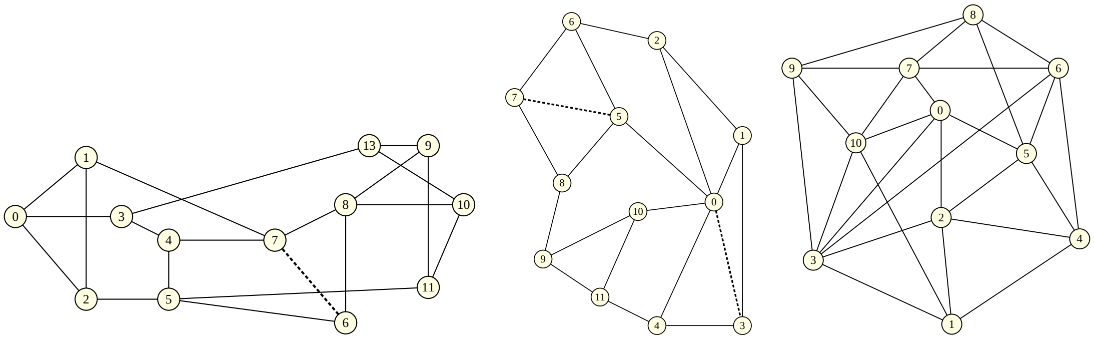
In this section, we present numerical results comparing the performance of the p-structure based scheme with the p-cycle one in [28]. We compare the two protection methods in terms of required spare capacity to provide $R_1 = 100\%$ and different R_2 levels.

By Menger's theorem [38], a graph is $k-$connected if and only if there are k edge-disjoint paths between every pair of nodes in the network, thus the removal of any $k - n$ edges will leave the graph $n-$connected. In communication networks, in order to design a fully survivable dual link failure scheme, the network physical topology should be at least 3-connected, i.e., all the nodes (all sub networks) should have at least three incident disjoint links (three-edge cuts). In Figure 6 we illustrate the three network topologies used in our study. To meet the 3-connectivity requirement for dual link failure survivability, we modified the NSF [39] and Polska [40] by the addition of the illustrated dashed lines, and kept the original COST239 [41].

The three modified network topologies NSF, Polska, and COST239 have an average nodal degree of 3.22, 3.33 and 4.72, respectively. For all networks, we consider a uniform traffic distribution and an arbitrary dual link failure model.

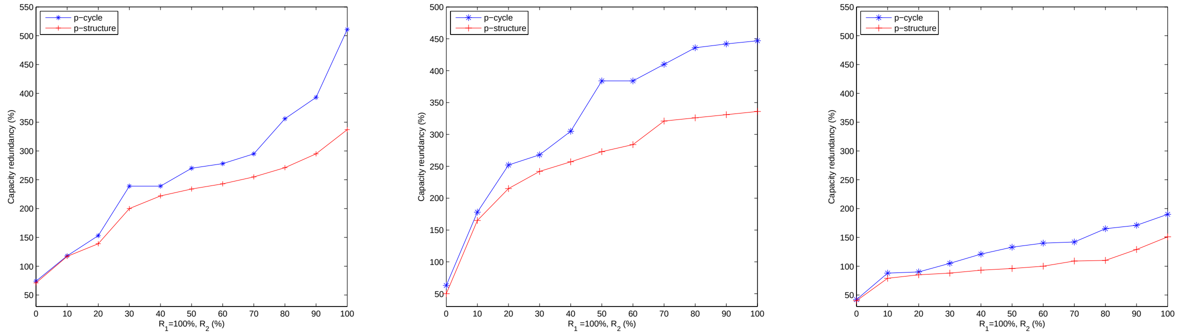
In Figure 7, we see the variation of the capacity redundancy (y-axis) as a function of the dual link failure restorability (x-axis) in the p-cycle and p-structure schemes. We recorded a $\sim [3\%, 5\%]$ of protection capacity saving with the p-structure based scheme over the p-cycle one when the objective is to reach $R_1 = 100\%$ and $R_2 = 0\%$ (origin of each plot) in all network topologies. The difference in spare capacity between the p-cycle and p-structure based schemes increases as the dual link failure restorability increases.

The required amount of spare capacity to provide $R_2 = 100\%$ in the p-cycle based protection scheme is ~ 5.2 and 4.5 the amount of protected capacity ($\sim 520\%$, and $\sim 450\%$ capacity redundant) in the NSF and Polska networks (sparse networks), respectively. The same $R_2 = 100\%$ level costs 150% and 100% less protection capacity when there is no constraint on the shape of the protection structures (using p-structures).



(a) Modified NSF Network (b) Modified Polska Network (c) COST239 Network

Figure 6: Network topologies



(a) NSF Network (b) Polska Network (c) COST239 Network

Figure 7: Capacity redundancy vs. dual link failure restorability

The saving in protection capacity related to the different R_2 levels in the p-structure over the p-cycle scheme varies in the interval $[5\%, 150\%]$ and $[5\%, 100\%]$ in the NSF and Polska networks, respectively. This difference is accentuated by the increasing level of R_2.

NSF and Polska networks are relatively sparser compared to COST239. Providing a dual link failure survivability even for a small class of traffic may cost excessively high when the network topology is sparse. COST239 offers a more effective support of dual link failures with both the p-cycle and p-structure based schemes. Thanks to its physical connectivity, dual link failures can be survived by rerouting the affected connections through diverse other protection paths. Furthermore, as there is no constraint on the shape of the protection structures in the (p-structures), this scheme is more likely to provide flexible and more efficient protection allocation than the p-cycle scheme. The saving in protection capacity in this case ranges within the interval $[5\%, 50\%]$.

In order to characterize the two protection schemes based on p-structures and p-cycles, we reported in Tables 1 and 2 some additional characteristics related to the shape of their protection structures, respectively. We considered three R_2 levels: 10%, 50% and 100%, and two topologies: NSF and COST239.

In Table 1, we recorded the number of p-cycles and p-structures in the optimal solutions of the two design problems in order to provide 10%, 50%, and 100% dual link failure survivability. We remark that the number of required distinct p-cycles in both networks, and p-structures in the NSF network increases as the level of R_2 increases. The number of p-structures in COST239 network varies differently from the others: for any R_2 level, this number is smaller than the number of required p-cycles. These variations come from the fact that when a higher number of SRLGs are assumed then larger number of distinct structures (especially sparse structures, e.g., p-cycles) are needed, especially in sparse networks (e.g., NSF network).

Table 1: Number of protection structures in the p-cycle and p-structure schemes

	R_2 = 10%		R_2 = 50%		R_2 = 100%	
	NSF	COST239	NSF	COST239	NSF	COST239
p-cycle	12	16	19	19	20	22
p-structure	13	11	14	15	19	11

Table 2: Protection parameters $p-$structure vs. p-cycle

	NSF Network												COST239 Network											
	R_2 = 10%				R_2 = 50%				R_2 = 100%				R_2 = 10%				R_2 = 50%				R_2 = 100%			
	$\bar{\mathcal{X}}_{x_\ell}$	σ_{x_ℓ}	$\bar{\mathcal{Y}}_{y_\ell}$	σ_{y_ℓ}	$\bar{\mathcal{X}}_{x_\ell}$	σ_{x_ℓ}	$\bar{\mathcal{Y}}_{y_\ell}$	σ_{y_ℓ}	$\bar{\mathcal{X}}_{x_\ell}$	σ_{x_ℓ}	$\bar{\mathcal{Y}}_{y_\ell}$	σ_{y_ℓ}	$\bar{\mathcal{X}}_{x_\ell}$	σ_{x_ℓ}	$\bar{\mathcal{Y}}_{y_\ell}$	σ_{y_ℓ}	$\bar{\mathcal{X}}_{x_\ell}$	σ_{x_ℓ}	$\bar{\mathcal{X}}_{y_\ell}$	σ_{y_ℓ}	$\bar{\mathcal{X}}_{x_\ell}$	σ_{x_ℓ}	$\bar{\mathcal{Y}}_{y_\ell}$	σ_{y_ℓ}
$p-$cycle	9.2	2.5	9.0	8.3	9.8	2.5	3.6	3.8	11.7	2.4	2.3	0.9	8.4	1.6	8.2	4.0	9.6	1.2	6.4	1.7	10.2	1.2	5.3	1.0
$p-$structure	9.0	3.6	7.9	8.7	10.6	3.5	4.6	4.3	13.0	4.2	3.9	2.0	7.4	6.1	9.8	11.5	8.5	4.9	7.5	8.5	11.7	10.0	7.2	8.4

In Table 2, we studied more in depth the shape and protection offered by the p-cycles and p-structures in the two proposed schemes. We considered herein two statistic distributions: The number of spanned links and number of protected links by each p-cycle and p-structure. The two distributions are characterized by $(\bar{\mathcal{X}}_{x_\ell}, \sigma_{x_\ell})$ and $(\bar{\mathcal{Y}}_{x_\ell}, \sigma_{y_\ell})$ which refer to their main value and standard deviation, respectively. We kept the NSF and COST2309 networks, and the three previous R_2 levels i.e., 10%, 50%, and 100%.

In NSF, on average, the number of spanned links by the p-cycles and p-structures increase as the dual link failure resiliency increases. Moreover, as R_2 increases, the p-structures tend to use slightly more links than the p-cycles do. Regarding the number of protected links in the NSF network, the p-structures protect more working links than the p-cycles do. There one exception, in the case $R_2 = 10\%$ where the difference in capacity between the p-structure and p-cycle schemes is $\sim 3\%$ (see Figure 7) and the average number of protected links by the p-cycles is larger than the p-structures. The standard deviations of the two distributions show a slightly larger discrepancy in the size (spanned links) and protected links between the p-structures and p-cycles. There is a larger difference among the p-structures in terms of size and protected links than among the p-cycles. This discrepancy in size and protection explains the difference in protection performance in Figure 7 ($R_2 = 10$ in NSF) and in Table 2.

In COST239 network, the same trend is observed regarding the size of the p-cycles and p-structures (number of spanned links). This parameter varies in line with R_2. The major difference with the NSF network is in the distributions of the protection and protected links of the p-cycles and p-structures. The size and number of protected link discrepancies in the p-structures distribution are almost equal to the p-structure average size and to the average number of protected links by each p-structure, respectively. In other words, there are more different p-structures (larger and smaller) with different protection capabilities than p-cycles. The flexibility in capacity allocation and distribution offered by the p-structure based scheme is better than the one offered by the p-cycle one, and this is corroborated by the protection capacity cost saving.

6 Conclusion

We proposed a protection capacity design framework for link-failure survivable networks that guarantees two quantified QoP classes: 100% single link and optimized dual link failure protection R_2 under a network failure model based on a discrete probabilistic distribution. We proposed a compact ILP formulation for the design problem, and used a scalable and efficient solution method based on a large scale optimization tool, named column generation. In our optimized design, allocation of protection capacity is performed in order to optimize the survivability of the network, without assuming any pre-defined shape protection plane. Therefore, all the possible protection structures are considered as candidates, provided that they can meet the needs of the different QoP classes.

We compared our proposal of p-structure scheme to the p-cycle based one in terms of protection capacity redundancy to provide the same R_1 and R_2 levels. We showed how protection capacity allocation and the construction of the overlay protection topologies (structure) is important in order to improve the network availability and to survive different link failure scenarios. A protection capacity saving of up to 50% in relatively dense network (COST239), and up to 150% in sparse networks (NSF, Polska). Another interesting finding is the size of the protection structures which increases as the required R_2 level increases in both COST239 and NSF networks. This reinforces the obtained results in [28], but is in contrast to what has been observed in [29] about the relation between the size of the protection structures and their resiliency. The p-structure scheme allows construction of flexible topologies that can effectively meet the requirement of different QoP classes.

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