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Abstract

The introduction of new applications that require high bandwidth, high service availability and reliability has generated many researches in the design of efficient survivable Wavelength Division Multiplexing (WDM) networks in order to respond to the growing demands of quality-of-service in telecommunication networks. Various design methods of survivable WDM networks have been proposed in order to increase the reliability of optical networks and thus their availability. Pre-configured and reserved protection capacity is the most widespread approach, and involves a backup protection plane that will be used in case of a failure in the network. In order to minimize the investment in protection capacity and meet the targeted resiliency, a decisive design concern is to minimize the required spare capacity budget to provide 100% protection against any single link failure.

In this paper, we explore the idea of designing protection planes using structures (called p-structures) with different shapes, each with its specific recovery delays, management overhead to recover from failure, and scalability warranty, as to better answer the various required qualities of services while addressing the different protection performance and efficiency parameters. While doing so, we propose a unified framework for the pre-planned protection design using p-structures, drawn after a general shapeless p-structure scheme, from which we can derive all the pre-configured protection structures already studied in the literature. We quantitatively compare all the already studied pre-planned protection structures under asymmetric traffic, among themselves and with the shapeless p-structures. Comparisons are made possible thanks to a unified column generation modeling. It enables an analysis of the pros and cons of the different pre-planned protection schemes.

Key Words: Resilient WDM networks, Pre-configured protection schemes, Column generation.

Résumé

L'introduction de nouvelles applications très gourmandes en bande passante, et qui demandent un temps de disponibilité du service avoisinant les 100%, a généré beaucoup de recherches dans le design de topologies résistantes aux pannes dans les réseaux optiques à multiplexage en longueur d'ondes.

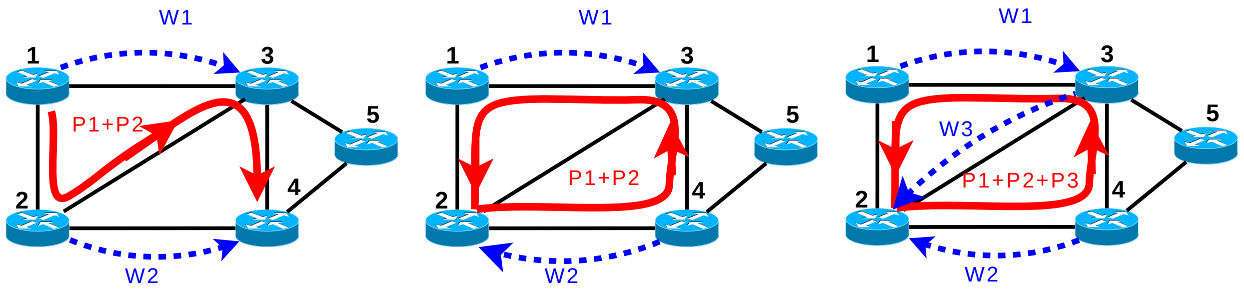
Dans cet article, on explore une nouvelle approche de design de schémas de protection basée sur les p-structures. La nouveauté de cette approche est que l'on ne se limite pas à des structures de formes pré-définies. On élabore des modèles mathématiques pour sélectionner les structures de protection les plus efficaces en terme de coût indépendamment de leurs formes.

1 Introduction

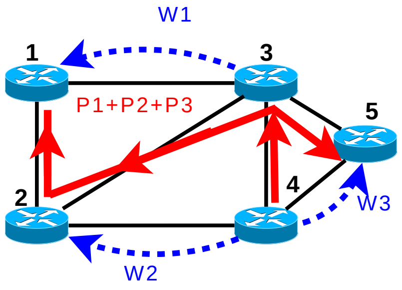
Wavelength Division Multiplexing (WDM) is the access technology that can economically and effectively supply the increasing demand for high bandwidth in backbone optical networks. In WDM networks, the frequency light band is divided into several sub bands, each carrying a single communication signal (wavelength channel). Thanks to the recent advances in optical signal transmission and processing, multiple wavelength channels of up to 40 Gbps can be multiplexed on a single optical fiber (duct) in today optical networks. Therefore, a fiber duct (pipe) can be filled up with multiple wavelength channels and carry out several Tbps. The tremendous capacity brought by the WDM technology to optical networks comes with a vulnerability issue in case of failures. Indeed, as the transport capacity of fibers is highly extended, a failure of any network component, even for a short period of time, can result in a tremendous traffic loss and traffic disturbance [9].

Survivable WDM optical networks are endued with mechanisms in order to recover automatically from network failures. Under normal operations, the traffic flow between two nodes is carried out on an end-to-end path (or, set of paths), called the *working path*. In case of a fiber failure (e.g., a cable cut), the recovery mechanism searches for an alternative *backup path* that is link (or node) disjoint from the working path, and switches the working traffic on it. The effective approach to perform recovery is, ahead of failures, through backup capacity reservation, or what is commonly called pre-configured (or pre-planned) protection capacity. Indeed, as backup capacity is reserved ahead of failures, the recovery mechanism will resume to backup path setting and traffic switching when a failure occurs. In addition, as backup paths are pre-reserved, the perturbed traffic is guaranteed to be recovered within a limited short delay (delay to set up backup paths).

Many different protection approaches using pre-configured capacity to achieve optimized resiliency against fiber failure (most common failure) have been proposed in the literature. The proposed protection schemes have been named after the shape of their protection structures, e.g., linear segment or path protection, rings, *p*-cycles [10] or *p*-trees [17, 30].



(a) Shared backup link protection (b) Ring protection (c) *p*-Cycle protection



(d) *p*-Tree protection

Figure 1: Pre-configured protection structures

The linear segment and path structures can be used either to protect end-to-end disjoint working paths or fiber links [18, 19], and shared by different connections as well as dedicated to protect only one connection. In Figure 1(a), the two working link channels (dashed lines) W_1 on link $\ell_1 = (v_1, v_2)$ and W_2 on link $\ell_2 = (v_3, v_4)$

are protected by the two linear backup paths (bold lines) $p_1 = (v_1, v_3, v_2)$ and $p_2 = (v_3, v_2, v_4)$ respectively. The two backup paths use one directed backup link channel along the spanned fiber links, and share the backup channel on link (v_2, v_3). Protection schemes based on linear structures offer high flexibility and scalability in providing protected capacity. Indeed, they can be effectively updated to protect new dynamic traffic patterns by an incremental extension of the existing protection structure, or by reshaping it to reduce the protection cost. In addition, high flexibility and sharing of protection capacity can be attained especially in sparse networks [12].

The ring protection structure has been initially deployed in ring access networks to provide protection for its on-ring links (links spanned by the protection ring). In case of a link failure, only the two end-nodes adjacent to the failed link need to perform dynamic rerouting of the perturbed traffic along "the long way" around the ring. Intermediate nodes along any backup path forward the traffic received on the incident link through its outgoing link on the protection structure. It thus results in a high speed recovery scheme. Figure 1(b) shows a case where working link channels W_1 and W_2 are sharing a ring protection structure. A single link failure on link $\ell_1 = (v_1, v_3)$ (resp. on $\ell_2 = (v_4, v_2)$) alters both the working paths W_1 and W_2 going through ℓ_1 (resp. ℓ_2) and the protection ring (Figure 1(b)). Working paths W_1 (resp. W_2) can be recovered around the ring through the backup path $P_1 = (v_1, v_2, v_4, v_3)$ (resp. $P_2 = (v_4, v_3, v_1, v_2)$). The recovery process is only performed at the two end-nodes of the failed link, e.g., at nodes v_1 and v_3 for link (v_1, v_3) by switching the working capacity on link (v_1, v_2) at node v_1, and incoming traffic along link (v_4, v_3) at node v_3 is send along the link (v_3, v_5) without any reconfiguration of the switch. Ring-based protection has been shown to be capacity inefficient when it is applied to mesh networks. The reason is that many protection rings may be required to provide 100% protection which results in a high spare capacity cost [4].

In [3, 10], Grover and Stamatelakis have extended the ring protection scheme and proposed a new capacity efficient scheme named pre-configured protection cycle or p-cycle. A p-cycle is a ring layout, thus inherits the fast restoration speed of rings. Moreover, in addition to the protection provided for on-cycle links, a p-cycle provides protection to links whose two end-nodes are on the p-cycle but not on the p-cycle itself (e.g., link (v_3, v_2) in Figure 1(c)), known also as straddling-cycle links. In Figure 1(c), in addition to the on-cycle links that are provided protection, the straddling-cycle working channel W_3 on link (v_3, v_2) can be provided one unit of protected capacity through the backup path $P_3 = (v_3, v_1, v_2)$. The p-cycle method has been justified theoretically to be a priori the most efficient pre-configured protection scheme in terms of capacity and switching delay [3]. However, because of their protection capacity requirement (i.e., more protection capacity than for linear structures), the p-cycle flexibility and efficiency in sparse networks or within constrained protection capacity budget is not as good as in highly connected networks [23, 12].

Among protection structures of predefined shapes, trees have received a lot of attention from researchers in optical network design. Several variants of protection schemes based on trees have been proposed: Pure p-trees [3, 11], hierarchical p-trees [25, 27], and redundant path protection trees [17, 30, 8, 7, 29]. Interest in protection tree structures has been motivated by their flexibility, scalability, and the rich literature on tree construction algorithms (distributed, centralized). Link protection schemes based on pure p-tree structures can provide protection only for straddling-tree links. Figure 1(d) illustrates a single shared p-tree that provides protection for its straddling working channels W_1, W_2, and W_3 on links $\ell_1 = (v_1, v_3)$, $\ell_2 = (v_2, v_4)$, and $\ell_3 = (v_5, v_4)$ respectively.

In order to provide 100% failure recovery, a p-tree based protection scheme needs to setup as many p-trees as possible in order to protect all the working channels. The main drawback of p-tree based schemes lies in their capacity inefficiency which can grow up to 200% [11]. However, their local restoration capabilities and flexibilities make them attractive in some specific networks.

So far, we have reviewed existing protection schemes in survivable WDM networks. All the existing protection schemes are based on predefined shape structures, i.e., the shape of the protection structures is chosen ahead of the definition of the protection scheme. Pre-defined shape protection structures, e.g., p-cycles are characterized by their a-priori protection efficiency, i.e., capacity efficiency (on-cycle and straddling-cycle links are protected in p-cycle) and recovery delay (only end-nodes perform dynamic switching in a p-cycle).

However, their efficiency and flexibility in tracking different traffic patterns and providing a required level of resiliency within an optimized protection capacity budget may be affected by their pre-defined shapes.

In this paper, we present a new general approach for setting the best overlaid protection made of protection structures with unrestricted shapes, called p-structures. Based on the traffic patterns, and with respect to a given optimization objective, we propose a framework for pre-planned protection design independently of the shape of the protection structures. The benefit of considering p-structures is twofold: It gives a better theoretical understanding of the other protection structures and it enables us to calculate theoretical bounds for the required protection capacity in order to optimize any quality-of-service protection parameter.

The remainder of this paper is organized as follows. Section 2 gives an overview of all the existing design approaches of predefined shape protection schemes for single link protection in survivable WDM networks, and ends with our contributions of independent shape structure p-structure scheme. Section 3 provides a generic mathematical model for identifying the best p-structures, from which we can derive specific mathematical models for each of the already studied predefined shape protection schemes. Extensive comparative performances are reported in Section 5, together with a discussion on how the performance parameters vary according to the network and traffic instances. Conclusions are drawn in Section 6.

2 Design of Pre-Configured Protection Schemes

2.1 State of the Art

The design problem of link-restorable WDM using pre-defined shape structures has attracted many researchers in the optical network community. Its corresponding optimization problem has been widely tackled by a two-step optimization approach, where the first step consists in identifying a set of promising eligible protection structures, i.e., paths, segment paths, p-cycles or p-trees, and the second step amounts to solving an Integer Linear Program (ILP) program where one selects the best protection structures in order to optimize the objective (e.g., minimize the network or the bandwidth or the node equipment cost).

Most access networks using WDM technology are based on ring topology. Indeed, therein, the design of a protection scheme is an easy task as the required amount of spare capacity to provide 100% restorability is equal to the amount of protected capacity. In mesh networks, designing a protection plan is more complex than in a ring due to the number of rings that are necessary to provide 100% survivability [9]. In [4], the authors have proposed an Automatic Protection Switching (APS) for link protection based on interconnecting the protection fibers in order to create a family of directed rings. The design problem is dealt with by inspection procedures of the mesh topology, and dividing it into different sub ring topologies. Different enumeration approaches have been proposed like node covering [28], cycle covering [4], ring covering [6], and double cycle covering [5].

Linear protection structures offer more flexibility in the design of protection schemes, especially in sparse networks [12]. Protection scheme based on linear structures can be either dedicated or shared, link or path oriented. In [15], the authors proposed ILP optimization models, and compared path and link protection in terms of spare-capacity utilization in order to provide 100% restoration in ATM mesh networks. Their design assumes the existence of two sets of working and restoration paths for each connection. In [18], the authors proposed ILP models for joint working and protection in dedicated and shared path protection, and shared link-protection schemes. A set of link disjoint routes between each node pair is assumed to be given, and the optimization objective is to minimize the total number of channels used on all the links. While restricting the path search in a potential path set addresses the time and space high consumption, it prevents from guaranteeing the optimal combination of paths, which may or may not be far from the heuristically output one. In [13], the authors added a limitation on the number of hops within a sequential optimization framework, in order to take into account some end-to-end delay recovery limits. In [9], a genetic algorithm has been used in order to generate eligible and better valued routes for working paths in shared path link protection schemes.

The two-step design approach has been used in many other schemes based on pre-defined shape protection structures like p-cycles and p-trees [25, 24, 20, 26, 18]. Protection schemes based on those structures usually include a pre-processing step consisting of enumerating explicitly all the cycles or the most valuable ones. Different limited p-cycle enumeration approaches have been proposed in [2] in order to increase the scalability of the optimization approach. However, all the proposed approaches that consist in fully or partially enumerating all the p-cycles in a network have been shown inefficient and non scalable in [21]. Column generation based solution methods have been applied in some design problems of survivable WDM networks based on p-cycles and p-trees [23, 21, 22, 16], and performance comparison regarding different protection parameters of those protection structures are provided in [23].

2.2 Pre-Configured Structure (p-Structure) Schemes

Restricting the shape of the candidate structures in the design of pre-configured protection schemes to a single shape has been adopted in order to simplify the related optimization problem. However, the performance and flexibility of the resulting protection scheme is highly depend on the shape of the protection structure, and less adapted to the varying traffic patterns. Let us consider the p-cycle in Figure 2.2 that protects the two link channels represented by the dashed links. We can evaluate its efficiency by its a-priori reliability (AR), i.e., how much traffic it could protect (Figure 2.2-(a)), and its effective reliability (ER), i.e., what it effectively protects (Figure 2.2-(b)). The proposed p-cycle can a priori protect 9 working channels (all the on-cycle and straddling-cycle links), however, as the ongoing traffic is only two link channels, the effectively protected capacity is 2 channels. This illustrates how inflexible are the protection schemes based on predefined shape protection, in providing protection within specific traffic patterns. Independently of the shape of the protection structure, the optimal protection scheme in this case is the one illustrated in Figure 3.

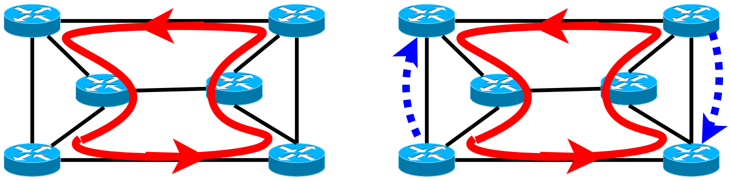

(a) AR = 9 channels (b) ER = 2 channels

Figure 2: p-cycle: AR $\neq$ ER

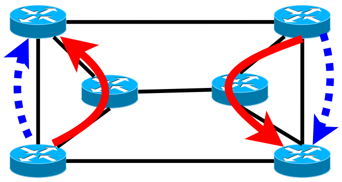


Figure 3: p-structure scheme

The design problem of survivable WDM networks using p-structures can be assimilated to a multi dimensional bin packing problem in combinatorial optimization. The dimension of the bin is measured by the number of links it is made of, and the objective is to select the protection structures that minimize the required protection capacity in order to achieve a targeted utility (in our case 100% reliability). Thus, using only pre-defined shape structures spanning specific dimensions may leave other dimensions unfilled because of their inflexibility in filling up uniformly the bin space.

In this paper, we propose a design of survivable WDM networks using protection structures with unrestricted shape. We develop a generic design model that is easily adaptable to generate any restricted shape protection structures. We define a generic column generation mathematical model where the selection of the protection structures is made in the master problem, and the design of the protection structures in the pricing problem.

3 A Generic Model for Protection Structures with Arbitrary Shapes

3.1 A Generic Model

We consider an optical WDM network, represented by a directed graph $G = (V, L)$ where V and L are the sets of nodes and links (arcs) indexed by v and ℓ, respectively. Between any two connected nodes, we assume two directional fibers in opposite directions, and ℓ denotes a generic link associated with a directional fiber. We denote by $\omega^+(v)$ (resp. $\omega^-(v)$) the set of outgoing (resp. incoming) links of v. We assume that there are no capacity limits on the links. Traffic is defined by the amount of bandwidth units $D_{sd} > 0$ for every pair of origin-destination nodes $(v_s, v_d) \in \mathcal{SD}$, where $\mathcal{SD}$ is the set of node pairs with traffic from v_s to v_d.

The model that is proposed below corresponds to a joint optimization of the working routes and the protection structures where the objective is to minimize the routing and protection costs. No assumptions are made on the shapes of the protection structures: Rings, p-cycles, p-trees, p-trails … are all among the potential p-structures. The choice of the shape of the protection structures is governed by the optimization criterion. Routing costs are such that the cost of routing one capacity unit on link ℓ is equal to c_ℓ. The requested number of bandwidth units from a source v_s to a destination v_d is modeled with flow variables φ_ℓ^{sd}, i.e., the number of bandwidth units to be carried out throughout link ℓ for the origin-destination (v_s, v_d) bandwidth requirements. Let P be the set of all possible protection structures. Each protection structure $p \in P$ uses a set of links $\ell \in p \subseteq L$ with spare capacity, such that $c_p = \sum\limits_{\ell \in p} c_\ell$ is equal to a spare bandwidth capacity unit structure cost.

In order to guarantee 100% restorability against any single span[1] failure (as links in opposite directions between two nodes share the same risk), we usually need a set of several protection structures, called p-structures. The number of required copies of each protection structure p is designated by the variable y_p. The protection relationship between a p-structure $p \in P$ and the links ℓ it protects, is defined by the coefficients of the matrix $A = (a_{\ell p})$ where $a_{\ell p} \in \mathbb{Z}^+$ is equal to the number of distinct backup paths, i.e., number of bandwidth capacity units, provided by the p-structure p to link ℓ.

We now state the Generic p-Structure (GpS) model which generates the best possible protection structures (p-structures) with respect to the objective z^{OBJ} defined by the working and protection routing costs.

Generic p-Structure (GpS) Model

Minimize:

$$z^{\text{OBJ}} = \overbrace{\sum_{\ell \in L} c_\ell \, \varphi_\ell^{sd}}^{\text{routing working costs}} + \overbrace{\sum_{p \in P} c_p \, y_p}^{\text{protection costs}}$$

subject to:

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^{sd} - \sum_{\ell \in \omega^-(v)} \varphi_\ell^{sd} = \begin{cases} D_{sd} & \text{if } v = v_s \\ -D_{sd} & \text{if } v = v_d \\ 0 & \text{otherwise} \end{cases} \qquad v \in V, (v_s, v_d) \in \mathcal{SD} \tag{1}$$

$$\sum_{p \in P} a_{\ell p} \cdot y_p - \sum_{(v_s, v_d) \in \mathcal{SD}} \varphi_\ell^{sd} \geq 0 \qquad \ell \in L \tag{2}$$

$$y_p \in \mathbb{Z}^+ \qquad p \in P \tag{3}$$

$$\varphi_\ell^{sd} \in \mathbb{Z}^+ \qquad (v_s, v_d) \in \mathcal{SD}, \ell \in L. \tag{4}$$

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[1] A span is the physical entity corresponding to the collection of all unit capacity links in parallel between two adjacent nodes.

The objective function evaluates the routing and protection routing costs. Constraints (1) ensure that the requested number of bandwidth units (bandwidth demand) is satisfied for every origin-destination node pair $(v_s, v_d) \in \mathcal{SD}$. Constraints (2) guarantee the allocation of protection structures to the protection of the working traffic in the network on each directed fiber link. Constraints (3) and (4) define the domains of variables y_p and φ_ℓ^{sd}.

The set P of p-structures can be constructed either off-line or on-line. As soon as the size of the network or the number of node pairs with traffic goes beyond a tens, it becomes very difficult to solve the model if all possible protection structures need to be explicitly generated. Then, there are two options. The first one is to go on with an off-line generation, but only of the most promising p-structures. It then leads to a heuristic solution scheme even if the resulting ILP model is solved exactly. The second option, and that is the one we will investigate in the sequel, is to deal with an on-line generation of the most promising structures with the help of the column generation techniques for the linear relaxation and of a specific algorithm (to be discussed later) for deriving integer solutions.

3.2 Solution of the GpS Model

The GpS model is a large scale Integer Linear Program (ILP) and, as such, will be solved using a branch-and-bound algorithm on a restricted set of variables. Although this can be viewed as a heuristic solution, we will see in the numerical results (Section 5) that, in practice, we get near optimal solutions with a very high precision, i.e., an average optimality gap below 0.1 %. Such a high precision is satisfactory and entitles us to make a fair evaluation of the performances and the efficiencies of the p-structures in comparison with the previously studied pre-defined protection structures.

Due to its large scale, the Linear Programming (LP) relaxation of the GpS model will be solved thanks to column generation techniques, and the restricted set of variables to be taken into account in the ILP solution will be in one-to-one correspondence with the set of generated columns until reaching the optimal LP solution.

In order to solve the continuous relaxation of the GpS model with a column generation model, we need to specify a decomposition scheme. Indeed, the GpS model of the previous section can be reinterpreted as a master problem in a column generation framework, that can be fed by an overlay network made of p-structures. Therefore, the pricing problem will be defined as a p-structure generator without any restriction on the shape of the protection structures. In order to remain with a scalable solution algorithm, instead of developing a branch-and-price algorithm, we will solve the integer linear program associated with the set of generated columns until the optimal solution of the continuous relaxation is reached.

The column generation algorithm iterates as long as a p-structures that improve the value of the objective function can be found, i.e., as long as p-structure with a negative reduced cost can be generated. The reduced cost of the variables y_p associated with the p-structures can be expressed as follows:

$$\overline{c}_p = c_p - \sum_{\ell \in L} a_\ell \, u_\ell,$$

where u_ℓ are the dual variables associated with constraints (2).

Given an optimal linear programming solution for a reduced set of structures, we get a set of dual variables u_ℓ from constraints (2). These correspond to the current cost for protecting a directed link $\ell \in L$. The sub-problem corresponding to a p-structure generation is intended to enumerate oriented structures of unrestricted shapes. In order to do so, we define three sets of variables. The first set is made of binary variables x_ℓ such that x_ℓ is equal to one if the directed link ℓ is part of the p-structure, and 0 otherwise. The second set is composed of binary variables $p_{\ell\ell'} \in \{0, 1\}$ such that $p_{\ell\ell'} = 1$ if there exists a restorability on the directed link ℓ' by the current p-structure that uses the directed link ℓ. In other words, $p_{\ell\ell'}$ indicates whether the current p-structure can provide an alternative backup path along ℓ for ℓ'. Finally, the third set of variables $z_\ell \in \mathbb{Z}^+$ is used to count how many alternative backup paths the current protection plan provides on directed links ℓ. We denote the source and the destination of a directed link ℓ by s_ℓ and d_ℓ respectively, and by $\overline{\ell}$ the link of opposite direction for ℓ. With these definitions, we can now define the unrestricted-shape p-structure optimization pricing problem:

Minimize:

$$\overline{c}_p \;=\; c_p - \sum_{\ell \in L} a_\ell \, z_\ell \;=\; \sum_{\ell \in L} c_\ell \, x_\ell - \sum_{\ell \in L} a_\ell \, u_\ell$$

subject to:

$$\sum_{\ell \in \omega^+(v), \ell \neq \ell'} p_{\ell\ell'} - \sum_{\ell \in \omega^-(v), \ell \neq \ell'} p_{\ell\ell'} = \begin{cases} z_{\ell'} & \text{if } v = s_{\ell'} \\ -z_{\ell'} & \text{if } v = d_{\ell'} \\ 0 & \text{otherwise} \end{cases} \qquad v \in V, \ell' \in L \tag{5}$$

$$p_{\ell\ell'} \leq x_\ell \qquad \ell \in L, \ell' \in L : \ell' \neq \ell \tag{6}$$

$$x_\ell + x_{\overline{\ell}} \leq 1 \qquad \ell \in L \tag{7}$$

$$z_\ell \in \mathbb{Z}^+, x_\ell \in \{0,1\} \qquad \ell \in L \tag{8}$$

$$p_{\ell\ell'} \in \{0,1\} \qquad \ell \in L, \ell' \in L. \tag{9}$$

Constraints (5) ensure $z_{\ell'}$ alternative backup paths for link ℓ'. The source and destination nodes of the protected oriented-link ℓ' have, each, $z_{\ell'}$ adjacent protecting oriented-links (originated at the source node and incident to the destination node). At all the remaining nodes (except source and destination of the protected oriented-link), these constraints guarantee protection capacity conservation. Constraints (6) say that a backup path can span a link only if it is part of the p-structure. Constraints (7) prevent the current p-structure from using both a link ℓ and the link $\overline{\ell}$ in the reverse direction. Finally, domain constraints (3) and (4) define the domains of variables x_ℓ, z_ℓ and $p_{\ell\ell'}$.

In the next section, we detail how to build protection plans with p-structures of a specific shape from the above unrestricted-shape based plan. A peculiarity associated with all the formulations except for protection p-trees and p-trails, is that more than one protection structure may be generated by a given pricing problem, e.g., two (or more) non-connected p-cycles may be found.

4 *p*-Structures with a Pre-Defined Shape

We describe in in the following paragraphs the models for generating particular structures of a predetermined shape.

4.1 *p*-Cycle Protection Structures

We consider simple (elementary) and non simple p-cycles. By non-simple p-cycles, we refer to cyclical structures that can cross any link (in both directions) at most once, and any node an unlimited number of times.

4.1.1 Non-Simple *p*-Cycle

Instead of generating general p-structures, we will now restrict the previous pricing model given by the objective function (3.2) and constraints (5) to (8) such that only non-simple p-cycles can be formed. This can be done with the following set of constraints:

$$\sum_{\ell \in \omega^+(v)} x_\ell = \sum_{\ell \in \omega^-(v)} x_\ell \qquad v \in V \tag{10}$$

With constraints (10), only non-simple p-cycles and p-cycles can be formed.

4.1.2 Simple p-cycle

In order to disallow non-simple p-cycles, we need each node to have at most two incident arcs in the p-cycle. The following constraints allow exactly two or zero adjacent arcs at any given node.

$$\sum_{\ell \in \omega^+(v)} x_\ell + \sum_{\ell \in \omega^-(v)} x_\ell \leq 2 \qquad v \in V \tag{11}$$

$$\sum_{\ell \in \omega^+(v)} x_\ell = \sum_{\ell \in \omega^-(v)} x_\ell \qquad v \in V \tag{12}$$

4.2 Ring Protection Structures

In a ring based protection scheme we need to restrict the protected links to be *on cycle* ones. This can easily be achieved by creating a limitation on the protected flow u_ℓ, with the following set of constraints:

$$z_\ell \leq x_\ell \qquad \ell \in L.$$

4.3 p-Tree Protection Structures

While in undirected graphs, p-tree structures are defined as acyclic graph structures, we need to be more precise for directed graphs. A directed p-tree structure is a loopless graph, such that all arcs are directed from the root to the leaves. In such a tree, only the forward arcs (arcs from a node to one of its descendants) are protected by the p-tree. In order to set the mathematical model for designing p-trees, we first need to decide on the root node in order to set the orientation of the tree. We use the decision variable r such that we r_v to 1 if v is the root node of the searched p-tree structure p, 0 otherwise, for $v \in V$. We next need two decision vectors x and t that are both associated with the tree skeleton: Variable x_ℓ will be equal to 1 if the link ℓ belongs to the tree, and 0 otherwise; variable t_v is equal to 1 if node v belongs to the tree, and 0 otherwise. Furthermore, we need the variables $u_v^{v'}$ such that $u_v^{v'} = 1$ if (i) the node v is the root node ($r_v = 1$) and (ii) the node v' is part of the tree ($t_{v'} = 1$), and 0 otherwise. Then we define a first flow vector p that ensures that a unit flow circulates, for each node v of the tree, from the root to that node. Its aim is to guarantee a proper construction of the tree (i.e., to guarantee a circuit free subgraph) with the flow variables $p_{v\ell} \in \{0,1\}$ along each link ℓ of the path from the tree root toward v. We also need decision vector z such that each variable $z_{\ell'} = 1$ if link ℓ' is protected, 0 otherwise. Note that, in order to facilitate the understanding of the model, we use the ℓ index for a link when dealing with the link design of the tree, and the ℓ' index for designating a protected link by the p-tree under construction. Last, we define the flow vector $\pi = (\pi_{\ell\ell'})$ that defines the protection paths of the forward links ℓ' protected by the p-tree. Given these definitions, we can now define the ILP model for the protection tree sub-problem.

minimize:

$$\sum_{\ell \in L} (c_\ell x_\ell - a_\ell u_\ell)$$

subject to:

$$\sum_{v \in V} r_v = 1 \tag{13}$$

$$\sum_{\ell \in \omega^+(v)} p_{v'\ell} - \sum_{\ell \in \omega^-(v)} p_{v'\ell} = \begin{cases} -t_{v'} & v = v' \\ u_v^{v'} & \text{otherwise} \end{cases} \qquad v, v' \in V \tag{14}$$

$$u_v^{v'} \geq r_v + t_{v'} - 1 \qquad v', v \in V \tag{15}$$

$$u_v^{v'} \leq r_v \qquad v', v \in V \tag{16}$$

$$u_v^{v'} \leq t_{v'} \qquad v', v \in V \tag{17}$$

$$p_{v'\ell} \leq x_\ell \qquad v' \in V, \ell \in L \tag{18}$$

$$\sum_{\ell \in \omega^-(v)} x_\ell = t_v - r_v \qquad v \in V \tag{19}$$

$$x_\ell + x_{\overline{\ell}} \leq 1 \qquad \ell \in L \tag{20}$$

$$z_{\ell'} \leq \frac{1}{2}(t_{s_{\ell'}} + t_{s_{\ell'}}) \qquad \ell' = (s_{\ell'}, d_{\ell'}) \in L \tag{21}$$

$$t_v \geq r_v \qquad v \in V \tag{22}$$

$$\sum_{\ell \in \omega^+(v), \ell \neq \ell'} \pi_{\ell\ell'} - \sum_{\ell \in \omega^-(v), \ell \neq \ell'} \pi_{\ell\ell'} = \begin{cases} z_{\ell'} & v = s_{\ell'} \\ -z_{\ell'} & v = d_{\ell'} \\ 0 & \text{otherwise} \end{cases} \qquad v \in V, \ell' \in L \tag{23}$$

$$\pi_{\ell\ell'} \leq x_\ell \qquad \ell, \ell' \in L : \ell \neq \ell' \tag{24}$$

$$r_v \in \{0,1\}, t_v \in \{0,1\} \qquad v \in V \tag{25}$$

$$u_v^{v'} \{0,1\}, t_v \in \{0,1\} \qquad v, v' \in V \tag{26}$$

$$x_\ell \in \{0,1\}, z_\ell \in \{0,1\} \qquad \ell \in L \tag{27}$$

$$p_{v'\ell} \in \{0,1\} \qquad v' \in V, \ell \in L \tag{28}$$

$$\pi_{\ell\ell'} \in \{0,1\} \qquad \ell, \ell' \in L \tag{29}$$

Constraint (13) ensures that a node is selected for the root of the p-tree under construction. We next ensure that the flow along the protection structure is from the root node to each of the nodes which belongs to the tree. Constraints (14) guarantee a unit flow circulation from the root node to each node belonging to the p-tree, and therefore prevent from cycles to appear in the p-structure design. Constraints (18) impose that a protection flow can only circulate on the p-tree links. Constraints (19) say that a node, except for the root node that has none, has exactly one parent node in the p-tree if it belongs to the p-tree. Constraints (22) ensures that, if a node is the root of the tree, then its tree indicator is equal to 1. Constraints (20) guarantee that a link will not be used in both directions. Constraints (21), together with (24) impose that, in order to be protected, a link should have both end-nodes in the p-tree. Constraints (23) ensure, for each link ℓ' that does not belong to the p-tree under construction, the existence of an alternate backup path, made of tree links, that protects links $\ell' = (s_{\ell'}, d_{\ell'})$. Finally, constraints (25) to (29) define the domains of the optimization variables.

4.4 Line-Segment Protection Structures

A protection p-trail is a protection tree which has never more than one out-going link. This is mathematically expressed with the following set of constraints:

$$\sum_{\ell \in \omega^+(v)} x_\ell \quad \leq \quad 1 \qquad v \in V. \tag{30}$$

Protecting p-trails are obtained by considering the p-tree model of the previous paragraph defined by the equations (13) - (29) with the addition of the set of constraints (30).

5 Results and Discussions

We implemented all the optimization models described in Section 3 (the new GpS model for unrestricted protection structures) and in Section 4 (the five classical shape restricted protection structures), and solved them using a combination of column generation and ILP techniques. All models have the same master problem as the generic GpS model, but different pricing models in order to generate the different shape restricted/unrestricted protection structures. The models and column generation/ILP algorithms were implemented in GAMS version 21.5 [1] and solved using CPLEX version 9.020 [14]. The tests were performed on a Sun Fire E6900 machine equipped with 24 UltraSPARC IV dual-core CPU's, each with at clock frequency of 1200 MHz, and having access to 96 GB memory.

Data for the network instances are described below in Table 1. The network size and the physical connectivity are two key properties that impact the evaluation of the different protection schemes. Physical connection between two adjacent nodes is made of two uncapacitated fiber links, with opposite directions.

Table 1: Network Instances

	Number of		Nodal
Networks	Nodes	Links	Degree
COST239	11	26	4.72
NSF	14	21	3.00
NJ-LATA	11	23	4.00
EON	19	37	3.85

We assume 100% single failure reliability and compare the proposed protection schemes according to two protection metrics: The capacity redundancy (protection capacity over protected working capacity), and the length of the backup paths. The capacity redundancy is the design parameter that reflects the cost of the protection plan. High capacity redundancy implies a high investment in network equipment that will be used only in case of a network failure. Efficient sharing of protection capacity is required in order to provide the required reliability at a low cost. The length of the backup path is another meaningful parameter in the recovery process. Longer backup paths result in longer restoration delays and higher management overheads. Indeed, optical media used in the transport of data channels are not perfect. Different imperfections due to different external phenomenons (e.g., physical impairments) may accumulate along backup paths and weaken the optical signals, and thus result in extra management efforts and delays.

5.1 Traffic Instances

We generated three categories of traffic based on the space distribution of network nodes. In the first category, the requests are uniformly distributed over source-destination pairs. Pairs of source and destination nodes are uniformly selected among the network nodes, and requests of 1, 2, or 3 units are setup in between. In the second and third categories, space distribution of nodes is taken into consideration. Two classes of unbalanced traffic have been generated: In the first class (Category 2), the dominant component of the traffic is local (traffic occurs between nodes that are near from each other), while, in the second class (Category 3), the inverse distribution is considered (traffic occurs between nodes that are far away from each other). The objective of performing experiments on the two space distributions is to measure how flexible the different protection structures are in providing backup paths of short lengths when the objective is to minimize the protection capacity budget.

5.2 Computational Results

We tested the new p-structure protection structure presented in Section 3 and compare it with the five different protection structure based schemes discussed in Section 4 on the 4 network topologies referenced in Table 1 and on the 3 different traffic categories. The tests were conducted with both sequential and joint optimization of working and protection routes. In the sequential optimization approach, working routes between node pairs are established prior to protection paths using a shortest path algorithm. In the joint optimization approach, working routes are jointly determined with the protection structures and therefore do not necessarily correspond to the shortest routes. This resulted in 144 experiments, out of which 12 were not successful due to excessive computing times (p-tree and p-trail structures for the EON network). The results are reported in the subsequent two sections.

5.2.1 Solution Quality and Scalability

We first look at the solution quality and scalability. For each protection scheme, we propose to examine three parameters:

- Integrality gap (or GAP for short). After the linear programming (LP) relaxation of the various protection models has been optimally solved by the column generation method, we solve optimally the ILP restricted master problem made of the candidate protection structures generated in order to reach the optimal LP solution. The resulting ILP solution is therefore only a lower bound on the optimal ILP solution of the master problem. In order to estimate its quality, we evaluate the gap (%) between the incumbent integer solution and the LP lower bound.
- The number of column generation iterations (or ITER for short), i.e., the number of times the pricing problem is solved.
- The running time (seconds) used for both the column generation algorithm and the MIP CPLEX solver (or CPU for short).

Table 2: ILP Solutions: Quality and Scalability Issues - Traffic Category 1 (Uniform Traffic)

Networks	COST239			NSF			NJ-LATA			EON		
Parameters	gap	iter	cpu	gap	iter	cpu	gap	iter	cpu	gap	iter	cpu
Sequential Routing and Protection Optimization												
p-structures	0.19	158	2,026	0.19	79	6,809	0.00	89	128	0.85	188	1,872
np-cycles	0.34	42	102	0.00	20	103	0.26	24	38	0.16	73	457
p-cycles	0.17	45	339	0.15	23	103	0.00	27	54	0.16	45	504
rings	1.94	58	85	0.29	39	76	0.18	44	61	0.50	95	528
p-trees	0.36	174	46,119	0.02	131	7,336	0.11	196	5,555	-	-	-
p-trails	0.25	172	48,997	0.19	99	4,333	0.04	156	6,098	-	-	-
Joint Routing and Protection Optimization												
p-structures	1.15	33	95	0.08	40	49,027	0.79	39	75	0.48	135	12,004
np-cycles	1.27	17	88	0.00	10	90	0.27	16	32	0.13	45	1,110
p-cycles	1.65	13	52	0.00	11	57	0.27	16	33	0.30	35	564
rings	0.73	19	51	0.15	25	72	0.39	25	51	0.26	56	590
p-trees	4.19	43	52,958	0.18	88	12,872	0.15	115	3,815	-	-	-
p-trails	3.88	38	30,012	0.25	75	12,096	0.24	91	4,136	-	-	-

As the results are fairly similar for all three traffic categories, we only report them for the first category in Table 2. We observe that the gap between the ILP solution and the LP solution is always less than 1%, except for the COST239 instance. This is therefore quite satisfactory for a fair comparison of the different protection structures. Hence, we refrain from implementing a full blown branch-and-price algorithm in order to get more accurate solutions.

Regarding the computing times and the number of iterations of the master problems, we see that they are much larger for p-trees and p-trails, and we observe a lack of solution scalability for some instances with the EON network. These are due to the long running times for solving the pricing problems in the column generation algorithm. Of course, heuristics could be developed in the future in order to speed up their solutions, in view of the fact that only protection structures with a negative cost (and not necessarily the most negative one) are sought for in the first iterations. The cyclical structures (rings, p-cycles) are the easiest and fastest to produce and optimize in the context of the pricing problems. The running time of the generic p-structure model is shorter than the ones of the p-tree and p-trail models even though, in the p-structure protection scheme, all possible protection structures are investigated as candidate protection structures.

5.2.2 Protection Performances and Qualities

Given the small optimality gaps of all the obtained solutions, we can now compare the efficiency of the different protection schemes. We compare the schemes on three protection metrics:

- Capacity Redundancy (CR): It is equal to the protection capacity divided by the protected working capacity, i.e., $(\frac{\text{bandwidth reserved for protection paths}}{\text{bandwidth used for working paths}})$.
- Average length of the protection paths (BCK): It is equal to the sum of lengths of all the backup paths divided by their number, where the length is evaluated by the number of links.
- Number of protection structures (N_p): It is equal to the number of selected protection structures.

Table 3: Protection Parameters - Traffic Category 1 (Uniform Traffic)

Networks	COST239			NSF			NJ-LATA			EON		
Parameters	CR	BCK	N_p	CR	BCK	N_p	CR	BCK	N_p	CR	BCK	N_p
Sequential Routing and Protection Optimization												
p-structures	1.41	4.30	6	1.68	5.59	8	1.55	4.75	10	1.66	6.00	10
np-cycles	1.46	3.97	7	1.73	8.07	8	1.66	4.19	9	1.71	7.38	12
p-cycles	1.46	5.09	8	1.74	7.91	9	1.69	4.57	10	1.72	7.98	12
rings	2.04	5.24	21	2.18	7.28	17	2.30	3.70	28	2.23	4.78	28
p-trees	1.76	4.71	14	2.79	5.24	30	1.99	3.07	25	-	-	-
p-trails	1.76	4.77	15	2.87	5.40	29	2.08	2.81	26	-	-	-
Joint Routing and Protection Optimization												
p-structures	1.29	3.99	2	1.63	5.79	7	1.50	4.36	8	1.58	7.04	11
np-cycles	1.29	5.68	5	1.68	8.69	6	1.60	4.66	6	1.63	8.30	11
p-cycles	1.29	5.74	5	1.68	8.72	6	1.60	4.95	7	1.63	9.31	11
rings	2.04	7.60	11	2.17	8.23	15	2.19	4.21	17	2.15	5.79	21
p-trees	1.69	4.74	13	2.73	5.31	25	1.94	2.85	18	-	-	-
p-trails	1.69	4.68	11	2.76	5.37	24	2.00	2.69	28	-	-	-

Table 3 presents the performance comparison of the different protection schemes with the first traffic category. We first observe that the physical connectivity of the network does affect the redundancy ranking of the studied protection schemes. All protection schemes have more redundancy in the NSF and EON networks (sparse networks) than in the NJ-LATA and COST239 networks (more connected networks). The p-structure based scheme is the least capacity redundant one among all the protection schemes, while the ring scheme is the most capacity redundant one (except in the sequential optimization for the NSF network).

Globally, we see that cyclical structures (simple and non-simple p-cycles) are less capacity redundant as only a small number of them are required in order to provide 100% reliability (N_p). However, they perform recovery with longer backup paths (BCK). Linear structures (p-treesand p-trails) are more capacity redundant than cyclical structures, and a larger number of structures are required to provide 100% reliability. As they are more flexible, they perform recovery with shorter backup recovery paths. The p-structure scheme gathers the advantages of the cyclical structures in terms of capacity redundancy and their ability to provide 100% reliability with a small number of structures, and that of linear structures in providing recovery along shorter backup paths.

As the generic p-structure scheme includes all possible protection structures in the network, it is not possible to find a protection scheme that can be more capacity redundant, or less flexible. In the COST239 network (joint optimization), the redundancy of the p-structure and p-cycle based schemes are identical.

The same trend is observed for the two new traffic distributions in Tables 4 and 5, i.e., physical distribution of the traffic does not impact much the performance of the various protection schemes, and the resulting backup paths are still more or less of the same length, even though the traffic distributions are not the same.

Table 4: Protection Parameters - Traffic Category 2 (Local Traffic)

Networks	COST239			NSF			NJ-LATA			EON		
Parameters	CR	BCK	N_p	CR	BCK	N_p	CR	BCK	N_p	CR	BCK	N_p
Sequential Routing and Protection Optimization												
p-structures	1.38	3.74	3	1.75	7.45	9	1.50	4.02	6	1.57	5.95	10
np-cycles	1.38	3.83	5	1.77	8.08	7	1.52	4.59	7	1.66	7.82	11
p-cycles	1.39	5.63	6	1.77	8.08	7	1.55	5.20	8	1.67	8.00	13
rings	2.16	5.62	26	2.23	7.16	19	2.13	4.42	23	2.31	6.58	30
p-trees	1.68	4.73	15	2.84	5.42	23	2.05	2.79	24	-	-	-
p-trails	1.69	4.42	16	2.92	5.64	24	2.10	2.64	28	-	-	-
Joint Routing and Protection Optimization												
p-structures	1.29	4.75	4	1.69	4.92	6	1.42	4.58	5	1.49	7.73	9
np-cycles	1.29	5.74	5	1.73	8.42	7	1.43	4.66	5	1.51	9.12	8
p-cycles	1.29	5.75	3	1.73	8.44	7	1.45	4.75	7	1.52	9.11	13
rings	2.23	7.76	12	2.23	7.76	12	2.10	4.08	18	2.27	7.08	20
p-trees	1.68	4.73	15	2.74	5.50	28	1.95	2.81	22	-	-	-
p-trails	1.65	4.34	14	2.76	5.38	25	2.01	2.61	25	-	-	-

Table 5: Protection Parameters - Traffic Category 3 (Long Distance Traffic)

Networks	COST239			NSF			NJ-LATA			EON		
Parameters	CR	BCK	N_p	CR	BCK	N_p	CR	BCK	N_p	CR	BCK	N_p
Sequential Routing and Protection Optimization												
p-structures	1.43	3.54	3	1.67	5.58	7	1.74	3.47	7	1.62	6.26	13
np-cycles	1.45	3.71	4	1.71	8.05	9	1.79	3.77	8	1.68	7.20	13
p-cycles	1.45	5.79	4	1.71	7.96	10	1.83	4.50	8	1.70	8.78	15
rings	2.14	5.49	17	2.14	7.14	17	2.40	4.52	16	2.30	5.58	37
p-trees	1.79	4.40	13	2.92	5.14	32	2.25	2.91	22	-	-	-
p-trails	1.85	4.53	14	2.96	5.22	28	2.34	2.82	21	-	-	-
Joint Routing and Protection Optimization												
p-structures	1.34	4.15	2	1.63	5.55	8	1.60	4.33	5	1.55	6.27	13
np-cycles	1.34	3.93	3	1.67	8.06	6	1.64	4.67	6	1.62	8.29	10
p-cycles	1.34	5.69	5	1.67	8.12	6	1.65	4.86	5	1.62	9.19	10
rings	2.14	5.95	15	2.13	8.48	9	2.14	5.22	13	2.20	7.25	21
p-trees	1.66	4.06	10	2.75	5.13	25	2.07	2.64	18	-	-	-
p-trails	1.66	4.60	10	2.81	5.36	24	2.12	2.50	18	-	-	-

Table 6: Average Performance Parameters

	p-structures	non simple *p*-cycles	regular *p*-cycles	rings	*p*-trees	*p*-trails
Average Capacity Efficiency						
SEQUENTIAL	1.58	1.63	1.64	2.21	2.23	2.29
JOINT	1.50	1.54	1.54	2.16	2.13	2.16
Average Backup Path Length						
SEQUENTIAL	5.05	5.89	6.62	5.63	4.27	4.25
JOINT	5.29	6.69	7.05	6.61	4.20	4.17
Number of Protection Structures						
SEQUENTIAL	7.67	8.33	9.17	23.25	22.0	22.33
JOINT	6.67	6.50	7.09	15.50	19.33	19.89

Table 7: Shape Distribution of the *p*-Structures

	p-structures	non simple *p*-cycles	regular *p*-cycles	rings	*p*-trees	*p*-trails
Traffic Category 1 (Uniform Traffic)						
SEQUENTIAL	34	0	0	4	0	7
JOINT	28	3	0	3	0	4
Traffic Distribution 2 (Local Traffic)						
SEQUENTIAL	28	2	0	8	0	3
JOINT	24	6	0	4	0	0
Traffic Distribution 3 (Long Distance Traffic)						
SEQUENTIAL	30	1	0	9	0	1
JOINT	28	0	0	1	0	5

In Table 6, we compare the average performances of the different protection schemes, over all four networks and all three demand patterns. Therein, we see that *np*-cycle and *p*-cycle based protection schemes are 4 to 5 % more capacity redundant than the *p*-structure scheme. Furthermore, while the average capacity redundancies of rings, *p*-trees and *p*-trails are comparable, they are worse than the redundancy of the *p*-cycle scheme. *p*-Trees and *p*-trails appear quite inefficient in protecting the NSF network and hence have a bad overall performance. Indeed, the NSF network is the sparsest of the four networks, so that an interpretation of the results is that *p*-trees and *p*-trails require denser networks than NSF in order to provide a satisfactory protection scheme.

The backup length for the different protection schemes averaged over all networks and all demands are given in the middle part of Table 6. The differences among the numbers are rather small except for the regular *p*-cycles, which offer longer backup paths, and for the *p*-trees and *p*-trail, which offer slightly shorter protection paths. The generic *p*-structure scheme provide backup paths of an average length in between the two linear and cyclical structure lengths.

The number of protection structures averaged over all networks and all demands can be seen in the last part of Table 6. The number of required structures in order to guarantee a 100 % single link protection is significantly higher in *p*-tree and *p*-trail protection schemes, while the *p*-cycle scheme requires far less structures in order to provide the same level of reliability. The generic *p*-structure scheme achieves a comparable number of protection structures to the non-simple *p*-cycle scheme.

We observe in Table 7 that very few *p*-structures are indeed some of the classical protection structures. For instance, for none of the network and traffic instances, the set of *p*-structures contains either a regular *p*-cycle or a *p*-tree, while rings, *p*-trails and non simple *p*-cycles are defining some of the *p*-structures. Such a distribution is a little bit unexpected taking into account that *p*-cycles are very often considered as the most efficient protection structures. One must note that not all *p*-structures can be fully pre-cross-connected as this is not required in their definition, and this might be the explanations of the missing p-cycle occurrence among the set of p-structures. On the other hand, we see that the performances are comparable, with respect to the capacity redundancy, in the case of p-structures and regular / non simple p-cycles (see the columns entitled CR in Tables 3 to 5), even through the building blocks are different. This might indicate that several optimal solutions exist, or at least several near optimal solutions. Again, there is no clear trends depending on the traffic category or the sequential/joint optimization scheme.

6 Conclusion

In this paper, we have proposed an original generic model for pre-configured protection structure design, called p-structures, from which, with the addition of shaping constraints, we can derive all previously proposed pre-defined shape protection structures. This has enabled us to compare 6 different protection schemes on 4 different networks of small to medium sizes. Based on this preliminary comparison, p-structures, np-cycles and p-cycles seems to offer the best network capacity efficiency, about 50 % more capacity efficient than rings, p-trees and p-trails.

Further research will be to measure the flexibility of those studied pre-configured protection structures in providing protection with additional design constraints, e.g., shorter recovery paths, spare capacity budgets. The recovery delay, and other quality-of-service parameters related to protection will be of high value in order to extend this study.

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