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Abstract

We propose a new design scheme of resilient Wavelength Division Multiplexing (WDM) networks by extending and reshaping pre-configured protection tree (p-tree) structures. The resulting protection scheme relies on optimized pre-cross connected structures that span all previously proposed protection patterns.

p-Tree-based protection schemes offer the advantages of scalability, local restoration capabilities, and failure impact restriction, but at the same time suffers from capacity inefficiency. While keeping these advantages, we propose an extension (reshaping) of the p-tree protection pattern that imposes no restriction on the shapes of the protection building blocks. Not only the resulting protection scheme remains scalable and highly flexible, but it also leads to pre-configured protection structures that improve much further on capacity efficiency and recovery delay.

We establish some new integer linear programming models, and use large scale optimization tools, namely column generation (CG) to solve them. Our CG-based solution method is highly scalable as it does not require an a priori explicit enumeration of the protection structures, but an efficient dynamic enumeration of only the most promising ones. Comparison are made with three other protection schemes, i.e, simple and non-simple p-cycles (fully pre-cross connected structures) as well as p-trees. Results show a clear advantage of the proposed extended-tree scheme with respect to flexibility, capacity efficiency, and restoration delay.

Key Words: Survivable WDM networks, pre-cross connected structures, p-tree, hybrid p-structures, column generation.

Résumé

On propose une nouvelle approche de design de schémas de protection dans les réseaux optiques à multiplexage en longueur d'onde basée sur les arbres de recouvrement. Une nouvelle approche de modélisation est proposée, et on adopte une méthode d'optimisation basée sur la génération de colonnes.

1 Introduction

Transparent optical networks using WDM and optical switching can economically supply the increasing demand for high bandwidth [1]. WDM access technology has enabled tremendous transport capacity in optical networks, which led to the critical problem of survivability following any failure in the network. In WDM networks, any failure along a fiber-link that carries hundreds of wavelength channels of up to 40*Gbps* each, may cause a harmful traffic disturbance [2].

Design of protection schemes has been motivated by the search of restoration mechanisms with low recovery delay and/or, protection structures with less redundancy, see, e.g., the comparison of shared link vs. path protection schemes [3,4,5]. Contrary to shared path protection schemes, link protection schemes perform local signaling and restoration to recover from a link failure [6]. Thus, they achieve higher restoration speed than shared path schemes. On the other hand, path protection schemes are usually more capacity efficient than link ones [6, 2]. In this study, we focus on the design of link-protection schemes.

In Pre-configured (p-) protection schemes like ring, path, p-tree and p-cycle [3, 4] where different structures are used as protection building blocks, the spare capacity is reserved and/or setup ahead of the failure occurrence. Significant spare capacity saving can be achieved with the sharing of these pre-configured structures [3, 4, 5].

The concept of pre-cross connected protection extends the pre-configuration of protection capacity from backup channels reservation to end-to-end setup of the backup paths, i.e., backup capacity is reserved and switched or cross-connected at all the optical nodes along the backup paths.

The ring and p-cycle protection schemes are such that the protection capacity can be totally pre-cross connected ahead of any failure. In case of a link failure, only the two-end nodes of the failing link need to switch the affected traffic into the backup protection capacity. No additional reconfiguration or signaling is needed at the other nodes as backup paths are pre-cross connected. Therefore, a high recovery speed is achieved. Similar performance can be obtained with linear pre-cross connected trails (PXT) structure [7]. In PXT, the backup path can also be totally pre-cross connected, though no additional reconfiguration is required at intermediate nodes in case of a link failure [7].

While the ability of pre-cross connecting the protection capacity with rings and p-cycles is due to the cyclical layout of both patterns, in the case of linear trails, it is due to the way the sharing is done. One common property lies in the fact that the backup capacity is organized in either Eulerian tours (cyclical layouts) or Eulerian trails (linear layouts).

In addition to the fact that pre-cross connected protection schemes require less management overhead and guarantee a low recovery delay, backup path integrity is guaranteed ahead of traffic switching. Due to different potential physical impairments, on the fly (real time) connection of optically transparent channels may not guarantee the transmission integrity (e.g., a BER $\leq 10^{-12}$) within a short time interval. An extra period of signal tuning is usually required before any transmission, which slow down the recovery process. With an end-to-end pre-cross connected backup protection path, an active monitoring and tuning of the signal parameters can be performed without any negative effect on the recovery delay.

Among the possible p-structures, trees have recently received attention as potential protection building blocks in the design of survivable WDM networks. Indeed, several variants have been proposed in the literature [3,5,8]. A p-tree based protection scheme offers several advantages such as failure impact restriction, flexibility, and scalability in provisioning protection capacity [5, 8]. One major disadvantage is, however, its capacity inefficiency (see Section 2).

In this study, we propose a new protection scheme based on a pre-configured extended-tree (p-eTree) protection pattern which keeps the p-tree advantages and remedy to its disadvantages of capacity inefficiency. We investigated in reshaping methods, so as, to obtain optimized pre-cross connected patterns (maximizing the number of totally pre-cross connected backup paths) with enhanced capacity efficiency and recovery delays.

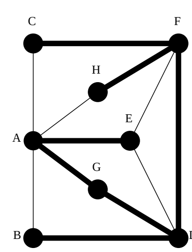
This paper is organized as follows. In Section 2, we present the p-tree protection scheme, its advantages and disadvantages, and what motivated us to move forward. In Section 3, we develop a high efficient optimization model that uses large scale optimization tools, namely column generation, in order to increase the scalability of the solution process. Computational results are discussed in Section 4, together with the comparison of the new pre-cross connected protection scheme against the p-cycle (simple and non simple) as well as the p-tree ones. We conclude with some future research directions.

2 p-pattern protection schemes

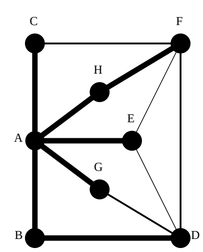
2.1 Pre-configured tree (p-tree)

The basic building blocks in p-tree protection schemes [3] are trees. A pre-configured tree (p-tree) can provide protection only for straddling-tree links (links whose two-end nodes are in the same tree, but do not define a tree link). In order to ensure 100% protection, multiple overlapping p-trees are required. In terms of capacity efficiency, p-tree based protection is known to be far less capacity efficient than the p-cycle protection [9]. In addition, as a basic protection pattern, a p-tree can not be considered as a totally pre-cross connected structure, unless, it is shaped like a linear trail (no bifurcation). However, the p-tree protection has some advantages over linear and cyclical protections. Firstly, when spare capacity is not uniformly distributed over the links of a network, cyclical structures like p-cycles may not be able to economically provide a given protection level [10]. Secondly, in case of a failure, it is possible to perform local restoration through dynamic cross connection of some backup segment paths. These advantages allow more flexibility in exploiting the spare capacity, and thus increases the possibility of multiple failures protection even though the protection scheme aims at only addressing the single failure protection issue.

Figure 1 illustrates a p-tree-based survivable WDM network $G(N, L)$ where N and L are the set of nodes and links respectively. The link spare capacity budget is given as follows: Each link ($\ell \in L$) has two units of spare capacity except for the links $\ell_{E,F}$ and $\ell_{E,D}$ which have no available spare capacity. Assume the objective is to protect the maximum possible amount of working capacity. Through dynamic cross-connection of spare capacity at nodes F and D in Figure 1-(a) and at node A in Figure 1-(b) it is possible to restore any one of the straddling-trees links.



(a)



(b)

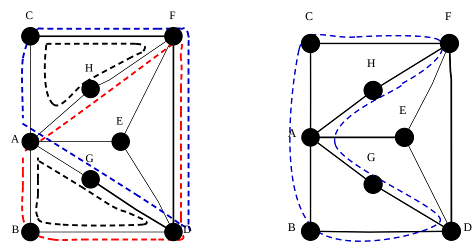
Figure 1: Pre-configured protection tree (p-tree) scheme

Although the flexibility in provisioning protection capacity is higher when the cross connects are made dynamically, the delay incurred by the dynamic setting of the paths (particularly when many sequential cross-connects need to be setup on the fly) may seriously slow down the dynamic provisioning operation, especially in transparent networks.

2.2 Pre-configured cycle (p-cycle)

The p-cycle protection scheme [11] is widely acknowledged as the most efficient pre-configured protection scheme in terms of capacity efficiency and switching delay [4]. In there, protection capacity is pre-cross connected ahead of any failure, and only the two end-nodes of an affected link need to perform dynamic switching in case of a link failure. However, when the distribution of spare capacity over the links is not uniform or in case of a sparse network, setting up a p-cycle may result in an expensive investment in terms of spare capacity [10].

In Figures 2-(a) and 2-(b), two optimal survivable designs based on simple and non-simple p-cycle respectively are illustrated. The spare capacity budget is the same as in Figure 1, and the resulting optimal design is as follows: Each of the simple p-cycle in (a) has one capacity unit while in (b) the single non-simple p-cycle has two capacity units.



(a) (b)

Figure 2: Pre-configured protection cycle (p-cycle) scheme

Compared to the previous p-tree design which uses 14 spare channels and provides only 10 protected channels, the two simple and non-simple p-cycle-based schemes use 18 and 16 channels, and provide 18 and 20 channels respectively.

Due to the link spare capacity budget constraint, none of the totally pre-cross connected cyclical structures can provide protected capacity on links $E-F$ and $E-D$. Existing solutions in the literature which consist to combine totally pre-cross connected patterns like p-cycles and linear trails [3,12] cannot remedy the problem in this case without affecting the capacity efficiency of the protection scheme.

2.3 Pre-configured extended-tree (p-eTree)

Our proposal for pre-configured extended-tree is motivated on the one hand, by the capacity efficiency and restoration speed of p-cycle schemes and, on the other hand, by the flexibility of p-trees and linear trails in providing protected capacity even within constrained spare capacity budgets.

Figure 3 illustrates a p-eTree protection scheme. Therein, we use two copies of the illustrated p-eTree structure. The bold lines represent the basic tree, and the dashed bold lines the extending tree links. The resulting structure is a hybrid one, composed of two sub structures. The first one is a pre-cross connected (cyclical dashed thin lines), and the second one is a linear trail which is incident to the first one, but not a priori cross-connected with it (link $E-A$).

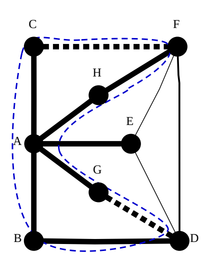


Figure 3: Pre-configured extended-tree (p-eTree) scheme

In order to set a p-eTree structure, we select an optimized tree (not necessarily a spanning tree), which we extend by some straddling-tree links, and cross-connect the spare capacity at some nodes of the extended-tree in order to form a cyclical pre-cross connected structure. The resulting pattern is an optimized pre-cross connected structure where, only a limited number of cross-connects need to be performed dynamically. In the example illustrated in Figure 3, only node A needs to perform dynamic cross-connection of protection capacity in case of a failure, and this is only when a failure occurs on link $E-F$ or $E-D$.

Let us have a look at the capacity efficiency of a p-eTree protection scheme. For the example in Figure 3, we use 18 spare channels and provide 24 protected channels, i.e., more protected channels compared to the previous p-tree and p-cycle scheme in Figures 1 and 2, respectively. Moreover, the capacity redundancy (ratio of protection capacity over protected capacity) of the p-eTree scheme is 0.75 whereas it is 0.8 and 0.9 for the non-simple and simple p-cycle schemes, respectively.

There is a priori no restriction on the shape of the building blocks in a p-eTree scheme. Consequently, expected protection building blocks can be of different shapes, e.g.,:

- A hybrid extended tree with a pre-cross connected part and an augmenting part made of branches that would be cross-connected on the fly as in Figure 3.
- A pre-cross connected trail (PXT) i.e., a tree without any branch point.
- A pure cyclical structure, either a simple or non-simple cycle, etc.

The p-eTree design approach extends the solution space of all previously proposed schemes with pure and hybrid p-patterns. In addition, the p-eTree-based protection scheme has both the advantages of cyclical and linear patterns in terms of capacity efficiency and flexibility in the provisioning of spare capacity, respectively.

Regarding the recovery delay, the resulting optimized pre-cross connected structure can approach the speed of a totally pre-cross connected structure. Indeed, when signaling messages to setup the cross-connects are send out-of-band at a very limited number of nodes, it is possible to setup these cross-connects in parallel with those at the end-nodes of the affected link.

In order to discuss the recovery delay, we introduce the following notation.

- D_n: Time for a node n to detect a link failure on one of its incident link.
- P_ℓ: Propagation delay on link ℓ.
- T_n: Time to process and transmit a message at node n.
- C_n: Time to setup and test a cross-connect at node n ($C_n > T_n + P_\ell$).

In order to simplify the discussion, we assume that setting and testing a cross connect takes the same amount of time at all the nodes ($C_n = C$), and that signaling is performed sequentially along the backup protection paths. Thus, the recovery delay in case of a hybrid or totally pre-cross connected pattern is equivalent to:

$$D_s + T_1 + P_{\ell_1} + T_2 + P_{\ell_2} + \cdots + C = D_s + \sum_{i=1}^{h} (T_i + P_{\ell_i}) + C, \tag{1}$$

where h is the number of nodes along the backup path that are sent a request to setup the backup path (can be half of the nodes when the two end-nodes participate in the recovery process). As setting up and testing cross connects at intermediate nodes are performed in parallel with message transmission and propagation, we do not include their incurred delay in the recovery delay formula.

The recovery delay in formula (1) is sensitive to the number of intermediate unset cross-connects. When there is none (totally pre-cross connected pattern), the recover delay becomes the same as a totally pre-cross connected pattern, i.e., $D_n + C$. With a p-eTree protection, we can maximize the protected working capacity, and implicitly the number of pre-cross connected backup paths. In Figure 3, the failure of any of the links which is part of the cyclical layout will require a recovery delay of $D_n + C$, and the off-cyclical layout link $E-A$ a recovery delay of $D_n + P_1 + T_1 + C \simeq D_n + C$, i.e., the recovery time of a totally pre-cross connected structure.

3 Mathematical models

In order to compute the optimal design of the p-eTree scheme described in Section 2, we propose a mathematical model to be solved by a large scale optimization technique, namely Column generation (CG). With the CG technique, no explicit enumeration of the candidate patterns is required ahead of the optimization method, globally efficient patterns are dynamically generated only when they are needed. Indeed, using CG consists in decomposing the optimization problem into two sub problems, the so-called master and pricing problems which are repeatedly solved in sequence until the optimality criterion is satisfied. Using the values of the dual variables of the master problem, the pricing problem generates new p-patterns, i.e., protection building blocks that are added to the master problem. The master problem, which is in charge of p-patterns selection, grows as promising p-patterns are added to the initial candidate set. For a reference on column generation, see, e.g., [13]. Hereafter, we develop the master and the pricing problems in order to maximize the number of protected working channels.

3.1 Master problem

Given a link spare capacity budget and a set of candidate p-eTree structures (generated dynamically by the pricing), the objective of the master problem is to find the optimal protection plan that provides the maximum protected working capacity.

We denote the working capacity on a link ℓ in the network by w_ℓ. Let t_ℓ be the transport capacity of each fiber link and p_ℓ its spare capacity budget. The objective of the master problem can therefore be expressed as follows:

$$\max \quad \sum_{\ell \in L} u_\ell w_\ell,$$

where u_ℓ is the utility of having a protected working channel on a link ℓ. We define two protection parameters a_ℓ^s and b_ℓ^s in order to encode the protection relationship between a p-eTree structure $s \in S$ and a link $\ell \in L$. $a_\ell^s \in \mathrm{Z}^+$ corresponds to the number of alternate backup paths and $b_\ell^s \in \{0,1\}$ to the number of spare channels provided and used respectively by the current p-eTree structure s. The variables of the optimization problem are w_ℓ and z^s, which encode the number of protected working channels on a link ℓ and the thickness (number of copies) of a p-eTree structure s, respectively.

The constraints of the master problem are:

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

$$\sum_{s \in S} b_\ell^s z^s + w_\ell \leq t_\ell \qquad \ell \in L \tag{3}$$

$$\sum_{s \in S} b_\ell^s z^s \leq p_\ell \qquad \ell \in L \tag{4}$$

$$w_\ell, z^s \in \mathrm{Z}^+ \tag{5}$$

Constraints (2) guarantee a link protection for w_ℓ working channels along each link $\ell \in L$. Constraints (3) limit the overall working and protection capacity to the transport capacity of each link $\ell \in L$. Constraints (4) setup a limit on the link spare capacity budget along each link.

3.2 Pricing problem

The pricing problem corresponds to the optimization problem of maximizing the reduced cost of the master problem. The pricing problem generates pre-configured extended-tree (p-eTree) structures to protect working link-channels in the network.

To ease the presentation, we start by presenting the pure p-tree optimization problem before we move to the extension added and the whole p-eTree.

We define the variables of the pricing problem used in shaping the p-tree $\mathcal{T}$ as follows: $r^i = 1$ if node i is the root-node of $\mathcal{T}$, 0 otherwise; $y_i^j = 1$ if node j is the parent-node of i in $\mathcal{T}$, 0 otherwise; and $x_\ell^{\mathcal{T}} = 1$ if link ℓ is a straddling-$\mathcal{T}$ link, 0 otherwise; as well as the following sets:
the set of adjacent nodes to node i,

$$\mathcal{V}(i) = \Big\{ j \in N : \{i,j\} \in L \Big\} \text{ for all } i \in N;$$

the set of adjacent nodes to link ℓ,

$$\mathcal{V}(\ell) = \Big\{ i,j \in N : \ell = \{i,j\} \in L \Big\} \text{ for all } \ell \in L;$$

and the set of adjacent links to a subset of nodes $V \subset N$,

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

The objective function of the pricing problem, i.e., the maximization of the reduced cost can be written as follows,

$$\max \left(\sum_{\ell \in L} \theta_\ell^1 a_\ell^s - \sum_{\ell \in L} \left(\theta_\ell^2 + \theta_\ell^3\right) b_\ell^s \right),$$

where θ_ℓ^1, θ_ℓ^2 and θ_ℓ^3 are the dual variables associated with constraints (2), (3) and (4), respectively. The constraints of the sub pricing problem (only the p-tree construction) are next defined in order to generate a single tree (not necessarily a spanning tree) at each iteration.

$$\sum_{i \in N} r^i = 1 \tag{6}$$

$$\sum_{j \in \mathcal{V}(i)} y_i^j + r^i \leq 1 \qquad i \in N \tag{7}$$

$$x_\ell^{\mathcal{T}} + y_j^i + y_i^j \leq 1 \qquad \ell = \{i,j\} \in L \tag{8}$$

$$2x_\ell^{\mathcal{T}} \leq \sum_{i \in \mathcal{V}(\ell)} \left(\sum_{k \in \mathcal{V}(i) \setminus \mathcal{V}(\ell)} y_i^k + r^i \right) \qquad \ell \in L \tag{9}$$

$$\sum_{i,j \in V} (y_i^j + y_j^i) \leq |V| - 1 \qquad V \subset N, i,j \in V \tag{10}$$

$$x_\ell^{\mathcal{T}}, y_i^j, r^i \in \{0,1\}, \qquad \ell \in L,\ i,j \in N \tag{11}$$

Constraint (6) identifies the root-node (one root-node). Constraints (7) select one parent in the p-tree for each node that is not a root-node. Constraints (8) prevent cycling on parent-son relationship (at most y_j^i or y_i^j equal to 1) if ℓ is not a straddling-tree link. Constraints (9) stipulate the necessary conditions for a link to be a straddling-tree link, i.e., each of its end-nodes should have a parent in the tree if it is not the root-node. Constraints (10) prevent unconnected components from arising in the network, e.g., under the form of cycles. Constraints (11) enforce the integrality of the variables.

So far, we have built a p-tree. Let us extend the p-tree structure to build a p-eTree protection pattern. The following variables are used to reshape the tree and count the number of alternate backup paths for each link ℓ. By extending the selected tree, we aim at forming an optimized pre-cross connected structure, but some branches of the tree may not be part of it.

$x_\ell^{\mathcal{OXC}}$ = 1 if ℓ belongs to the pre-cross connected p-eTree, 0 otherwise.

$x_\ell^{\mathcal{BCK}}$ = number of disjoint backup paths for link ℓ.

The constraints of the second part of the pricing are as follows:

$$x_\ell^{\mathcal{OXC}} \leq x_\ell^{\mathcal{T}} + y_j^i + y_i^j \qquad \ell = \{i,j\} \in L \tag{12}$$

$$\sum_{\ell \in \mathcal{E}(v)} x_\ell^{\mathcal{OXC}} = 2n_v \qquad v \in N \tag{13}$$

$$x_\ell^{\mathcal{BCK}} \leq \sum_{\ell' \neq \ell, \ell' \in \mathcal{E}(v)} x_{\ell'}^{\mathcal{OXC}} \qquad v \in \ell, \ell \in L \tag{14}$$

$$x_\ell^{\mathcal{BCK}} \leq \sum_{\ell' \in \mathcal{E}(V)} x_{\ell'}^{\mathcal{OXC}} \qquad V \subset N, \ell \in L \tag{15}$$

$$x_\ell^{\mathcal{OXC}} \in \{0,1\}, x_\ell^{\mathcal{BCK}}, n_v \in \mathrm{Z}^+ \qquad \ell \in L, v \in N \tag{16}$$

Constraints (12) restrict the extensions to the links beign either on-tree or straddling-tree links, in order to define the p-eTree structure. Constraints (13) guarantee that the pre-cross connected structure will involve nodes with an even degree (Eulerian tour). Constraints (14) are used to count the number of alternate backup paths for each link in the pre-cross connected p-eTree. Constraints (15) prevent from straddling two pre-cross connected sub-structures. Constraints (16) are integrality constraints.

In order to feed the master problem with p-structures found by the pricing problem, we need to express the parameters a_ℓ^s and b_ℓ^s as functions of the variables of the pricing problem: a_ℓ^s encodes the available number of backup paths for link ℓ, either ℓ is part of the pre-cross connected structure (on, or straddling it, which implies that $x_\ell^{\mathcal{BCK}} > 0$) or none of these two cases (i.e., is not protected by the pre-cross connected structure). Thus,

$$a_\ell^s = x_\ell^{\mathcal{BCK}} + \inf\left\{x_\ell^{\mathcal{T}}, 1 - x_\ell^{\mathcal{OXC}}, \lfloor 1 - \varepsilon x_\ell^{\mathcal{BCK}} \rfloor\right\}, \varepsilon << 1.$$

Parameter b_ℓ^s encodes the spare capacity used by the p-eTree on link ℓ. A spare capacity channel is used either by the basic tree (on-tree), or by the pre-cross connected part of the p-eTree. Thus,

$$b_\ell^s = \sup\left\{x_\ell^{\mathcal{OXC}}, y_i^j + y_j^i\right\} \qquad \ell = \{i,j\} \in L.$$

4 Performance results

In this section, we compare the capacity efficiency of the new p-eTree protection scheme with three others: p-tree, simple and non-simple p-cycle schemes [14,15], and we evaluate its restoration delay as a function of the number of unset cross connects.

We consider four network topologies: NSF, COST239 - 19 links, New Jersey LATA, and COST239 - 26 links, each has an average nodal degree of 3, 3.4, 4.1 and 4.3, respectively. In order to investigate on how the link spare capacity budget affects the capacity efficiency, we select three distributions of random link spare capacity budgets for each network. Each random distribution is characterized by its average spare capacity p on each link and its standard deviation σ. For the first distribution (first set of vertical bars in each sub figure in Figure 4), all the links of the network have been assigned the same transport capacity (60 channels) and the same spare capacity (20 channels), thus (p, σ) = (20, 0). Other distributions are described in Figure 4 (x-axis).

We depict in Figure 4 the variation of the number of protected capacity units (channels) as a function of the selected spare capacity budget distributions. The first observation is that, when all the links of any of the considered networks are given the same spare capacity (first distribution), then the p-eTree and the non-simple p-cycle provide the same protected capacity. In such a case, the simple p-cycle protection provides $\sim$ 4%) less protected capacity, and the pure p-tree $\sim$ 50% in the first two networks (sparse networks) and $\sim$ 30% in the two last networks (more connected networks). The equivalent performance of the non-simple p-cycle and p-eTree schemes tells us that the protection building blocks in the p-eTree scheme are purely cyclical structures (pre-cross connected).

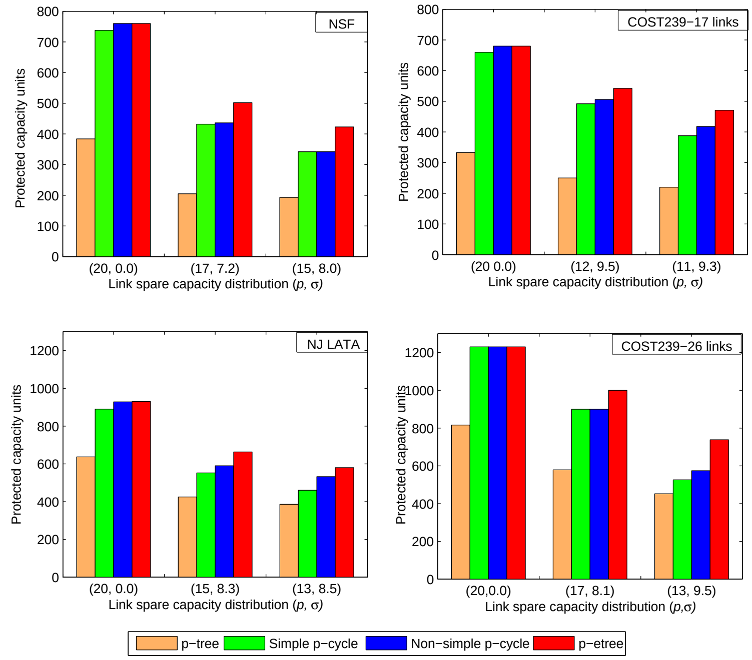


Figure 4: Distribution of the provided protection capacity

When the spare capacity is redistributed over the interval $[0, 30]$ according to the second and third distributions, the protected capacity becomes different from the case where a uniform spare capacity is applied. Within all the considered spare capacity budget distributions, the p-eTree protection provides the highest amount of protected capacity units. The protected capacity by the p-eTree in the COST239 - 26 links is 23%, 28% and 43% better than that provided by the non-simple p-cycle, simple p-cycle, and p-tree protection, respectively.

Table 1 illustrates the drop in the amount of protected capacity (%) due to the new distributions of spare capacity in COST239 -26 and NJ LATA networks. All the four protection schemes are sensitive to the dispersion of the link spare capacity values (increase of σ). The p-eTree has the least drop among all the four compared schemes. The p-tree is the second less affected scheme by the new distribution of spare capacity (distribution 2 in COST239 26 links and the NJ LATA network). The results in Table 1 give us a clear indication that linear patterns can be of higher flexibility over cyclical patterns especially with constrained link spare capacity budgets.

Table 1: Lost protected capacity units (%)

		p-tree	p-cycle		p-eTree
			simple	non-simple	
COST239	Dist 1	29%	27%	27%	18%
	Dist 2	44%	57 %	53%	40%
NJ LATA	Dist 1	33%	37%	36%	28%
	Dist 2	39%	48 %	42%	32%

The advantage of the p-eTree protection over the p-cycle (either simple or non-simple) ones in terms of capacity efficiency is due to the protection building blocks in the p-eTree-based protection scheme. Indeed, as pure cyclical, linear and hybrid structures are combined by the p-eTree scheme, the resulting protection plan can not be less efficient or less flexible than any of the pure cyclical or linear based protection schemes.

In order to evaluate the recovery delay of the p-eTree-based protection scheme, we looked at the shape of the protection structures. Table 2 gives the recovery delay of the protection plan provided by the p-eTree in case of the second distribution of link spare capacity (last set of bars of all the sub figures in Figure 4).

The results shows that between $\sim$ 80% and 90% of the protection capacity is pre-cross connected, and 10% to 23% require an additional delay of only $T + P$ to restore from any link failure. The percentage of protection capacity that requires a restoration delay ≥ 2 (T+P) is very low $\leq 2\%$. Thus, a high restoration delay compared to any totally pre-cross connected scheme is obtained.

Table 2: Recovery Delay

	$D+C$	$D+C+T+P$	$\geq D+C$ $+2(T+P)$
NSF	81%	17%	2%
COST239 -19 links	89%	11%	0%
NJ LATA	85%	15%	0%
COST239-26 links	77%	23%	0%

We assume $D_n = D, T_n = T$ for all n
and $P_\ell = P$ for all ℓ, to simplify the exposure.

5 Conclusion

In this study we have proposed a novel pre-configured protection scheme where no restriction is imposed on the shape of the protection building blocks. By extending trees, we have built a pre-configured extended-tree (p-eTree) protection scheme where the number of pre-cross connected backup paths are implicitly optimized. We have compared our scheme to three other pre-configured schemes, and showed that our scheme is more capacity efficient than all the p-pattern based schemes and still, achieves a recovery delay comparable to the delay of totally pre-cross connected schemes.

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