A Novel Efficient Design of Survivable WDM Mesh Networks

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***Abstract*—The design of survivable WDM mesh networks based on *p*-cycles has been extensively studied. However, most of studies only deal with a single link failure rather than node failure. In this paper, we develop a new scalable and efficient design method for computing node-protecting *p*-cycles in order to ensure network survivability. The performance of our new proposed design method makes an obvious improvement ∼20% in capacity redundancy over that of the previous one.**

The conventional design methods formulate the problem of *p*-cycle design as an Integer Linear Program (ILP). To solve the ILP, the prerequisite is to a priori enumerated all possible *p*-cycle candidates. For a large network, the resulting ILP may be intractable as the huge number of cycles may exist. We propose a new design and solution method based on large scale optimization tools, namely Column Generation (CG), where *p*-cycle candidates are generated on-line when needed. The main advantage of our CG-based method is that no *p*-cycles are a-priori off-line enumerated; the generation of the promising set of *p*-cycles is embedded in the optimization process.

Extensive experiments have been conducted for comparison. Experimental results show that our new proposed method outperforms the previous method in terms of capacity efficiency.

***Index Terms*—*p*-cycles, node protection, column generation**

I. INTRODUCTION

WDM (Wavelength Division Multiplexing) mesh networks are promising as next-generation backbone networks as its intelligence, scalability and huge-bandwidth. With the WDM techniques, a single fiber can be divided into hundreds of non-overlapped high-speed wavelengths, each with a bandwidth of 100Gbps or above for parallel data transmission [1]. Due to its high-speed characteristic, a single fiber cut may lead to huge data and revenue loss. However, WDM mesh networks prone to failure [2]. Therefore, WDM mesh optical network survivability against a single failure is a very important issue in the design of WDM mesh networks.

Two different kinds of mechanisms have been suggested to ensure WDM mesh network survivability. One is restoration. With this kind of mechanism, restoration paths are calculated on the fly in the event of failure occurrence. No resources are pre-reserved for any failure. The other is protection. With this mechanism, protection paths are calculated and spare capacities along the backup paths are reserved before any single failure occurs. Disrupted traffic is switched to the backup paths in case of failure. Protection outperforms restoration in terms of recovery time as well as guaranteed survivability. Restoration cannot provide 100% guaranteed survivability since restoration path may not be found upon failure due to resources limitation.

To ensure survivable WDM mesh networks, various kinds of protection approaches have been proposed (e.g. [3]–[6]). SONET rings are favored thanks to their fast recovery speed, which is less than 60ms. However, redundant capacity required by SONET rings is at as much as working capacity. Ramamurthy and Sahasrabuddhe and Mukherjee in [4] proposed shared backup link protection and shared backup path protection. Xu and Xiong and Qiaoin in [5] presented shared segment protection for survivable WDM mesh networks. These protection approaches are more capacity efficient that SONET rings. However, this efficiency is achieve at the price of the recovery speed.

Among all protection approaches for WDM mesh networks from a single failure, *p*-cycles (short for Preconfigured Protection Cycles) [3] are preferable due to its unique characteristics, i.e., SONET ring-like recovery speed and mesh-like capacity efficiency. As a preconfigured protection structure, in the case of failure, only end nodes of failed link perform real-time switching for rerouting the disrupted traffic. Thereby, SONET ring-like recovery speed can be obtained. Moreover, a *p*-cycle cannot only protect on-cycle links, as SONET ring does, but also can protect straddling links. A straddling link of a *p*-cycle is a link with two end nodes on the *p*-cycle but itself not. Thus, *p*-cycles can achieve mesh-like capacity efficiency.

p-Cycles have attracted extensive attentions (e.g., [7]–[11]). Most of them explore the protection against a single link failure. Only very few studies have investigated the design of *p*-cycles for protection against a single node failure. Stamatelakis and Grover in [12] proposed node-encircling *p*-cycles (NEPC) for node protection which is quite less capacity efficient. Schupke [13] proposed an Automatic protection switching (APS) enhancement to provide means for node failure protection based on *p*-cycles. Shen and Grover [14] extended link *p*-cycles to

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path segment protection for link and node failure recovery. Kodian and Grover [15] proposed Failure-Independent Path-Protecting (FIPP) *p*-cycles against link and node failure. Onguetou and Grover [16] proposed a new insight and approach to node failure protection with ordinary p-cycles. Their later work in [17], [18] proposed a two-hop-segment strategy for node protection while retaining the simplicity of the *p*-cycle operation (see Section II).

In order to provision *p*-cycles in WDM mesh networks against a single failure, the conventional way is to formulate the problem as an Integer Linear Program (ILP). Solution to the ILP requires the pre-enumeration all possible *p*-cycle candidates. As the number of *p*-cycles may increase exponentially with the increase of network scale (e.g., the number of links), the resulting ILP may become intractable for design of large-scale survivable optical networks. If one only considers a subset of *p*-cycle candidates, the solution quality may not be guaranteed. The authors in [19], [20] studied link and node protection using respective ordinary *p*-cycles and non-simple *p*-cycles. And they proposed scalable approaches to solve the ILP model where candidates are generated dynamically when needed.

In this paper, we investigate the design of node-protecting *p*-cycles with the two-hop-segment strategy. The objective is to minimize spare capacity usage with 100% guaranteed survivability against the single failure of a link or a node. Note that for a node failure, only the working paths through the node are considered for protection. In constrast with the design in [18], our new proposed design method allows a *p*-cycle to protect multiple cocurrent affected working paths from a single node failure only if the associated protection paths are disjoint (see Section II). We also propose a new design approach using large scale optimization tools, namely, Column Generation (CG) (see, e.g., [21] for a basic reference). Based on CG techniques, our approach generates *p*-cycles on the fly when needed during the optimization process. In contrast with the work in [19], we propose a novel efficient scalable algorithm for design node-protection *p*-cycles.

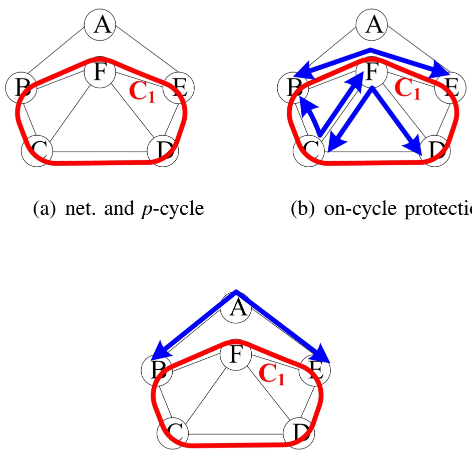
The rest of the paper is organized as follows. In Section II, *p*-cycles are illustrated for node protection. In Section III, we present a CG formulation for the design of *p*-cycles ensuring full node protection. In Section IV, we compare our design with the previous one. Conclusions are made in Section V.

II. Basic Principle of Node-protecting *p*-Cycles

In this section, before illustrating the idea of our proposed design method for node and link protection, we introduce the principle of the two-hop-segment strategy for node protection using *p*-cycles.

A. protection of links and nodes

p-Cycles are originally suggested for protection against a single link failure. Very recent research [17] proposes the two-hop-segment strategy for node protection using *p*-cycles. A two-hop segment consists of two consecutive links of a working path. If a *p*-cycle can protect both links of a two-hop segment, the *p*-cycle can protect the intermediate node (the common node of the two links) of this segment in an on-cycle protection manner, i.e., recover one unit traffic flow through this node. If only two end nodes of a two-hop segment are sitting on a *p*-cycle rather than the intermediate node, the *p*-cycle recovers two units of traffic flows along the segment in a straddling manner.



(a) net. and *p*-cycle (b) on-cycle protection

(c) straddling protection

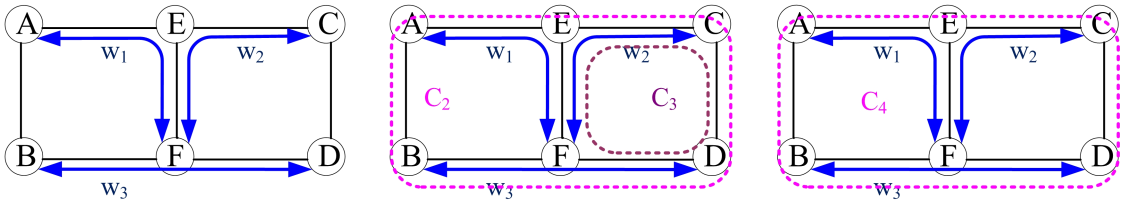
Fig. 1. Protection principal of node-protecting *p*-cycles

Fig. 1 illustrates the principal of node-protecting *p*-cycles. Fig. 1(a) shows a network topology and a *p*-cycle C_1. Fig. 1(b) shows that, two-hop segments (e.g., B-C-F, C-F-D and B-F-E) can be protected in the on-cycle manner against the failure of a node (e.g, node C or F). For example, upon the failure of node C, two nodes B and F switch the affected traffic on C_1. Upon the failure of node A, as shown in Fig. 1(c), two end nodes B and E of the affected segment B-A-E automatically switch the disrupted traffic on protection paths B-F-E and B-C-D-E. Thus, two units of the affected working flows can be recovered.

B. Comparisons of the design methods

The 2-hop method in [17] allows a *p*-cycle to protect only one traffic flow on the affected working paths in the case of a node failure. We proposed a new design method [19]. This method allows a *p*-cycle to recover multiple traffic flows on the concurrent affected working paths upon a node failure provided that the associated protection paths are disjoint. Thereby, the capacity efficiency of node-protecting *p*-cycles can be greatly improved.

Fig. 2 compares our proposed design method with the one in [18]. Fig. 2(a) shows an example instance. There, three demands are respectively routed on working paths W_1, W_2 and W_3. Fig. 2(b) shows that, with the design



(a) An example instance (b) Solution with method in [18] (c) Solution with method in [19]

Fig. 2. Comparison of the design methods

method in [18], two p-cycles (C_2 and C_3) are employed to protect against a single node failure. These two p-cycles costs 10 units of spare capacity.

Fig. 2(c) shows that one p-cycle C_4 is enough to protect against any single node failures using our proposed method. In case of node F failure occurrence, protection pathes A-B-F and C-D-F along p-cycle C_4 carry respectively the affected traffic on W_1 and W_2. The C_4 spare capacity cost is then 6 units. In contrast with the method in [18], our new proposed design can save 40% spare capacity usage.

III. A Column Generation Model

Let us represent an optical network by a graph $G = (V, L)$, where V represents the set of nodes ,indexed by v, and L represents the set of links, indexed by ℓ. Let $\omega(v)$ be the set of links attached to node v. ω_ℓ is the number of traffic units on link ℓ. For a working path $p \in P$, let d_p be the number of traffic units carried on it, and V_p be its all intermediate node set.

We develop an ILP model to design p-cycles in a WDM mesh network in order to ensure 100% surivivability against any single link/node failure. In order to handle the scalable issue appeared in the conventional design methods, we use Column Generation (CG) techniques to solve the ILP model. Column generation is large-scale optimization tools, which is used to solve large-scale optimization model. With the CG techniques, the original design model is decomposed into two correlated problems: the master problem and the pricing problem. The master problem takes repsonsiblity of selecting candidates from the candidate set. This candidate set is incremental and calculated on the fly by the pricing problem at each iteration of the CG algorithm. To facilitate description of our design method, we name the master problem and the pricing problem together as a CG model.

The key to use the CG techniques consists in the composition scheme of the original problem. Here, we use the same scheme as those in [19], [20], [22]. The master problem selects node-protecting p-cycles from the candidate set such that all (intermediate) nodes and links in an optical network are protected against any single failure. The pricing problem is used to generate node-protecting p-cycles on dynamically in each iteration of the optimization process. The master problem below is quite similar to the ones in [19], [20] thanks to their same functionality. However, the associated candidate constructions here are different.

A. The master problem

The objective of the master problem is to minimize the spare capacity usage for protection against a single link/node failure.

p-Cycles are associated with configuration set C. A configuration c corresponds to a cycle with multiple copies φ that protects a set of links and relay nodes of working paths. A configuration c is associated with a vector $(a^c_\ell)_{\ell \in L}$ and a matrix $(a^c_{pv})_{p \in P,\, v \in V_p}$. The element $a^c_\ell \in \{2\varphi, \varphi, 0\}$ and $a^c_{pv} \in \{2, 1, 0\}$ encodes the number of protection paths provided by the configuration c for link ℓ and for working path p against the failure of its relay-node v, respectively. Let COST_c be the cost of the configuration c

Variables z_c encodes the number of copies of configuration c that are selected in the current solution. The mathematical model can then be written as follows.

$$\min \quad \sum_{c \in C} \text{COST}_c\, z_c$$

$$\text{subject to:} \quad \sum_{c \in C} a^c_\ell\, z_c \geq \omega_\ell \qquad \ell \in L \qquad (1)$$

$$\sum_{c \in C} a^c_{pv}\, z_c \geq d_p \qquad p \in P,\ v \in V_p \qquad (2)$$

$$z_c \in \mathbb{Z}^+ \qquad c \in C \qquad (3)$$

Constraints (1) assure that all traffic units on links are protected against any single failure for a WDM mesh network. Constraints (2) ensure that all traffic flows through intermediate nodes of working paths are protected against a single failure. Constraints (3) are variable domain constraints.

B. The pricing problem

The pricing problem corresponds to the optimization problem with the objective of minimizing the so-called reduced cost of the master problem, and subject to a set of constraints for configuration construction. The reduced cost can be written as follows.

$$\overline{\text{COST}_c} = \text{COST}_c - \sum_{\ell \in L} u_\ell a^c_\ell - \sum_{p \in P} \sum_{v \in V_p} u_{pv} a^c_{pv} \qquad c \in C,$$

where u_ℓ and u_{pv} are dual variables associated with constraints (1) and constraints (2) respectively.

Let us introduce the following notations for presenting the pricing problem.

SETS and PARAMETERS

$V_{p,v}$ the set of nodes on working path p.

$\omega(v,p)$ the set of links on working path p.

$\varepsilon(v,p)$ the set of links on path p incident on the node v.

$\omega(V')$ the set of links whose one end node belongs to the set V' but the other does not.

P_v the set of working paths going through node v.

$\tau_v^\ell =$ 1 if link ℓ is on path p adjacent to node v; 0 otherwise.

VARIABLES

$b_\ell =$ 1 if link ℓ is on the current cycle; 0 otherwise.

$s_\ell =$ 1 if link ℓ straddles the current cycle; 0 otherwise.

$y_v =$ 1 if node v is on the current cycle; 0 otherwise.

$x_{pv}^\ell =$ 1 if link ℓ protects a path p against the failure of its relay node v; 0 otherwise.

η_ℓ the spare units reserved on link ℓ for rerouting the affected working paths upon their relay-node failure.

φ the copies of the current cycle, i.e., the maximal spare units of on-cycle links for protecting against the related relay-node failure.

α_ℓ the spare units reserved on the on-cycle link ℓ.

β_ℓ the protected traffic units on the straddling link ℓ.

With these notations, the objective function of the pricing problem can then be re-written as follows.

$$\min \quad \overbrace{\sum_{\ell \in L} \Lambda_\ell \alpha_\ell}^{\text{COST}_c} - \sum_{\ell \in L} u_\ell \overbrace{(\alpha_\ell + 2\beta_\ell)}^{a_\ell^c} - \sum_{p \in P} \sum_{v \in V_p} u_{pv} \overbrace{\sum_{\ell \in \varepsilon(v,p)} x_{pv}^\ell}^{a_{pv}^c}$$

The pricing problem includes the three parts of constraints. The first part defines a unit cycle, which is the same as that in [17]. The first part of constraints are defined next.

$$\sum_{\ell \in \omega(v)} b_\ell = 2\, y_v \qquad v \in V \tag{4}$$

$$s_\ell \le y_v - b_\ell \qquad v \in V,\ \ell \in \omega(v) \tag{5}$$

$$s_\ell \ge y_v + y_{v'} - b_\ell - 1 \qquad v, v' \in V,\ \ell = \{v, v'\} \in L \tag{6}$$

$$\sum_{\ell \in \omega(V')} b_\ell \ge y_v + y_{v'} - 1 \qquad V' \subset V,\ 3 \le |V'| \le |V| - 3 \quad v \in V',\ v' \in V \backslash V' \tag{7}$$

Any on-cycle node must have two incident on-cycle links. This is ensured by constraints (4). The following three sets of constraints is used to identify straddling links. (5) and (6) identifies straddling links. These two sets of constraints say that a link can be a straddling link if its two end nodes are on-cycle and the link itself is not on-cycle. Constraints (7) prevent generating a configuration which includes multiple different cycles. Otherwise, it burdens the determination of straddling links. These four sets of constraints are the same as those presented in [19] for the same purpose.

The second part is defined as follows. The constraints in the this part is responsible for determining a set of intermediate nodes of working paths which can be protected by the current cycle against a single failure.

Constraints (8) say that a working path can be protected against its relay node failure if its two links adjacent to this node are both protected by the current cycle. Also, the constraints denote that at most one protection path can be provided by the current cycle for recovering a working path against the node failure. Constraints (9) ensure that only on-cycle links are eligible for protecting working paths against the failure of their relay node. Constraints (10) say that, if the link of a working path is adjacent to its relay node, this link cannot be on the protection path. Constraints (11) - (13) are classical flow conservation constraints for defining the protection paths, which can be found in [19], [20] as well. Constraints (11) say that a protection path must end at two on-path nodes that are adjacent to the protected relay node. Constraints (12) and (13) together ensure that for intermediate nodes of a protection path, the number of outgoing and incoming flow must be identical.

$$\sum_{\ell \in \varepsilon(v,p)} x_{pv}^\ell \le x_{\ell'} + s_{\ell'} \qquad p \in P,\ v \in V_p,\ \ell' \in \omega(v,p) \tag{8}$$

$$x_{pv}^\ell \le b_\ell \qquad p \in P,\ v \in V_p,\ \ell \in L \tag{9}$$

$$x_{pv}^\ell \le 1 - \tau_v^\ell \qquad p \in P,\ v \in V_p,\ \ell \in L \tag{10}$$

$$\sum_{\ell \in \omega(v')} x_{pv}^\ell = \sum_{\ell \in \omega(v'')} x_{pv}^\ell \qquad p \in P,\ v \in V_p,\ v', \quad v''\ (v' \ne v'') \in V_{p,v} \backslash \{v\} \tag{11}$$

$$\sum_{\ell \in \omega(v')} x_{pv}^\ell \le 2 \qquad p \in P,\ v \in V_p,\ v' \in V \backslash V_{p,v} \tag{12}$$

$$\sum_{\ell, \ell' \in \omega(v') | \ell \ne \ell'} x_{pv}^\ell \ge x_{pv}^{\ell'} \qquad p \in P,\ v \in V_p, v' \in V \backslash V_{p,v} \tag{13}$$

The third part determines the copies of the current cycle for protecting working paths from the failure of the intermediate nodes. The third part of constraints is next written.

Upon the failure of a node, working paths through the node are all disrupted. Constraints (14) determine the number of spare units needed on an on-cycle link for protecting the affected working paths. Constraints (15) determine the copies of the current cycle, i.e., the maximal number of spare units among all on-cycle links for recovering the protected working paths. Constraints

(16) ensure the same spare units, are reserved on each on-cycle link in order to retain the pre-configuration property of a p-cycle. Constraints (17) determine the number of protected copies of each straddling link, which equals to the number of copies of the current cycle.

The final two sets of constraints is variable domain constraints.

$$\sum_{p \in P_v} x_{pv}^{\ell} \leq \eta_\ell \qquad \ell \in L,\ v \in V \tag{14}$$

$$\varphi \geq \eta_\ell \qquad \ell \in L \tag{15}$$

$$\varphi + M(b_\ell - 1) \leq \alpha_\ell \leq \varphi \qquad \ell \in L \tag{16}$$

$$\varphi + M(s_\ell - 1) \leq \beta_\ell \leq \varphi \qquad \ell \in L \tag{17}$$

$$b_\ell,\ s_\ell,\ y_v,\ x_{pv}^{\ell} \in \{0,1\} \qquad \ell \in L,\ v \in V,\ p \in P \tag{18}$$

$$\eta_\ell,\ \varphi,\ \alpha_\ell,\ \beta_\ell \in \mathbb{Z}^+ \qquad \ell \in L,\ v \in V,\ p \in P \tag{19}$$

IV. Computational Results

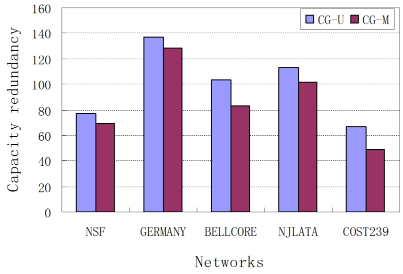
We evaluate the performance of our new proposed design (CG-M) in comparison with the design (CG-U) proposed in [18]. As the goal of this paper is to propose a scalable and capacity efficient design method, we compare CG-M with the design (CG-U) proposed in [18] in terms of capacity redundancy. Capacity redundancy is defined as the ratio of spare capacity usage over working capacity usage. We also compare these two designs in terms of the number of the distinct candidates selected in the final solution as well as the average length (the number of links) of p-cycles. Both design methods are implemented in C++ and solved by CPLEX 12.0 MIP solver.

A. Data instances

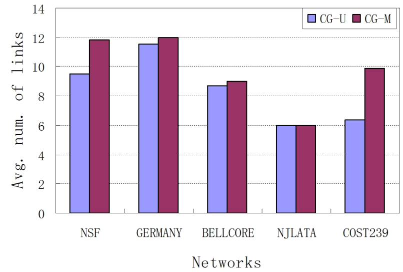
Five network instances have been used for evaluation and comparison. Table I lists each instance with different topology characteristics, including the number of nodes, the number of links and the node degree. Also, it lists the number of demands and the working capacity cost for each instance. Working capacity cost is the cost of optical channels for routing demands on the shortest paths. Each element in the traffic matrices indicates the number of unit requests between each node pair, which is uniformly distributed on the interval [1..20].

TABLE I
Network Instances

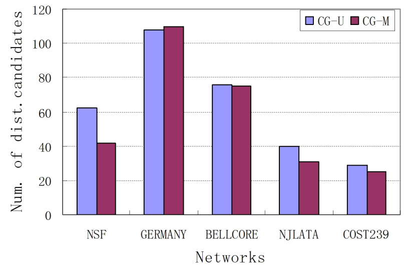
Networks	Nodes	Links	Node Degree	Num. Dems	W. Cost
NSF [23]	14	21	3.0	91	1970
GERMANY [23]	17	26	3.1	136	4034
BELLCORE [24]	15	28	3.7	105	2610
NJLATA [24]	11	23	4.2	55	943
COST239 [25]	11	26	4.7	55	792



(a) capacity redundancy



(b) average size of p-cycles



(c) num. of distinct candidates

Fig. 3. Solution performances: CG-U vs. CG-M

B. Numerical comparisons

The following experimental results are obtained from CG-U and CG-M. The solutions of CG-U and CG-M are obtained with an integrality gap less than 0.1%.

Fig. 3(a) presents the capacity redundancy of the solutions of CG-U versus CG-M over five network instances. For each network instance, the CG-M solutions show less capacity redundancy (more capacity efficient) than the CG-U ones, which keeps in line with the example in Section II-B. The differences of capacity redundancy between CG-U and CG-M range from ∼7% to ∼20%. The new design suggests that p-cycles are efficient protection approaches for both link and node protection against a single failure.

Fig. 3(b) shows the comparisons on the average size of the solutions from CG-U and CG-M. For each network, the average length of the p-cycles with CG-M is larger than CG-U, as measured by the average number of links. The larger the p-cycle is, the more likely it is to enable working paths share the protection path against a single node failure. Thus, the resulting solutions are more capacity efficient.

Fig. 3(c) presents the number of distinct candidates selected in CG-U and CG-M. For each network instance, CG-U requires less distinct p-cycles than with the CG-M model. Thus, CG-U outperforms CG-M in terms of management.

V. CONCLUSION

This paper investigates the design of full node-protecting p-cycle in WDM mesh networks. The purpose is to develop an (capacity) efficient and scalable design method. The new proposed design method enables a p-cycle protect multiple simultaneously failed working paths from a node failure only if the associated protection paths are disjoint. We cope with the scalability issue using large scale optimization tools, i.e., Column Generation (CG). In contrast with the traditional p-cycle designs, our new proposed CG-based method calculates the promising set of p-cycles on-line when needed.

Extensive experiments have been conducted on five network instances. Numerical results show clearly that our new proposed CG-based design method outperforms the previous one in terms of capacity efficiency. Our proposed method can improve the capacity redundancy up to $\sim$20% over the previous method.

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