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A Segmentation Method for Shared Protection in WDM Mesh Networks

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Abstract—Shared link and shared path protections have been recognized as preferred schemes to protect traffic flows against network failures. In recent years, another method referred to as Shared Segment Protection has been studied as an alternative solution for protection. This method is more flexible and efficient in terms of capacity utilization and restoration time. However, to our best knowledge, this method has mostly been studied in dynamic provisioning scenarios in which searching for restoration paths is dynamically performed after a failure has occurred. In this paper, based on the path segmentation idea, we propose a method to generate good candidate routes for traffic demands in static provisioning. These candidates are used as input parameters of an Integer Linear Programming (ILP) model for shared backup protection. Numerical results show that the capacity efficiency resulting from these candidates is much better than the best known Shared Backup Path Protection (SBPP) schemes. In addition, although the restoration time of our scheme is a little bit longer than those implementing link protection, it is still faster than path protection schemes.

I. INTRODUCTION

Survivability in WDM mesh networks is recognized as a crucial issue in network design. When a failure occurs at a fiber link, the affected traffic is rerouted via alternate paths, referred to as backup paths. Such backup paths can be predetermined (offline provisioning), or determined after a failure has occurred (online provisioning). The success of online provisioning depends on the availability of network resources. Thus, although online provisioning does not require much spare capacity, it does not guarantee 100% restoration. In this paper, we study a class of survivability in which offline provisioning is employed to ensure 100% restoration. These schemes, however, require some spare capacity assigned to backup paths, and the challenge is to minimize this spare capacity.

Spare capacity requirements mainly depend on the method of capacity allocation for the backup paths, which could be dedicated or shared; and the restoration strategy, which could be link protection or path protection. For fast restoration, the carrier is transmitted in both primary and backup paths (1+1 configuration), and the backup paths can not share wavelength channels. On the other hand, shared protection can only use the 1:1 configuration where backup paths may use the same wavelength channel. Naturally, the capacity efficiency of shared protection schemes is better than dedicated schemes, but the compromise is a slower restoration time.

In terms of the restoration strategy, the two protection alternatives are link protection and path protection. Link protection recovers the failure of working channels on a single fiber link through local detouring between the two end nodes of the failed link. Path protection recovers the failure of connections through end-to-end detouring of the affected connections. Research has shown that path protection offers better capacity utilization but link protection offers faster restoration [1], [2].

In recent years a different class of protection scheme known as “shared segment protection” has been introduced. Shared segment protection is a “hybrid” scheme between shared link protection and shared path protection in which each primary path is divided into non-overlapping or partial overlapping domains, called protection domains [3], [4], [5]. Shared segment protection schemes offer better capacity utilization, even compared to the best known shared path protection schemes. Furthermore, the restoration time of shared segment protection is better than shared path protection, but longer than shared link protection. This is because of two main reasons: 1) shared segment protection utilizes the capacity released from failed working traffic for restoration; 2) restoration path in shared segment protection is usually shorter than shared path protection and longer than shared link protection.

To date, shared segment protection have extensively been studied for dynamic restoration, where the backup paths are determined after the failures occur [3], [6], [4], [5]. In this paper, we study the shared segment protection for static protection where backup routes are pre-planned. For optimization purposes, a preferred approach is to use an Integer Linear Programming (ILP) model to select the optimal protection routes among the candidates. In this paper, we first propose a method to determine set of candidates for each connection. A feature of our method is that a candidate is divided into several sub segment candidates, which allows backup paths of different connections to share wavelength channels even if their working paths are not disjoint. Next, an ILP model is proposed which provides the optimal solution for shared protection (using the generated set candidates).

The rest of this paper is organized as follows. Section II reviews the methods for link/path protection and segment protection. A framework for segmentation of candidate routes is proposed in Section III. In Section IV we introduce an algorithm for segmentation and present our ILP model for shared protection. Numerical results are presented and analyzed in Section V. Finally, Section VI summarizes the paper and proposes some future directions for this research.
II. RELATED WORK

Shared protection in WDM networks is defined as protection schemes where backup routes are allowed to use the same wavelength channels. The three popular categories of shared protection are shared link protection, shared path protection, and shared segment protection. Shared link and shared path protection have been studied extensively [1], [7], [2], [8], [9], [10], [11], [12]. The authors in [1], [7], [2] propose ILP models for different shared protection schemes, e.g., dedicated path protection, shared path protection, and shared link protection. These models have been studied extensively [1], [7], [2] use two distinct sets of candidate routes. [1], [7] and [2] use shared-path protection and shared-link protection. The capacity utilization and restoration time resulting from these protection schemes are investigated. It is reported that shared-path protection provides significant savings in capacity utilization over dedicated-path and shared-link protection, and dedicated-path protection provides marginal savings in capacity utilization over shared-link protection. On the other hand, shared-link protection offers the fastest restoration. Similar results have been reported in [8], [9]. All ILP models used in these papers are of the path-link form, that is the solution is selected from a pre-determined set of candidate routes. [1], [7] and [2] use two distinct sets of candidates for working and backup routes, while [9] employs a set of disjoint-paths pairs. All of these sets of candidates are determined over simple networks. In reality, fiber links of WDM networks may be bundled into a conduit. These links are said to have the same risk, referred to as a shared-risk group. Let us consider a set of candidate routes in this context is more complicated and can be found in [10], [11], [12]. In recent years, shared segment protection schemes [13], [4], [5], [6], [3], [14] have been considered as alternate solutions in shared protection. [13], [4] and [5] propose ILP models and heuristics (namely PROMISE), for finding multiple segments of a backup route against the failure of a single active (working) route. This is performed on simple networks [5], or with Share-Risk Group constraints [13], [4]. A similar ILP model for finding the multiple segments backup of a working path can be found in [6]. This model and the former are in the link-flow form and can only be applied for a single working path. A heuristic algorithm called Cascaded Diverse Routing (CDR) is used to resolve the computational problem of the ILP model. This algorithm yields better performance in terms of capacity utilization over the PROMISE due to the extra efforts in locating the working segments at the expense of longer computation time. The capacity utilization and the restoration time of shared segment protection schemes have been reported to be better than shared path protection schemes. Hence, shared segment protection can balance the tradeoff between the capacity utilization and the restoration time. In static provisioning at the design phase, the ILP models for segment-based approaches are proposed in [14]. These are, however, non-joint models when working routes are given. In this paper, we investigate the benefits of shared segment protection at the design phase with joint optimization in which multiple segments of working/backup routes are jointly determined. We propose a framework for segmenting pairs of disjoint-path candidates, and then use an ILP model to find the optimal solution using these candidates.

III. THE SEGMENTATION OF CANDIDATES

One approach to solving the capacity design problem under protection constraints is to use an ILP model to find the optimal solution from the set of given candidates. This set of candidates is formed by finding eligible pairs of disjoint-paths between the source and the destination node of a traffic connection. The following criteria are used to ensure 100% restoration:

- A pair of primary/backup paths for a connection have to be disjoint.
- Backup paths of different connections can only share the same wavelength channel on a link if their primary paths are disjoint.

![Dedicated backup paths](image1)

**Fig. 1. Joint Primary/Joint Backup - Dedicated Backup Paths**

The second condition implies that if two primary paths are joint at an arbitrary link, then their backup paths either have to be disjoint, or assigned different wavelength channels on the same links, as shown in Fig. 1. In that figure, if link (3-5) fails on which primary paths $p_1$ and $p_2$ are joint, then the traffic on $p_1$ and $p_2$ are rerouted to their corresponding backup paths $r_1$ and $r_2$ which join at link (6-8). Thus, to ensure 100% restoration from the failure of link (3-5), $r_1$ and $r_2$ are assigned distinct (dedicated) wavelength channels on link (6-8). In other words, there are two wavelength channels used on link 6-8 for restoration.

![Shared backup paths](image2)

**Fig. 2. Joint Primary/Joint Backup - Shared Backup Paths**

Let us consider a scheme as shown in Fig. 2. We split the path $p_1 = (1 \rightarrow 3 \rightarrow 5 \rightarrow 7 \rightarrow 9 \rightarrow 10)$ into two path segments $p'_1 = (1 \rightarrow 3 \rightarrow 5 \rightarrow 7)$ and $p''_1 = (7 \rightarrow 9 \rightarrow 10)$, and split the corresponding backup path $r$ into $r'_1 = (1 \rightarrow 2 \rightarrow 7)$ and $r''_1 = (7 \rightarrow 6 \rightarrow 8 \rightarrow 10)$. In this case, the backup
path $r_2$ can share a wavelength channel on link $(6 - 8)$ with $r_2^{r'}$, since primary paths $p_2^p$ and $p_2$ are disjoint. In addition, the total number of physical hops used by sub pairs $(p_1^p, r_1')$ and $(p_2^p, r_2')$ is equal to that of the original pair $(p_1, r_1)$. This means that if we have a method to segment the primary path into sub-primary paths in such a way that the total capacity used by the sub-backup paths is not larger than those used by the original backup path, then we should achieve better capacity utilization compared to the traditional shared backup path protection schemes. It is worth noting that the idea behind this approach is somewhat similar to the concepts of “stub reuse” introduced by W.D. Grover in [9], where the working channels of failed primary paths are reused to recover other failed primary paths.

In this part, we propose a method to segment pairs of disjoint paths and use these sub-path pairs as additional candidate routes for selection in the ILP model.

Studies in the literature use the $K$-best pairs of disjoint paths between the source and the destination as routing candidates for each traffic demand. These pairs of disjoint paths may be link-disjoint or node disjoint, and the segmentation approach is different for each case.

A. Link-Disjoint Path-Pair Segmentation

A path-pair between two nodes in a network are link-disjoint if they have at least one intermediate node in common which is neither the source node nor the destination node, but they do not have any common link. Let us consider the example shown in Fig. 3, where the pair of link-disjoint paths $(p, r)$ from source node $s$ to destination node $d$ contains two nodes $a_1$ and $a_2$ in common. This path-pair can be segmented into three node-disjoint sub-path-pairs $(p_i, r_i)$ for Segment $i$ ($i = [1 \ldots 3]$).

![Fig. 3. Link-Disjoint Path-Pair Segmentation](image)

The merging of these sub-path-pairs forms the original link-disjoint path-pair, hence they satisfy the requirements of shared protection. We shall now introduce a proposition which forms the basis for the developments in this paper.

**Proposition 3.1:** The set of segment path-pairs for a link-disjoint path-pair offers better routing options than the original path pair in terms of capacity utilization and restoration time.

**Proof:**

Clearly, the backup paths and the primary paths of the sub segments of a path-pair are sub paths of their original backup and primary paths respectively. Hence, if the original backup path can share a wavelength channel with any other backup path, one of its sub backup paths can also share the same wavelength channel with that backup path.

On the other hand, if a sub backup path can share a wavelength channel with another sub backup path, their original backup paths may not necessarily be able to share the same wavelength, since the disjointness of the corresponding primary paths is not guaranteed.

For convenience of discussion from here after, we refer to the set of sub segments of a link-disjoint path-pair as the “link-segment path-pair”.

B. Segmentation of Node-Disjoint Path-Pairs

The segmentation of node-disjoint path-pairs is not as simple as the link-disjoint case. Because of the characteristics of node-disjoint path-pairs, the segmentation may not be able to maintain the integrity of the backup path, meaning that merging of the backup segments may not necessarily give the same path as the original backup path. In that case, we generate a new multiple segments backup route, based on the original backup path, for each segment of the primary path. We shall now consider all possible cases when segmenting node-disjoint path-pairs.

![Fig. 4. Node-Disjoint Path-Pair Segmentation](image)

Let $p = \{s, a_1, \ldots, a_m, d\}$ and $r = \{s, b_1, \ldots, b_m, d\}$ be the primary path and the backup path of a node-disjoint path-pair.

**Axiom 3.1:** A node-disjoint path-pair can be segmented if there exists a node $a_k \in p$ ($k = [1 \ldots n]$) that connects to a node $b_i \in r$ ($i = [1 \ldots m]$).

- **Case 1:** $a_k, k = [1 \ldots n]$ connects with $r$ at only one node $b_i, i = [1 \ldots m]$.

  We divide the original path-pair $(p, r)$ into two sub-path-pairs $(p', r')$ and $(p'', r'')$, defined as:
  
  - $p' = \{s, a_1, \ldots, a_k\}, r' = \{s, b_1, \ldots, b_i, a_k\}$
  - $p'' = \{a_k, \ldots, a_m, d\}, r'' = \{a_k, b_i, \ldots, b_m, a_k\}$

  The total hops used by the sub backup paths is one hop larger than the original backup path. However, this candidate offers the possibility of shared segment protection, and the associated advantages.

- **Case 2:** $a_k, k = [1 \ldots n]$ connects with $r$ at least two nodes $(b_i, b_j), i < j, (i, j) = [1 \ldots m]$.

  The original path-pairs $(p, r)$ can be segmented into two sub path-pair segments $(p', r')$ and $(p'', r'')$, defined as:
  
  - $p' = \{s, a_1, \ldots, a_k\}, r' = \{s, b_1, \ldots, b_i, a_k\}$
  - $p'' = \{a_k, \ldots, a_j, d\}, r'' = \{a_k, b_i, \ldots, b_j, a_k\}$

  The benefit of this segmentation is dependent on the number of hops between nodes $b_i, b_j$, and can be described in terms of the quantity $j - i$:
  
  - $j - i = 1$: the total hops used by the sub backup paths is 1 hop larger than the original backup path.
the total hops used by the sub backup paths is less than or equal to those used by the original backup path, and hence this is a potential candidate. However, the merging of these segments forms a link-disjoint path-pair that may already exist in the best K candidates. This reveres to the case of segmenting link-disjoint path-pairs, which we have already discussed.

IV. THE PROPOSED SEGMENTATION METHOD FOR SHARED PROTECTION

In this part, we propose a method to improve the shareability between candidates in shared protection schemes by segmenting candidates in shared backup path protection. We first propose two algorithms for link (Algorithm 1) and node (Algorithm 2) segmentation and then introduce principles to select potential candidates.

Algorithm 1: Link-Disjoint Path Pair Segmentation (LDPPS)

Input: A link-disjoint candidate path-pair \((p, r)\).
Output: Sub path-pairs \((p^i, r^i), i = 1 \ldots k\).

1. Find the set of common nodes \(A = \{p \cap r\} \setminus \{s, d\}\), denoted by \(A = \{a_1, \ldots, a_{k-1}\}\).
2. Segment \((p, r)\) into \(k\) sub path pairs \((p^i, r^i)\) using the method described in Section III-A.

Algorithm 1 returns the set of sub segment path-pairs while the output of Algorithm 2 may include more than one set of sub segment path-pairs. In next part, we shall introduce some principles for nominating the candidate routes for the ILP model.

Algorithm 2: Node-Disjoint Path Pair Segmentation (NDPPS)

Input: A node-disjoint candidate path-pairs \((p, r)\).
Output: Sub path-pairs \((p^i, r^i), i = 1, 2\).

1. for each node \(a_k \in p \setminus \{s, d\}\) do
   2. if there exists two neighbours \((b_i, b_j \in r, i < j, (i, j) \neq \{s, d\}\) of \(a_k\) then
      3. Segment \((p, r)\) into 2 sub path-pairs \((p^i, r^i)\), \(i = 1, 2\) using theory in Section III-B;
   4. else if there exists only one neighbour \((b_i \in r, i \neq \{s, d\}\) of \(a_k\) then
      5. Segment \((p, r)\) into 2 sub path-pairs \((p^i, r^i)\), \(i = 1, 2\) using theory in Section III-B;
   6. end if
7. end for

Principles for Generating the Set of Candidate Routes

- A link-disjoint path-pair is substituted by a link-segment path-pair resulted from Algorithm 1. The link-segment path-pair is considered as a single path-pair candidate.
- All node-disjoint path-pairs are maintained as candidate routes.
- If Algorithm 2 yields two sub segment path-pairs for \((j - i \geq 2)\) for node-disjoint path-pairs, if the merging of these sub segments will form a link-disjoint path-pair which is already in the original set of \(K\) candidate path-pairs, these sub segment path-pairs are released. Otherwise, it is considered as a candidate.
- The two sub segment path-pairs resulting for \((j - i = 1)\) are added to the set of candidates if the merging of these sub segments is not in the original set of \(K\) candidate path-pairs.
- If two sub segment path-pairs result from a single node \(b_i\), then the two sub segment path-pairs are added to the set of candidates.

It is worth noting that for each node disjoint path-pair candidate, there may be more than one sub segment path pair generated. In order to obtain optimal solutions, all of these are considered as candidate routes in our ILP model.

A. The ILP Model for Shared Backup Protection

In this section, after describing our notation, we will introduce an ILP model for shared backup protection using candidate routes in Section IV.

- \(G(V, E)\): the physical topology of a network, where \(V = \{v_1, \ldots, v_N\}\) and \(E = \{e_1, \ldots, e_M\}\) are the sets of \(N\) network nodes and \(M\) network links respectively.
- \(T = \{t_l | l = 1, 2, \ldots, D\}\): the set of \(D\) traffic demands.
- \(d_t\): the volume of demand \(t_i\).
- \(R_t^i\): the set of \(K_t^i\) non-segmented candidates between end nodes of \(t_i\).
- \(b_{i,p}, b_{i,r}\): indicator constants which are set to 1 if the working and backup path of \(r_i^o\) use link \(e_j\), or 0 otherwise.
- \(\delta_{i,j}^o\): the decision variable indicating the volume of traffic demands carried on candidate \(r_i^o\).
- \(w_j\): the number of working wavelength channels on link \(e_j\).
- \(s_j\): the number of spare wavelength channels on link \(e_j\).
- \(R_t^i\): the set of \(K_t^i\) segmentation candidates between the end nodes of \(t_i\).
- \(s_{r_i^o,h}\): the set of \(K_t^i\) segmentation candidates between the end nodes of \(t_i\).
- \(n_{r_i^o,h}\): the number of segments of candidate \(r_i^o\).
- \((\alpha_{i,p}, \alpha_{i,r})\): indicator constant set to 1 if the working path and the backup path of segment \(s_{r_i^o,h}\) use link \(e_j\) respectively, or 0 otherwise.
- \(\beta_{i,j}^o\): the decision variable indicating the volume of traffic demands carried on candidate \(r_i^o\).

We now present our ILP model for shared protection which will yield the optimal routing solution using the set of candidates which were generated in the last section.

Objective

\[ \text{Minimize: } \sum_{e_j \in E} (w_j + s_j) \]

Constraints

1) Selection constraint:

\[ \sum_{k=1}^{K_t^i} \delta_{i,k}^o + \sum_{k=1}^{K_t^i} \beta_{i,k}^o = d_t, \quad \forall t_i \in T \] (1)
2) Sufficient capacity for working channels:

\[ w_j = \sum_{t_i \in T} \left( \sum_{h=1}^{K} b_{i,j}^{k} a_{i,j}^{k} + \sum_{k=1}^{n_{i,k}} h_{i,j}^{k} a_{i,j}^{k} \right), \quad \forall e_j \in E \]

(2)

3) Sufficient capacity for backup channels:

\[ a_j \geq \sum_{t_i \in T} \sum_{h=1}^{K} b_{i,j}^{k} a_{i,j}^{k} + \sum_{k=1}^{n_{i,k}} h_{i,j}^{k} a_{i,j}^{k} + \sum_{t_x \in T} \sum_{k=1}^{K} b_{x,j}^{k} a_{x,j}^{k} \delta_{i}^{k}, \quad \forall (e_j, e_j') \in E : e_j' \neq e_j \]

(3)

4) Capacity constraint:

\[ w_j + s_j \leq W_j, \quad \forall e_j \in E \]

(4)

5) Integer constraints:

\[ \delta_{i}^{k} \in \{0, 1, \ldots, d_i\}, \quad w_{i,j}, s_{i} \in \{0, \ldots, W\}, \quad \forall e_i \in E \]

(5)

The objective function minimizes the total capacity utilized by working and backup channels. The selection constraint in (1) ensures enough routes and volume for each traffic demand. Constraints (2) and (3) ensure that sufficient capacity is available for working and backup routes. The capacity constraint in (4) enforces the upper limit on the number of wavelength channels used on each fiber link.

V. SIMULATION RESULTS

We shall examine the number of constraints and variables in our proposed ILP model in comparison with the shared backup path protection model in [9]. The other performance metrics used for the purpose of comparison will be the capacity utilization and the restoration time. For convenience of discussion, we use SBPP to refer to the original ILP model for shared backup path protection in [9], and SSP to refer to our proposed shared segment protection model.

A. The Number of Constraints

The number of constraints in our SSP model can be calculated as \( D + 2M + \frac{1}{2}M(M - 1) \). This is the same as the number of constraints of the SBPP model in [9].

B. The Number of Decision Variables

In our model, additional variables are resulted from the segmentation of node-disjoint path-pairs, and the number of these additional variables depends on the network topology and the value of \( K \) in SBPP. We simulate 30 random networks, with the number of nodes selected randomly in the range 14 to 22, of nodal degree 3, and 10000 random traffic connections. The simulation is performed for \( K \) values of 3, 4 and 5. The results are shown in Fig. 5 and Fig. 6. We observe in Fig. 5 that the percentage of path-pairs that are segmented using Algorithm 2 is decreasing as the number of network nodes increases. For example, for \( K = 3 \), this percentage decreases from 6% to around 3% when the number of nodes increases from 10 to 22. Obviously, this would amount to a decrease in the percentage of additional variables that are introduced into our model as a result of segmentation. It should be noted in Fig. 5 that although link segmentation (indicated by dashed lines) is higher than node segmentation for the simulated networks, it has no bearing on the number of variables in our model.

Fig. 5. The Percentage of Connections Protected through Segmentation for Random Networks of Nodal Degree 3

Fig. 6. Percentage of Additional Variables Introduced as a Result of Segmentation for Random Networks of 14 Nodes

Fig. 6 shows that the percentage of additional variables due to node segmentation increases with higher values of \( K \), reaching a peak when the average nodal degree is around 3.5. This can be explained as follows. In a sparse network, which has an average nodal degree of say less than 3, the primary paths may be long but their nodes do not have many neighbors, making segmentation harder to achieve. Hence the number of additional variables resulting from segmentation is low. When the nodal degree increases to around 3.5, the primary paths are long and their nodes have many neighbors, increasing the chance of segmentation protection, and thus increasing the number of additional variables. However, when the nodal degree is too high, say 4 or higher, there are more routing options available and on average the number of hops in the primary paths becomes smaller, making it harder to perform segmentation. Hence the number of additional variables resulting from segmentation decreases.
C. The Capacity Utilization and the Restoration Time

Capacity utilization is measured as the percentage of the total capacity used in the network over the maximum capacity provided by that network. For a number of random networks simulated, we use the average of the total capacity required as a performance metric to compare the results of the SSP and the SBPP models. These results are shown in Fig. 7 for 30 random networks of \( N = \{14, 18, 22\} \) nodes with nodal degree 3, with \( K = 3 \). The number of connections in each traffic pattern varies from 10 to 20 and the maximum demand volume per connection is 3.

We note that when the number of network nodes increases from 14 to 22, the average of the total capacity required by SSP is always lower than SBPP. In the worst case, SSP will yield the same results as SBPP, if the segmentation is not necessary. In addition, the required capacity in SSP has better improvement over SBPP when the number of traffic connections increases. Similar results are achieved for other values of \( K = [4, 5] \).

The time for restoring a connection against a failure depends on such factors as failure detection time, switching time and synchronization time between the source and the destination nodes. A formula for calculating the restoration time can be found in [2]. In this paper, the restoration time is assessed through the number of hops needed to restore the affected connections when single link failures occur. The comparison of the restoration time between SSP and SBPP is shown in Fig. 8 for random network topologies of \( N = 14 \) nodes, nodal degree 3 and \( K = 4 \). It can be seen that the number of restoration hops in SSP is lower than SBPP. For instance, the average number of restoration hops for 10 traffic connections is 5 hops in SSP and 6.2 hops in SBPP. This is because for some traffic connections affected by a link failure, end-to-end rerouting may not be necessary and it might be sufficient to only reroute on shorter backup segments.

VI. CONCLUSION AND FUTURE WORKS

In this paper we have proposed a framework for determining segmentation candidate path-pairs, to be used in an ILP model for shared path protection. The number of variables in our model is higher than those in shared path protection schemes, but it offers a better capacity utilization and improved restoration time. These are important objectives when optimizing a network at the design phase. Our future work will focus on generating good candidates for shared protection that can satisfy multiple qualities of protection (MQoP). That is, different restoration requirements can be combined into a complete model to calculate the best solution according to specific objectives such as real cost, capacity utilization and/or congestion levels.

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