

# A New Provisioning Framework to Provide Availability-Guaranteed Service in WDM Mesh Networks

Jing Zhang<sup>†</sup>, Keyao Zhu<sup>†</sup>, Hui Zang<sup>‡</sup>, and Biswanath Mukherjee<sup>†</sup>

<sup>†</sup>Dept. of Computer Science, Univ. of California, Davis, CA 95616, USA

<sup>‡</sup>Sprint Advanced Technology Laboratories, Burlingame, CA 94010, USA

<sup>†</sup>{zhangj, zhuk, mukherje}@cs.ucdavis.edu, <sup>‡</sup>hzang@sprintlabs.com

**Abstract** – In this paper, we present a connection-provisioning framework to satisfy customers' availability requirements using appropriate protection schemes. The framework contains two parts: (a) WDM mesh network service availability analysis; and (b) a connection-provisioning approach using the analysis. We present the availability analysis for connections with different protection schemes (i.e., unprotected, dedicated, or shared protected) and propose an integer linear program (ILP) based provisioning approach for static traffic. We verify the theoretical availability analysis through simulations, and demonstrate the effectiveness of our provisioning approach using numerical examples.

**Index Terms**—Optical network, WDM, protection, connection provisioning, service reliability, connection availability.

## I. INTRODUCTION

With the increase of mission-critical Internet applications, customers are increasingly requiring highly-reliable network services. The service reliability is represented by the *connection availability*, which is the probability that the connection will be found in the operating state at a random time in the future [1]. Connection availability is defined in the Service Level Agreement (SLA) along with revenue and penalty. How to provision customers' connection requests to avoid penalty as well as minimizing cost is one of the main concerns to a service provider.

With the maturing of wavelength-division multiplexing (WDM) technology, one single fiber link can carry a large amount of data (on the order of terabits per second). Therefore, the failure of a network component (e.g., fiber link, optical crossconnect (OXC), amplifier, etc.) can lead to huge loss in data and revenue, and can dramatically affect the connections' availabilities especially when connections are unprotected or cannot be restored. A connection's availability is determined by the network components' availabilities along its route [2], [3]. In order to achieve the required service reliability, a network operator needs to carefully provision a customer's request while considering the network component failure probabilities, failure repair times, connection restoration times, etc.

By pre-reserving extra resources for each connection request, *protection*, a proactive procedure, can be used to increase service reliability against network failures. A variety

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of protection schemes have been studied in the literature, i.e., link-rerouted vs. path-rerouted, dedicated vs. shared, etc. [4]-[7]. A general framework which can provide a proper protection scheme to a customer's service request according to its SLA-defined availability requirement and network components' availability characteristics will benefit a network operator in resource efficiency and service scalability. It is also able to handle multiple simultaneous failures.

We propose a new framework for cost-effective connection provisioning to satisfy connections' availability requirements defined in the SLA. The framework consists of two components: (1) availability analysis for different protection schemes in WDM mesh networks; and (2) an efficient provisioning approach using the availability analysis to provide appropriate protection based on a customer's SLA.

The paper is organized as follows. Section II provides availability analysis for network components and connections under different protection schemes. Section III formally states the connection-provisioning problem with service reliability consideration. As a preliminary study, we propose a three-step provisioning approach using our availability analysis to provide unprotected and 1+1-protected services in Section IV. In Section V, we verify our availability analysis through simulations, and demonstrate the effectiveness of our provisioning approach using numerical examples. Finally, Section VI concludes this study.

## II. AVAILABILITY ANALYSIS FOR WDM MESH NETWORK

We analyze the availability of a connection in a mesh network with the following assumptions.

- 1) A system (component, path, connection, etc.) is either available (functional) or unavailable (experiencing failure);
- 2) Different network components fail independently;
- 3) For any component, the interarrival time between failures and the failure-holding time are independent memoryless processes.

The availability of a system is the fraction of time the system is "up" during the entire service time. If connection  $t$  is carried by a single path, its availability (denoted by  $A_t$ ) is equal to the path availability; if  $t$  is dedicated or shared

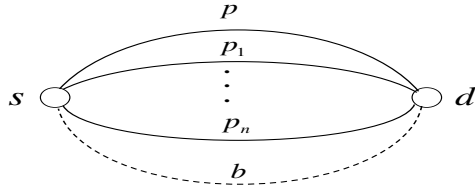


Fig. 1. Shared-path protection example.

protected,  $A_t$  will be determined by both the primary and the backup paths.

#### A. Network Component Availability

The availability of a network component  $j$  (denoted as  $a_j$ ) can be calculated based on the component's failure rate (denoted as  $\lambda_f$ ) and the average time to fix a failure, i.e., failure-holding time (denoted as  $H_f$ ) as follows:

$$a_j = \frac{1/\lambda_f - H_f}{1/\lambda_f} = 1 - H_f \times \lambda_f \quad (1)$$

Please see [8] for typical data on network component (transmitter, receiver, fiber link, etc.) failure rate and repair time.

#### B. End-to-End Path Availability

Path  $i$  is available only when all the network components along its route are available. Let  $a_j$  denote the availability of network component  $j$ . Let  $S_i$  denote the set of network components used by path  $i$ . Then  $A_i$  can be computed as follows:

$$A_i = \prod_{j \in S_i} a_j \quad (2)$$

#### C. Availability for a Dedicated-Path-Protected Connection

In dedicated-path protection, connection  $t$  is carried by one primary path  $p$  and protected by one backup path  $b$  which is link-disjoint with  $p$ .  $t$  is "down" only when both  $p$  and  $b$  are unavailable.  $A_t$  can be computed as follows:

$$A_t = 1 - (1 - A_p) \times (1 - A_b) = A_p + (1 - A_p) \times A_b \quad (3)$$

where  $A_p$  and  $A_b$  denote the availability of  $p$  and  $b$ , respectively.

#### D. Availability for a Shared-Path-Protected Connection

In shared-path protection, connection  $t$  is carried by one primary path  $p$ , protected by one link-disjoint backup path  $b$ , and the backup resources can be shared by other backup paths as long as their primary paths are not traversing the same link with  $p$ . Figure 1 shows a specific example where path  $p$ ,  $p_1$ , ..., and  $p_n$  are sharing the same backup path  $b$ . (This is only a simple example; backup sharing, in general, can be more complex.) Let us denote  $S_p$  as a set that contains all the primary paths (except  $p$ ) whose backup paths are sharing some resources with  $b$ . In the example shown in Fig. 1,  $S_p = \{p_1, p_2, \dots, p_n\}$ .  $t$  will be available if:

- 1)  $p$  is available; or
  - 2)  $p$  is unavailable,  $b$  is available, and the failure on  $p$  happens before failures to the other primary paths in  $S_p$ .
- Therefore,  $A_t$  can be computed as follows:

$$A_t = A_p + (1 - A_p) \times A_b \times \sum_{i=0}^n \frac{1}{i+1} \times p_i \quad (4)$$

where  $A_p$  and  $A_b$  denote the availability of  $p$  and  $b$ , respectively;  $n$  is the size of  $S_p$ ; and  $p_i$  is the probability that exactly  $i$  primary paths in  $S_p$  are unavailable. The correctness of Eqn. (4) is verified through simulation in Section V-A. Note that it may not be necessary for us to enumerate all the possible simultaneous failure cases (up to  $n$ ) since the probability for  $i$  simultaneous failures decreases significantly as  $i$  increases. We find that it will only take several seconds to compute Eqn. (4) when several tens of connections are in the sharing group and up to 10 simultaneous failures are considered using a computer with a 1.4 GHz Pentium processor and 512Mbytes RAM; thus, the computation is feasible in a practical network.

### III. GENERAL PROBLEM STATEMENT

The problem of cost-effective connection provisioning to satisfy the connections' availability requirements on a given physical topology (fiber network) is formally stated below.

We are given the following inputs to the problem.

- 1)  $G = (V, E, A, W)$ , the network topology where  $V$  is the set of nodes,  $E$  is the set of fiber links,  $A : E \rightarrow (0, 1)$  is the availability function for each link (where  $(0, 1)$  denotes the set of real numbers between 0 and 1),  $W : E \rightarrow Z^+$  specifies the number of free wavelengths on each link (where  $Z^+$  denotes the set of positive integers).
- 2)  $T = \{t = \langle s, d, A'_t \rangle\}$ , the set of connection requests where  $s$  is the source,  $d$  is the destination, and  $A'_t$  is the availability requirement of connection request  $t$ . Each  $t$  requires one full wavelength capacity.

Our goal is to determine the route for each connection request and protect them if necessary to minimize the total network cost (wavelength links, particularly).

### IV. OUR APPROACH: INTEGER LINEAR PROGRAM (ILP)

To optimize network resource usage, we must distinguish those *one-path-satisfiable connections*, whose availability requirements can be satisfied without using any backup path. Let  $T_1$  denote the one-path-satisfiable connection set, and  $T_2$  denote the set of remaining connections (i.e., *protection-sensitive connections*). Based on the availability analysis, our connection-provisioning approach consists of the following steps:

- 1) Connections are classified into two groups  $T_1$  and  $T_2$ .
- 2) For a connection in  $T_1$ , one path is needed to carry each of them. We use an integer linear program (ILP) to find the routes which could satisfy the connections' availability requirements while minimizing resources (wavelength links) used. The ILP is given in Section IV-B.

- 3) As an initial study, dedicated-path protection is considered to protect connections in  $T_2$ . The problem of providing dedicated-path protection while satisfying the connections' availability requirements is mathematically formulated. Formulations are shown in Section IV-C. We also discuss the nonlinearity of the formulations and propose two schemes to approximately solve them.

#### A. Connection Classification

Suppose a single path  $p$  is used to carry connection  $t$ . The availability of  $p$  ( $A_p$ ) is equal to multiplication of the availabilities of links it traverses. (In what follows, we consider links as the only network components used by a path but it is straightforward to incorporate other network components as well.) Suppose path  $p$  traverses links  $l_1, l_2, \dots, l_n$ . We call  $p$  is a *reliable path* for connection  $t$  if and only if:

$$A_p = A_{l_1} \times A_{l_2} \times \dots \times A_{l_n} \geq A'_t \quad (5)$$

where  $A_{l_i}$  is the availability of link  $l_i$ ,  $1 \leq i \leq n$ , and  $A'_t$  is the required availability of connection  $t$ . If we compute the logarithm of both sides of Eqn. (5), we obtain:

$$\log A_p = \log A_{l_1} + \log A_{l_2} + \dots + \log A_{l_n} \geq \log A'_t \quad (6)$$

Since  $A_{l_i}$  and  $A'_t$  are between 0 and 1,  $\log A_{l_i}$  and  $\log A'_t$  have negative values. Multiplying both sides by  $-1$ , we get:

$$-\log A_p = -\log A_{l_1} - \log A_{l_2} - \dots - \log A_{l_n} \leq -\log A'_t \quad (7)$$

Now, we can observe that, if the cost of link  $l_i$  ( $C_{l_i}$ ) is defined as such a function of its availability (i.e.,  $C_{l_i} = -\log A_{l_i}$ ), the cost is additive and the path with minimum cost will be the path with maximum availability (such a path is denoted as the *most-reliable path* (MRP)). Through this proposed *Multiplication-to-Summation* (MS) technique, a standard shortest-path algorithm can be applied to compute the MRP. If the availability of a MRP is smaller than  $A'_t$ , we know that protection is needed for connection  $t$ . Therefore, we can classify the connections into two groups: one-path-satisfiable connections ( $T_1$ ), and protection-sensitive connections ( $T_2$ ).

#### B. ILP for One-Path-Satisfiable Connections

Our MS technique enables us to formulate the problem of provisioning connections in  $T_1$  into an ILP since (nonlinear) multiplication has been converted into (linear) summation. We will use following notations in our mathematical formulations:

- 1)  $m$  and  $n$  denote end points of a physical fiber link.
- 2)  $s$  and  $d$  denote source and destination of a given end-to-end connection request  $t$ .

The mathematical formulation for one-path-satisfiable connections is as follows. (While we consider full wavelength-conversion here, the extension to the wavelength-continuous case is straightforward.)

#### • Given:

- $N$ : Number of nodes in the network.
- $P_{mn}$ : Number of fiber links interconnecting node  $m$  and node  $n$ .  $P_{mn} = P_{nm} = i, i > 0$ , if and only if there exists  $i$  physical fiber links between nodes  $m$  and  $n$ ; 0 otherwise.
- $W_{mn}$ : Number of free wavelengths on link  $(m, n)$ .
- $A_{mn}$ : Availability of link  $(m, n)$ . If there are multiple fibers between a node pair, they have same availability if they traverse the same fiber bundles.
- $\alpha_{mn}$ : Availability parameter of link  $(m, n)$  where  $\alpha_{mn} = -\log A_{mn}$ .
- $T_1 = \{t = \langle s, d, \alpha_t \rangle\}$ : Connection request set, where  $\alpha_t$  is the availability parameter of connection  $t$  and defined as  $\alpha_t = -\log A'_t$ .

#### • Variables:

- $P_{mn}^t$ :  $P_{mn}^t = 1$  if connection request  $t$  is routed through fiber link  $(m, n)$ ; otherwise,  $P_{mn}^t = 0$ .

#### • Objective: Minimize the total wavelength links used.

$$\text{Minimize} : \sum_t \sum_{m,n} P_{mn}^t \quad (8)$$

#### • Constraints:

- On physical route flow-conservation constraints:

$$\sum_m P_{mk}^t = \sum_n P_{kn}^t \quad \text{if } k \neq s, d \quad \forall t, k \quad (9)$$

$$\sum_m P_{ms}^t = \sum_n P_{dn}^t = 0 \quad \forall t \quad (10)$$

$$\sum_n P_{sn}^t = \sum_m P_{md}^t = 1 \quad \forall t \quad (11)$$

- On link capacity constraints:

$$\sum_t P_{mn}^t \leq P_{mn} \times W_{mn} \quad \forall m, n \quad (12)$$

- On connection availability constraints:

$$\sum_{m,n} P_{mn}^t \times \alpha_{mn} \leq \alpha_t \quad \forall t \quad (13)$$

#### C. Mathematical Formulation for Protection-Sensitive Connections

For connections in  $T_2$ , we provide dedicated-path protection to them. The problem to be solved now is to route each connection  $t$  in  $T_2$  using two link-disjoint paths while satisfying  $A'_t$  and minimizing the resources used. The problem is mathematically formulated as follows (using the same notations as in the formulations in the previous subsection):

#### • Variables:

- $P_{mn}^{tp}$ :  $P_{mn}^{tp} = 1$  if primary path of connection  $t$  is routed through fiber link  $(m, n)$ ; otherwise,  $P_{mn}^{tp} = 0$ .
- $P_{mn}^{tb}$ :  $P_{mn}^{tb} = 1$  if backup path of connection  $t$  is routed through fiber link  $(m, n)$ ; otherwise,  $P_{mn}^{tb} = 0$ .

#### • Objective A: Minimize the total wavelength links used.

$$\text{Minimize} : \sum_t \sum_{m,n} (P_{mn}^{tp} + P_{mn}^{tb}) \quad (14)$$

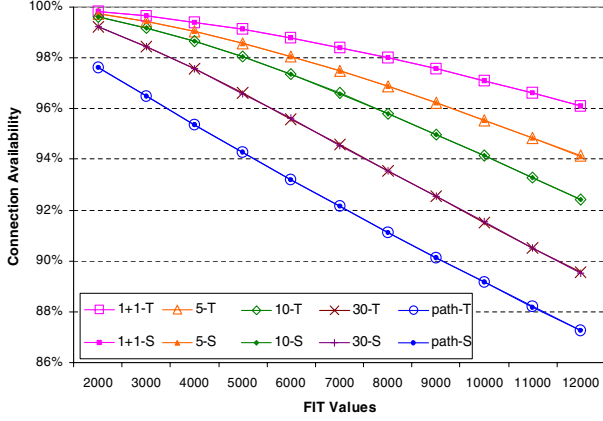


Fig. 2. Simulated vs. theoretically-computed availabilities for a dedicated or shared-path-protected connection when  $n = 0, 5, 10$ , or  $30$ , and for different  $FIT$  values (T is for theoretical values and S is for simulated values).

- **Constraints:**

- On physical route flow-conservation constraints: They are similar to Eqns. (9)-(11) except that constraints are needed for both primary ( $P_{mn}^{tp}$ ) and backup ( $P_{mn}^{tb}$ ) paths.
- On link capacity constraints:

$$\sum_t (P_{mn}^{tp} + P_{mn}^{tb}) \leq P_{mn} \times W_{mn} \quad \forall m, n \quad (15)$$

- On connection availability constraints:

$$\text{Define } x = \sum_{mn} P_{mn}^{tp} \times \alpha_{mn} \quad (16)$$

$$y = \sum_{mn} P_{mn}^{tb} \times \alpha_{mn} \quad (17)$$

$$1 - (1 - e^{-x}) \times (1 - e^{-y}) \geq A'_t \quad \forall t \quad (18)$$

Due to the nonlinearity of Eqn. (18), the problem cannot be solved as an ILP. One approximation approach is to solve the ILP formulations without the constraints in Eqn. (18), i.e., optimize network resources to provide 1+1 protection for connections of  $T_2$  without considering the availability constraints. Since the dedicated-protection scheme may significantly improve the connections' availabilities, it is expected that the availabilities of most of the connections in  $T_2$  can be satisfied using this approximation.

Another approximation is to solve the ILP formulation by modifying the objective A in Eqn. (14) as follows.

- **Objective B:**

$$\text{Minimize} : \sum_t \sum_{m,n} (P_{mn}^{tp} \times \alpha_{mn} + P_{mn}^{tb} \times \epsilon) \quad (19)$$

where  $\epsilon$  is a constant which is much smaller than the minimal link-availability parameter. This objective tries to maximize the availabilities of the primary paths, and at the same time, minimizes the total wavelength links used by the backup paths.

## V. ILLUSTRATIVE NUMERICAL RESULTS

### A. Verification of Availability Analysis

We verify the theoretical availability analysis for a connection  $t$  which is dedicated or shared-path protected through simulations. As an example,  $t$  is assumed to have infinite holding

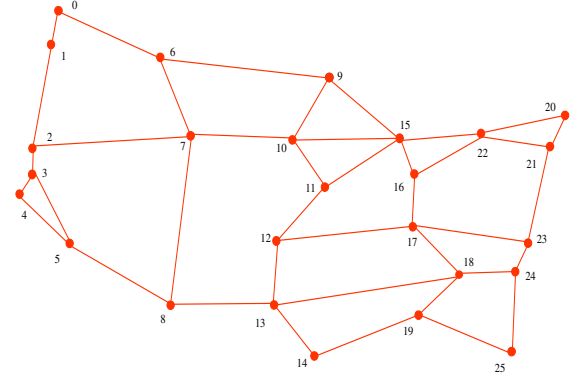


Fig. 3. A sample network topology.

time, and is carried by one primary path  $p$  (which traverses one link with length 1000 km) and protected by a backup path  $b$  (which traverses one link with length 3000 km). Failures occur independently on each fiber link following a Poisson process. The average failure arrival rate is normalized in the unit of  $FIT^1$ . For illustration purposes, we assume that the fiber-failure rate depends only on the fiber length. Failure-holding time follows a negative exponential distribution with a mean value of 12 hours. In shared-path protection case,  $b$  is shared among  $n$  other connections, as shown in Fig. 1. When  $b$  is released by a connection, it will be used in a first-come first-serve manner to restore other connections whose primary paths are experiencing failures.

In Fig. 2, we compare the simulated connection availabilities with the results from theoretical analysis under different values of  $n$ , i.e.,  $n = 0, 5, 10$ , or  $30^2$ . We can observe that the simulation results perfectly match our theoretical analysis. In Fig. 2, the lowest two curves show the simulated and the theoretical connection availabilities without any protection (again they show excellent match). Our results indicate that a connection's availability will: (1) improve if it is dedicated or shared-path protected; (2) decrease with the increase of shareability; and (3) decrease when failure rate ( $FIT$ ) increases.

### B. Network Performance Using the Proposed Availability Analysis and ILP Provisioning Approach

The network shown in Fig. 3 is used as a sample topology in our study. It has 26 nodes and 80 unidirectional links. (Each edge in Fig. 3 is composed of two unidirectional links, one on each direction.) For illustration purposes, the availability of each link is a preassigned value which could be 99%, 99.9%, or 99.99%. The connection request set  $T$  has 1000 connections, which are randomly generated and uniformly distributed among all node pairs. The availability requirements of the connection requests are uniformly distributed among 98%, 99%, 99.5%, 99.7%, or 99.9%. (Note that these numbers are just for illustration purposes.)

<sup>1</sup>Failure-in-time, number of failures per 10 km of fiber in  $10^9$  hours.

<sup>2</sup>Note that the connection is dedicated-path protected when  $n = 0$ .

TABLE I

RESULTS FROM ILP FORMULATIONS FOR FIVE PROVISIONING SCHEMES.

| Scheme | $W$ | $ASR$ | $W$ -Links |
|--------|-----|-------|------------|
| I      | 87  | 30.2% | 3361       |
| II     | 174 | 98.8% | 8442       |
| III    | 163 | 98.6% | 6707       |
| IV     | 163 | 99.9% | 7048       |
| V      | 163 | 100%  | 6720       |

TABLE II

STATISTICAL RESULTS FOR SCHEME III.

|       | Conn. | $W$ | Unsatisfied Conn. | $W$ -Links |
|-------|-------|-----|-------------------|------------|
| $T_1$ | 453   | 73  | 0                 | 1455       |
| $T_2$ | 547   | 90  | 14                | 5252       |

Table I compares the performance of different provisioning schemes in terms of the number of wavelength channels needed ( $W$ ), connection availability satisfaction rate ( $ASR$ ), and total wavelength links ( $W$ -Links).  $W$  denotes the number of wavelength channels the network needs to have, which is equal to the number of wavelength channels on the most congested fiber link in each scheme.  $ASR$  represents the fraction of the connections whose availability requirements have been satisfied through different schemes.  $W$ -Links denotes the total number of consumed wavelength fiber links. Note that, in each scheme,  $W$  is equal to the minimal number of wavelength channels through which the network can carry all the connection requests.  $W$ -Link is optimized according to the value of  $W$ .

In Scheme I, all connections are provisioned without any protection, and network resources are optimized without any connection-availability consideration. In Scheme II, all connections are provisioned with 1+1 protection, and the network resources are optimized without any connection-availability consideration. In Scheme III, connections are first classified into  $T_1$  and  $T_2$ . Connections of  $T_1$  are provisioned using the ILP approach in Section IV-B. Connections of  $T_2$  are provisioned using the ILP approximation (in Section IV-C) with Objective A (Eqn. (14)). Scheme IV is similar to Scheme III except that for connections in  $T_2$ , Objective B (i.e., Eqn. (19)) is used.

We can observe from Table I that, Scheme I consumes the least amount of resources compared with the other schemes. But in Scheme I, only 30.2% of the connections can meet the required availabilities. By providing 1+1 protection to all connections, Scheme II can significantly improve the connection availability satisfaction rate (i.e.,  $ASR$ ); however, it also consumes a large amount of resources. One can also observe that there are still some connections whose availability requirements are not satisfied in Scheme II. This is because, for these connections, the primary and the backup paths are the most resource-efficient path pair but they may not be reli-

able enough.

Through connection classification and traffic optimization, both Schemes III and IV jointly optimize  $ASR$  and resource usage. Schemes III and IV use less wavelength channels and around 20% less  $W$ -Links compared with Scheme II. Table II shows statistical information on connection classification, resource usage, and service satisfaction for Scheme III. We can see that all the connections in  $T_1$  and most of the connections in  $T_2$  (except 14 connections) receive the required services, which leads to Scheme III's 98.6%  $ASR$ , shown in Table I.

Compared with Scheme III, Scheme IV further increases  $ASR$  by consuming a little more network resources (i.e.,  $W$ -Links). Based on this observation, we develop another approach, Scheme V, which can be viewed as a joint procedure of Schemes III and IV. In Scheme V, instead of applying the optimization objective B (Eqn. (19)) to all the connections in  $T_2$ , we only apply it to the 14 availability-unsatisfied connections in Scheme III. By consuming 13 more  $W$ -Links (but no more wavelength channels), Scheme V can achieve 100%  $ASR$  compared to Scheme III.

Other network topologies and different connection demands were also tried, and similar results were observed.

## VI. CONCLUSION

We presented a novel provisioning framework which can cost-effectively provide appropriate protection services according to customers' availability requirements. The numerical results showed the correctness of our availability analysis and the effectiveness of our provisioning approach. As an initial study, we only considered static traffic and unprotected or dedicated-path-protected services. The study of availability-aware connection-provisioning for dynamic traffic and shared-protected service is in progress and not included in this paper.

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