Wavelength Converter Management in All-optical Networks with Arbitrary Topologies Using Abstracting Techniques[1]

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***Abstract*—Previous works have shown the wavelength conversion can considerably reduce the blocking probability in all-optical networks, but most of analytical models and algorithms are proposed under simplifying assumptions or restricted to specific cases. In this paper, we first introduce an abstracting technique called Blocking Island (BI) paradigm. A Blocking Island Hierarchy (BIH) can be constructed by using the BI paradigm and bottleneck links can be easily identified in BIH. We then propose the wavelength placement algorithms using this abstracting technique both in static traffic case and dynamic traffic case. To make sure our algorithm is applicable in arbitrary topologies and any incoming traffic patterns, a simulation-based optimization approach is employed. In the simulation, we show the performance improvement obtained by full wavelength conversion can almost be achieved by using limited number of wavelength converters with careful placement. In a random generated network topology, we demonstrate our algorithm outperforms the best existing allocation scheme.**

***Keywords*—Wavelength conversion, blocking Island, wavelength division multiplexing**

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) divides the bandwidth of a single fiber into different wavelength channels and there is no interference between transmissions on each wavelength. There are two types of architectures of WDM optical networks: single-hop and multi-hop [1] [2]. In single hop systems, a link is directly set up between each node pair. Any communication session is completed within one hop. So there is no need for the wavelength translation and wavelength converters have no effect on the blocking performance. Although the single hop architecture is simple, it needs a huge number of wavelengths and high switching capacity going through each node. The implementation of a large size single-hop optical network is not feasible. As a result, a multi-hop architecture is proposed. In multi-hop systems, a lightpath of a pair of node can consist of several path segments. If there is no wavelength translation in the intermediate nodes, a connection must be established along a route using a common wavelength on all of the links making up the route. This wavelength continuity constraint may be removed by the introduction of wavelength converters, which are devices that take the data modulated on an incoming wavelength and transfer it to a different outgoing wavelength. Obviously, wavelength converters improve the network blocking performance. Ideally, each node in the network is able to remove the wavelength continuity constraint completely. However, because of the expensive hardware cost and node complexity, we usually only have a limited number of wavelength converters. In light of the constraint of expense and node complexity, an important problem arises: given a limited number of converters, how we place them in the network so that maximum network performance improvement is achieved.

There are two cases of wavelength conversion: 1) Complete conversion. Any wavelength can be converted into any other wavelength and such wavelength converters exist in every node. 2) Limited number of converters and limited range of conversion. This means only part of the network nodes has wavelength converters and those wavelength converters may only have limited range of conversion. The limited range of conversion means either it can only translate limited incoming wavelengths or the translation capacity is limited. There are three types: *a*) a limited number of nodes are provided with full range convertibility, meaning all incoming wavelengths can be translated to any other outgoing wavelengths; *b*) converters with limited range of wavelength conversion are placed at all nodes; *c*) converters with limited range of wavelength conversion are placed at a subset of nodes.

Why some nodes are more suitable to place a wavelength converter than others. The whole idea is based on an observation that in an all-optical network, some nodes are handling much heavier traffic load. It is because the topology of an optical network is often irregular and the incoming traffic is often nonuniform [3]. In addition, the allocation distance between wavelength converters may also affect the blocking performance [4].

We propose an algorithm using abstracting techniques to allocate the limited number of wavelength (all three types) in all-optical networks with arbitrary topology. We adopt the simulation-based optimization approach in which we first collect the utilizing statistics of each node and then perform the optimization of the allocation of wavelength converters. In the simulation, we show by optimizing the placement of limited number of wavelength converters, the blocking performance is very close to that of a network with full wavelength conversion at every node. We also compare our algorithm with the best

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existing allocation. The results demonstrate that our algorithm can greatly reduce the overall blocking probability.

The organization of the paper is as follows. In section II, we discuss the related work. In section III, we introduce an abstracting technique called Blocking Island (BI). Our algorithm is proposed in section IV. In section V, The benefits of our wavelength converter placement algorithm are studied by simulation in various network topologies. We provide our conclusions in section VI.

II. Related Work

The importance of wavelength converter placement has been explored and analyzed in various papers. Subramanian *et al.* [5] provide an important observation: wavelength converters greatly increase the blocking performance of a mesh-torus network with a degree of connectivity between those of ring and the hypercube. Lee and Li [6] proposed a shortest path routing algorithm to reduce the number of converters. The node configuration they employ is called *share-per-node* and they assume every node is equipped with the same and limited number of *full-wavelength converters* (FWCs). Notice the concept of FWC is different from our wavelength converter. FWC can only convert one incoming wavelength to any outgoing wavelength. So if a node is provided with full wavelength convertibility, the number of FWCs needed is equal to the total number of outgoing channels of that node. Based on the concept proposed by Lee and Li [6], Xia and Leung [3] improve the result by using a simulation-based optimization approach. To the best of our knowledge, this allocation requires the smallest number of FWCs to achieve a given blocking probability. [6] and [3] mainly focus on the type *b* wavelength converter placement problem. In terms of type *a* and *c* wavelength converter placement problems, the benefits of using wavelength converters in wavelength routed all-optical networks have been studied in [7]-[11] under various assumptions. Usually, the analytical models are derived from simple topologies and algorithms are proposed under statistical independence assumptions. Although good performance can be obtained, those algorithms are restricted to the specific cases and independence assumptions. Wan *et al.* [12] and Subramanian *et al.* [4] consider the optimal placement of wavelength converters. Wan *et al.* [12] shows the optimal placement is tractable in topologies like trees and trees of rings. Subramanian *et al.* [4] considers the placement of wavelength converters on a path assuming link load independence. We can get the optimal solution on some simple topologies such as the path, bus, tree and ring, but it proves to be very computational intensive.

III. Blocking Island Paradigm

In this section, we introduce an abstracting technique called Blocking Island (BI). We assume all the network requests are unicast traffic and the only QoS parameter taken into account is bandwidth. The network physical topology consists of m nodes arbitrarily connected by n bi-directional links. We depict it by a network graph $G=(V, L)$, where $|V|=m$, $|L|=n$. A request is defined by a triple: $d_u=(x_u, y_u, \beta_u)$, where x_u and y_u are distinct nodes of the network and β_u is the bandwidth requirement.

Developed from Artificial Intelligence, namely constraint satisfaction and abstraction and the theory of phase transition, BI (blocking island) [13] provides an efficient way of abstracting resource (especially bandwidth) available in a communication network. The goal is to find one and only one route for each demand so that the QoS requirements of the demand are simultaneously satisfied.

BI clusters parts of network according to the bandwidth availability. A β-*BI* for a node x is the set of all nodes of the network that can be reached from x using links with at least β available bandwidth. For example, in *Figure 1*, N_1 is a *40-BI* for node *V1*.

β-*BI* has some very useful properties. Below we list a few without proof (for a proof, see [13]).

Unicity: there is one and only one β-*BI* for a node. Thus if S is the β-*BI* for a node, S is the β-*BI* for every node in S.
Partition: β-*BI* induces a partition of nodes in a network.
Route existence: give a request $d_u=(x_u,y_u,\beta_u)$, it can be satisfied if and only if the node x_u and y_u are in the same β_u-*BI*.
Inclusion: If $\beta_i<\beta_j$, the β_j-*BI* for a node is a subset of the β_i-*BI* for the same node.

Using the concept β-*BI*, we can construct a recursive decomposition of Blocking Island Graphs in decreasing order of βs, e.g. $\beta_1>\beta_2>\ldots>\beta_n$. we call this layered structure of Blocking Island Graphs a Blocking Island Hierarchy (BIH). For example according to the demand *40>20>10*, we have such a BIH (Figure 1).

Given a request, using Routing Existence property we immediately know whether the request can be satisfied or not. It may be argued that a link-state routing protocol and Dijkstra's algorithm are also capable of checking the route existence. However, one of the key requirements of resource allocation in communications systems is the ability of responding very quickly to the question: can I have a route between A and B with a bandwidth X? Thanks to the route existence property of the Blocking Islands paradigm, unlike the link-state routing, this question can be answered without having to compute a route.

Based on BIH, we propose a new routing heuristic called the *lowest level* heuristic. It first does the routing in the lowest Blocking Island (it means the BI with the highest bandwidth requirement) which includes the nodes of the request, and then if there is no such a route, we route the request in the father of the original BI, until the bandwidth requirement of the demand is reached. Since the lower a BI is in the BIH, the smaller it is. We can save the searching space and achieve considerable computational gain. Also by routing first in the lower BI, we preserve the bottleneck links for the future use, reducing the risk of future allocation failures.

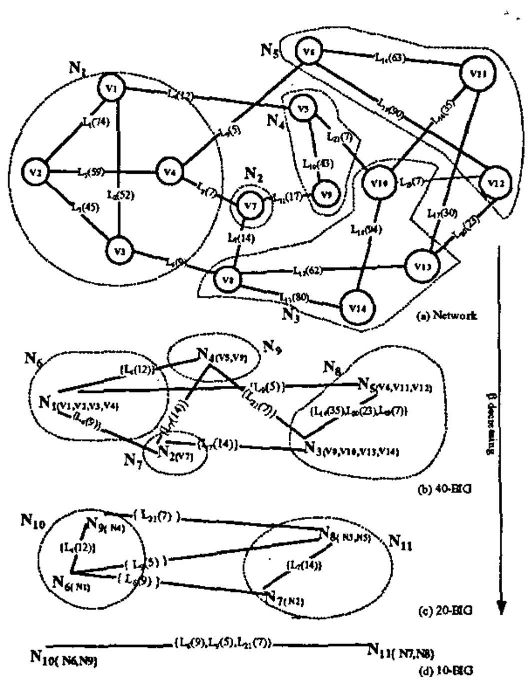

Fig.1 . The blocking island hierarchy for bandwidth requirement *{40, 20, 10}*. (a) Network graph; (b) *40-BIG*; (c) *20-BIG*; (d) *10-BIG*

The lowest level heuristic should be combined with the shortest path heuristic. We first try the routes at the lowest level possible in the BIH in shortest path route order; then the routes at the next level in shortest path route order, etc.

By employing the *lowest level* heuristic, we also inherently balance the workload amongst each wavelength and each node; therefore it can be viewed as a kind of overall load-balancing.

IV. PLACEMENT OF WAVELENGTH CONVERTERS

The placement of limited range wavelength converters at a subset of nodes is a NP complete problem in an arbitrary mesh network [6]. Given a certain number of wavelength converters, our objective is to reduce the blocking probability by allocating them in appropriate places. For an arbitrary topology and dynamic incoming traffic, it is nearly impossible to give an analytical model. All previous models are proposed under simplifying assumptions. In order to get an algorithm which is widely applicable and not restrained to any specific model and assumption, we adopt a simulation based optimization approach used in [3].

In this section, we propose a heuristic algorithm based on BI paradigm to place converters in arbitrary networks at a subset of nodes.

The basic idea is simple: try to find the most congested nodes and put converters on them. Since BI paradigm is to balance the load in the whole network by keeping the integrity of the blocking islands, we could easily decide the bottleneck links using BIH (Blocking Island Hierarchy). Our main idea is as follows. First assume each node of the network has complete wavelength conversion capacity. Then we record the utilization statistics for each node through processing the incoming traffic generated by computer simulation. Also based on the incoming traffic bandwidth requirement, we build the BIH. Usually we construct the BIH from bandwidth requirement 1 to w; w is the number of wavelengths in a fiber. Then based on the statistics of each node and the bottle neck links in the BIH, we place the wavelength converters.

1) *Static traffic*

If the incoming traffic of computer simulation is static, we first assume full conversion at any node. This means there is no wavelength assignment problem. We treat the network as one blocking island with the link capacity equal to the number of wavelengths. Since the traffic is static, we know all the requests in advance. According to the bandwidth requirements, we build the BIH. We also record the utilization statistics for each node. We then order requests by decreasing length of their MNH (minimum number of hops) distance and use the lowest level heuristic [13] to do the routing. In figure 1, we can see, the lower level a BI is in the BIH, the smaller it is and thereby we could achieve a computation gain. In addition, the lower a BI is, the more resource is available in the BI. We save the comparatively critical links for the future use. This scheme can be viewed as an over all load balancing.

After accommodating all the requests, check the BIH and utilization statistics. We could easily pick up bottleneck links and nodes with high volume of traffic. Then we can place converters on those nodes. The detailed algorithm is as follows:

Algorithm 1: Static Converter Placement
Input:
A set of static traffic requests and N converters
Output:
The placement of those N converters
Description:

1. Transform the network into a network without wavelength constraint;
2. Build the BIH based on the bandwidth requirement;
3. Order traffic requests by decreasing length of MNH(Minimum Number of Hops) distance;
4. Select an unallocated traffic request and route it using the lowest level heuristic [13]. The principle is to route a request in the lowest β-*BI*, where β-*BI* is the highest bandwidth requirement blocking island that accommodates the endpoints of the request. If the request can not be routed, record blocking information;
5. Update BIH and the utilization statistics for each node;
6. If the request set is empty, go to step 7; otherwise, go to step 4;
7. Check the utilization statistics for each node to order nodes in the decreasing order of traffic volume. Also check the BIH to identify the most congested links (bottle neck links);

8. Using the congested links and the statistics of traffic volume to decide N most congested nodes and place converters on them;

2) Dynamic Traffic

If the incoming traffic of computer simulation is dynamic, we first assume full conversion on any node. Every time a connection request arrives, reconstruct the BIH and record the bottleneck links. We also record the call duration statistics for each node. That is, for each transmission, how long the corresponding nodes are occupied. After testing enough number of requests, we calculate the tightness of each link and the call duration statistics for each node. For any link L, we define the number of times becoming bottleneck link as B_L and the total number of connection requests as N. Then

Tightness of a link $L = B_L / N$

Order all the links in decreasing value of tightness and order all the nodes in decreasing value of call duration statistics. The first link in the list with the highest call duration statistics has the highest priority to be put a converter on one of its two nodes. The second link has the second highest priority and so on. The detailed algorithm is as follows:

Algorithm 2: Dynamic Converter Placement
Input:
Dynamic traffic requests and N converters
Output:
The placement of those N converters
Description:

1. Transform the network into a network without wavelength constraint;
2. Build the BIH based on the bandwidth requirement from 1 to 1 to w; w is the number of wavelengths in a fiber;
3. A connection request arrives. Route the request using the lowest level heuristic [13].
4. Record the call duration statistics on the nodes along the route. Update BIH and record the Bottleneck links. In our case, we choose the link with bandwidth 1 as bottleneck links;
5. If a new request comes, go to step 3, otherwise, go to step 6;
6. Calculate the tightness of each link and the call duration statistics of each node;
7. Place N wavelength converters on nodes with the most congested links and largest call duration statistics

3) Routing and Wavelength Assignment

After a certain number of wavelength converters have been allocated to certain nodes, we should design a RWA algorithm to get good blocking performance. We extended the BI_RWA algorithm proposed in [14] to do the routing and wavelength assignment with limited number of wavelength converters.

In order to apply BI paradigm to the WDM optical networks to solve the Routing and Wavelength Assignment (RWA) problem, we first transform the network topology to BIG network model. Define a network topology G (V, L, W) for a given WDM optical network, where V is the set of nodes, L is the set of bidirectional links and W is the set of wavelength per fiber link. Assume this is a single fiber network without wavelength converters. The set of wavelength on each fiber link is the same. Each connection request needs to be allocated over a route and assigned one wavelength. The network can be abstracted into $|W|$ blocking island graphs (BIGs). Each BIG starts with one blocking island (BI) representing a wavelength and has the same topology as the original WDM optical network. So the BIG network model BIG $(m_1, m_2, \ldots m_{|W|})$ can be obtained from a given network topology G as follows. The topology of G is replicated $|W|$ times denoted by $m_1, m_2, \ldots m_{|W|}$. Each BIG m_i, which is made of one BI at the beginning, represents a wavelength and the link capacity is 1. An example is shown in figure 2.

It is obvious that this BIG network model is a simplified blocking island graph. All the properties such as Unicity, Partition and Route Existence still hold. Based on the BIG network model, we propose the BI_RWA algorithm and we also show it performs very well both in static traffic case and dynamic traffic case.

If we know the placement of converters and the conversion range of those converters, we simply replace the original BIG with the modified BIG as the initial input Graph in this case. For example, in figure 2, if we have a converter on node A that can convert wavelengths between 1 and 3 and a converter on node C that can convert wavelengths between 2 and 3, a converter on node B that can convert wavelengths among 1, 2, 3. The modified BIG network model is illustrated in figure 3.

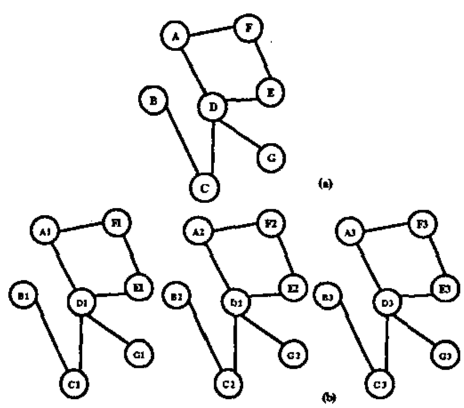

Fig. 2. (a) A network topology G with 3 wavelengths on each fiber link (b) The corresponding blocking island graph (BIG) with 3 blocking islands, where all links have a capacity of 1.

Five converter links $A1A3$, $B1B2$, $B2B3$, $B1B3$ and C2C3 are added into the original BIG. Here we assume the converter is used exclusively. That means when there is one route using the converter converting wavelength from a to b, any other route can't use it converting wavelength from b to a at the same time. So the converter links are bi-directional and the capacity is 1. Notice in calculating the shortest path, the weight of the converter links is 0.

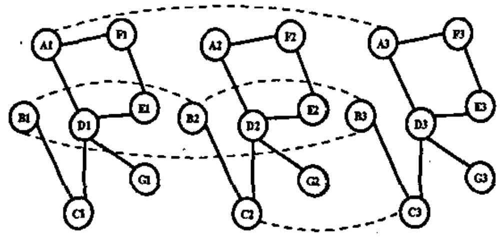

Fig.3. The BIG network with limited number of converters.

V. NUMERICAL RESULTS

Simulations have been carried out to examine the performance of placement of wavelength converters in the NSFNET with 14 nodes and 21 links, see figure4. The second network has a randomly generated topology [15], shown in figure 6, with 15 nodes and 29 links.

We use the same Dynamic Traffic Generator model employed in [15]. Calls (requests) arrive at each node according to an independent Poisson process with arrival rate α. An arriving session is equally likely to be delivered to any node in the network. The session holding time is exponentially distributed with mean $1/\mu$. Thus, the load per s-d node pair is $\rho = \alpha / N(N-1)\mu$, where N is the number of nodes in the network. Note that a node may engage in multiple sessions and several sessions may be simultaneously conducted between an s-d node pair. In our simulation, extensive tests are carried out to ensure a steady state is reached.

Figure 4 shows the 14 node NSFNet and the placement of wavelength converters. We assume the uniform traffic and employ the static converter placement algorithm to identify the most congested nodes. We place full-wavelength-converters on those nodes to test the blocking probability. In our case, we select 5 most congested nodes to place wavelength converters, as shown in figure 4. Those 5 nodes are then evaluated in figure 5 with dynamic traffic, where 10 wavelengths for each fiber are considered.

Figure 5 shows the benefit of using limited number of WCs, which can achieve a decent blocking probability (compare to no WCs) at the lower hardware cost by optimizing the location in the network. In figure 5, we can see, at lower loads, the blocking probability with wavelength converters is significantly lower, while at higher loads, the network without wavelength converters has low blocking probability (crossover effect). This phenomenon is due to the sub optimal routing algorithm. Since the networks are usually designed to only have 1-2% blocking probability, this needs not to be considered.

In figure 7, the random generated network topology has been explored for the comparison of different allocation and RWA algorithms. We assume the number of wavelengths is 8 and this is a single fiber all-optical network. The allocation and RWA algorithm we use to do the comparison is proposed in [3]. To our knowledge, it is the best existing allocation and RWA scheme without being restricted to any particular network model or assumption.

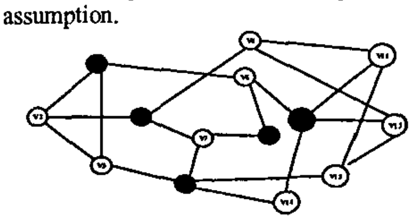

Fig. 4. 14 nodes NSFNet with 5 wavelength converters

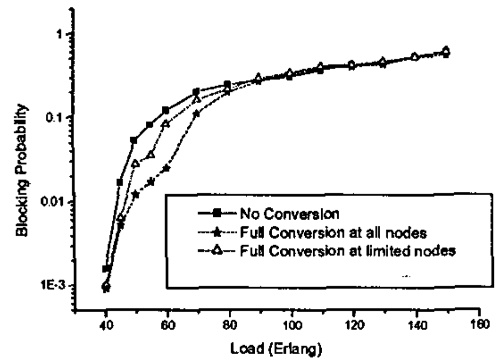

Fig. 5. Placement of Converters in 14 NSFNet

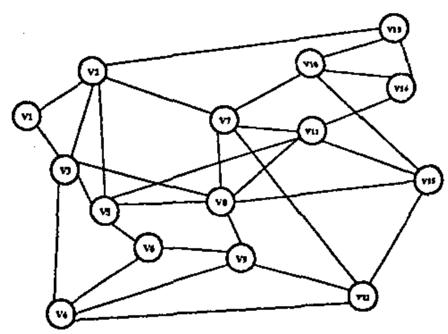

Fig. 6. A random generated topology

Because this allocation and RWA scheme is proposed in a different node configuration called *share-per-node*, we need to modify the algorithm so that it can be applied in this scenario. Based on the node statistics and bottleneck links, we place wavelength converters at corresponding nodes. In this example, we place full wavelength converters at four nodes. They are *V2, V4, V8* and *V10* in our algorithm and *V4, V5, V12, V13* in the best existing allocation scheme. In figure 7, we can see the blocking probability of both algorithms is much better than that of no wavelength conversion. And our method can give significant better performance. For example, when the load is 50 Erlang, the blocking probability of our method and the best existing allocation and RWA scheme is 2.3% and 4.1%, respectively.

Figure 8 shows the performance of our algorithm for the usage of limited range wavelength converters. The number of wavelength is 8 and it is a single fiber all optical network. The results show a better performance can be obtained by putting limited range of wavelength converters at every node. The blocking probability is reduced significantly when the degree of conversion is 1. When the degree of conversion is 2, the performance is very close to that of the complete wavelength conversion. However, putting limited range of wavelength converters at every node is still very expensive.

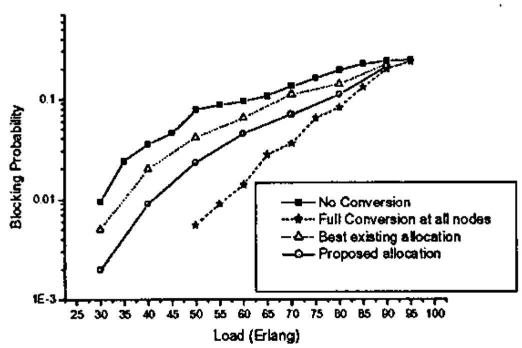

Fig. 7. Performance of the proposed algorithm and the best existing allocation scheme.

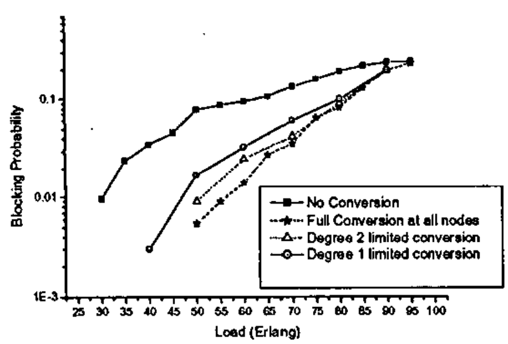

Fig. 8. Limited range conversion at all nodes in the random generated network topology

VI. CONCLUSION

In this paper, inspired by some artificial intelligence abstraction concepts, we have designed a framework to solve the placement of wavelength converters in all optical networks. A set of algorithms for the placement of wavelength converters in arbitrary networks have been proposed. By employing the simulation-based optimization process, we make sure the effectiveness of our algorithms in arbitrary topologies and incoming traffic patterns. We also propose an extended BI_RWA algorithm to solve the routing and wavelength assignment problem with wavelength conversion. Simulation results have demonstrated our algorithms performed very well under different topologies. Compared with the best existing allocation scheme, our algorithm can greatly reduce the blocking probability.

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