

A Progressive First-hit RWA Framework for Optical Networks with Blocking Optical Cross-connects

Dannan Hong and Tong Ye*

State Key Laboratory of Photonics and Communications, Shanghai Jiao Tong University, Shanghai, China
{hdn0514, yetong}@sjtu.edu.cn, *Corresponding Author

Abstract: A progressive first-hit routing and wavelength assignment framework is proposed for multi-fiber optical networks equipped with blocking optical cross-connects, which can achieve up to 460-fold reduction in running time without any sacrifice in blocking probability. © 2026 The Author(s)

1. Introduction

With the rapid growth of bandwidth-intensive services, such as high-definition video streaming and online gaming, optical networks have to increase capacity by deploying multiple fibers on each link. This trend forces the number of ports on optical cross-connects (OXC), a key component of the optical node, to exceed 100 in the near future.

However, the design of large-scale nonblocking OXC is quite challenging. The dimension of standard OXC is completely determined by the port count of commercial wavelength-selective switch (WSS), which is limited to 49 [1]. Current proposals of large-scale nonblocking OXC in [2-4] suffer from high cost and significant insertion loss. In this context, blocking OXC become an option, e.g., FLEX [5], HIER [6], ring-type OXC [7], stacked OXC [8], and sparsely intra-connected OXC [9].

Though blocking OXC offer low cost, their installation in an optical network remarkably complicates routing and wavelength assignment (RWA). In the optical network with nonblocking OXC, RWA can be performed using only link state information, as a lightpath (LP) request will never be blocked by the OXC. However, in the optical networks with blocking OXC, LP requests may still be blocked due to the routing contention within OXC, even if an available wavelength can be found along a path. To lower the blocking probability (BP), the switching state of each OXC should also be considered in RWA, leading to high-complexity RWA algorithms. Refs. [5-7] propose an auxiliary graph to describe both the optical-link state and the OXC switching state, which makes the time complexity of RWA algorithms increase quadratically with the port count of the OXC. To reduce the running time, Refs. [8-9] resort to using k -shortest-path (KSP) based algorithms, which may sacrifice the blocking performance. Even so, the KSP algorithms have to check all the combinations of fibers on the links along all the alternative paths, resulting in a high time complexity.

In this paper, we propose a progressive first-hit RWA (p-RWA) framework, which can be applied to optical networks equipped with different types of blocking OXC to greatly reduce the running time without sacrificing the blocking performance. Our proposal is motivated by the fact that an LP request is seldom blocked by the internal contention within the OXC when the network traffic load is not very high, which is a common situation in practice. Thus, we first attempt to find an LP for each request by relying almost solely on the link state information, which will succeed with a high probability. If we fail to find an LP (typically with a small probability), we consider both the link state information and the switching state of OXC. Our simulation results confirm that our framework can significantly outperform the previous algorithms in running time.

2. Progressive First-hit RWA Framework

We consider a multi-fiber network, where the set of optical nodes is denoted by V and the set of optical links is denoted by E . Each optical link installs F bidirectional fibers, each of which carries W wavelengths. The number of the optical nodes directly connected to the i -th optical node is defined as the nodal degree of optical node i and is denoted as D_i . Let x be the add/drop (A/D) ratio of optical node i . It follows that the OXC of optical node i has $D_i F$ input/output ports on the line side, and $x D_i F$ ports on the A/D side. Fig. 1(a) plots a 6-node multi-fiber network, where $F = 2$ and $W = 2$.

The p-RWA framework consists of three sub-algorithms, called link-level RWA, direction-level RWA, and port-level RWA, respectively. These three sub-algorithms perform RWA using different amounts of state information, as we present as follows.

Link-level RWA performs RWA only using link state information, i.e., wavelength availability on optical links. Fig. 1(b) illustrates the idea of link-level RWA. We produce W graphs for W wavelength planes. In the w th graph, each vertex represents an optical node, and each directed edge stands for wavelength w from one node to another. An

edge has F free wavelength channels if it is completely idle. The number displayed on each edge is its weight, which equals infinity if all F channels are busy and equals the number of occupied channels plus 1 otherwise. The graphs in Fig. 1(b) are called link-level auxiliary graphs. We first search the shortest path across all the W graphs, as Fig. 1(b) shows, and then check if an LP can be established by examining the switching states of OXCs of the optical nodes along this path, using a depth-first search (DFS) algorithm. The time complexity of link-level RWA is $O(WN^2)$, where N is the number of optical nodes. Obviously, the link-level RWA may be unable to build an LP though there is a feasible RWA in the network. For example, if the shortest path in Fig. 1(b) is unavailable due to the internal blocking of optical node 2, it will miss the opportunity to set up an LP along the path on wavelength plane 2.

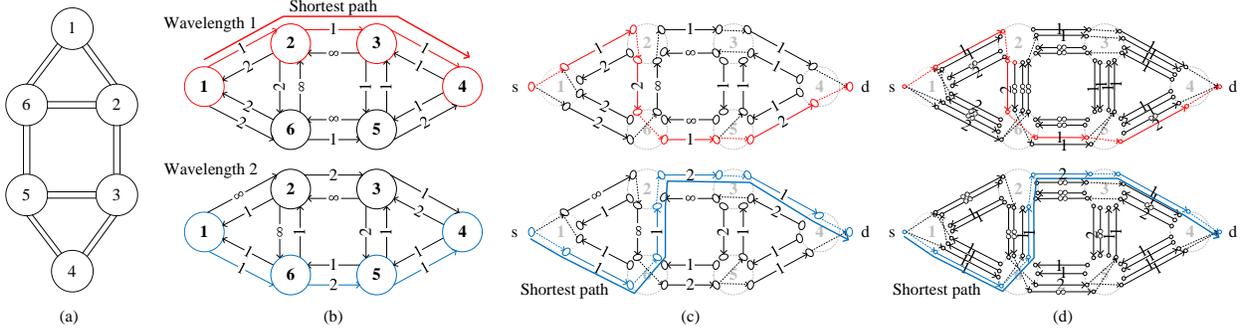


Fig. 1. Illustration: (a) physical network, (b) link-level RWA, (c) direction-level RWA, and (d) port-level RWA, where $F = 2$ and $W = 2$.

In addition to the link state information, direction-level RWA considers the reachability between each pair of input direction and output direction of OXCs. Fig. 1(c) provides an example. Vertex i in Fig. 1(b) is broken into $2D_i$ vertices in Fig. 1(c), each representing an incoming direction or an outgoing direction of optical node i , where $i = 1, 2, \dots, N$. We also add two vertices, denoted by s and d , which correspond to the add system of the source and the drop system of the destination, respectively. If there is an optical link from a node to another, introduce a solid directed edge to connect the corresponding vertices in Fig. 1(c). The weight of solid edge in Fig. 1(c) is defined in the same manner as that in Fig. 1(b). Moreover, in a node, if an outgoing direction is reachable by an incoming direction, we introduce a dotted directed edge with a weight of 0 between the corresponding vertices, which partially delineates the switching state of the OXC. The graphs in Fig. 1(c) are called direction-level auxiliary graphs. We first find the shortest path in all graphs from s to d and then check whether an LP can be set up along this path using a DFS algorithm. The time complexity of direction-level RWA is $O(W(ND)^2)$, where $D = \max_i D_i$. Similar to link-level RWA, direction-level RWA has the problem of missing the feasible RWA.

Port-level RWA uses both the link state information and the reachability between each pair of input and output ports of OXCs. As Fig. 1(d) plots, vertex i in Fig. 1(b) is now broken into $2D_iF$ vertices, each standing for an input port or output port of optical node i . Similar to Fig. 1(c), we also add vertices s and d for the source and the destination in Fig. 1(d). We introduce edges and their weights to each graph in a way similar to that in Figs. 1(b) and (c). The graphs in Fig. 1(b) are called port-level auxiliary graphs. We search for the shortest path across all the graphs. Clearly, the port-level RWA can always establish an LP, as long as there is a feasible RWA. Compared to the previous two algorithms, the port-level RWA has the highest time complexity, which is $O(W(NDF)^2)$.

The p-RWA framework can now be presented as follows:

- S1. Execute link-level RWA. If a feasible path is found, go to S4; if the request is blocked by OXCs on the found path, proceed to S2; otherwise, reject the request and jump to S5.
- S2. Perform direction-level RWA. If a feasible path is found, head to S4; if the request is blocked by OXCs on the found path, turn to S3; otherwise, reject the request and jump to S5.
- S3. Carry out port-level RWA. If a feasible path is found, proceed to S4; otherwise, reject the request and jump to S5.
- S4. Allocate wavelengths on the links along the found path to establish an LP for the request.
- S5. Terminate the RWA procedure.

It is easy to demonstrate that our framework has the following property. If an LP can be found by link-level RWA, it must be one of the shortest paths in the direction-level auxiliary graphs; if an LP can be found by direction-level RWA, it must be one of the shortest paths in the port-level auxiliary graphs. This indicates that our p-RWA framework has no performance loss in BP.

3. Applications in Optical Networks with Blocking OXCs

We evaluate the performance of p-RWA framework in 10-node CERNET [10] and 26-node MCNF-NET [11], as Fig. 2 shows. The number of fibers per link is $F = 10$ and each fiber carries $W = 8$ wavelengths. A/D ratio of each node is $x = 60\%$. The arrival of LP requests to each node pair follows a Poisson process with rate λ and the holding time of an LP is an exponentially distributed random variable with mean $\mu = 1$. It follows that the traffic load is given by $\rho = \lambda/\mu$. We apply p-RWA to three kinds of networks, which are respectively equipped with blocking Clos-type OXC [4], FLEX [5], and HIER [6]. The blocking Clos-type OXC is obtained by only using $W = 8$ OCSs in the central stage. Each simulation generates 10^6 requests to measure the BP and the running time of the RWA algorithms.

Figs. 2(a)-(c) present the simulation results under different scenarios. Fig. 2(a) studies the network with blocking Clos-type OXC. Obviously, we need port-level RWA to minimize the BP, if p-RWA is not applied. Fig. 2(a) thus compares p-RWA with port-level RWA. As one can see, the BPs of p-RWA and port-level RWA are the same under different traffic loads. This confirms that p-RWA has no performance loss in BP. Also, the running time of p-RWA is smaller than that of port-level RWA by 64 times when ρ is light and by 51 times when ρ is heavy in CERNET. This is attributed to the fact that, when ρ is light, the internal blocking probability of OXC is low and p-RWA can build an LP and thus early terminate with a very high probability after only executing its first step S1. Increasing ρ raises the probability of executing steps S2 and S3 of p-RWA, thereby increasing the running time of p-RWA. Moreover, Fig. 2(a) displays, when the network scale grows larger (from 10-node CERNET to 26-node MCNF-NET), the decrease in running time becomes more remarkable. Fig. 2(b) compares the BP and the running time of p-RWA with the routing, fiber, band, and spectrum assignment (RFBSA) algorithm proposed by [5] in the network deploying FLEX. Compared to RFBSA, p-RWA achieves the same BP but with much shorter running time. Fig. 2(c) further plots the results of networks equipped with HIER. The algorithm for comparison is the dynamic wavelength grouping and fiber selection (DWGFS) algorithm proposed in [6]. As Fig. 2(c) shows, p-RWA outperforms DWGFS in BP, since DWGFS does not consider the utilization of fibers on each link when performing RWA. Moreover, p-RWA runs much faster than DWGFS due to its progressive first-hit mechanism.

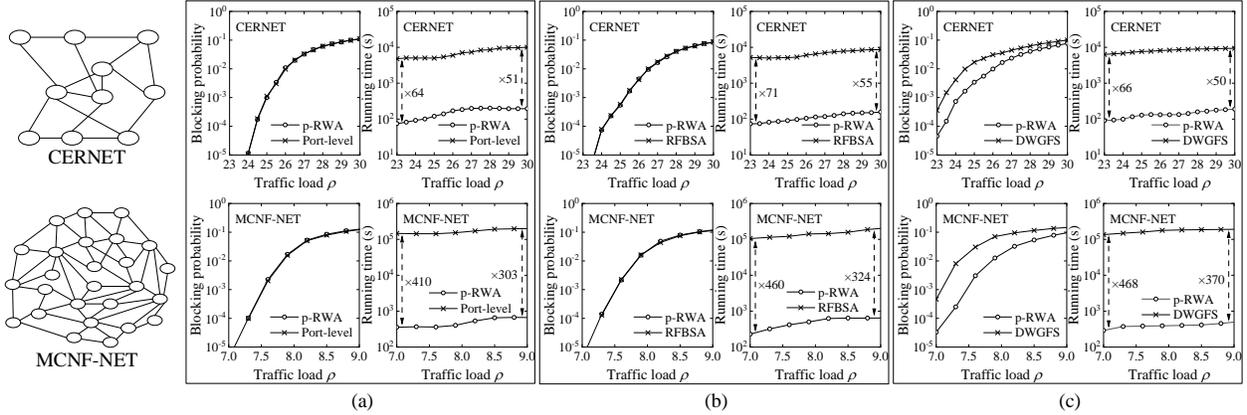


Fig. 2. Performance evaluation in the networks equipped with: (a) blocking Clos-type OXC, (b) FLEX, and (c) HIER.

4. Conclusion

We propose a low-time-complexity p-RWA framework for multi-fiber networks with blocking OXCs. Extensive simulation results confirm that our p-RWA framework can reduce the running time by 50 to 460 times without any performance loss in blocking probability.

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5. References

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